Design and Performance Overview of the ePIC Detector at the EIC

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Outline

- Electron-Ion Collider
- Detector Requirements
- ePIC Detector Design
- Various Subsystems
- Summary

EIC NAS Science Pillars

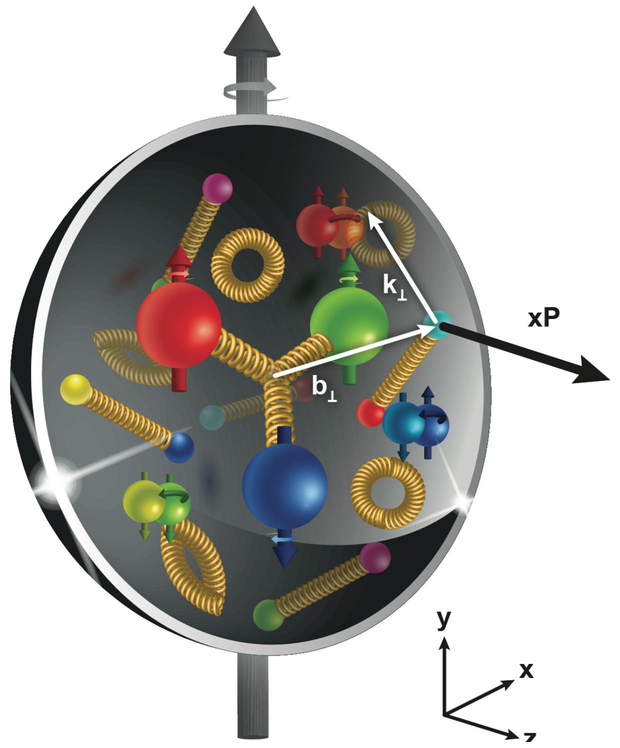
The EIC will unravel the different contribution from the quarks, gluons and orbital angular momentum

SPIN is one of the fundamental properties of matter.
All elementary particles, but the Higgs carry spin.
Spin cannot be explained by a static picture of the proton
It is the interplay between the intrinsic properties and interactions of quarks and gluons

Does the mass of visible matter emerge from quark-gluon interactions?

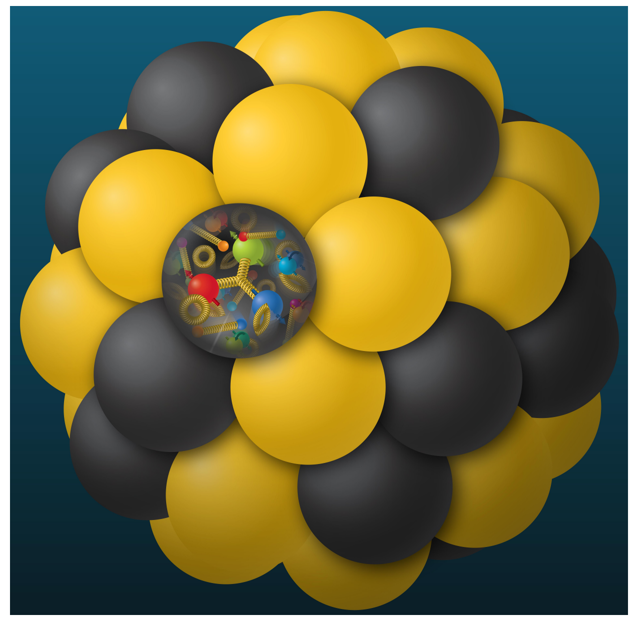
Atom: Binding/Mass = 0.00000001
Nucleus: Binding/Mass = 0.01
Proton: Binding/Mass = 100

For the proton the EIC will determine an important term contributing to the proton mass, the so-called “QCD trace anomaly



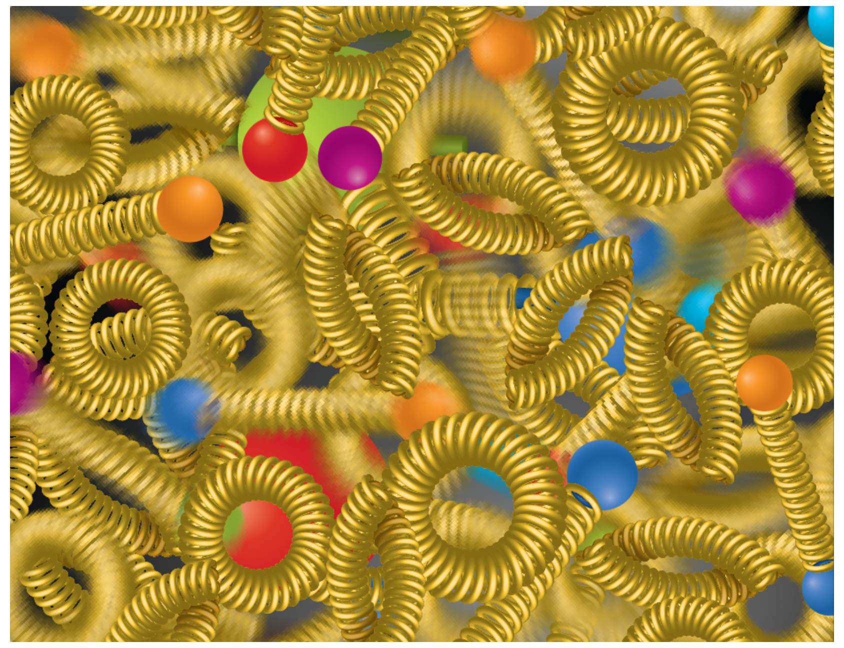
How can we understand their dynamical origin in QCD?

What is the relation to Confinement
How are the quarks and gluon distributed in space and momentum inside the nucleon & nuclei?
How do the nucleon properties emerge from them and their interactions?



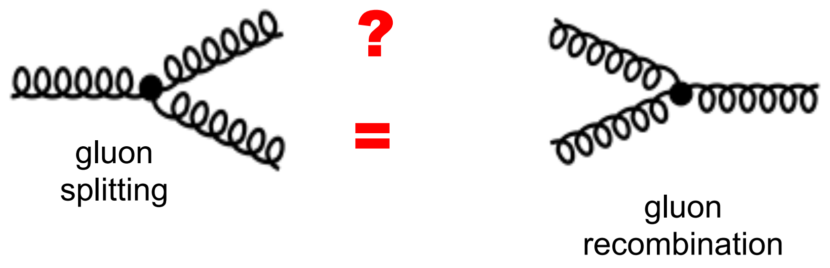
How do the confined hadronic states emerge from quarks and gluons?

Is the structure of a free and bound nucleon the same?
How do quarks and gluons, interact with a nuclear medium?
How do the quark-gluon interactions create nuclear binding?



What happens to the gluon density in nuclei? Does it saturate at high energy?

How many gluons can fit in a proton?
How does a dense nuclear environment affect the quarks and gluons, their correlations, and their interactions?

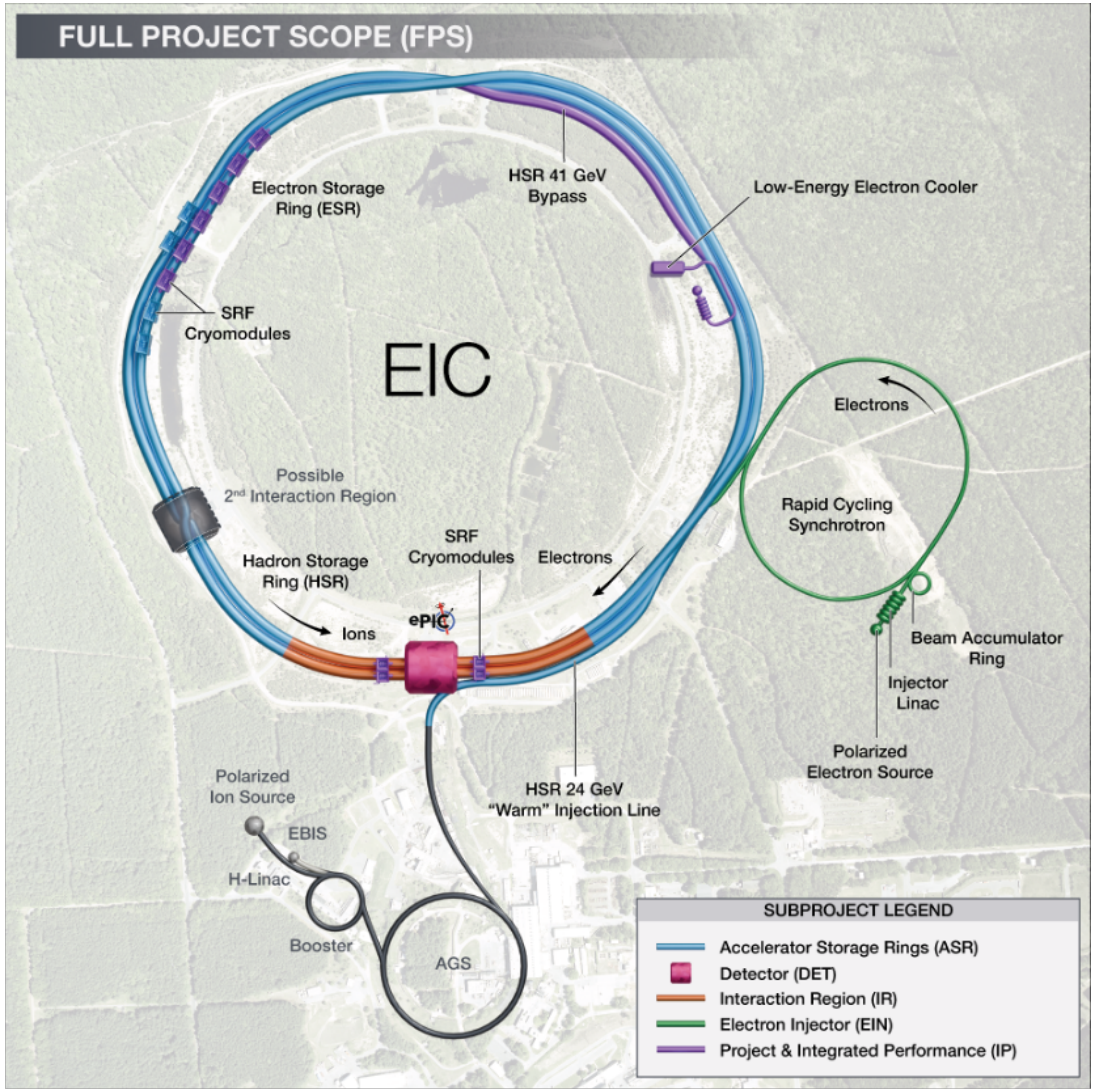


EIC: Project Overview and Capabilities

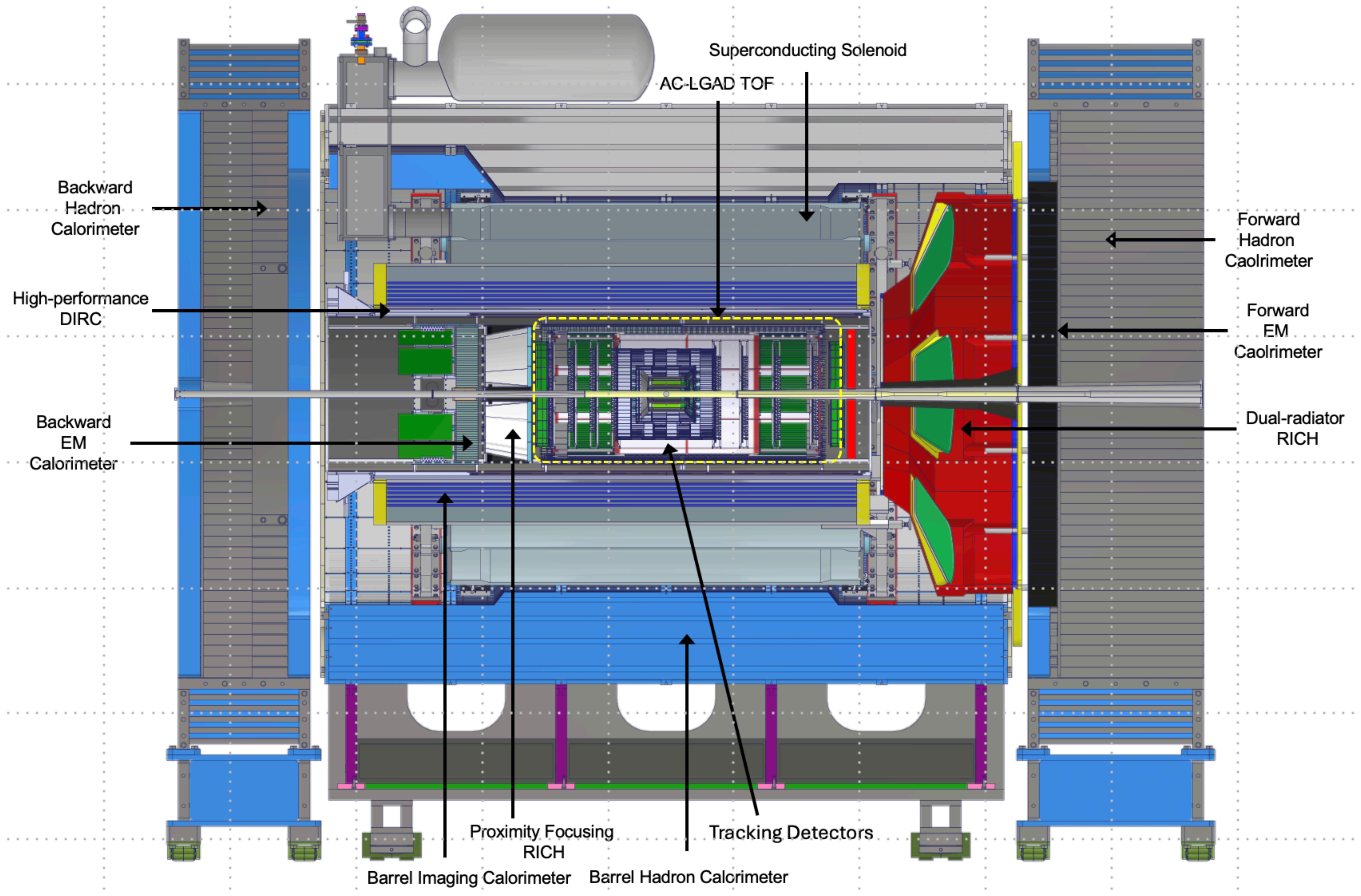
- A single integrated line-item construction project executed as subprojects with well-defined deliverables, interfaces, and Key Performance Parameters.
  - Accelerator Storage Rings (ASR)
  - Detector (DET)
  - Interaction Region (IR)
  - Electron Injector (EIN)
  - Project and Integrated Performance (IP) (includes Energy & Luminosity Ramp-up (ELR))
- RHIC operations concluded in late January 2026, enabling the start of Electron-Ion Collider construction. Anticipate CD-2/3 for ASR and CD-2 for DET in 2026.
- EIC initial science begins in 2035

