Physics and design of the eh detector

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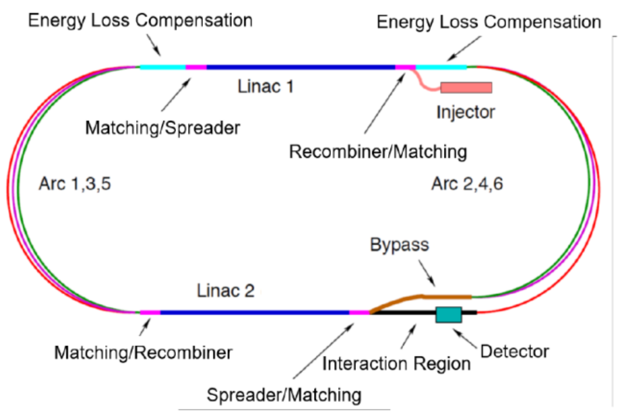
aaaa (remote presentation)

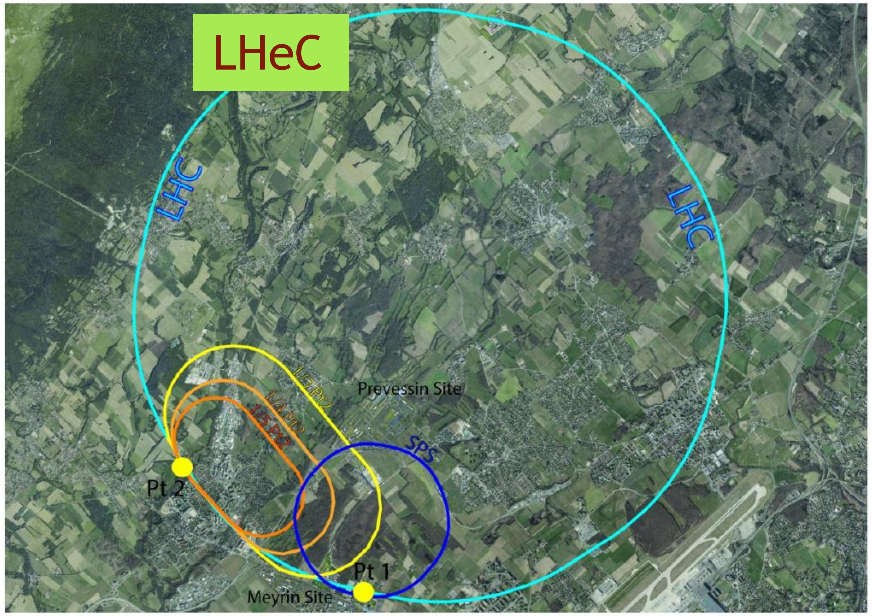
This talk

- 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

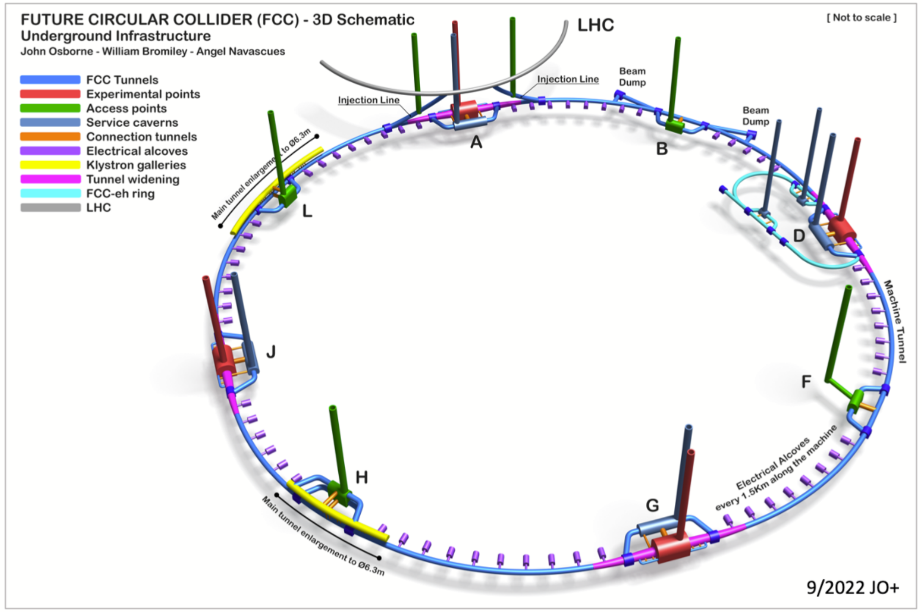


LHeC baseline:
50 GeV(e) × 7 TeV (p) 2.76 TeV/nucl. (A)

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

FCC-eh

CDR: 8 point FCC: point D

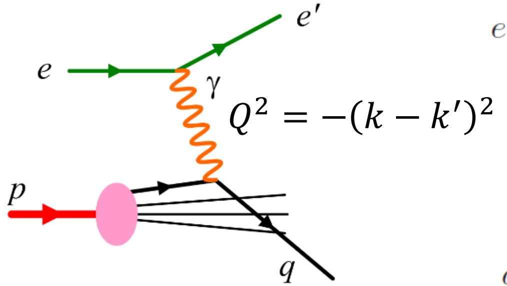


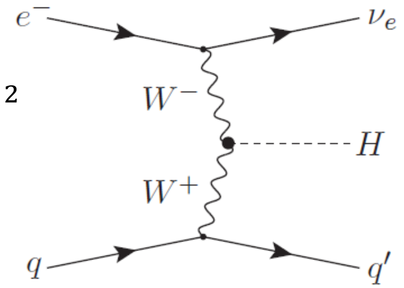
60 GeV(e) × 20 - 50 TeV (p)
7.9 - 19.7 TeV/nucl. (A)

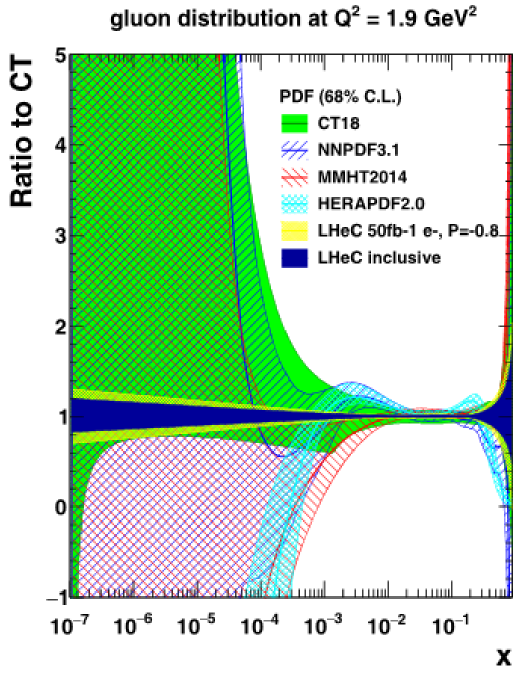
- $\sqrt{s} = 2.2 - 3.5\ (p)$ or $1.4 - 2.2\ (\mathrm{A})$ TeV
- $10^{34}\ \mathrm{cm^{-2}s^{-1}}$

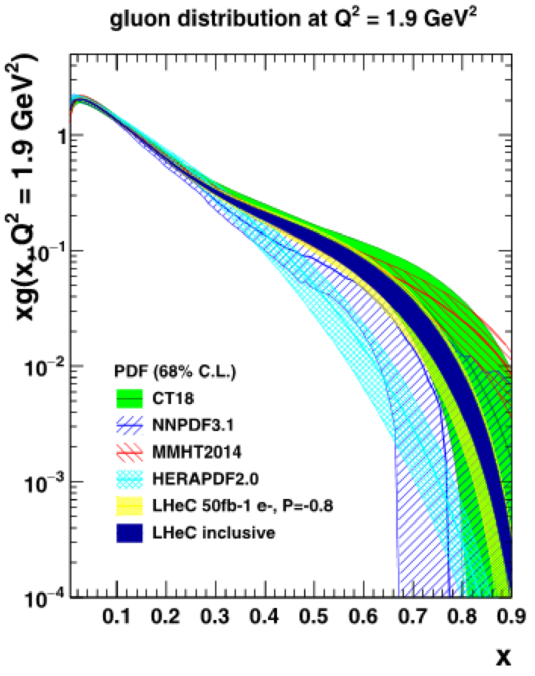
High-energy ep/eA collisions

- 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

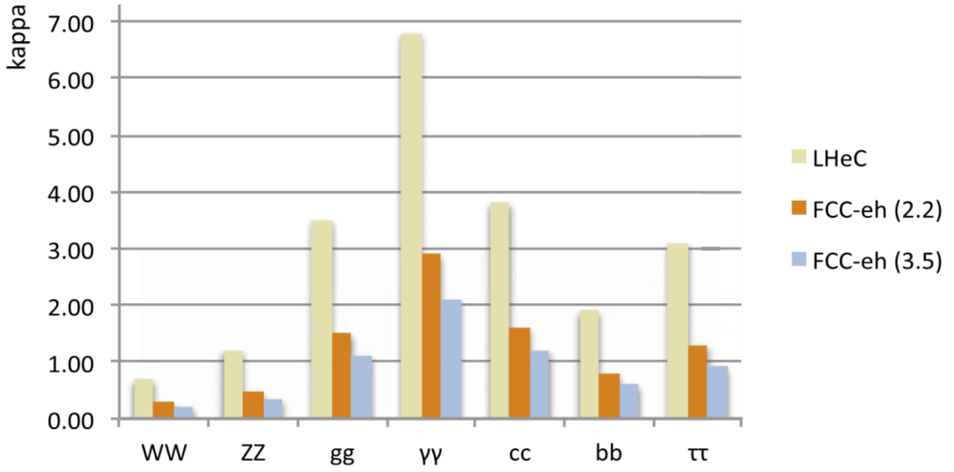
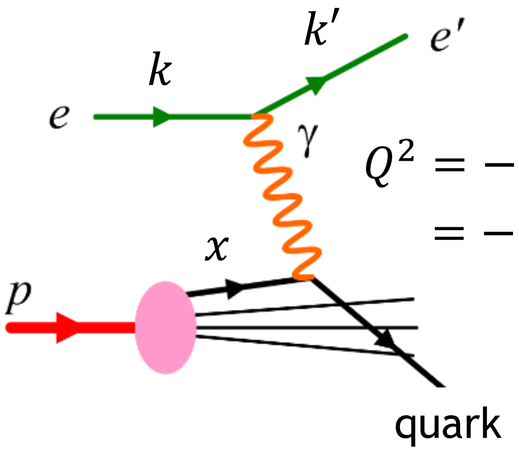


Figure 106. Summary of uncertainties of Higgs couplings from *ep* for the seven most abundant decay channels, for the LHeC (gold), the FCC-eh at 20 TeV of proton energy (brown) and for $E_p = 50$ TeV (blue).

