Detector R&D Requirements for Strong Interaction Experiments at Future Colliders

① Electron Ion Collider (EIC)

② ALICE 3 – A Next Generation Heavy-Ion Detector at the LHC

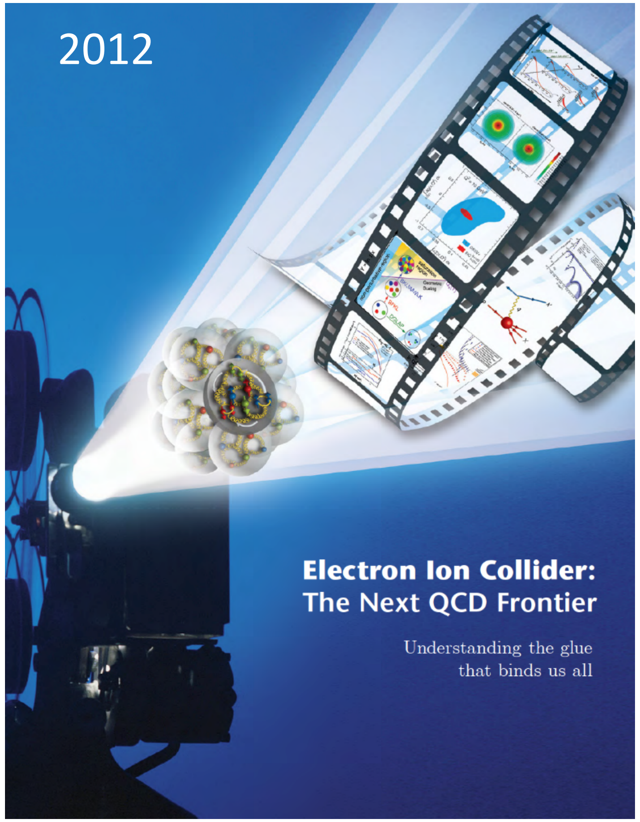
③ LHeC & FCC-eh/eA

Luciano Musa (CERN)

Credits:

- *EIC: Elke Caroline Aschenauer (BNL,), Rolf Ent (JLAB) and Thomas Ullrich (BNL), S. Dalla Torre (INFN TS)*
- *LHeC & FCC-eh: Max Klein (Liverpool)*
- *ALICE 3: Jochen Klein (CERN), Marco Van Leeuwen (Nikhef)*

Electron Ion Collider

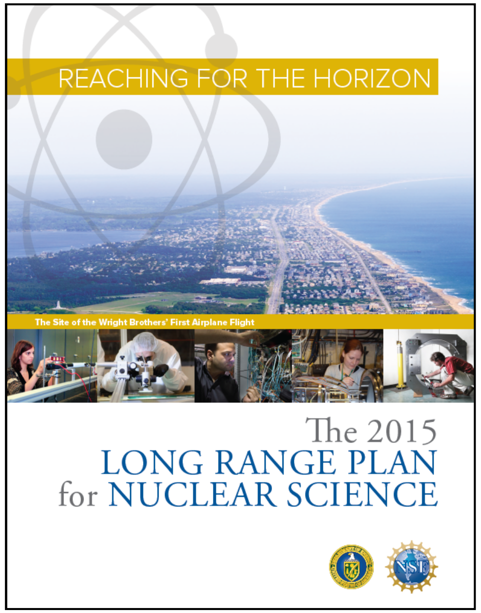


"The quantitative study of matter in this new regime [where abundant gluons dominate] requires a new experimental facility: an Electron Ion Collider."

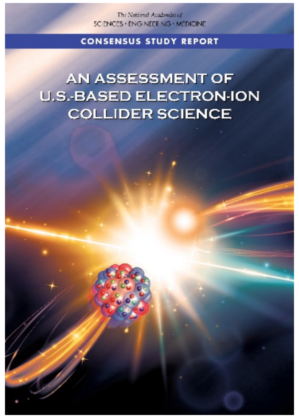
The Science Mission

1. How does the mass of the nucleon arise?
2. How does the spin of the nucleon arise?
3. What are the emergent properties of dense systems of gluons?

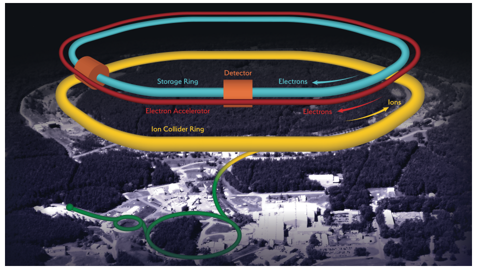
2015 - US Nuclear Physics Long Range Plan: "a high-energy high-luminosity polarized EIC [is] the highest priority for new facility construction following the completion of FRIB."



2018 – National Academy EIC Review: "The committee find that the science than can be addressed by the EIC is compelling, fundamental and timely."



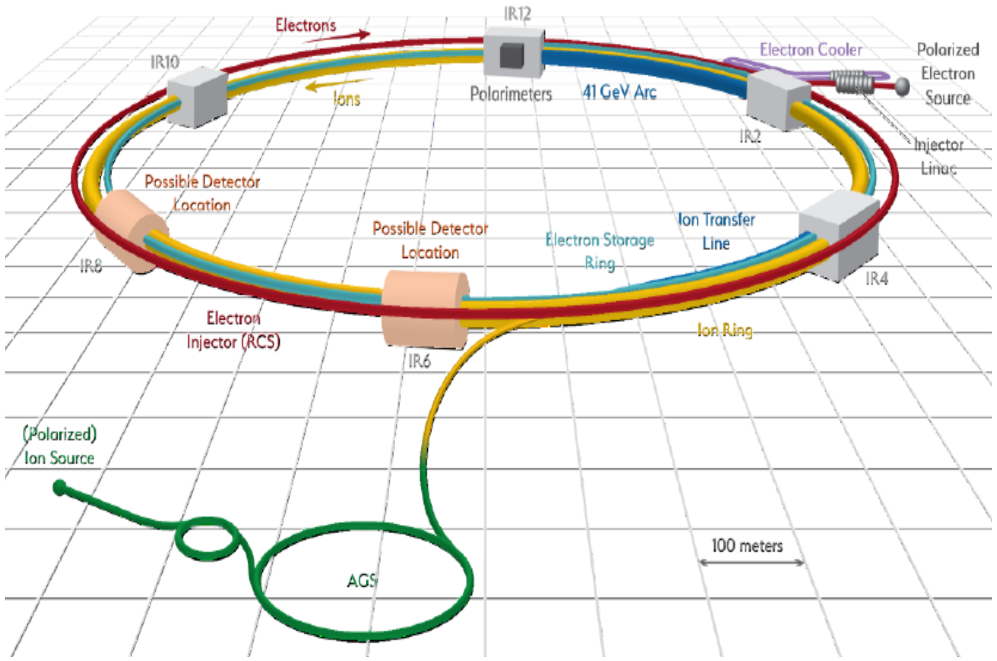
Jan 2020 – U.S. DOE gives EIC CD-0 (Mission Need) and selects BNL to host the EIC



26-28 Jan 2021
EIC CD-1 (Alternative and Cost Range)

Electron Ion Collider

Design using most of the existing RHIC facility



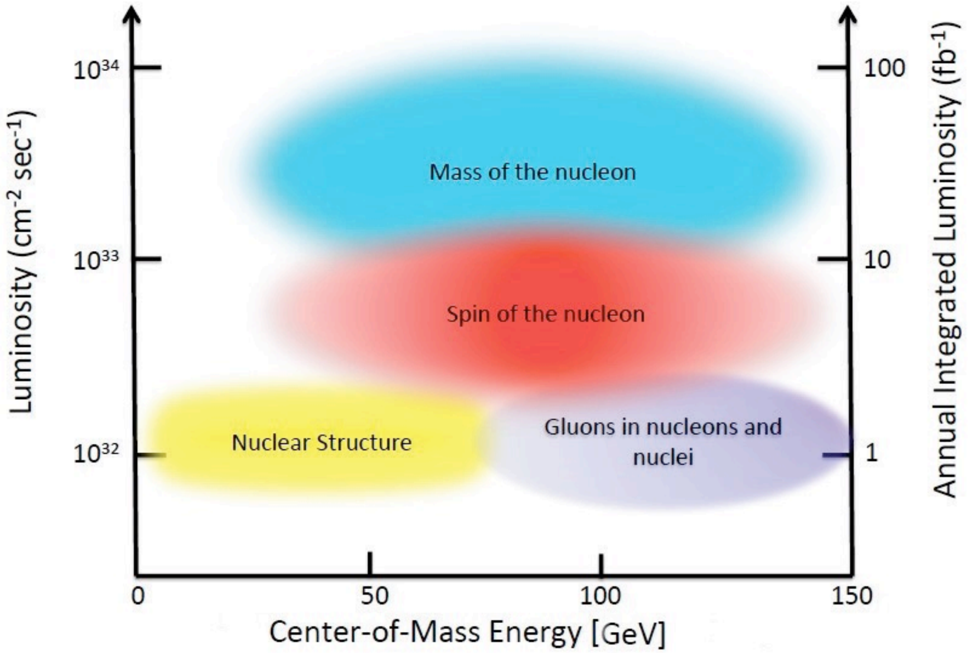
Utilize existing operational <u>hadron collider:</u>

E_p: **41, 100 … 275 GeV** / E_{ion}: **41 … 110 GeV/n**

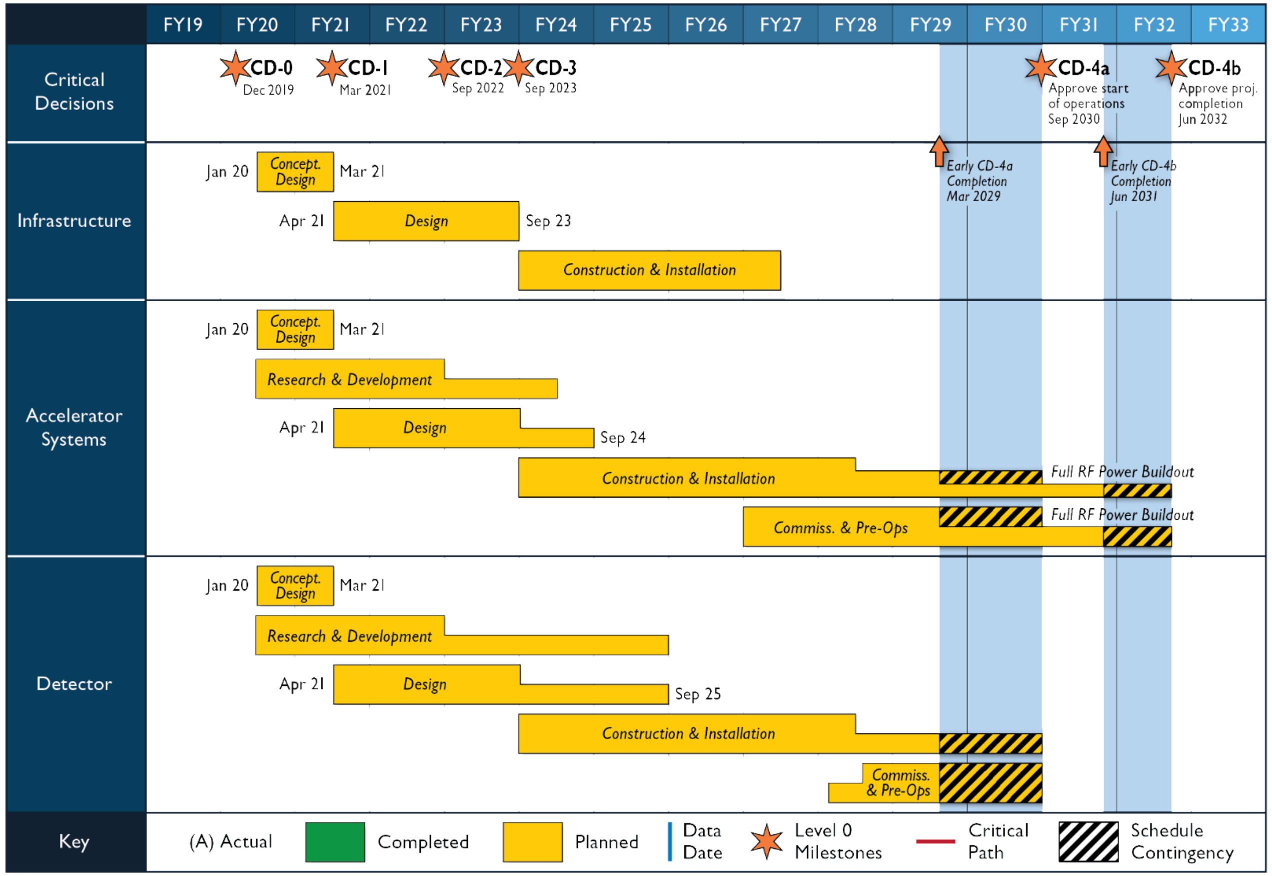
Add <u>electron storage ring</u> (E_e: **5 … 18 GeV**), cooling in existing RHIC tunnel and electron injector.