EIC Key Performance Goals:

- High luminosity: $L = 10^{33}\text{-}10^{34}\,\mathrm{cm^{-2}\,s^{-1}}$
- Highly polarized beams : $P \sim 70\,\%$
- Broad center-of-mass energy: $\sqrt{s} = 29\text{ - }141\,\mathrm{GeV}$
- Wide range of ion species, from proton to uranium



ePIC: EIC General Purpose Detector



26 subsystems over ± 40 m

to measure particle momenta, energy and particle type

- ❖ 3 electromagnetic calorimeters
- ❖ 3 hadronic calorimeters
- ❖ Silicon and Micro-pattern gas detectors
- ❖ 3 RICH detectors + time-of-flight
- ❖ 7 Auxiliary detectors (Si + HCal + ECals)
- ❖ electron and hadron polarimetry
- ❖ Integration, Installation and Infrastructure
- ❖ Non-Beam Commissioning

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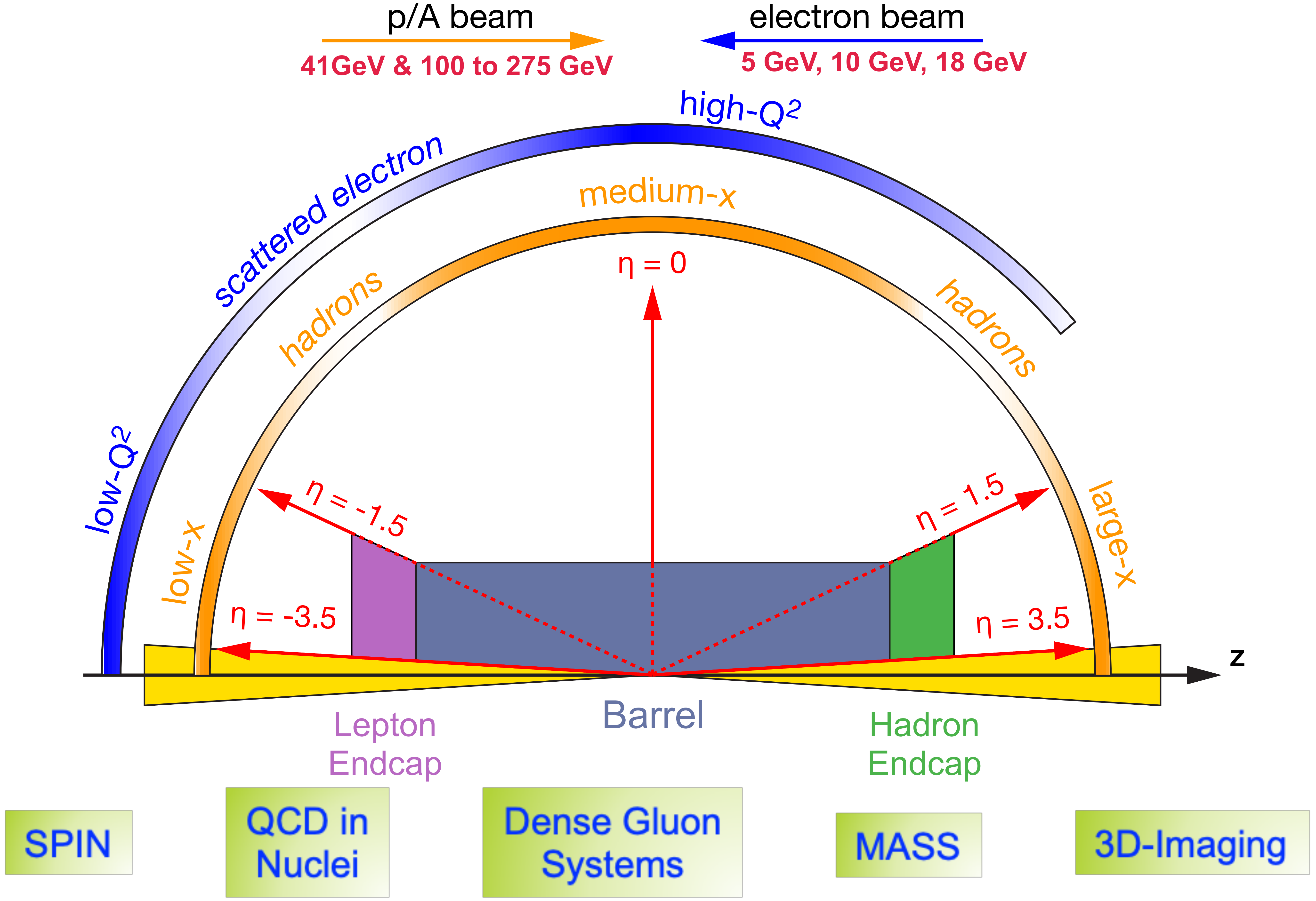
High scientific flexibility

- ◉ Fully streaming readout electronics and data acquisition
- ◉ Integration AI/ML capabilities from the start

ePIC Kinematics

- Asymmetric beam energies
- Detection of scattered electron
- Detection of all produced particles especially the ones scattered under very small angles into the detectors along the beam line
- Asymmetric detector with an electron and a hadron end cap



ePIC Requirements

Vertex detector → Identify primary and secondary vertices
- Low material budget: ~0.05% X/X0 per layer
- High spatial resolution: ~10 μm pitch CMOS Monolithic Active Pixel Sensors (MAPS)

Central tracker → Measure charged particle momenta
- Silicon MAPS tracking layers combined with large-area micro-pattern gas detectors
- MPGD technologies: μRWELL and Micromegas

Electron and hadron endcap tracker → Measure charged
- Particle momenta
- Silicon MAPS disks combined with micro-pattern gas detectors

Particle Identification → pion, kaon, proton separation
- Wide momentum range RICH detectors (modular and dual-radiator RICH), DIRC, and Time-of-Flight systems High-resolution timing detectors (HRPPDs, LGAD): ~20-30 ps

EM calorimeter → Measure photons (energy and angle), identify electrons
- $PbWO_4$ crystals (electron-going/backward region), W/ScFi SPACAL (hadron-going/forward region)
- Barrel: Pb/ScFi sampling calorimeter with imaging section or scintillating glass option

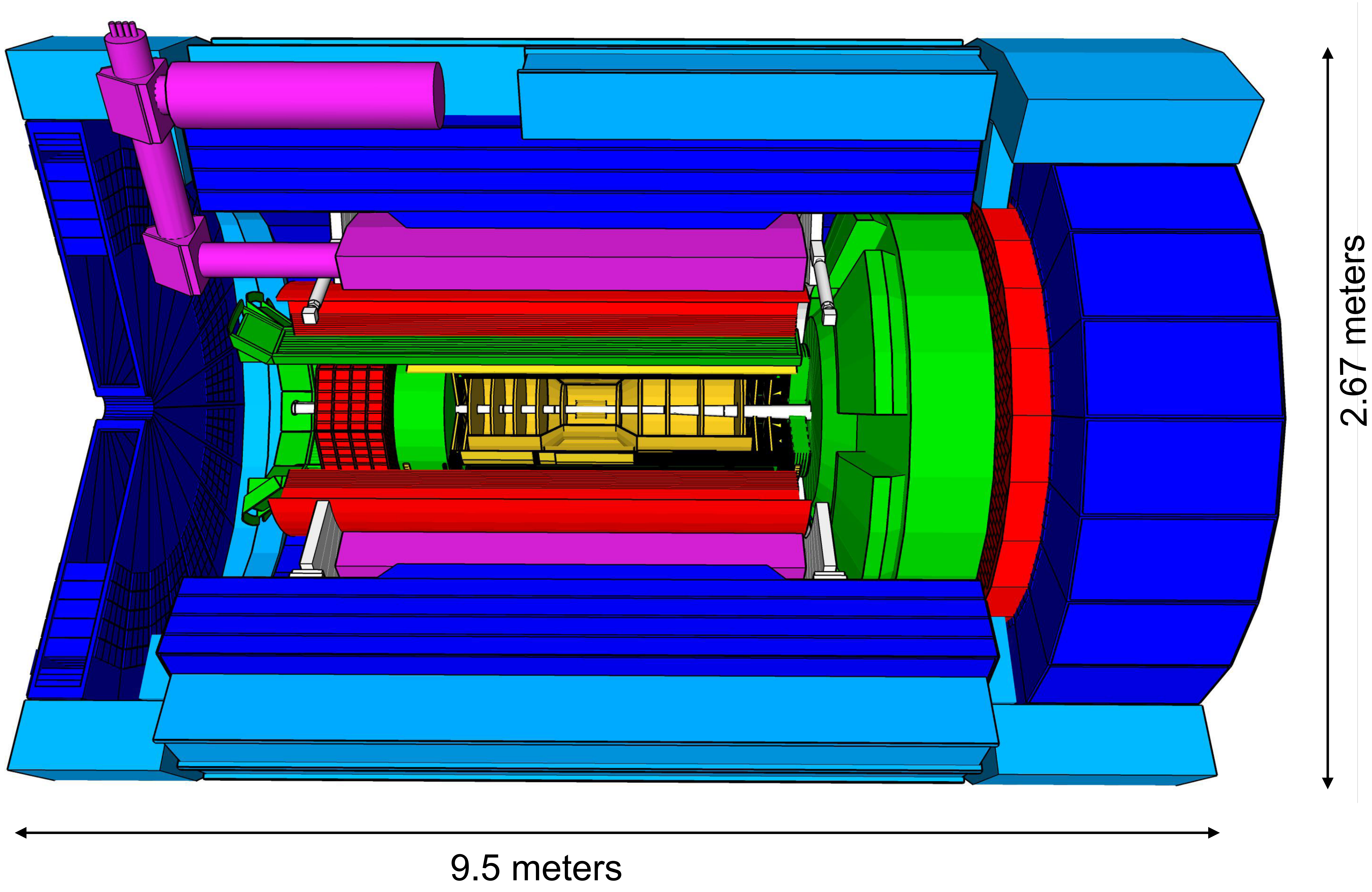
Hadron calorimeter → Measure charged hadrons, neutrons, and K_L^0
- Target resolution ~50%/√E ⊕ 10% for low-energy hadrons (~20 GeV scale)
- Steel–scintillator sampling calorimeter with longitudinal segmentation

DAQ & Readout Electronics → trigger-less / streaming DAQ
- High-rate data acquisition with advanced online processing

Very forward and backward detectors → detect particles scattered at very small angles
- Silicon tracking detectors integrated with beam line spectrometer elements
- Zero-degree electromagnetic and hadronic calorimeters

ePIC Central Detector

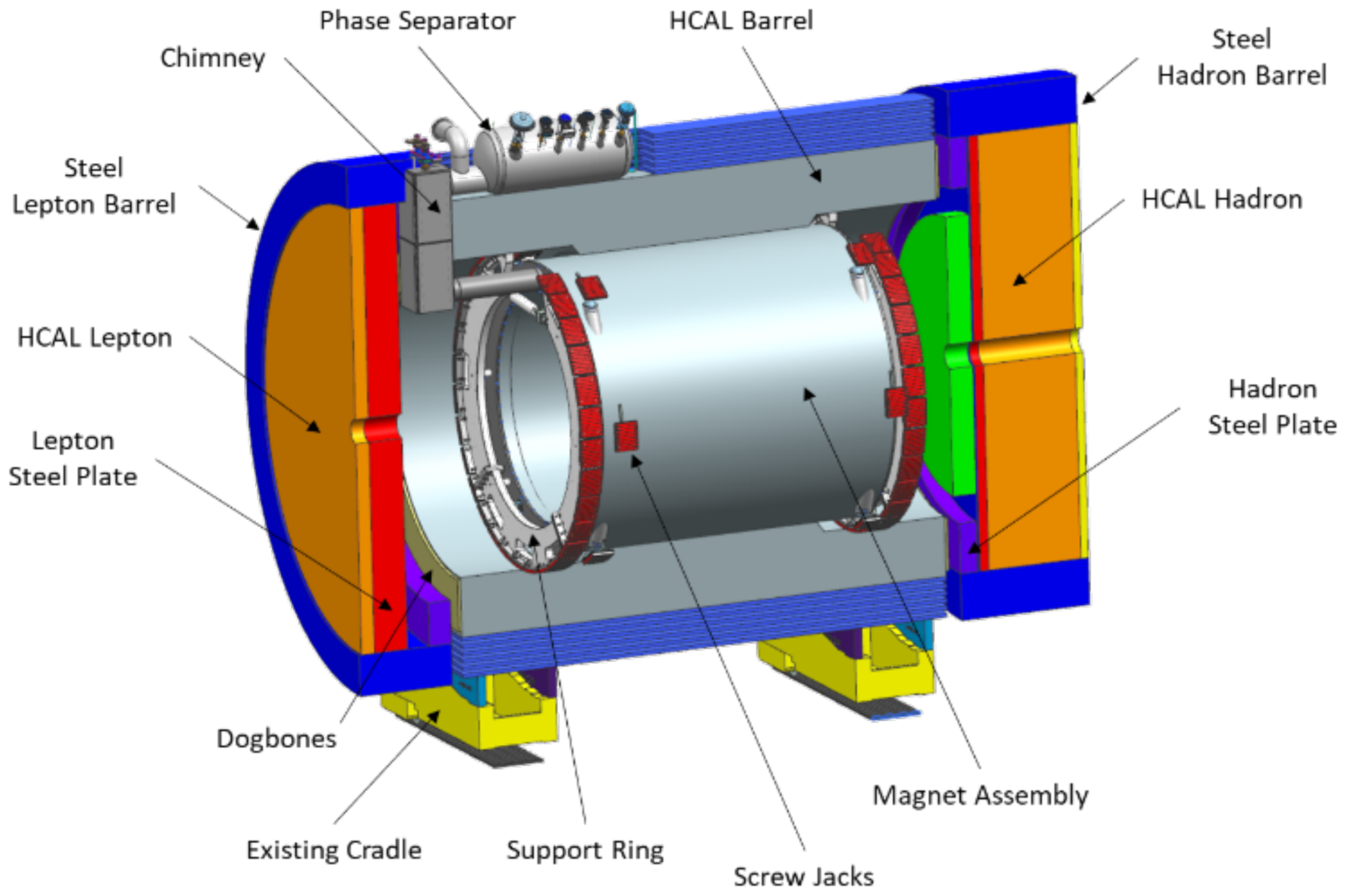
- Hadronic Calorimeters
- Solenoid Magnet
- Electromagnetic Calorimeters
- Particle Identification
- Tracking