P Agostini et al 2021 J. Phys. G: Nucl. Part. Phys. 48 110501

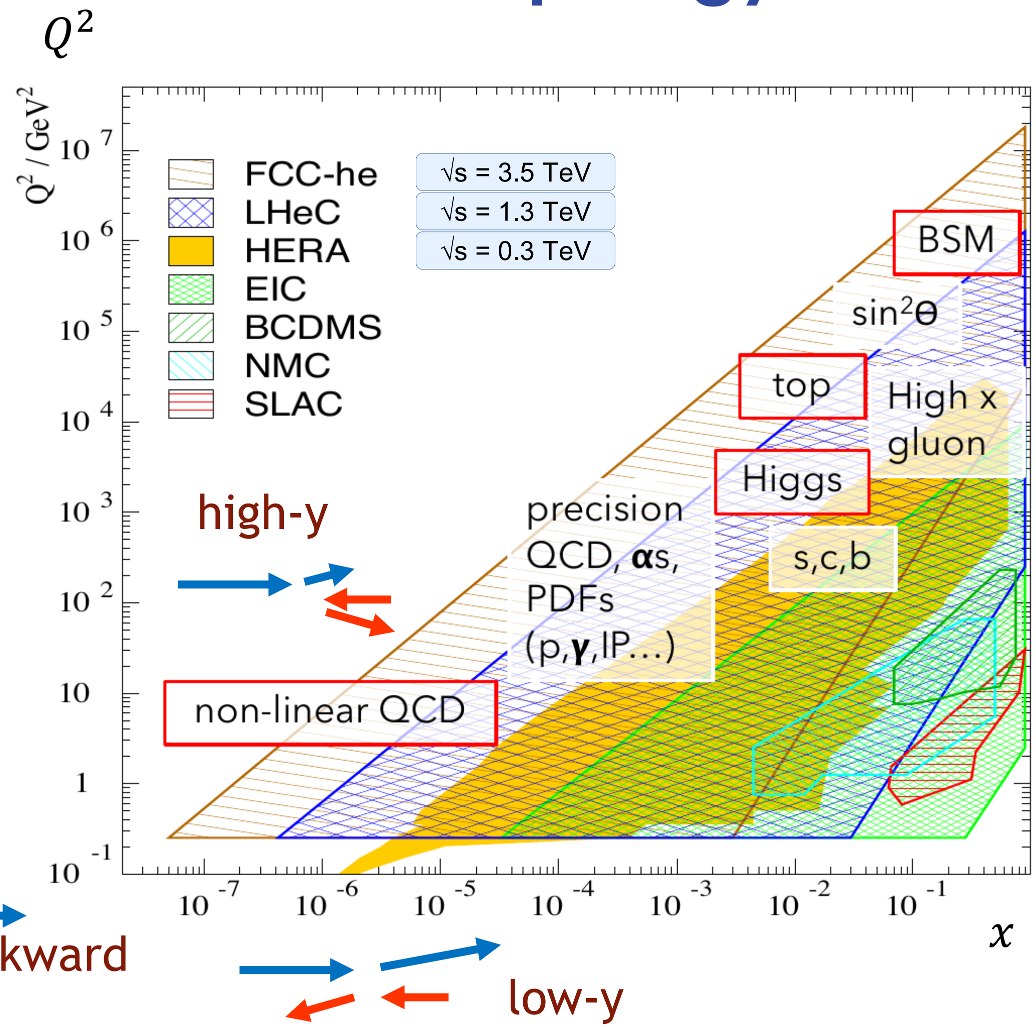
DIS kinematic plane and event topology

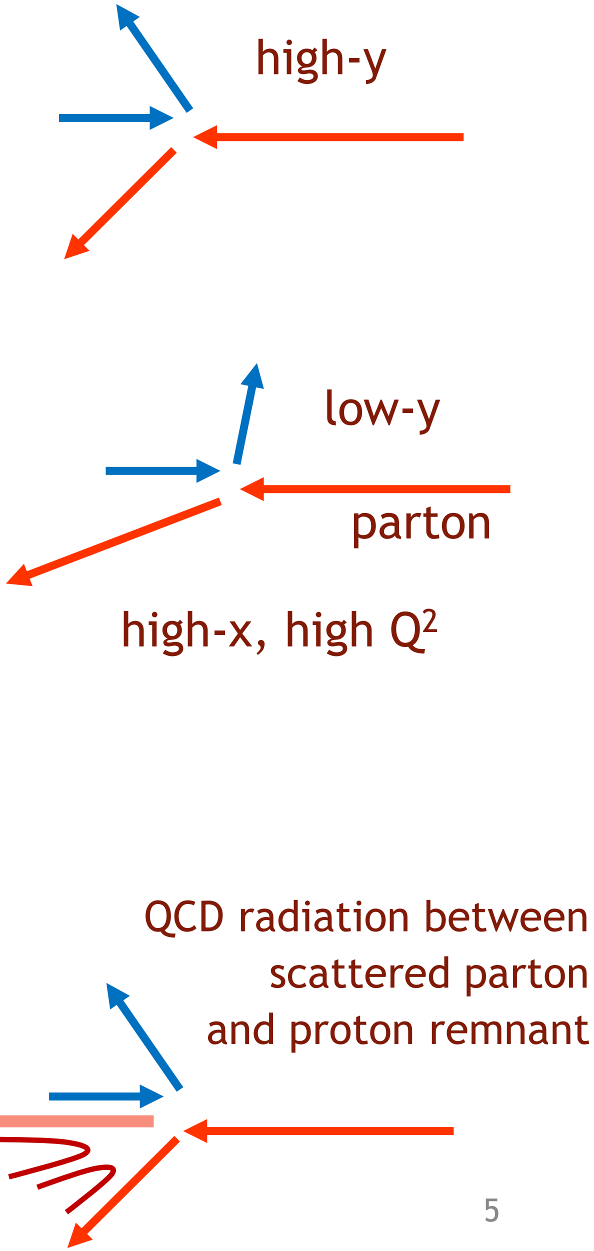


$$Q^2 = -(k - k')^2 = -q^2$$

$$x = \frac{Q^2}{p \cdot q} \quad y = \frac{p \cdot q}{p \cdot k}$$

$$sxy = Q^2$$





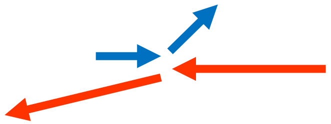
- Assymetric energy flow
  - particles go to incoming proton direction (forward), e to backward
- But they go to **everywhere** in practice, especially in small angles

Processes & Challenges (1): Neutral Current (NC) $ep \to eX$

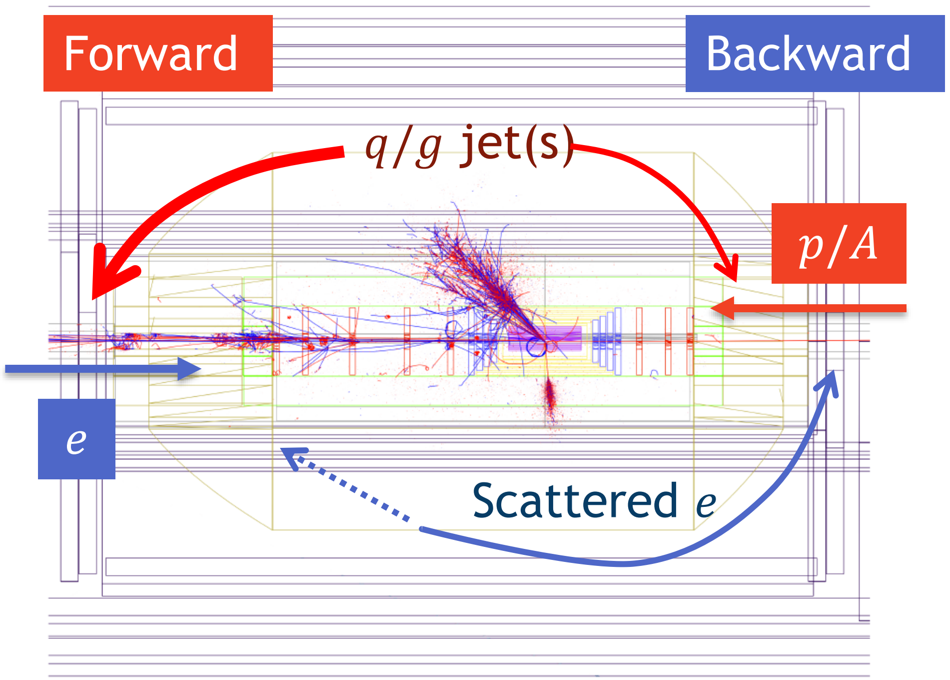
low-x / low-Q^2 events

- Scattered electron (e) towards small angle (< 179°)
- 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 $\gamma p \to X$**
- b/c tagging for decomposing pdf beyond $\eta = 3$

high-x / high-Q^2 events

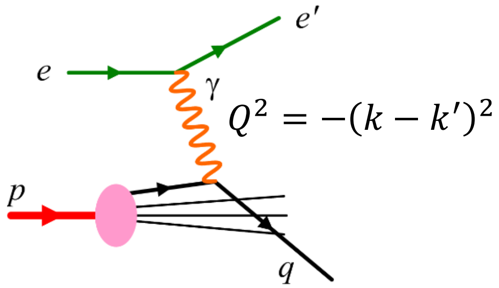


- electrons almost everywhere
- very high-energy jets ($O(\mathrm{TeV})$) also everywhere, especially in forward



An NC (leptoquark) event at LHeC

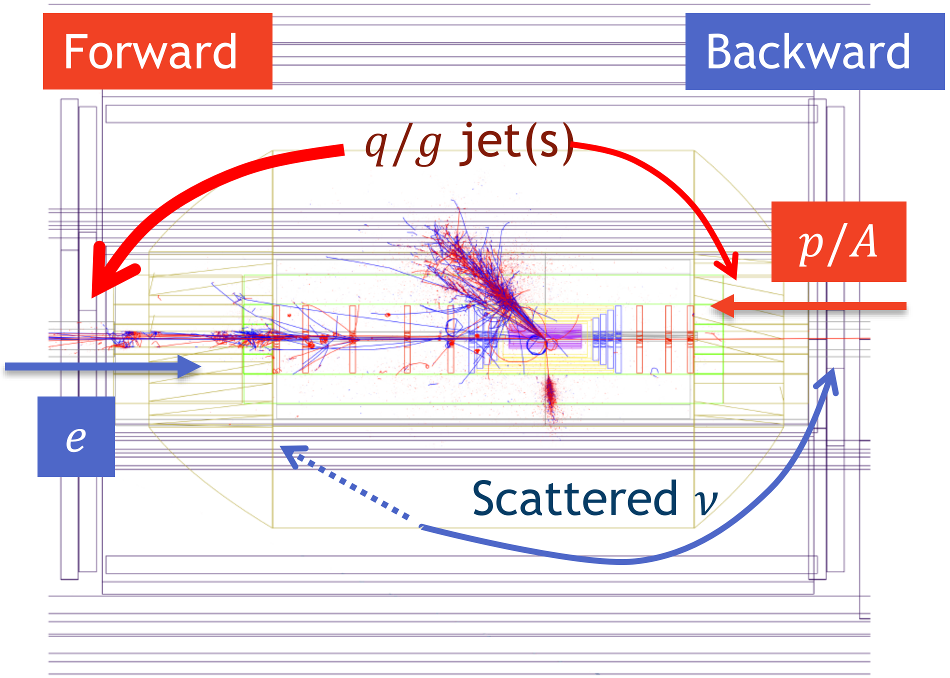
- Hermetic and thick EM and Hadron calorimetry
  - Fine granularity for e/π separation (esp. backward = e direction)
- Fine-pitch + small X_0 tracking for vertexing
  - for heavy-flavour tagging (esp. forward)



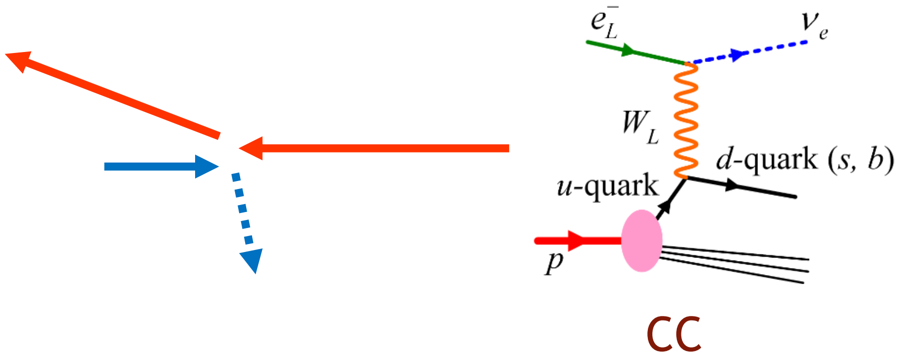
NC

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

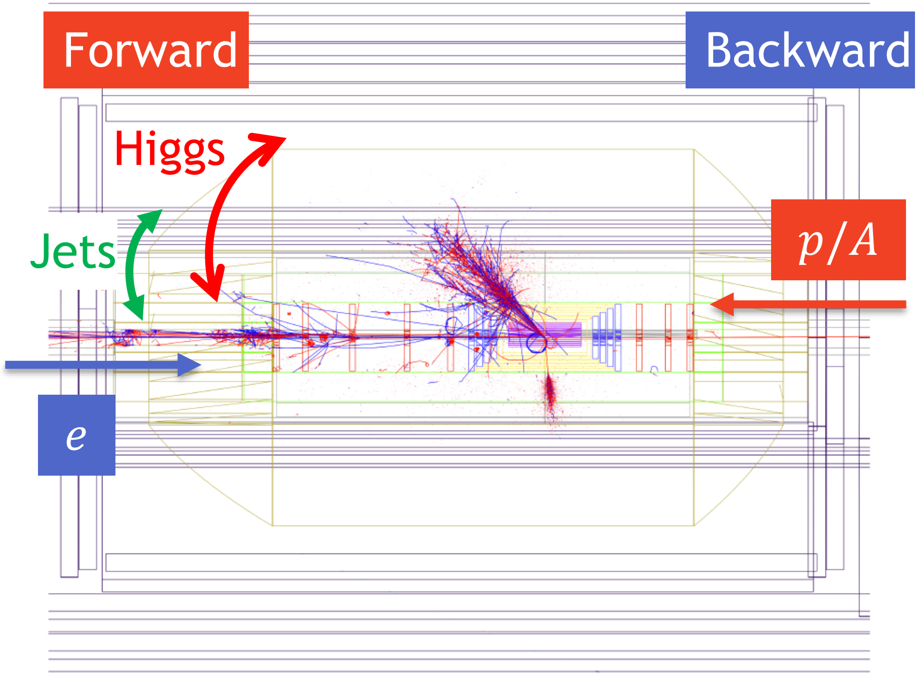


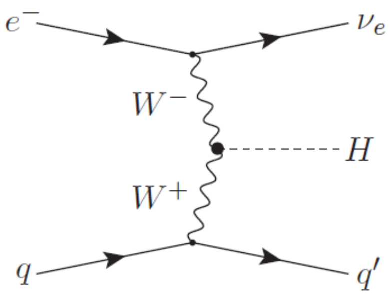
- Hermeticity (esp. forward)
- good HadCal resolution (e/h etc.)
  - tracking should help (particle flow algorithm)

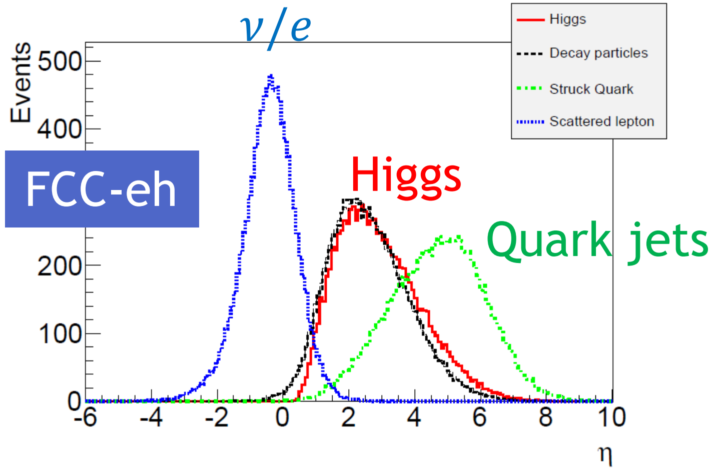


Processes & Challenges (3) Higgs / EW / top / BSM

- 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 <u>forward</u> direction
    - Jet resolution for mass reconstruction
- EW and top physics
  - similar mass range: similar requirement for flavour and jets
- BSM physics
  - high-mass → large-x events