Two interaction regions

- Center of Mass Energies: 20 GeV – 140 GeV
- Maximum Luminosity: 10^{34} $cm^{-2}s^{-1}$
- e, p, A Beam Polarization: > 70%
- Ion Species Range: p to Uranium



Electron Ion Collider



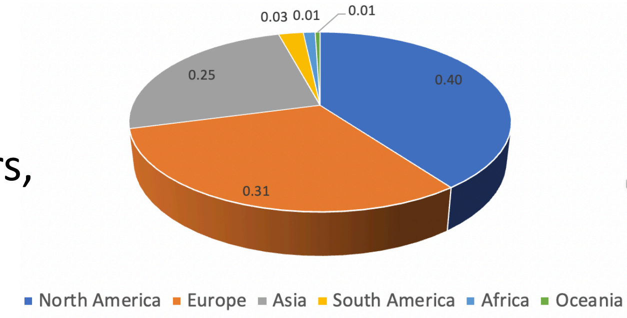
CD-0: Mission Need
CD-1: Alternative and Cost Range
CD-2: Performance baseline
CD-3: Start construction
CD-4a: Start operation
CD-4b: Full RFPower Installed

Worldwide Interest in EIC Program

The EIC User Group http://www.eicug.org/

Formed 2016

- February 2021:
- 1253 collaborators,
- 33 countries,
- 251 institutions



Setting the stage

Ongoing EIC User Group "Yellow Report" Effort (2020)

- Refine requirements and detector concept

EIC Project: EOI, May – November 2020

- EoI for potential cooperation on exp. equipment

Next (Mar – Dec 2021)

- Issue Call for Detector Proposals
- Start Selection of Detector(s)

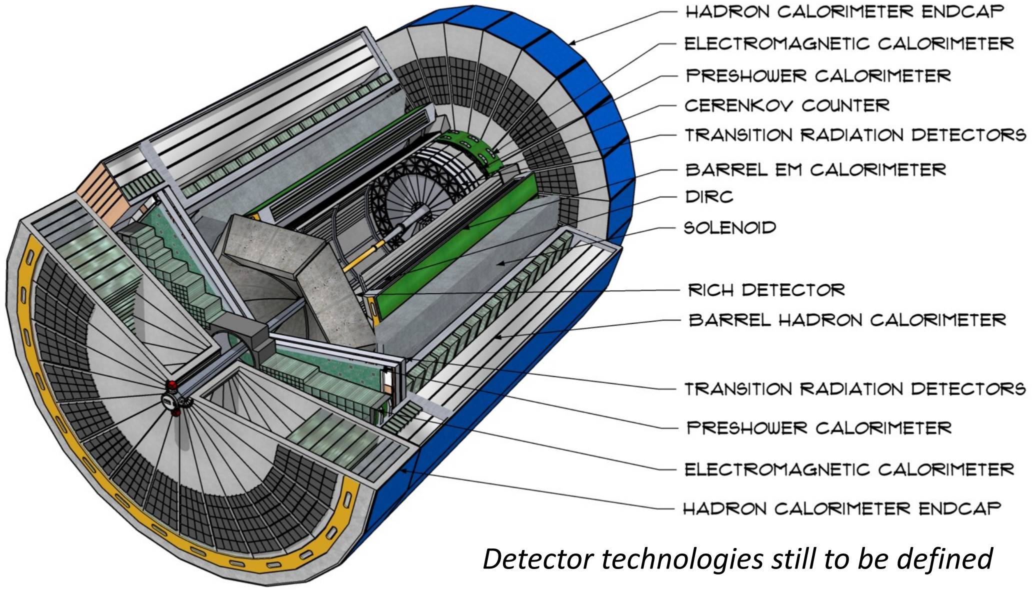
Electron Ion Collider

Detector General Requirements

- Large rapidity ($-4 < \eta < 4$) coverage;
  and far beyond in especially far-forward detector regions
- High precision low mass tracking
  - small (μ-vertex) and large radius tracking
- Electromagnetic and Hadronic Calorimetry
  - equal coverage of tracking and EM-calorimetry
- High performance PID to separate π, K, p on track level
  - also need good e/π separation for scattered electron
- Large acceptance for diffraction, tagging, neutrons from nuclear breakup: critical for physics program
  - Many ancillary detector integrated in the beam line: low-Q^2 tagger, Roman Pots, Zero-Degree Calorimeter, ….
- High control of systematics
  - luminosity monitor, electron & hadron Polarimetry

Not further discussed here

Integration into Interaction Region is critical



Detector technologies still to be defined

Low pile-up, low multiplicity, data rate ~500kHz (full lumi)

Moderate radiation hardness

Main Challenges
- PID
- EMCal at < 2%/ $\sqrt{E}$

Electron Ion Collider

EICUG: Yellow Report (YR) Initiative

Detector requirements and design driven by EIC Physics program and defined by EIC Community

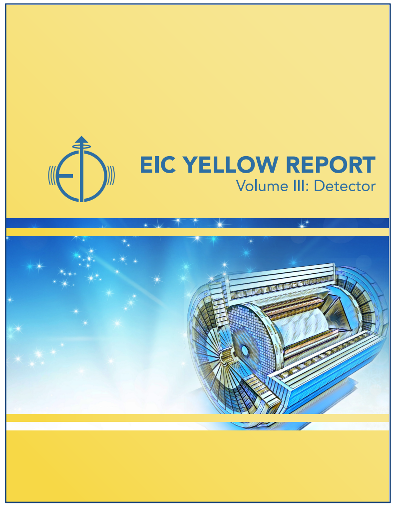
Physics Topics → Processes → Detector Requirements

Physics Working Group:

- Inclusive Reactions
- Semi-Inclusive Reactions
- Jets, Heavy Quarks
- Exclusive Reactions
- Diffractive Reactions & Tagging

Detector Working Group:

- Tracking + Vertexing
- Particle ID
- Calorimetry
- Far-Forward Detectors
- DAQ/Electronics
- Polarimetry/Ancillary Detectors
- Central Detector: Integration & Magnet
- Forward Detector: IR Integration



Provides critical input for detector proposals – handoff between Physics & Detector Working Groups in "**interactive detector matrix**": Collects physics requirements "real time", lists all technologies for a given region, and links to studies that established the numbers

EIC – Possible Detector Tehnologies

Possible detector technologies for the Main Detector fulfilling the physics requirements

Note: **setup used for CD1** – **many decisions still open** ➪ will be decided by the Collaboration

system	system components	reference detectors	detectors, alternative options considered by the community		
tracking	vertex	MAPS, 20 um pitch	MAPS, 10 um pitch		
	barrel	TPC	TPC [a]	MAPS, 20 um pitch	MICROMEGAS [b]
	forward & backward	MAPS, 20 um pitch	GEMs with Cr electrodes		
ECal	barrel	Pb/Sc Shashlyk	SciGlass	W powder/ScFi	W/Sc Shashlyk
	forward	W powder/ScFi	SciGlass	Pb/Sc Shashlyk	W/Sc Shashlyk
	backward, inner	$PbWO_4$	SciGlass		
	backward, outer	SciGlass	PbWO4	W powder/ScFi	W/Sc Shashlyk [c]
h-PID	barrel	High performance DIRC & dE/dx (TPC)	reuse of BABAR DIRC bars	fine resolution TOF	
	forward, high p	fluorocarbon gaseous RICH	double RICH combining	high pressure Ar RICH	
	forward, medium p	aerogel	aerogel and fluorocarbon		
	forward, low p	TOF	dE/dx		
	backward	modular RICH (aerogel)			
e/h separation at low p	forward	TOF & areogel & gaseous RICH	adding TRD		
	backward	modular RICH & TRD	Hadron Blind Detector		
HCal	barrel	Fe/Sc	RPC/DHCAL	Pb/Sc	
	forward	Fe/Sc	RPC/DHCAL	Pb/Sc	
	backward	Fe/Sc	RPC/DHCAL	Pb/Sc	

[a] TPC surrounded by a micro-RWELL tracker
[b] set of coaxial cylindrical MICROMEGAS
[c] also Pb/Sc Shashlyk

Source: *EIC CDR Experimental Equipment, Nov 2020, Table 8.4*

EIC – performance of reference detector

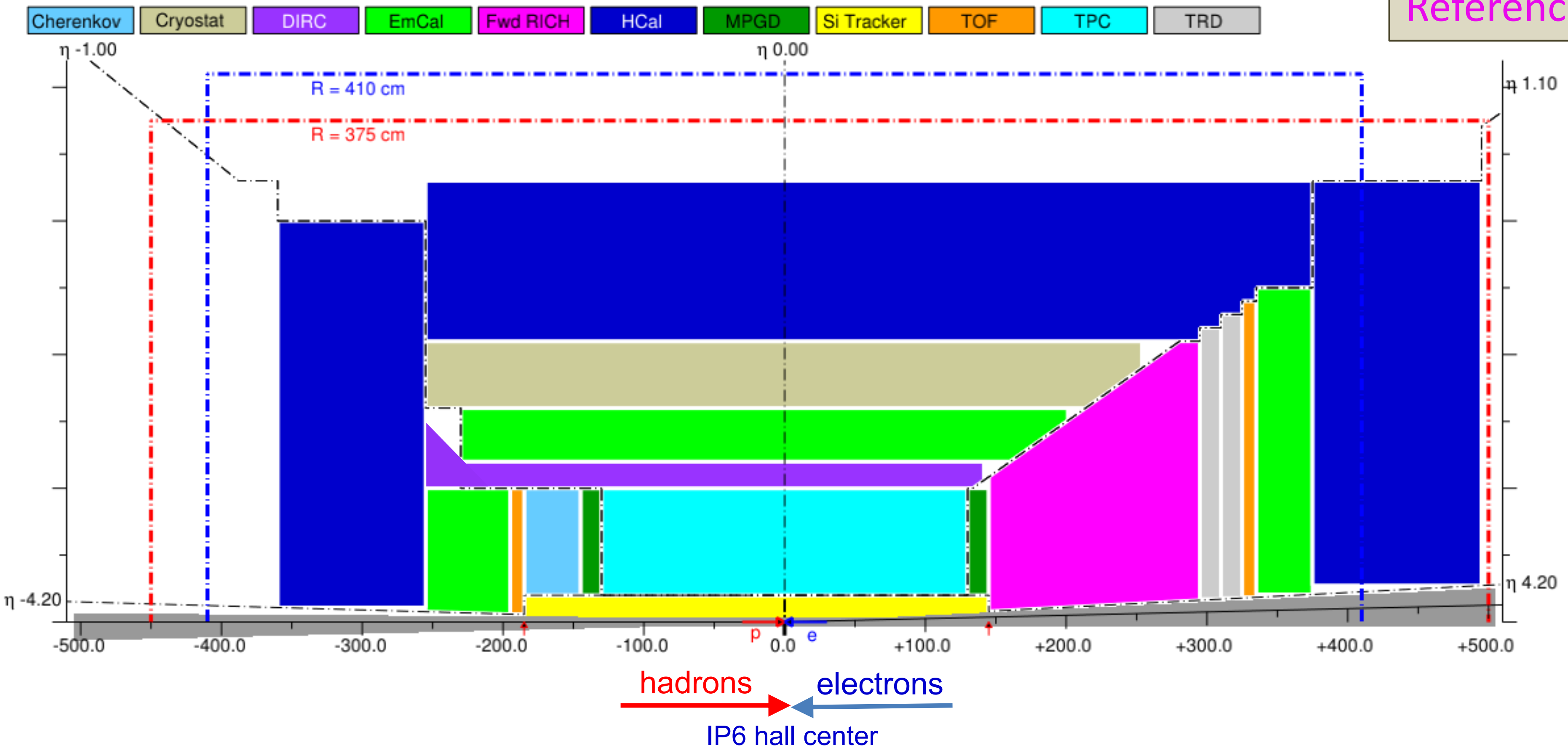
Source: *EIC CDR Experimental Equipment, November 2020*

η	θ	Nomenclature			Tracking: Resolution	Tracking: Relative Momentum	Tracking: Allowed X/X_0	Tracking: Minimum-pT	Tracking: Transverse Pointing Res.	Tracking: Longitudinal Pointing Res.	Electrons and Photons: Resolution σ_E/E	Electrons and Photons: PID	Electrons and Photons: Min E Photon	π/K/p: p-Range (GeV/c)	π/K/p: Separation	HCAL: Resolution σ_E/E	HCAL: Energy	Muons
< -4.6		↓ p/A	Far Backward Detectors	low-Q2 tagger														
-4.6 to -4.0					Not Accessible													
-4.0 to -3.5						Reduced Performance												
-3.5 to -3.0			Central Detector	Backward Detector		σ_p/p ~0.2%×p⊕5%	~5% or less X	70-150 MeV/c (B=1.5 T)			1%/E ⊕ 2.5%/√E ⊕ 1%	π suppression up to 1:1E-4	20 MeV	≤ 10 GeV/c	≥ 3 σ	50%/√E⊕10%	~500MeV	Muons useful for bkg, improve resolution
-3.0 to -2.5																		
-2.5 to -2.0						σ_p/p~ 0.04%×p⊕2%												
-2.0 to -1.5									dca(xy) ~ 40/pT μm ⊕ 10 μm	dca(z) ~ 100/pT μm ⊕ 20 μm	2%/E ⊕(4-8)%/√E ⊕ 2%	π suppression up to 1:(1E-3 - 1E-2)	50 MeV					
-1.5 to -1.0																		
-1.0 to -0.5				Barrel		σ_p/p ~0.04%×p⊕1%		200 MeV/c	dca(xy) ~ 30/pT μm ⊕ 5 μm	dca(z) ~ 30/pT μm ⊕ 5 μm	2%/E ⊕(12-14)%/√E ⊕ (2-3)%	π suppression up to 1:1E-2	100 MeV	≤ 6 GeV/c		100%/√E+10%		
-0.5 to 0.0																		
0.0 to 0.5																		
0.5 to 1.0																		
1.0 to 1.5				Forward Detectors		σ_p/p ~0.04%×p⊕2%		70 - 150 MeV/c (B = 1.5 T)	dca(xy) ~ 40/pT μm ⊕ 10 μm	dca(z) ~ 100/pT μm ⊕ 20 μm	2%/E ⊕ (4*-12)%/√E ⊕ 2%	3σ e/π up to 15 GeV/c	50 MeV	≤ 50 GeV/c		50%/√E+10%		
1.5 to 2.0																		
2.0 to 2.5																		
2.5 to 3.0						σ_p/p ~0.2%×p⊕5%												
3.0 to 3.5																		
3.5 to 4.0		↑ e		Instrumentation to separate charged particles from photons		Reduced Performance												
4.0 to 4.5					Not Accessible													
> 4.6			Far Forward Detectors	Proton Spectrometer														
				Zero Degree Neutral Detection														

Interactvie version of this matrix ➪ Yellow Report Physics Working Group Wiki page: https://physdiv.jlab.org/DetectorMatrix/

