07/10/2025, CFNS Fixed Target Workshop

ePIC and Beam Tests

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ORNL

Lots of material in these slides was taken from Thomas Ullrich's excellent presentation at

"Precision QCD Predictions for ep Physics at the EIC" here at CFNS

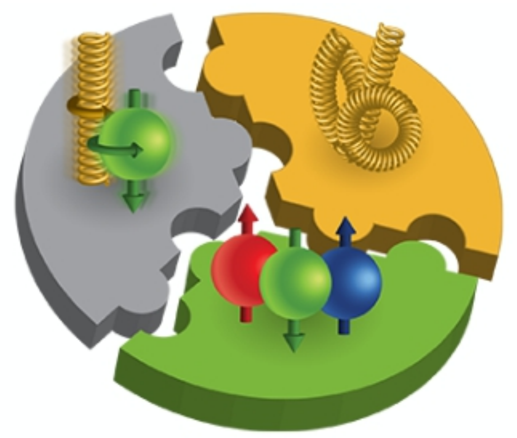
Many thanks to his help and support!

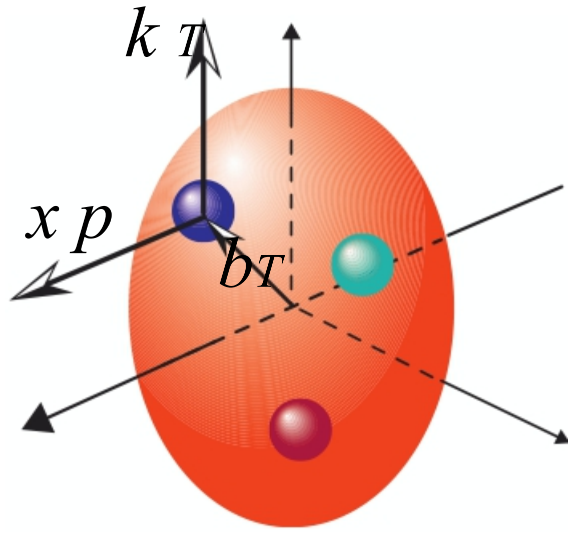
EIC Physics (= QCD Physics)

Investigate with precision the universal dynamics of gluons to understand the emergence of hadronic and nuclear matter and their properties

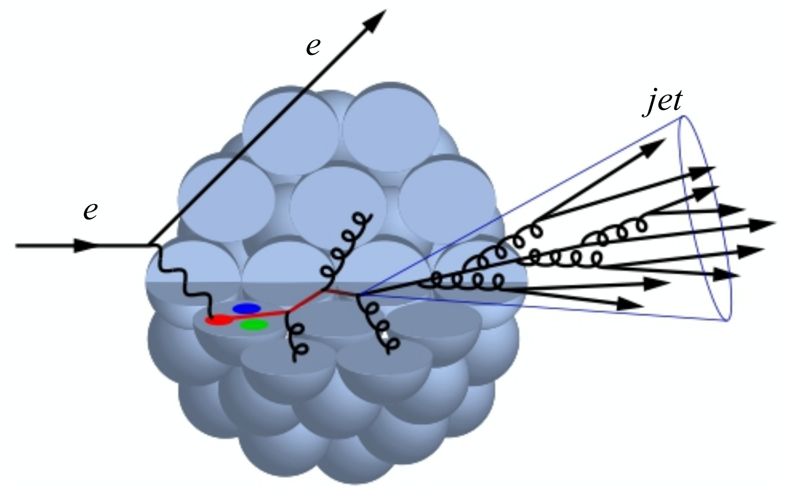
Central Questions:

- How are sea quarks and gluons, and their spins, distributed in space and momentum inside the nucleon? How do the nucleon properties emerge from them and their interactions?

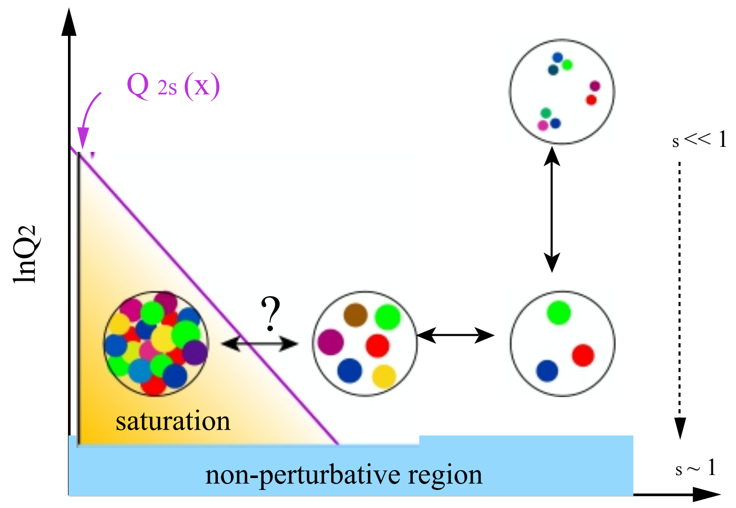




- How do color-charged quarks and gluons, and colorless jets, interact with a nuclear medium? How do confined hadronic states emerge from these quarks and gluons?

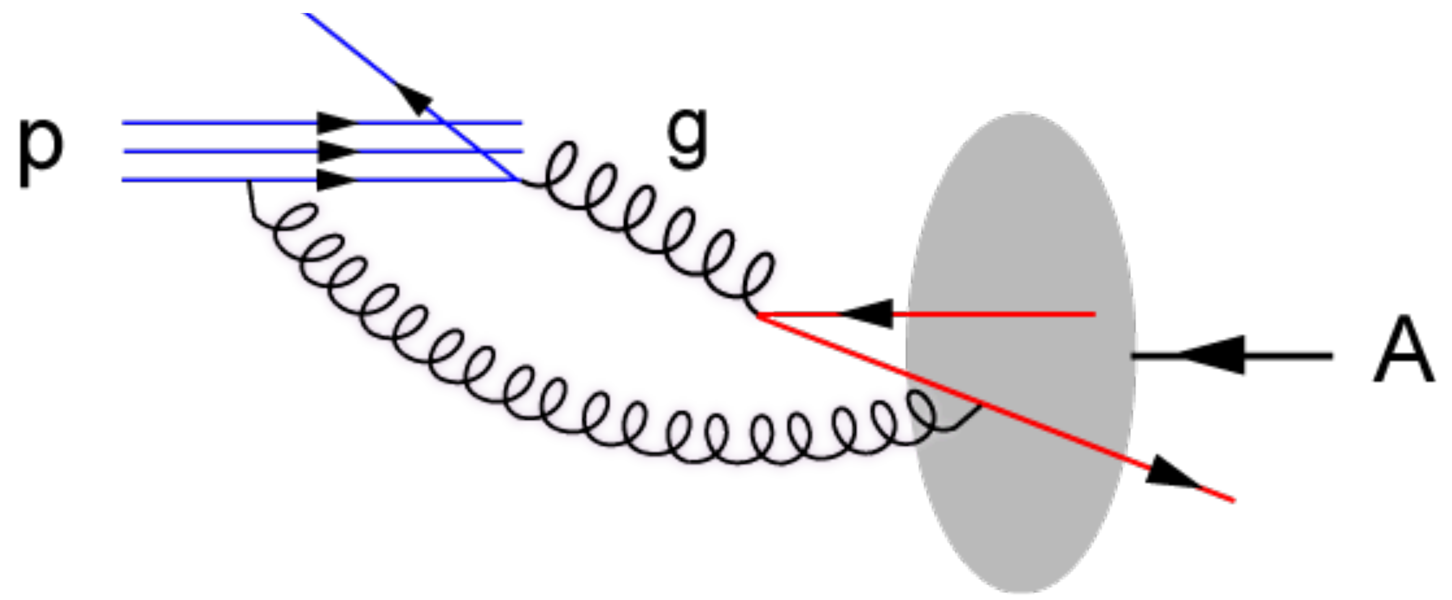


- What happens to the exploding gluon density at low-x in hadronic matter? Does it saturate at high energy, giving rise to a gluonic matter with universal properties?



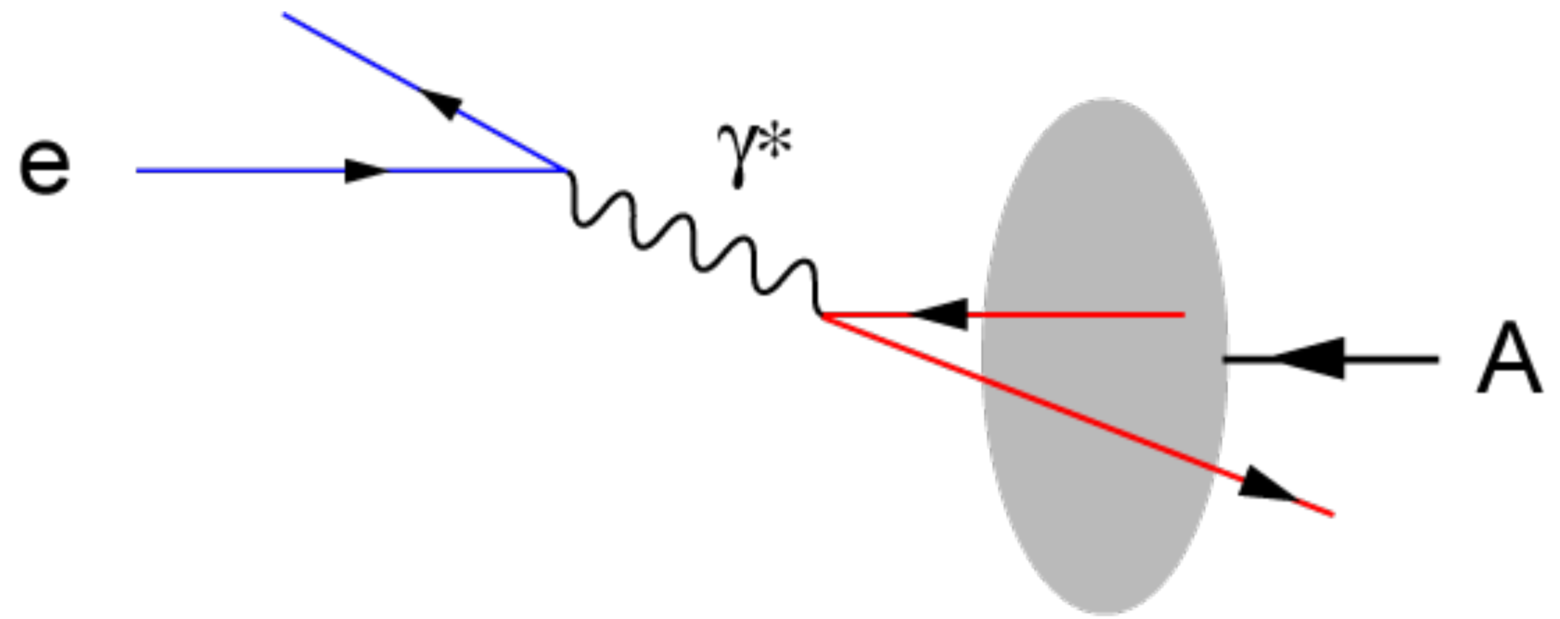
What Can Provide Answers?

Hadron-Hadron



- Test QCD
- Probe/Target interaction directly via gluons
- lacks the direct access to x, Q^2

Electron-Hadron (DIS)



- Explore QCD & Hadron Structure
- Indirect access to glue
- High precision & access to partonic kinematics

Both are complementary and provide excellent information on properties of gluons in the nuclear wave functions

Precision measurements $\Rightarrow$ **DIS** due to unprecedented exact knowledge of QED

Reality Check

Designing a dream machine is easy but

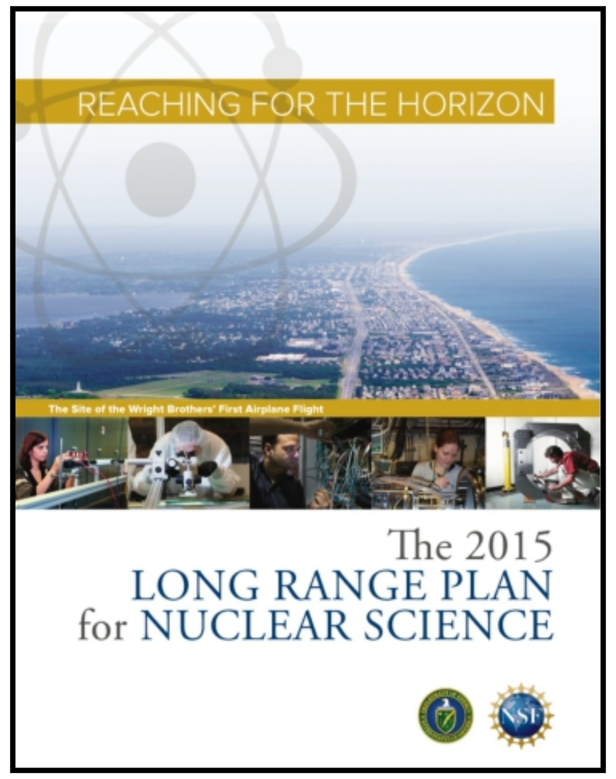
- It has to be fundable
- The technology has to be available
- Path of failed efforts is long: Isabelle, SSC, …

Find the parameters that do the job and that actually can be realized!

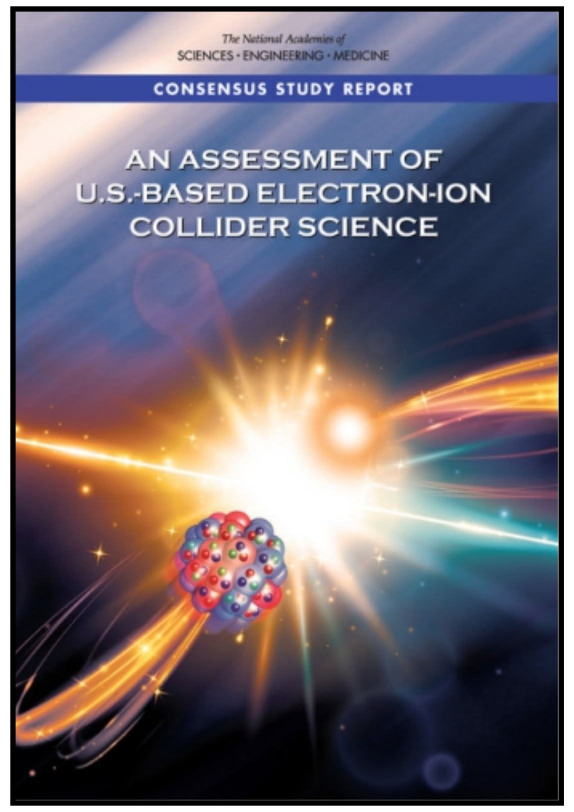
EIC:

- Highly polarized (70%) e- and p beams
- Ion beams from D to U
- Variable center-of-mass energies from $\sqrt{s}$=20-140 GeV
- High collision luminosity 10^{33-34} $cm^{-2}s^{-1}$ (HERA ~ 10^{31})
- Possibilities of having more than one interaction region

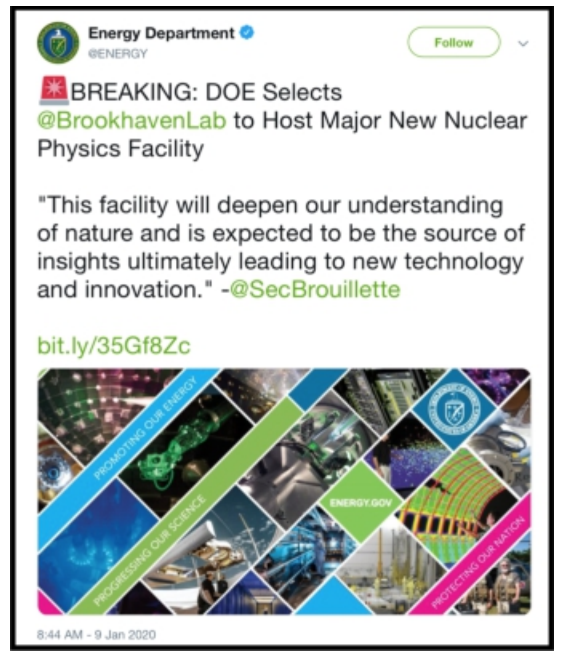
Status of EIC



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

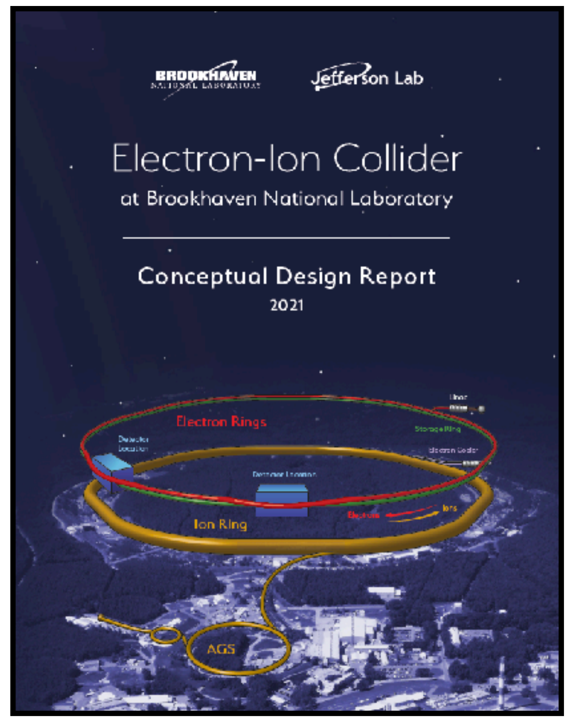


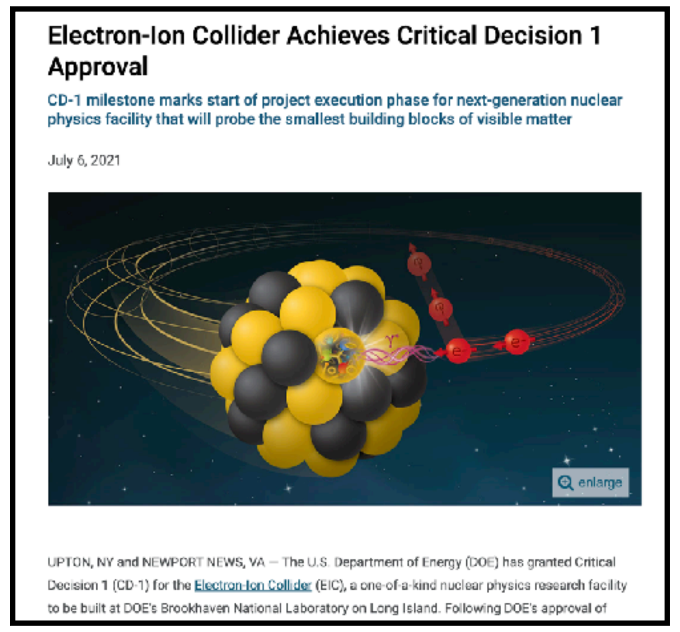
2018: National Academy EIC Review
"The committee finds that the science that can be addressed by an EIC is compelling, fundamental and timely."



December 2019/January 2020:
After science, cost, and host review DoE gives EIC CD-0 (*Approve Mission Need*) and selects BNL as the hosting site. BNL and JLab are the hosting labs.
Project management officially started 4/1/2020.

January/February 2021: Release of CDR, CD-1 Review

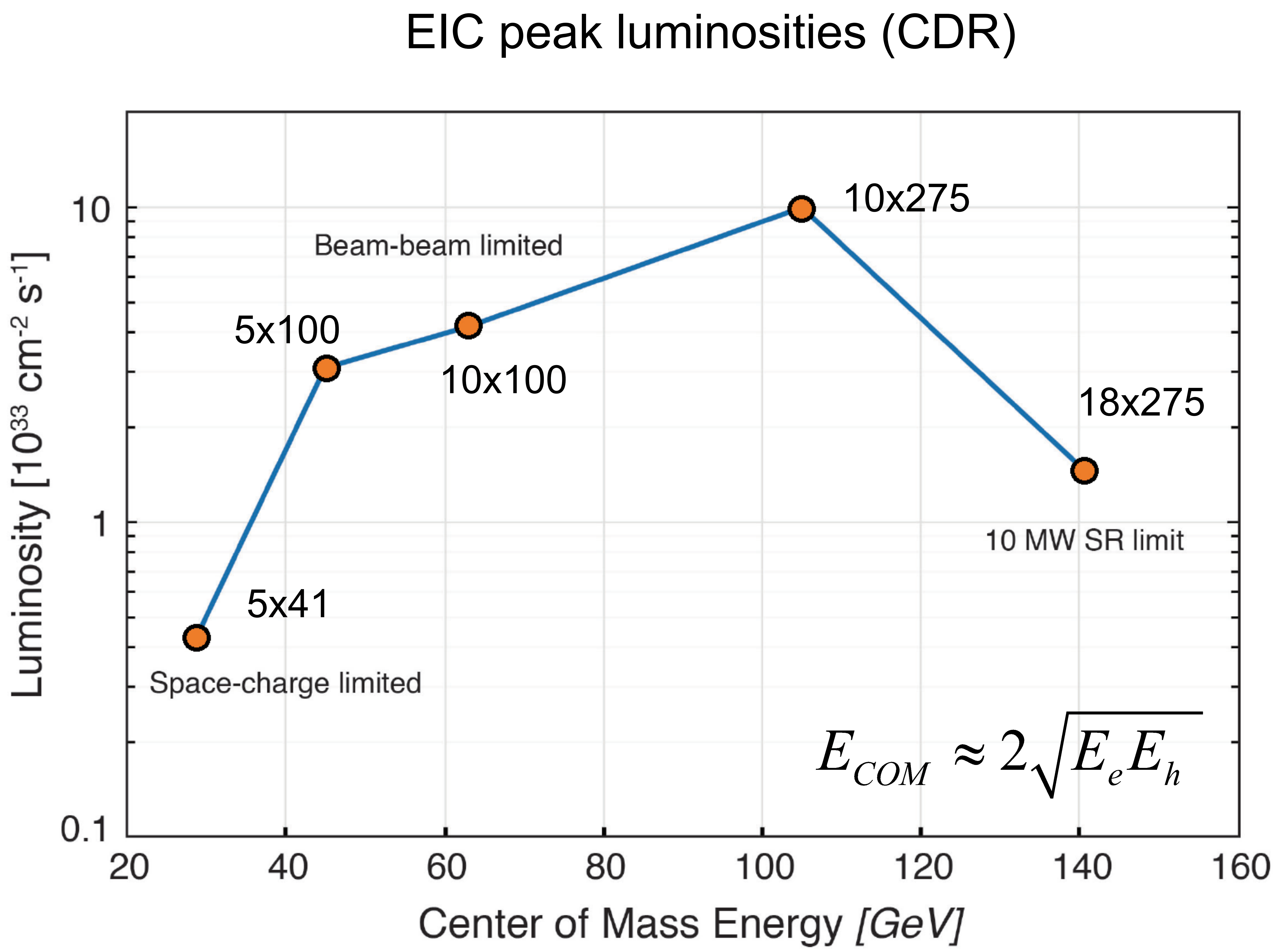




July 2021: CD-1 (*Approve Alternative Selection and Cost Range*) received.
Original cost estimate: $2 - 2.6 B
$100M from New York State towards infrastructure

April 2024: EIC project passes CD-3A for Long-Lead Procurements

e+p Luminosity versus Center-of-Mass Energy

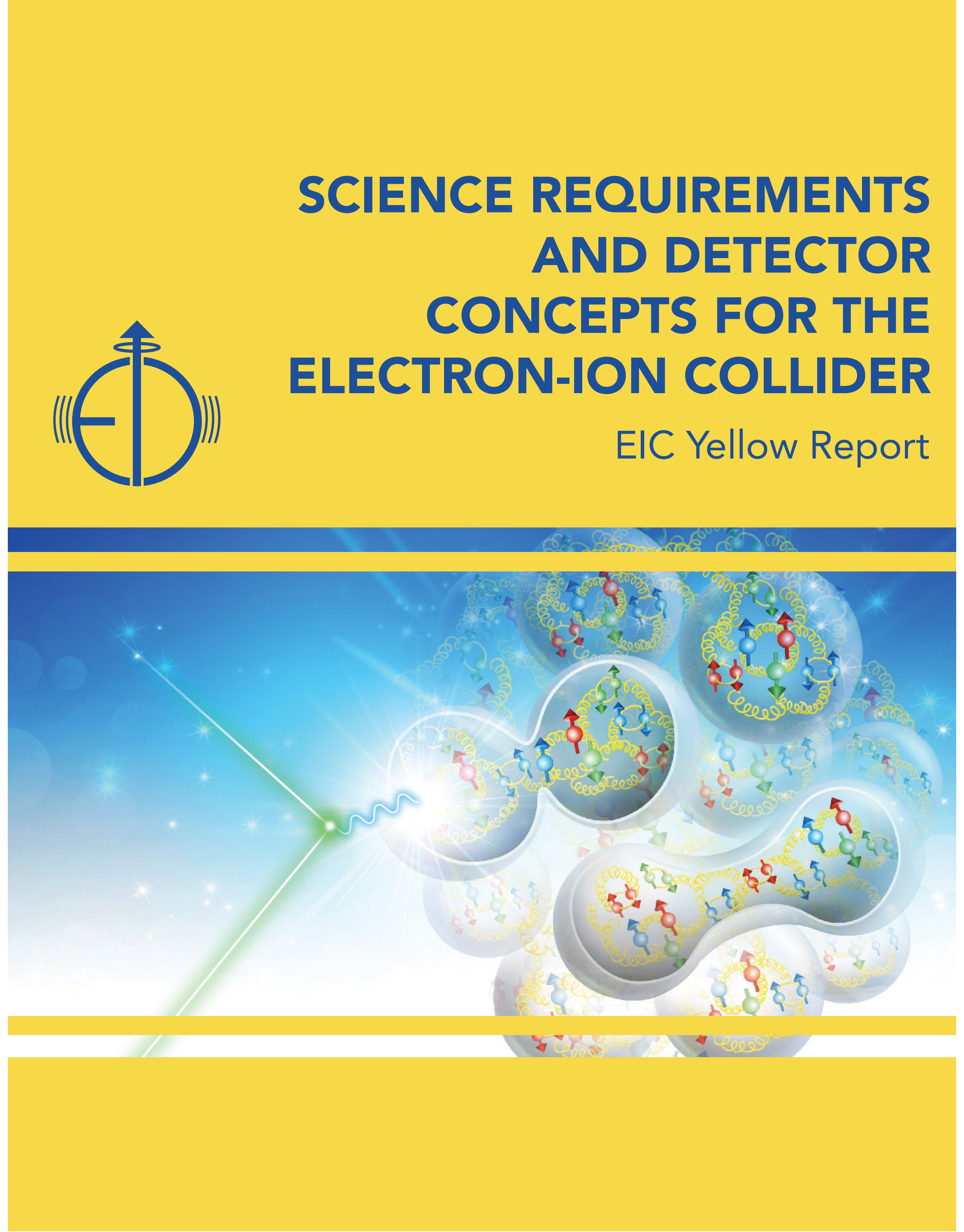


- Planning of beam use will be critical to increase physics output
  - Balance: $\mathscr{L}, \sqrt{s}, A$
- Electron-nucleon luminosities in e-A collisions are similar within a factor of 2 to 3

