Detector R&D Challenges in CERN Energy-Frontier Lepton-Hadron Studies

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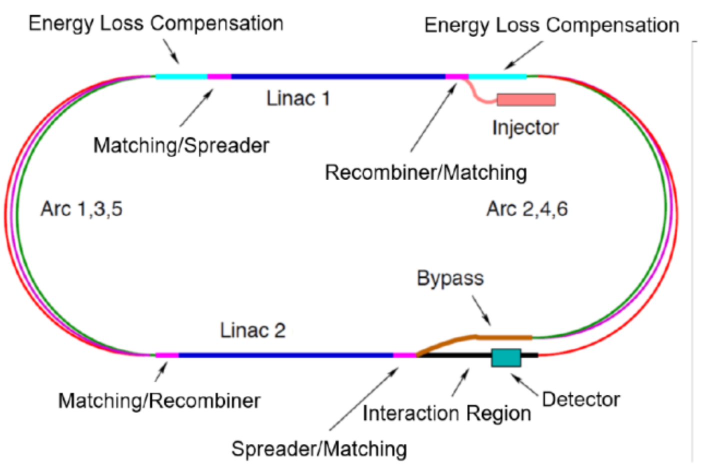
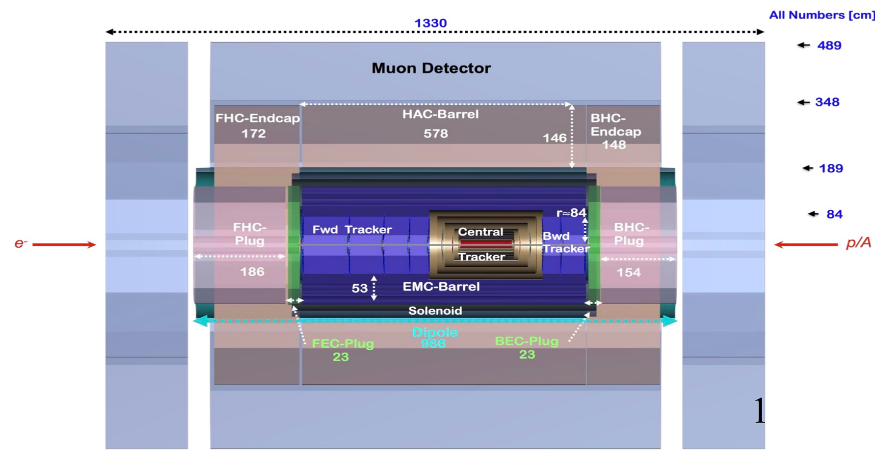
with Yuji Yamazaki (Kobe)
(and P Kostka, A Polini)