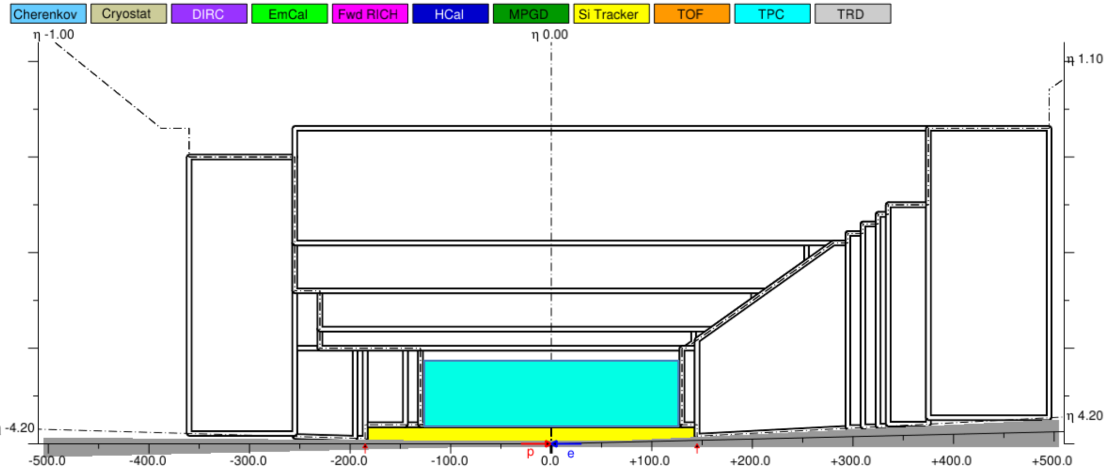
Electron Ion Collider

Reference Detector



- -4.5 /+5 m machine element free region for central detector
- 25 mrad crossing angle
- Individual detector component space allocations provided by the Yellow Report Working Groups

EIC – Tracking

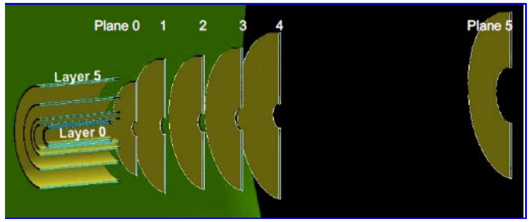


Detector Requirements

- Vertex (central): $\sigma_{xyz} \sim 20\mu m$, $d_0(z) \sim d_0(\varphi) \sim (20/p_T \text{ GeV} + 5)\ \mu m$
- Resolution
  - central: $\sigma(p_T)/p_T \sim 0.05\% \cdot p_T \oplus 0.5\%$
  - fwd/bwd ($1<|\eta| < 2.5$): $\sigma(p_T)/p_T \sim 0.05\% \cdot p_T \oplus 1\%$
  - fwd/bwd ($2.5 <|\eta| < 3.5$): $\sigma(p_T)/p_T \sim 0.1\% \cdot p_T \oplus 2\%$
- Material budget: $X/X0 \lesssim 5\%$
- Minimum p_T: 100 MeV/c pions, 135 MeV/c Kaons

All-silicon option

6-layer barrel, 5+5 disks



for back/forward regions

Option: light (Cr) GEMs for the most external disks

Sensor: MAPS with $\leq 20\mu m$ pitch, …

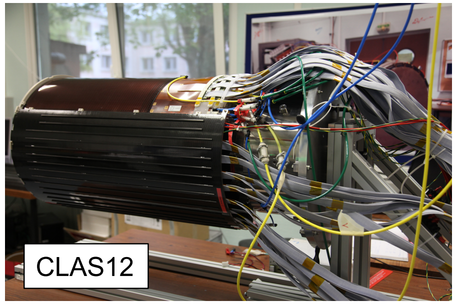
Needs new sensor to meet EIC requirements
⇨ consortium of EIC groups joined the ongoing sensor development effort for ALICE ITS3 (CERN)

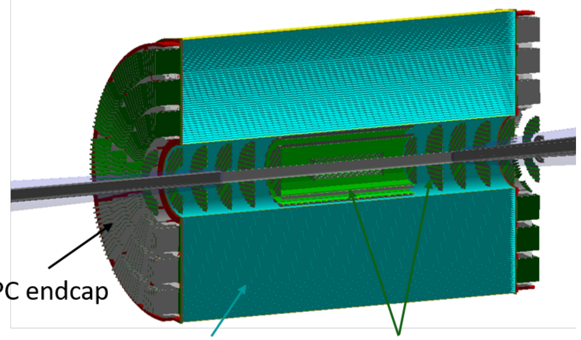
Hybrid option

silicon vertex + TPC (barrel), 7 silicon disks for back/forward

option 1: TPC + external layer of MPGD, supports tracking + time

option 2: coaxial layers of μ–RWELLs

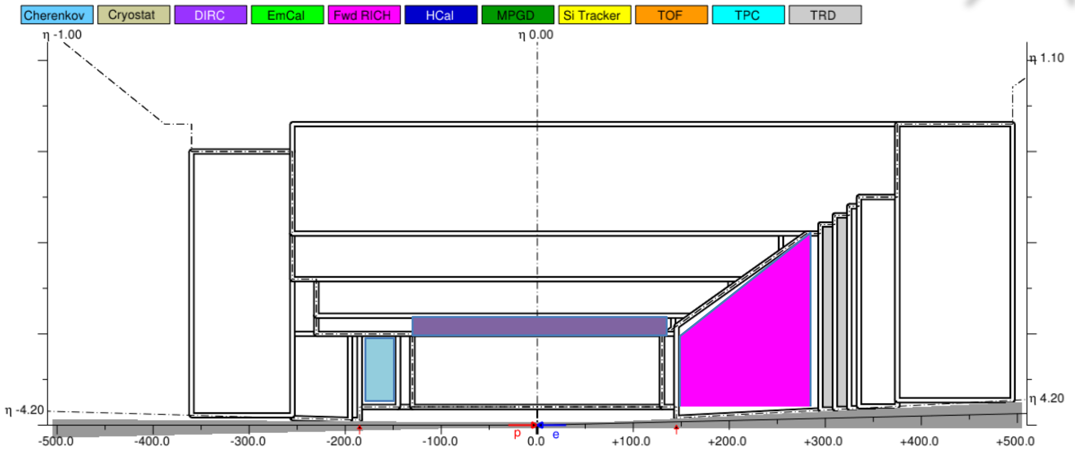




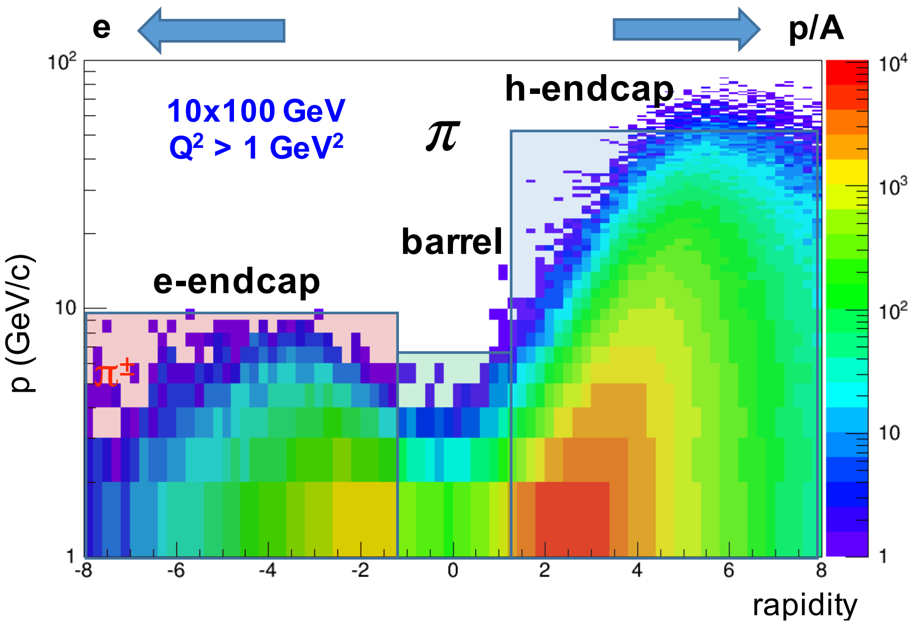
EIC – hadron ID

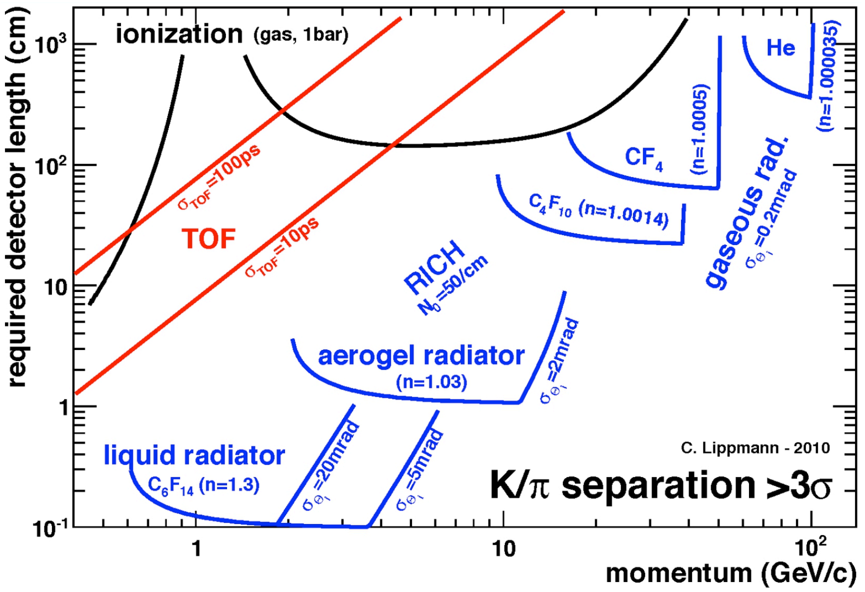
Requirements

- $\pi^{\pm}$, $K^{\pm}$, $p^{\pm}$ separation over a wide range $|\eta| \leq 3.5$
- Resolution: $\pi/K \sim$ 3-4 σ , $K/p > 1\ \sigma$
- Momentum-η correlation a different PID technology
  - $-5 < \eta < 2$: $0.2 < p < 10$ GeV/c
  - $2 < \eta < 5$: **$0.2 < p < 50$ GeV/c**
- Hadron cut-off: B=1T ⇨ $p_T > 200$MeV, B=3T ⇨ $p_T > 500$MeV



Needs more than one technology to cover the entire kinematics





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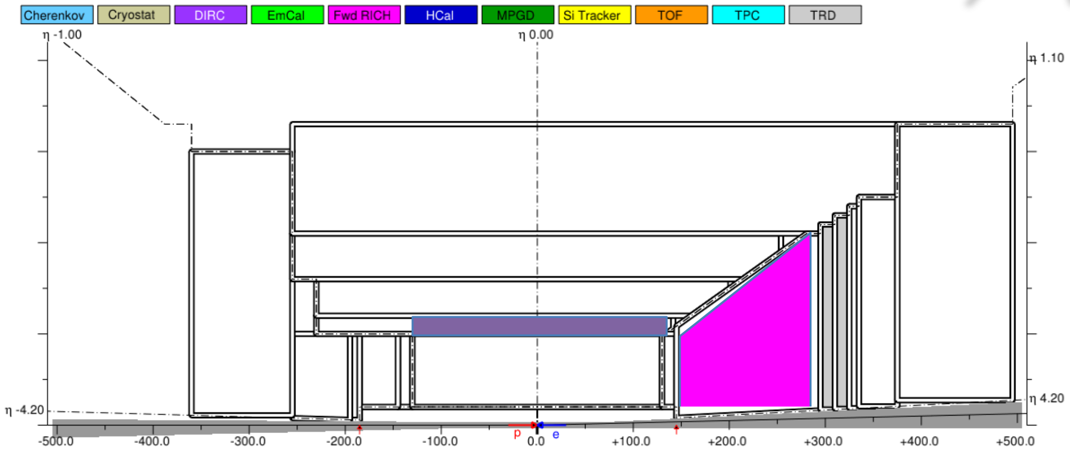
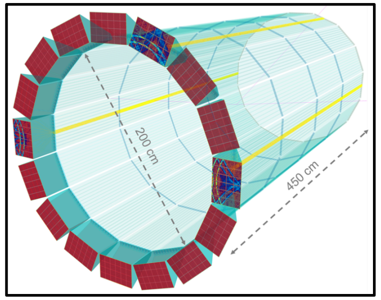


Barrel

Reference: hpDIRC (high performance DIRC)

- Quartz bar radiator, light detection with MCP-PMTs
- Fully focused
- π/K separation $\sim 3\ \sigma$ @ 6 Gev/c
- Reuse of BaBar DIRC as alternative

R&D e.g.: add timing to the DIRC



dE/dx from TPC, complementary

- expected resolution ~ STAR, sPHENIX

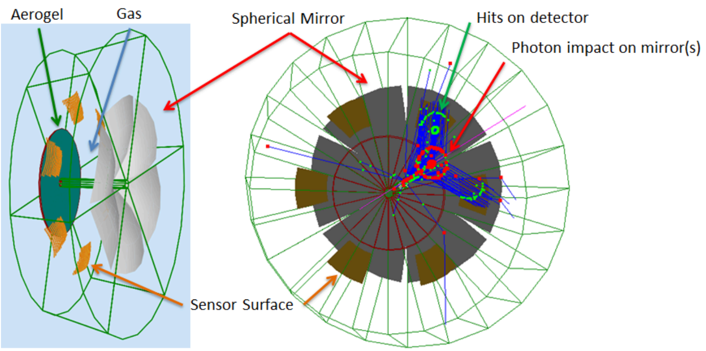
TOF (~ 1m lever arm)

- LGAD (Low Gain Avalanche Detector)

Forward

Reference: dRICH (dual RICH)

- Aerogel and C-F gas radiators
- Full momentum range
- Sensor: Si PMs (TBC)
- π/K separation $\sim 3\ \sigma$ @ 50 Gev/c



Windowless RICH

- Gaseous sensors (MPGDs), CF_4 as radiator and sensor gas
- Low p complements required (TOF with 2.5m lever arm/aerogel (mRICH)