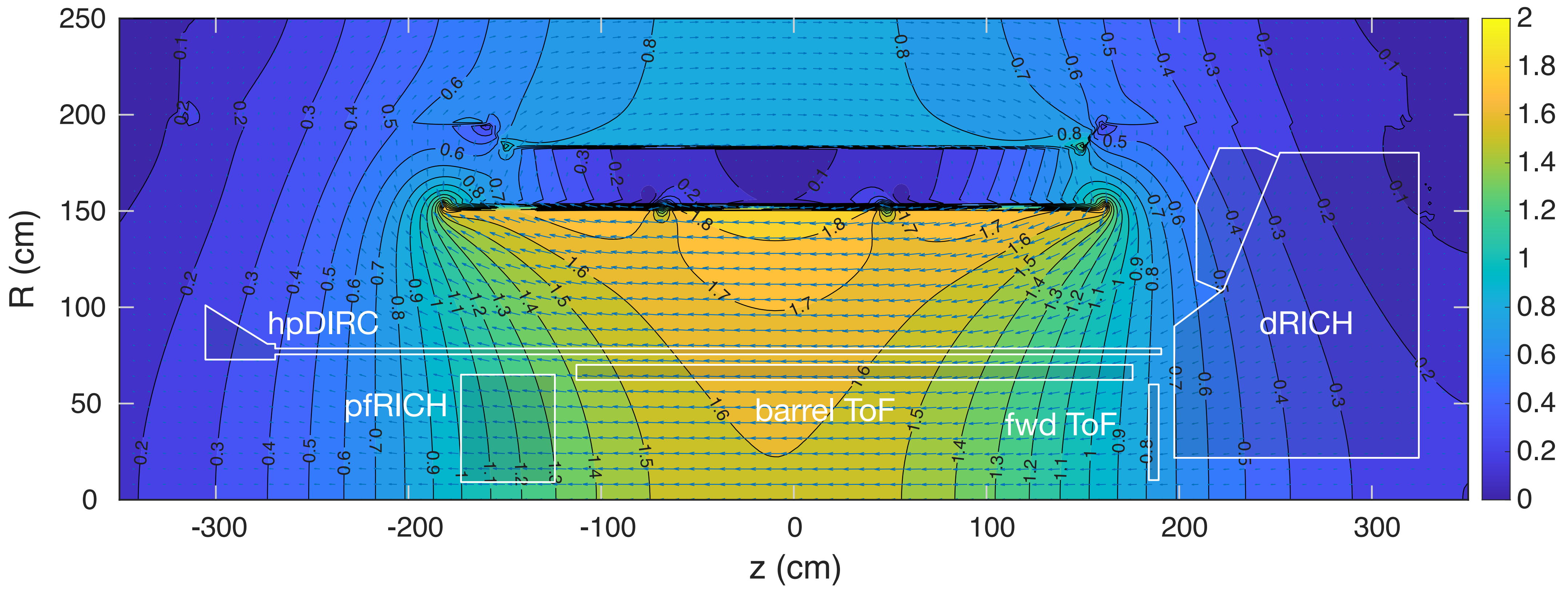


ePIC Solenoid Magnet

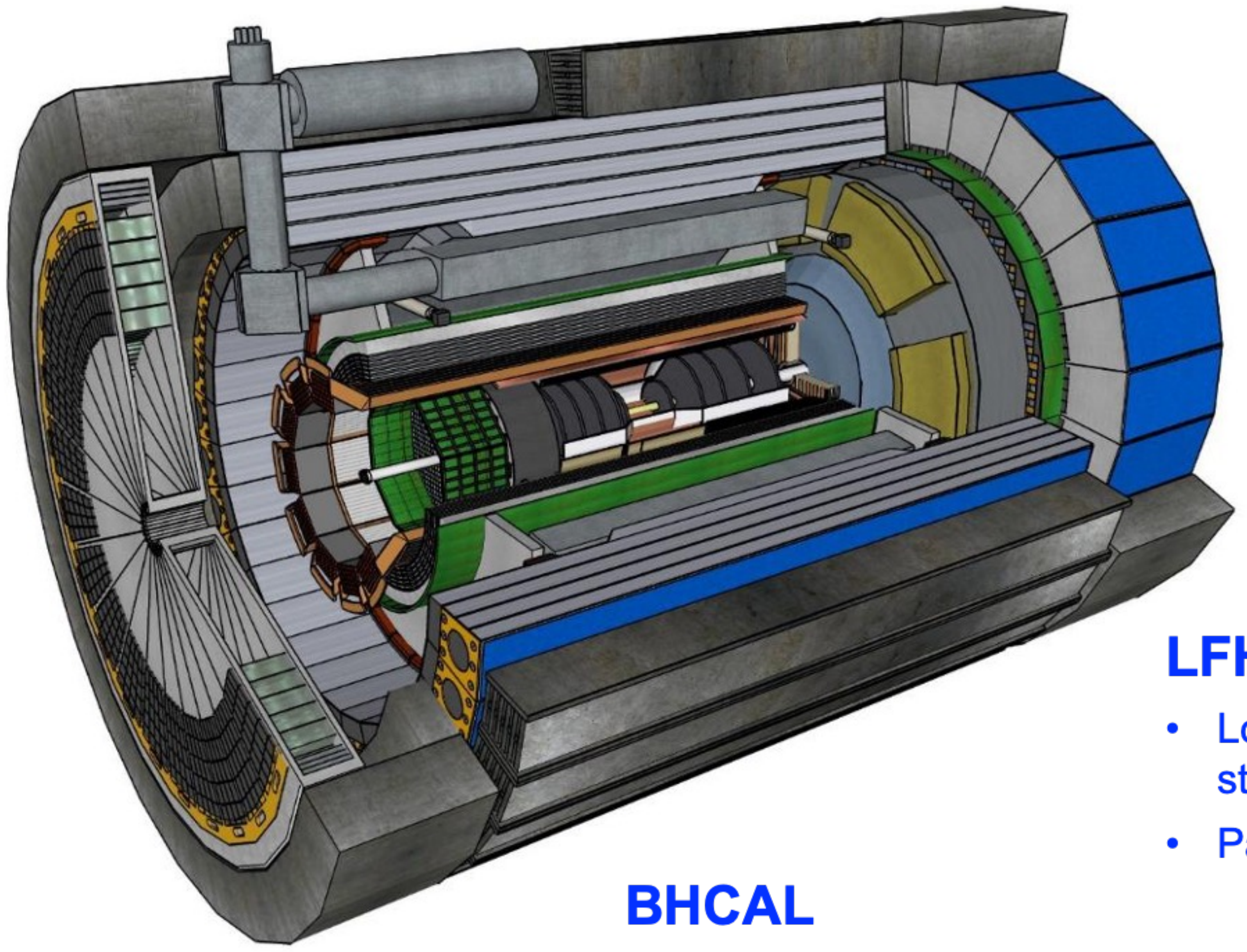
Magnet Requirements

Parameter	Value	Unit
Nominal central field at IP	2.0	T
Operating field range	0.5 – 2.0	T
Magnetic field polarity	Bipolar	
Coil length	3492	mm
Warm bore diameter	2840	mm
Cryostat length	< 3850	mm
Cryostat outer diameter	< 3540	mm
Yoke diameter	≤ 6500	mm
Axial yoke length	≤ 9500	mm
Field uniformity in the Flat Field area	12.5 %	
Fringe field on IR magnets	< 10	G
Projectivity in RICH area	< 10	T/Amm^2
Nuclear interaction length	< 0.5	g/cm^2
Charging voltage	< 10	V
Fast discharge voltage (max)	± 500	V
Quench hot spot temperature	< 150	K
Temperature margin	> 1.5	K
Current margin (I/I_{SSL})	$< 30\%$	
Operating temperature	4.5	K





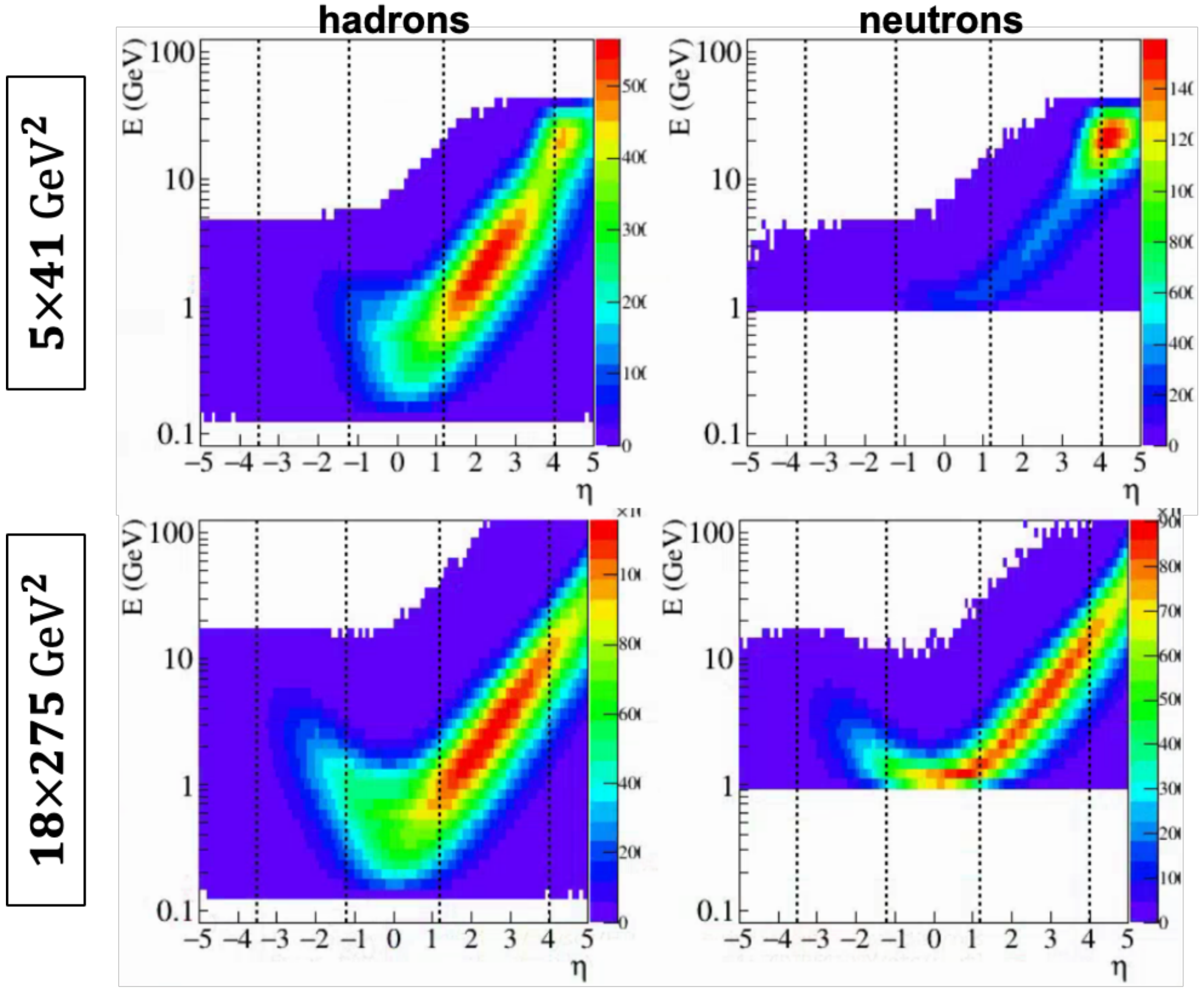
Hadronic Calorimetry at ePIC



LFHCAL
- Longitudinally segmented steel/scintillator
- Part of the solenoid flux return

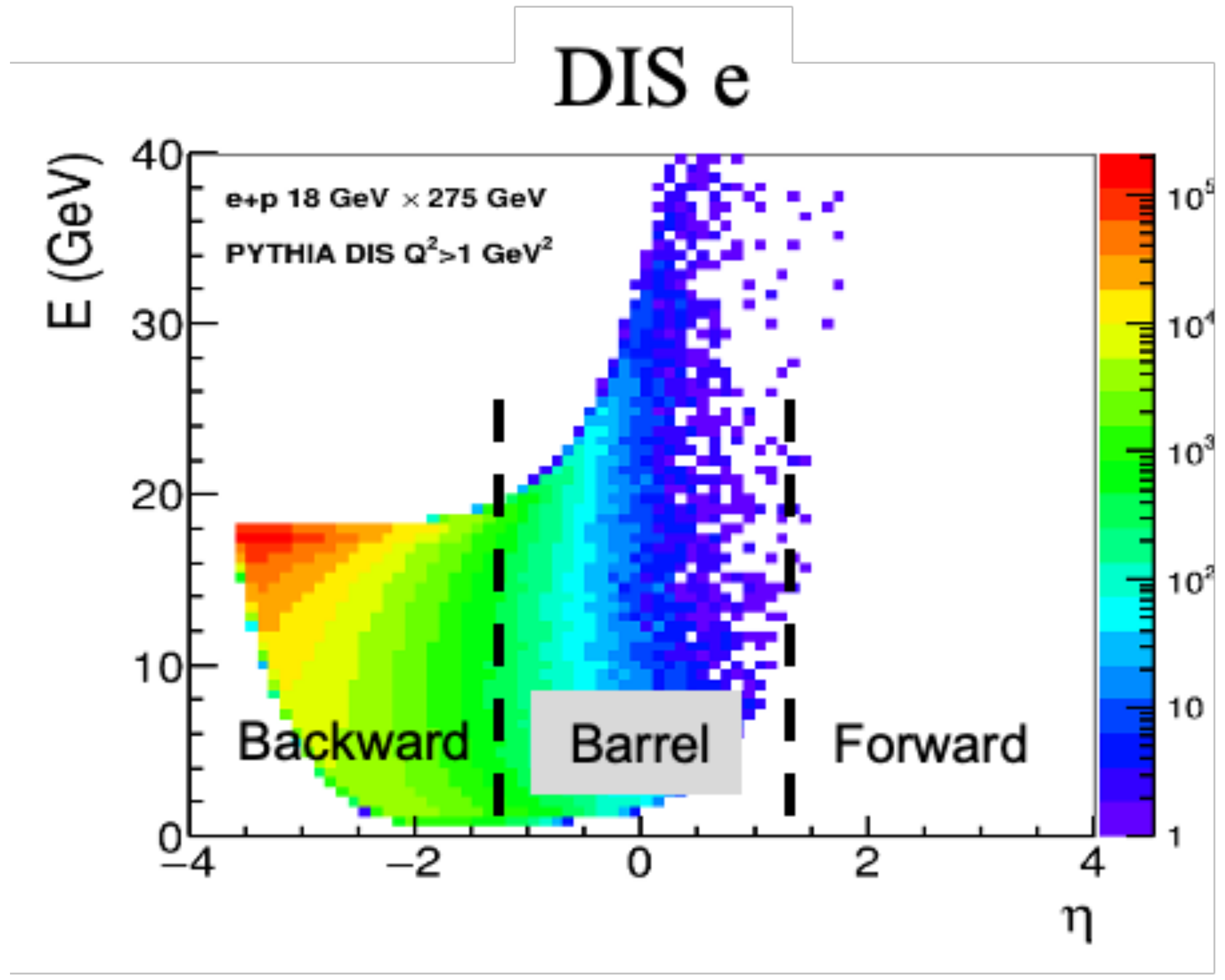
BHCAL
- Refurbished steel/scintillator
- Outer sPHENIX HCAL