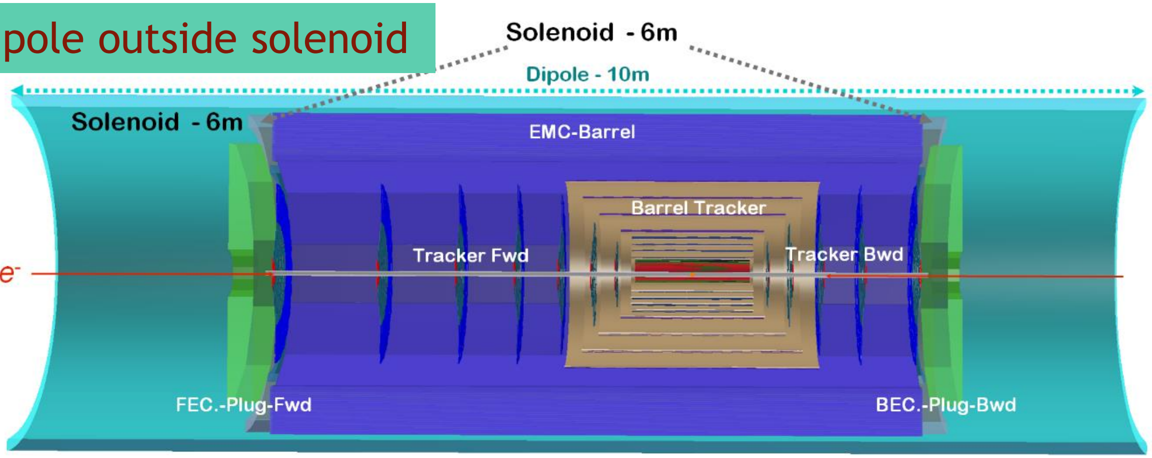


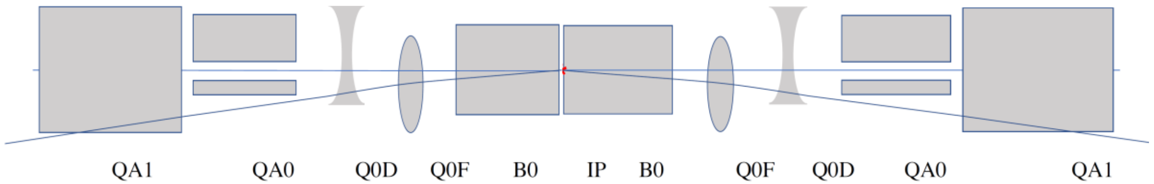
■ generic detector for high-Q^2 NC/CC should also serve for these processes

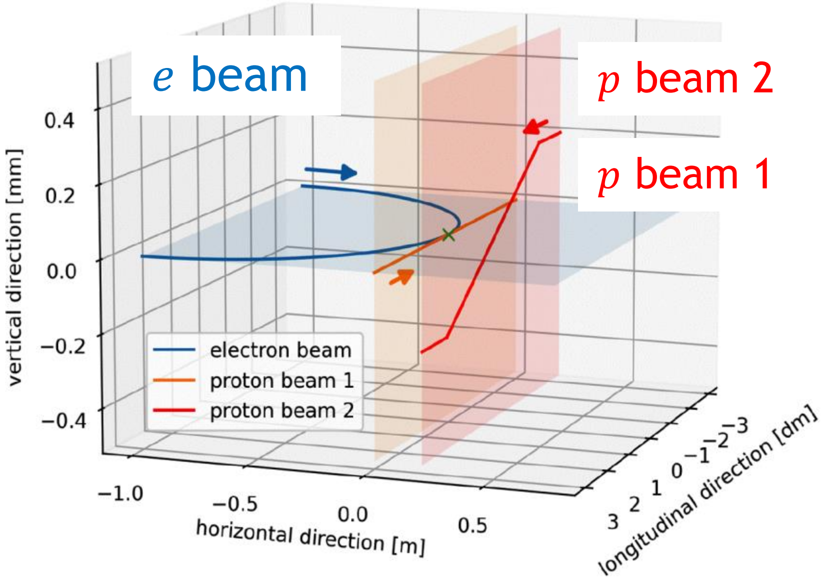
Machine-detector interface: IP and magnets (from LHeC)

- 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

Green: dipole outside solenoid



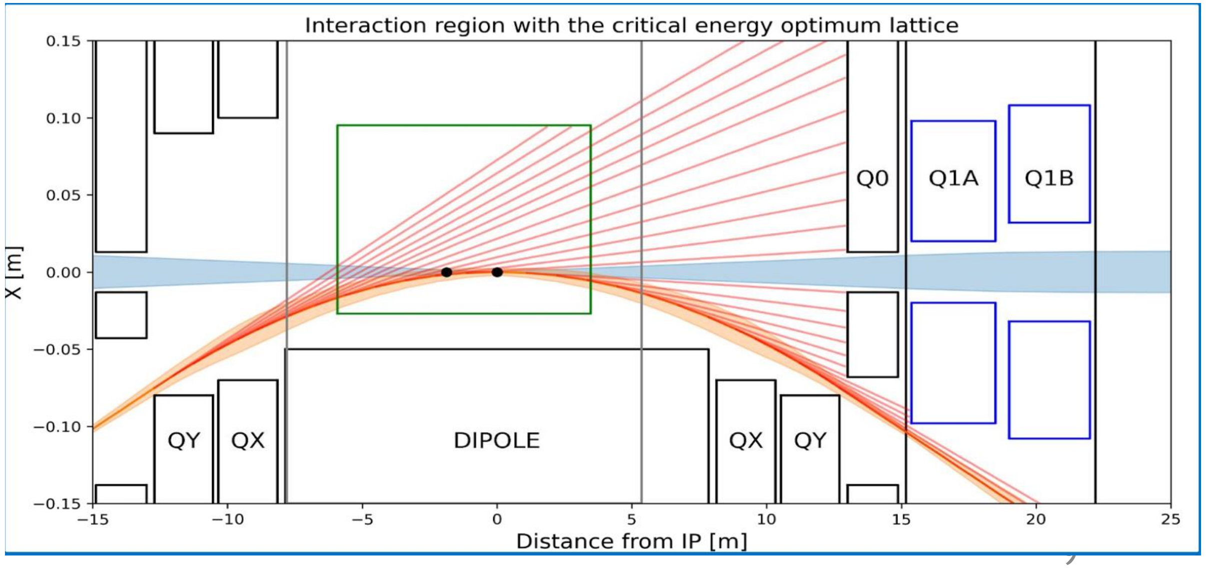




Synchrotron radiation fan (orange) - optimised optics

p beam 1

e beam



courtesy Daniel Hanstock from his master thesis

LHeC: New IR design for both eh and hh collisions at IR2

The baseline LHeC detector

Place for compensating solenoids not shown

Covering from 1 to 179 degrees

- All-silicon tracker with extended forward wheels
- EM calorimeter
  - LAr (barrel) or Si-Pb / Si-W
- Solenoid and dipole
- HCAL
  - Fe/Pb-sci. or Si-W
  - Si-W (endcap forw.)
- Muon system
  - embedded in return yoke

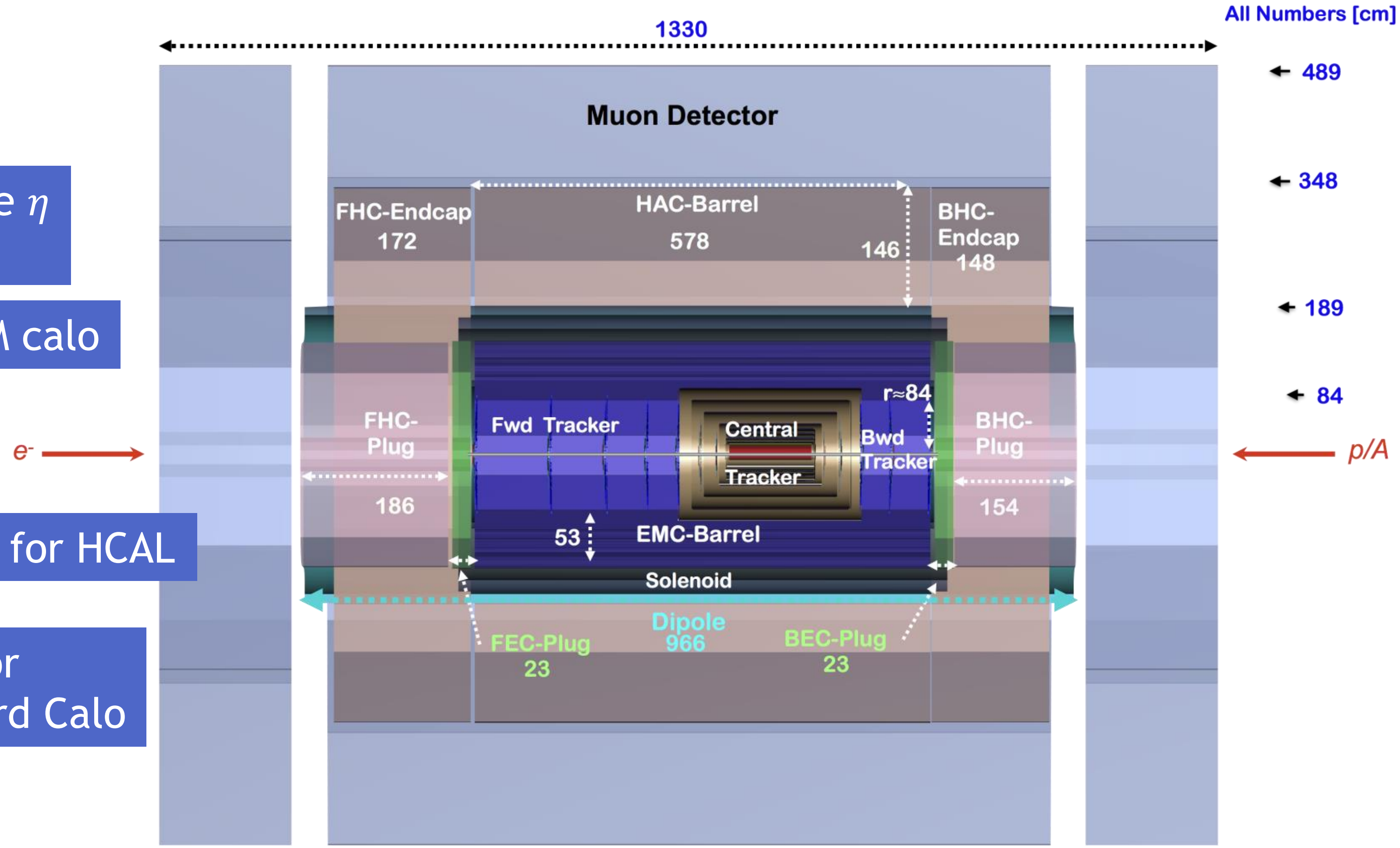
+ Forward/backward detectors along beamline

Covering wide η with small X_0

fine segment EM calo

Good resolution for HCAL

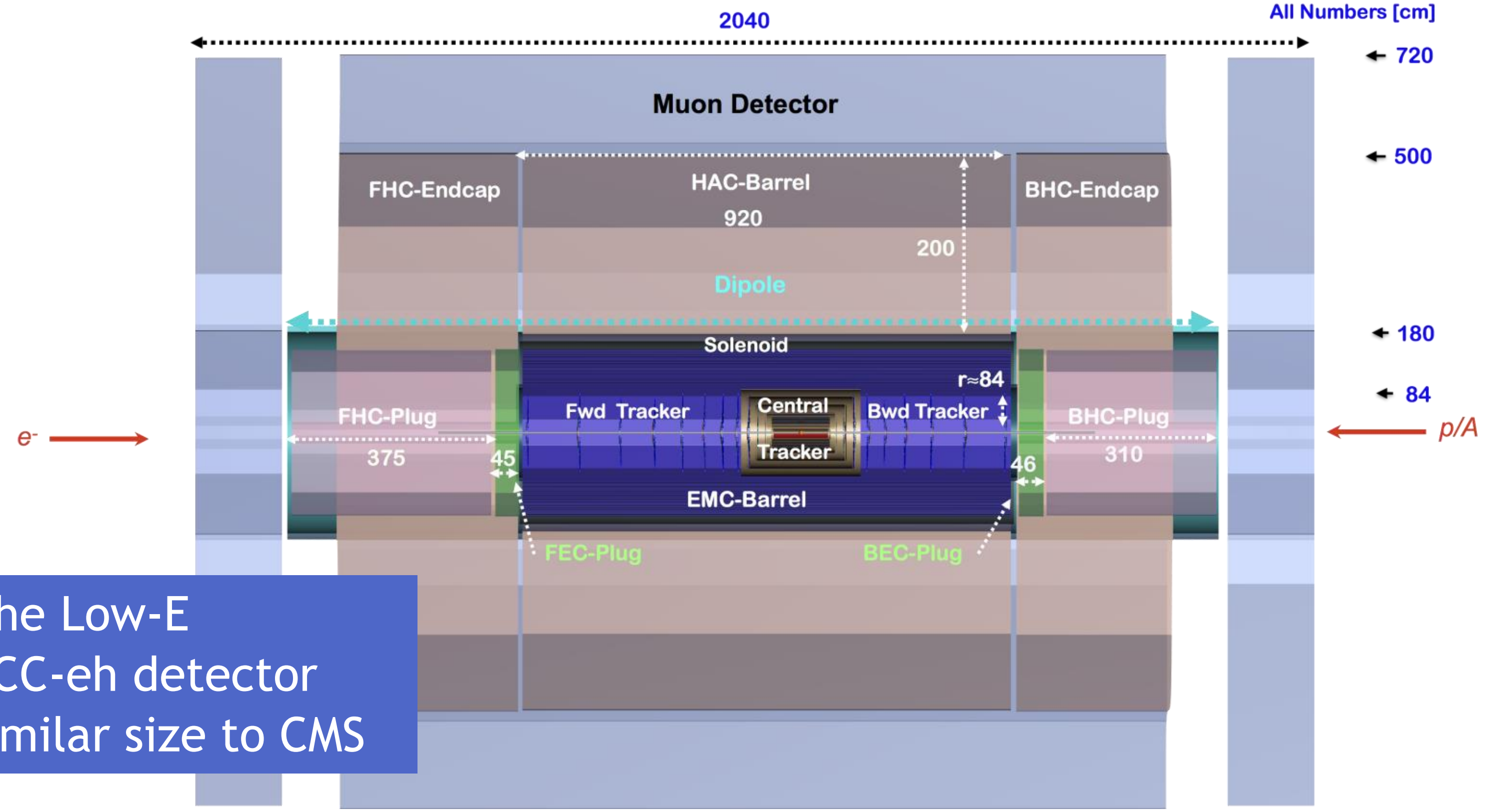
rad-hard for very forward Calo



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 propertlies (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 $\sim \log E_{had}$ for calo**