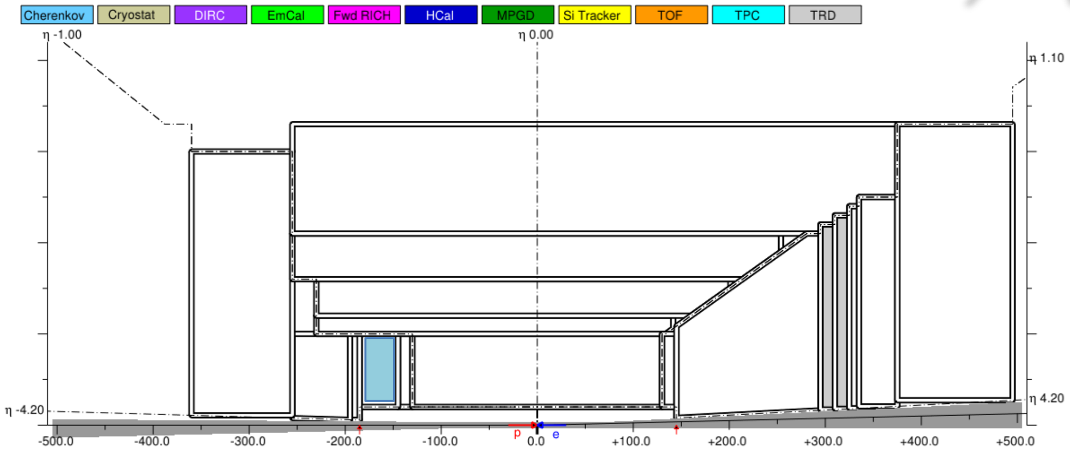
HP-RICH (high-pressure RICH)

- Eco-friendly alternative to dRICH
- Ar @ 3.5 bar / 2 bar ⟺ C_4F_{10} @ 1 bar / CF_4 @ 1 bar

EIC – hadron ID

Requirements

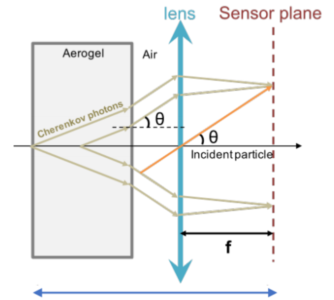
- $\pi^{\pm}$, $K^{\pm}$, $p^{\pm}$ separation over a wide range $|\eta| \lesssim 3.5$
- Resolution: $\pi/K \sim$ 3-4 σ , $K/p > 1\ \sigma$
- Momentum-η correlation a different PID technology
  - $-5 < \eta < 2$: $0.2 < p < 10$ GeV/c
  - $2 < \eta < 5$: **$0.2 < p < 50$ GeV/c**
- Hadron cut-off: B=1T ➪ $p_T > 200$MeV, B=3T ➪ $p_T > 500$MeV



Backward

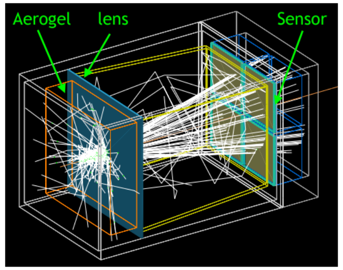
Reference: mRICH
(Modular RICH)

- **Aerogel** Cherenkov
- Focused by Fresnel lens
- e, π, K, p
- Sensor: SiPM / LAPPDs
- Adaptable to include TOF
- π/K separation
  $\sim$ 3 σ @ 10 Gev/c



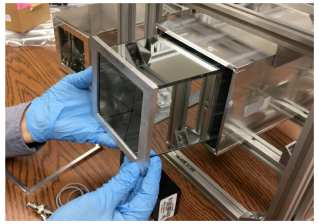
~ (aerogel thickness + lens focal length)

(Not to scale, for illustration purpose only)

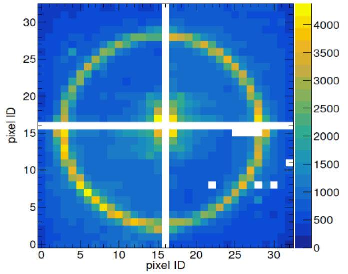


Geant4 Simulation

With realistic material optical properties



2nd mRICH prototype was tested at Fermilab Test Beam Facility in June/July 2018



TOF with 2m lever arm, 2 options

- **LAPPD** (Large Area picos Photon Detector)
  - MCP, Cherenkov in window, 5-10 psec
- **LGAD** (Low Gain Avalanche Detector)
  - Silicon Avalanche, 25-35 ps
  - Accurate space point for tracking
  - Relevant also for central barrel

HBD (Hadron Blind Detector)

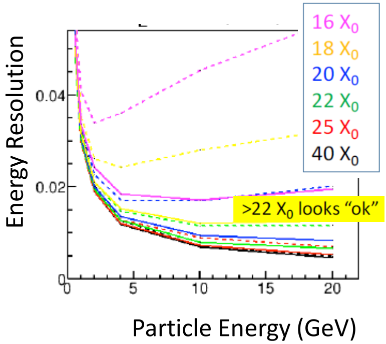
- Unfocussed CF_4 Cherenkov det.
- π-threshold ~ 4GeV
- New gain stage proposed to improve e/π separation

EIC – ECal

Backward arm

High-resolution important in region $-4 < \eta < -2$

- Determines electron kinematics
- Physics requires ~2%/ /√ E
- Particle E: ~0.02 – 18 GeV



Outer part alternatives

- Pb/Sc, W/Sc Shashlik
- W poweder/ScFi Sampling

REFERENCE

$PbWO_4$ crystals (inner)

- Compact, radiation hard, luminiscence yield to achieve high energy resolution, including the lowest photon energies

SciGlass (Outer)

- EIC eRD51
- More cost efficient, easier manufacturing
- Potentially better optical properties

Sensor: SiPMs (TBC)

Barrel

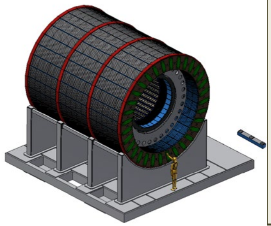
Physics requires 10-12%/√ E in region $-1 < \eta < 1$

- Particle E: ~0.1 – 35 GeV

REFERENCE

Pb/Sc, W/Sc Shashlik

- Pb, W absorber g high density absorber can provide 8-15%/√ E, energy resolution can be tuned by adjusting sampling fraction and frequency



W poweder/SciFi

- Compact, resolution 12-14%/ √ E

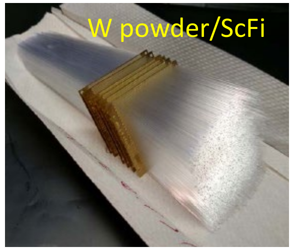
Higher resolution

- $PbWO_4$, SciGlass

Forward arm

Physics requires 10%/√ E in region $1 < \eta < 4$

- Particle E: ~0.5 – 100 GeV • High Q^2/high x



Pb/Shashlik, W/Sc Shashlik
SciGlass

REFERENCE

W poweder/ScFi

- Absorber: tungsten powder matrix with embedded scintillating fibers (0.5mm diameter).
- Modules can be made 2D projective
- Readout with light guides and SiPMs

EIC – Photon Detection Technologies

Photon Detection Technology critical for many PID devices

- High-gain: 10^5 - 10^6
- Small pixels with individual readout: O(1mm pitch)
- Good timing (even with small signals): $\lesssim$100ps (DIRC), $\lesssim$ 800ps (mRICH, dRICH)
- Tolerance to magnetic field (1.5 - 3 T) and radiation (up to 10^{11} n_{eq}/cm^2)

Possible solution driven by detector performance and operational parameters, with cost optimizaton in mind

Viable candidates for EIC applications

- Multi-anode PMTs (MaPMTs)
- Commercial Microchannel-Plate PMTs (MCP-PMTs)
- Large-Area Picosecond Photodetectors (LAPPDs)
- Gaseous Electron Multipliers (GEMs) a for gas-only RICH
- Silicon PMs (SiPMs)

R&D needs

LAPPDs: very promising, but not yet suitable for EIC

➪ need pixelization

➪ Reduce sensitivity to B field

GEM-based photosensors (low-cost, radiation hard)

- Improve performance in the UV useful for gas-only RICH
- develop of photocathode sensitive in the visible region

SiPM/SPAD: promising, quickly improving (driven mostly by automotive sector), cheap technology

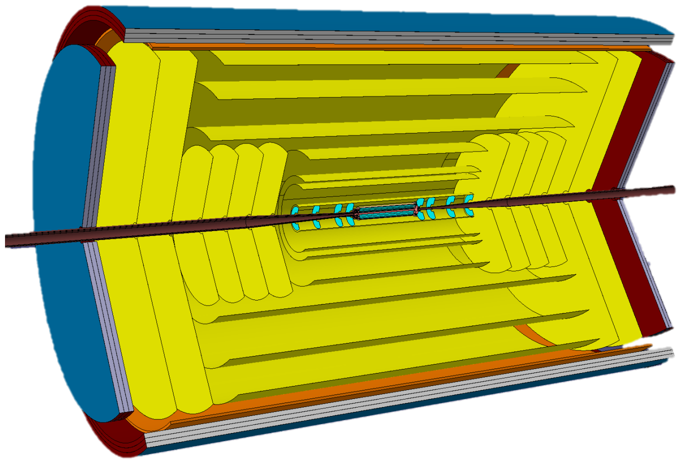
➪ can be operated up to 3T

➪ Reduce sensitivity to neutron damage

➪ Reduce DCR (presently too high for DIRC applications)

➪ Increase fill factor

ALICE 3: a next generation HI detector for Run 5+



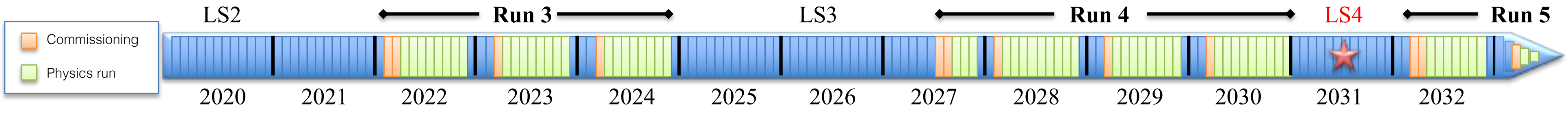
The Science Mission

1. What are the **mechanisms of hadron formation** in QCD?
2. Can we prove the realization of **chiral symmetry restoration** (fundamental property of QCD)?
3. Are there violations of **fundamental properties of quantum field theories**?

Developing the Science Case

- Idea for new dedicated heavy-ion experiment at the LHC developped within ALICE in the course of 2018
- Presented at the heavy-ion town meeting (CERN, Oct 2018)
- Expression of Interest submitted as input to the EPPSU:
  - Expression of Interest, Physics Briefing Book, Presentation Granada, Summary Granada
- Plans presented at several conferences in 2019, 2020
- Physics and detector working groups formed (Sep 2020) to host physics discussion and detector studies
- Letter of Intent in preparation for submission to LHCC by end of 2021

Initiative supported in ESPPU



ALICE 3: a next generation HI detector for Run 5+

Fast and ultra-thin detector with precise tracking and timing

- **Ultra-lightweight** silicon tracker with excellent vertexing
- **Fast** to profit from higher luminosity (also with nuclei lighter than Pb): 50-100x Run 3/4
- **Large acceptance** ⇨ barrel + end caps $\Delta\eta = 8$
- **Particle Identification**: TOF determination ($\lesssim$20 ps time resolution), Cherenkov, pre-shower/calorimetry
- **Kinematic range** down to very low p_T: $\lesssim$ 50 MeV/c (central barrel), $\approx$ 10 MeV/c forward (dedicated detector)

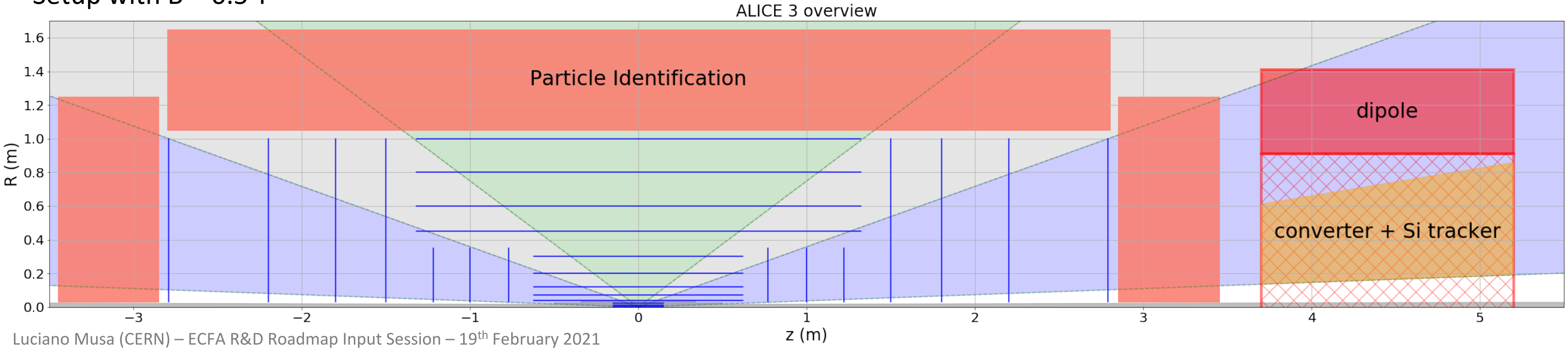
~12 tracking barrel layers + disks based on CMOS Active Pixel Sensors

Particle identification based on TOF, Cherenkov, em. shower

Dedicated forward detector for soft photons (conversion + Si tracker)

Further detectors under study (e.g. muon ID)

Setup with B = 0.5 T



ALICE 3: a next generation HI detector for Run 5+

Possible detector technologies

System	System component	Reference detector	Alternative options		Physics channel
Tracking	Central - Inner Tracker	MAPS, < 10μm pitch	-		Multi-charmed baryons, dielectrons (HF rejection)
	Central - Outer Tracker	MAPS, ~ 20μm pitch	-		Multi-charmed baryons
	Forward & Backward	MAPS, ~ 20μm pitch	-		HF correlations, low-momentum dileptons and photons
h-PID	Central	TOF + RICH (aerogel)	TOF + DIRC	fine resolution TOF (5ps)	Multi-charmed baryons
	Forward & Backward	RICH (aerogel) + TOF	RICH (gas) + TOF?	fine resolution TOF (5 ps)	Low p_T pions: chiral production
e-h separation	Central	TOF + RICH (aerogel)	TOF + preshower/ECAL		Di-electrons, quarkonia, X(3872)
	Forward & Backward	RICH (aerogel) + TOF	Preshower/ECAL + TOF?		Very low mass di-electrons
low-energy photons	Forward	Converter + Si-tracker	High-resolution ECal		Soft theorems
Ecal	Barrel	Sci-Crystal + Sci-Glass (long. segmentation)	metal-scint		Photons, jets
	Forward & backward	Sci-Glass	metal-scint		
Muons	Barrel	Iron absorber + chambers			New quarkonia, X(3872)