Recall in pp colliders: $\mathscr{L} \propto \sqrt{s}$

Detector Planning

- The DOE-NP supported EIC Project includes **one** detector and **one** IR in the reference costing
- The EIC is capable of supporting a science program that includes **two** detectors and **two** interaction regions.
- The community (EIC User Group) is strongly in favor of two general purpose detectors
  - Complementarity, cross-checking, cross-calibration/reduction of systematics (see HERA), mitigating of overall risk
- **EIC User Group “Yellow Report” Effort**
  - Initiative to advance the state and detail of requirements and detector concepts in preparation for the realization of the EIC.
  - 1 year effort concluded in March 2021 with a comprehensive “Yellow” Report
  - 902 Pages, 414 authors from 121 institutions, 675 figures
  - Nucl. Phys. A 1026 (2022) 122447, arXiv:2103.05419

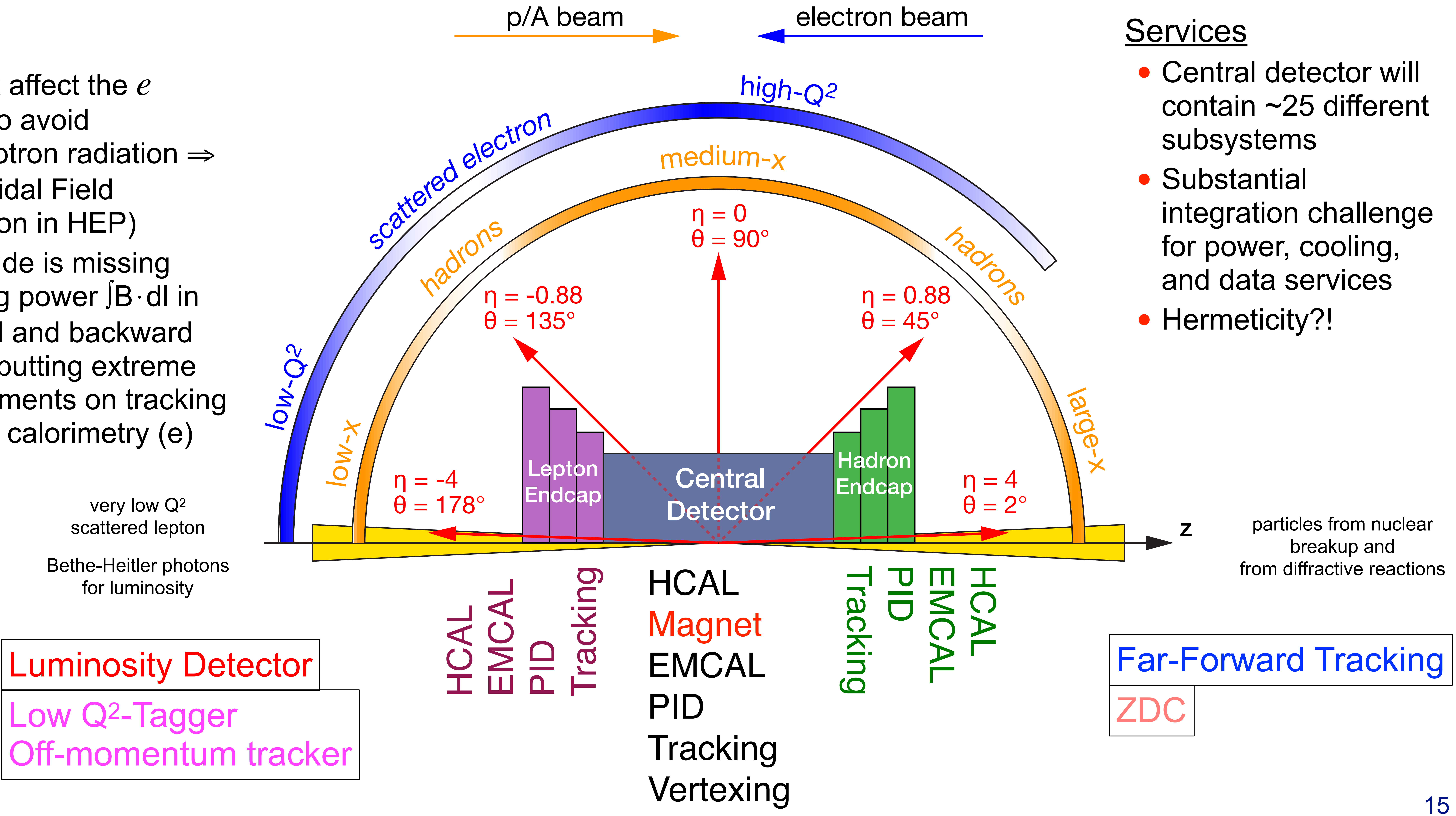


η	Nomenclature	Tracking: Resolution	Tracking: Relative Momentun	Tracking: Allowed X/X_0	Tracking: Minimum-p_T (MeV/c)	Tracking: Transverse Pointing Res.	Tracking: Longitudinal Pointing Res.	Electrons and Photons: Resolution σ_E/E	Electrons and Photons: PID	Electrons and Photons: Min E Photon	π/K/p: p-Range	π/K/p: Separation	HCAL: Resolution σ_E/E	HCAL: Energy	Muons
< -4.6	Low-Q2 tagger														
-4.6 to -4.0		Not Accessible													
-4.0 to -3.5			Reduced Performance												
-3.5 to -3.0	Backward Detector		$\sigma_p/p \sim 0.1\% \times p \oplus 2\%$	~5% or less	150-300			$1\%/E \oplus 2.5\%/\sqrt{E} \oplus 1\%$	π suppression up to $1:10^{-4}$	20 MeV	≤ 10 GeV/c	≥ 3σ	$50\%/\sqrt{E} \oplus 10\%$	~500MeV	Muons useful for background suppression and improved resolution
-3.0 to -2.5															
-2.5 to -2.0			$\sigma_p/p \sim 0.02\% \times p \oplus 1\%$												
-2.0 to -1.5						dca(xy) ~ $40/p_T$ μm ⊕ 10 μm	dca(z) ~ $100/p_T$ μm ⊕ 20 μm	$2\%/E \oplus (4\text{-}8)\%/\sqrt{E} \oplus 2\%$	π suppression up to $1:(10^{-3}\text{-}10^{-2})$	50 MeV					
-1.5 to -1.0															
-1.0 to -0.5	Barrel		$\sigma_p/p \sim 0.02\% \times p \oplus 5\%$		400	dca(xy) ~ $30/p_T$ μm ⊕ 5 μm	dca(z) ~ $30/p_T$ μm ⊕ 5 μm	$2\%/E \oplus (12\text{-}14)\%/\sqrt{E} \oplus (2\text{-}3)\%$	π suppression up to $1:10^{-2}$	100 MeV	≤ 6 GeV/c		$100\%/\sqrt{E} \oplus 10\%$		
-0.5 to 0.0															
0.0 to 0.5															
0.5 to 1.0															
1.0 to 1.5	Forward Detectors		$\sigma_p/p \sim 0.02\% \times p \oplus 1\%$		150-300	dca(xy) ~ $40/p_T$ μm ⊕ 10 μm	dca(z) ~ $100/p_T$ μm ⊕ 20 μm	$2\%/E \oplus (4^*\text{-}12)\%/\sqrt{E} \oplus 2\%$	3σ e/π up to 15 GeV/c	50 MeV	≤ 50 GeV/c		$50\%/\sqrt{E} \oplus 10\%$		
1.5 to 2.0															
2.0 to 2.5															
2.5 to 3.0			$\sigma_p/p \sim 0.1\% \times p \oplus 2\%$												
3.0 to 3.5															
3.5 to 4.0	Instrumentation to separate charged particles from photons		Reduced Performance												
4.0 to 4.5		Not Accessible													
> 4.6	Proton Spectrometer														
	Zero Degree Neutral Detection														

EIC General Purpose Detector Concept

Magnet

- Cannot affect the e beam to avoid synchrotron radiation ⇒ Solenoidal Field (common in HEP)
- Downside is missing bending power $\int B \cdot dl$ in forward and backward region putting extreme requirements on tracking (h) and calorimetry (e)



Services

- Central detector will contain ~25 different subsystems
- Substantial integration challenge for power, cooling, and data services
- Hermeticity?!

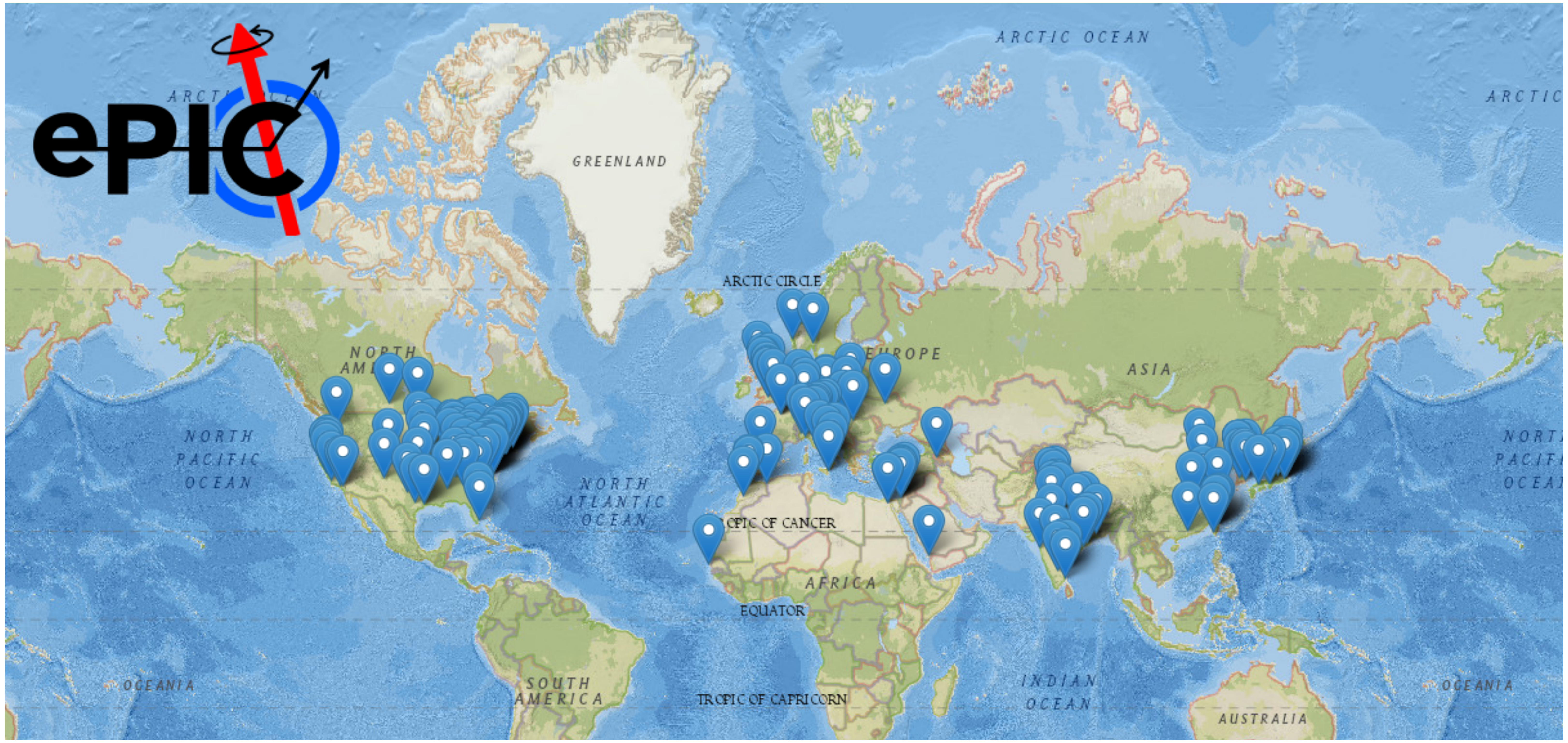
Brief Review of Requirements (see Yellow Report)

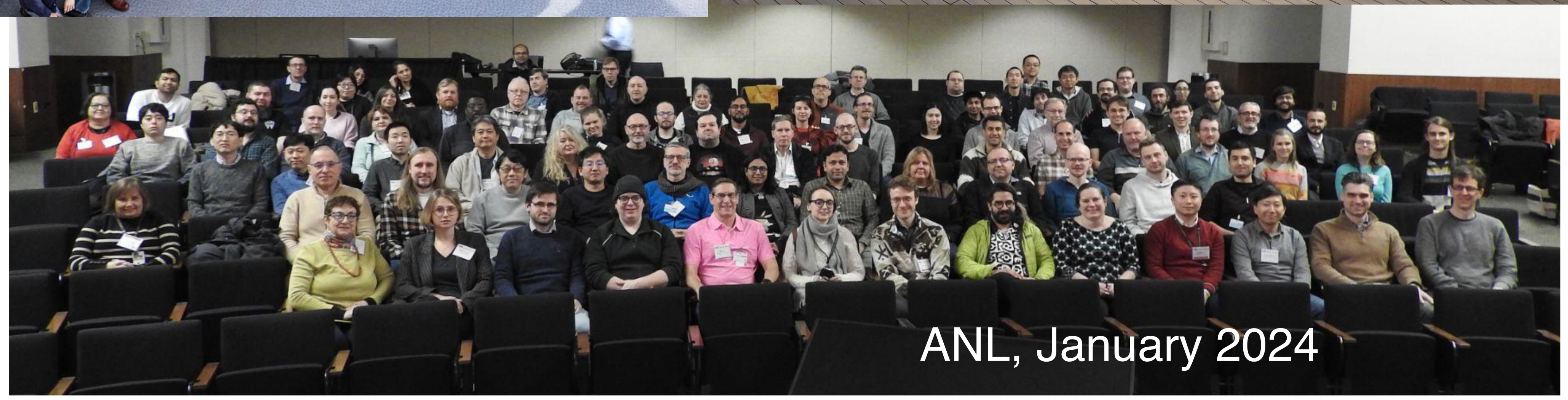
- Hermetic detector, low mass inner tracking
- Moderate radiation hardness requirements
- Electron measurement & jets in approx. -4 < η < +4
- Good momentum resolution
  - central: $\sigma(p)/p = 0.05\,\%\,p \oplus 0.5\,\%$
  - fwd/bkd: $\sigma(p)/p = 0.1\% \oplus 0.5\,\%$
- Good impact parameter resolution:
  - $\sigma = 5 \oplus 15/p \sin^{3/2}\theta\ (\mu\mathrm{m})$
- Excellent EM resolution
  - central: $\sigma(E)/E = 10\,\%/\sqrt{E}$
  - backward: $\sigma(E)/E < 2\,\%/\sqrt{E}$
- Good hadronic energy resolution
  - forward: $\sigma(E)/E \approx 50\,\%/\sqrt{E}$
- Excellent PID π/K/p
  - forward: up to 50 GeV/c
  - central: up to 8 GeV/c
  - backward: up to 7 GeV/c
- Low pile-up, low multiplicity, data rate ~500kHz (full lumi)

Hermeticity, low mass, and PID requirements make EIC detector design challenging

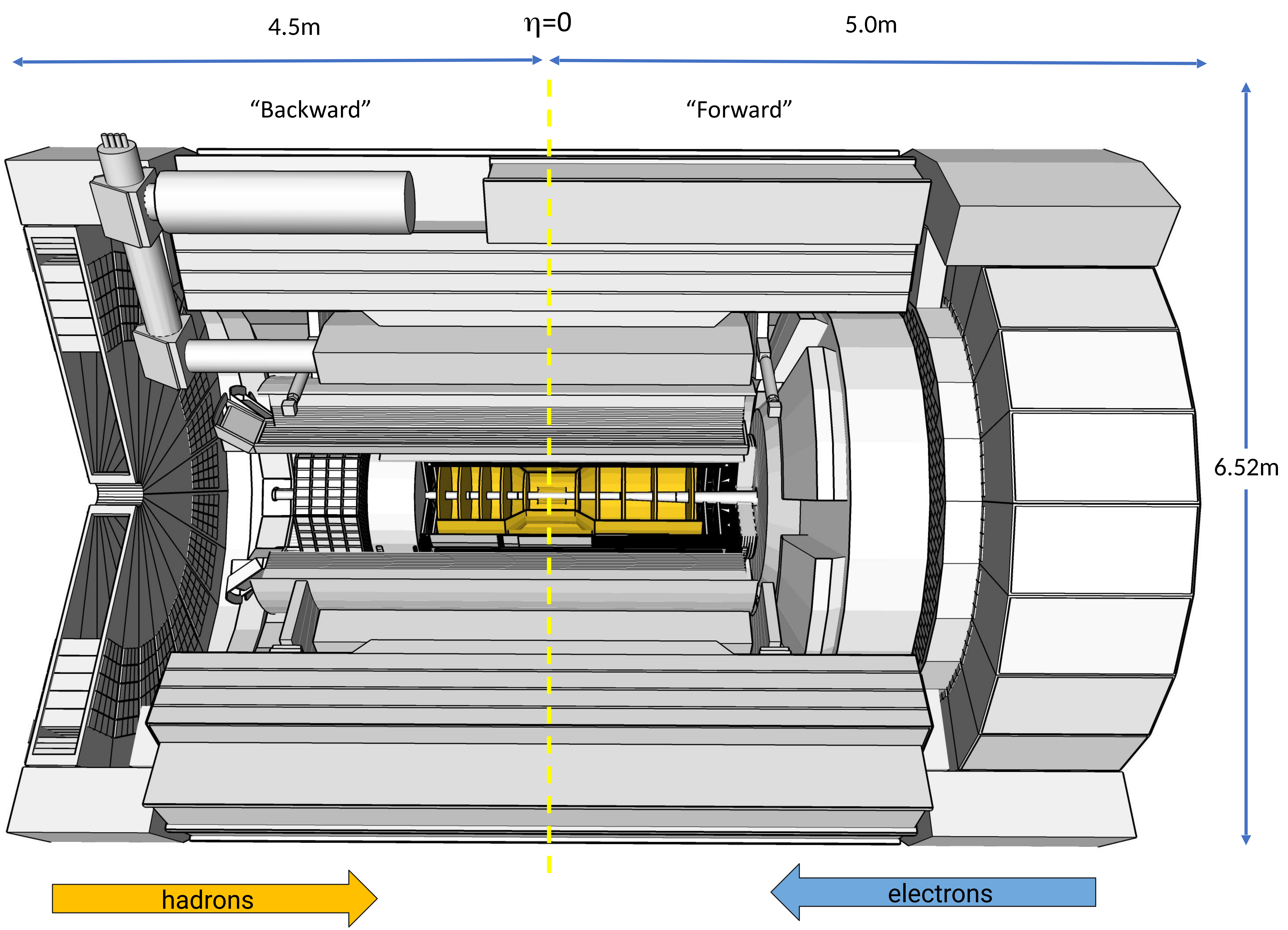
electron Proton and Ion Collider experiment ePIC

- ePIC was founded in July 2022
- ePIC is a community of scientists dedicated to realizing the EIC science mission
- They work closely with the EIC Project formed by the two host labs, BNL and JLab
- ePIC is international:
  - 893 Members
  - 177 Institutions
  - 29 Countries





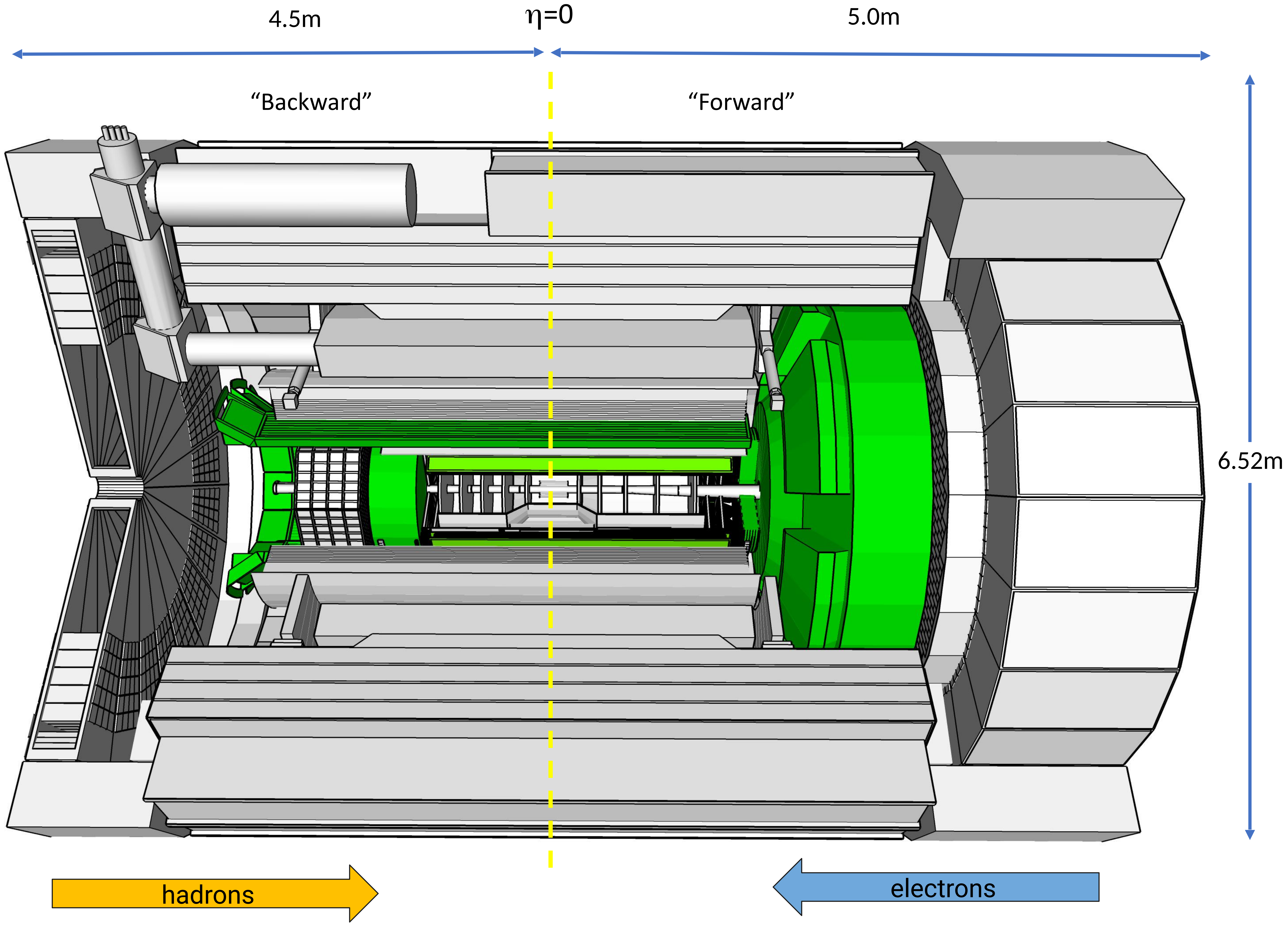
ePIC Overview



Tracking:

- New 1.7T (2.0T) solenoid
- Si MAPS Tracker
- MPGDs (μRWELL/μMegas)

ePIC Overview



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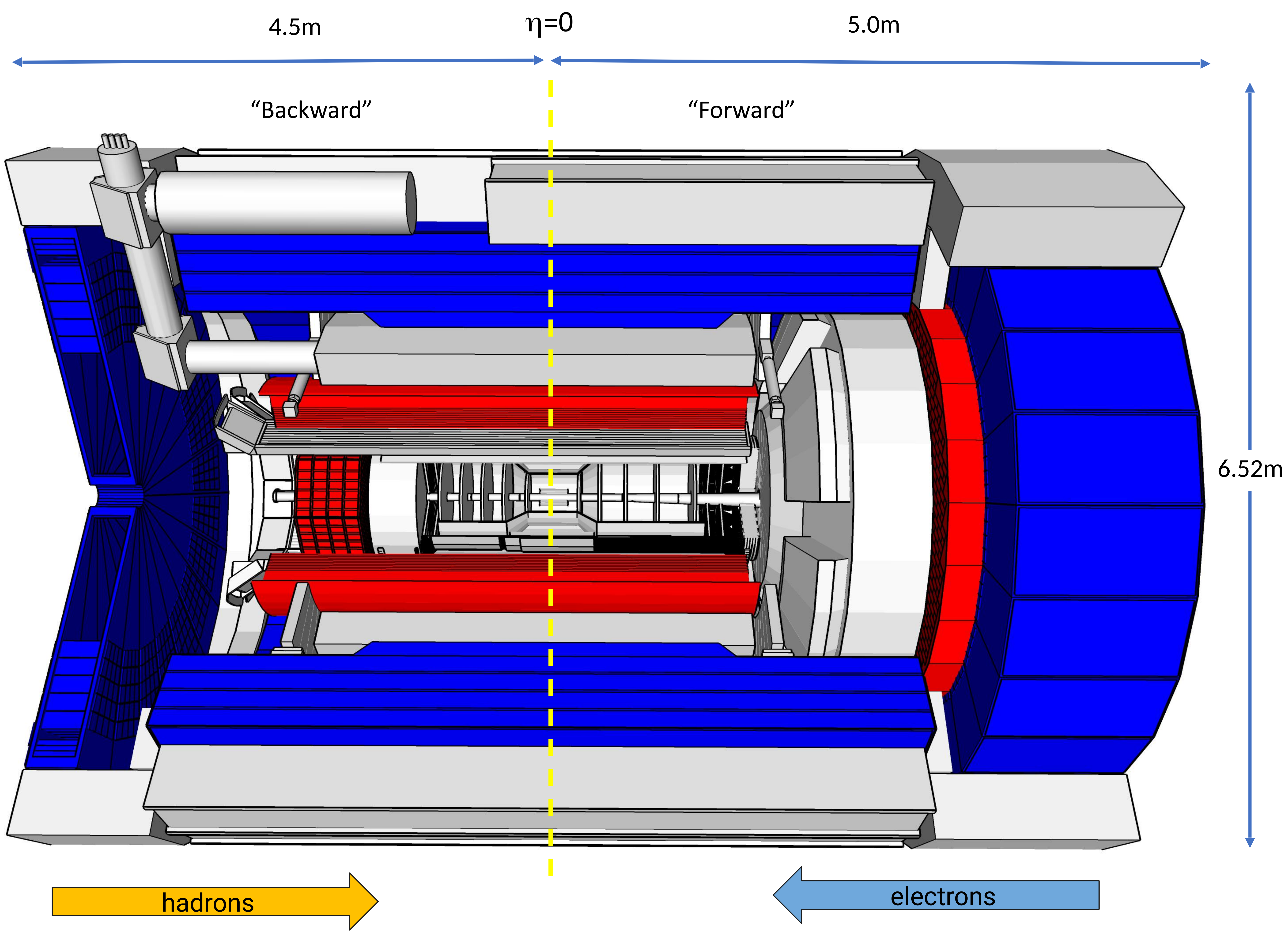
PID:

- high-performance DIRC
- proximity-focused RICH
- dual-radiator RICH
- AC-LGAD (~30ps TOF)

ePIC Overview



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PID:
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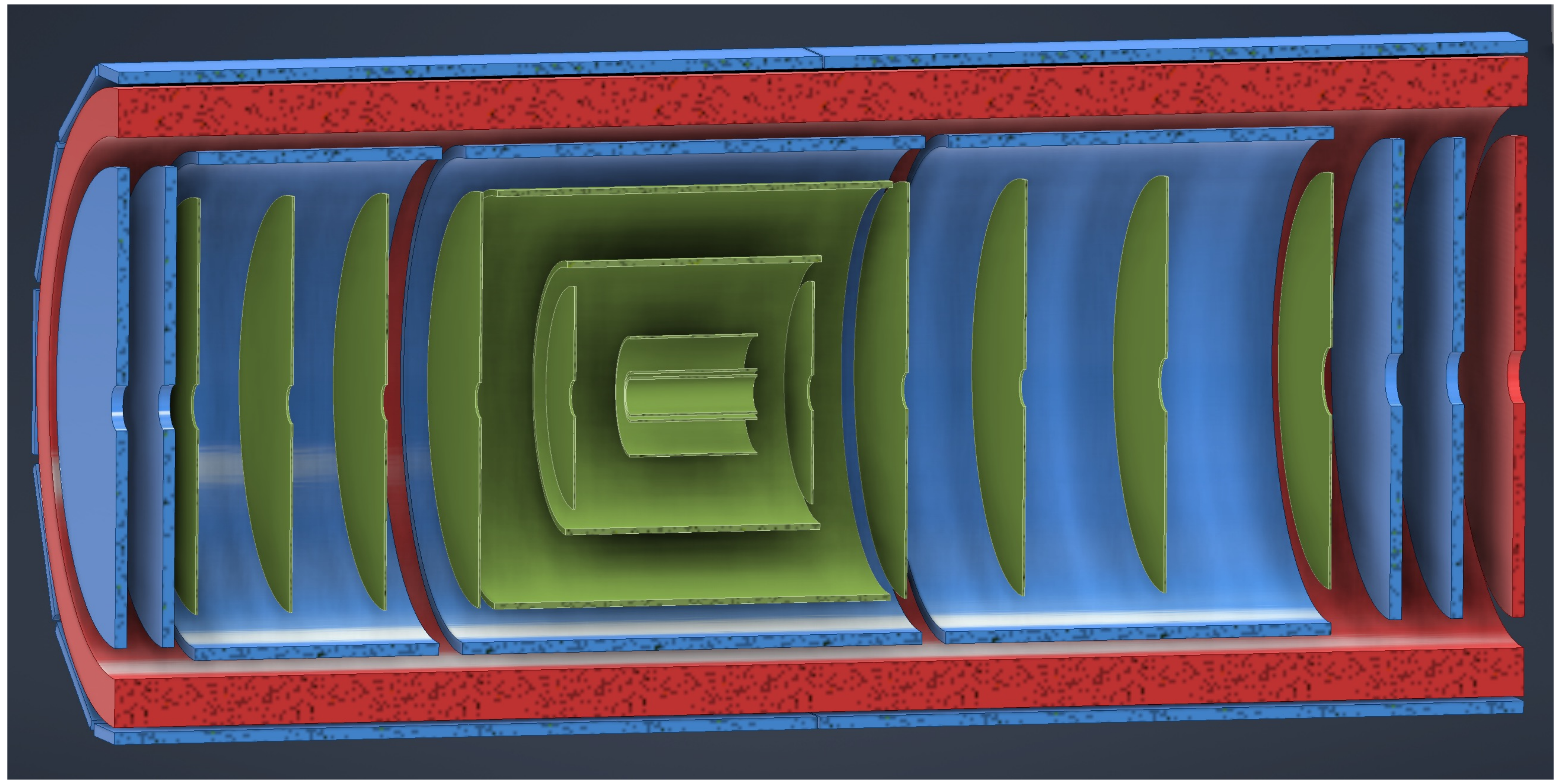
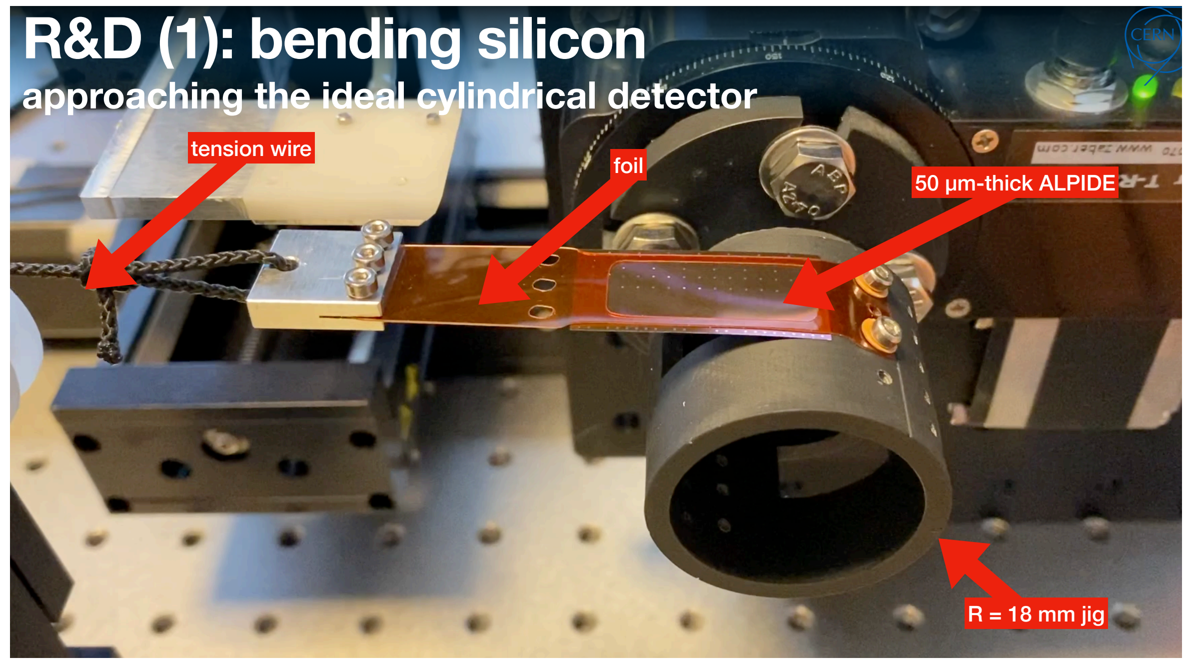
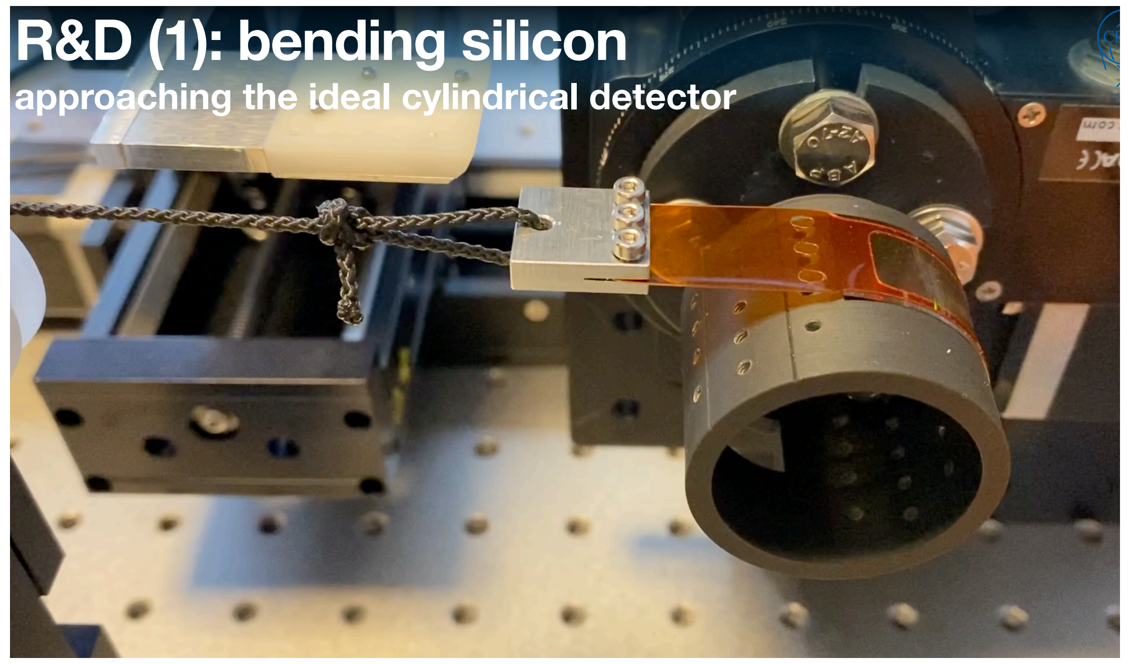
Calorimetry:
- Imaging Barrel EMCal
- PbWO4 EMCal (backwards)
- Finely segmented EMCal +HCal in forward direction
- Outer HCal (sPHENIX re-use)
- Backwards HCal (tail-catcher)

Barrel Tracking

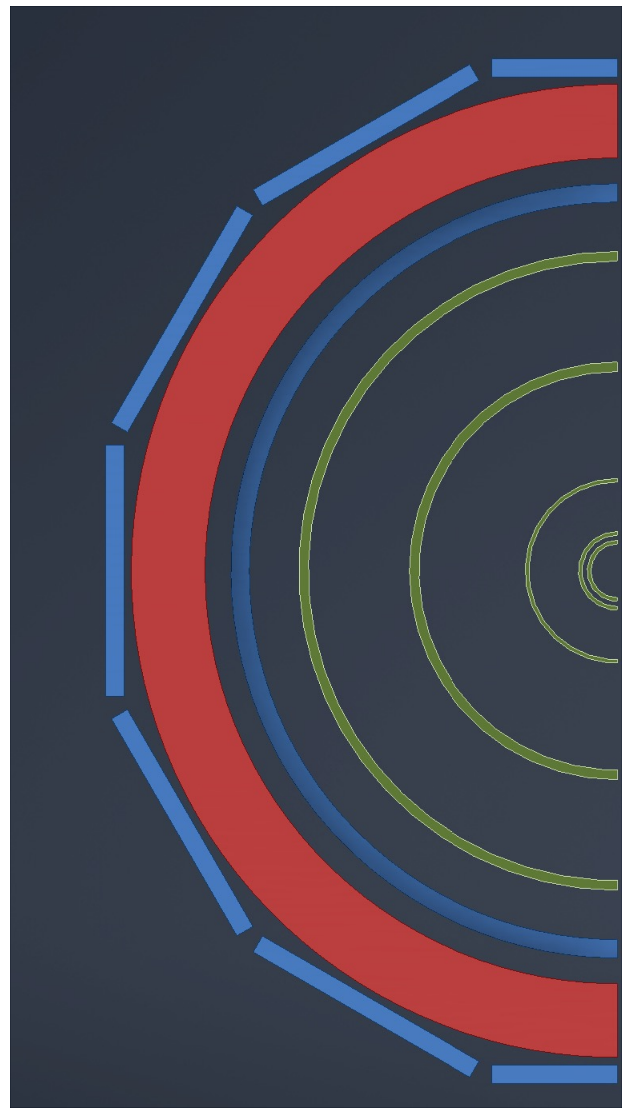


SVT MPGDs ToF (fiducial volume)





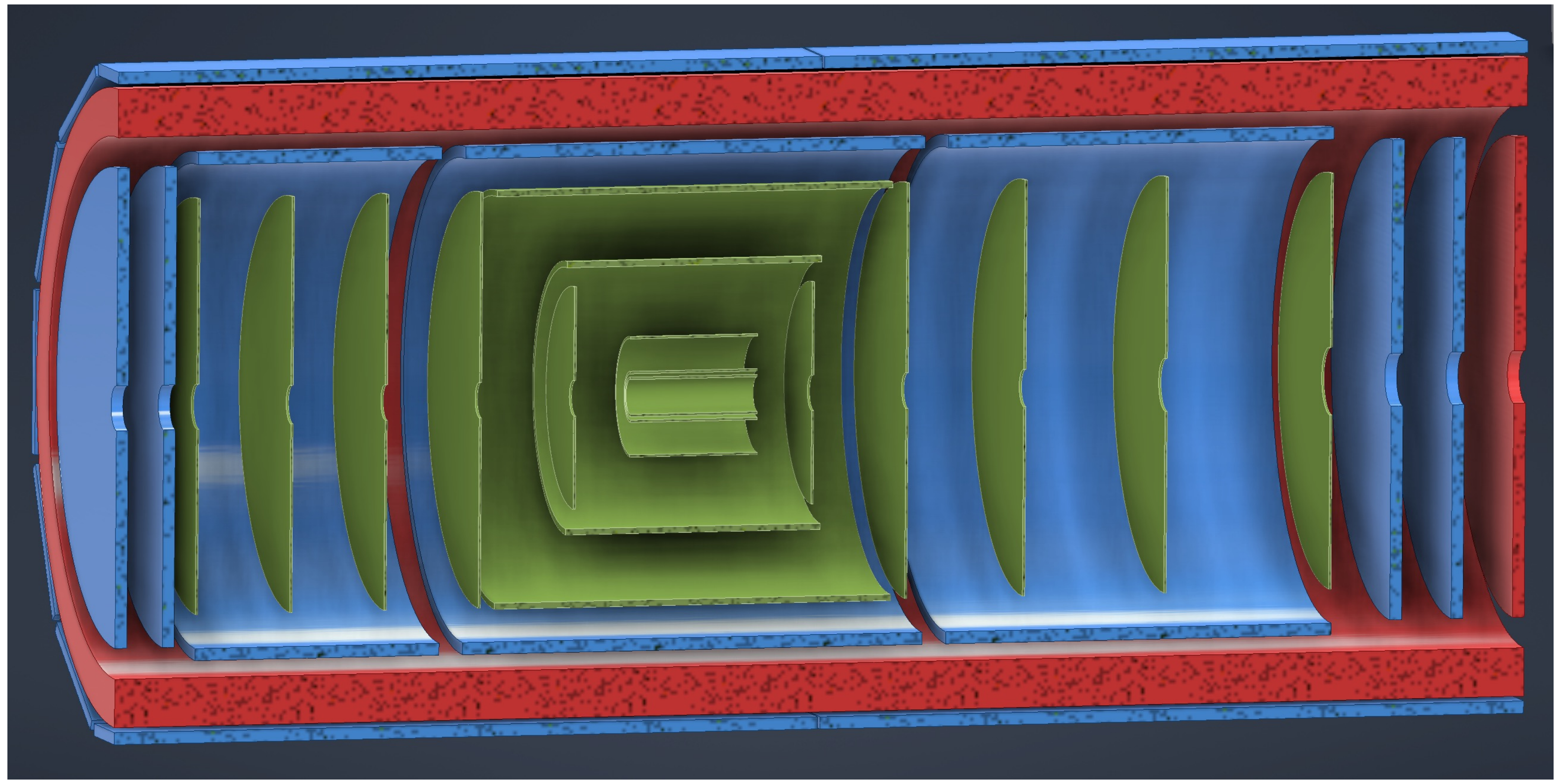
Bending 20 μm silicon

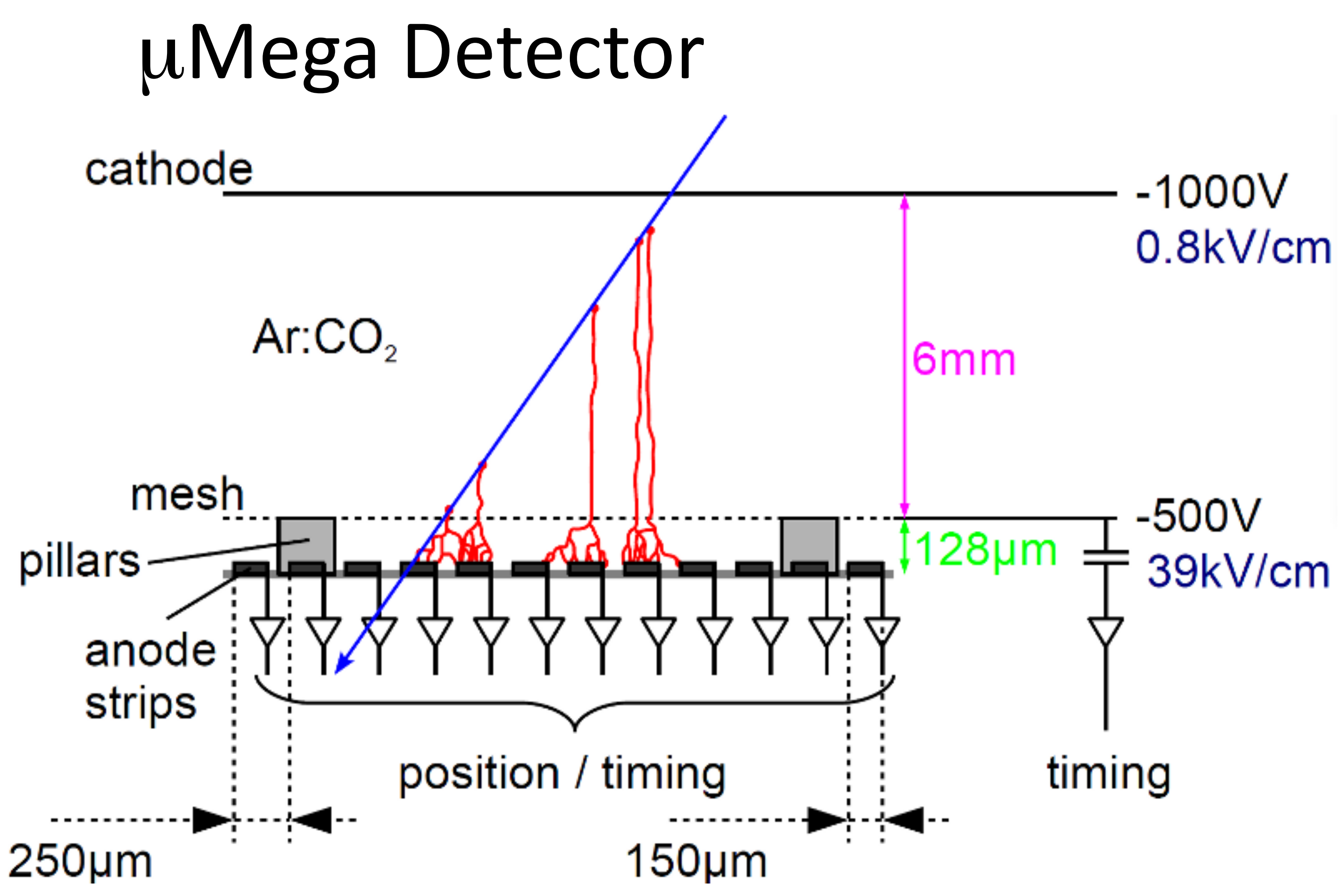


Si Vertex/Inner Barrel (3 layers)

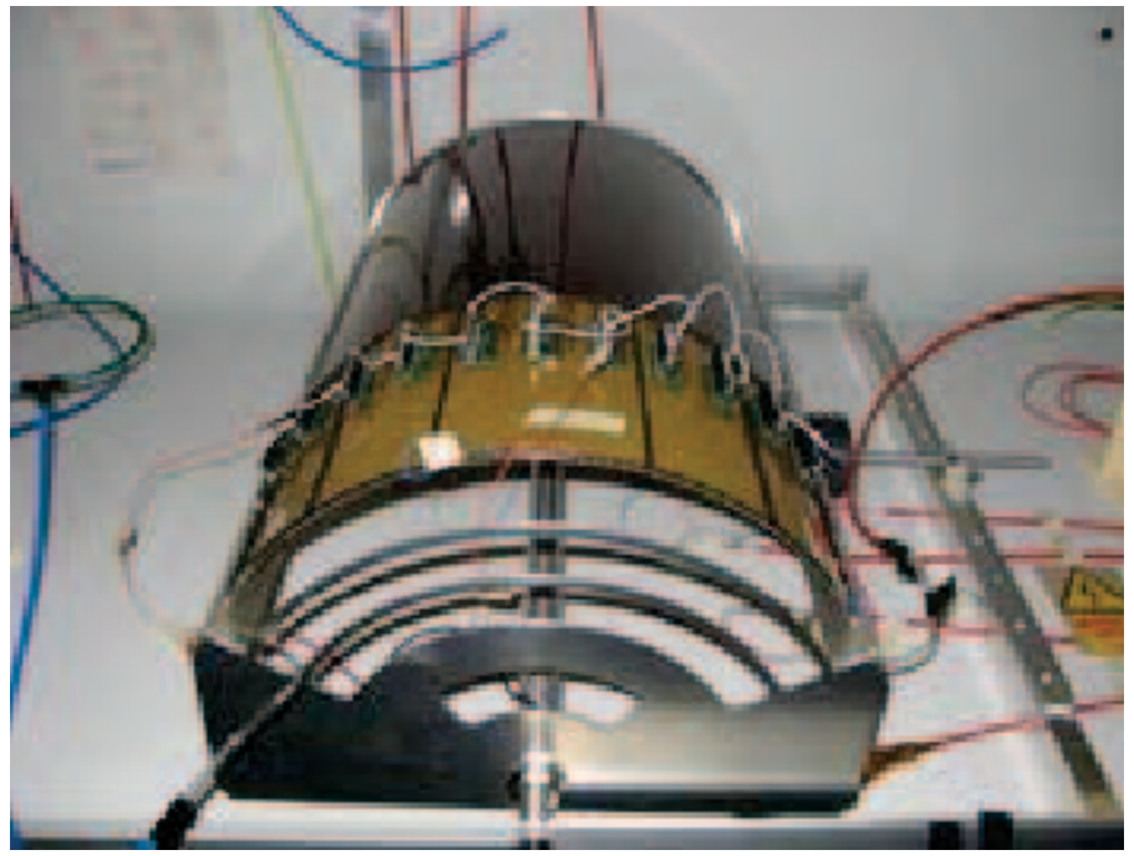
- ITS3/sensor: Joint effort with ALICE/CERN (SVT Consortium)
- Large-area, wafer-scale, stitched sensors bent around beam pipe using latest 65 nm MAPS technology
- Small pixels (20 µm), low power consumption (<20 mW/cm^2) and material budget (~0.05% X/X_0) per layer
- Vertex layers optimized for beam pipe bake-out and ITS-3 sensor size

Barrel Tracking

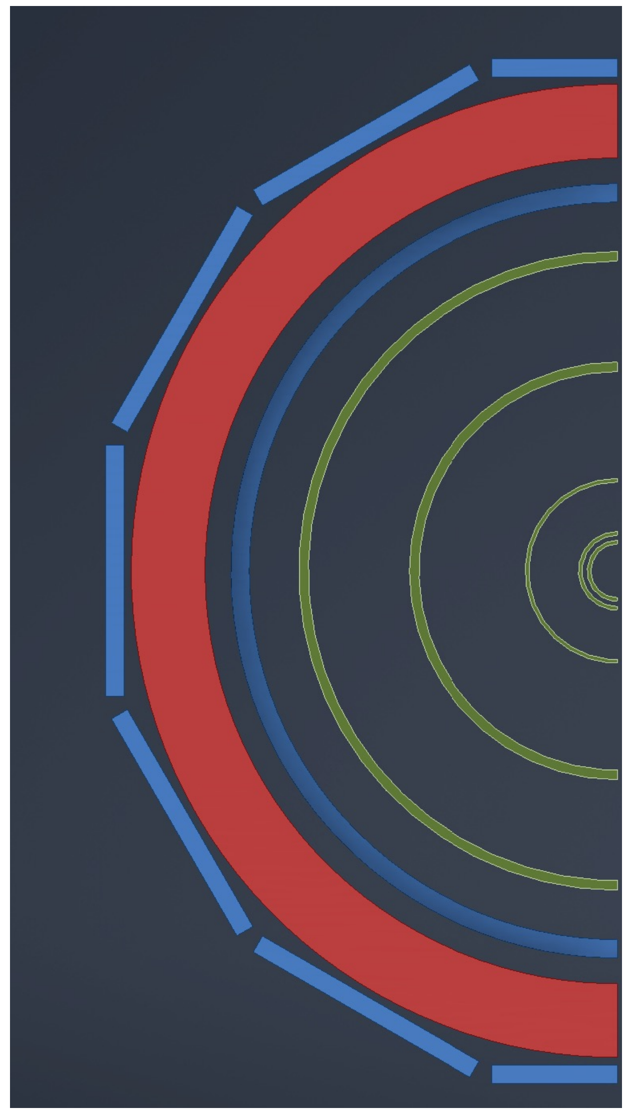




Cylindrical µMega



SVT MPGDs ToF (fiducial volume)