Synergy Workshop between ep/eA and pp/pA/AA Experiments

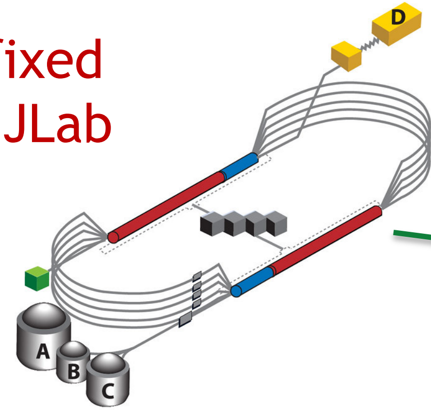
29 February 2024



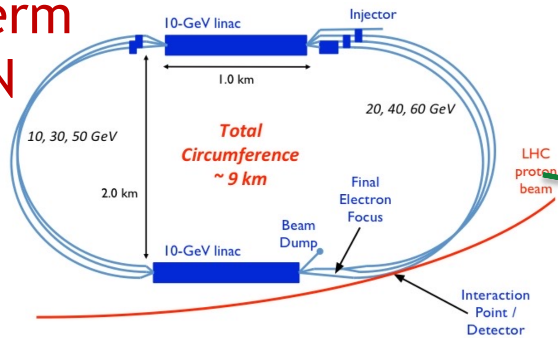


Current and Future ep Colliders

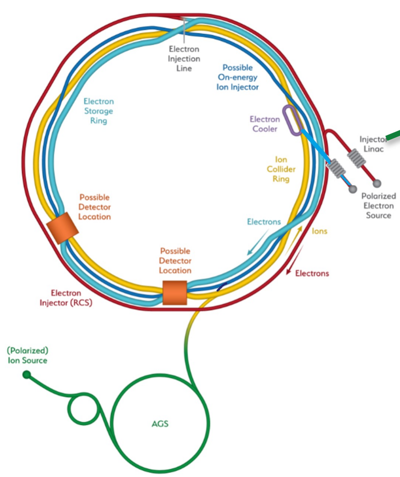
Ongoing fixed target @ JLab

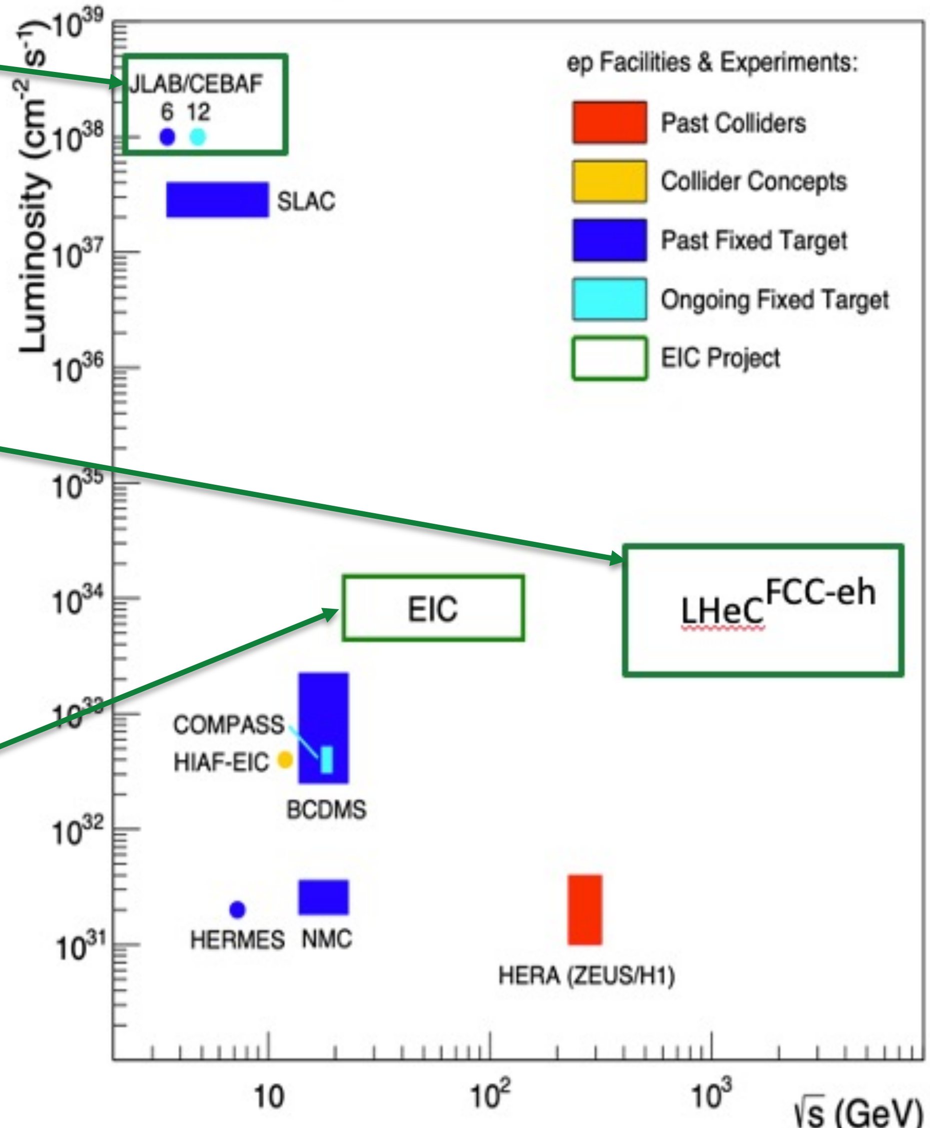


Longer-term @ CERN

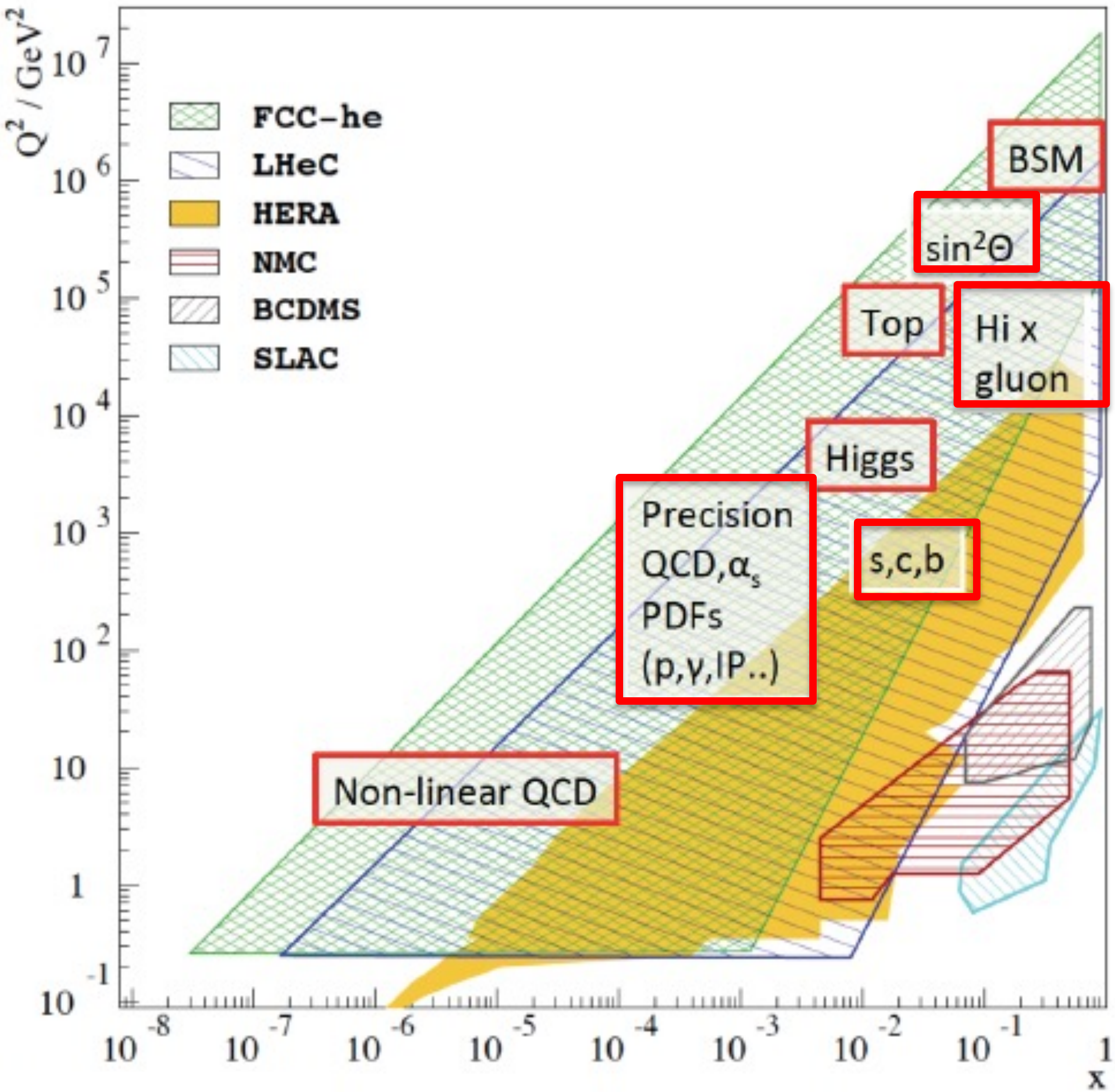


On-target for early 2030s @ BNL





LHeC Physics Targets and Detector Implications



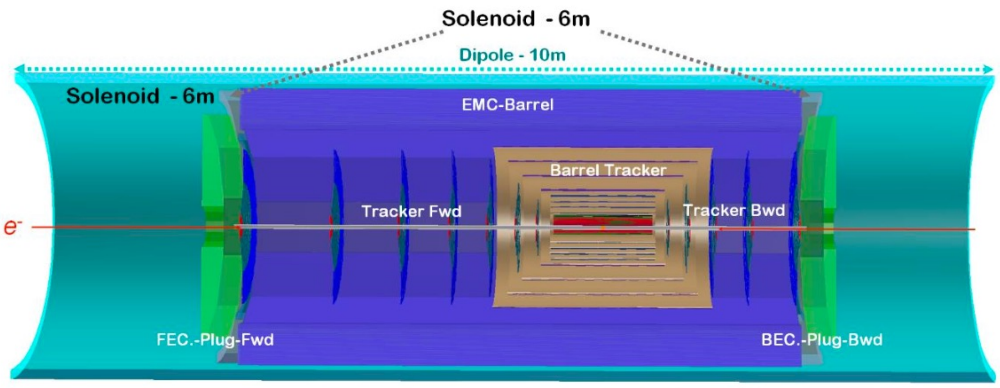
Standalone Higgs, Top, EW, BSM programme

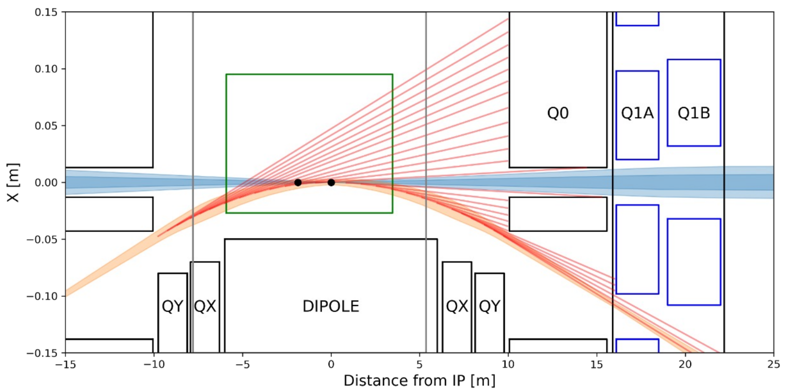
→ General purpose particle physics detector
→ Good performance for all high p_T particles
→ Heavy Flavour tagging

Precision proton PDFs, including very low x parton dynamics in ep,eA

→ Dedicated DIS exp't
→ Hermeticity
→ Hadronic final state resolution for kinematics
→ Flavour tagging / PID
→ Beamline instruments

Interaction Region Challenges: Synchrotron

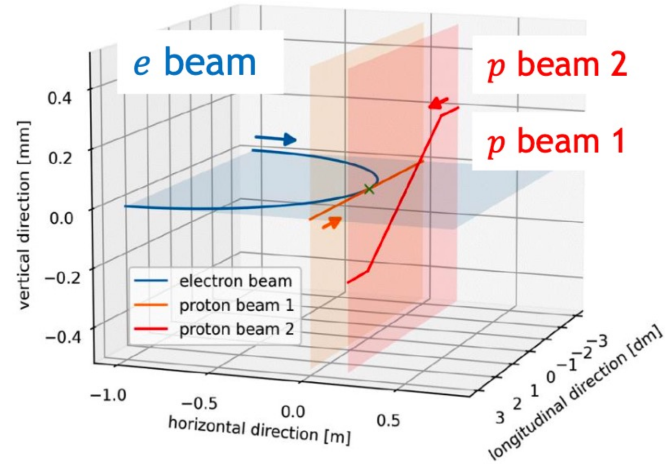




- Dipole magnets bend electrons to head-on collisions with p-beam-1

- p-beam-2 carried in a different plane

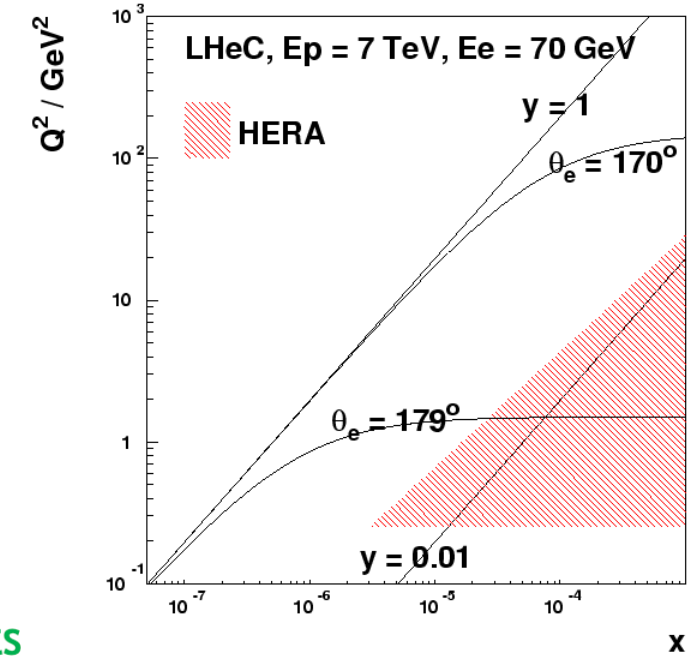
- Synchrotron mitigated with elliptical beampipe, collimators and absorption on the Q0 (normal conducting) quadrupole



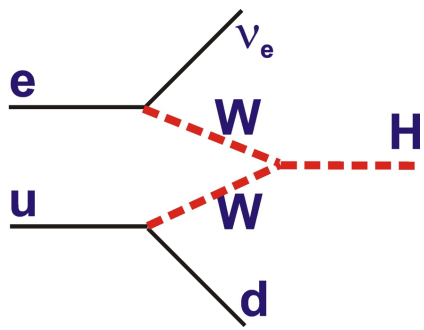
Fluences from collisions and pile-up (~0.1) are tiny compared with LHC pp collisions

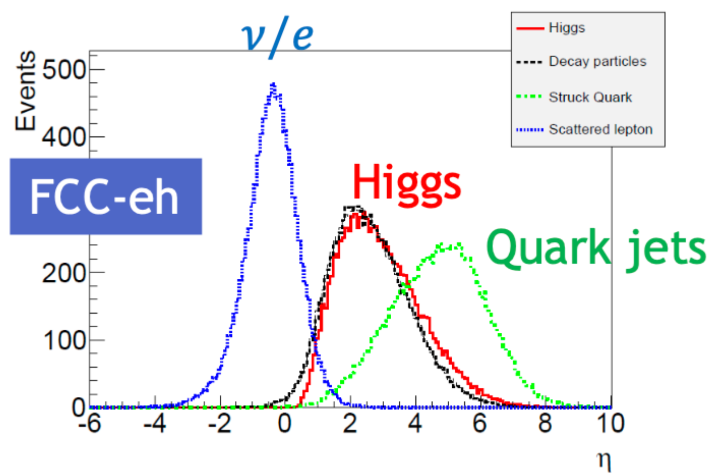
Main Detector Challenges: Hermiticity

- Access to Q^2=1 GeV^2 for all x requires scattered electrons to 179°

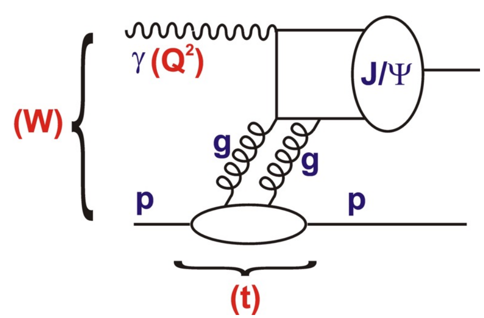


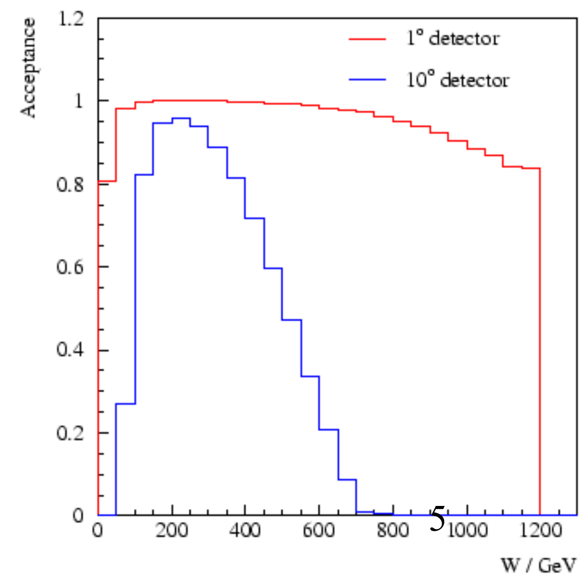
- Higgs production dominated by forward jet configurations





- High W exclusive J/Ψ requires lepton reconstruction up to 179°





The ep/eA study at the LHC and FCC – new impactful goals for the community

WG4

2023 | WS | 2024 | WS | 2025 | TWS | *input to ESPP*

proton and nuclear structure from EIC and HERA to LHeC and FCC-eh
novel QCD with high-energy DIS physics: what do we discover when breaking protons and nuclear matter in smaller pieces

general-purpose high-energy physics programme: precision physics and searches
enabling direct discoveries and measurements in EW, Higgs and top physics with high-energy DIS collisions

ep-physics empowering pp/pA/AA-physics (LHC and FCC)
improving the ATLAS, CMS, LHCb and ALICE discovery potential with results from a high-energy DIS physics programme

developing a general-purpose ep/eA detector for LHeC and FCC-eh
critical detector R&D (DRD collaborations), integrate in the FCC framework, one detector for joint ep/pp/eA/pA/AA physics

developing a sustainable LHeC and FCC-eh collider programme
design the interaction region, power and cost, coherent collider parameters & run plan, beam optimization, …