ALICE 3: a next generation HI detector for Run 5+

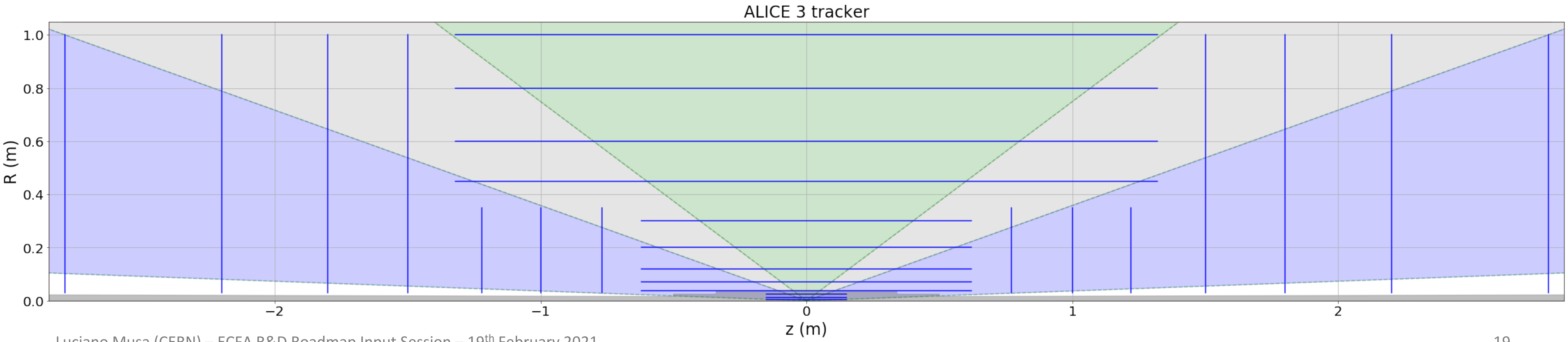
Inner Tracker

- DCA resolution < 25 um at p_T = 100 MeV/c (first layer close to IP)
- X/X_0 < 0.1 % / layer
- ultra-thin cylindrical CMOS sensors (MAPS) with pixel pitch ≲ 10 um
- ~10^{14} 1 MeV n_{eq}/cm^2 @ R = 1 cm (1 month Ar-Ar)

Outer Tracker

- relative p_T resolution
  - central: ~2 % (η < 1.75)
  - forward: ~10% (η = 3)
- overall material budget < 10 % X_0 to maintain p_T resolution in moderate B field (0.5 T)
- thin CMOS sensors (MAPS) with pixel pitch ~20 um
- ~10^{12} 1 MeV n / cm^2 @ R = 20 cm (1 month Ar-Ar)

Pixel timing resolution (resolve buch structure) < 25ns



ALICE 3: a next generation HI detector for Run 5+

Particle identification

Electron identification

- Low-mass di-electron spectra: 50 MeV/c < p_T < 3 GeV/c
  need hadron rejection > 1000x with electron efficiency > 80 %
- Electrical conductivity: 10 MeV/c < p_T < 100 MeV/c
  electron ID in forward region (p boosted by x10 at η ~3)

Hadron identification

- HF decay chains: 50 MeV/c < p_T < 5 GeV/c
  > 3 sigma separation of π/K/p

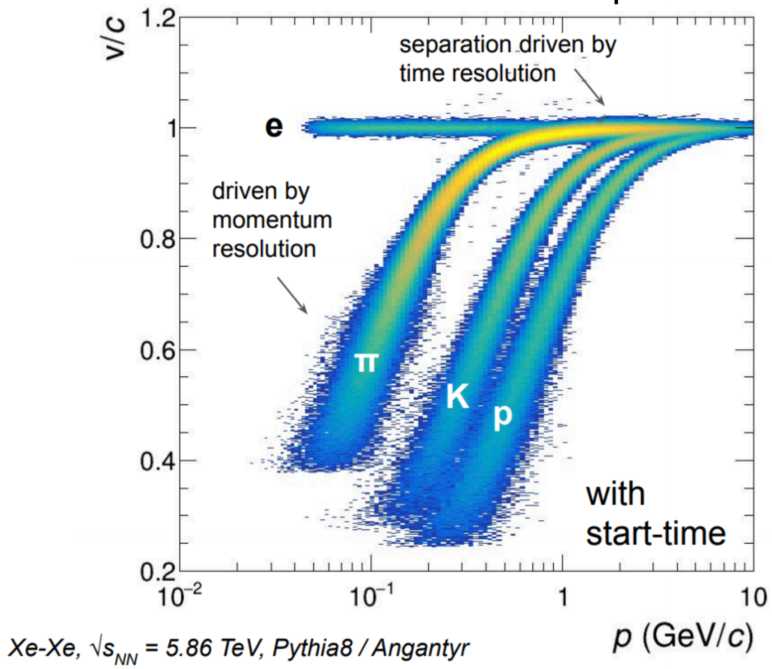
Photon detection

- Very low-energy photons for soft theorems: 10 MeV/c < p_T < 100 MeV/c
  clean identification, energy measurement
- Pointing to primary vertex for background rejection O(mm)

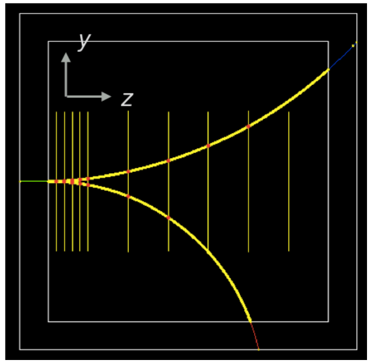
Muon identification

- Quarkonia & exotica: extend muon identification to lower p_T (~1 GeV/c)

TOF with σ_{TOF} = 20 ps



forward conversion tracker

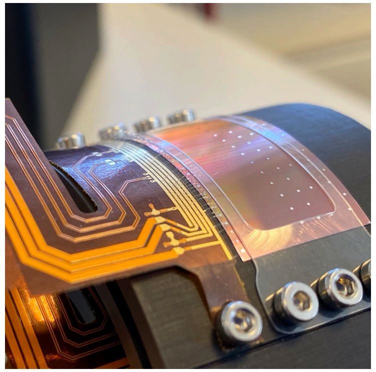


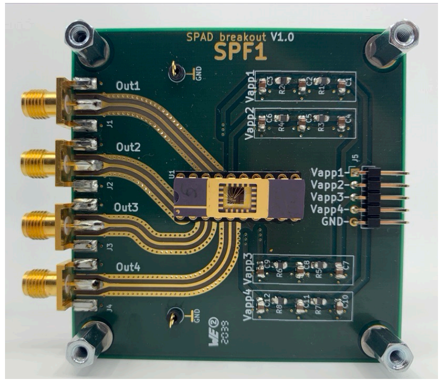
ALICE 3: a next generation HI detector for Run 5+

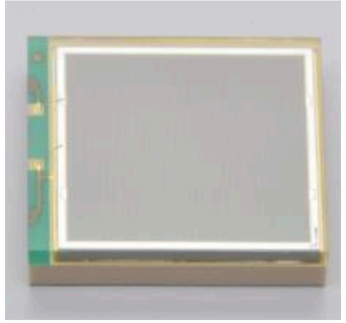
CERN

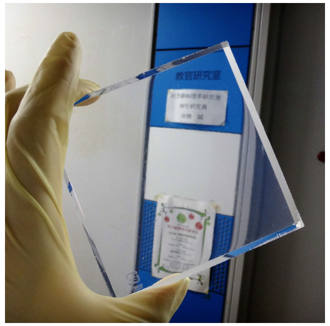
R&D needs and Challenges

- Inner tracker
  - minimal distance from IP requires retractable detector
  - ultra-thin layout: flexible wafer-scale sensors (**MAPS**)
  - position resolution **O(1 um)** requires small pixel pitch ⇨ small feature-size technologies
- Outer tracker
  - **large areas** to instrument: develop **cost-effective sensors & modules**
  - low material budget requires lightweight mechanics, cooling and services
- Time of Flight
  - large areas to instrument: develop cost-effective sensors
  - **TOF resolution < 20 ps** needed on the system level
    requires advances both on sensors and microelectronics
- Cherenkov
  - aerogel RICH: large area of single photon efficient sensors (visible light) (**SiPM/SPAD**, **MAPS**, **LAPPD**, …)
  - or develop other geometries, e.g. DIRC, for large occupancy?
- Photon detection at low p_T
  - develop system for very low p_T photons with pointing resolution







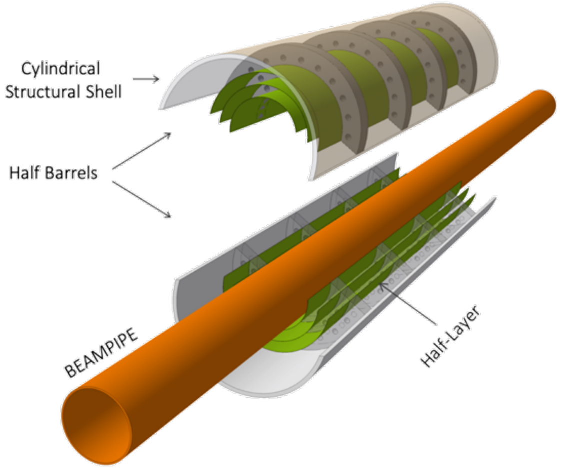


ALICE 3: a next generation HI detector for Run 5+

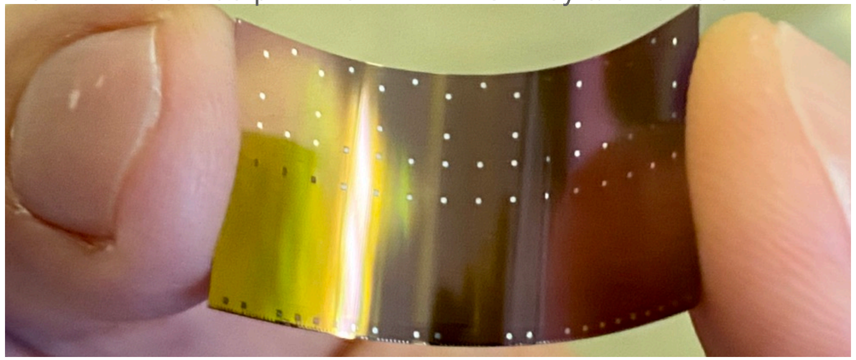
R&D on cylindrical vertex layers

Innermost layers with ultra-thin, minimal material budget MAPS layers

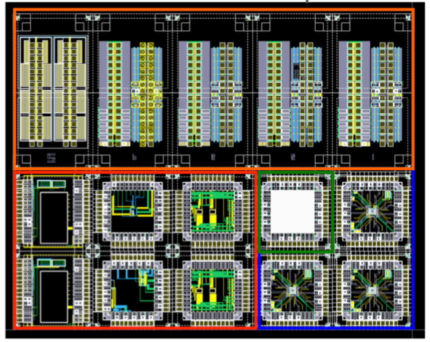
- Replace ALICE ITS innemorst layers in LS3
- Vertex layers for ALICE 3



R&D with bent 50 µm-thick ALPIDEs: they are flexible!



Submission in 65 nm process



Bending of wafer-scale chips

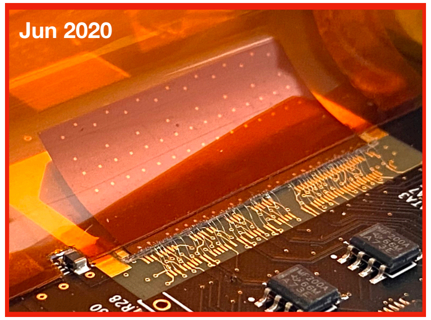
R&D running full steam for ITS3

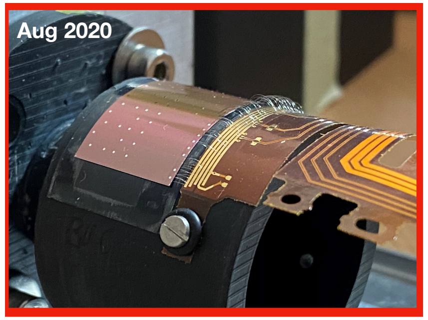
Tests on bent silicon devices

- Mechanical integration of 300mm wafer-scale dummy chips
- Lab and beam tests of curved ALPIDEs
- Interconnection studies

Key role and drive in 65nm CIS process evaluation

- Test chips and systems under design





Future: extend R&D to smaller feature-size technology (e.g. 28nm)