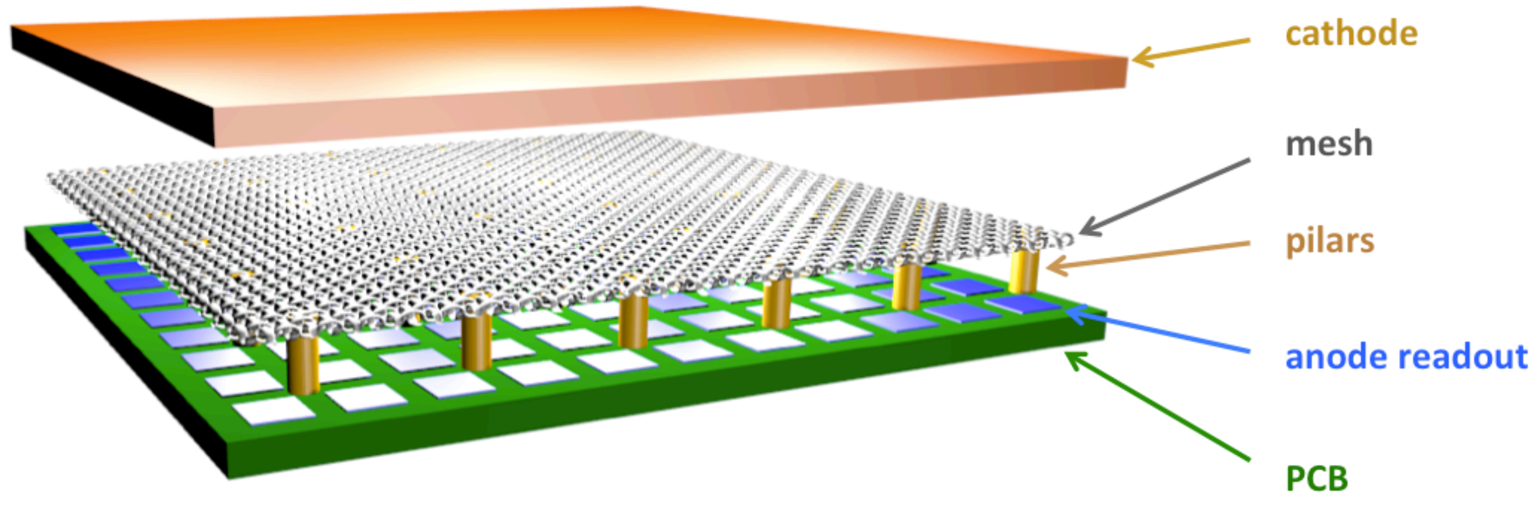


Si Tracking/Outer Barrel (2 layers)

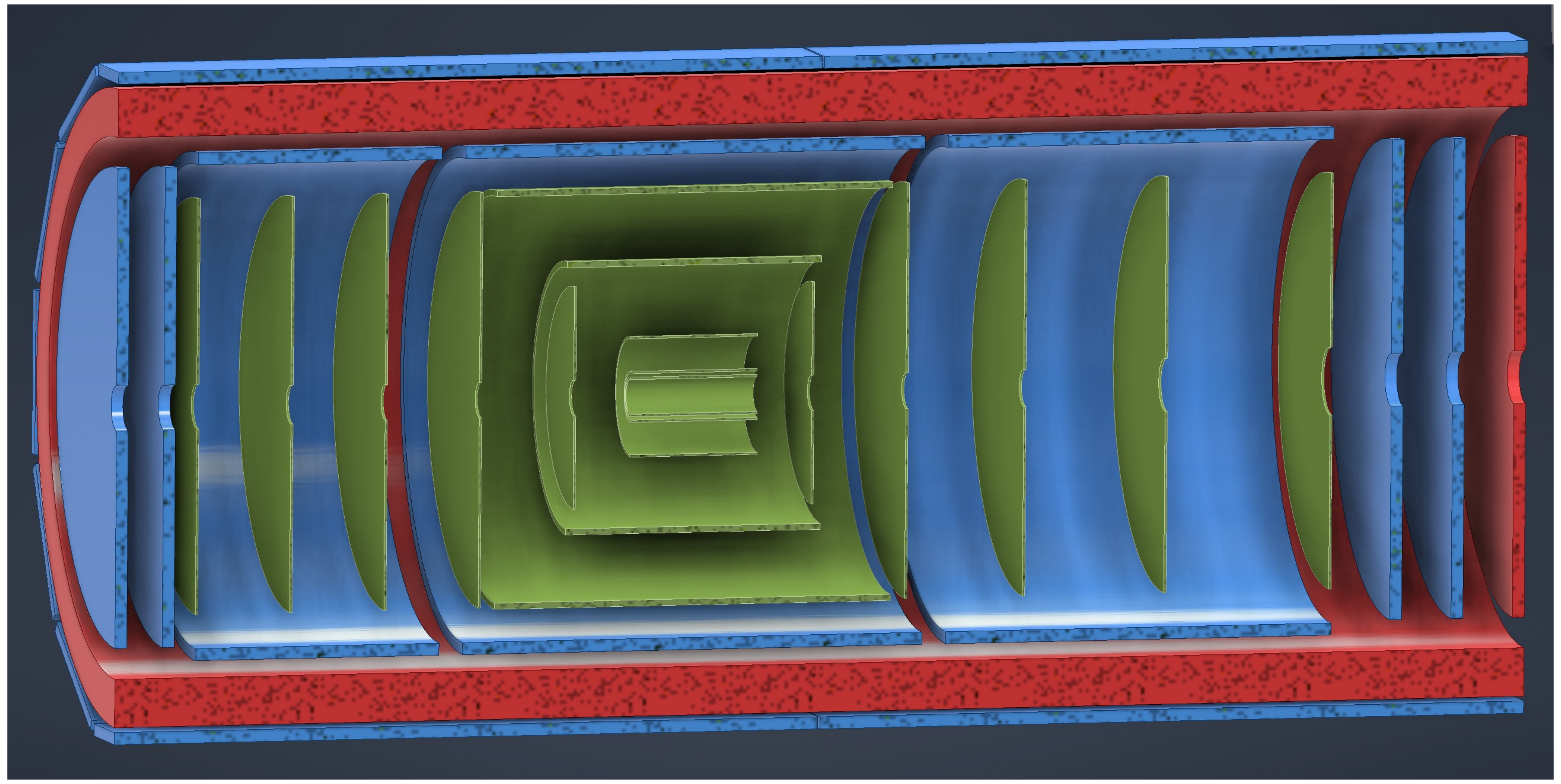
- EIC sensors derived from ITS3
  - not wafer-stiched: too expensive for large area (8 m2) due to low yield

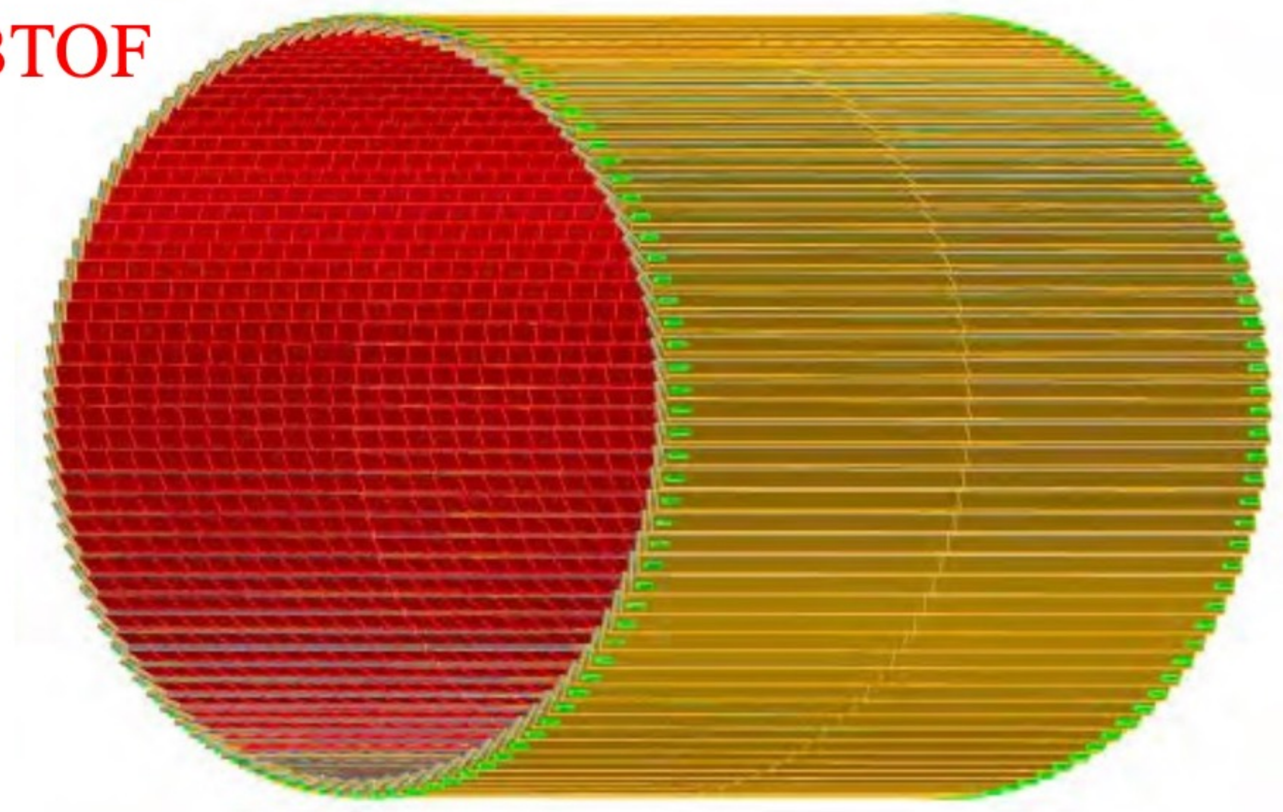
Cylindrical MPGD Layer

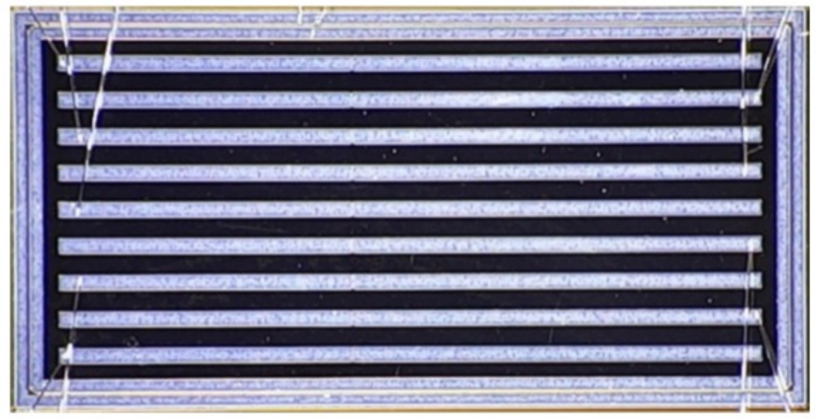
- Either Micromegas or Thin Gap MPGDs
- Important for pattern recognition



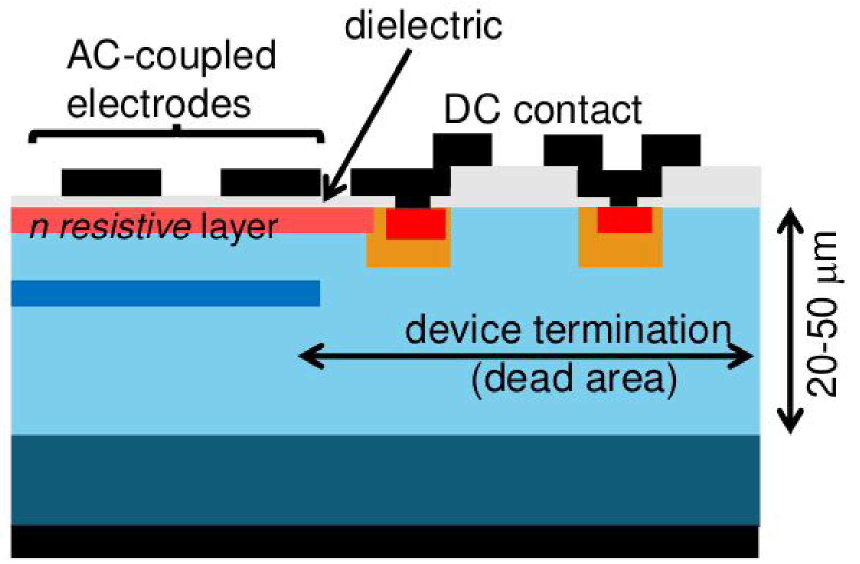
Barrel Tracking

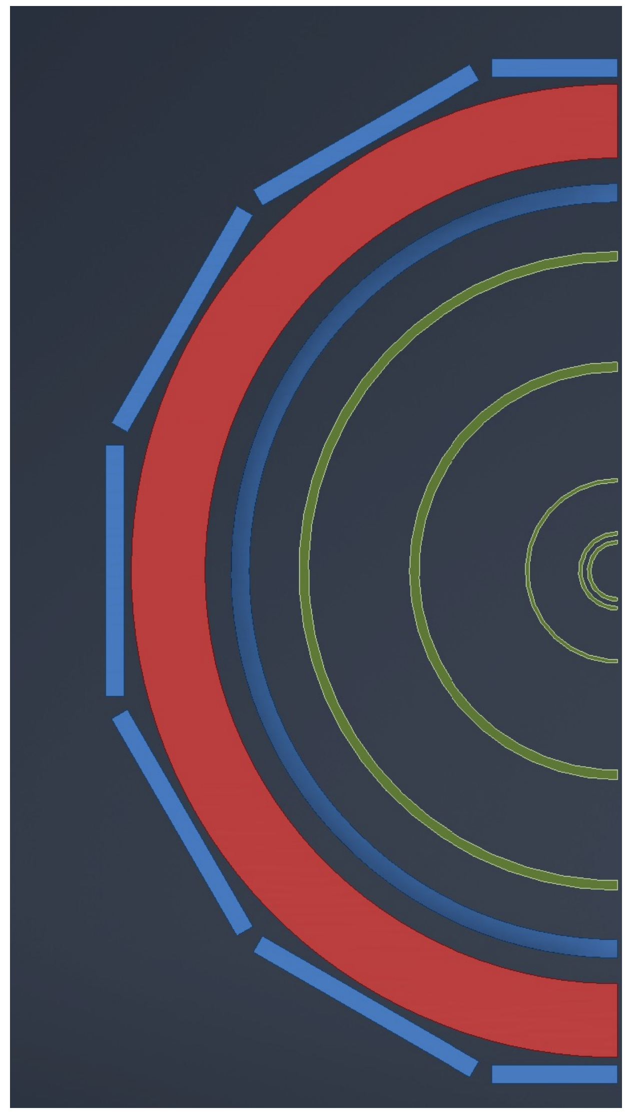






	Area (m²)	Channel size (mm²)	# of Channels	Timing Resolution	Spatial resolution	Material budget
Barrel TOF	10	0.5*10	2.4M	35 ps	30 μm in $r \cdot \varphi$	0.01 X_0

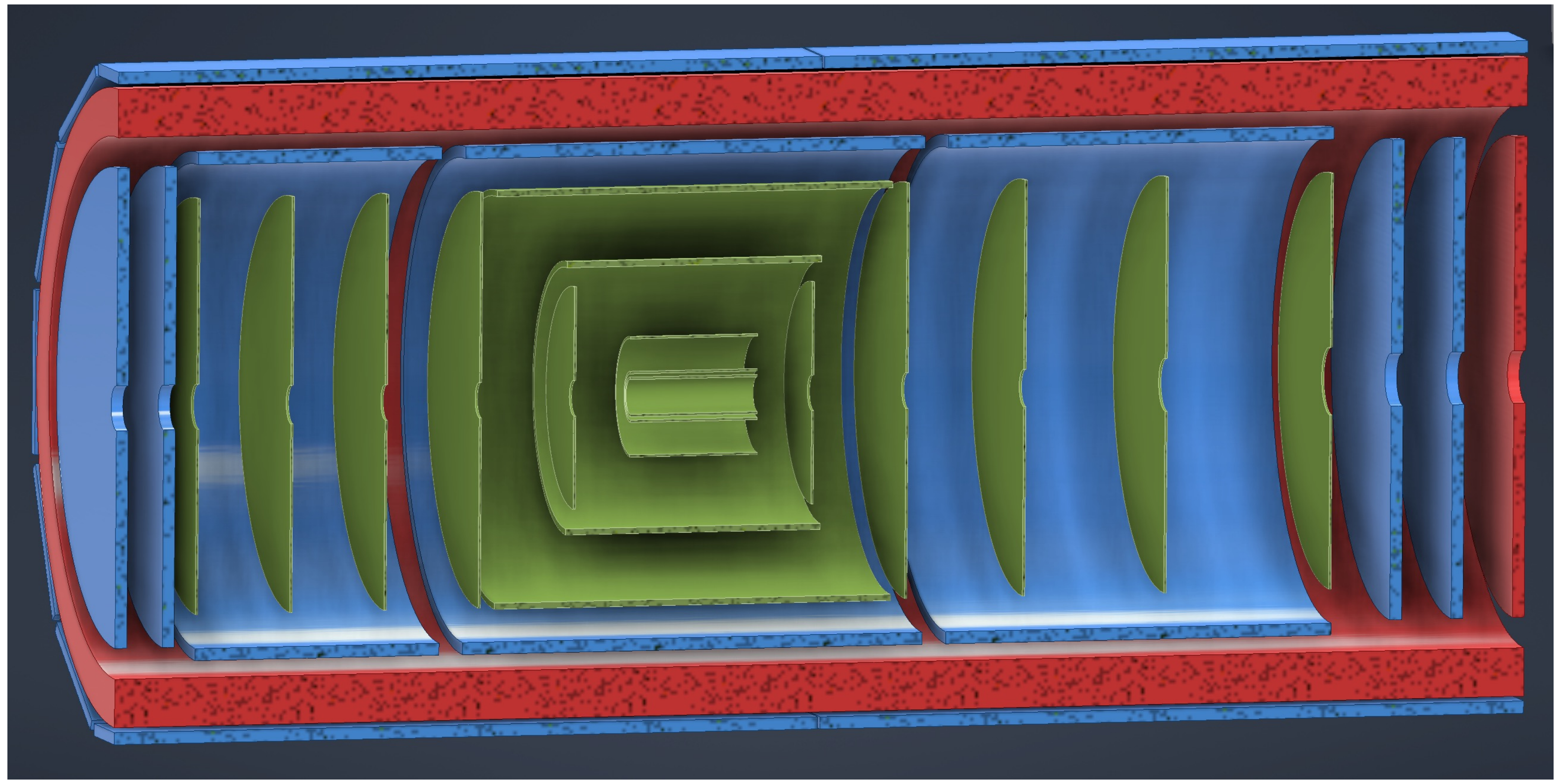




AC-LGAD TOF

- Serves for tracking and low-p_T PID
- Additional space point for pattern recognition / redundancy

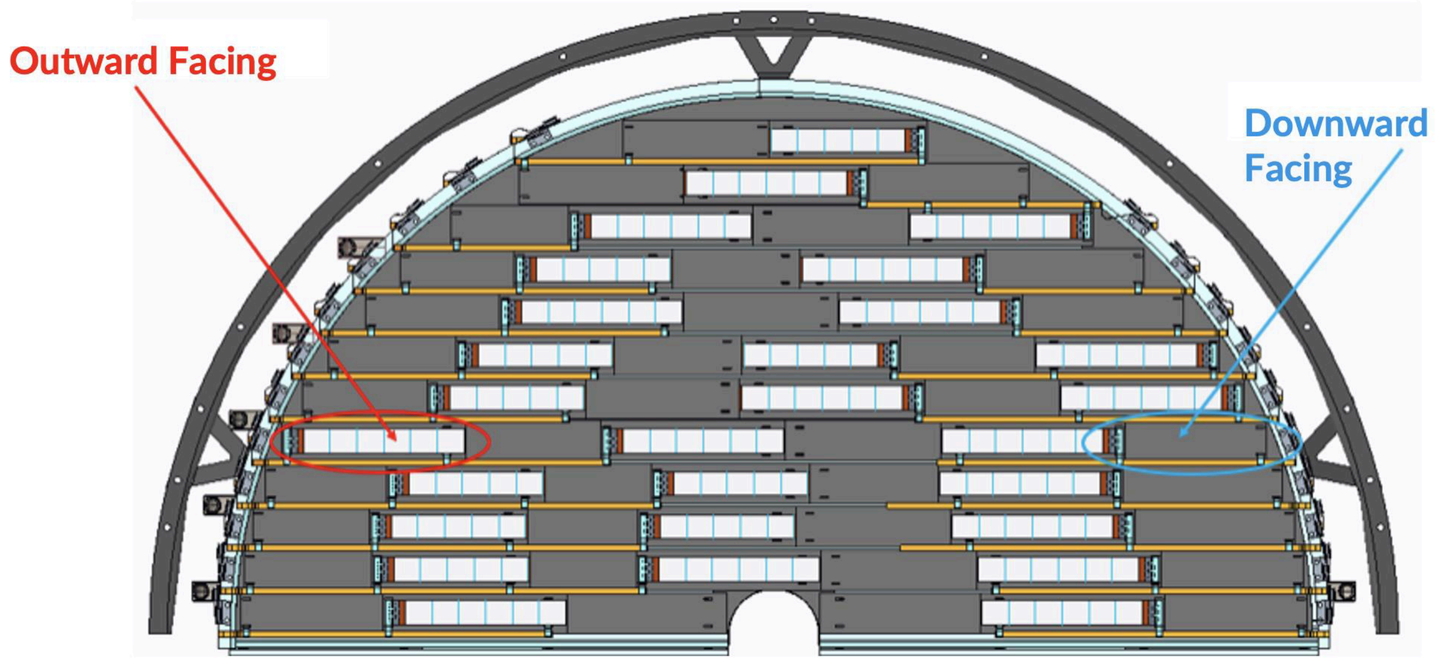
Forward-Backward Tracking



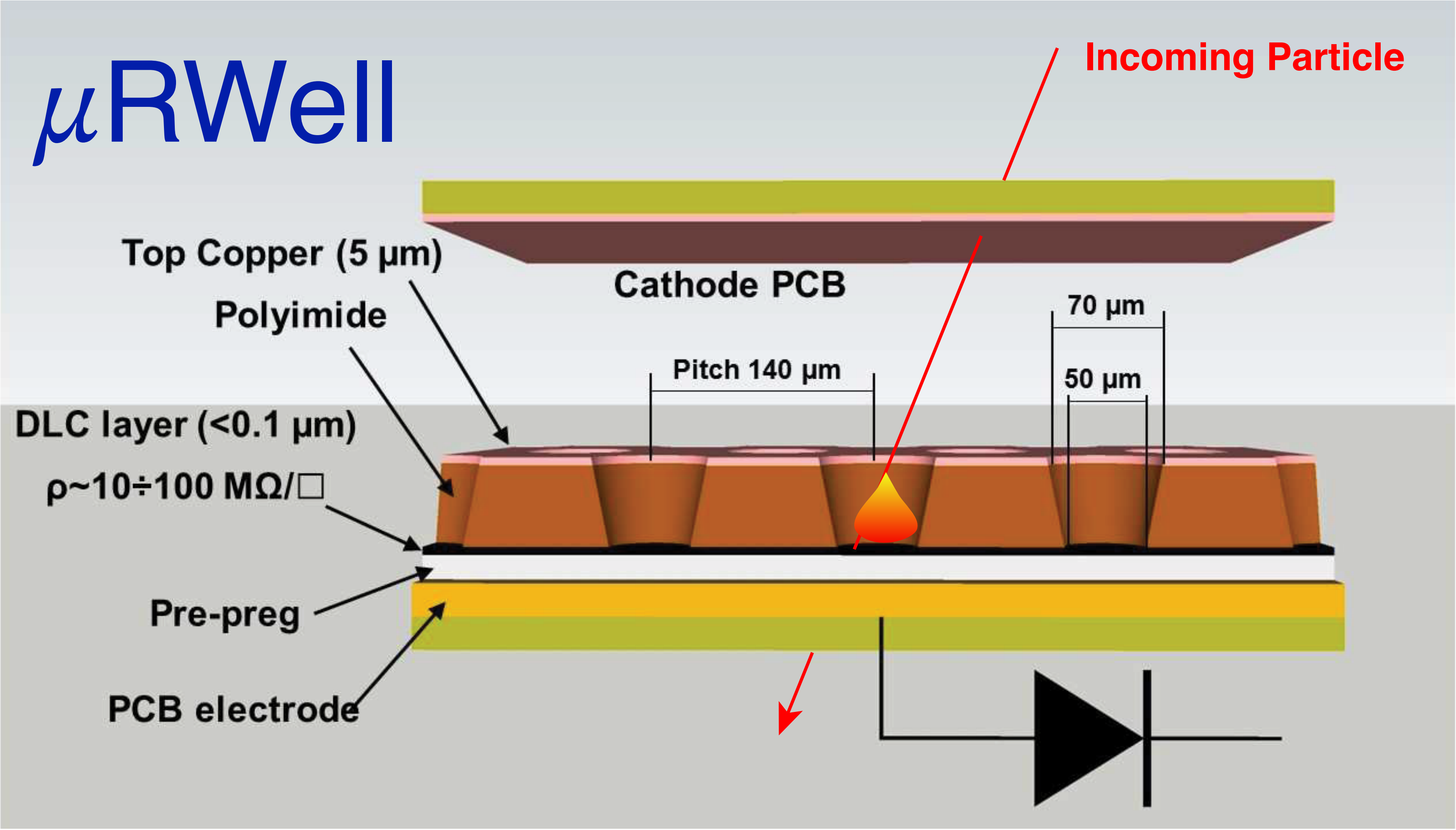
SVT MPGDs ToF (fiducial volume)

Disk	-z	+z	X/X_0
Si 1	250	250	0.24
Si 2	450	450	0.24
Si 3	650	700	0.24
Si 4	850	1000	0.24
Si 5	1050	1350	0.24
MPGD	1100	1480	~1
MPGD	1200	1610	~1