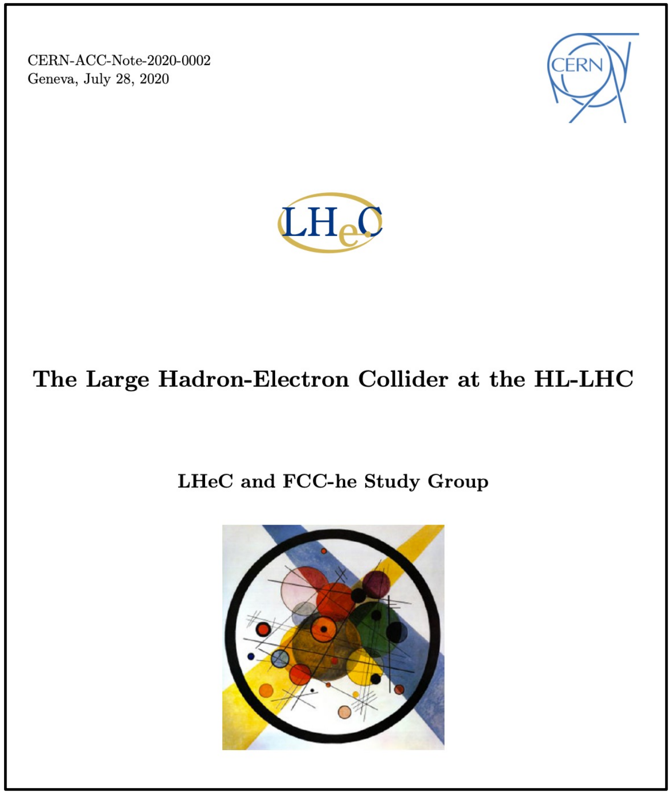
- typically 2-3 conveners per theme
- annual ep/eA workshops (**WS**)
- final thematic workshop with closing reports to inform the upcoming Strategy process with impactful information (**TWS**)
- inform the community with regular ep/eA Newsletters
- everybody is welcome to join

Coordination Panel: N. Armesto, M. Boonekamp, O. Brüning, D. Britzger, J. D'Hondt (spokesperson), M. D'Onofrio, C. Gwenlan, U. Klein, P. Newman, Y. Papaphilippou, C. Schwanenberger, Y. Yamazaki

… A high-performance detector for next-generation highest energy, highest luminosity ep/eA collisions in a harsh synchrotron radiation environment

… A combined ep / eA (and perhaps pp / pA / AA) collider detector (for the first time ever)

Input Material and Connections


CERN-ACC-Note-2020-0002
Geneva, July 28, 2020

The Large Hadron-Electron Collider at the HL-LHC

LHeC and FCC-he Study Group

2008 2009 2010 2012 2014 2015 2017 2018 2019 2022

What we have already:

- 10 dedicated workshops over 15 years
- Original LHeC CDR (2012)
- Updated CDR (2020)
  → integrating (HL-)LHC ideas

Where we can learn / improve now:

- Connections to new / ongoing European DRD R&D collaborations
- Connections to more specific future colliders (FCC, ILC, CLIC…)
- Connections to Electron Ion Collider

Detector Overview (as in 2020 CDR Update)

Compact

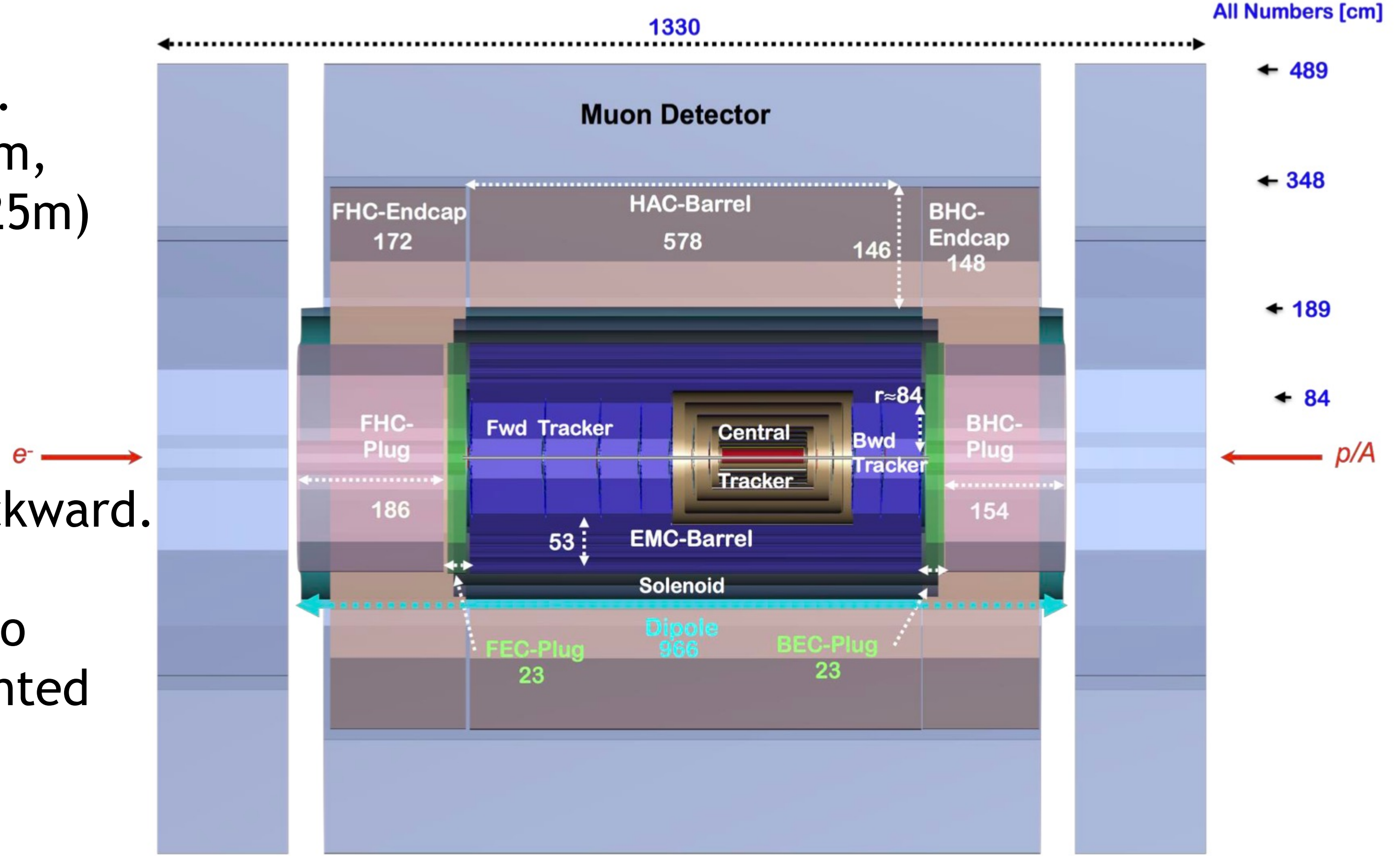
13m x 9m (c.f. CMS 21m x 15m, ATLAS 45m x 25m)

Hermetic

- 1° tracking acceptance forward & backward.

- Beamline also well instrumented

Modular



‘Could be built now’, but many open questions:

- A snapshot in time, borrowing heavily from (HL)-LHC (particularly ATLAS)
- Possibly over-specified (eg for radiation hardness)?
- Possibly lacking important components for ep/eA (eg. Particle ID)
- Not particularly well integrated or optimised

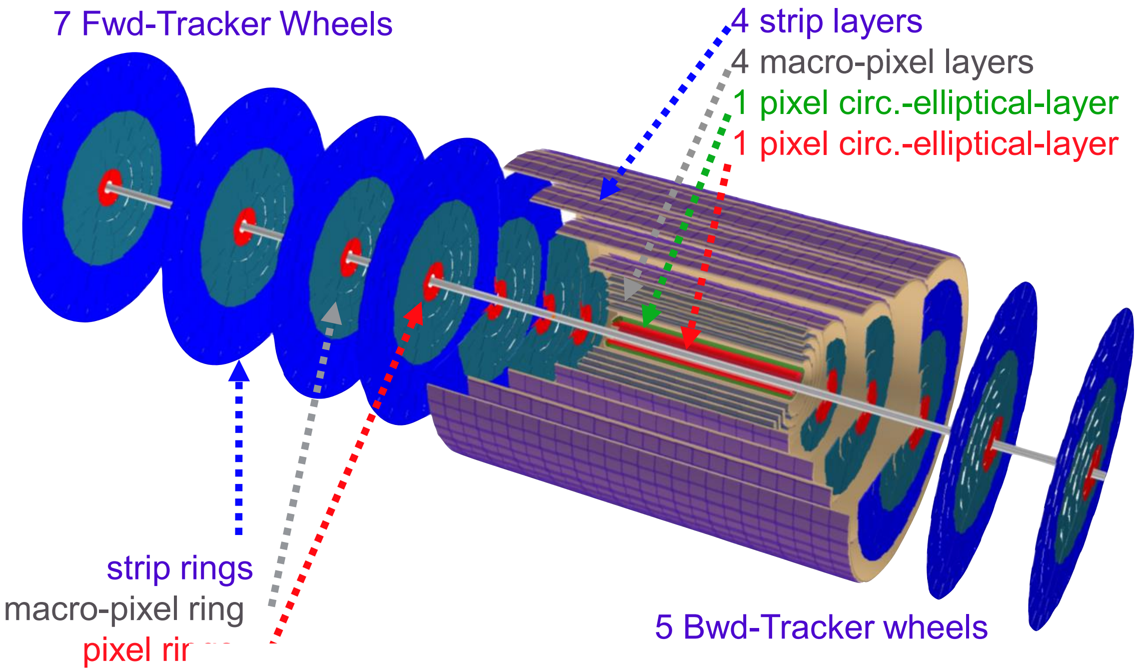
Central Tracker in CDR-Update

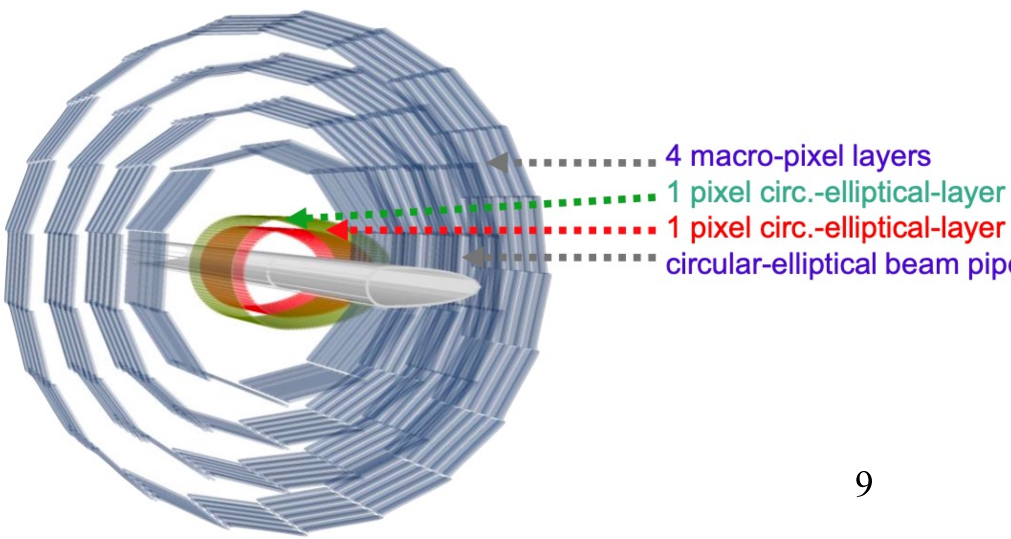
- All silicon

- HV-CMOS MAPS technology is low material (0.1mm) and cost-effective

- Bent / stitched wafers for inner layers (as ALICE and ePIC)