ALICE 3: a next generation HI detector for Run 5+

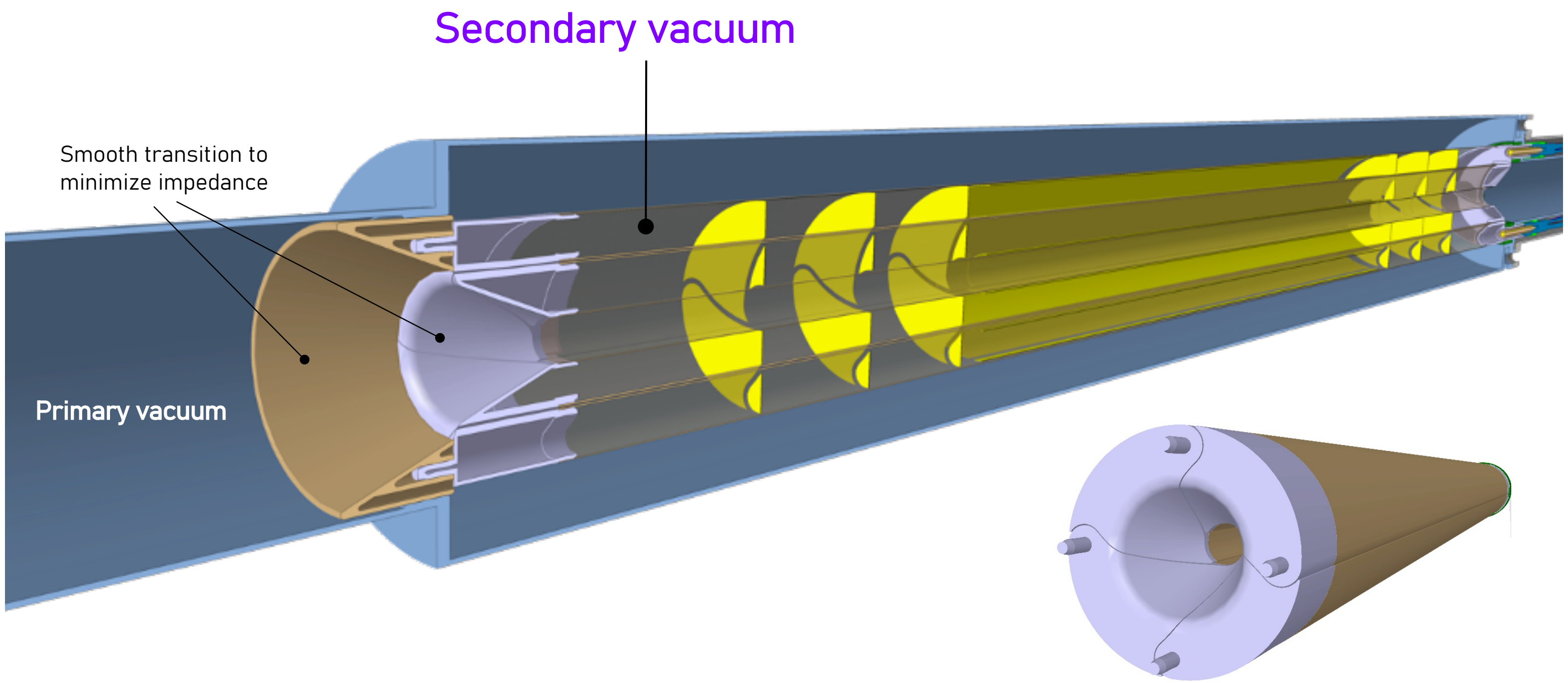
Ultra-lightweight vertex and tracking detectors

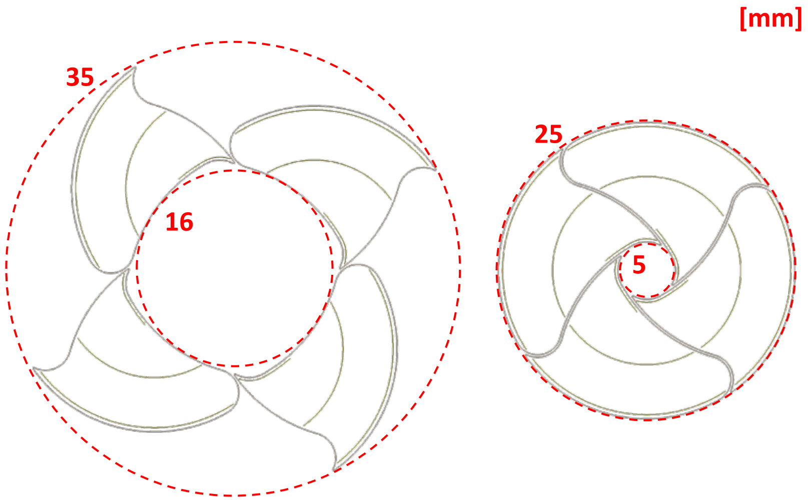
Positioning first layers as close to IP as possible

→ Need large R&D effort on advanced materials, mechanics and cooling

An example of ongoing studies for ALICE 3

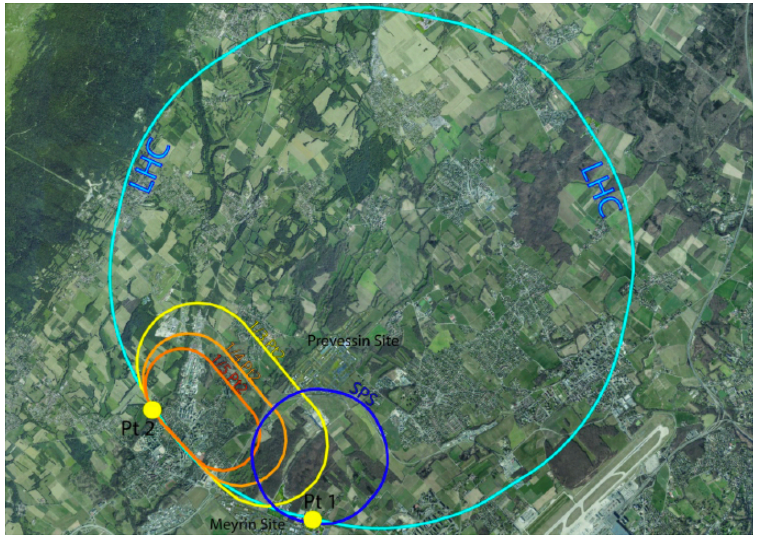
A (**futuristic**) rectractable Vertex Detector





Hadron-Electron Collisions at the LHC and FCC

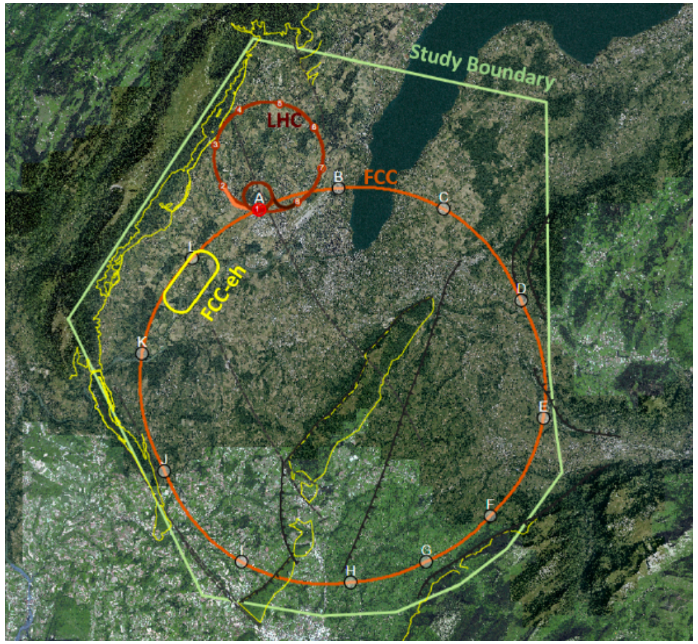
LHeC, PERLE and FCC-eh



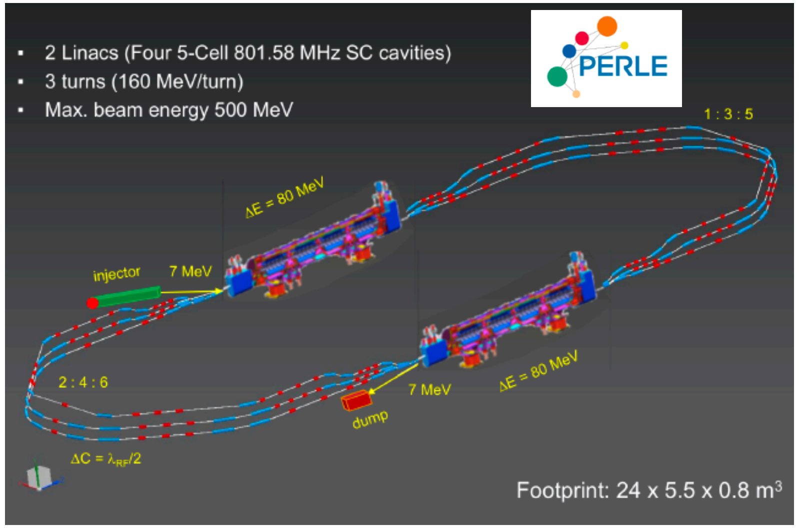
Powerful ERL for Experiments @ Orsay
CDR: 1705.08783 J. Phys.G
CERN-ACC-Note-2018-0084 (ESSP)

Operation: 2025+, Cost: O(20) Meuro

LHeC ERL Parameters and Configuration
I_e = 20mA, 802 MHz SRF, 3 turns ⇨
E_e=500 MeV a first 10 MW ERL facility



50 x 7000 GeV^2: 1.2 TeV ep collider
Operation: 2035+, Cost O(1) BCHF
CDR (2012): 1206.2913 J.Phys.G
Upgrade to 10^{34} cm^{-2}s^{-1}, for Higgs, BSM
CERN-ACC-Note-2018-0084 (ESSP)
Update **CDR published in 2020**
arXiv:2007.14491, subm J.Phys.G



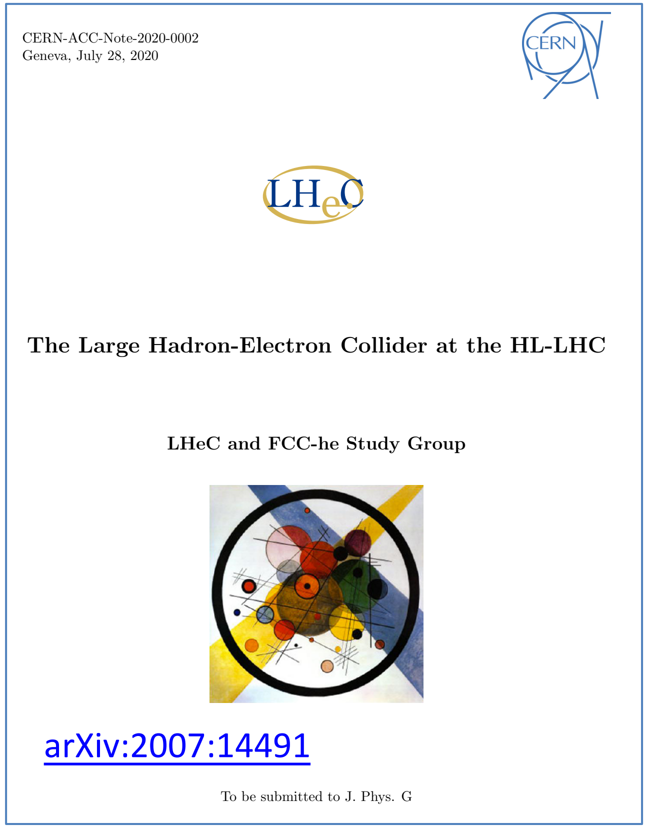
60 x 50000 GeV^2: 3.5 TeV ep collider
Operation: 2050+
Cost$_{(\text{of ep})}$ O(1-2) BCHF
Concurrent operation with FCC-hh
FCC CDR:
Eur.Phys.J.ST 228 (2019) 6, 474 Physics
Eur. Phys.J.ST 228 (2019) 4, 755 FCC-hh/eh

Courtesy of M. Klein (HK Conference, 19.01.2021)

Hadron-Electron Collisions at the LHC and FCC

Physics with Energy Frontier DIS

Published in 2020


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

LHeC

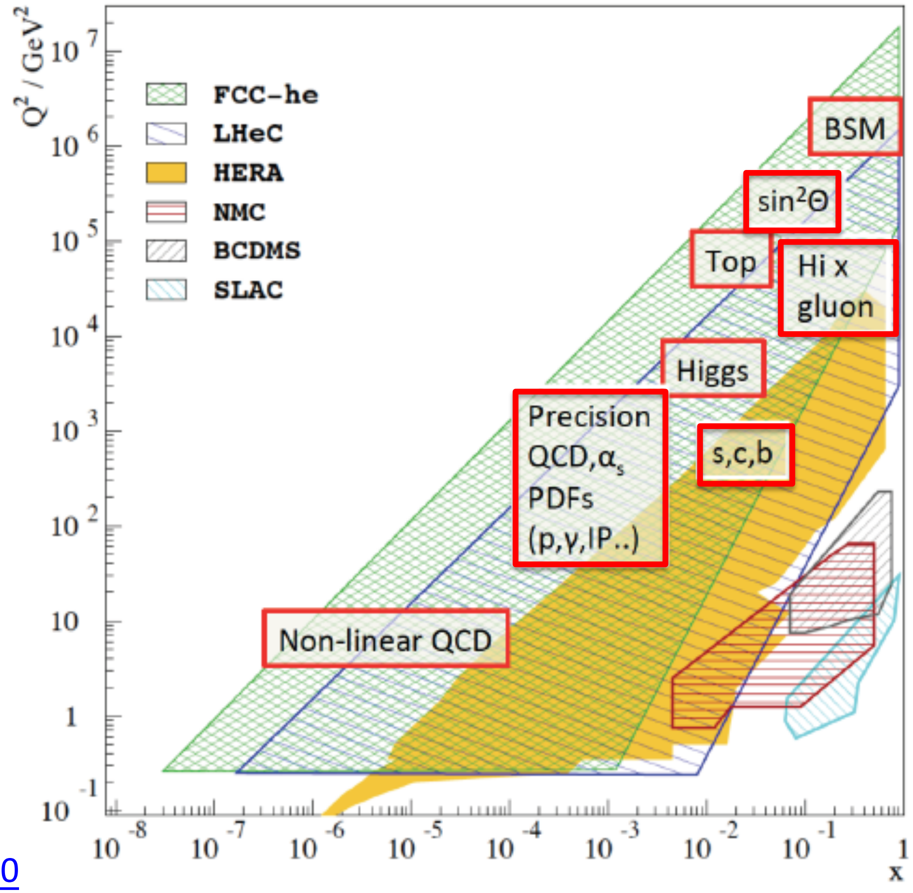
The Large Hadron-Electron Collider at the HL-LHC