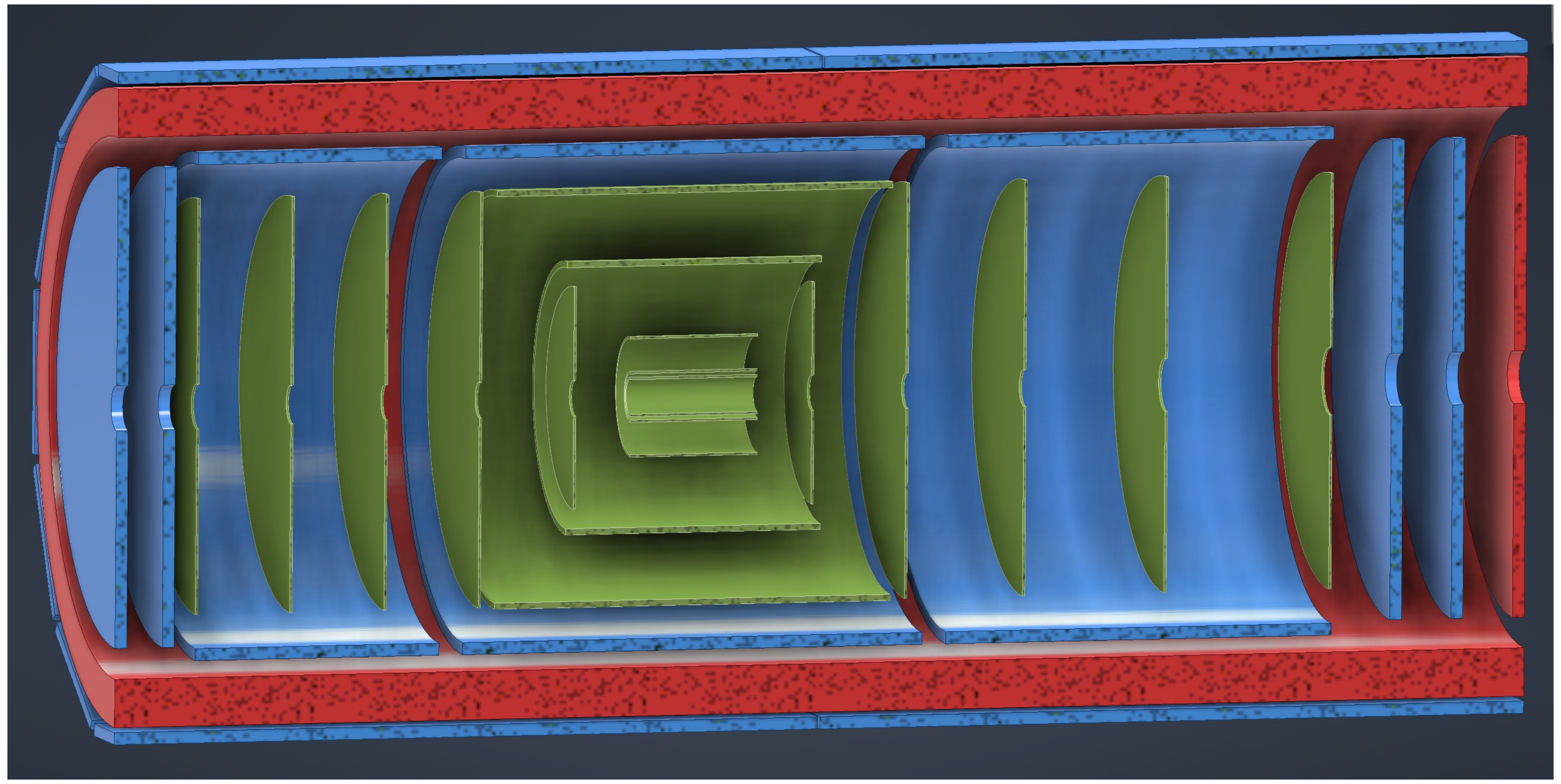
Disk layout design in progress



- 5 Si + 2 μRWell discs in forward/backwards direction (ITS-3 based large area sensor design)
- High resolution requirements hard to meet
  - Increase lever arm by maximizing tracker extent in z
  - Pattern recognition with realistic background studied
  - Ongoing optimization
  - Can potentially impact *t* measurement in e+A

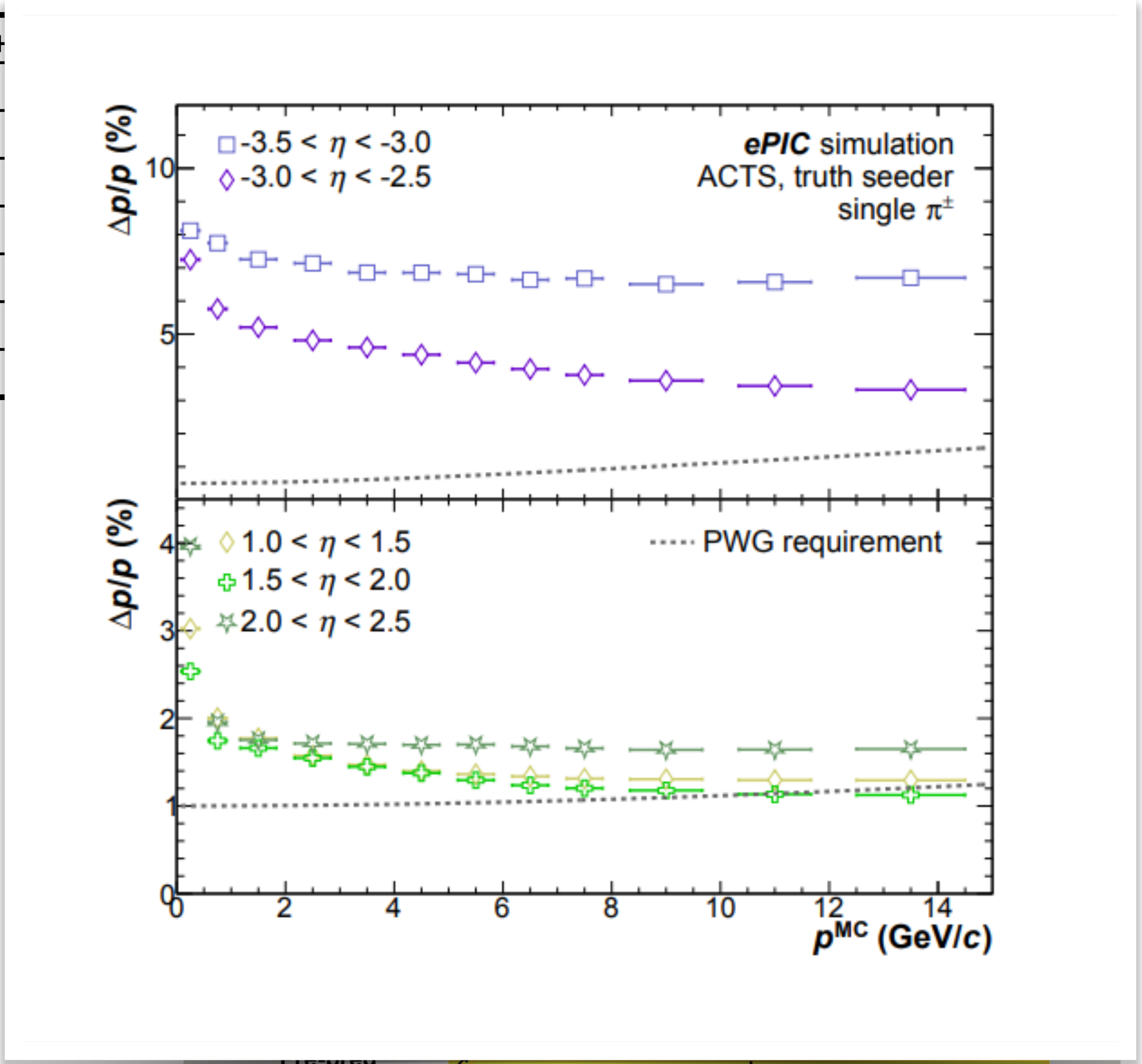


Forward-Backward Tracking



SVT MPGDs ToF (fiducial volume)

Disk	-z	+
Si 1	250	
Si 2	450	
Si 3	650	
Si 4	850	
Si 5	1050	
MPGD	1100	
MPGD	1200	



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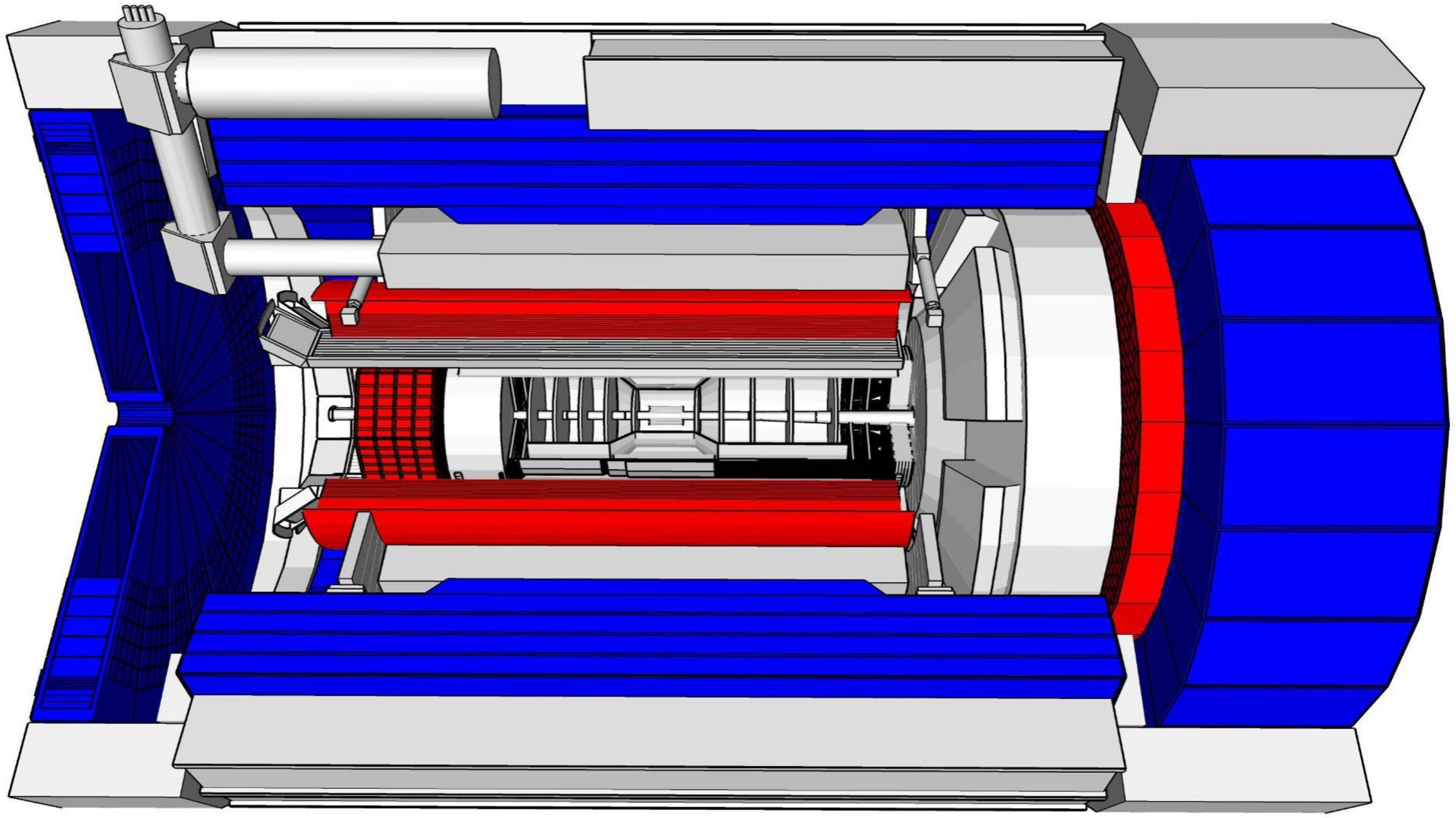
Calorimetry



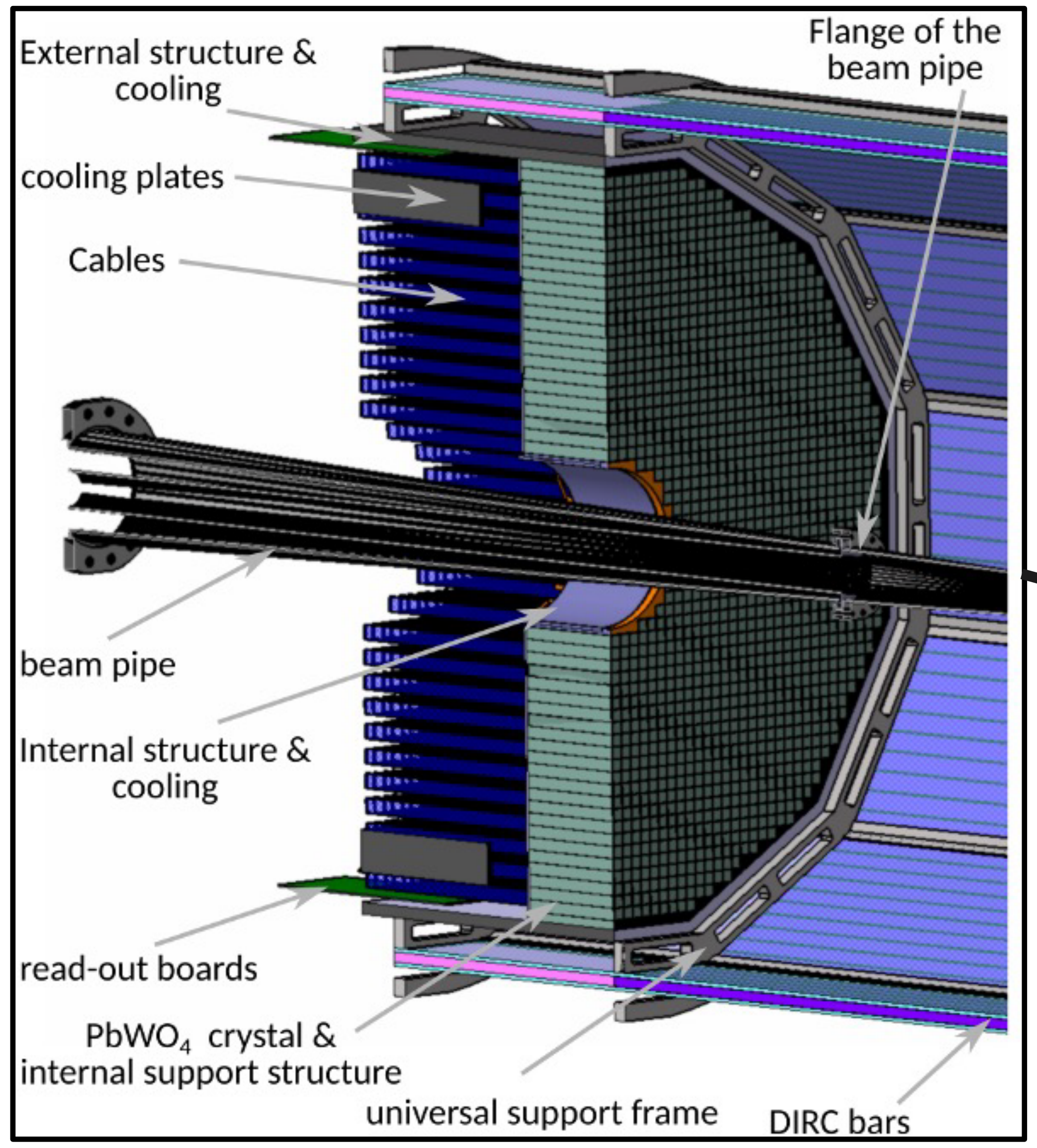
Calorimeters with wide range of acceptances (backward, barrel, forward) and different technologies:

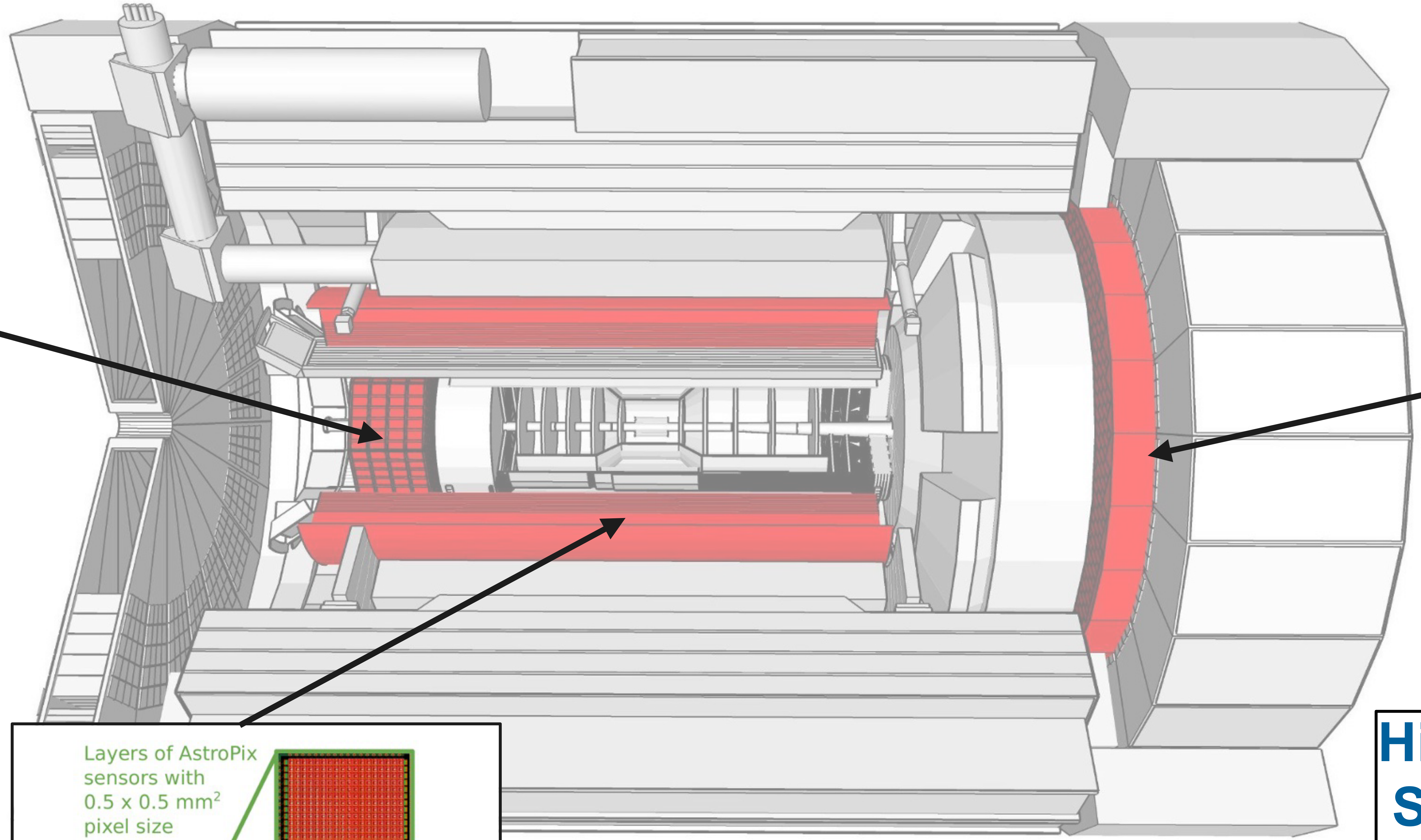
- Electromagnetic Calorimeter.
- Hadronic Calorimeter.

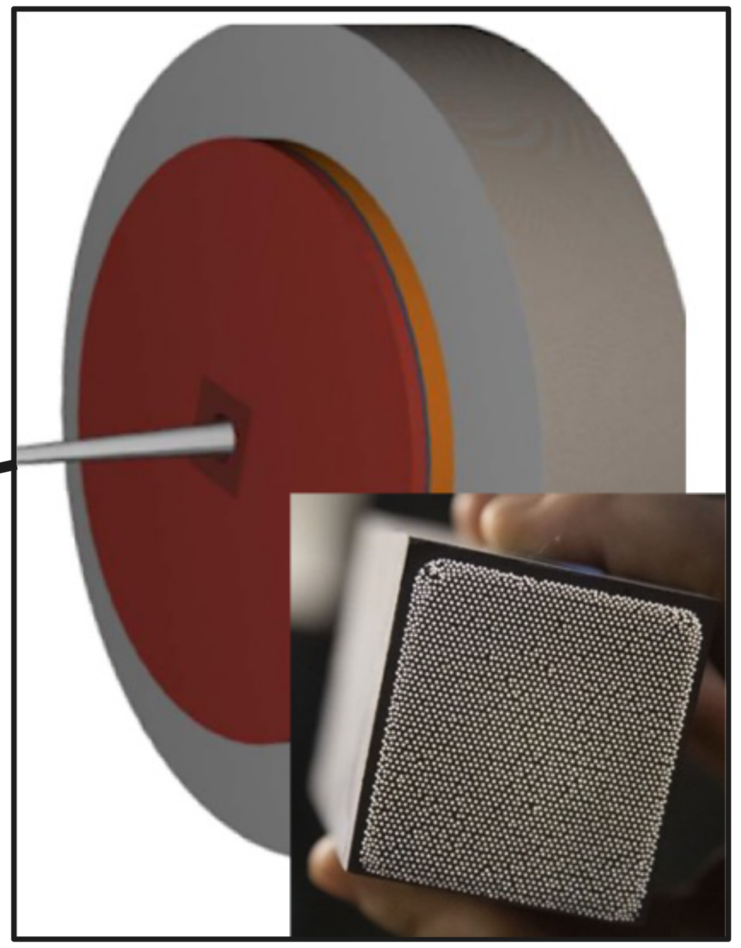
Purpose:

- Detect the scattered electron and separate them from π (up to 10^{-4} suppression factor in backward and barrel ECal)
- Improve the electron momentum resolution at backward rapidities (2-3%$/\sqrt{E} \oplus (1-2)\%$ for backward ECal)
- Provide spatial resolution of two photons sufficient to identify decays $\pi^0 \to \gamma\gamma$ at high energies from ECals
- Contain the highly energetic hadronic final state and separate clusters in a dense hadronic environment in Forward ECal and HCal

Electromagnetic Calorimetry



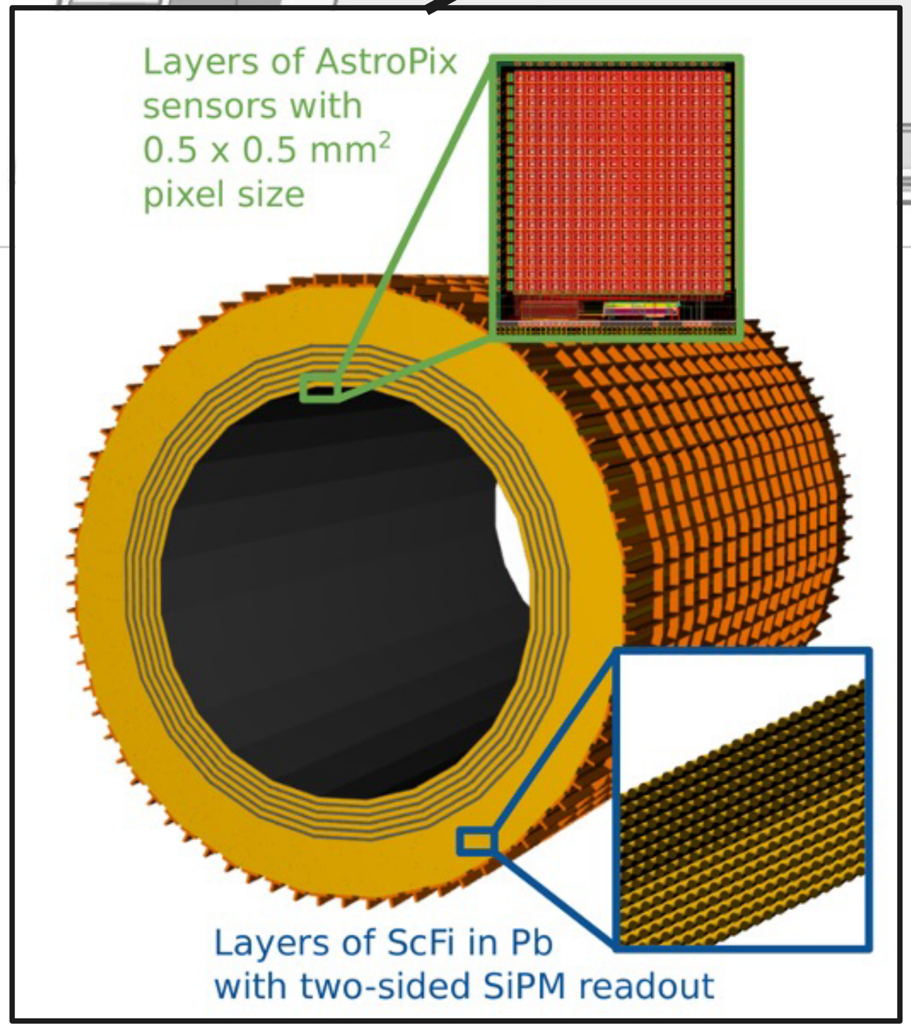




Backward EMCal

$PbWO_4$ crystals

- 2 × 2 × 20 cm^3 crystals
- Readout: SiPMs
  10μm pixel
- Depth: ~20 X0
- Cooling to keep temperature stable within ± 0.1 ^{o}C