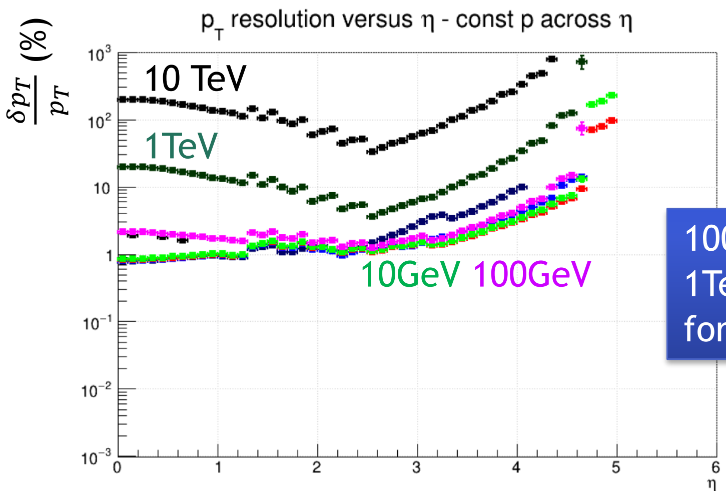
- Semi-elliptical inner layers



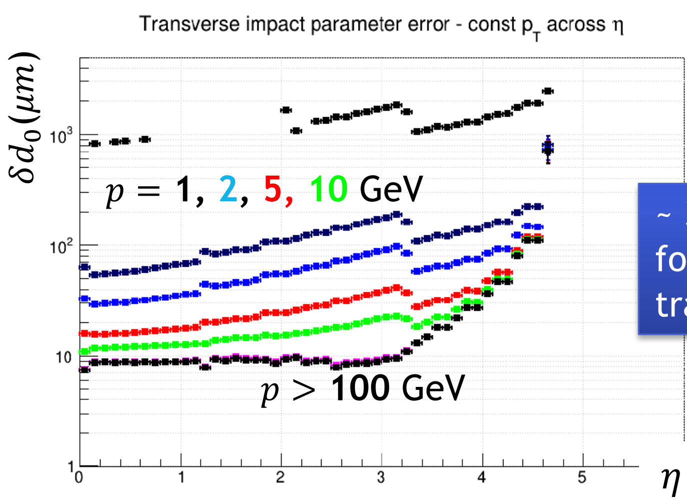


Pitch (μm)	$r\phi$	z
pixel	25	50
macro pixel	100	400
strip	100	10-50mm

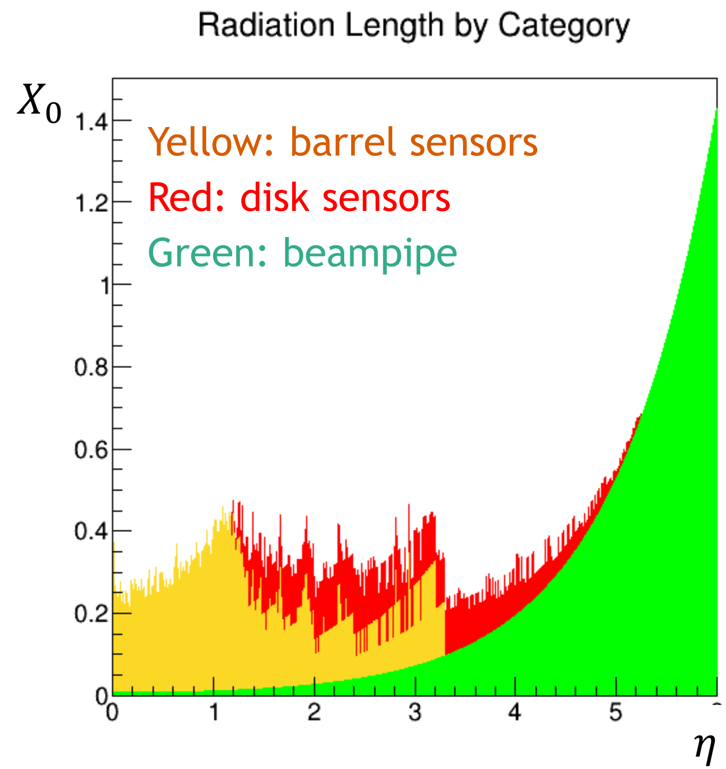
Tracking Performance



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



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



- Material budget is ~20% of a radiation length up to η~4.5

- p_T and impact parameter resolutions (from tkLayout) show high performance over wide η range.

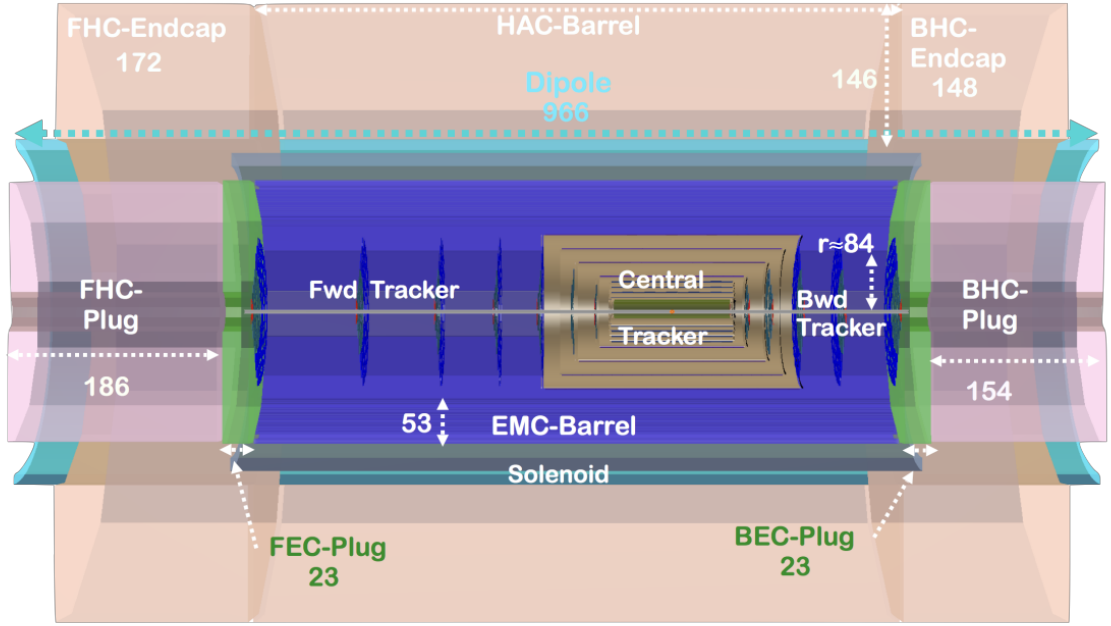
Calorimetry in CDR-Update

- ‘Accordion’ geometry Lar EM Barrel (|η|<2.8), inside solenoid / dipole

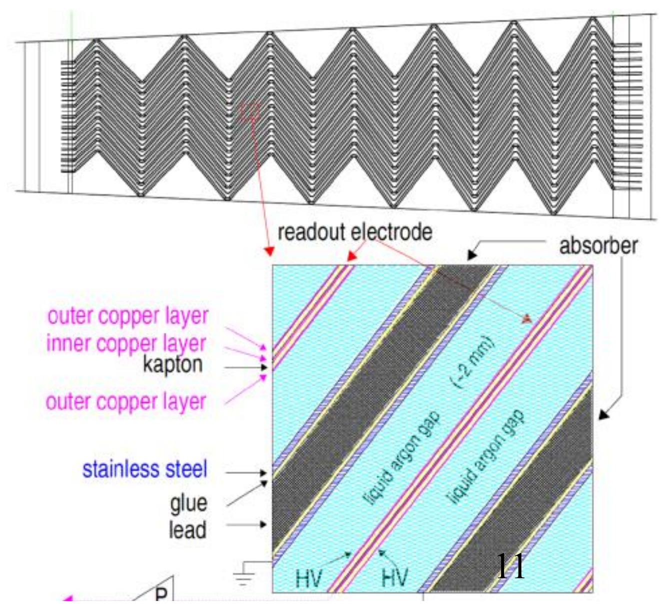
- Plastic-scintillator HCAL for e/h separation

- Finely segmented plugs (W, Pb, Cu) for compact showering, with Si sensors

- 25-50 X_0 and ~10λ throughout acceptance region



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°



Barrel ECAL Performance

GEANT4 response to electrons at normal incidence

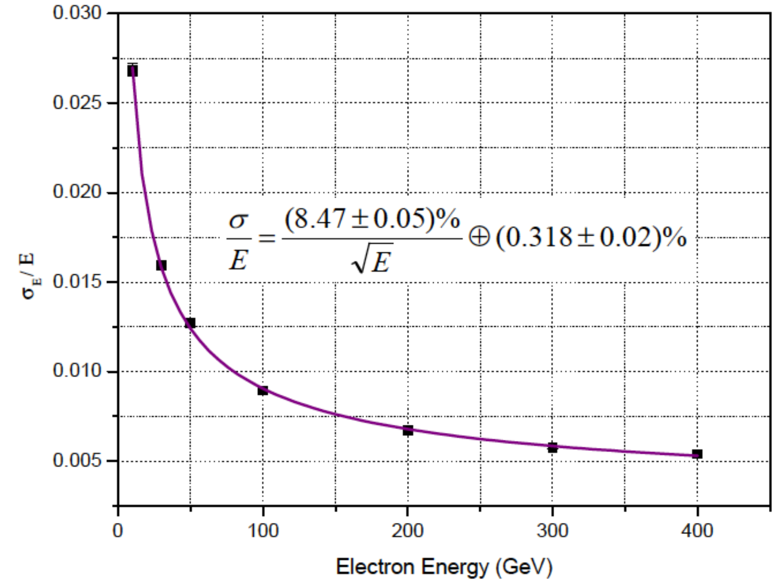
- Benchmarked against 'warm' alternative Sci-Pb design