LHeC and FCC-he Study Group

arXiv:2007:14491

To be submitted to J. Phys. G

5 page summary: ECFA Newsletter Nr. 5, Aug 20



Raison(s) d'être of ep/eA at the energy frontier

Cleanest High Resolution Microscope: QCD discovery

Empowering theLHC/FCC Search Programme

Trasnformation of LHCC/FCChh into high precision Higgs facility

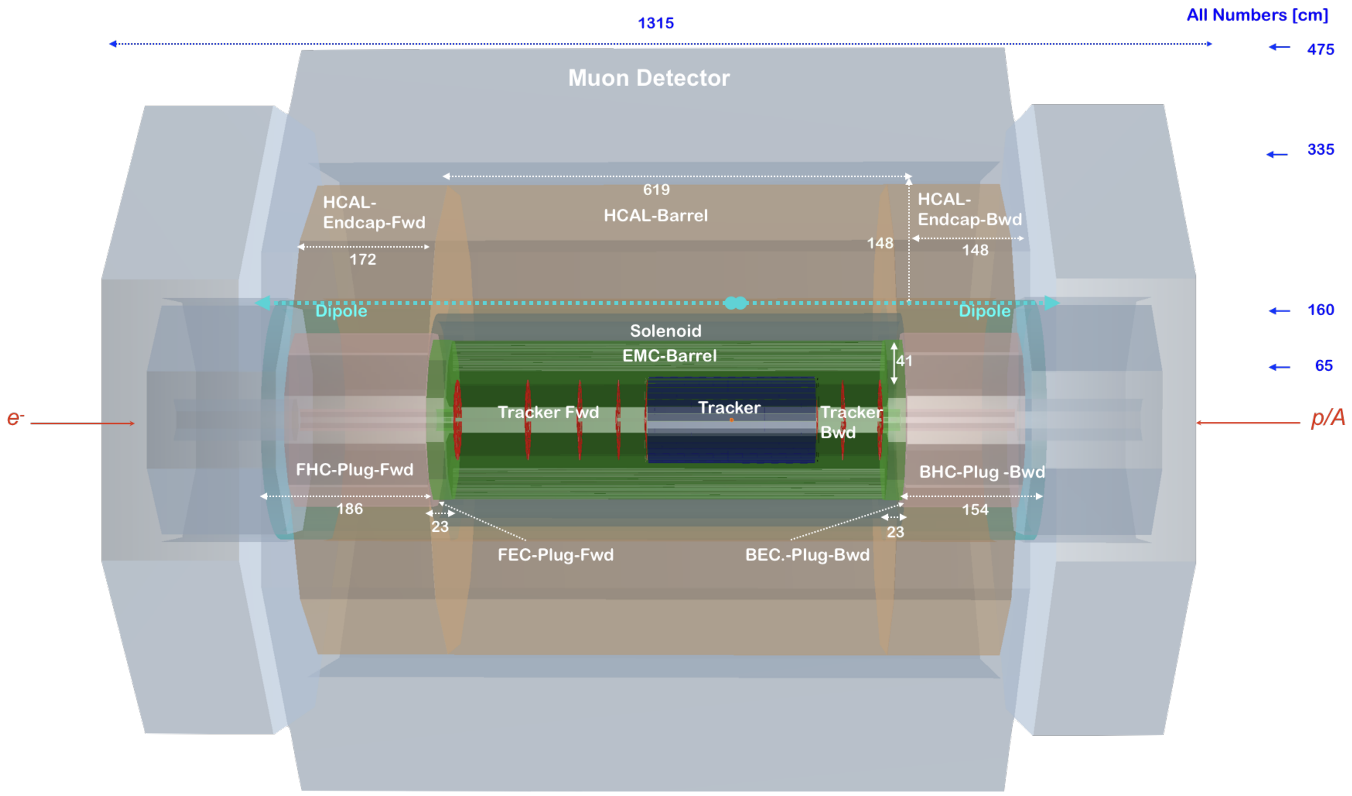
Discovery (top, H, heavy ν's)

A unique Nuclear Physics Facility

Courtesy of M. Klein (HK Conference, 19.01.2021), slides 3-4

Hadron-Electron Collisions at the LHC and FCC

LHeC Detector Design 7/2020



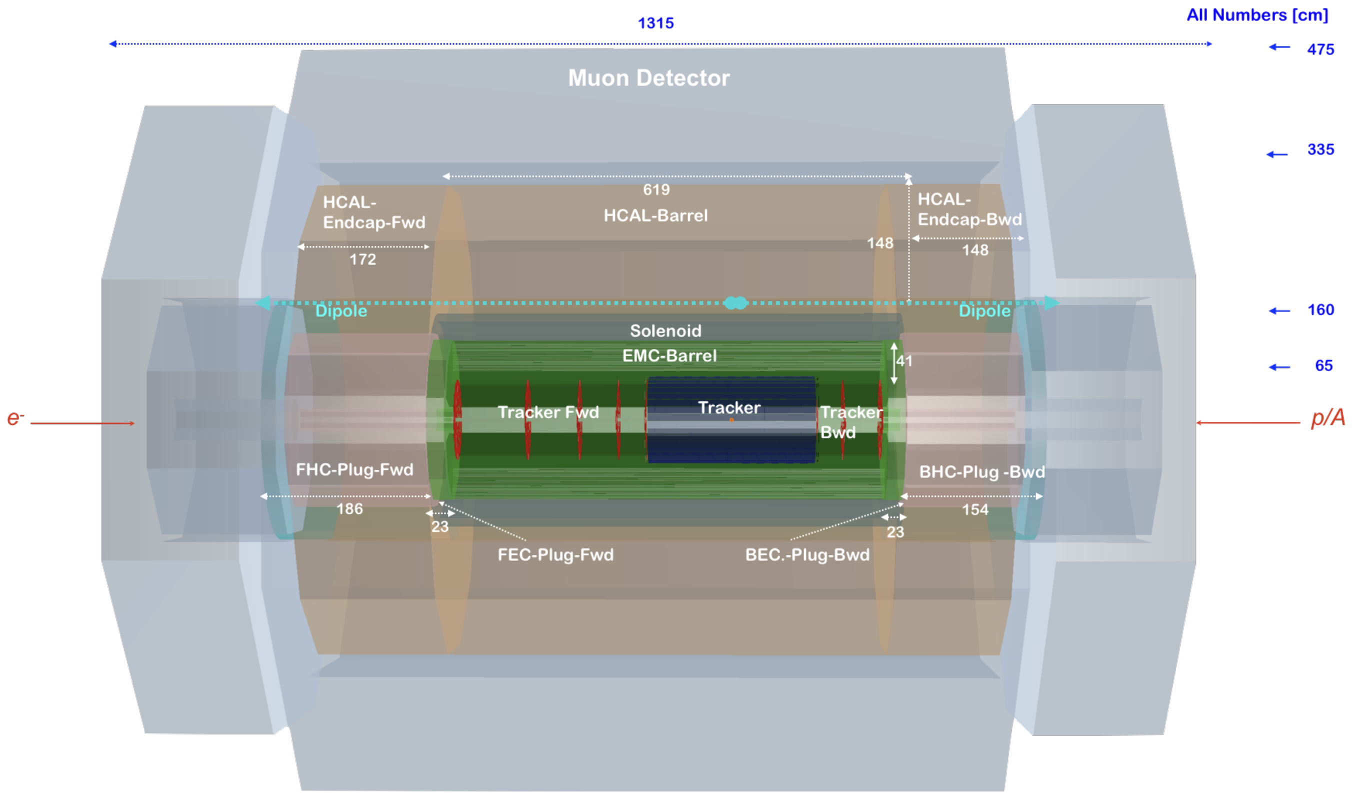
Current design leans heavily on HL-LHC technologies
But they are over-spec'ed for radiation hardness

General detector requirements

- **High-resolution tracking system**
  - primary and secondary vertex resolution down to small angles
  - precise p_T measurement and matching to calorimeter
- **Full coverage calorimetry**
  - Electron energy 10%/√E calibr. 0.1%
  - Hadronic energy 10%/√E calibr. 1%
  - Tagging of backward scattered electrons and photons
  - Tagging of forward scattered photons, neutrons and deuterons
- **Full coverage muon system**
  - Tagging and combination with tracking, no independent p measurement

Hadron-Electron Collisions at the LHC and FCC

LHeC Detector Design 7/2020



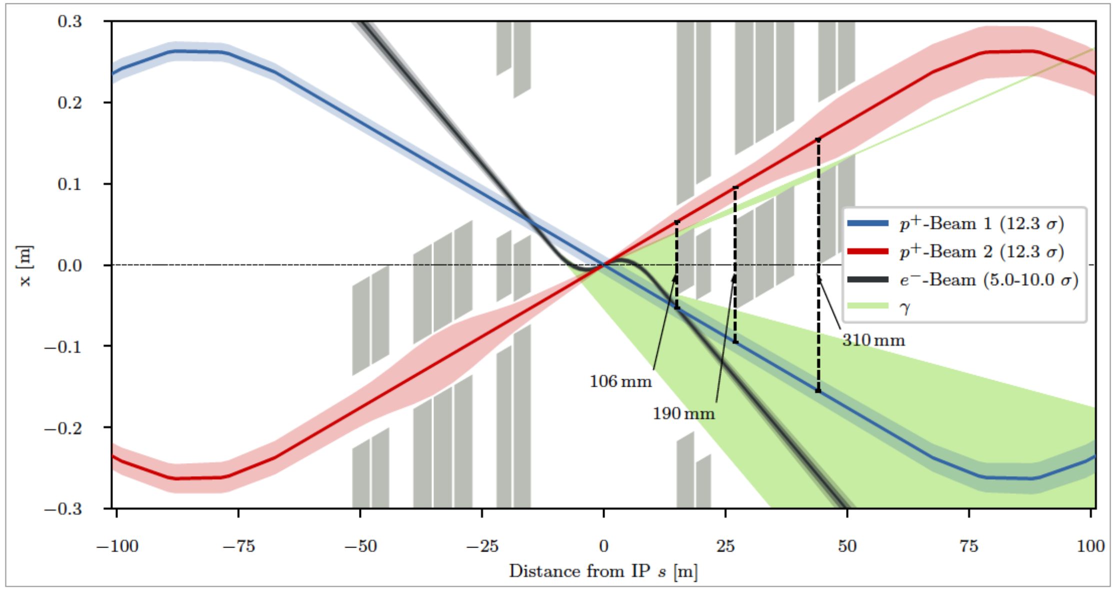
Key elements to the detector design

- LHeC will run simultaneously with the LHC ⇨ 3 beam IR with compatible optics
- Modular for assembly above ground and rapid installation
- No pileup
- Low radiation wrt pp
- Tracker radius: 60 cm
- Magnetic field: B = 3.5T
- Length x Diameter = 13 x 9 m^2

Chalanging technology aspects related to the design of the interaction region

Hadron-Electron Collisions at the LHC and FCC

Synchronous ep/pp operation



Head-on collisions: large synchrotron radiation fan from outgoing e-beam ➪ Eliptical beampipe accomodates synchrotron fan

Complex magnet configuration

- Solenoid Detector Magnet (3.5T)
- Dual dipole magnets (0.15 – 0.3 T) throughout detector region (|z| < 14m)
  - to guide e-beam in and out
  - bend e-beam into head-on collision with p-beam
  - Safely extract the distorted e-beam
- 3.5T superconducting NbTi/Cu solenoid in 4.6K liquid helium cryostat

Baseline design concept relies on present technology for detector magnets

Solenoid and dipoles have a common support cylinder in a single cryostat; free bore of 1.8m; extending along the detector with a length of 10m

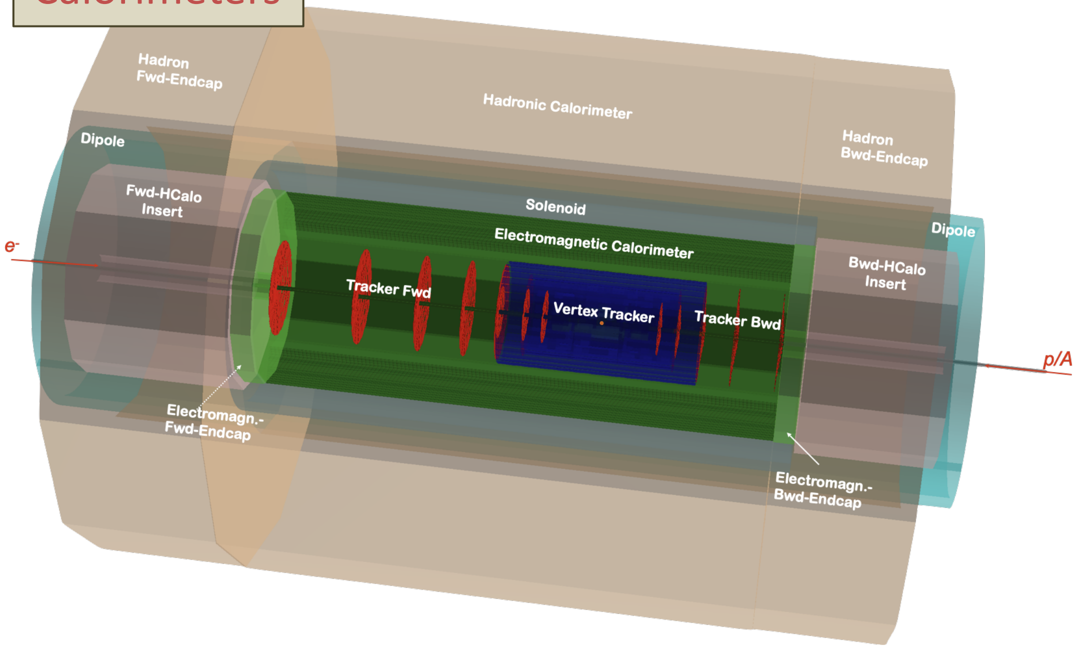
2T scaled up to 3.5T

H. Ten Kate (1st CERN EP-R&D Workshop)

New ideas on thin magnets (cf. E. Perez at FCC workshop) and R&D programe for FCC relevant for LHeC

LHeC – The Large Hadron-Electron Collider at the HL-LHC

Calorimeters



- Complete coverage: $-5 < \eta < +5.5$
- Forward Region: dense, high density jets of few TeV
- Backward Region: in DIS only deposit of $E < E_e$
- Calorimeter depth
  - ECAL: 30 X_0 barrel & backward, ~ 50X_0 forward
  - HCAL: 7.1-9.3 Λ_I barrel & backward; 9.2-9.6 Λ_I forward
- Detector technologies (ala ATLAS):
  - ECal: Pb/LAr with accordeon geometry
  - HCAL: Pb/Scintillating tiles
  - Alternative: ECAL: Pb/Scintillator ➪ eliminate cryogenics

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
η_{max}, η_{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