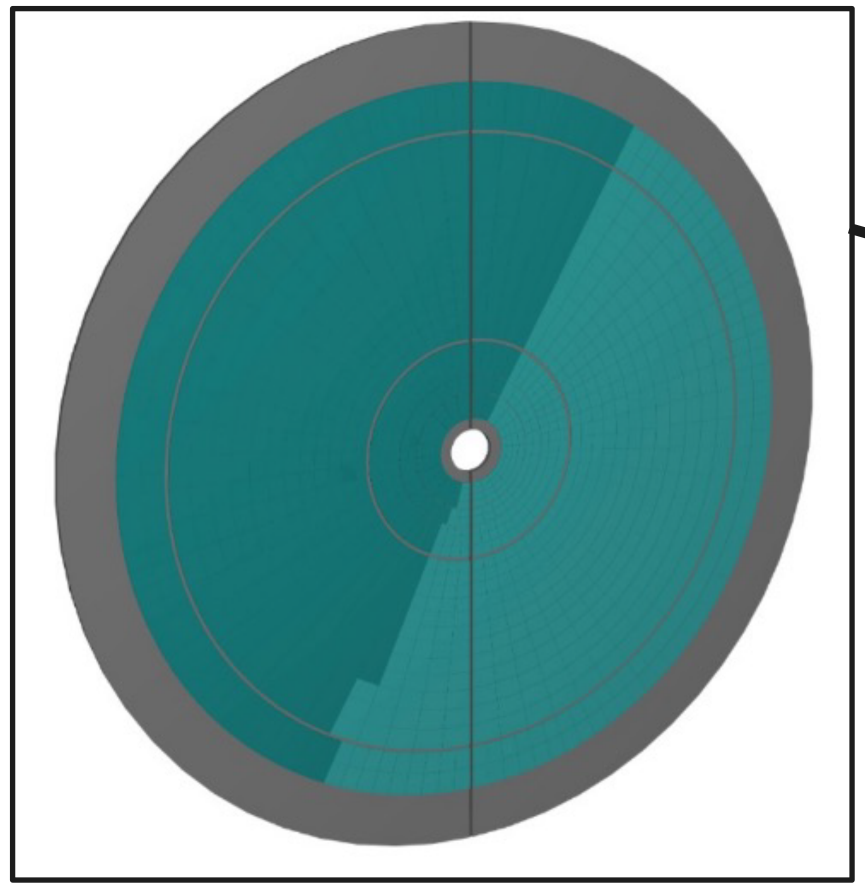
Imaging Barrel Calorimeter

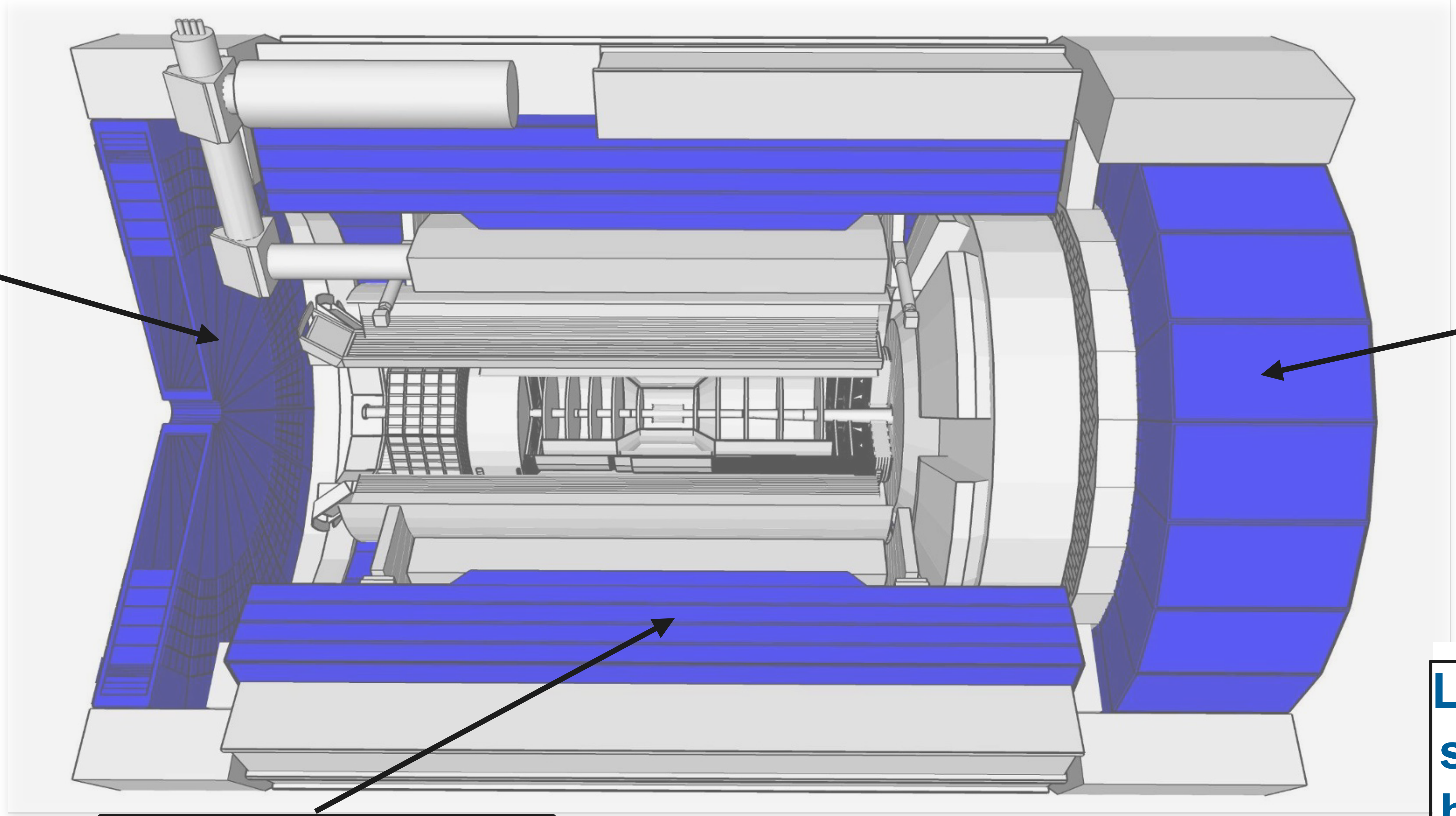
- 4(+2) layers of AstroPix MAPS sensor, 500x500 μm
- Interleaved with scintillating fiber/Pb layers
  - 2-side SiPM readout, 50 μm pixel
- Depth: ~17.1 X0

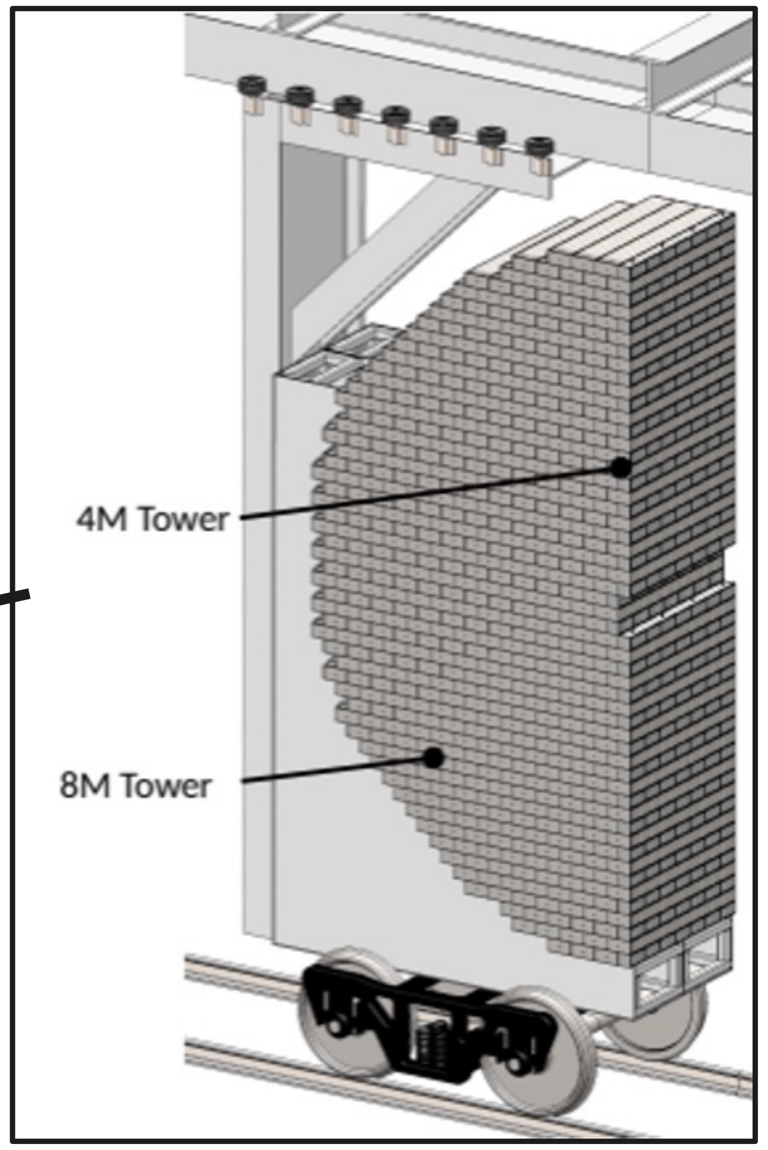
High granularity W/ SciFi EMCal

- Tungsten powder mixed with epoxy + scintillating fibers
- 5 cm x 5 cm x 17 cm blocks
- 4 independent towers per block
- Readout: 4 SiPM per tower, 50 μm pixel
- Depth: ~23 X0

Hadronic Calorimetry







Backwards HCal

- Steel + large scintillator tiles sandwich
- SiPM readout
- Exact design still in progress

Barrel HCAL (sPHENIX re-use)

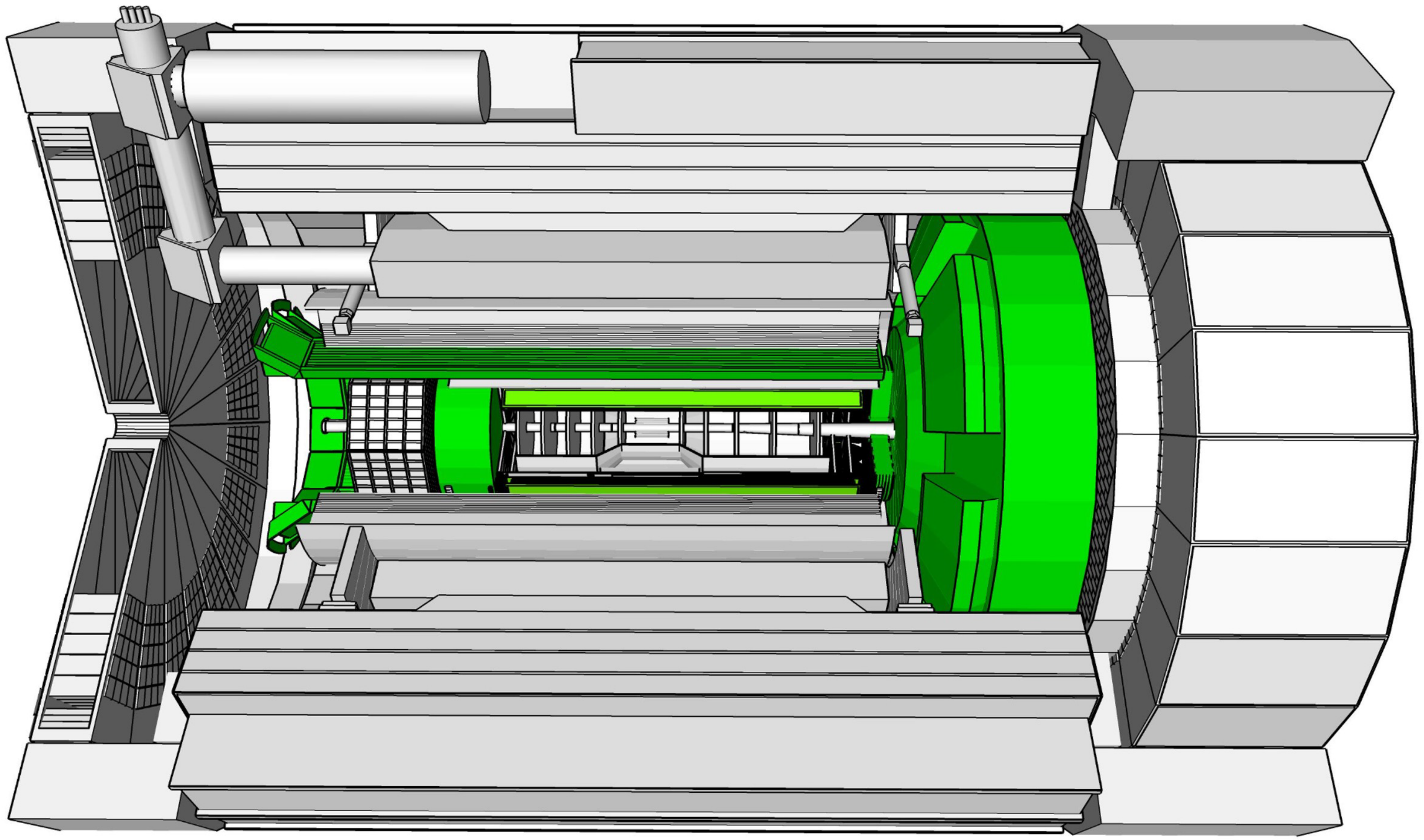
- Tilted Steel/Scintillator plates with SiPM readout

Refurbish for EIC
- Minor radiation damage replace SiPMs
- Upgrade electronics to HGCROC
- Reading out each tile individually

Longitudinally separated HCAL with high-η insert

- Steel + Scintillator SiPM-on- tile
- Highly segmented longitudinally
- 65 layers per tower
  - 565,760 SiPMs
- Stackable for “easy” construction

Particle ID (PID)



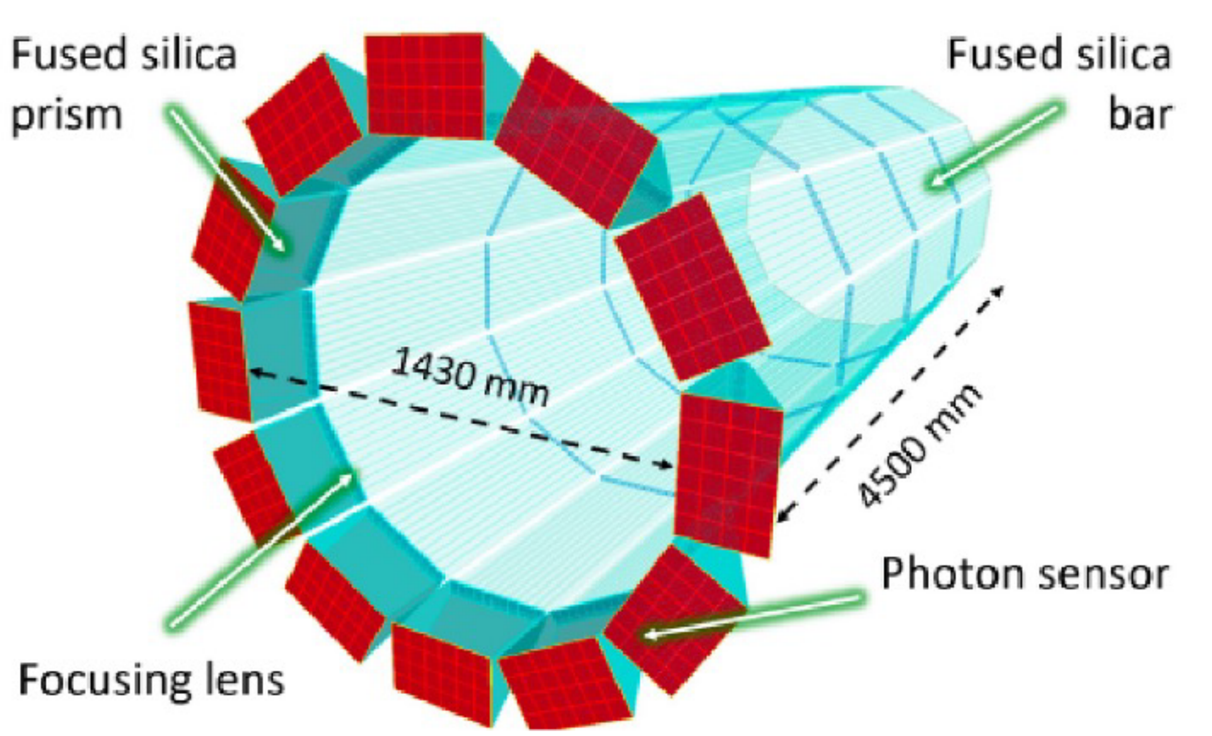
Rapidity	π/K/p and π^0/γ	e/h	Min p_T (E)
-3.5 – -1.0	7 GeV/c	18 GeV/c	100 MeV/c
-1.0 – 1.0	8-10 GeV/c	8 GeV/c	100 MeV/c
1.0 – 3.5	50 GeV/c	20 GeV/c	100 MeV/c

Particle Separation Needs

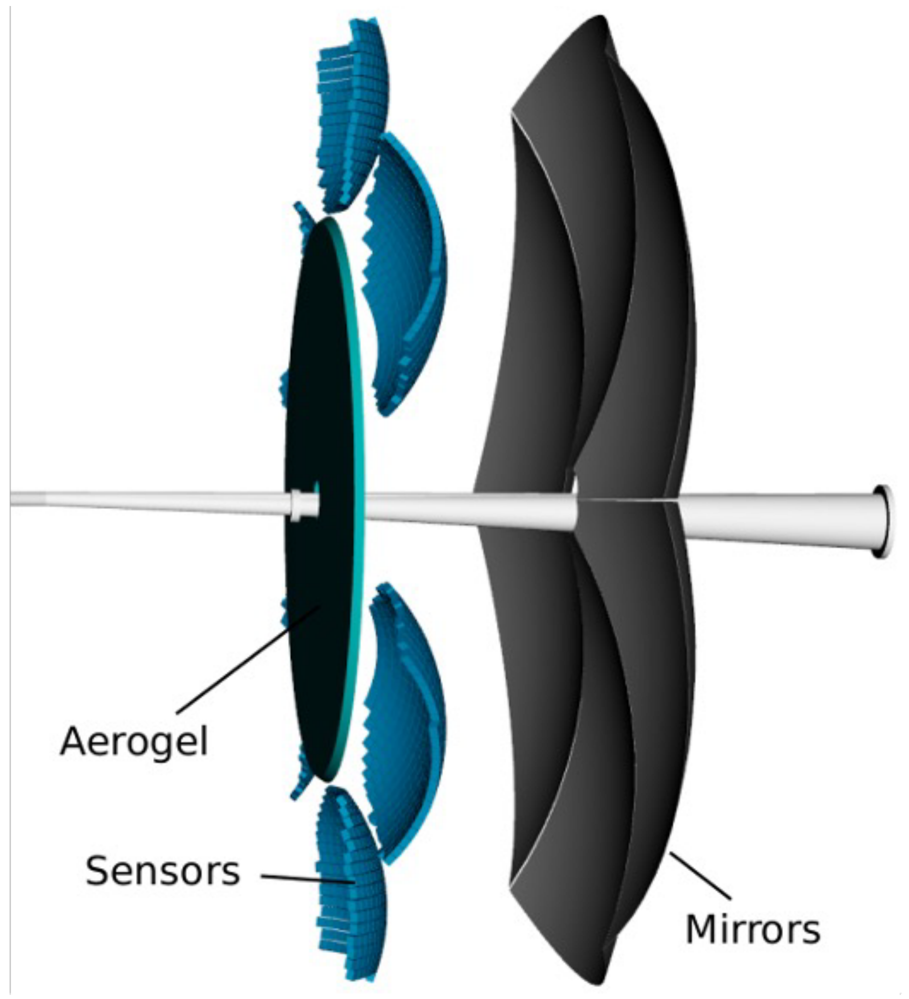
- Electrons from photons ⟶ 4π coverage in tracking
- Electrons from charged hadrons ⟶ mostly provided by calorimetry and tracking, PID detectors at low p
- Charged pions, kaons and protons from each other on track level ⟶ Cherenkov detectors
- Cherenkov detectors, complemented by other technologies at lower momenta: ToF
- Demands on PID are unique to ePIC

Particle ID (PID)

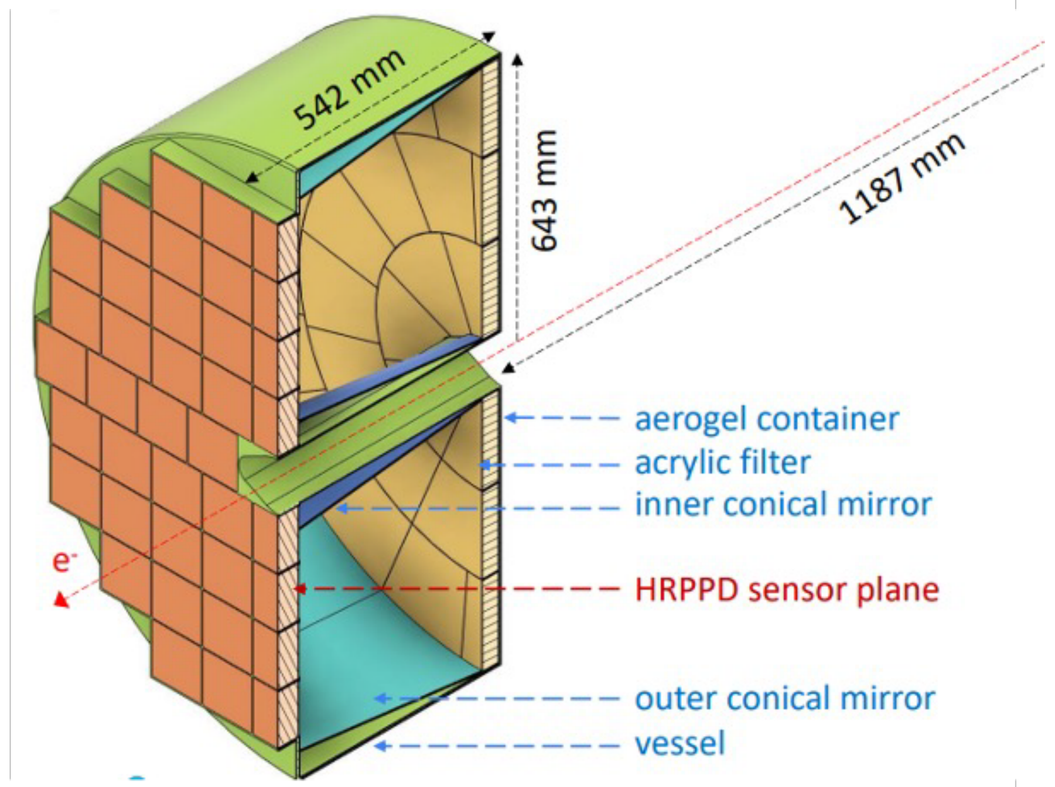
High-Performance DIRC (hpDIRC)

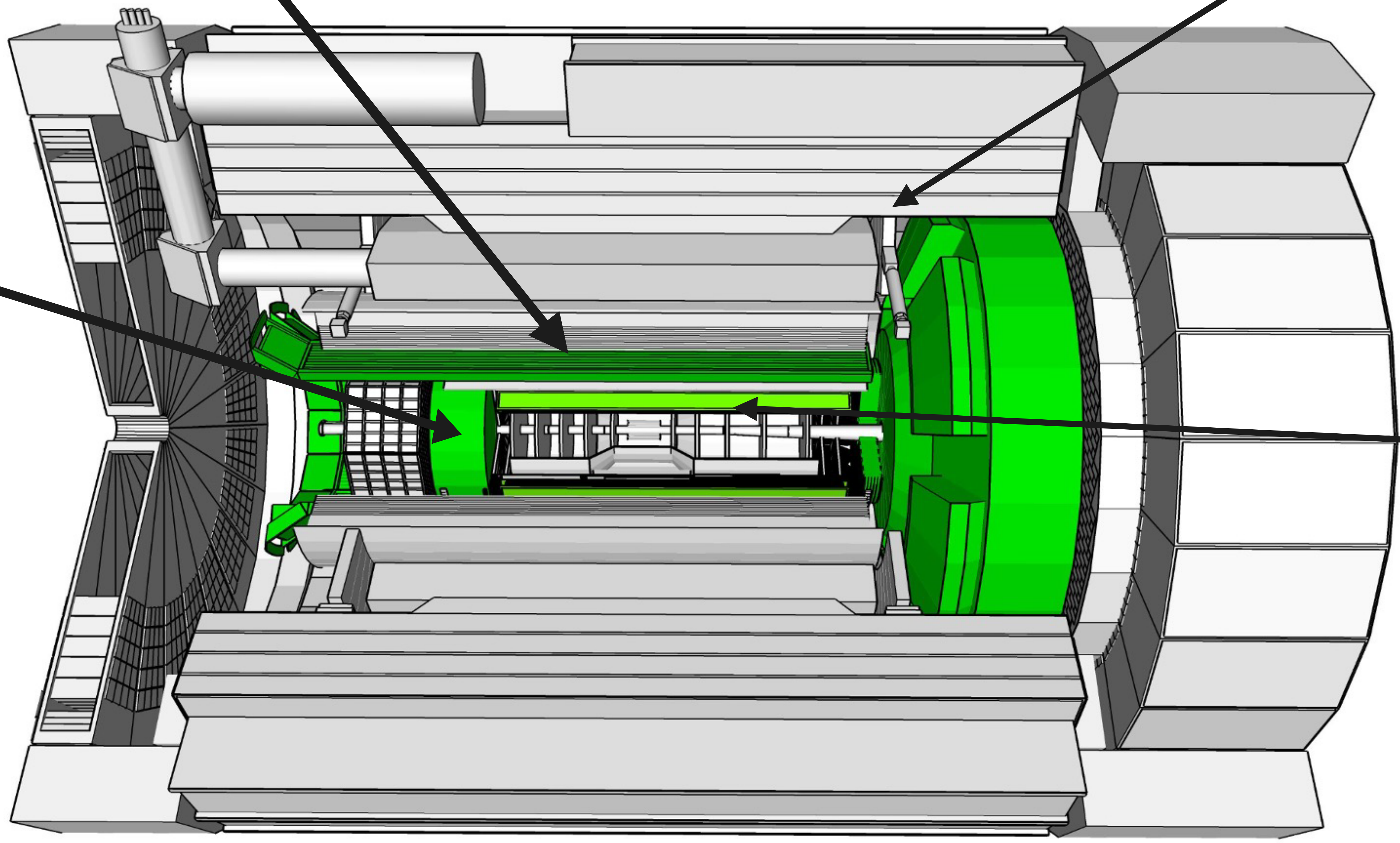


Dual-Radiator RICH (dRICH)