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

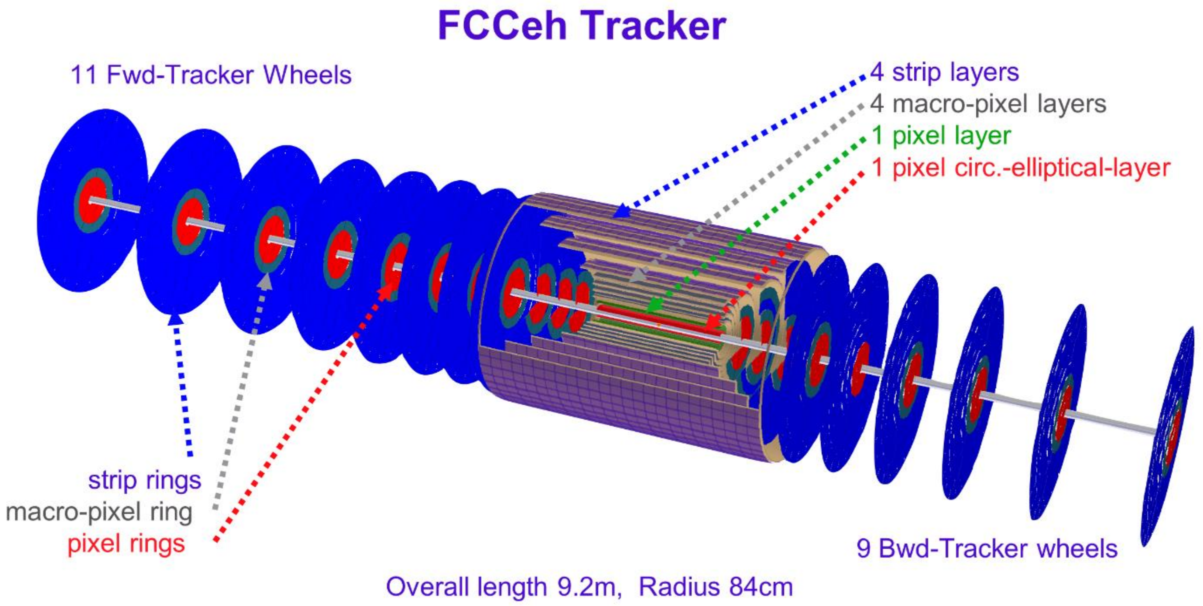
Most demanding: forward detectors

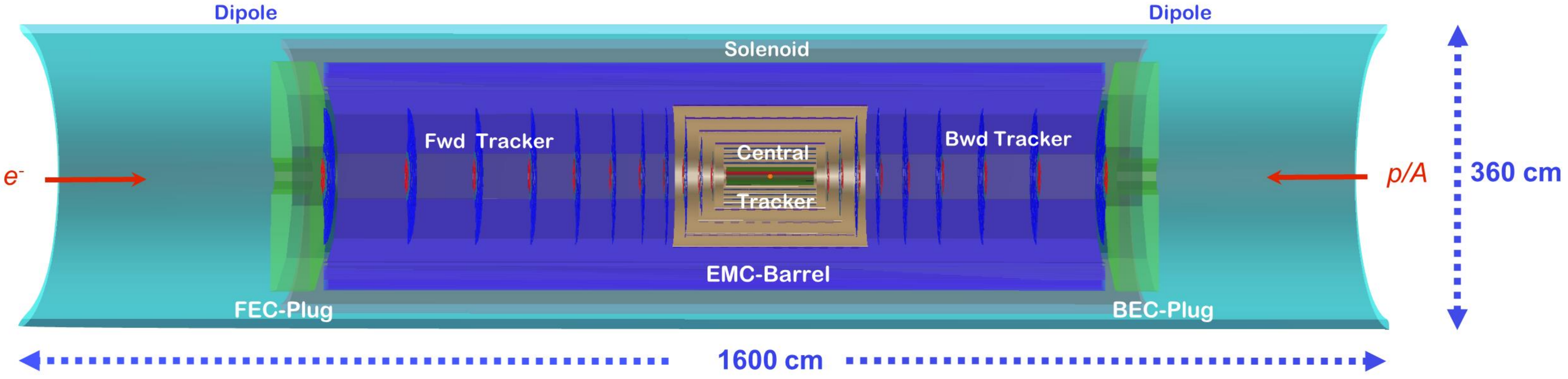
The Low-E
FCC-eh detector
similar size to CMS

Central tracker extension for FCC-eh

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

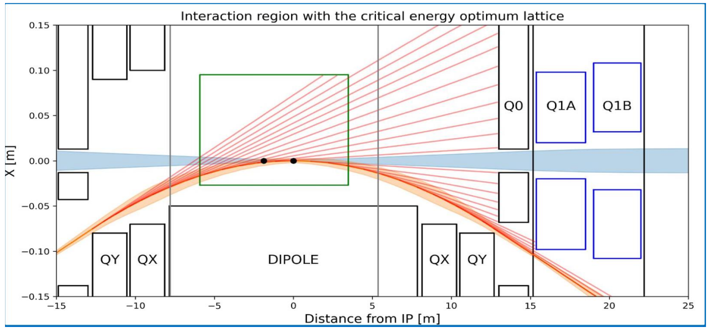
- More layers in Forward / Backward
  - 6m (LHeC) to 9.2m in length, rapidity coverage 5.3 → 5.6
  - # of forward disk: 4 → 7 or 8
- Planar (cost) and inclined (performance) options being considered
  - Inclined option: < 10% of X_0 achieved all over
- Area of rapid development: the final design would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

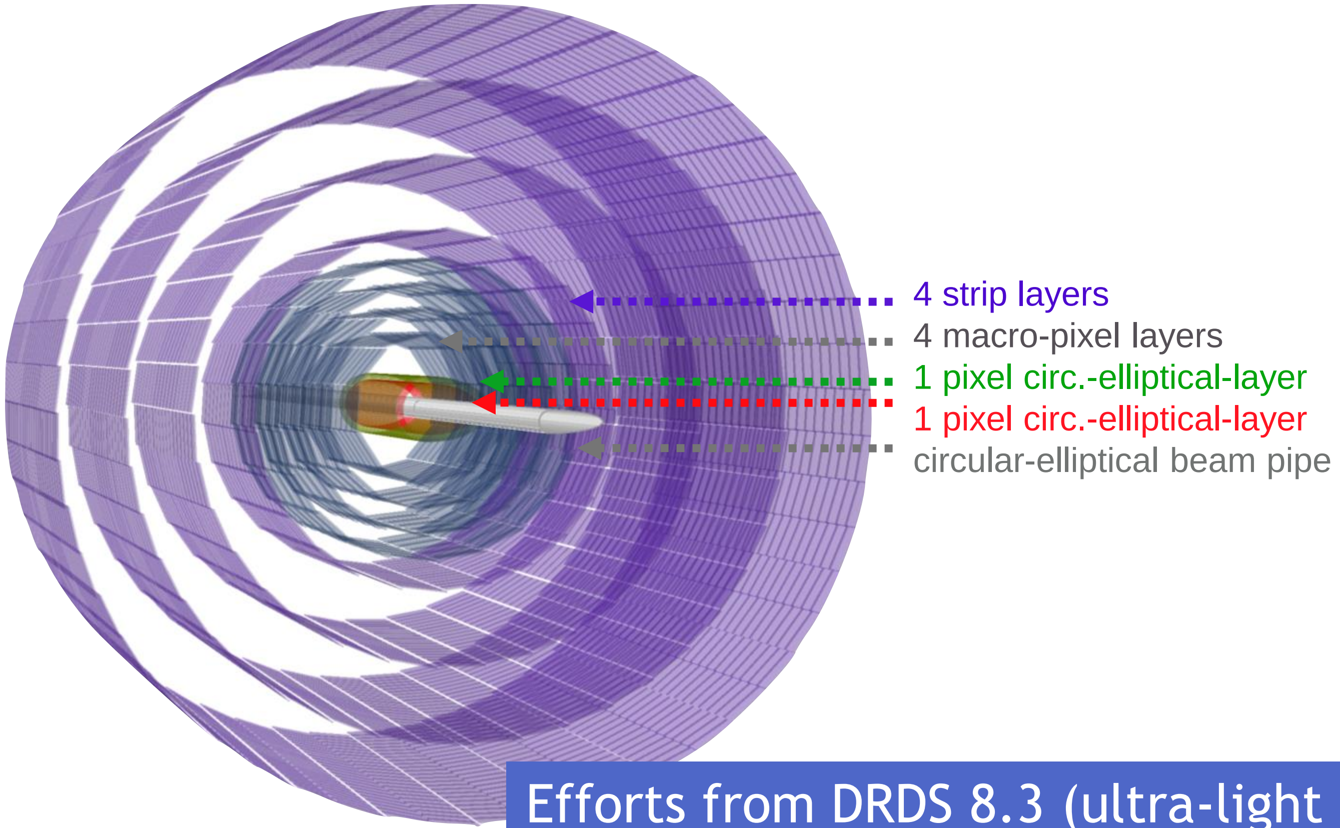


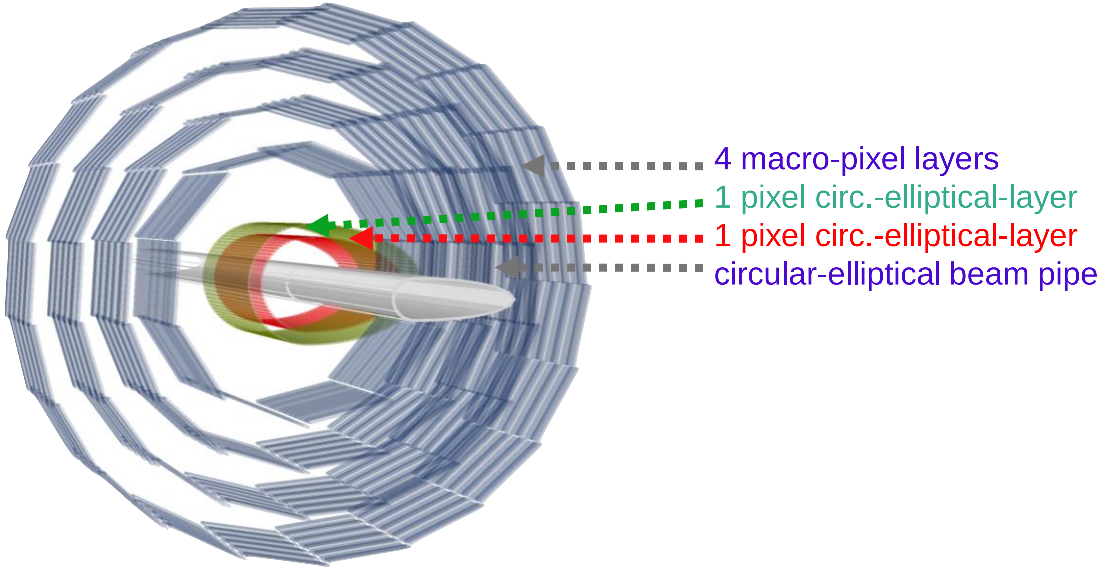


Barrel sensors and beampipe (version LHeC)

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



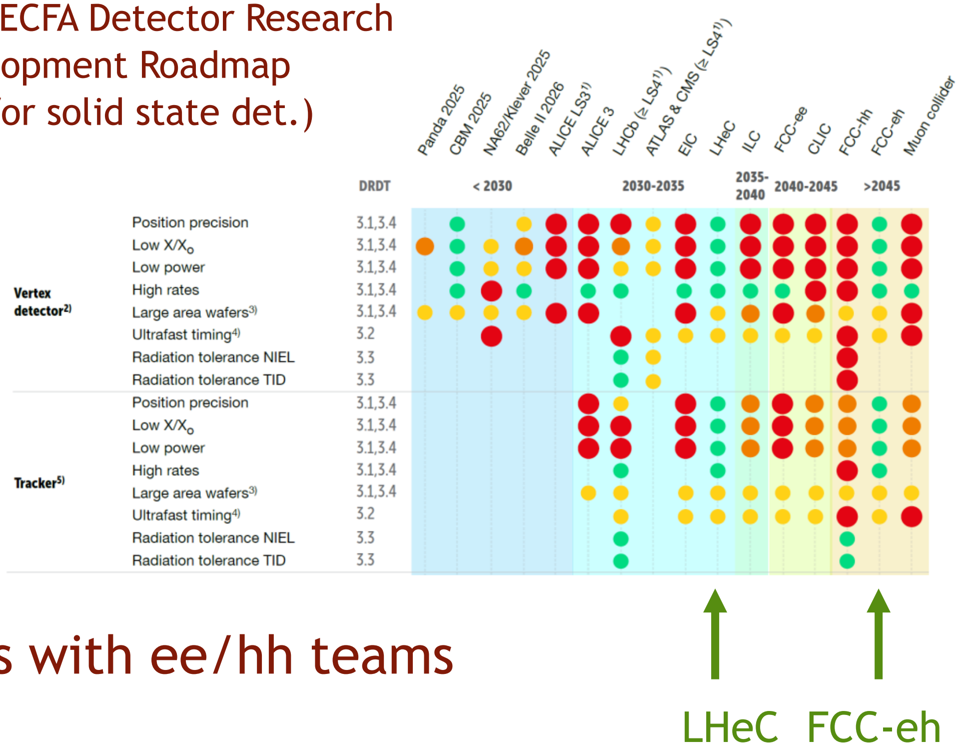




Efforts from DRDS 8.3 (ultra-light stable high precision mechanics, Machine-detector interfaces) should be persued

Detector challenges for FCC-eh

The 2021 ECFA Detector Research and Development Roadmap Fig. 3.1 (for solid state det.)