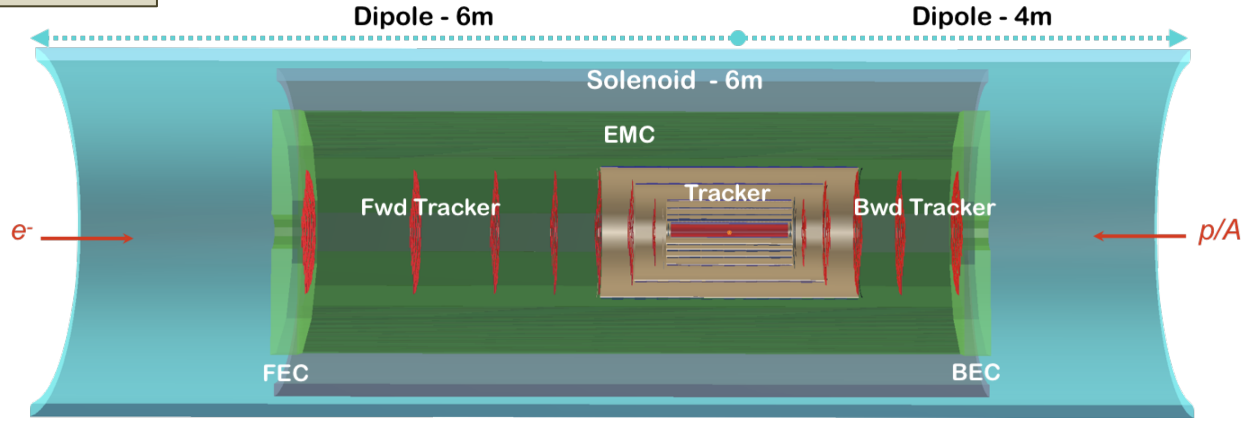
Forward/Backward Calorimeters

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
η_{max}, η_{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

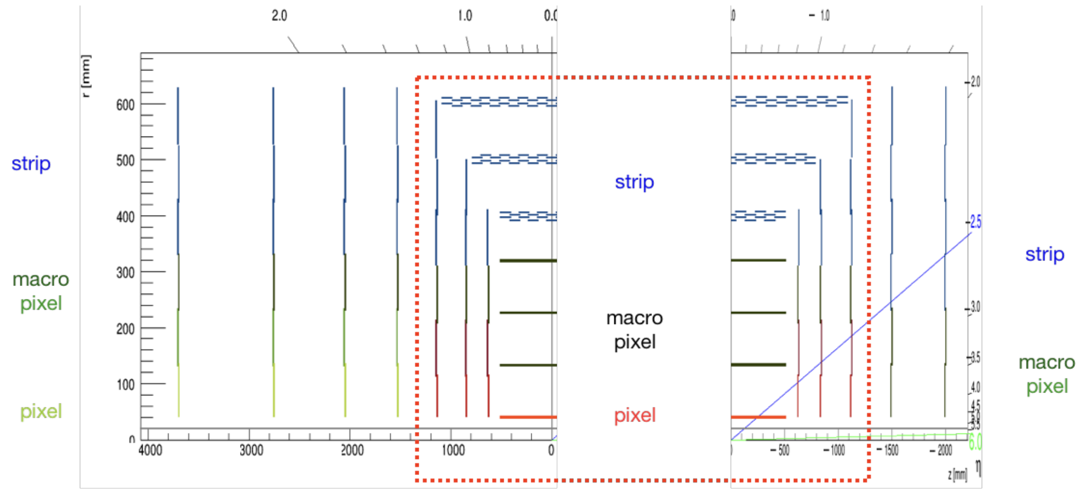
CDR-2020 (arXiv:2007:14491), tables 12.3 and 12.4

LHeC – The Large Hadron-Electron Collider at the HL-LHC

Tracker



- 7 concentric layers + 7/5 forw/backw disks
- Coverage: $|\eta| \lesssim 5$; $R_{out} \approx 60$cm, $R_{in} \approx 3$cm
- Total active Si surface: $\approx 41\ m^2$
- Impact resolution: 5-10μm
- Technologies: MAPS, Si-strips



Barrel & ECAP Layers/Wheels

Barrel & ECAP Layers/Wheels

Tracker (LHeC)	Inner Barrel pix	Inner Barrel pix_{macro}	Inner Barrel strip	ECAP pix	ECAP pix_{macro}	ECAP strip
η_{max}, η_{min}	$3.3, -3.3$	$2.1, -2.1$	$1.4, -1.4$	$\pm[4.1, 1.8]$	$\pm[2.4, 1.5]$	$\pm[2.0, 0.9]$
Layers (Barrel)	1	3	3			
Wheels (ECAP)				2	1	1-3
Modules/Sensors	320	4420	3352	192	192	552
Total Si area [m^2]	0.3	4.6	17.6	0.8	5.6	3.3
Read-out-Channels [10^6]	224.5	1738	20.6	322.4	73.3	17.0
$pitch^{r-\phi}$ [μm]	25	100	100	25	100	100
$pitch^{z}$ [μm]	50	400	50k [2]	50	400	10k [1]
Average X_0/Λ_I [%]		7.2 / 2.2			2.2 / 0.7	

[1] Reaching $pitch^{r-\phi}$ when using two wafer layers rotated by 20 mrad is achievable.

FCC-eh – The Large Hadron-Electron Collider at the FCC

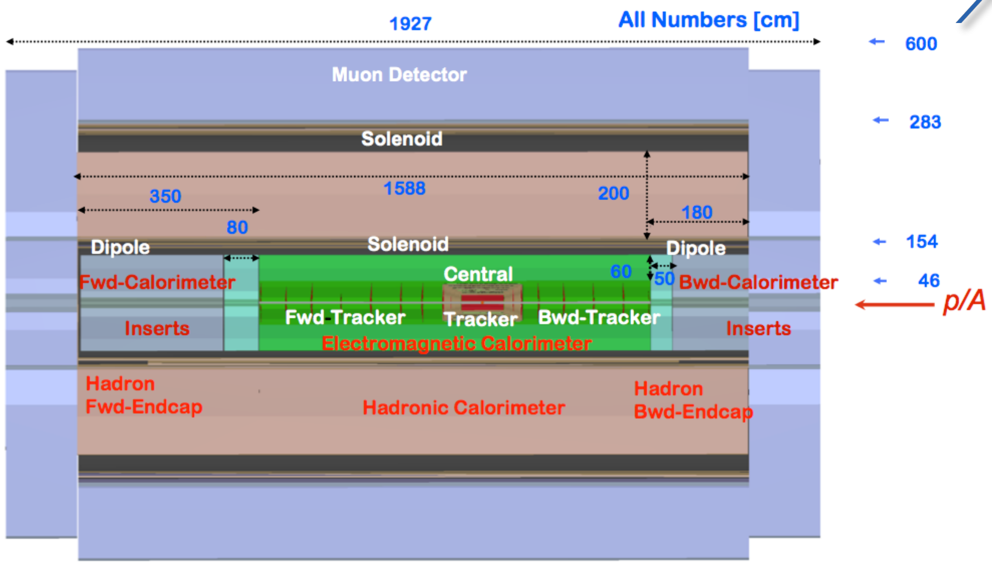
FCC-eh – The Large Hadron-Electron Collider at the FCC

Similar schemes in collision with protons of 7 TeV (**LHeC**), 13 TeV (**HE-LHeC**) and 50 TeV (**FCC-eh**)

Detector scales in size by up to ln (50/7) ~2

Double Solenoid + Dipole

Even larger tracking region to retain 1^0 performance



R&D Needs for LHeC and FCC-eh

- Current (baseline) proposal based on detecor technologies for HL-LHC and FCC-hh ⇨ no (need for) dedicated R&D
- **Detector performance/cost optimization will benefit singificantly from R&D in several areas:**
  - High-resolution, low-power MAPS for vertex and inner tracking layers (low radiation envinronment)
  - Low-power & low(er) cost silicon sensors and module assembly for (large surface) outer tracker
  - Progress on ECal technologies, in particular remove need for cryogenics
  - R&D on thin magnet technologies

Final Remarks

The challanging detector requirements for the EIC, ALICE 3 and LHeC/FCC-eh call for a broad R&D program

Trackers

- CMOS Active Pixel Sensors for vertex and tracking layers: small pitch pixels, low-power, fast timing
- Low-cost, highly automated, module assembly, integration and test for large area trackers
- Advanced materials, mechanics and cooling
- Improved and novel micropattern gaseous detectors

Hadron and electon ID detectors

- TOF determination
- Many different applications of RICH technologies

⇨ All critically depend on R&D on photon sensors ⇨ key to ultimate performance and cost

High-precision calorimetry

- High-resolution ECal typically requires Lead Tungstate ($PbWO_4$) crystals
- Crystals are expensive, few vendors a QA issues, moderate production capacity, raw material shortage

⇨ R&D on scintillating glasses and other materials

Others: microelectronics, free-streaming readout, magnets, …

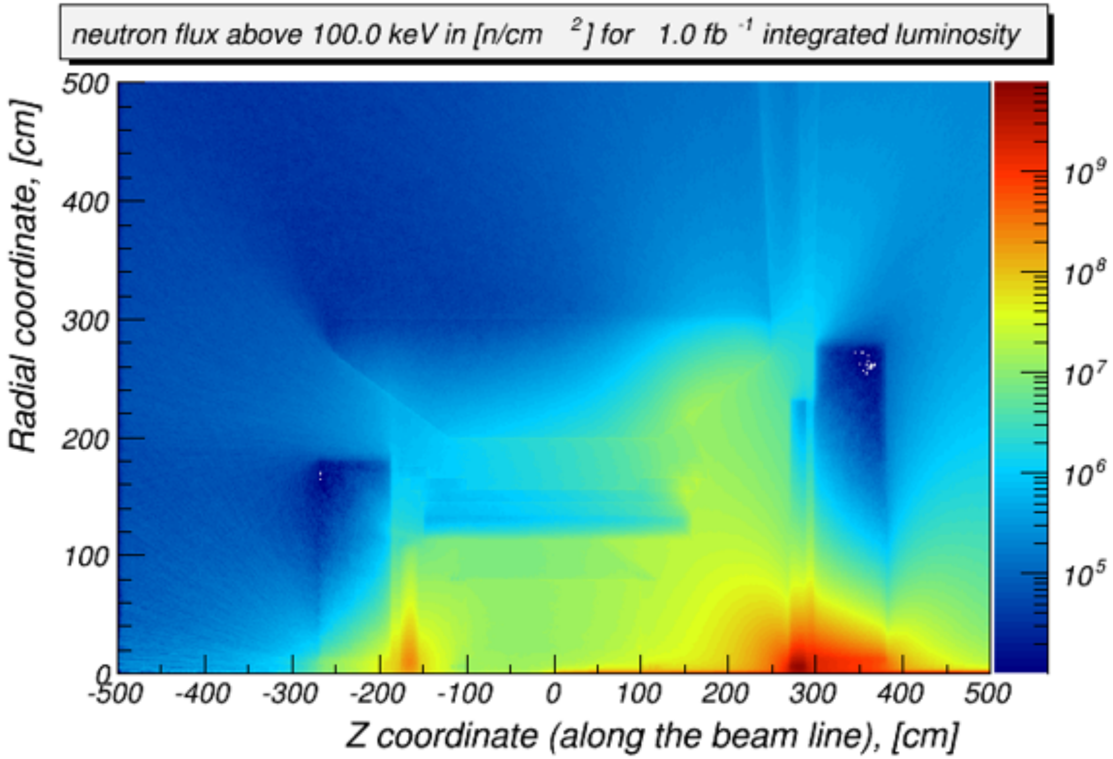
BACKUP

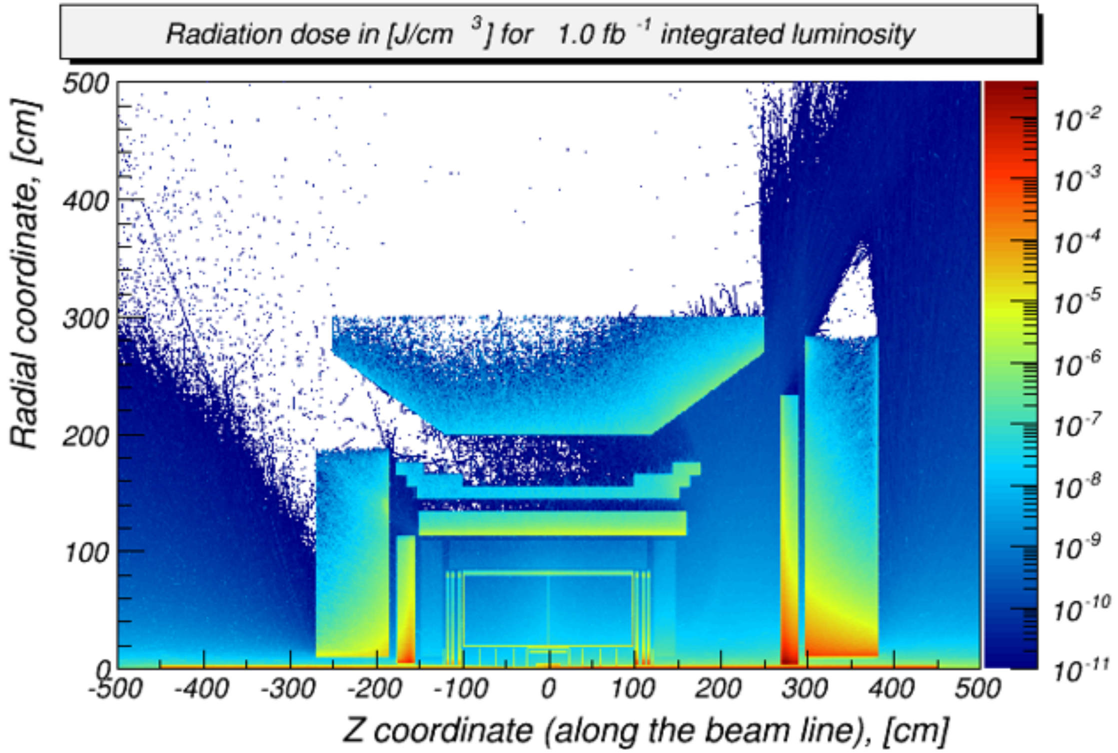
EIC – radiation environment

Ionization Radiation dose and neutron fluency
20 GeV e-beam on 250 GeV p-beam

Max ionizing radiation dose: **2.5 kRad / year**

Max fluency: $\lesssim$ **10^{10} neutrons/cm^2 per year**





Source: *EIC CDR Experimental Equipment, Nov 2020, Figures 8.6 and 8.7*