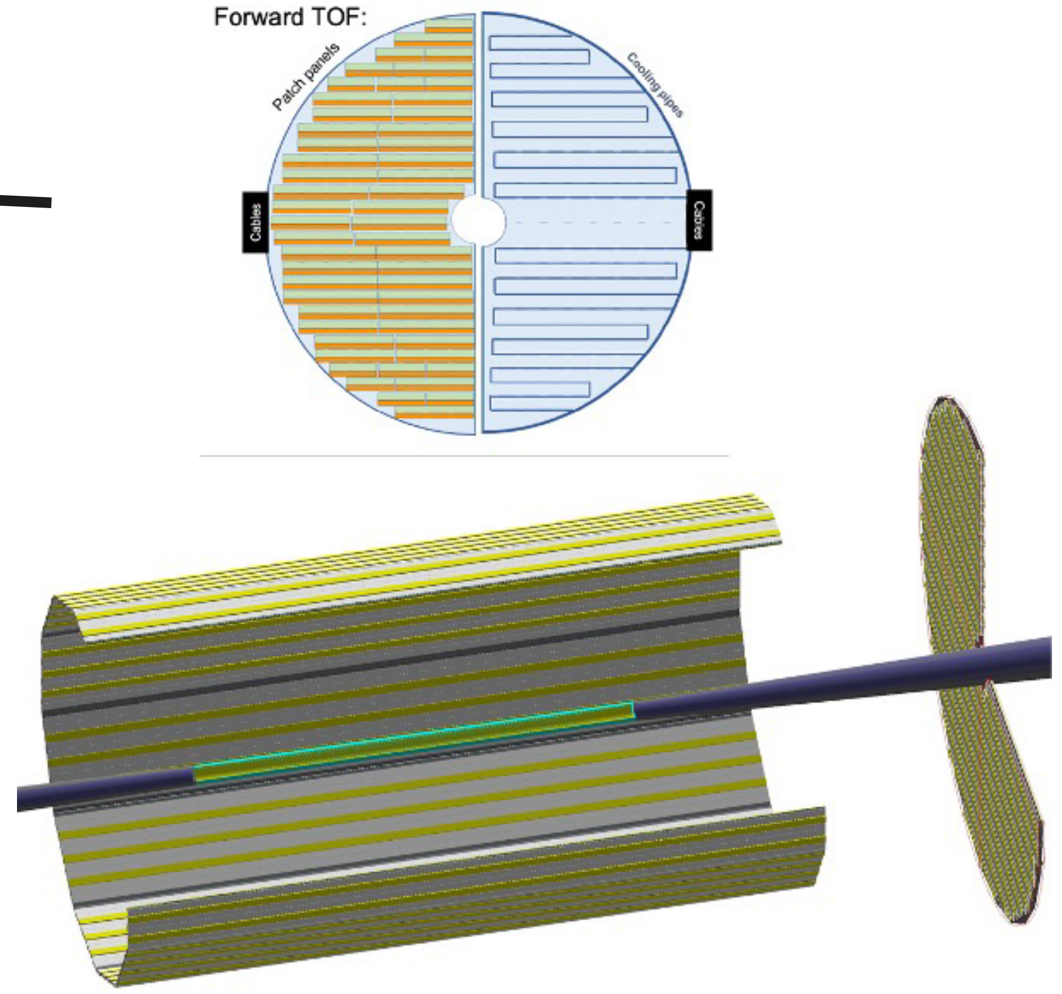


Proximity Focusing RICH (pfRICH)

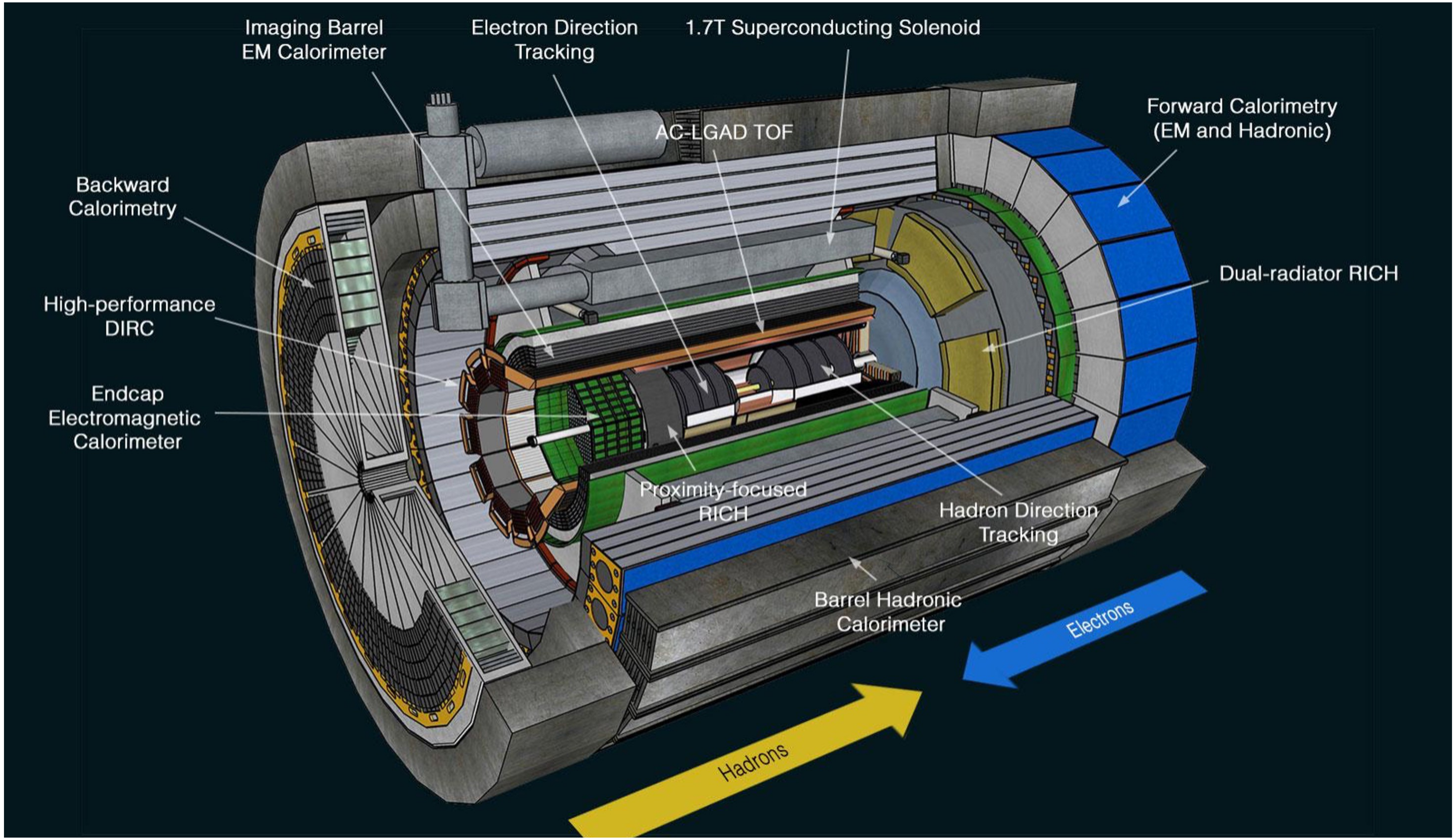




Time-of-Flight (ToF)

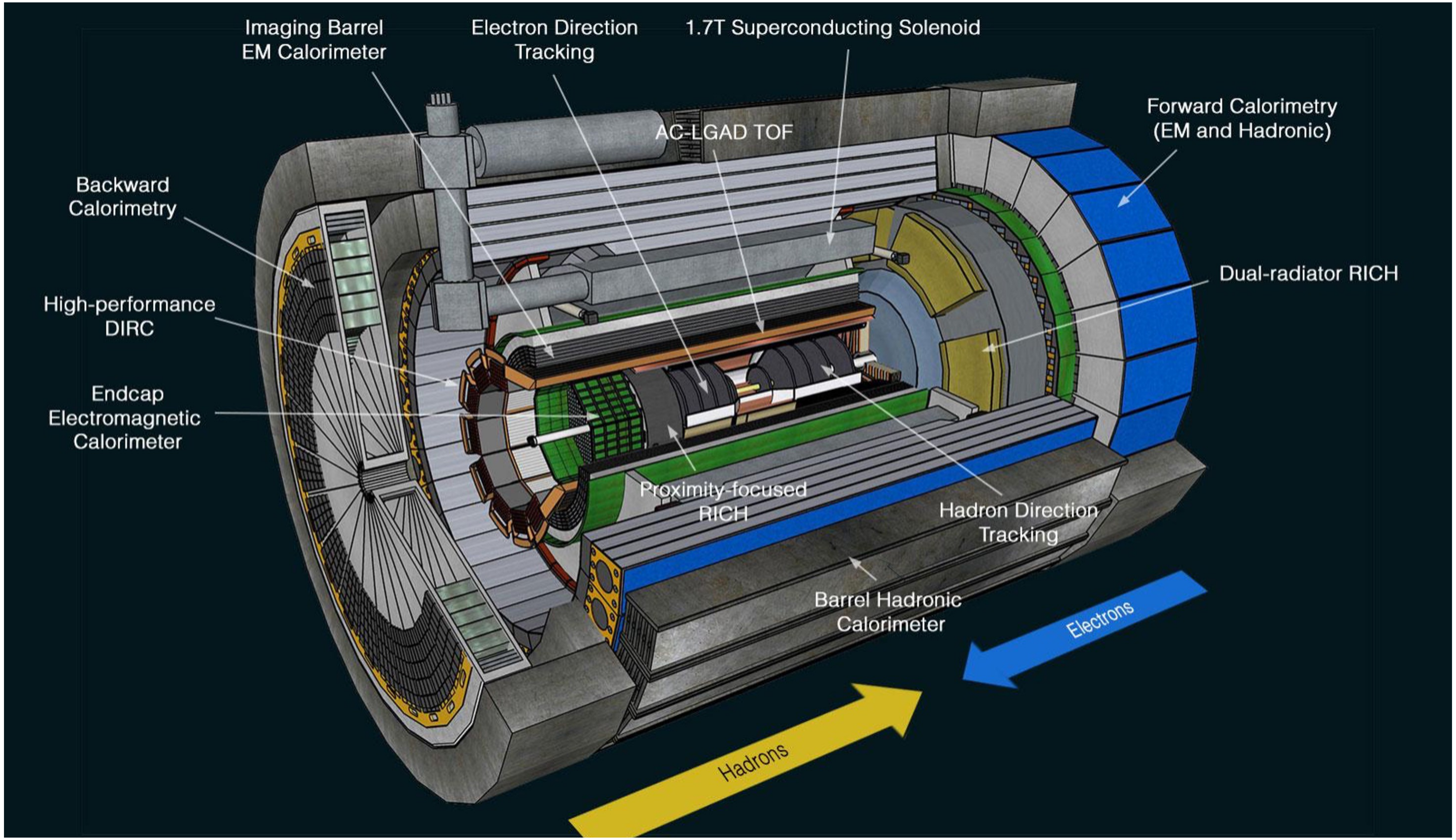


Are we done?



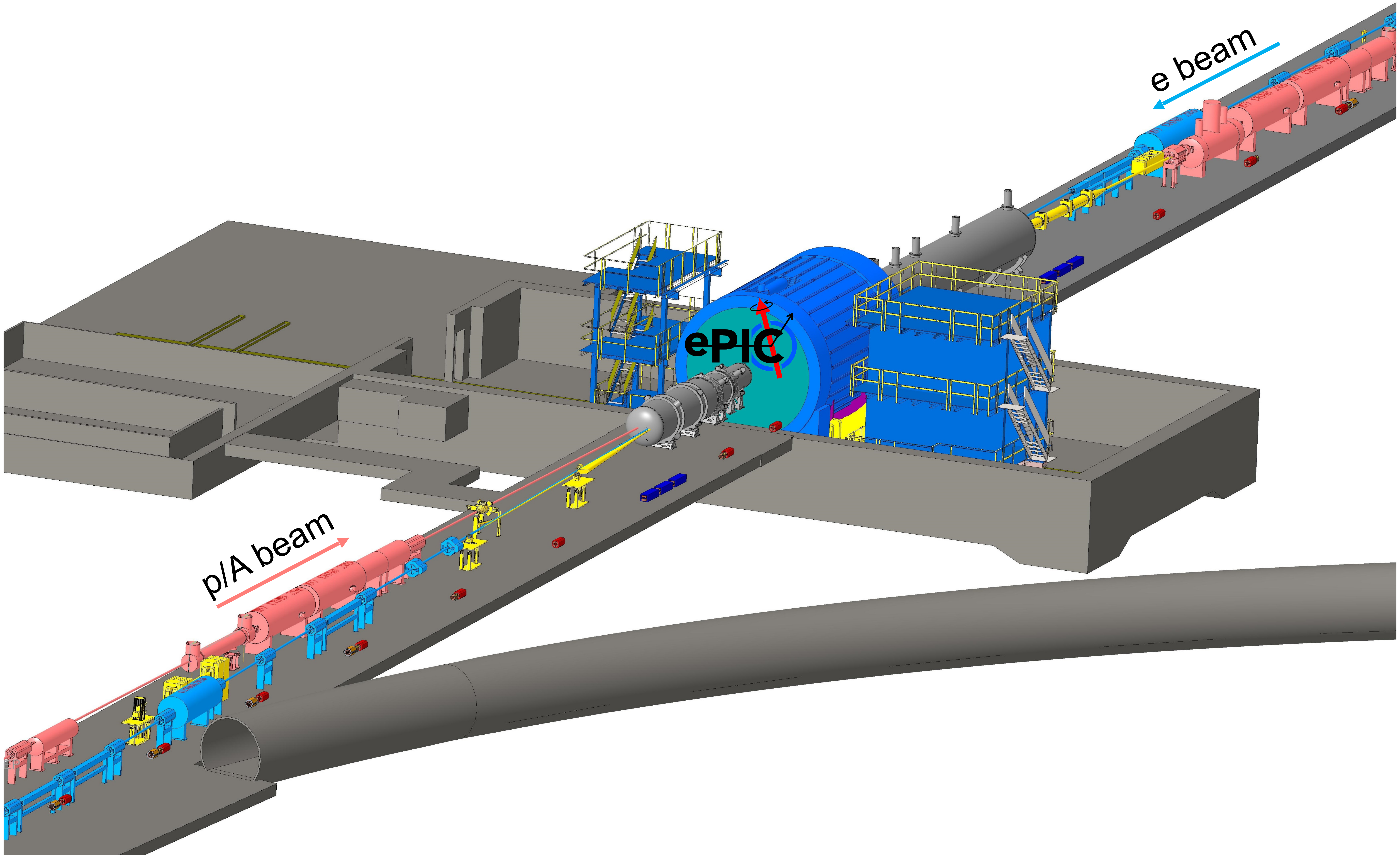
Imaging Barrel
EM Calorimeter
Electron Direction
Tracking
1.7T Superconducting Solenoid
AC-LGAD TOF
Forward Calorimetry
(EM and Hadronic)
Backward
Calorimetry
Dual-radiator RICH
High-performance
DIRC
Endcap
Electromagnetic
Calorimeter
Proximity-focused
RICH
Hadron Direction
Tracking
Barrel Hadronic
Calorimeter
Electrons
Hadrons

Are we done?



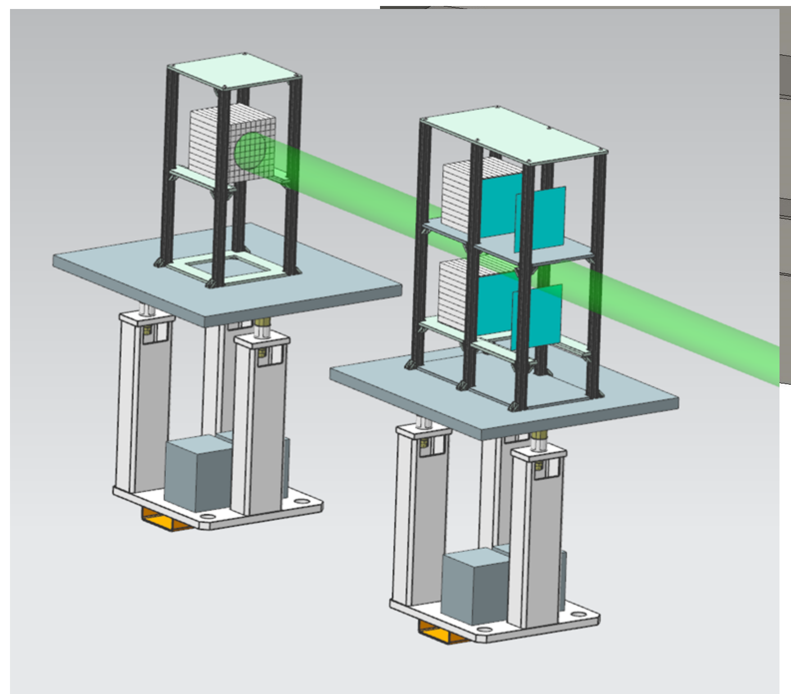
Perfect and necessary, but not sufficient …

ePIC Far-Forward/Far-Backward Detectors

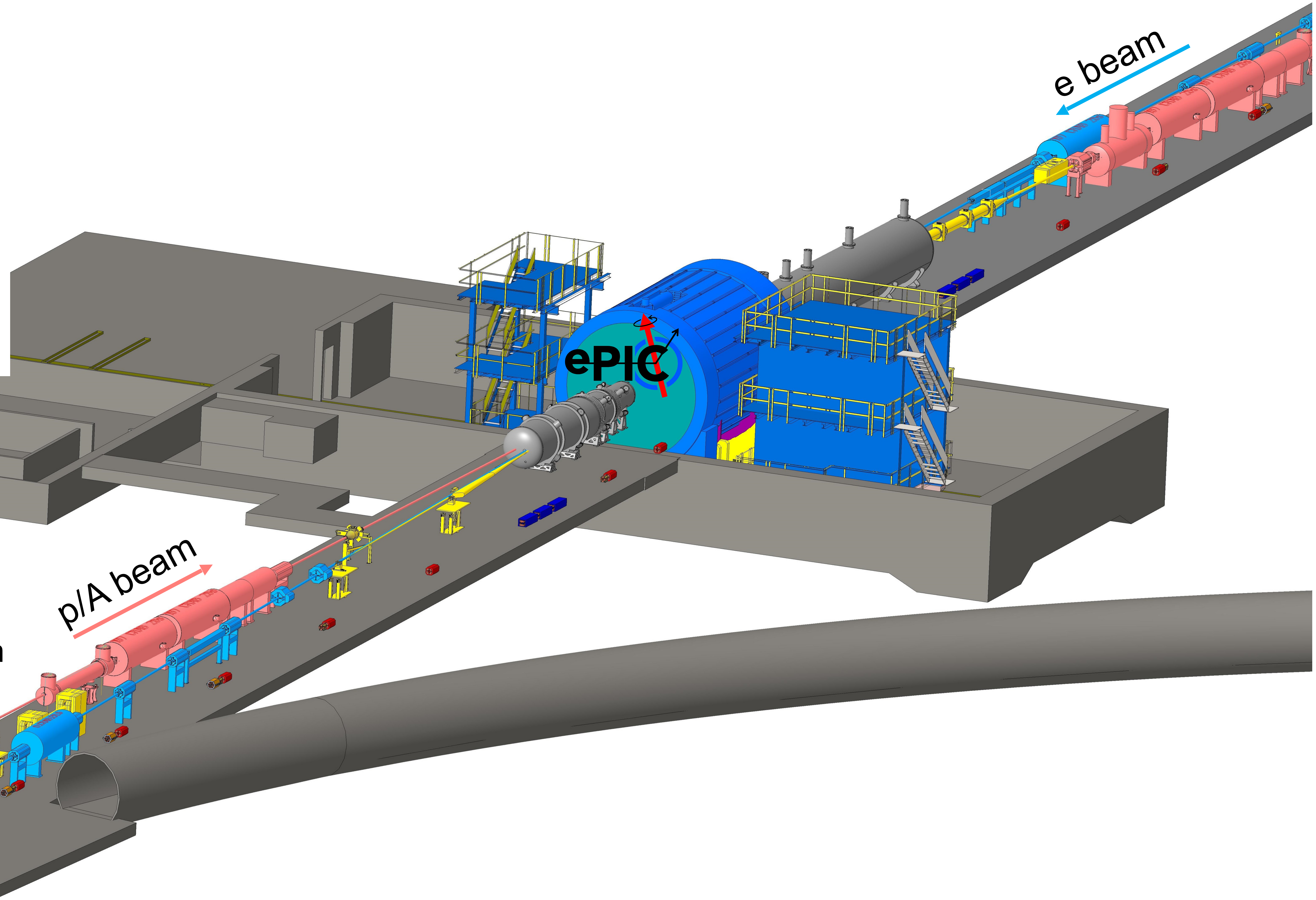


ePIC Far-Forward/Far-Backward Detectors

Main Function:
measure bunch-by-bunch luminosity through Bethe-Heitler process
Technology:
Pair-spectrometer: each with 2 tracking layers of AC-LGAD / FCFD



Luminosity System



ePIC Far-Forward/Far-Backward Detectors

Main Function:
measure bunch-by-bunch luminosity through Bethe-Heitler process
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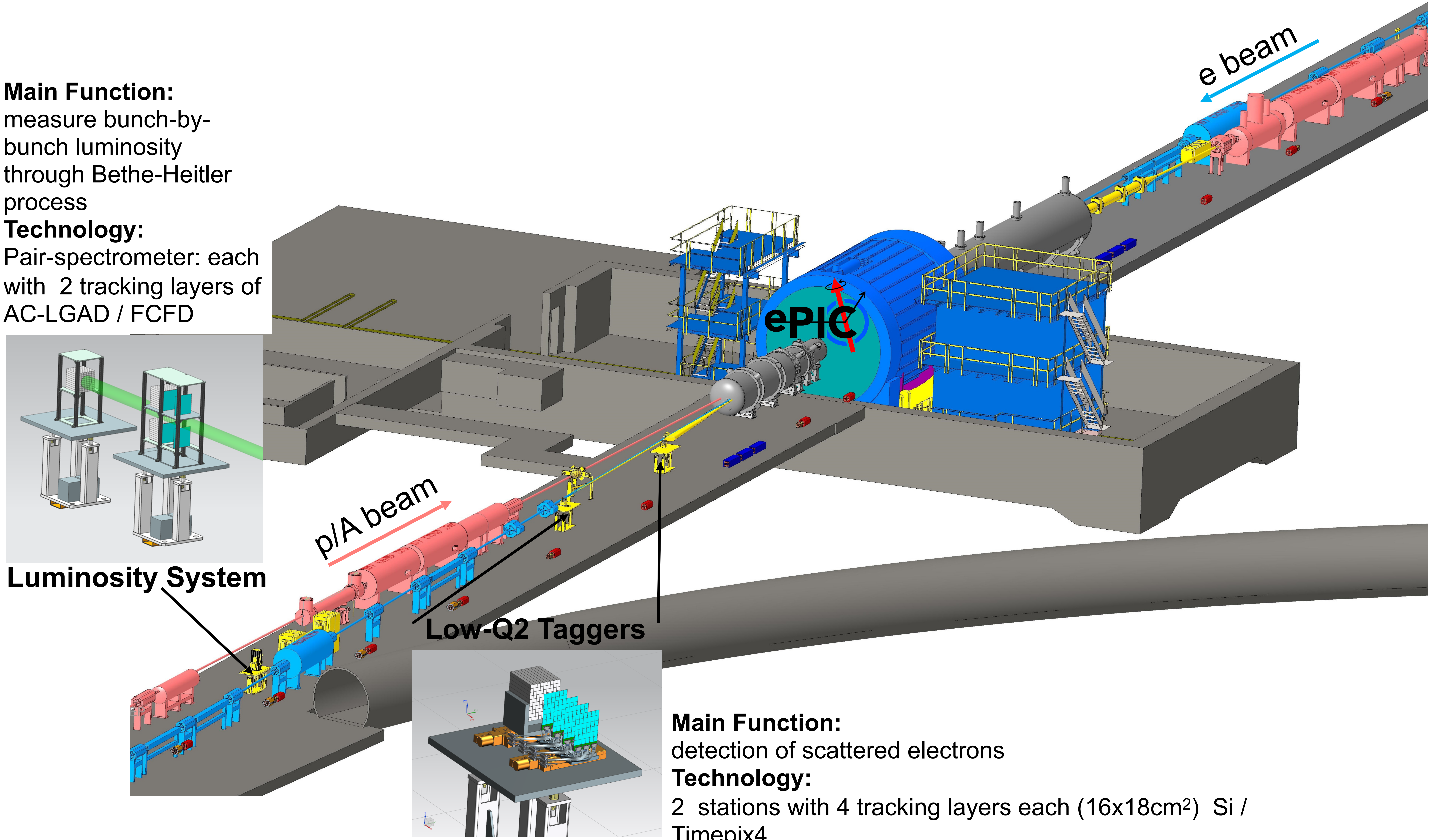
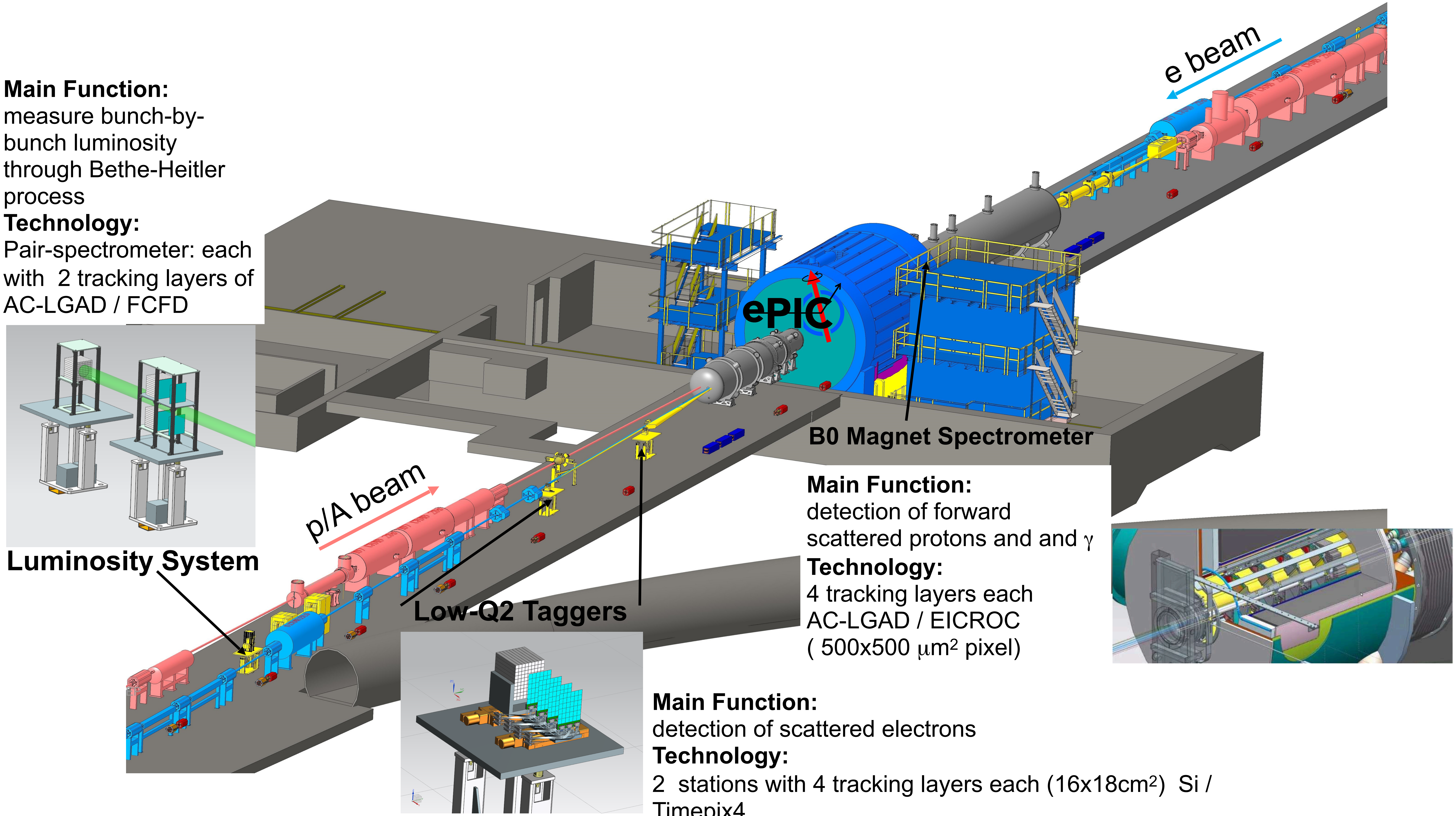