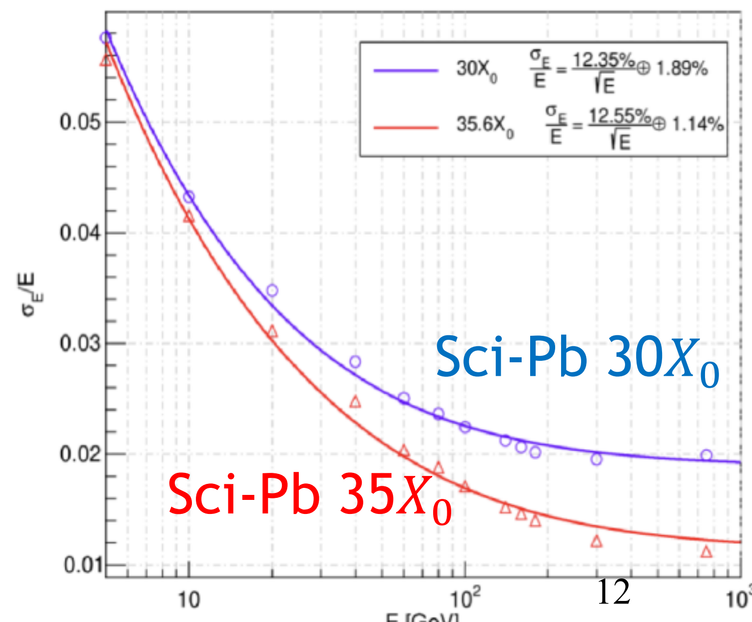
LAr ($\sim 25X_0$)	$8.47/\sqrt{E} \oplus 0.32\%$
Sci-Pb ($30X_0$)	$12.55/\sqrt{E} \oplus 1.89\%$

[cf ATLAS: 10%/√E + 0.35%]

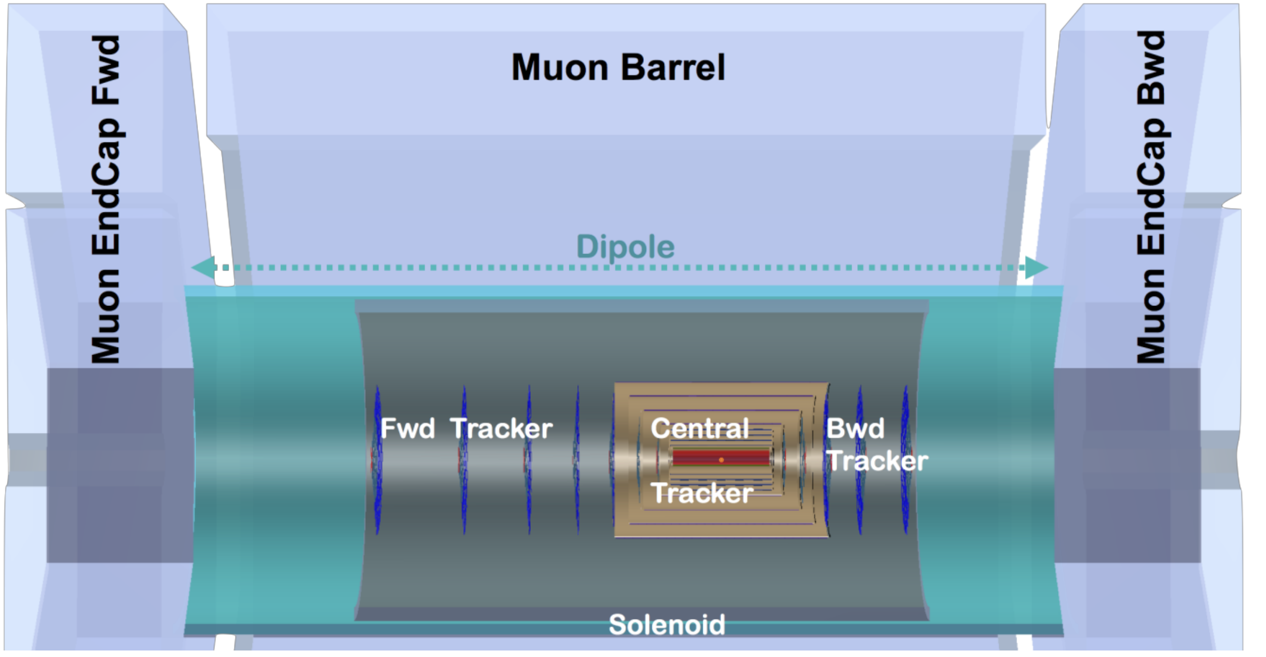
- Comparable resolution

- Cold Lar version currently preferred (segmentation, radiation stability …)





Muons in CDR Update



No dedicated outer magnetic field in current design

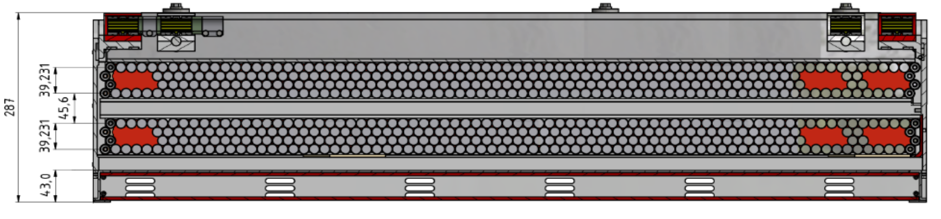
→ Momentum measurement in central tracker.

→ Outer muon detectors for tagging / triggering

Borrowing HL-LHC technologies

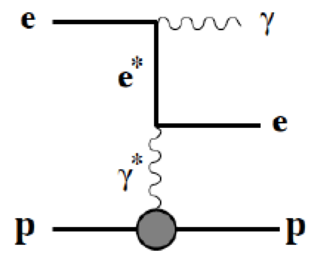
→ Multiple layers of thin RPCs (1mm gas gap) for fast response

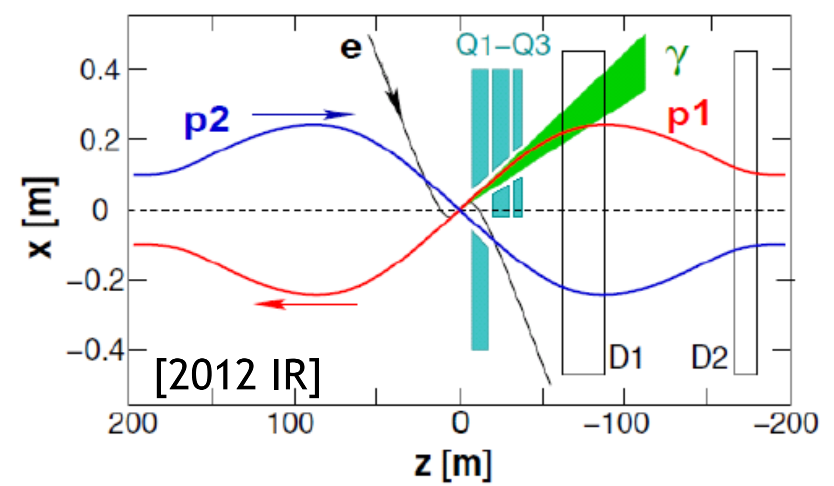
→ Small (1.5cm diameter) MDTs for spatial precision



ATLAS Phase-I RPC-MDT assembly

Beamline Instrumentation in CDR Update





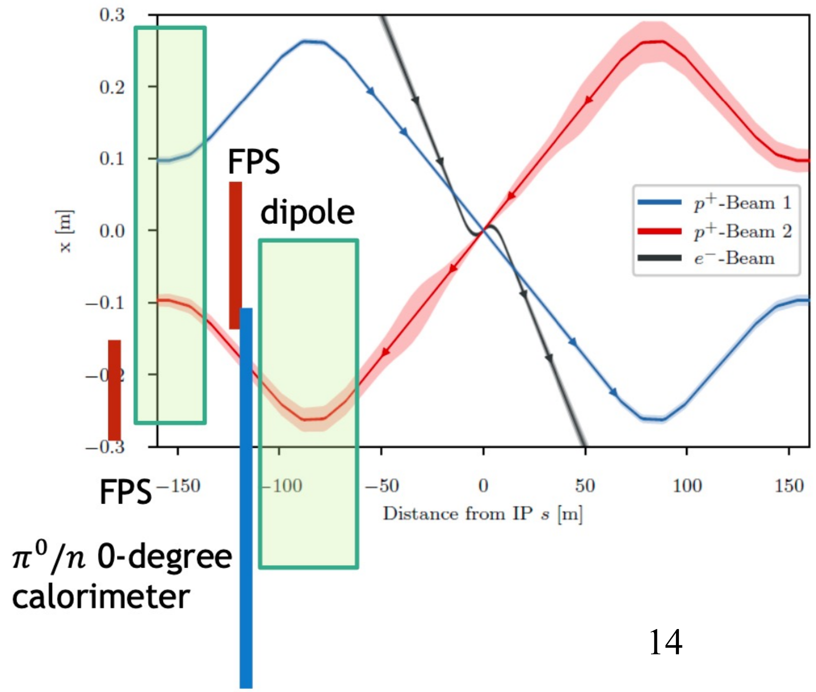
Outgoing electron direction:

- Photoproduction e-taggers 14-62m and
- Photon detector at around 120m for lumi (Bethe-Heitler ep→epγ)

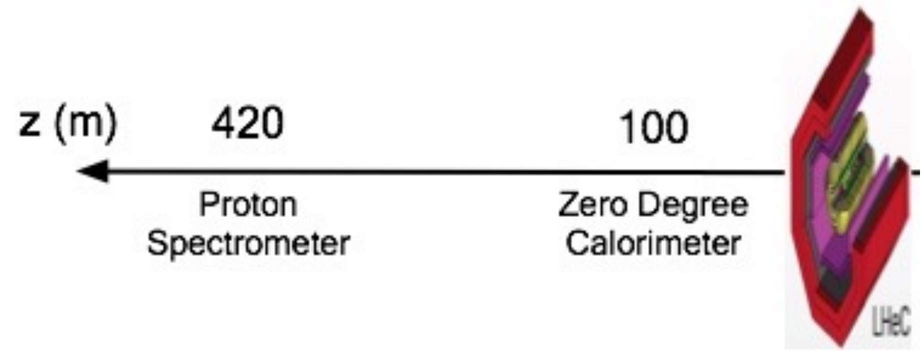
Outgoing proton direction:

- Space for ±30cm Si-W ZDC at 110m … could have highly segmented design similar to ALICE FoCAL

- Roman pot-based proton spectrometer at ~200m (as per ATLAS/CMS) → fractional proton energy-loss ξ~0.1
- Also at ~120m (new → ξ~0.2)
- Challenges to cover lowest ξ …