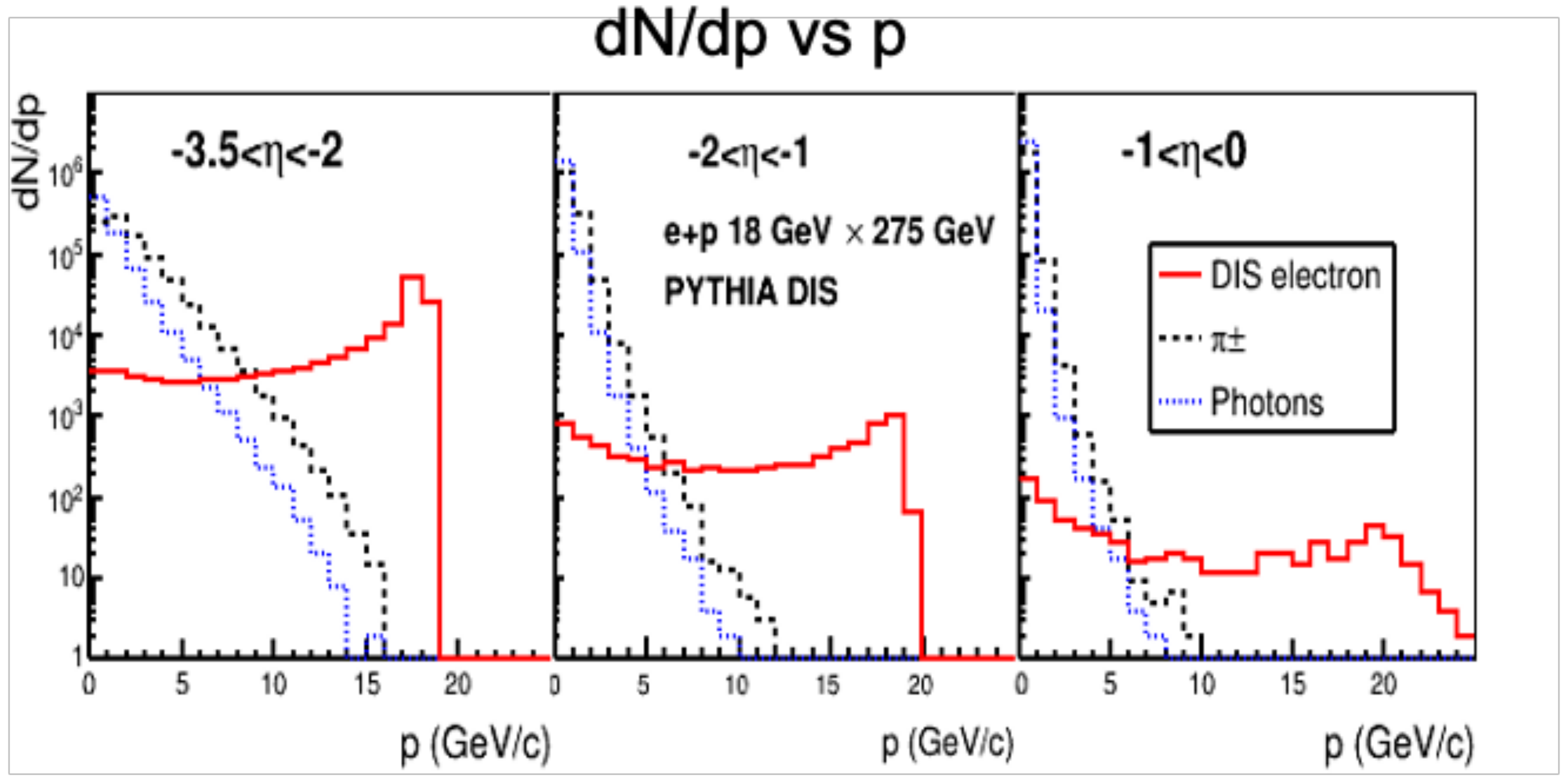
nHCAL
- Steel/scintillator
- Not part of the magnetic flux return



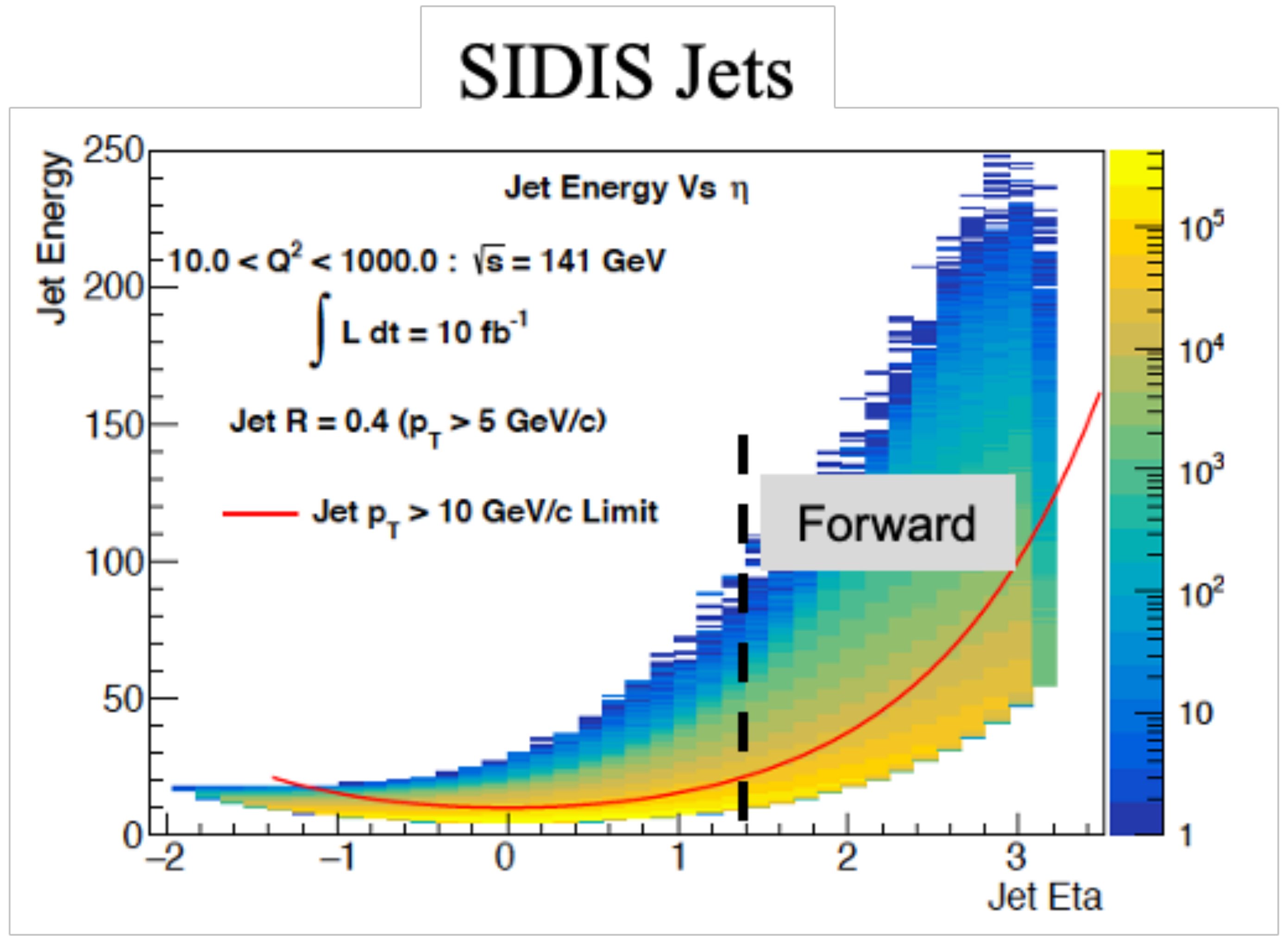
- Neutrons and K_L^0 are about 10% of all hadrons
- Hadron energies at midrapidity are generally low
- Backward rapidities only significant at highest $\sqrt{s}$

EM Calorimetry at ePIC

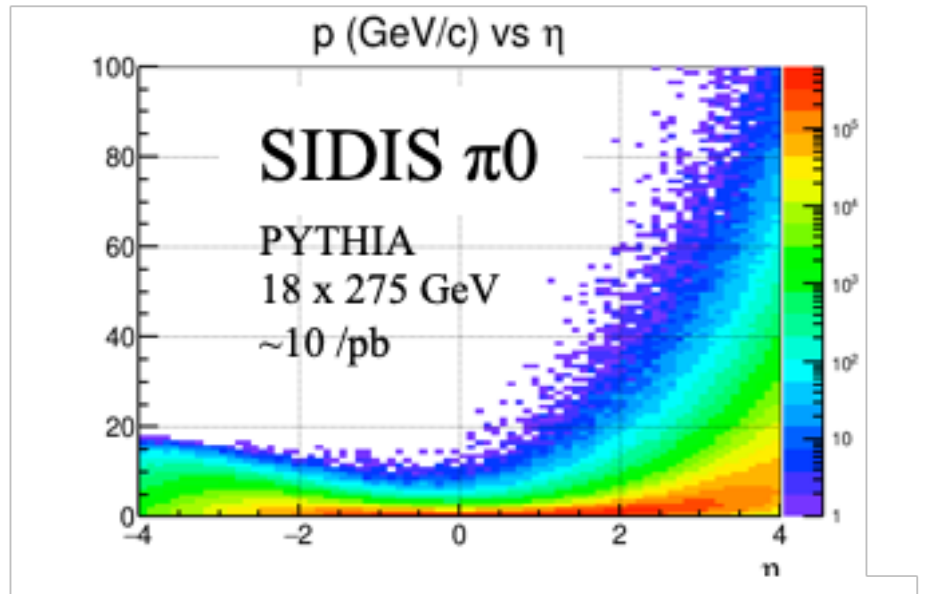


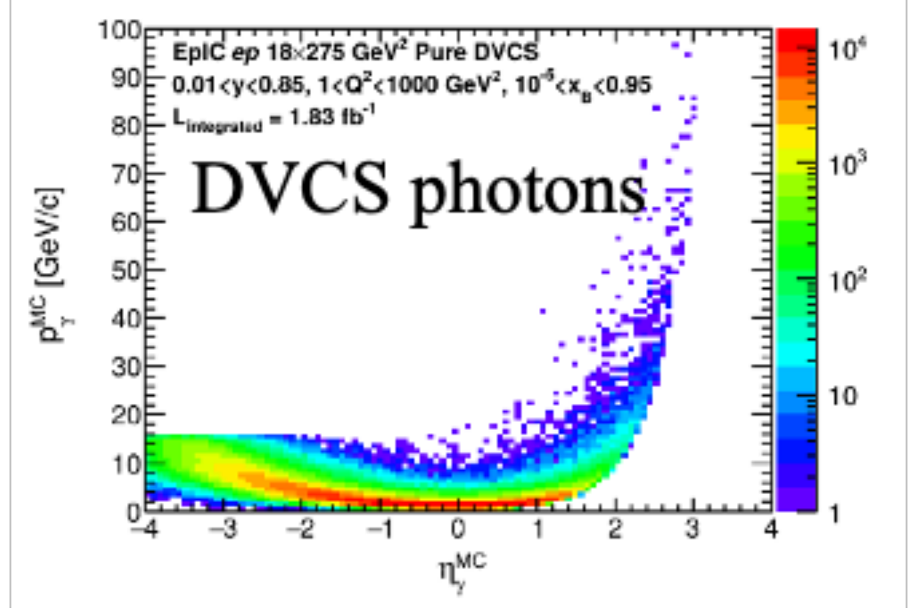


- Mainly barrel and backward
- **Hadron suppression up to a factor of 10^4**
- Energy/Momentum measurement is critical:
  $\frac{\sigma_{Q^2}}{Q^2} \sim \frac{\sigma_{E'}}{E'}$; $\frac{\sigma_x}{x} \sim \frac{1}{y}\frac{\sigma_{E'}}{E'}$
- **Highest resolution EMCal in the most backward region** (due to degraded tracking mom. res.)
- **Lowest material budget** (to minimize Bremsstrahlung)