Officially the detector is thought to be relatively "easy"

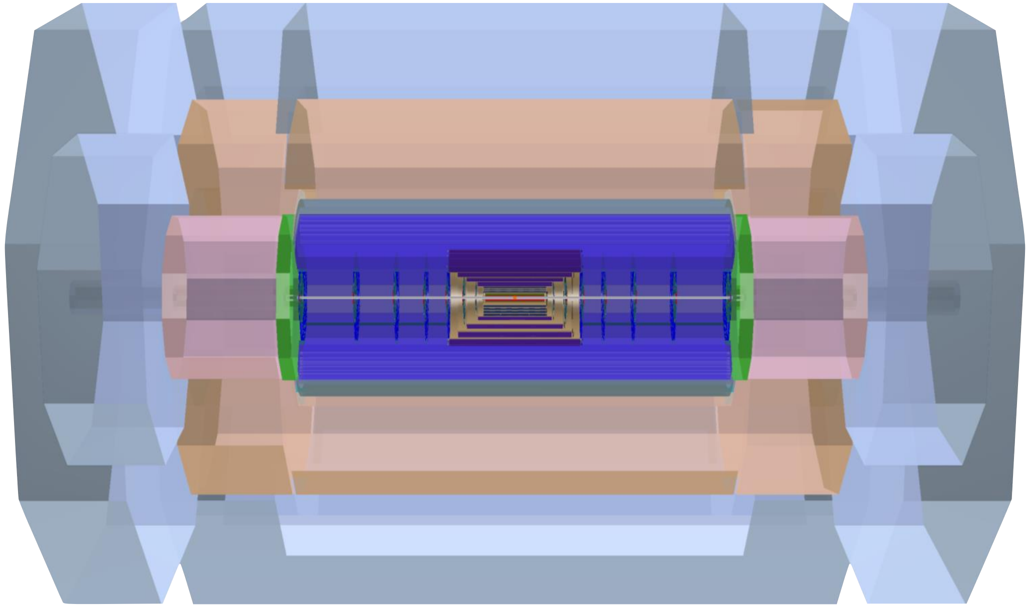
- cross section 1/1000 of pp collisions: radiation ~ lower by > 2 digits
- almost no pile-up

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/π separation), **forward (energy flow for $\eta > 3$)**
- Targeting track resolution at 5μm 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-η detectors chosen for precision rather than radiation
  - **… and detectors will be better calibrated through DIS events**



A symmetrized LHeC detector

- 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

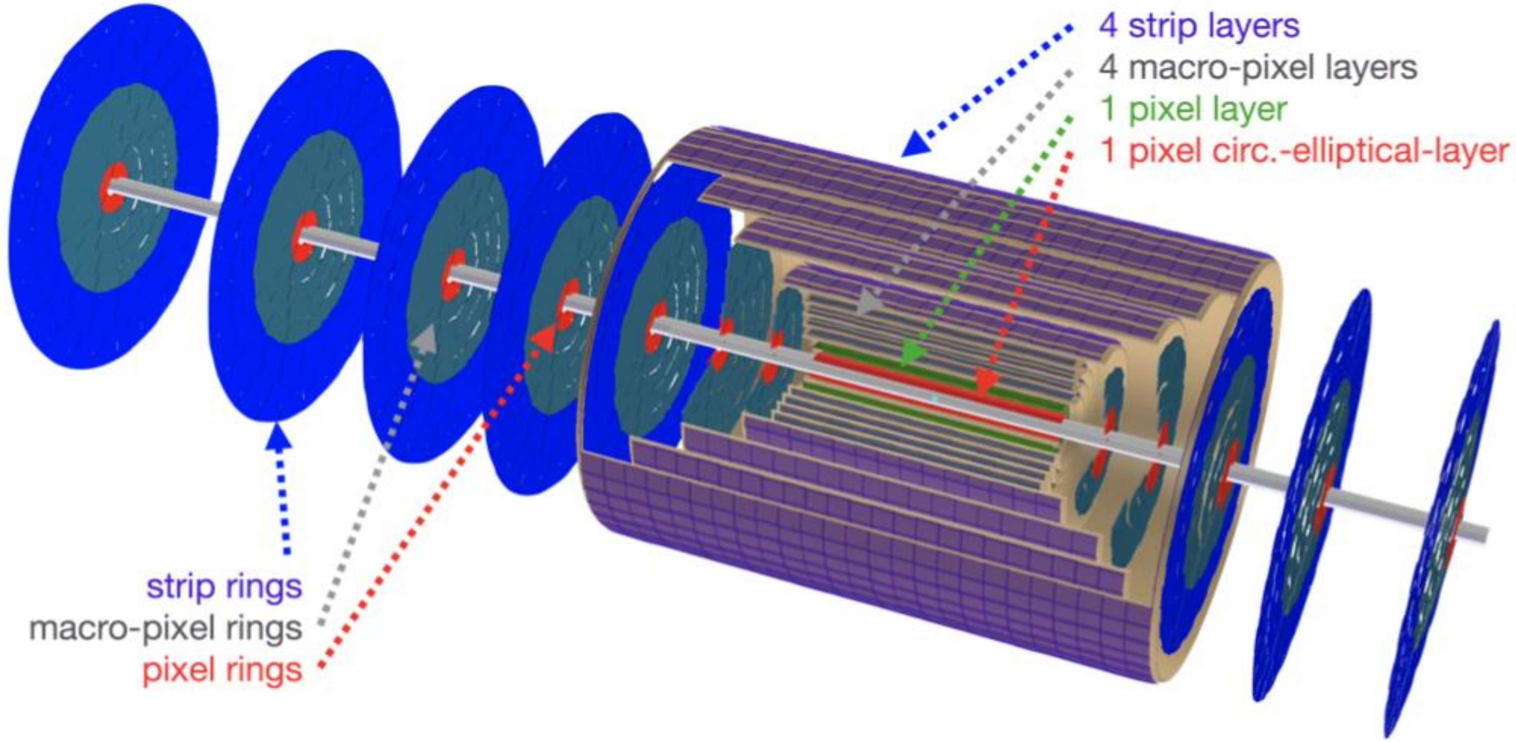
- A version of the FCC-eh baseline detector
  - extension of the LHeC detector, which performs well also for FCC-eh

- 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
  - very detailed studies in LHeC CDR 2012 LHeC Study Group, 2012 J. Phys. G: Nucl. Part. Phys. 39 075001
  - for FCC-eh detector in FCC CDR vol. 3 EPJ Special Topics **228**, 755–1107(2019)
- CDR update in 2020 (P Agostini et al 2021 J. Phys. G: Nucl. Part. Phys. 48 110501) motivated by:
  - 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
  - Extension to hh collisions discussed
- Further development in IP design in 2021/2022 for concurrent eh/hh operation



Inner Tracker

Rapidity to ~5

r_O = 60 cm

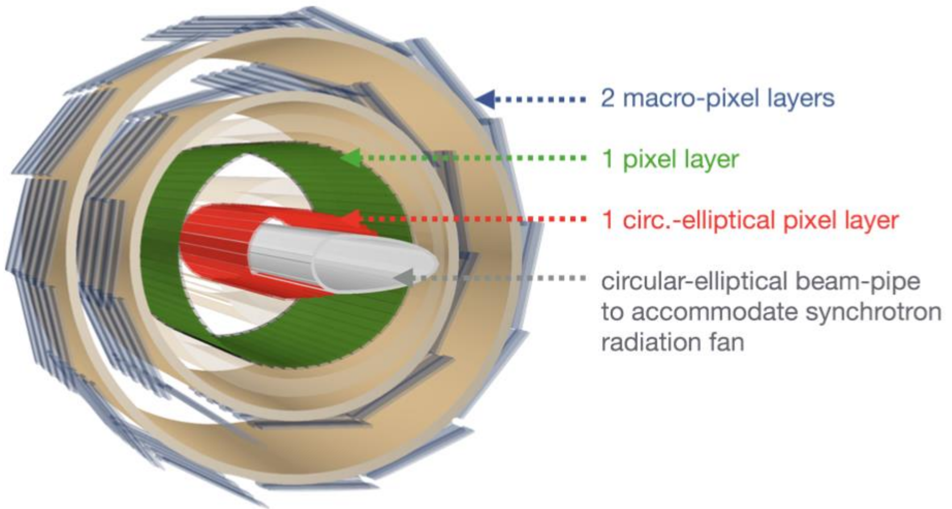
impact resolution 5-10 μm

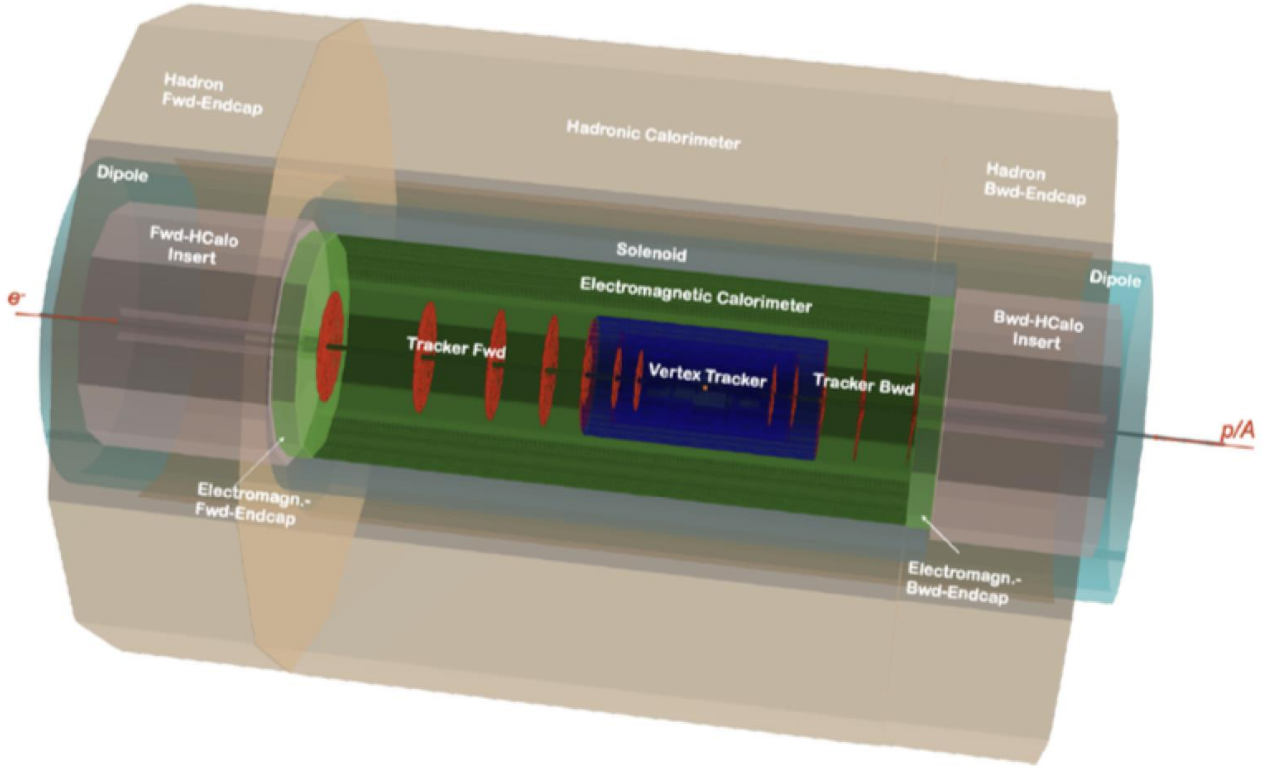
40.7 m^2 Si

LHeC Trackers

η_{max}, η_{min}	
Wheels	
Modules/Sensors	
Total Si area	[m^2]
Read-out-Channels	[10^6]
$pitch^{r-\phi}$	[μm]
$pitch^z$	[μm]
Average X_0/Λ_I	[%]
incl. beam pipe	[%]

LHeC Tracker Part		η_{max}	η_{min}	$\#Layers_{Barrel}$
Inner Barrel	pix	3.3	-3.3	2
	pix_{macro}	2.	-2.	4
	strip	1.3	-1.3	4
				$\#Rings_{Wheels}$
End Caps	pix	4.1/-1.1	1.1/-4.1	2
	pix_{macro}	2.3/-1.4	1.4/-2.3	1
	strip	2./-0.7	0.7/-2.	1-4
Fwd Tracker	pix	5.2	2.6	2
	pix_{macro}	3.4	2.2	1
	strip	3.1	1.4	4
Bwd Tracker	pix	-2.6	-4.6	2
	pix_{macro}	-2.2	-2.9	1
	strip	-1.4	-2.5	4
Total $\eta_{max/min}$		5.2	-4.6	





LHeC Calorimeters

Complete coverage to +- 5 in (pseudo)rapidity

Central Region: 2012: LAr, 2020 Sci/Fe option.