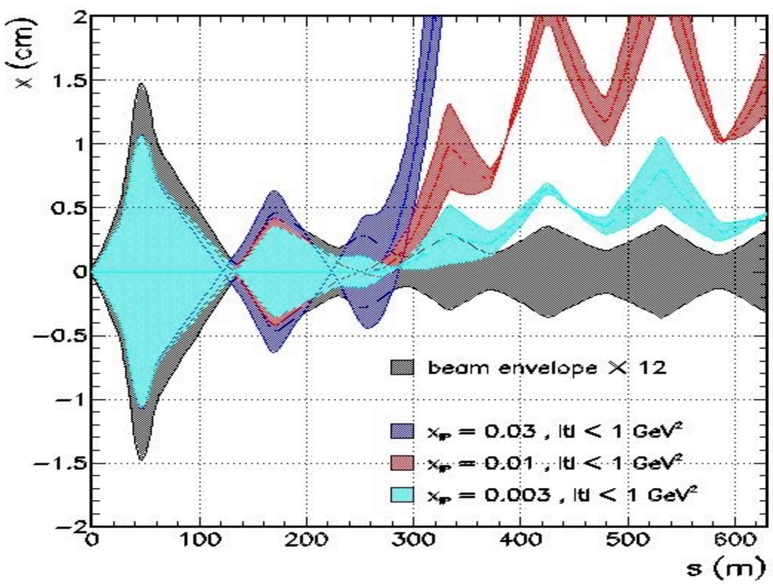


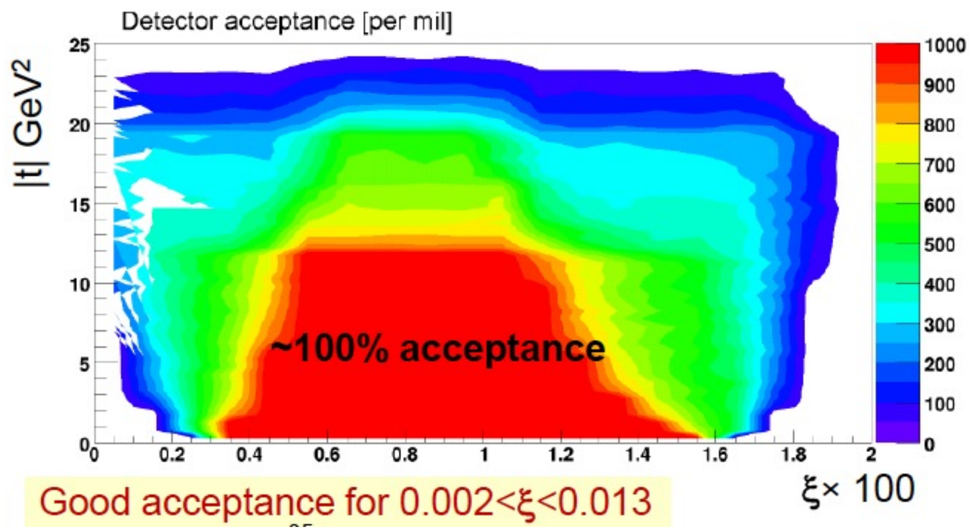
Low ξ p-spectrometer based on FP420?...



The FP420 R&D Project: Higgs and New Physics with forward protons at the LHC

arXiv:0806.0302v2 [hep-ex] 2 Jan 2009

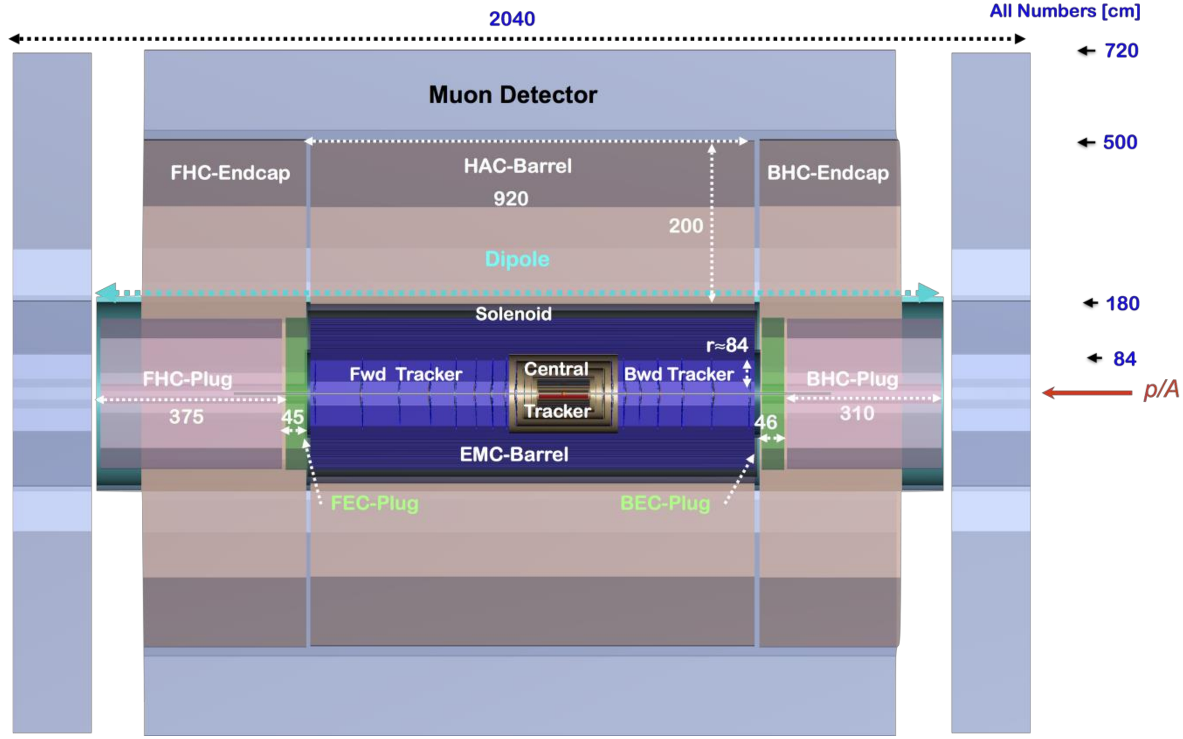




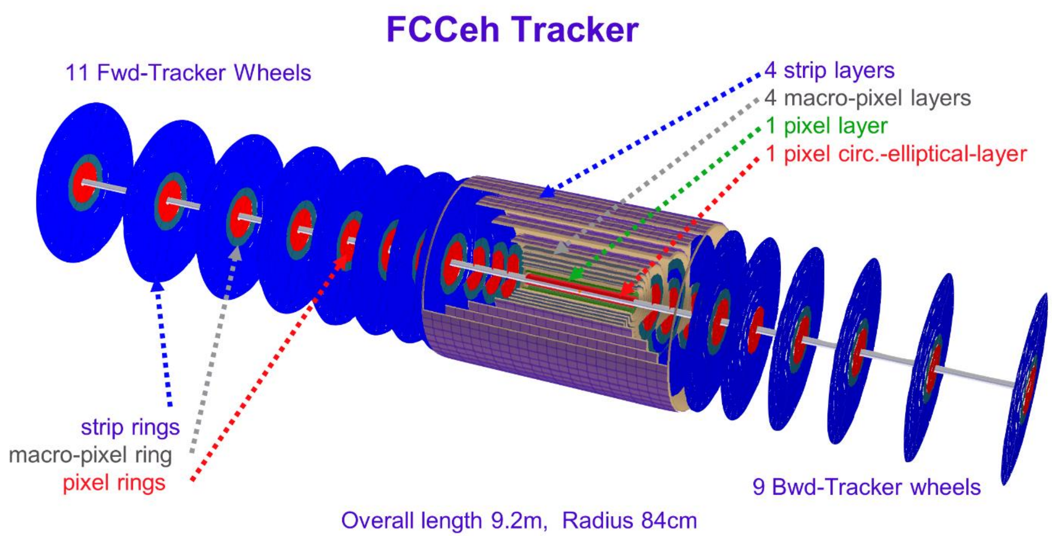
- Requires access to beam though cold part of LHC

- Low ξ can also be accessed via rapidity gap method, but with associated systematics

Modifications for 50TeV protons: FCC-eh



Current (limited!) design is scaled-up version of LHeC detector



- Required calo depth scales logathmically … overall dimensions 20x7m retains 12-15 interaction lengths

- Longer tracker (~9m) to retain 1° acceptance … tilted wheels?

Adaptions for Combined ep, eA, pp, pA, AA Interaction Point?

Promising feasibility study of proton beam optics and machine-detector interface

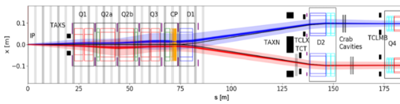
Slide from K. Andre'(CERN)

https://indico.ijclab.in2p3.fr/event/8623/

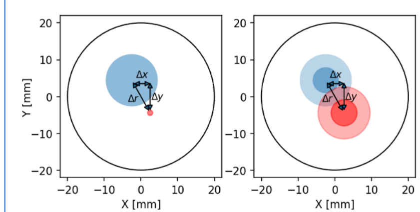
Requires symmetrised detector

Combined hh|eh interaction region

- Based on HL-LHC optics and lattice design, the **two proton beams must be housed in the same quadrupole aperture** unlike the past LHeC proton interaction design.
- Horizontal separation at the IP and vertical crossing angle to avoid parasitic interactions.
- The second proton beam should have a **flexible optics design**:
  - a **relaxed optics design, during eh operation**, as it acts as a spectator beam with an "injection like optics",
  - a **collision optics design, during hh operation**, to realise the HL-LHC luminosity
- Tradeoff between quadrupole aperture and achievable beam size at the IP for both eh and hh configurations.



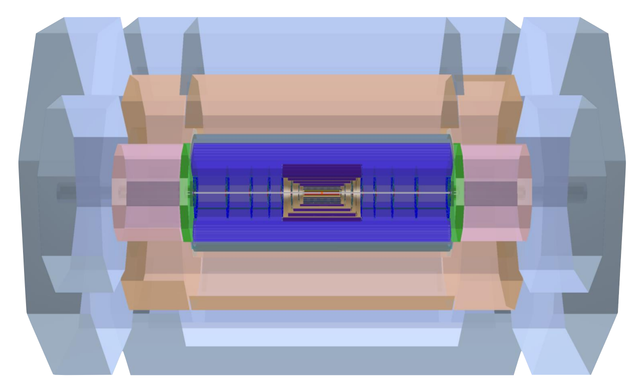
LHC proton beam trajectories from the IP to the matching quadrupole Q4



Relaxed (left) and collision optics (right) in a quadrupole aperture

- Mirroring forward half retains eh performance and would already be suitable for many hh tasks

- Requires a major re-assessment: tracker radiation hardness, dedicated particle ID detectors, beamline instrumentation …