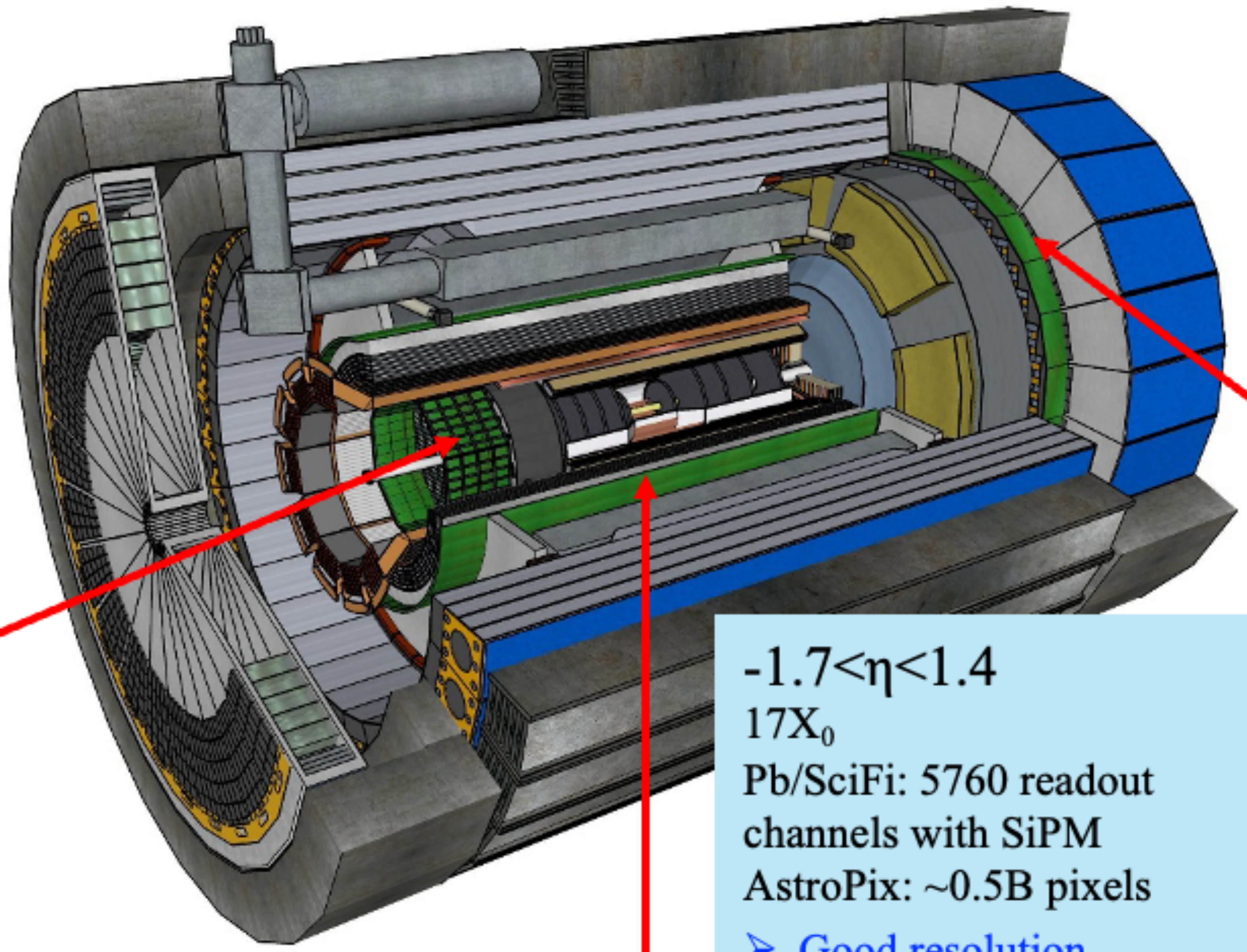
- Assists SIDIS (jets) measurements
- Focus on forward acceptance
- Large dynamic range
- Benefits from **e/h~1** (for jets)
- Participates in DIS kinematics reco through hadronic final state (JB)
- Decay photons define **minimal energy boundary**



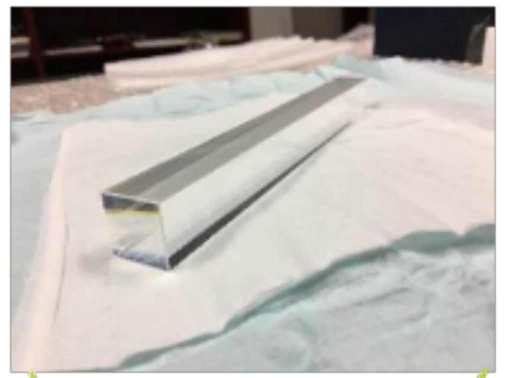


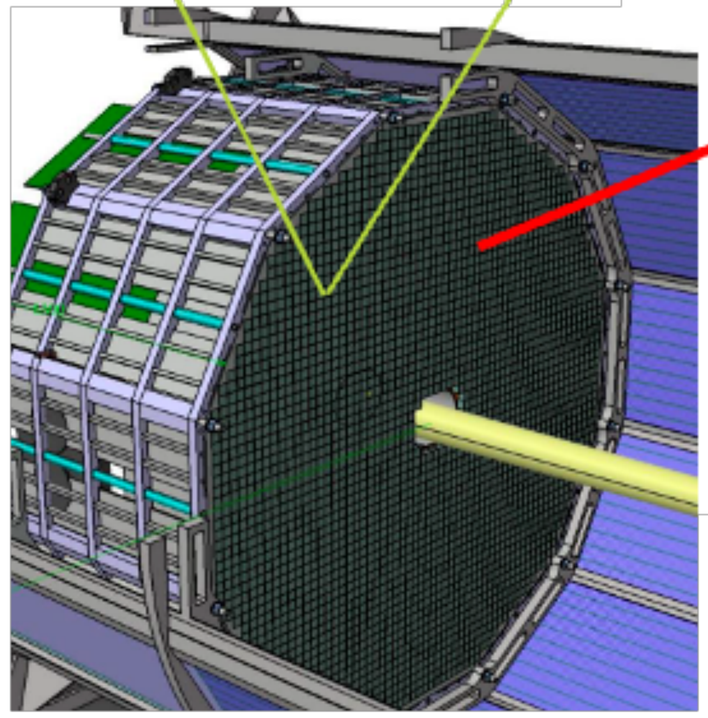
- Photon and π0 measurements
- **γ**/π0 discrimination
- Benefits from **good resolution and high granularity**

EM Calorimetry at ePIC



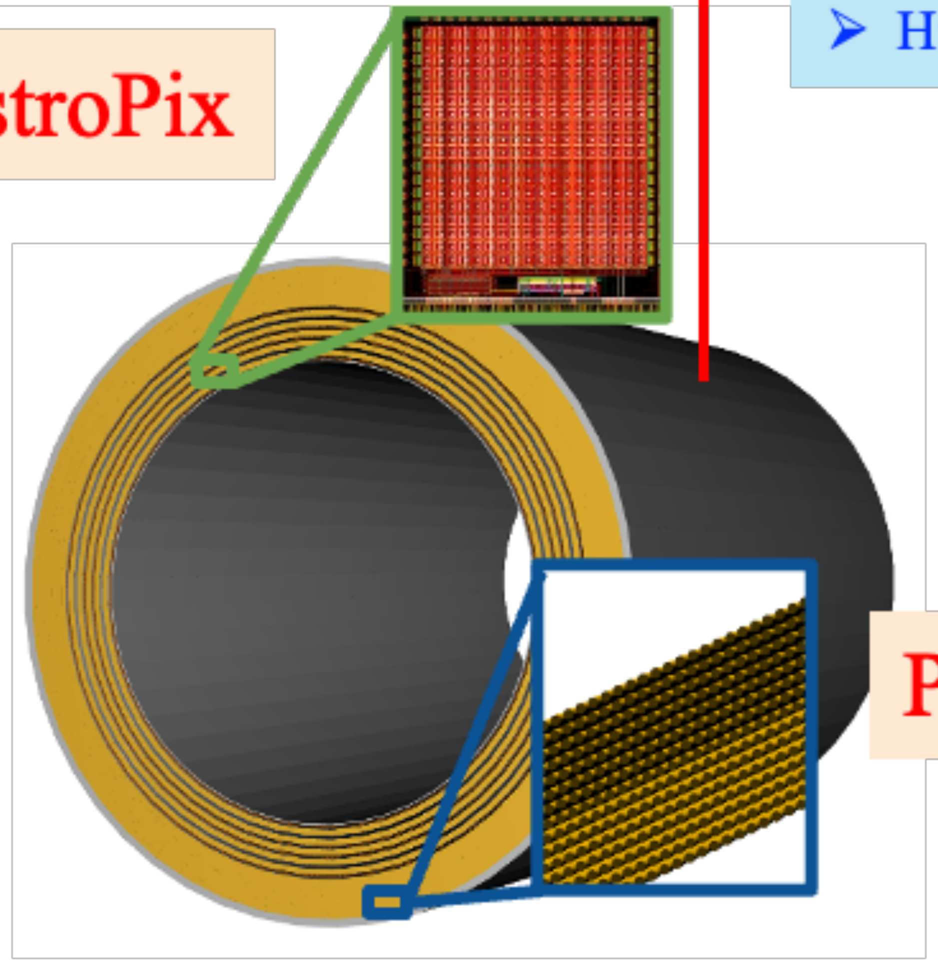
PbWO4





-3.5<η<-1.7
$22X_0$, ~3k crystals, SiPM readout
- High resolution
- High e/π separation for eID

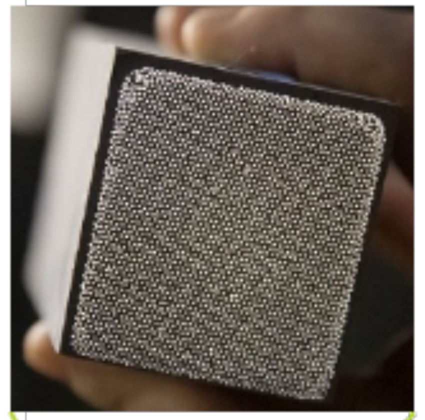
AstroPix

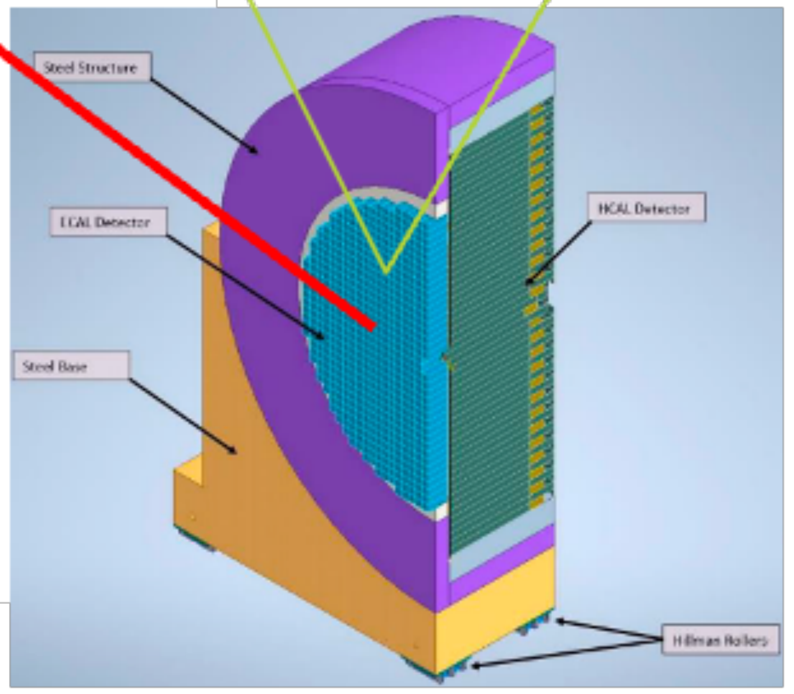


Pb/SciFi

-1.7<η<1.4
$17X_0$
Pb/SciFi: 5760 readout channels with SiPM
AstroPix: ~0.5B pixels
- Good resolution
- High e/π separation for eID