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 $E < E_e$

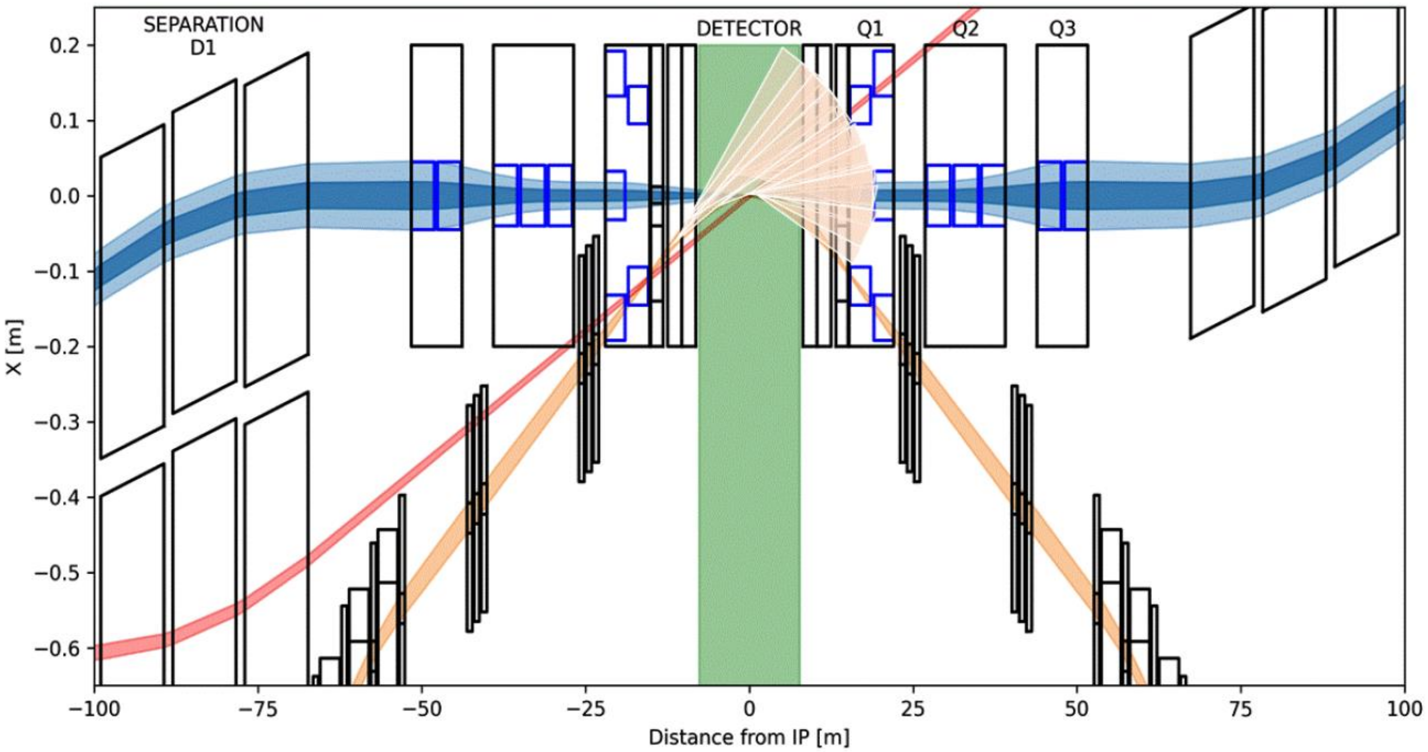
Barrel Calorimeters

Calo (LHeC)	EMC	HCAL		
	Barrel	Ecap Fwd	Barrel	Ecap Bwd
Readout, Absorber	Sci,Pb	Sci,Fe	Sci,Fe	Sci,Fe
Layers	38	58	45	50
Integral Absorber Thickness [cm]	16.7	134.0	119.0	115.5
$\eta_{\max}, \eta_{\min}$	2.4, −1.9	1.9, 1.0	1.6, −1.1	−1.5, −0.6
$\sigma_E/E = a/\sqrt{E} \oplus b$ [%]	12.4/1.9	46.5/3.8	48.23/5.6	51.7/4.3
Λ_I / X_0	$X_0 = 30.2$	$\Lambda_I = 8.2$	$\Lambda_I = 8.3$	$\Lambda_I = 7.1$
Total area Sci [m^2]	1174	1403	3853	1209

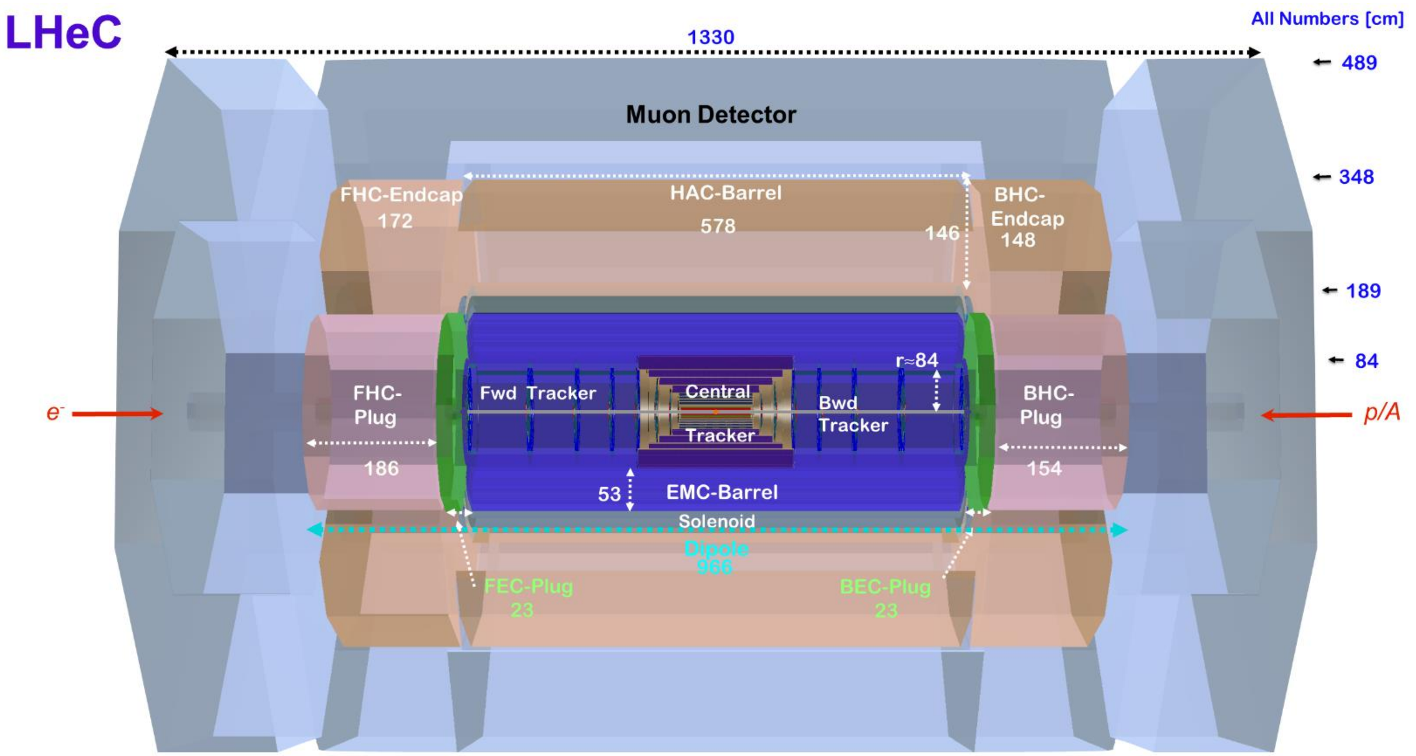
Forward/Backward Calorimeters

Calo (LHeC)	FHC Plug Fwd	FEC Plug Fwd	BEC Plug Bwd	BHC Plug Bwd
Readout, Absorber	Si,W	Si,W	Si,Pb	Si,Cu
Layers	300	49	49	165
Integral Absorber Thickness [cm]	156.0	17.0	17.1	137.5
$\eta_{\max}, \eta_{\min}$	5.5, 1.9	5.1, 2.0	−1.4, −4.5	−1.4, −5.0
$\sigma_E/E = a/\sqrt{E} \oplus b$ [%]	51.8/5.4	17.8/1.4	14.4/2.8	49.5/7.9
Λ_I / X_0	$\Lambda_I = 9.6$	$X_0 = 48.8$	$X_0 = 30.9$	$\Lambda_I = 9.2$
Total area Si [m^2]	1354	187	187	745

arXiv:2007.14491


SEPARATION
D1
DETECTOR
Q1
Q2
Q3
0.2
0.1
0.0
−0.1
−0.2
−0.3
−0.4
−0.5
−0.6
X [m]
−100
−75
−50
−25
0
25
50
75
100
Distance from IP [m]

Radiation environment



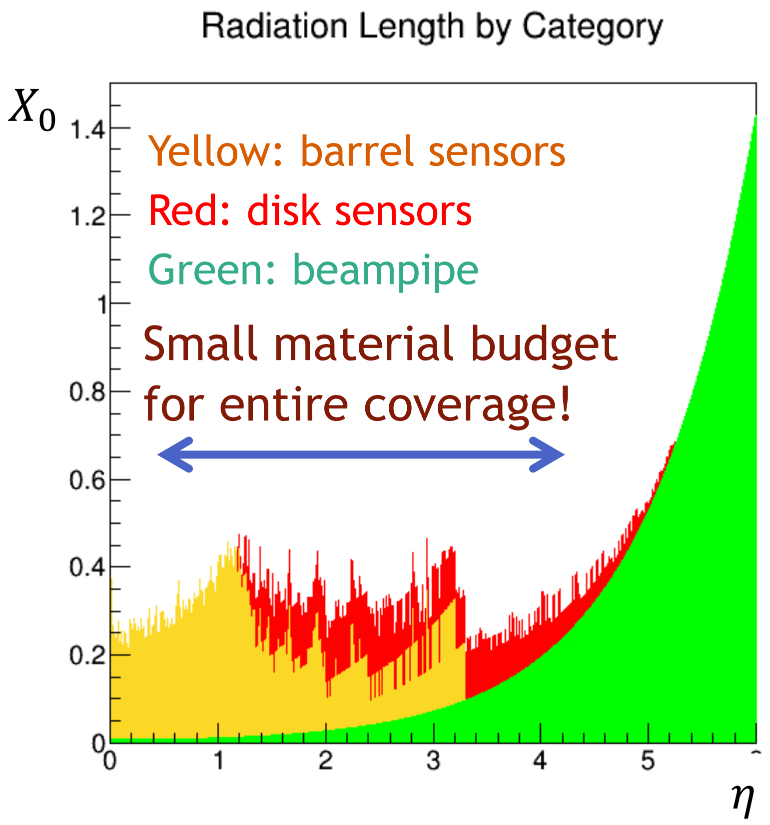
- The luminosity: similar to LHC ($\mathrm{O}(10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1})$)
- **Total cross section: < 1/200**

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

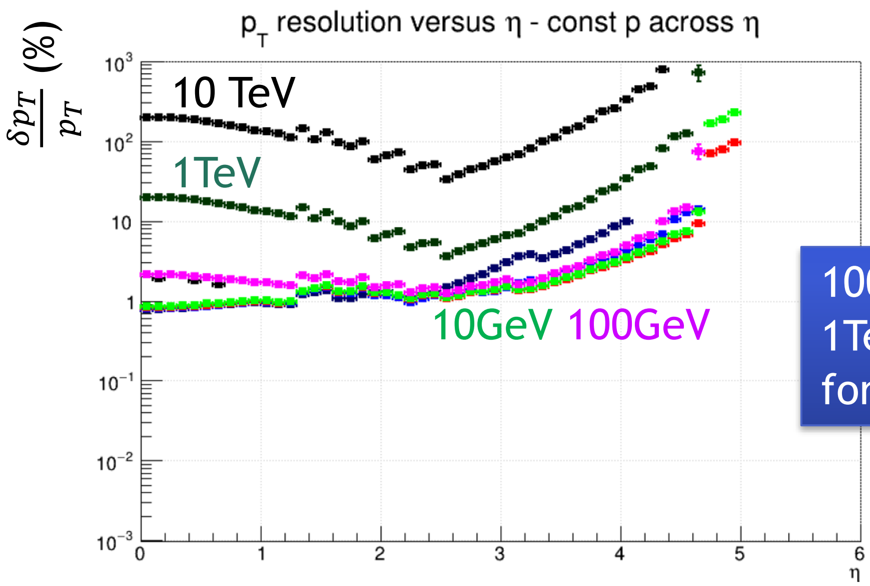
  - # of pileups per bunch $\langle\mu\rangle \simeq 0.1$
    No need for pile-up correction
    Can use PFA and calorimeter variables
    without correction (e.g. missing p_T, rapidity gap…)
  - # of integrated dose in forward region $\ll 10^{14}\ 1\mathrm{MeV}\ n_{eq}$