Main Function:
detection of scattered electrons
Technology:
2 stations with 4 tracking layers each (16x18cm^2) Si / Timepix4

ePIC Far-Forward/Far-Backward Detectors



Main Function:
measure bunch-by-bunch luminosity through Bethe-Heitler process
Technology:
Pair-spectrometer: each with 2 tracking layers of AC-LGAD / FCFD

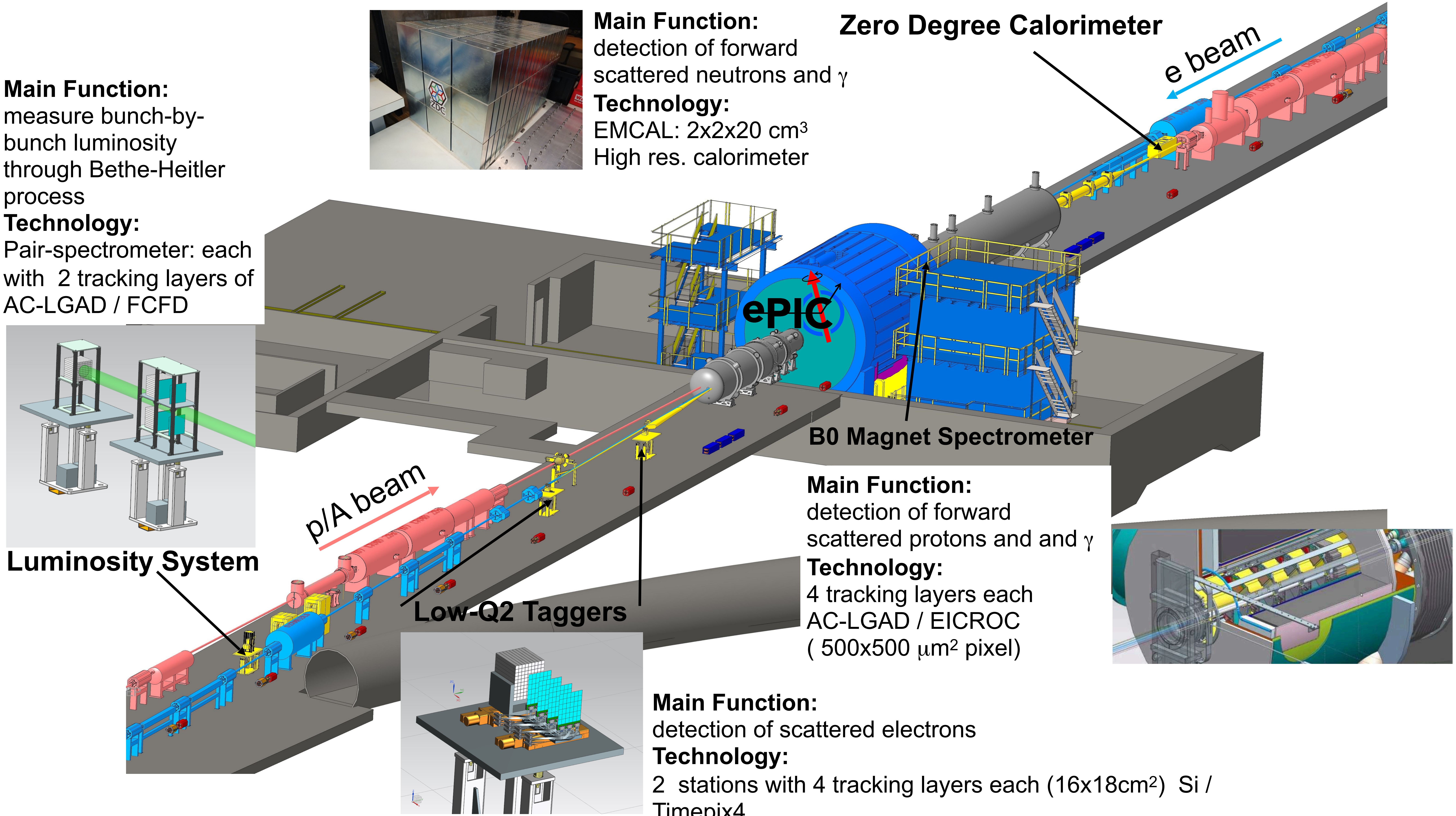
Main Function:
detection of forward scattered protons and and γ
Technology:
4 tracking layers each AC-LGAD / EICROC (500x500 μm^2 pixel)

Main Function:
detection of scattered electrons
Technology:
2 stations with 4 tracking layers each (16x18cm^2) Si / Timepix4

ePIC Far-Forward/Far-Backward Detectors

Main Function:
detection of forward scattered neutrons and γ
Technology:
EMCAL: 2x2x20 cm^3
High res. calorimeter

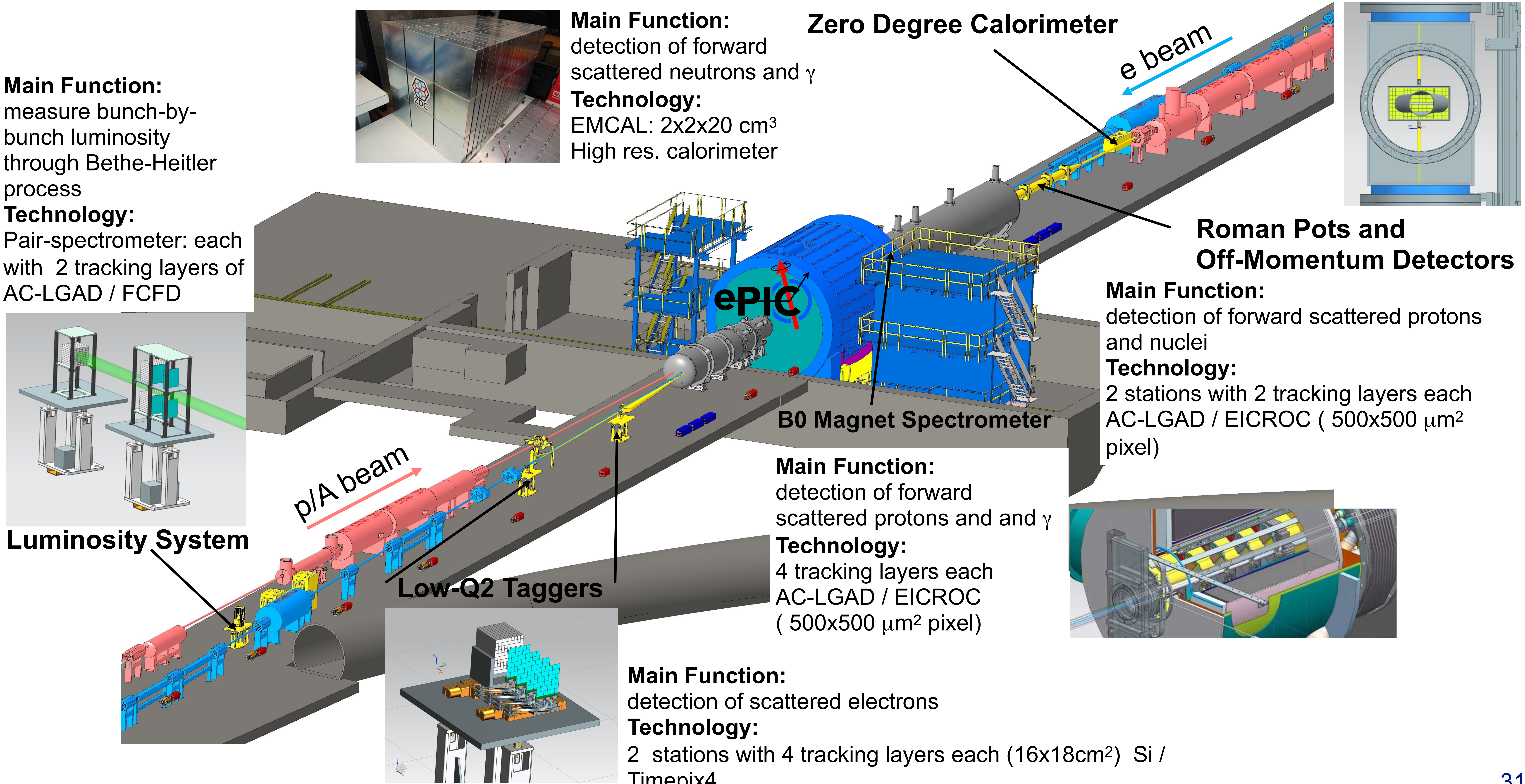
Main Function:
measure bunch-by-bunch luminosity through Bethe-Heitler process
Technology:
Pair-spectrometer: each with 2 tracking layers of AC-LGAD / FCFD



Main Function:
detection of forward scattered protons and and γ
Technology:
4 tracking layers each AC-LGAD / EICROC
(500x500 μm^2 pixel)

Main Function:
detection of scattered electrons
Technology:
2 stations with 4 tracking layers each (16x18cm^2) Si / Timepix4

ePIC Far-Forward/Far-Backward Detectors



Main Function:
detection of forward
scattered neutrons and γ
Technology:
EMCAL: 2x2x20 cm^3
High res. calorimeter

Zero Degree Calorimeter

Main Function:
measure bunch-by-bunch luminosity through Bethe-Heitler process
Technology:
Pair-spectrometer: each with 2 tracking layers of AC-LGAD / FCFD

Luminosity System

Roman Pots and Off-Momentum Detectors

Main Function:
detection of forward scattered protons and nuclei
Technology:
2 stations with 2 tracking layers each
AC-LGAD / EICROC (500x500 μm^2 pixel)

B0 Magnet Spectrometer

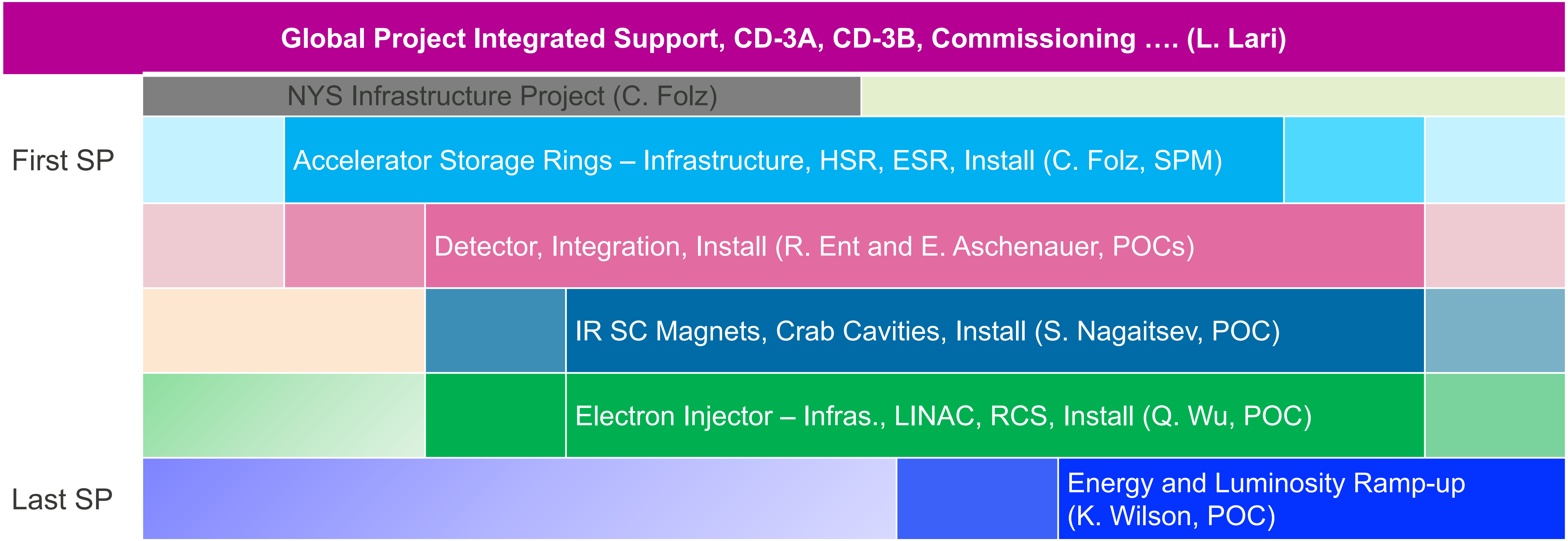
Main Function:
detection of forward
scattered protons and and γ
Technology:
4 tracking layers each
AC-LGAD / EICROC
(500x500 μm^2 pixel)

Low-Q2 Taggers

Main Function:
detection of scattered electrons
Technology:
2 stations with 4 tracking layers each (16x18cm^2) Si / Timepix4

Project Delivery Strategy

Deliver the full EIC facility scope using subprojects and the phased implementation of the EIC project scope. The strategy enables the start of the EIC construction when the first subproject is ready and the start of the EIC science program during collider commissioning, concurrent with the final subproject equipment installation. Line-Item Construction Project includes the full scope required to meet EIC facility performance requirements.

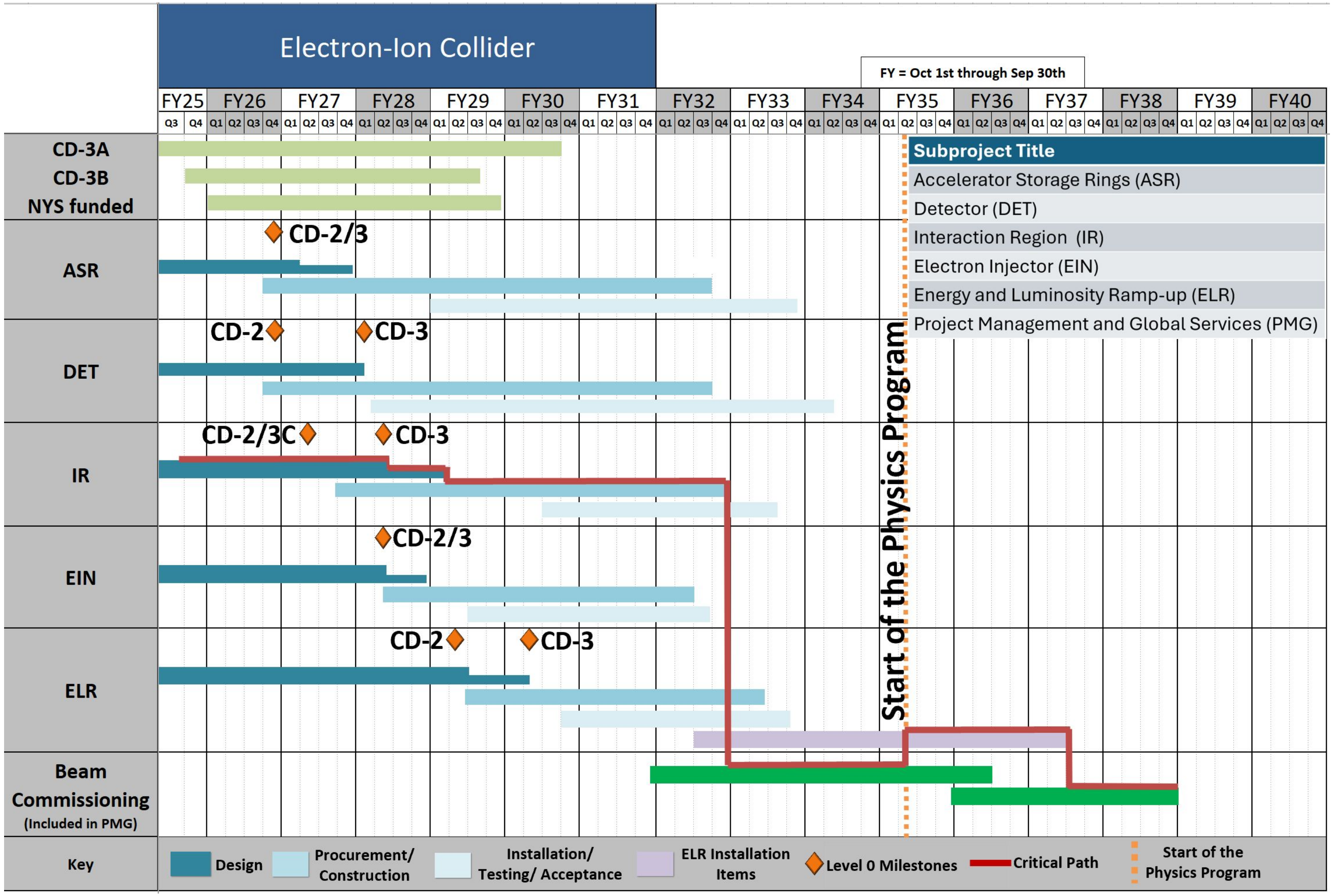


EIC Construction Project

CD-3x & NYS Scope	**CD-3A, Long Lead Procurement**	3A: ~40% scope in ASR; ~6% IR; 54% in DET
	CD-3B, Long Lead Procurement	3B: ~75% scope in ASR; 25% DET
	NYS Civil Construction Project	Site Preparation work and construction of Service Buildings and support systems related to the ASR subproject.
Initial Science Program Scope	**Accelerator Storage Rings (ASR)**	Hadron Storage Ring Modifications, Electron Storage Ring (10 GeV) and related infrastructure.
	Detector (DET)	ePIC Detector including SC magnet, detector systems, and integration and installation.
	Interaction Region (IR)	Interaction Region including the SC magnets and 197 MHz crab cavities.
	Electron Injectors (EIN)	Electron Injectors (LINAC, BAR & RCS @ 10 GeV) and related infrastructure.
Full Scope	**Energy and Luminosity Ramp-up (ELR)**	Accelerator scope required to increase Energy (18GeV e-, RCS SRF & Cryo, 394 MHz crab cavities, 41 GeV by-pass, ESR and HSR RF amplifiers, etc.)
PM & CX	**Project Management and Global Services (PMG)**	Project and Technical integration support to entire project and integration and beam commissioning.

In-Kind Contribution Plan: 5% or more of the accelerator scope and 30% of the detector scope. New accelerator opportunities.

EIC Reference Schedule - Subprojects



Detector:

CD-2-IPR Review: June 2026

CD-2 ESAAB: Q42026

CD-3-IPR Review: Q4FY27

CD-3 ESAAB: Q1FY28

Oak Ridge National Laboratory

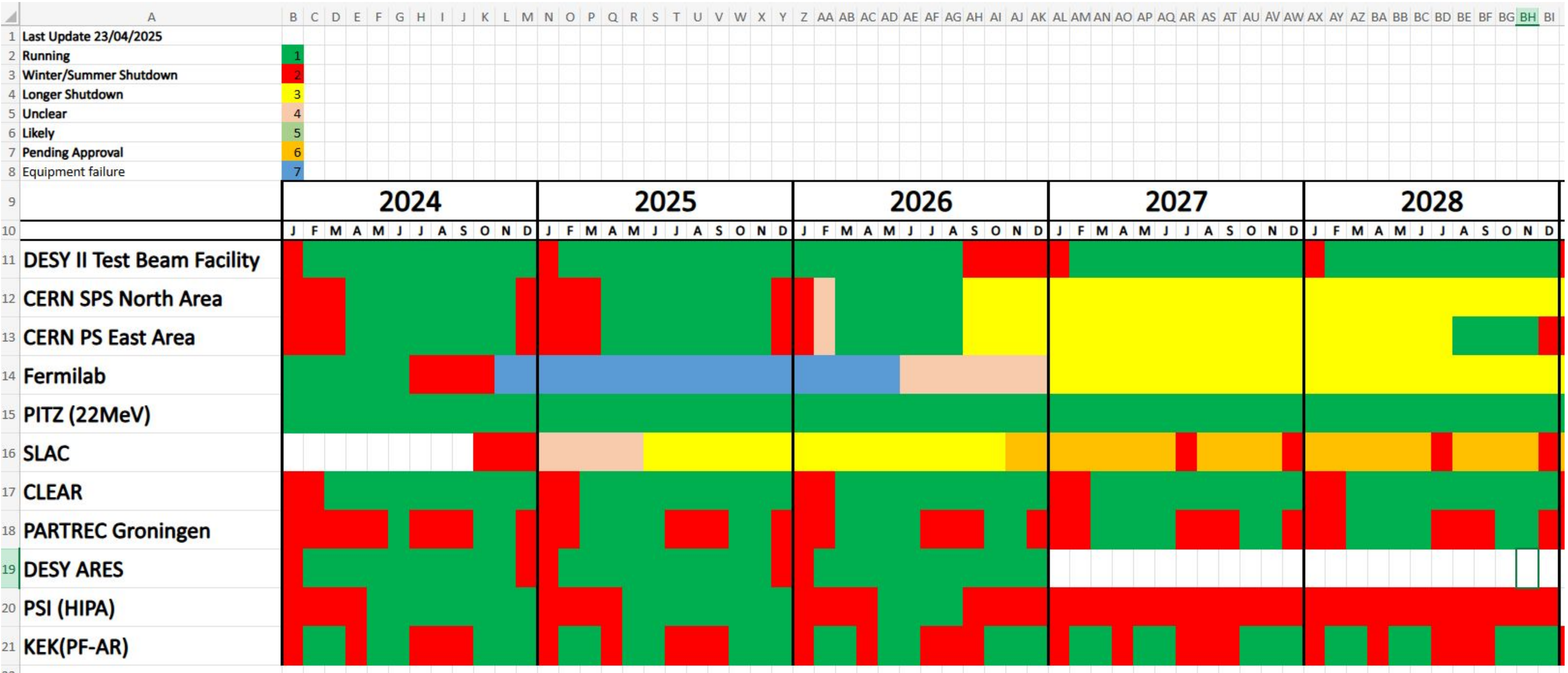
ePIC Beam Time Requirement Projections

- ePIC consists of (at least) 15 independent Detector Subsystem Collaborations (DSCs)
  - Small overlap in technologies and designs - individual prototype beam test progression:
    - at least: initial prototype, engineering prototype, production validation - often more
- Estimated beam time requirements (input for European Particle Physics Strategy Update EPPSU):
  - 2026: 31 weeks
  - 2027: 27 weeks
  - 2028: 28 weeks
  - … this is a small but significant fraction of available beam facilities in the world.
  - already includes beam time sharing and parasitic operation configurations.

Beam Facilities Availability 2024+

From CERN Database:

- https://test-beam-facilities.web.cern.ch/
- https://cernbox.cern.ch/s/wRuLiYuAwqgS5xx



The Great Hadron Drought of 2026+

- We are entering a true drought in hadron beam facilities starting 2026
- Even if all facilities come back on time, they will be seriously overbooked
- A (hadron) beam test facility at BNL would be a significant reduction of risk for ePIC
  - Ease of access, low transportation time, cost and risk
  - Continuous verification of production samples
  - Relatively ease of multi-detector setup

The Ideal Beam Test Facility - Beams

- Mixed hadrons: 1GeV up to full AGS storage energy
  - Interesting for PID, calorimeters
  - Tracking detectors prefer highest momentum to minimize multiple scattering
- Electron enriched absorber configuration
- Muon configuration (beam stop)
  - Wide area muon beams are very useful for calorimeter calibration + parasitic running
- Variable beam focusing system
  - Including collimators for rate adjustment
- He/Vacuum tubes for precision low energy beams?
- Support from beamline experts

The Ideal Beam Test Facility - Area

- Crane + operators, solid ground
- Moving stages of various sizes/weight limits
  - Remote operation from counting house
- Gas system integration: gas lines in/out of beam area, N + CDA available?
- Low impedance ground bars **everywhere**

- Counting house with network connectivity and signal/power feedthroughs to beam area
  - Full remote access

- Staging area in same hall
  - Fast turnover between beam times
  - Can receive parasitic muon beams? “Sequential” beam areas with beam stop?

The Ideal Beam Test Facility - Equipment

- Trigger scintillators
- Differential Cherenkov system for clean hadron selection?
- Dedicated pixel telescope?
  - Several systems available at FTBF, CERN beam tests
- Dedicated timing sensor test bench?
  - FTBF has “permanent” setup with timing reference MCP-PMT and 8+ very fast oscilloscope channels
- Easy access to beam + environmental conditions logging
- Cabinets full of (tested!) NIM modules :-)
  - Or just a few CAEN N1081-style programmable NIM logic modules?
- Access to standard electronics (a la CERN EPOOL)
  - Access to technician for simple soldering, machine shop work…

The Ideal Beam Test Facility - A Full Slice of ePIC

- ATLAS and CMS famously have (had?) full slices of their detectors in combined beam tests at SPS
  - Not sure how successful that was, but planning beam area to fit cannot hurt…