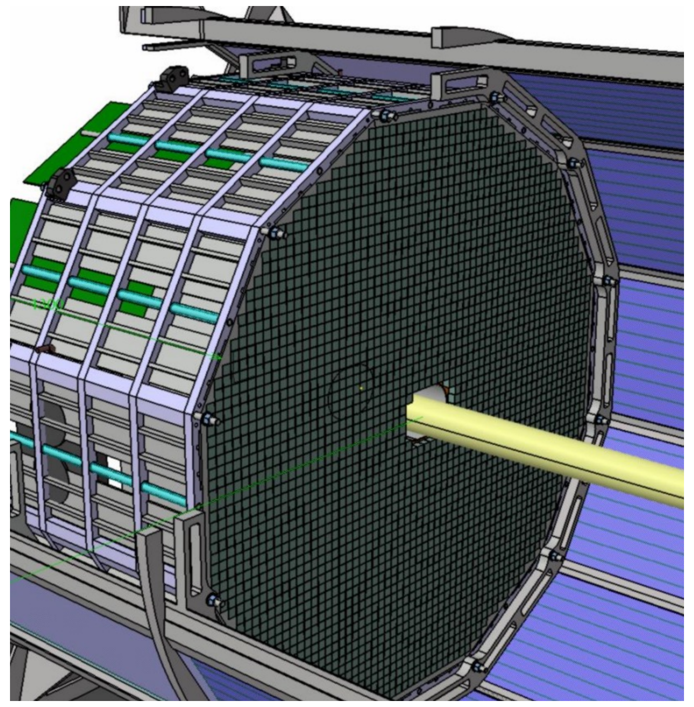
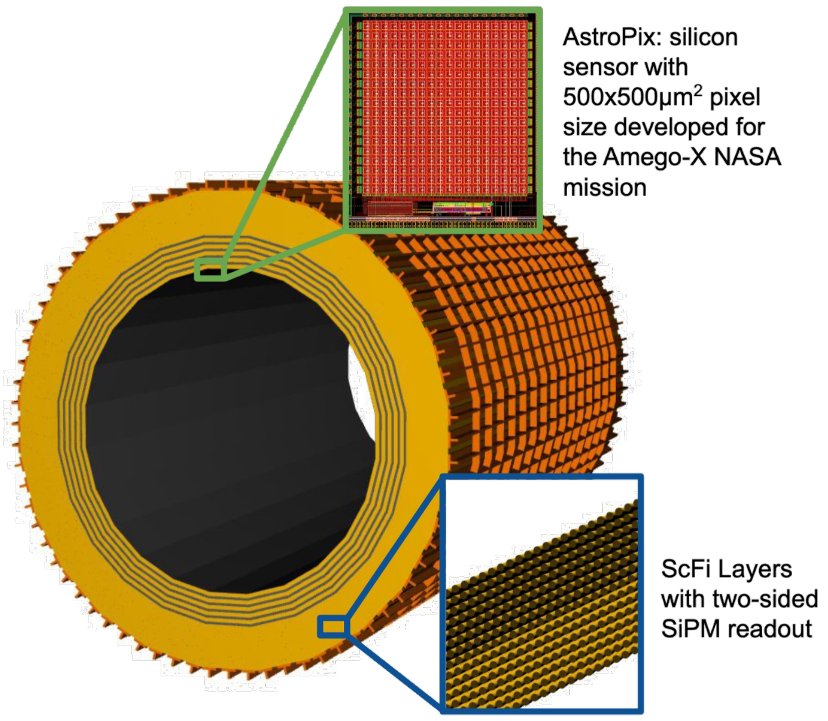
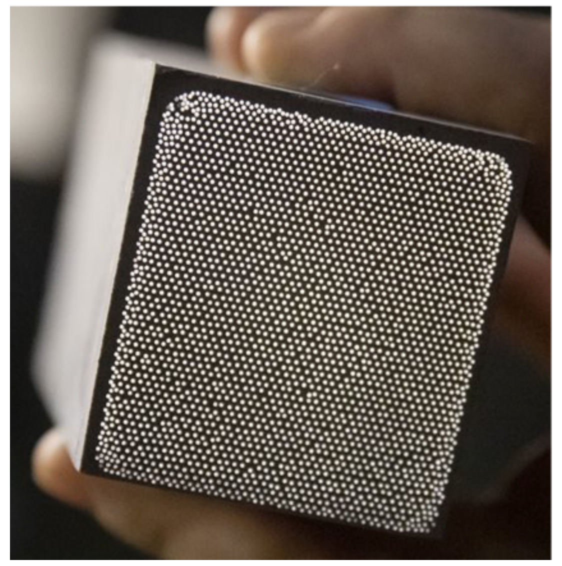
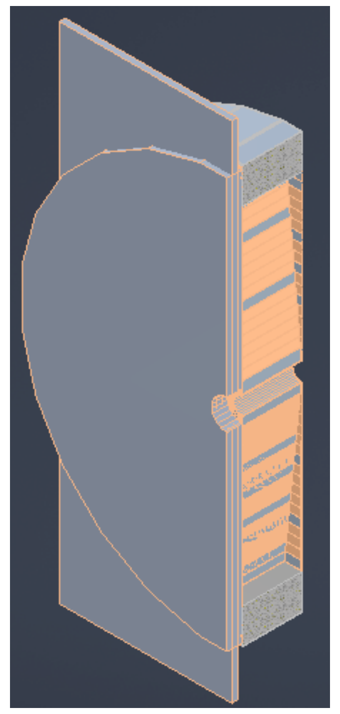
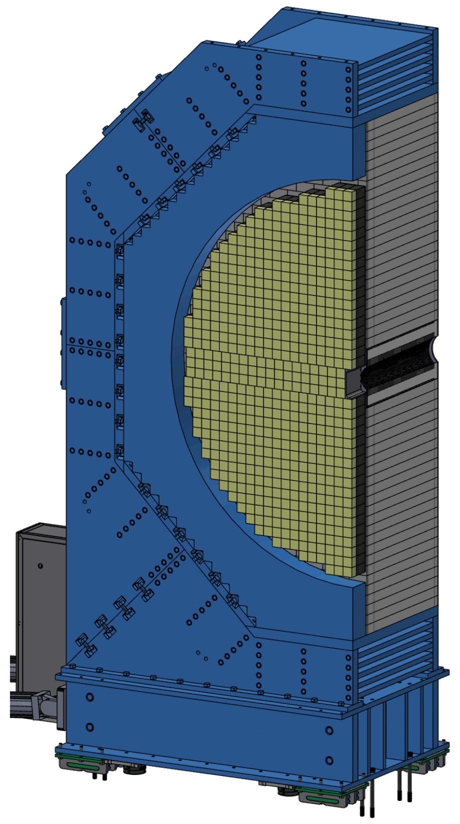
W/SciFi



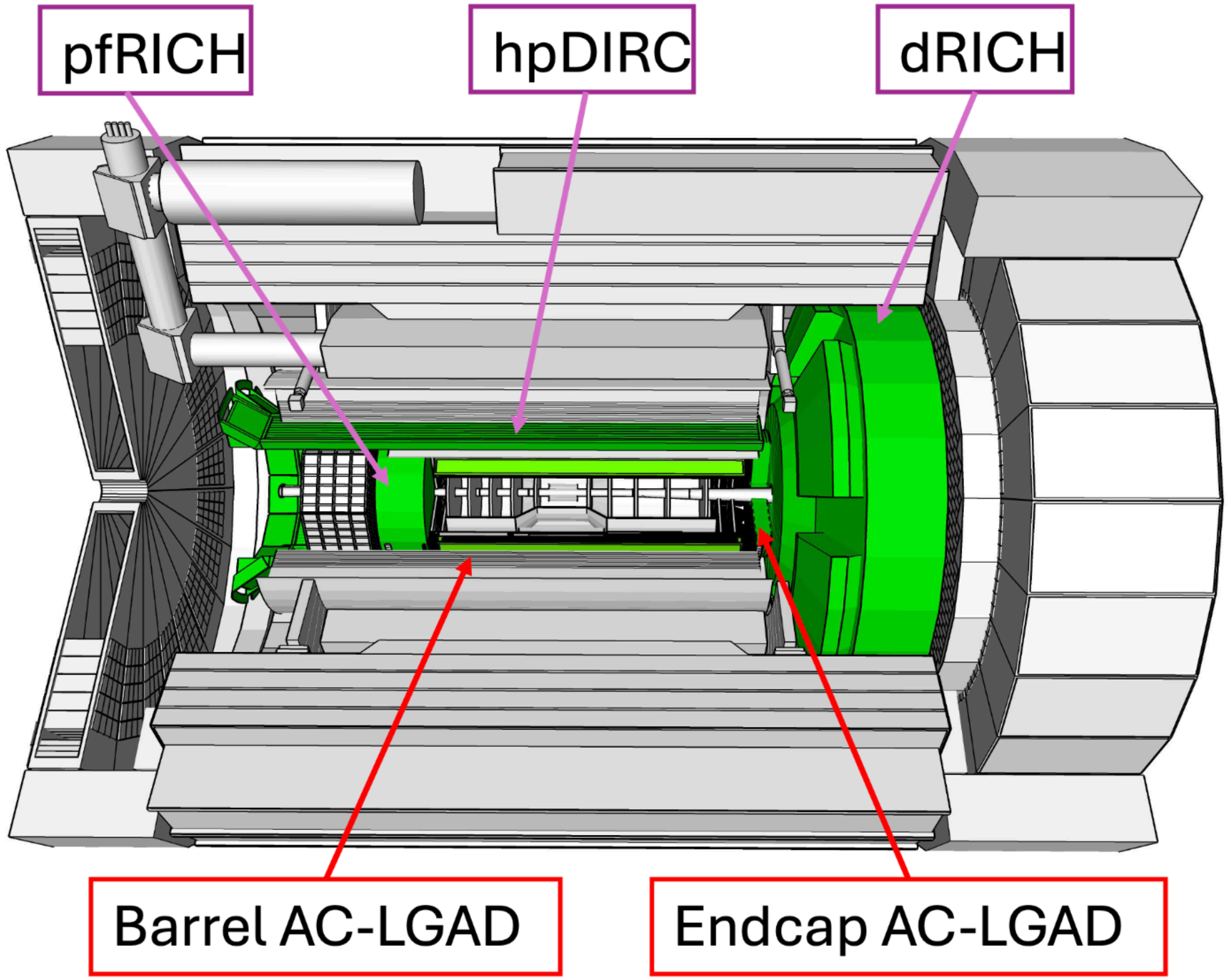


1.4<η<3.7
$23X_0$, ~18k towers, SiPM readout
- Good resolution
- High granularity for π0
- e/h~1 for jets

ePIC Calorimetry at a Glance

	Backward ECal	Barrel ECal	Forward ECal	Backward HCal	Barrel HCal	Forward HCal
						
Main Function	scattered lepton detection -> very high-precision	scattered lepton and γ detection, hadronic final state characterization	lepton and γ detection, hadronic final state characterization → π^0, γ separation	muon and neutral detection→ improved jet Energy reconstruction	muon and neutral detection →improved jet Energy reconstruction	particle-flow measurements
Proven Technology	PbWO4 – crystals →long lead procurement	Pb/SciFi sampling part using SiPMs combined with imaging section (6 layers) interleaving Pb/SciFi with ASTROPIX	Tungsten-powder + SciFi SPACAL design Developed through EIC R&D and applied successfully in sPHENIX	Steel + Scintillator SiPM-on-tile	Steel + Scintillator design re-used from sPHENIX	longitudinal segmented Steel + Scintillator SiPM-on-tile Pioneered by CALICE analog HCal High resolution insert next to beam-pipe
World's first at ePIC	SiPM as Photon sensors	Use of ASTROPIX in Calorimetry				first-time full-size CALICE like calorimeter in collider experiment

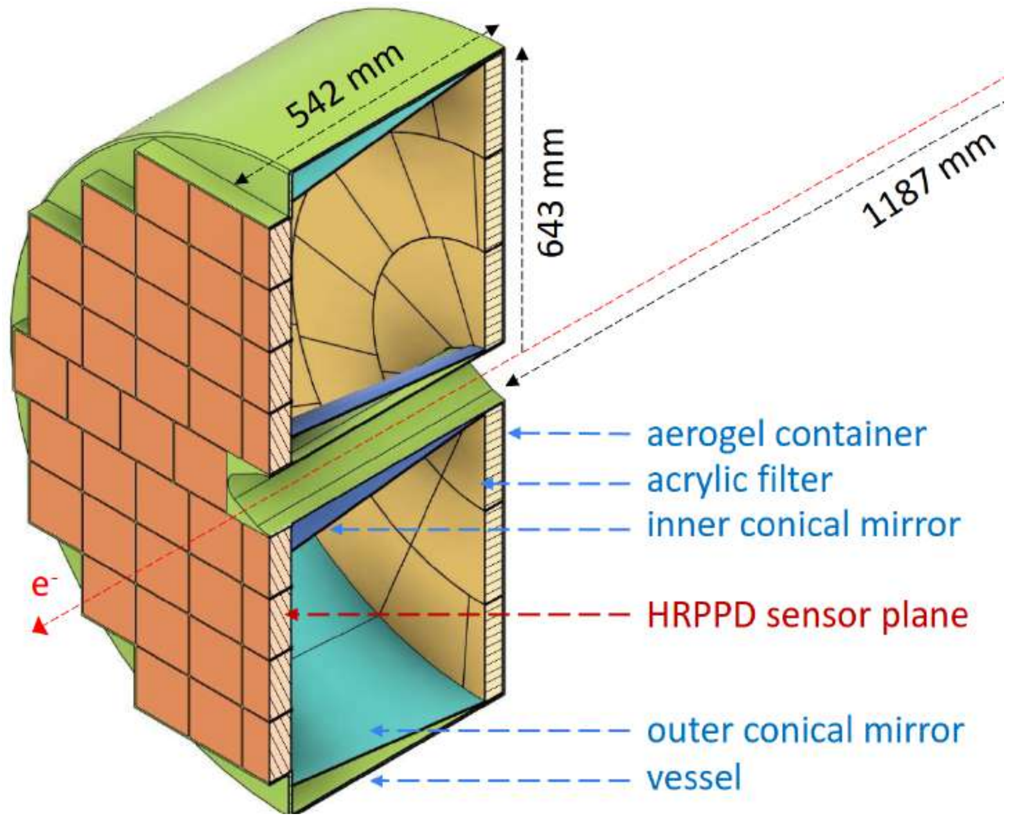
Particle Identification at ePIC



- Two different techniques for particle identification
  - Cherenkov imaging
  - Time of Flight
- Cherenkov imaging detectors in ePIC
  - Proximity Focussing RICH (pfRICH)
  - High Performance DIRC (hpDIRC)
  - Dual-radiator RICH (dRICH)
- Time of Flight detectors in ePIC
  - Barrel AC-LGAD Time of Flight
  - Endcap AC-LGAD Time of Flight

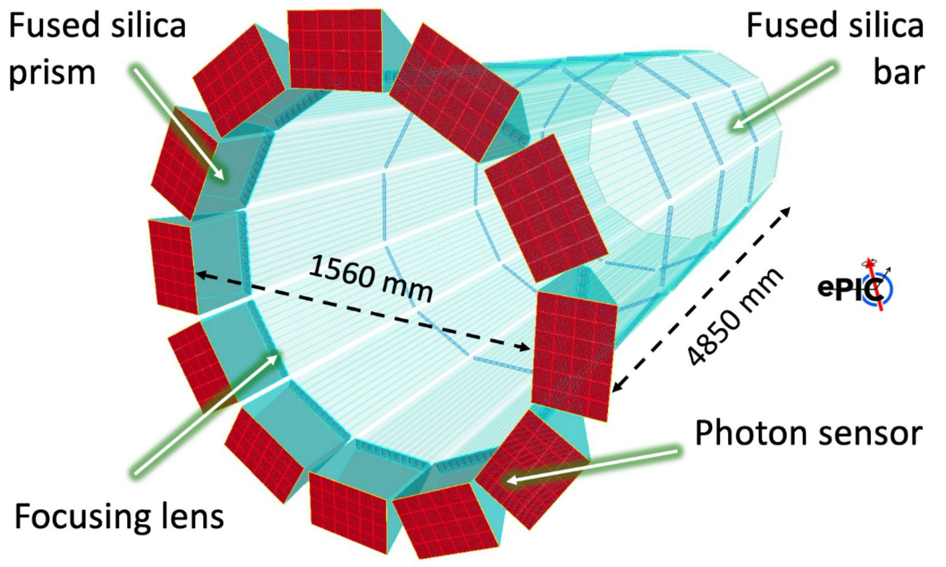
Particle Identification at ePIC

Backward RICH (pfRICH)