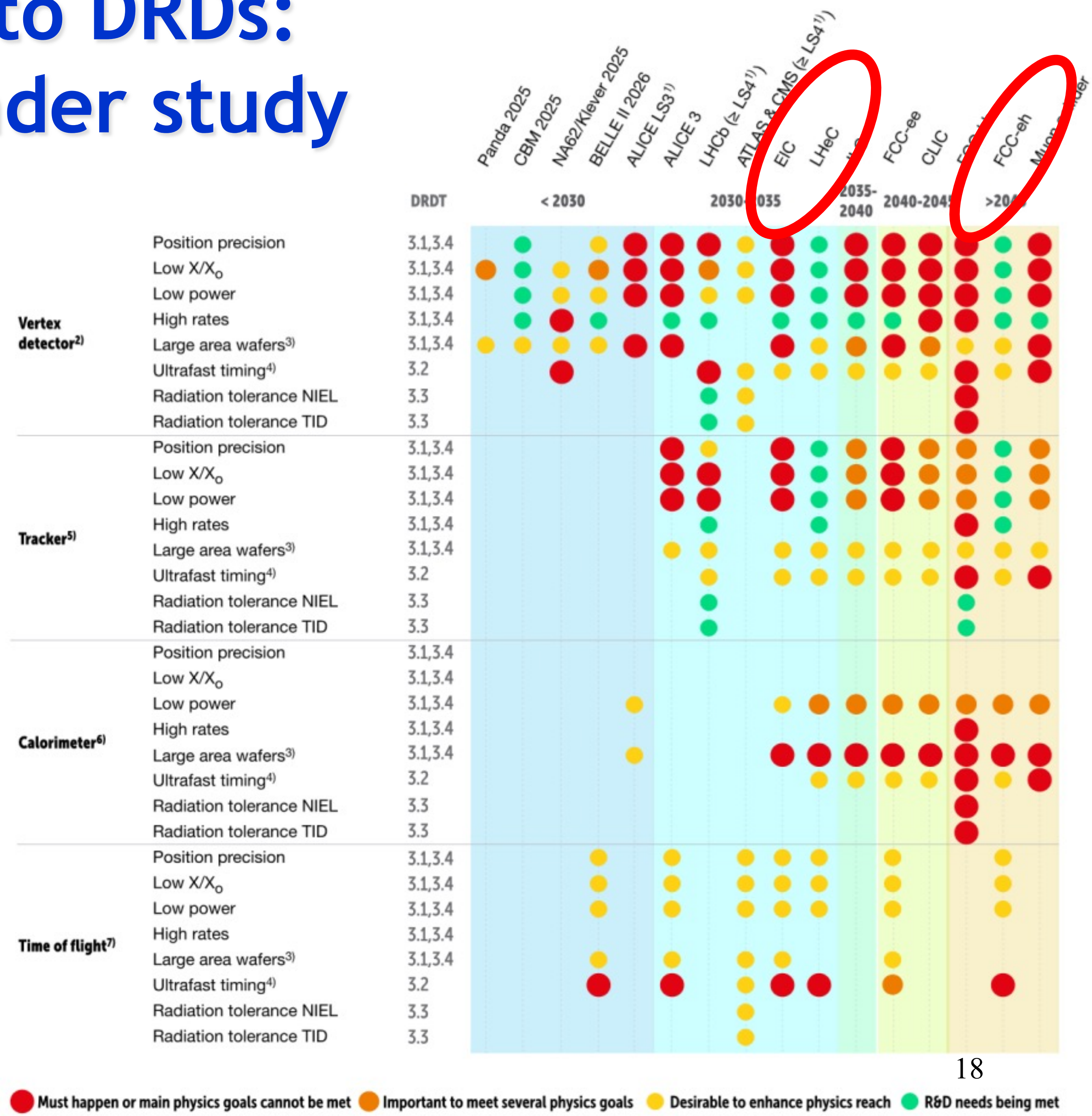


- ep calibration opportunies (hadrons v electron) may benefit hh programme?

Mapping to DRDs: already under study

(From ECFA European R&D roadmap)

e.g. Solid State Devices



Comparison with ePIC@EIC

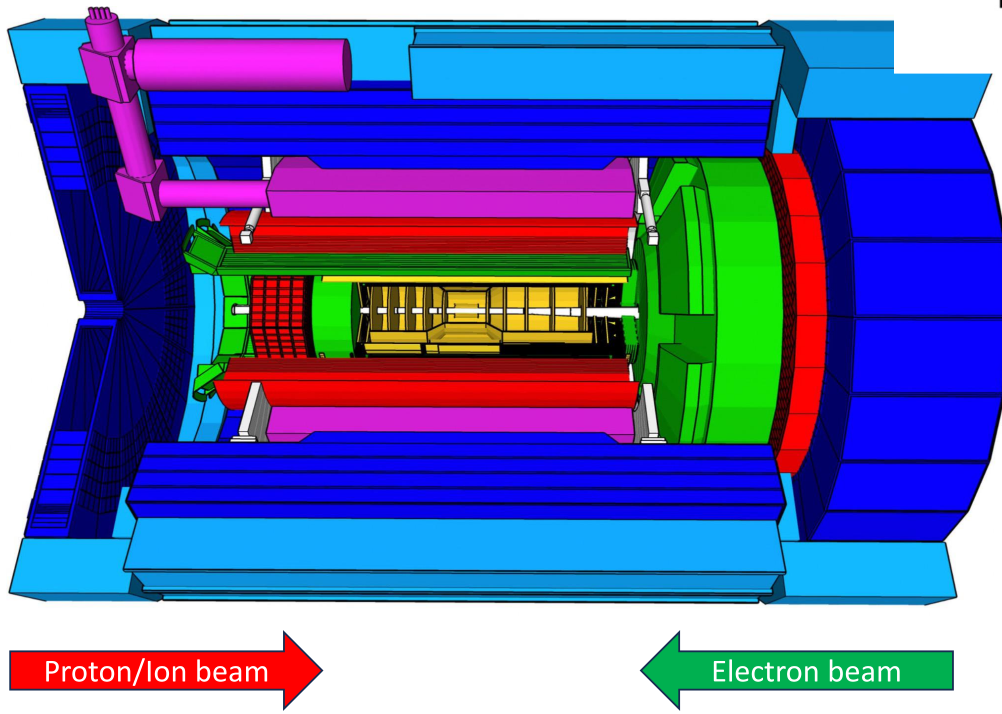
Magnet
- New 1.7 T SC solenoid, 2.8 m bore diameter

Tracking
- Si Vertex Tracker MAPS wafer-level stitched sensors (ALICE ITS3)
- Si Tracker MAPS barrel and disks
- Gaseous tracker: MPGDs (μRWELL, MMG) cylindrical and planar

PID
- high performance DIRC (hpDIRC)
- dual RICH (aerogel + gas) (forward)
- proximity focussing RICH (backward)
- ToF using AC-LGAD (barrel+forward)

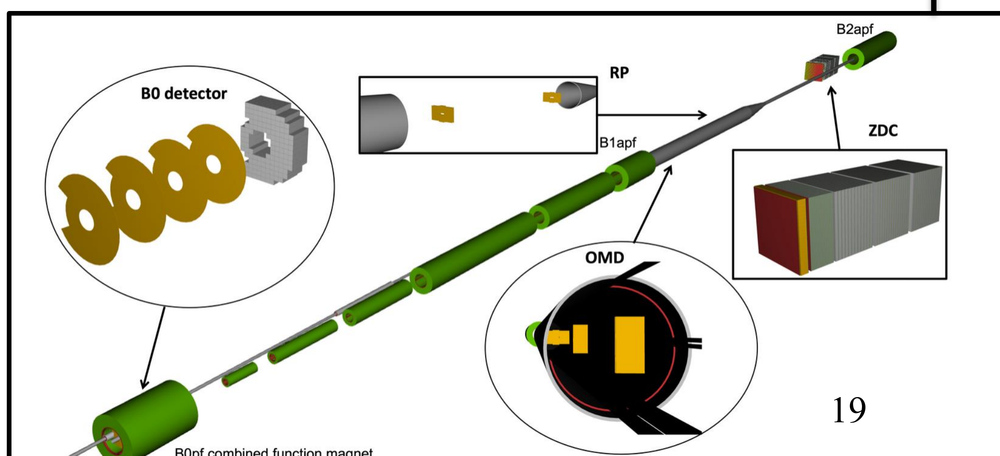
EM Calorimetry
- imaging EMCal (barrel)
- W-powder/SciFi (forward)
- $PbWO_4$ crystals (backward)

Hadron calorimetry
- FeSc (barrel, re-used from sPHENIX)
- Steel/Scint – W/Scint (backward/forward)



- Optimised for inclusive, semi-inclusive and exclusive DIS at smaller $\sqrt{s}$ but comparable lumi

- Interesting to compare with LHeC / FCC-eh → different reference point from LHC GPDs

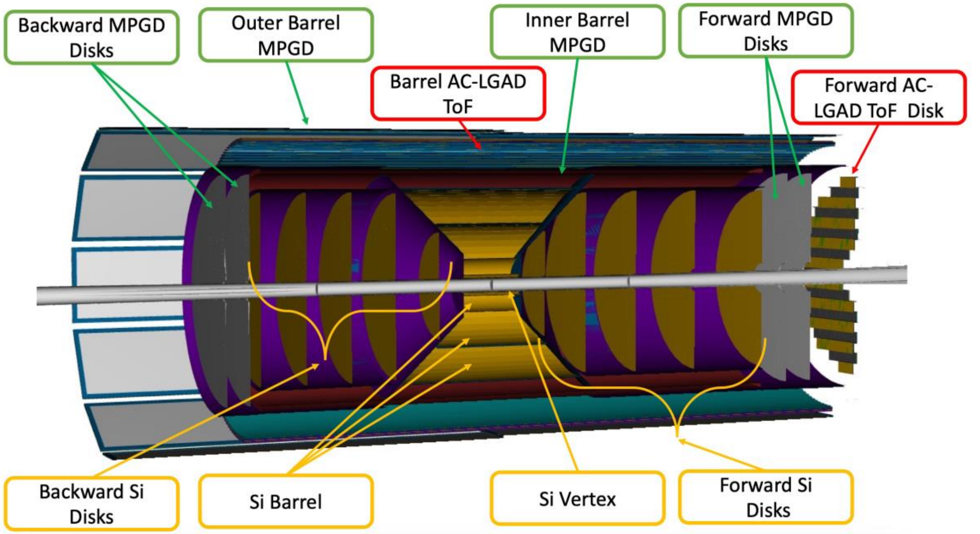


EIC Tracking Detectors

- MAPS silicon detectors (65nm)

… leaning heavily on ALICE ITS3: Stitched wafer-scale sensors, thinned and bent around beampipe → $0.05X_0$ per layer for inner layers

- LGAD layers for fast timing (~20ns)

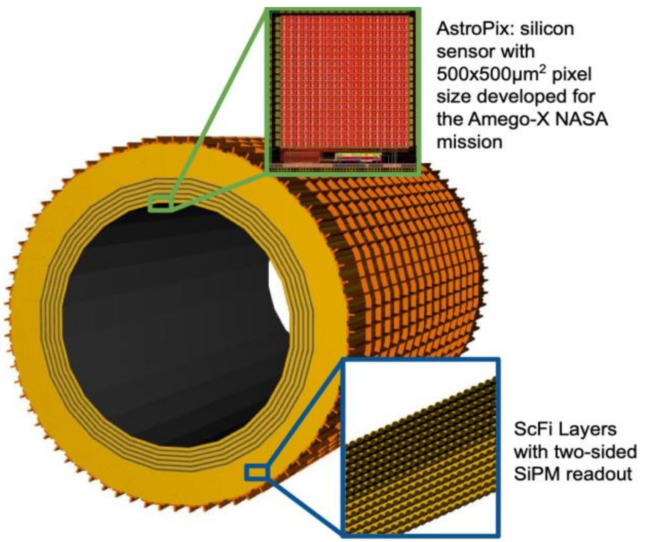


EIC Barrel Imaging ECAL

- 4 MAPS (Astropix) layers for position resolution

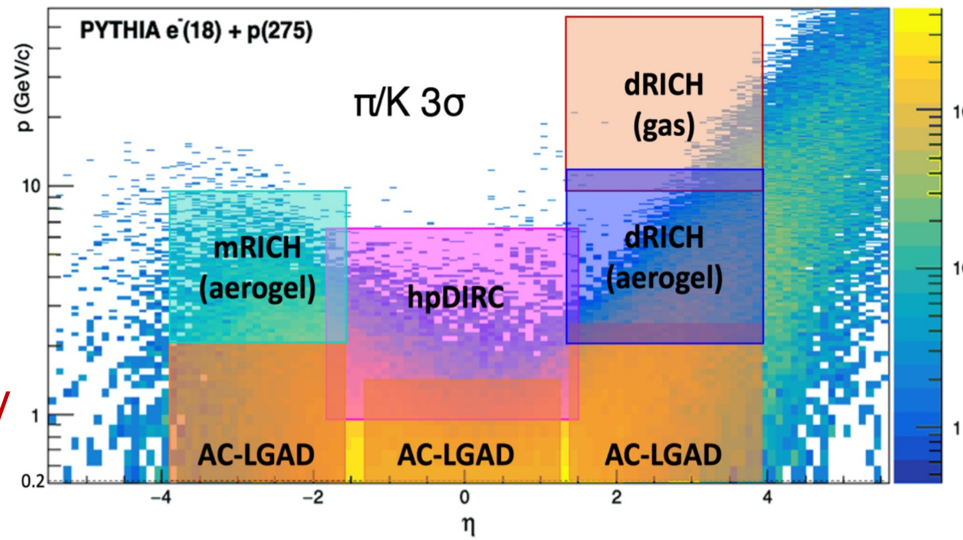
- Interleaved with 5 Pb/SciFi layers for energy resolution