- 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

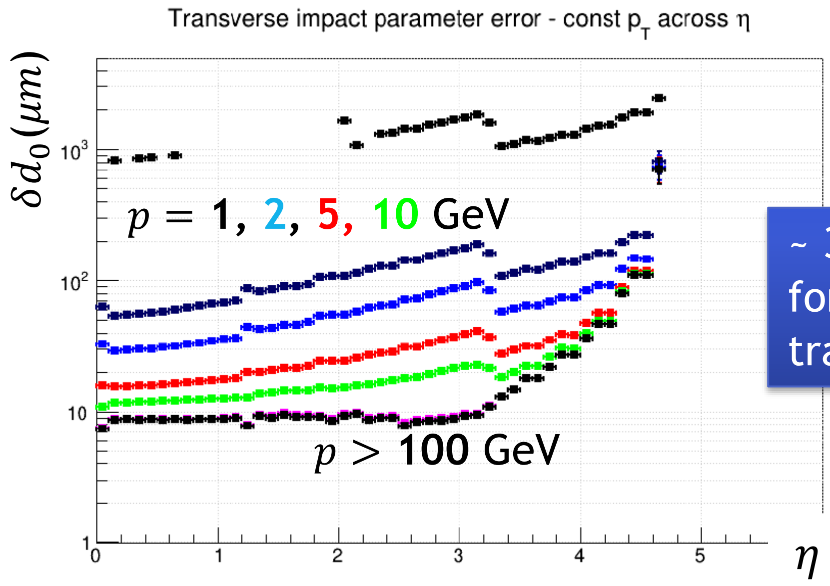
Central tracker: performance



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



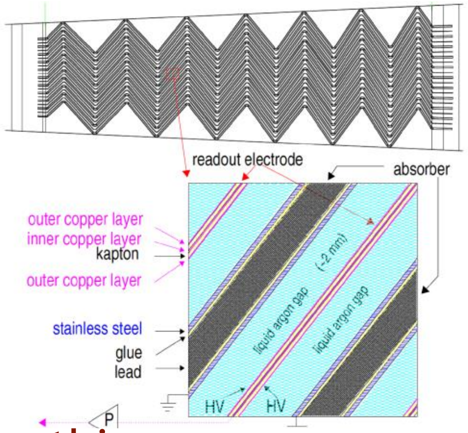
100MeV – 100 GeV: 1-3%
1TeV: 5-30%
for $\eta < 4$

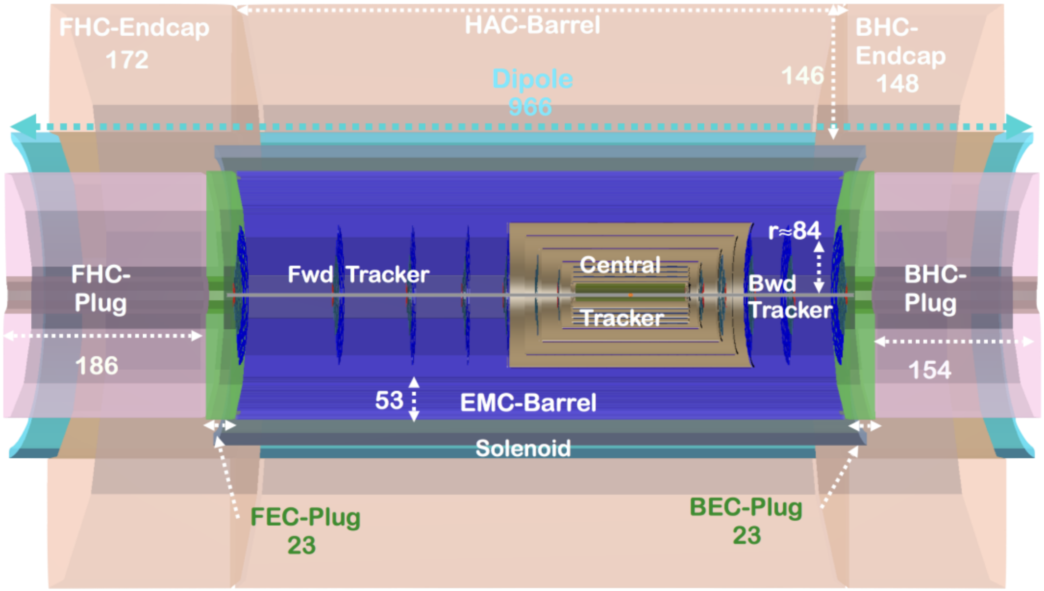


~ 30 μm resolution for high momentum tracks at $\eta \sim 4$

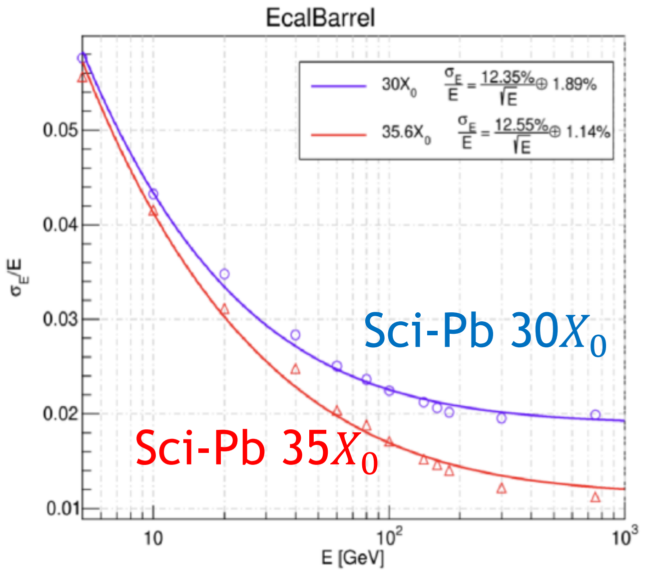
Calorimetry

- 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 → modular (easy install inside the L3 magnet)
  - Comparable performance: LAr still advantageous for resolution, segmentation, radiation stability





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 + small η endcap	LAr	$-2.3 < \eta < 2.8$	$6.6° - 168.9°$
Had barrel+Ecap	Sci-Fe	(~ behind EM barrel)	
EM+Had very forward	Si-W	$2.8 < \eta < 5.5$	$0.48°$ –
EM+Had very backward	Si-Pb	$-2.3 < \eta < -4.8$	$-179.1°$

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 Λ_I for 7 → 20 → 50 TeV steps
  - 9.6 →12.7 Λ_I (forward endcap) for 7 → 20 TeV
- Challenging: shower separation in very forward rapidity regions

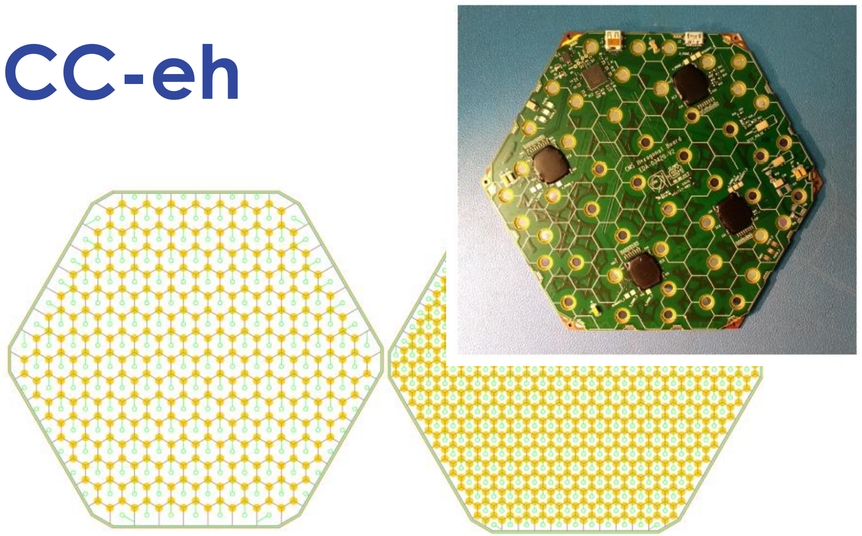


Figure 2.4: Drawing of hexagonal 8″ silicon wafers, with layout of large, 1.18 cm^2, sensor cells (left), and small, 0.52 cm^2, cells (right).

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

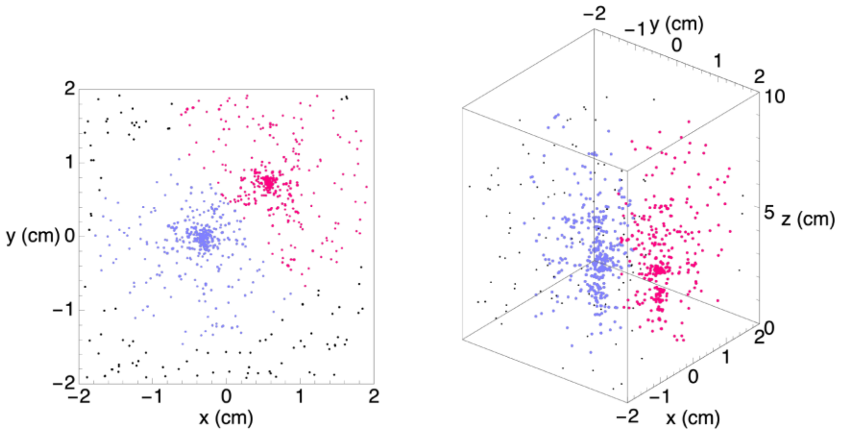
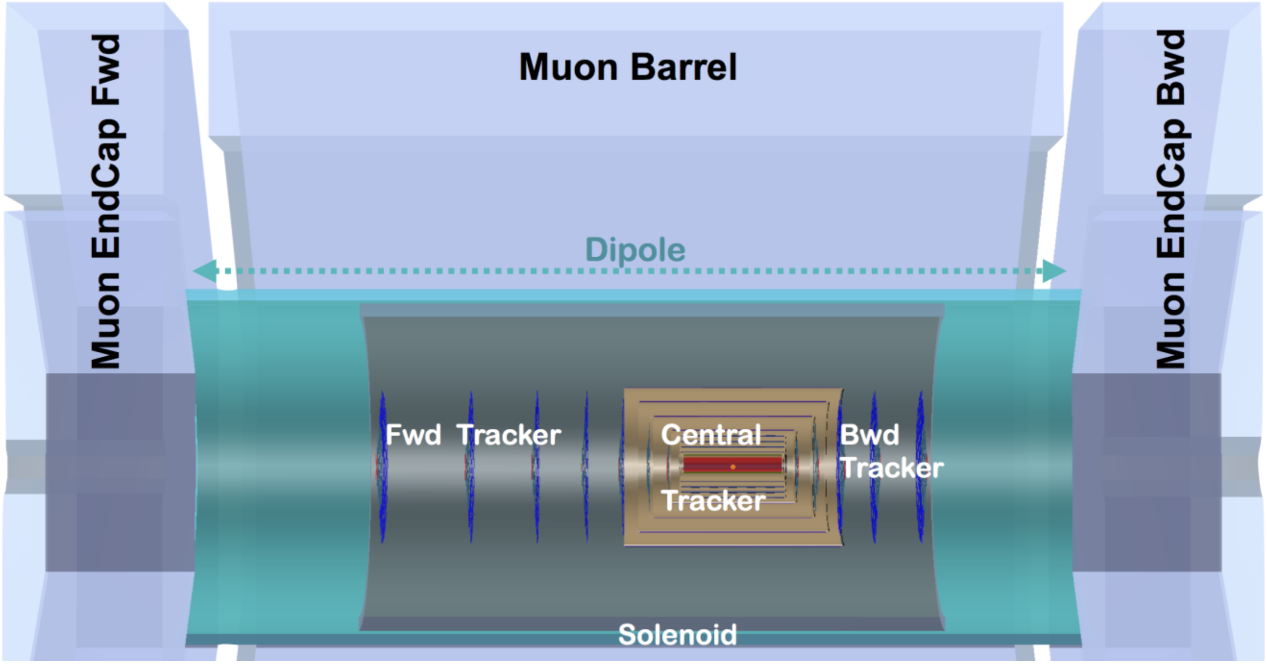


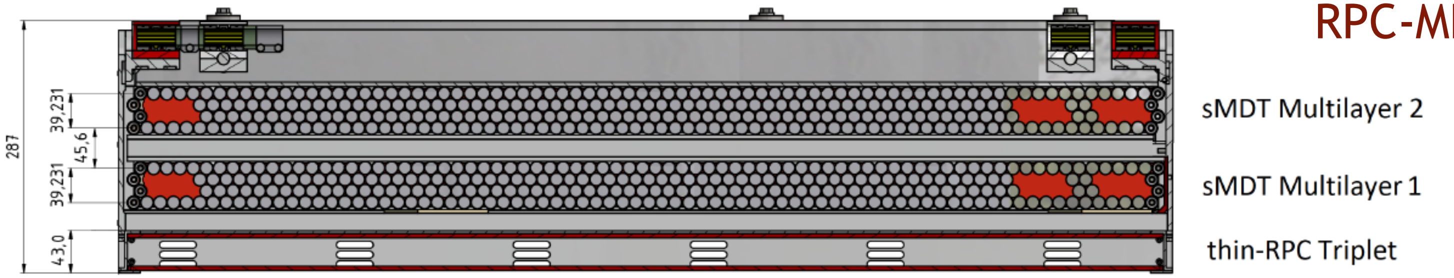
Fig. 54: Different projections of a single-event measurement (hit pixels) of two electrons of $E = 5.4$ GeV from a test beam in the pixel prototype. The left panel shows the transverse distribution summing longitudinally over all layers, the right panel shows a side view of the same event. The hits that 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