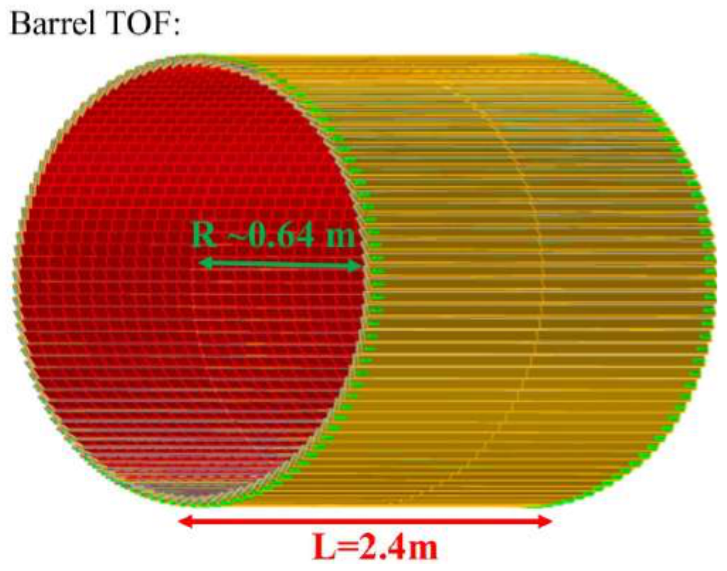
- π/K/p of 3σ separation up to 7 GeV/c
- Utilizes long proximity gap (~30 cm) with 1.04 refractive index aerogel
- High-Rate Picosecond Photon Detectors (HRPPD) as photosensor with single photon timing resolution of ~30-40 ps

Barrel DIRC (hpDIRC)



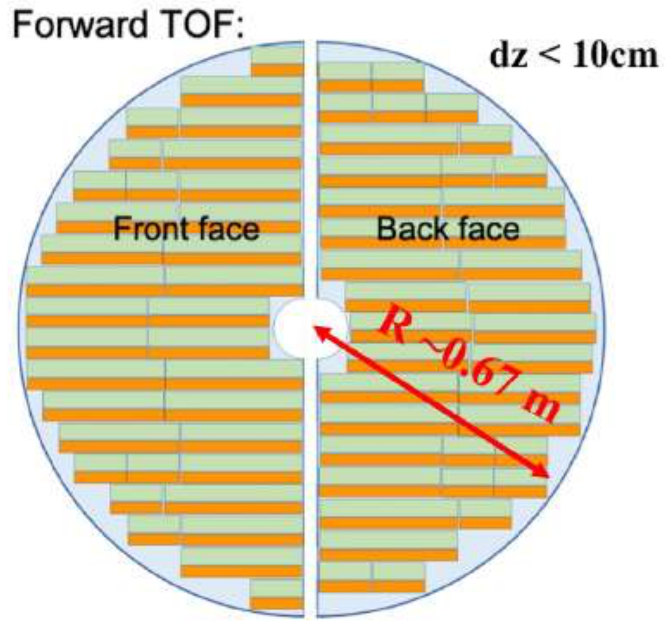
- π/K/p of 3σ separation up to 6 GeV/c
- Quartz bars as radiators
- Saphire lens as focusing optics
- Compact Solid fused silica prism as expansion volume
- MCP-PMT as photosensors.

Barrel TOF



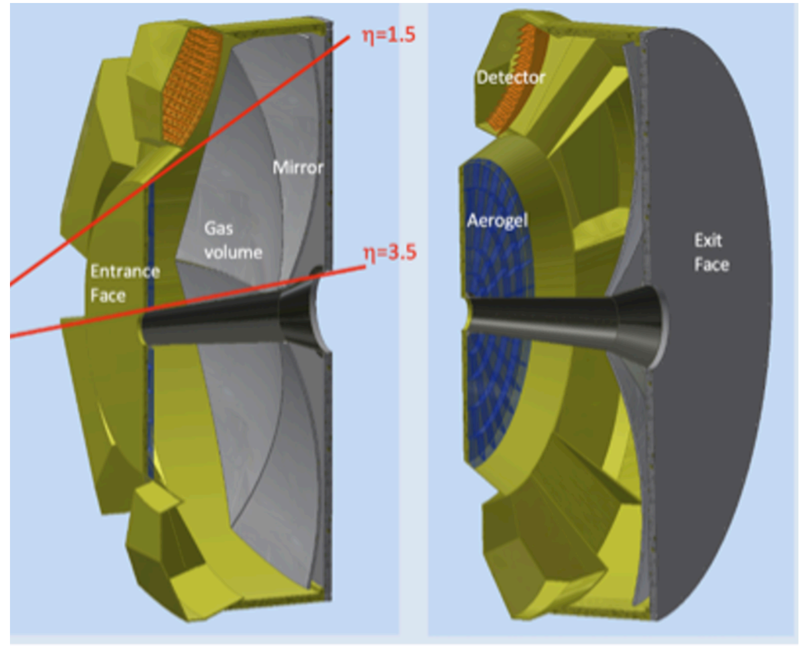
- π/K of 3σ separation between 0.2-1.2 GeV/c
- AC-LGAD strip sensors with timing resolution of ~ 35 ps.

Forward TOF



- π/K of 3σ separation between 0.2 to 2.3 GeV
- AC-LGAD pixel sensors with timing resolution of ~ 20 ps

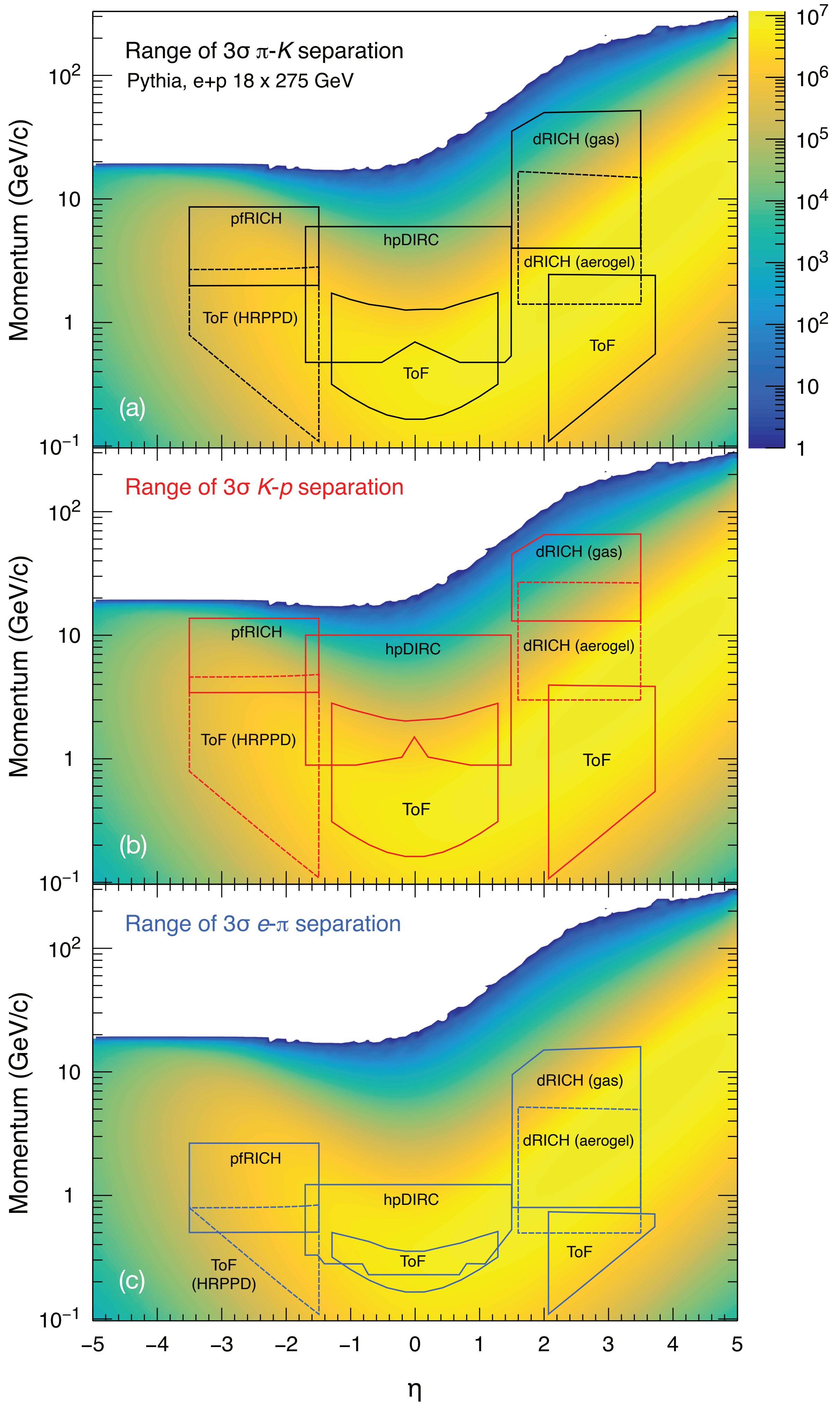
Forward RICH



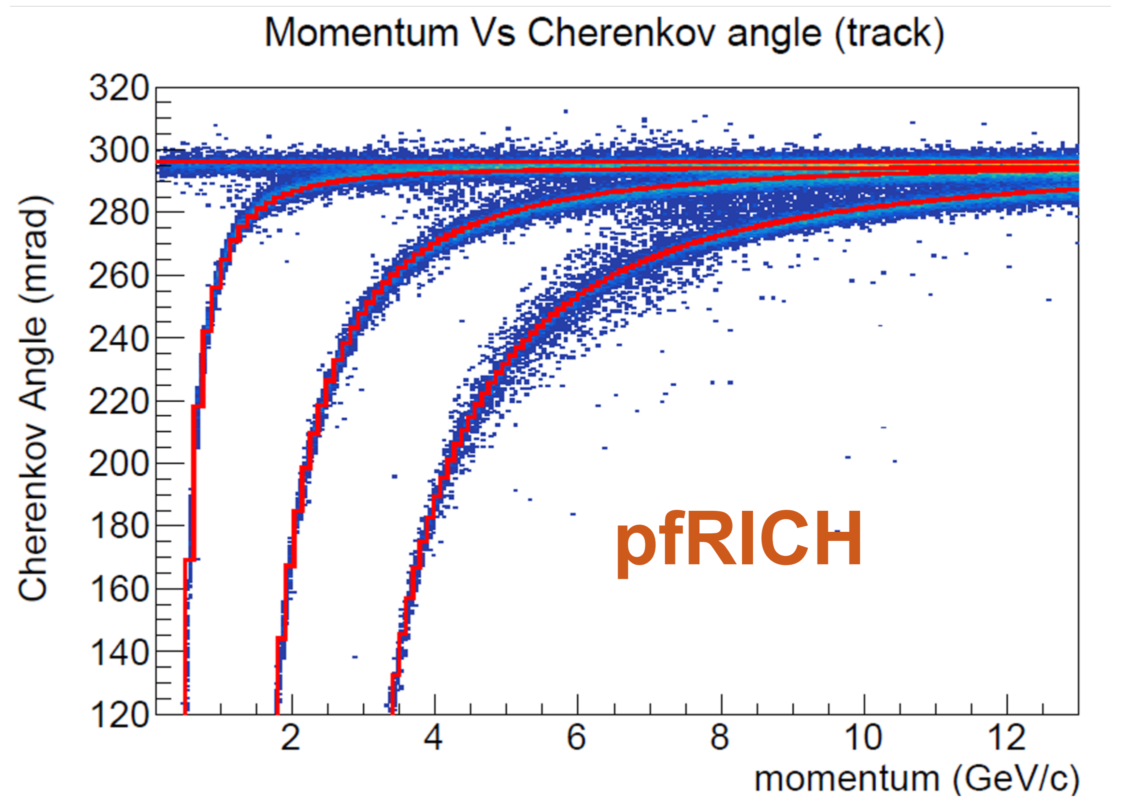
- π/K of 3σ separation between 3 and 50 GeV/c.
- Aerogel (n = 1.026) and C_2F_6 gas as two different radiators.
- Focusing mirror
- SiPM as Photosensors