- Followed by large Pb/SciFi section



EIC Particle Identification

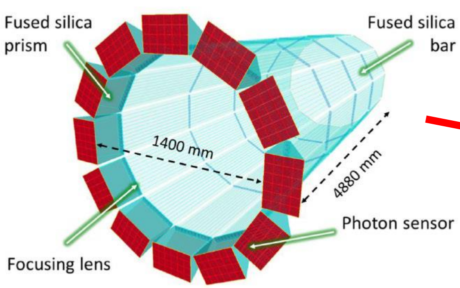
- SIDIS programme relies on π / K / p (and other PID) separation …
- Cerenkov detectors at high momentum, augmented by AC-LGADs / ToF at low momentum

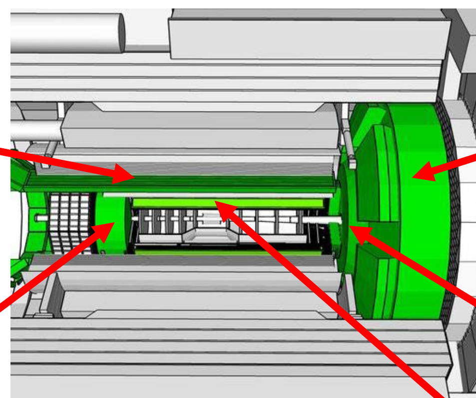


ePIC detector design – PID

High-Performance DIRC

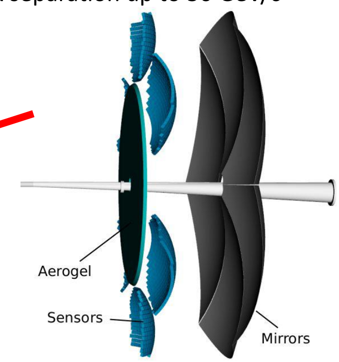
- Quartz bar radiator (reuse BaBAR bars)
- Sensors: MCP-PMTs
- π/K separation up to 6 GeV/c





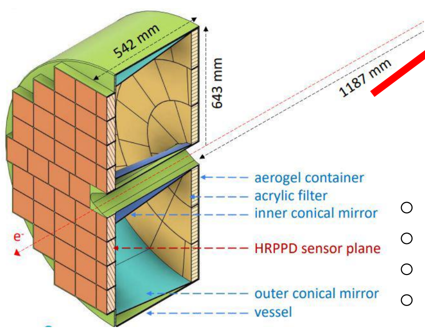
Dual-Radiator RICH (dRICH)

- C_2F_6 Gas Volume and Aerogel
- Sensors: SiPMs tiled on spheres
- π/K separation up to 50 GeV/c



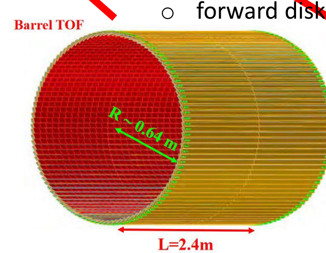
AC-LGAD TOF

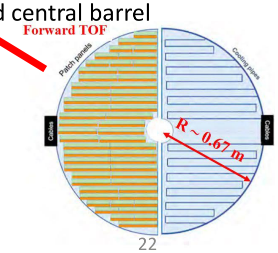
- t = ~30 psec / s = 30 µm
- Accurate space point for tracking
- forward disk and central barrel



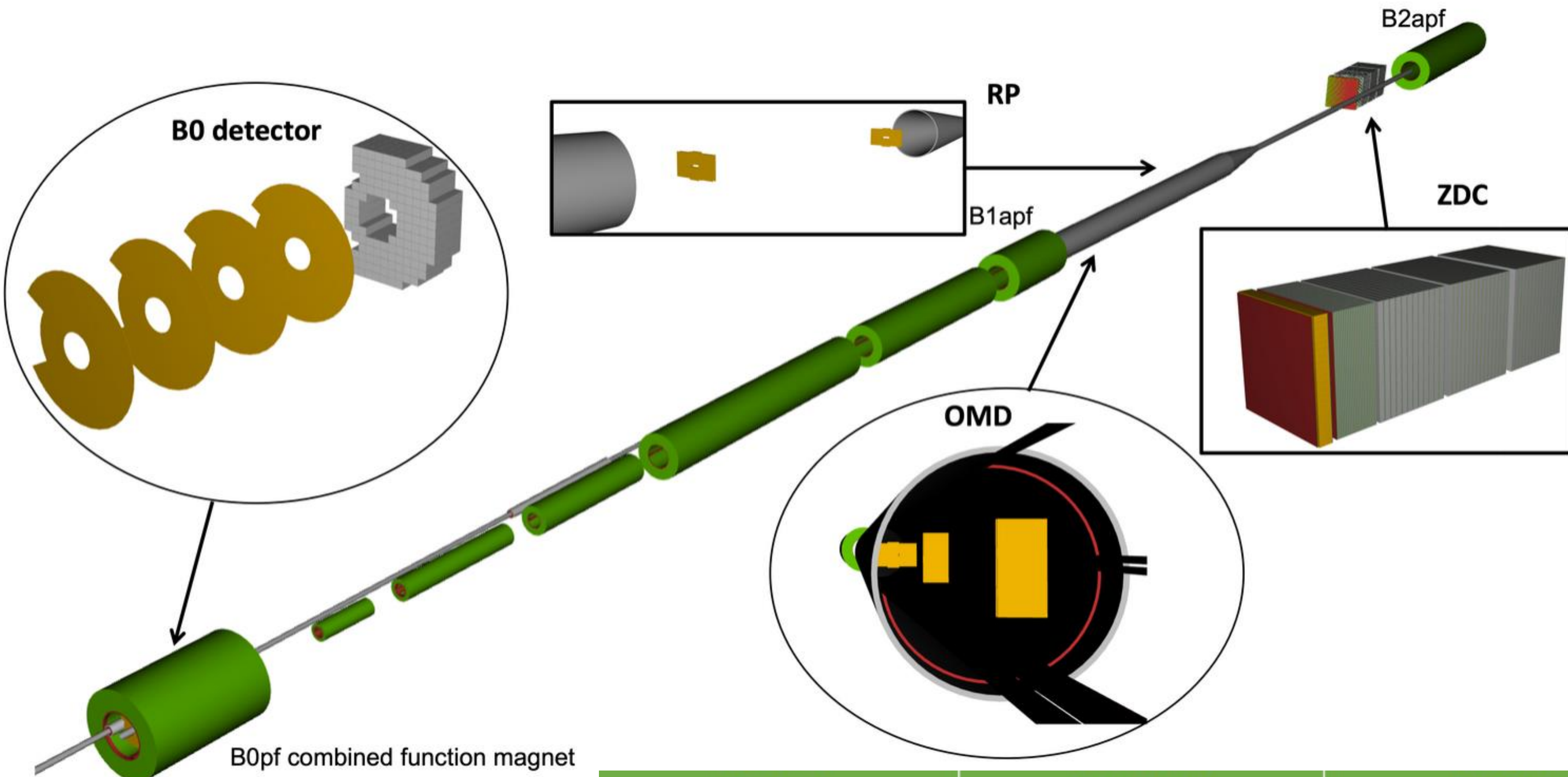
Proximity Focused (pfRICH)

- Long Proximity gap (~40 cm)
- Sensors: HRPPDs (also provides timing)
- π/K separation up to 10 GeV/c
- e/π separation up to 2.5 GeV/c





EIC Far Forward Region



~Hermetic forward coverage except for beampipe

Detector	Acceptance	Particles
Zero-Degree Calorimeter (ZDC)	$\theta < 5.5\ mrad$	Neutrons, photons
Roman Pots (2 stations)	$0^{*} < \theta < 5.0\ mrad$ (*10σ beam cut)	Protons, light nuclei
Off-Momentum Detectors (2 stations)	$0 < \theta < 5.0\ mrad$	Charged particles
B0 Detector	$5.5 < \theta < 20\ mrad$	Charged particles, tagged photons

Some Open Topics

… including both consolidation and 'from scratch' addition of new capabilities

<u>Design / simulation code base development</u>

- Common framework to investigate (integrated) detector response

<u>Detailed synchrotron radiation simulations</u>

- Explore impact on inner regions more thoroughly

<u>Optimising technology and layout of detectors near beamline</u>

- Inner tracker technology / layout (Fluences? Sensor placement close to the beam)
- Forward / Backward instrumentation fully integrated with the IR design

<u>Adding Particle ID capabilities (Cerenkov, TOF)</u>

- (p_T / η) ranges / technologies to connect with EIC SIDIS and physics in AA
- Compromises with respect to other detector components?

<u>Developing a Trigger / DAQ scheme</u>

- Understanding the physics and background rates
- Obtaining a (triggered or streaming) concept for data acquisition

<u>Review aspects of the detector 'inherited' from ATLAS?</u>

- Are calorimeter and muon designs really ideal for use in ep / eA?

<u>LHeC versus FCC-eh</u>

- Implications of higher energies … 'same again only bigger', or smarter?

<u>A joint detector eh and hh detector?</u>

- Technical challenges in simultaneously serving e-h and h-h studies
- Opportuities for cross-calibration and systematics reduction

“Circles in a circle”
Wassily Kandinsky (1923)
Philadelphia Museum of Art

SUMMARY

- LHeC / FCC-eh presents fresh instrumentation challenges

- A ‘technically possible now’ LHeC design exists from CDR-update

- Extension to FCC-eh yet to be studied in detail

- Many opportunities for new studies and conections …

  - Synergies with EIC detectors that approach reality
  - New technologies in European DRD programme & developments towards future energy frontier colliders

Self-subscribe to the WG mailing list: ep-eA-WG4-structure@cern.ch