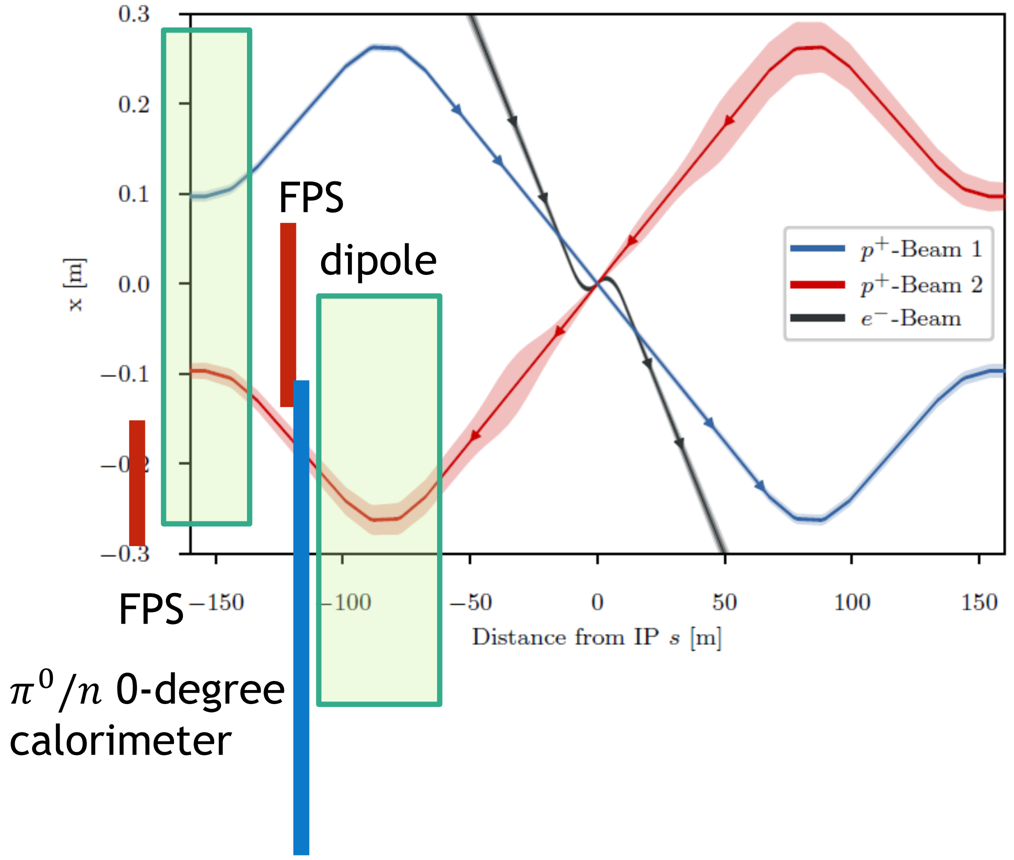
- Baseline: no dedicated magnetic field (solenoid return thru iron only)
  - Momentum by central tracker
  - Good tagging + fast trigger
  - 3-stations, each with ≥ double layer
- HL-LHC technology serves for that
  - Very thin RPC (1mm gas gap) for higher rate capability and timing (<1ns)
  - sMDT: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



ATLAS Phase-I
RPC-MDT assembly

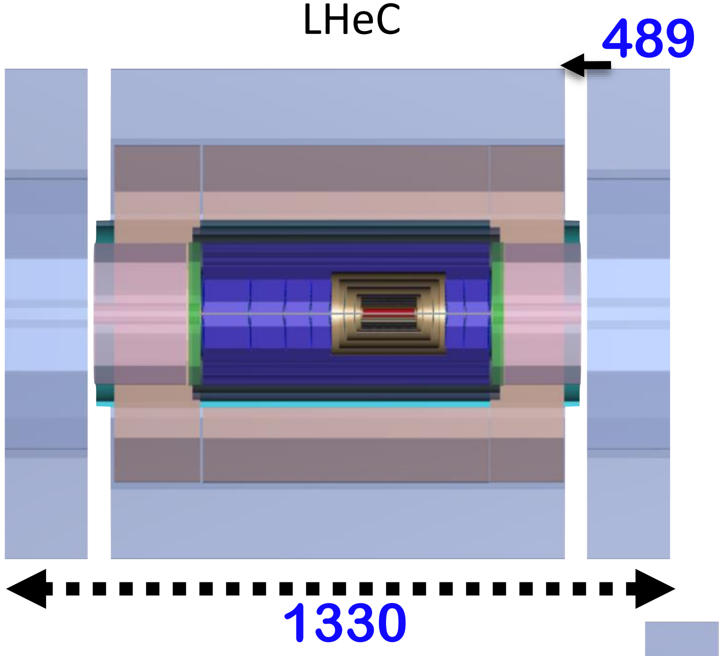
Around zero-degrees

- Backward e tagger + photon tagger
  - for photoproduction and luminosity ($ep \rightarrow ep\gamma$)
- 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 ± 30 cm: shower leak moderate
  - Aperture very big: 0.35 mrad or 2.4 GeV in p_T
- ZDC 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

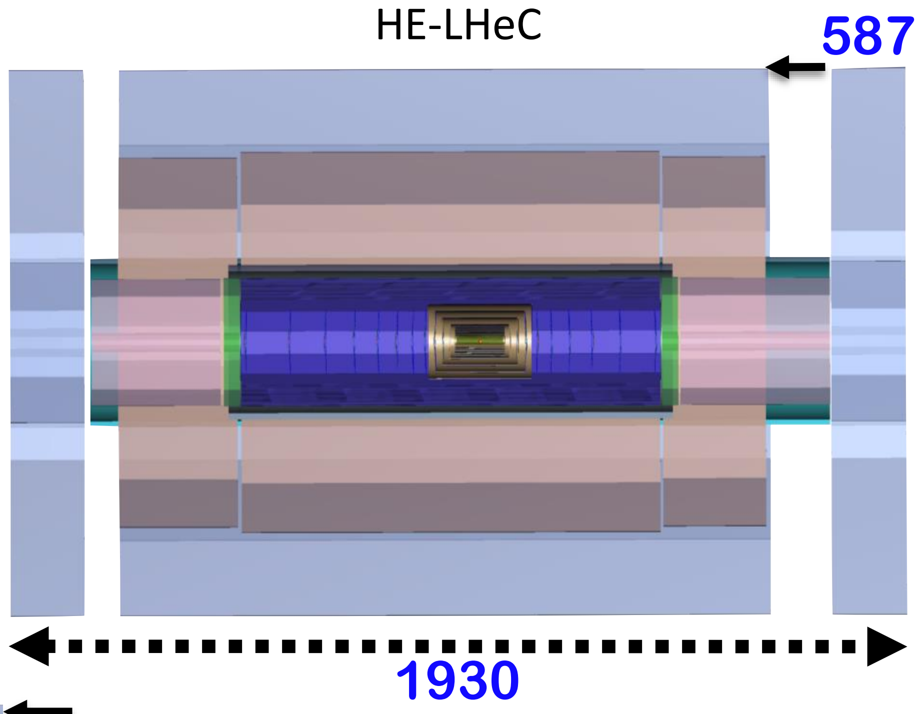


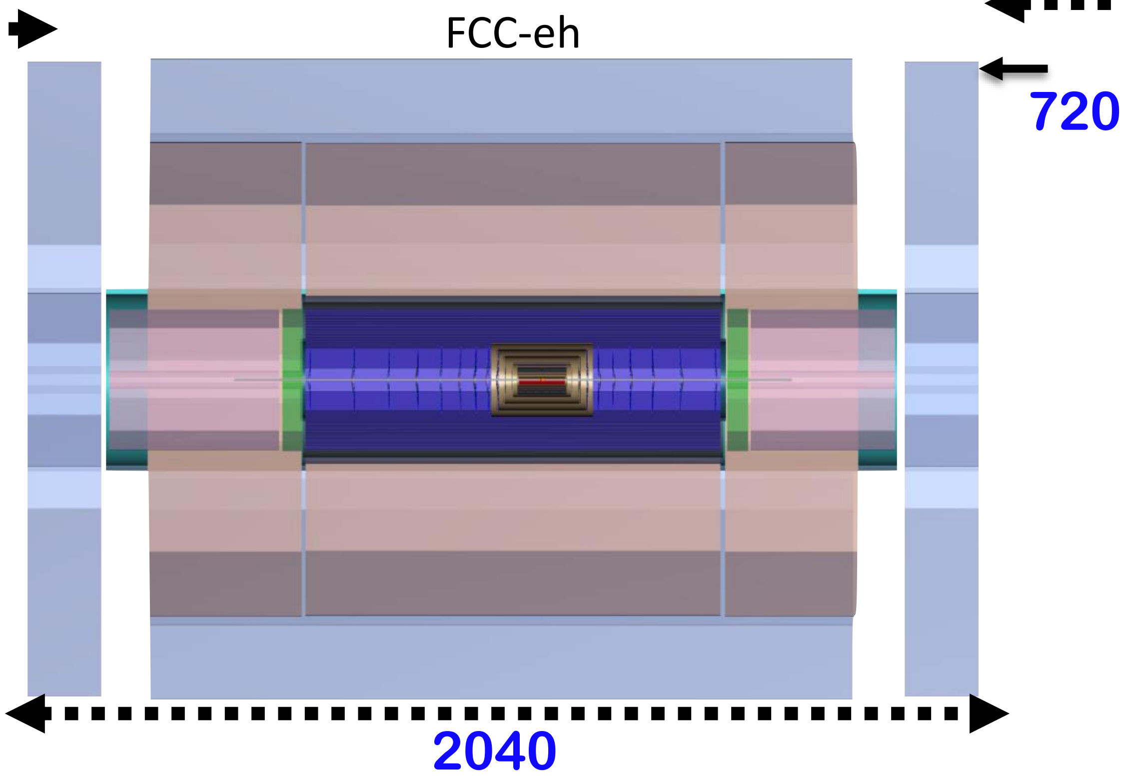
IP design 2020 and the candidate places for forward detectors

LHeC – HE-LHeC – FCC-eh



All Numbers [cm]



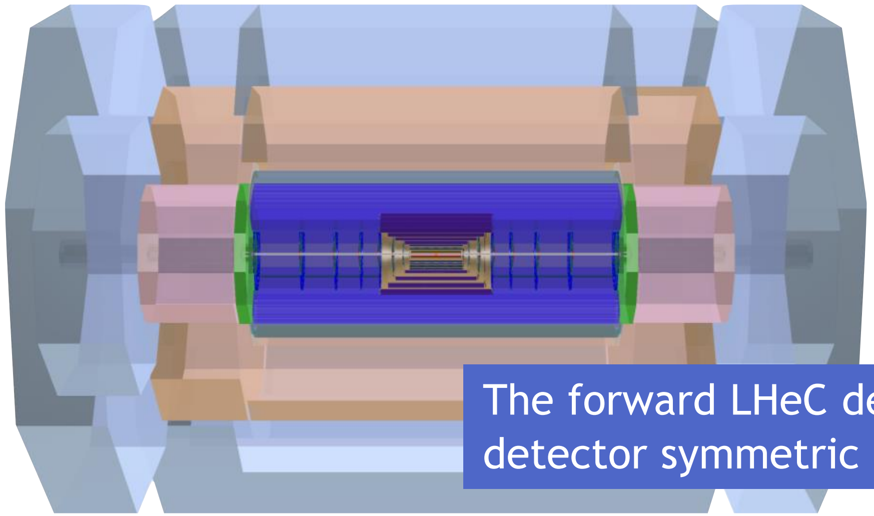


HE-LHeC still fits inside the L3 magnet!

Running the LHeC detector for hh collisions

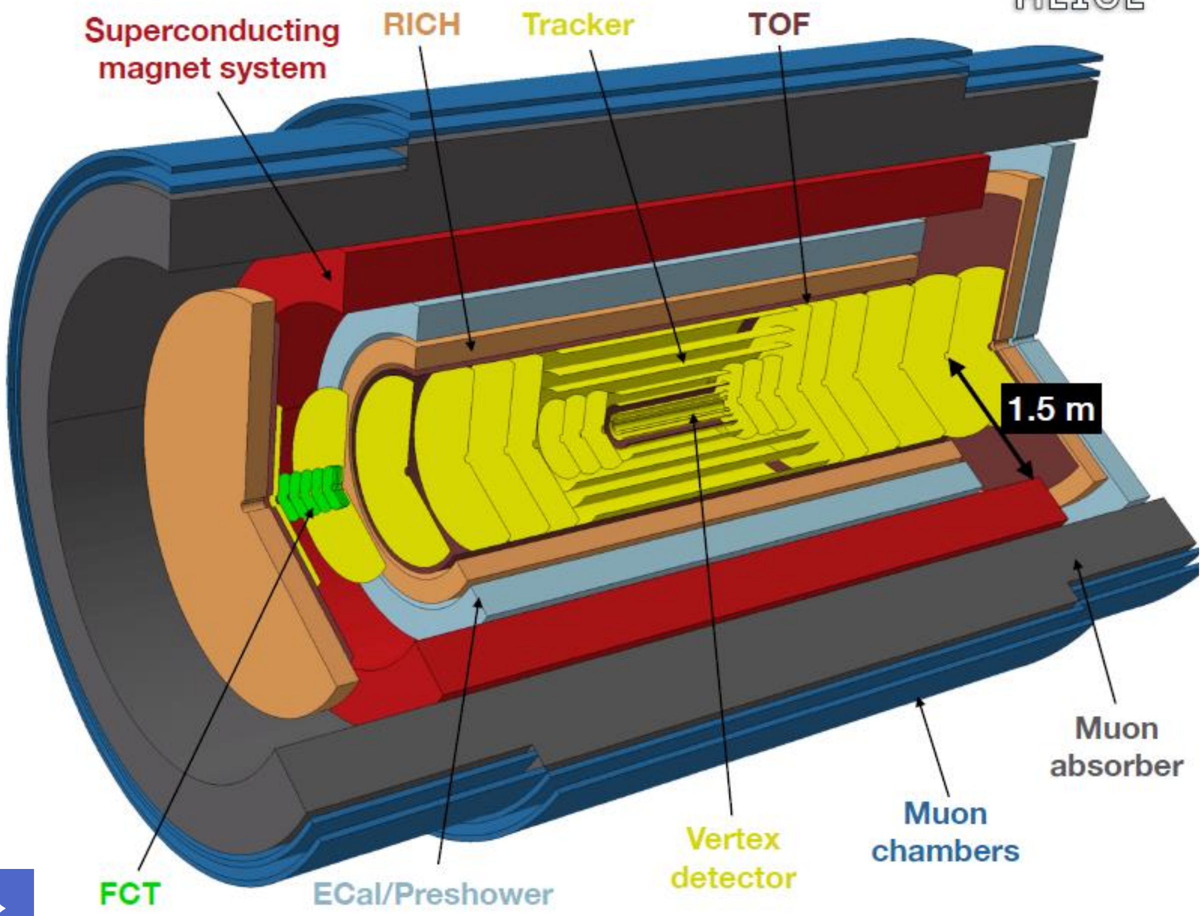
The LHeC detector is very similar to:

- 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



The forward LHeC detector mirrored → detector symmetric for hh-interactions

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