Particle Identification at ePIC

ePIC PID Requirements



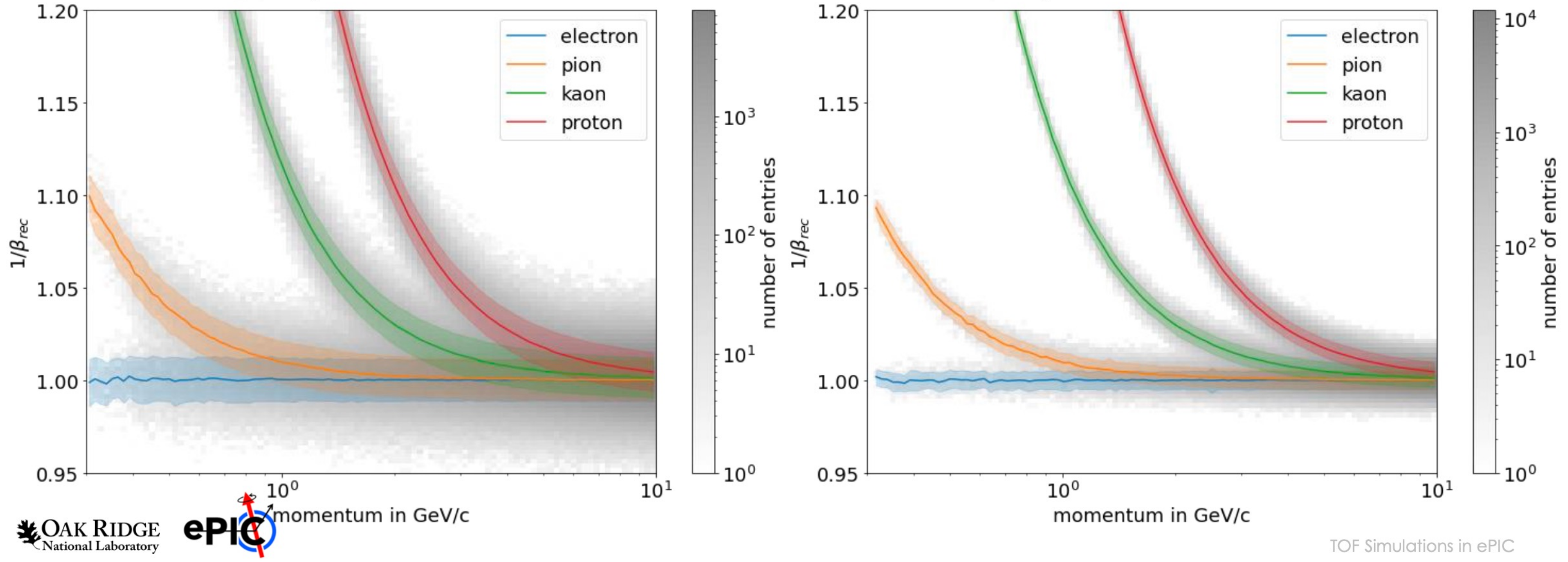
PID Simulated Performance @ ePIC

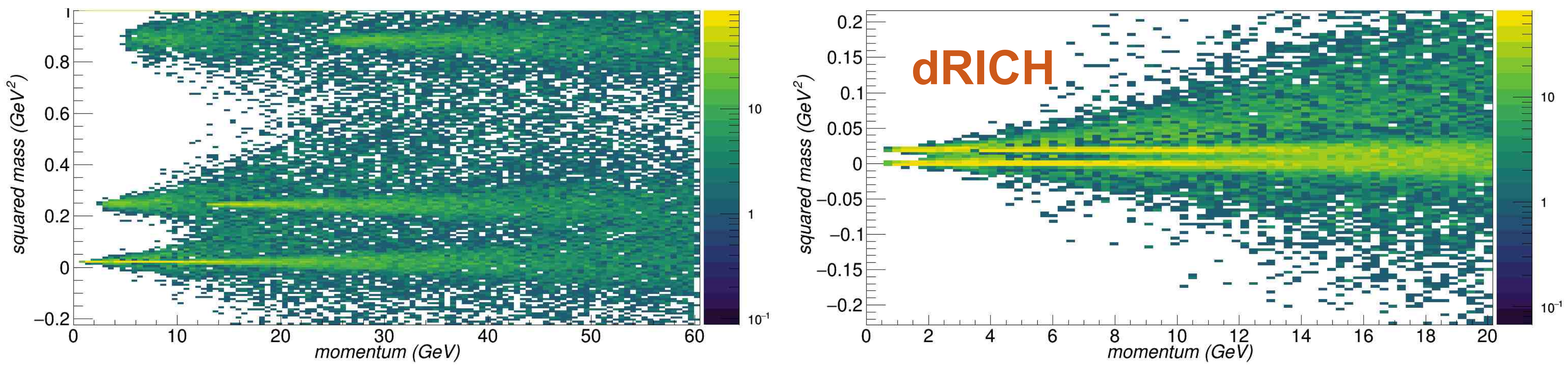


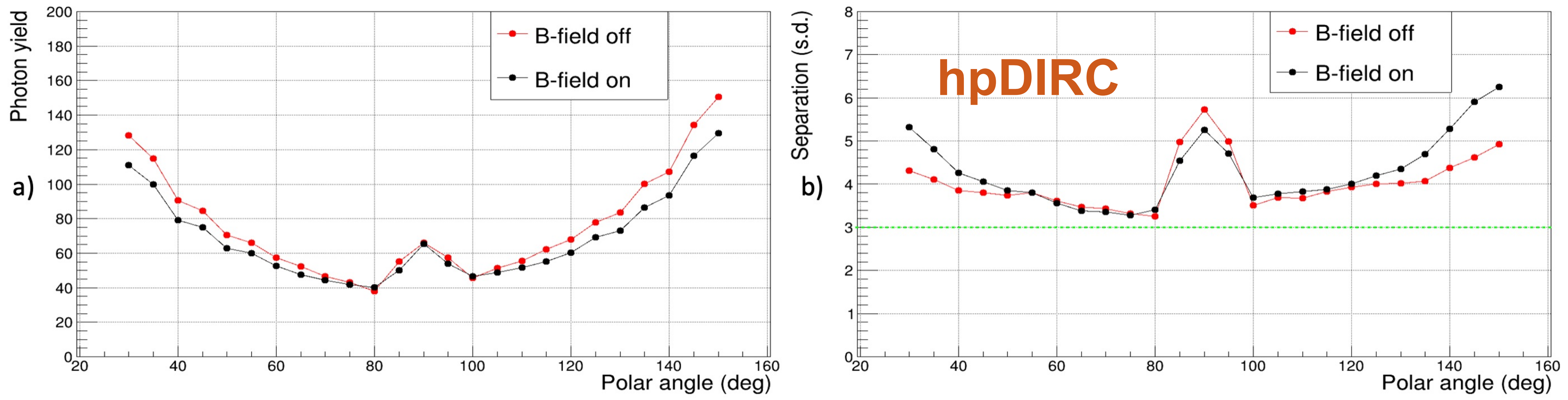
- Barrel Region
  - e/pi up to 0.5 GeV/c
  - pi/K up to 1.9 GeV/c
  - K/p up to 3.1 GeV/c

ToF

- Endcap Region
  - e/pi up to 0.8 GeV/c
  - pi/K up to 2.7 GeV/c
  - K/p up to 4.6 GeV/c







Tracking subsystems at ePIC

Two different technologies for charged particle tracking

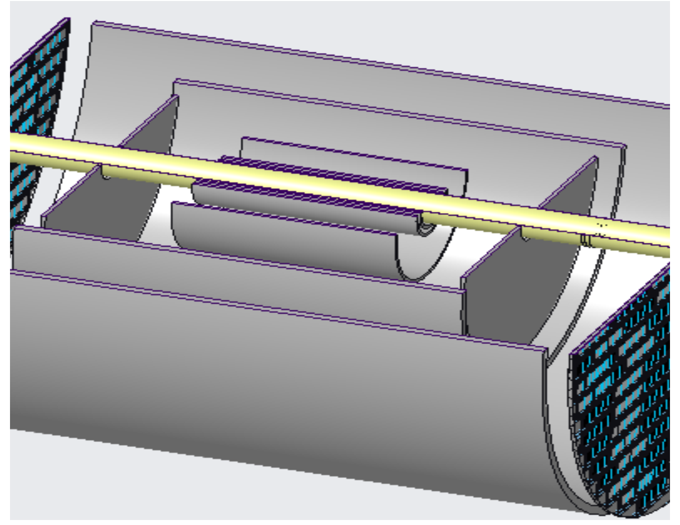
- **Silicon based trackers**
  - SVT (Silicon Vertex Tracker) Endcaps
  - SVT (Silicon Vertex Tracker) OB
  - SVT (Silicon Vertex Tracker) IB
  - AC-LGAD Barrel & Endcap

- **Gas based trackers**
  - CyMBaL (Cylindrical MicroMegas Barrel Layer)
  - μRWELL-BOT (μRWELL Barrel Outer Tracker)
  - μRWELL-ECT (μRWELL End Cap Tracker)

Tracking subsystems at ePIC

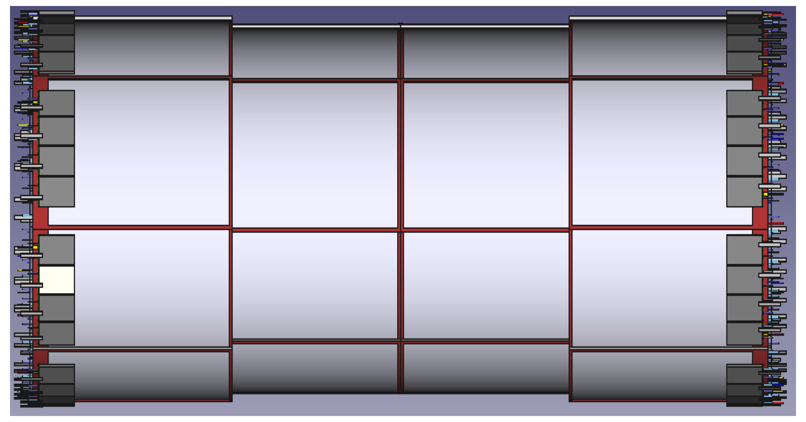
BARREL TRACKERS

Silicon vertex tracker based on ALICE ITS3



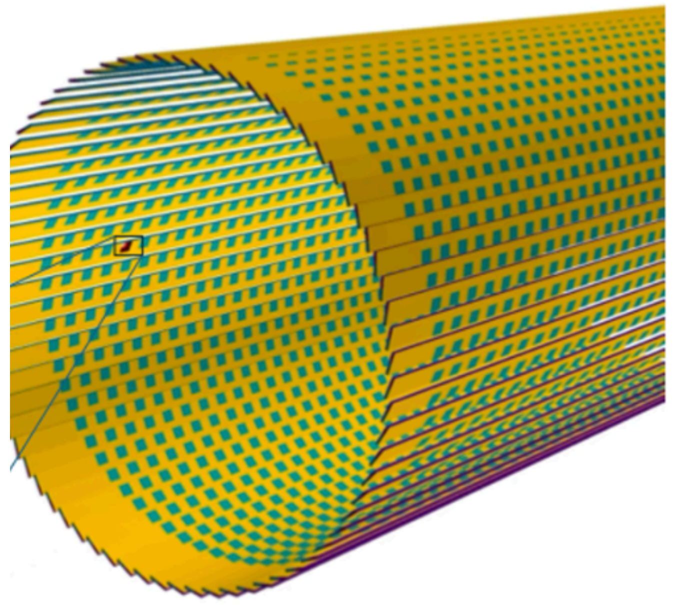
- Displaced vertex reconstruction
- Momentum resolution of $0.05\%pT \oplus 0.5\%$ and spatial resolution $20\mu m/pT \oplus 5\mu m$

CyMBaL based on µMegas technology



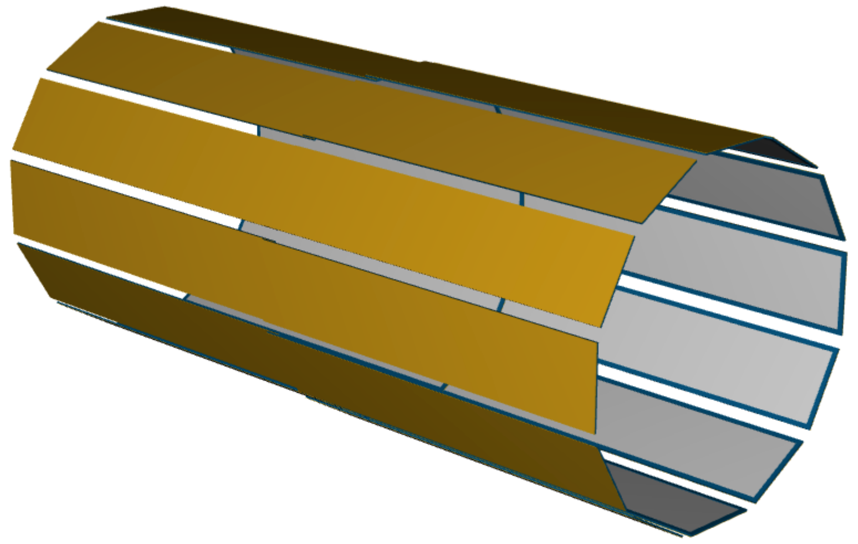
- Provide redundancy and pattern recognition for tracking

Barrel AC-LGAD



- Provide additional space point with spatial resolution of ~ 30 μm

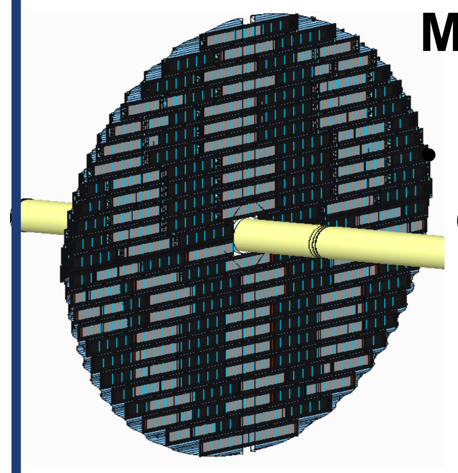
µRWELL-BOT based on µRWELL technology



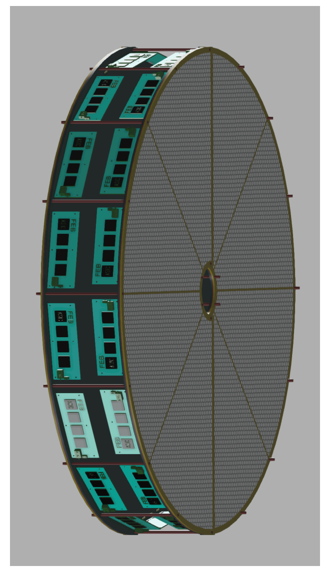
- Placed close to hpDIRC to improve angular and space point resolution to aid in PID.
- Provide redundancy and pattern recognition for tracking

Backward (e^- end cap) trackers

MAPS disks



- Momentum resolution of $(0.1)\%pT \oplus 1.0$ $(2.0)\%$ and spatial resolution $30\mu m/pT \oplus$ $(20\text{-}40)\mu m$

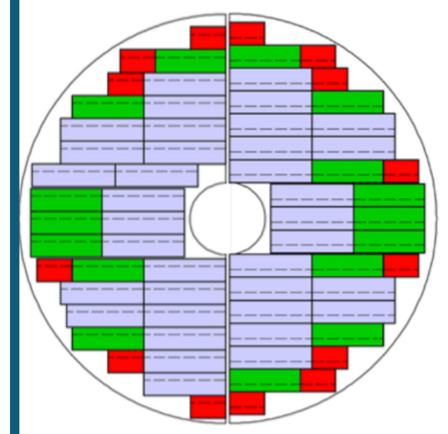


µRWELL disks

- Provide redundancy and pattern recognition for tracking.
- Aid in background rejection

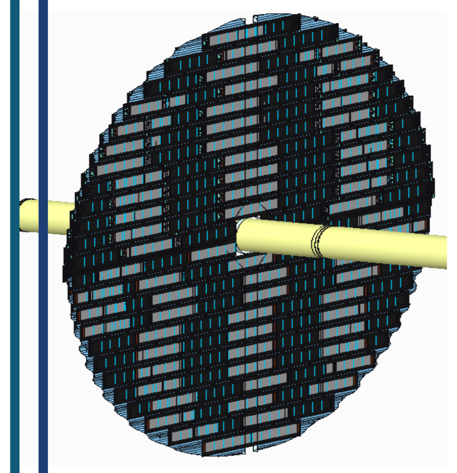
Forward (hadron end cap) trackers

AC-LGAD disk

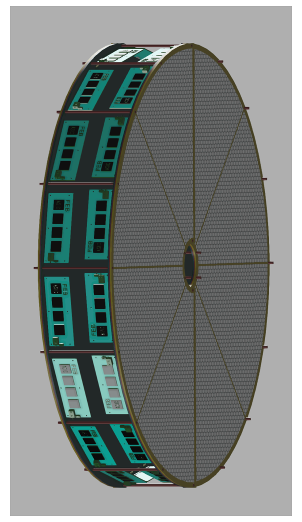


With 30 um spatial resolution aid in providing additional space point

MAPS disks



- Momentum resolution of $(0.1)\%pT \oplus 1.0$ $(2.0)\%$ and spatial resolution $30\mu m/pT \oplus$ $(20\text{-}40)\mu m$



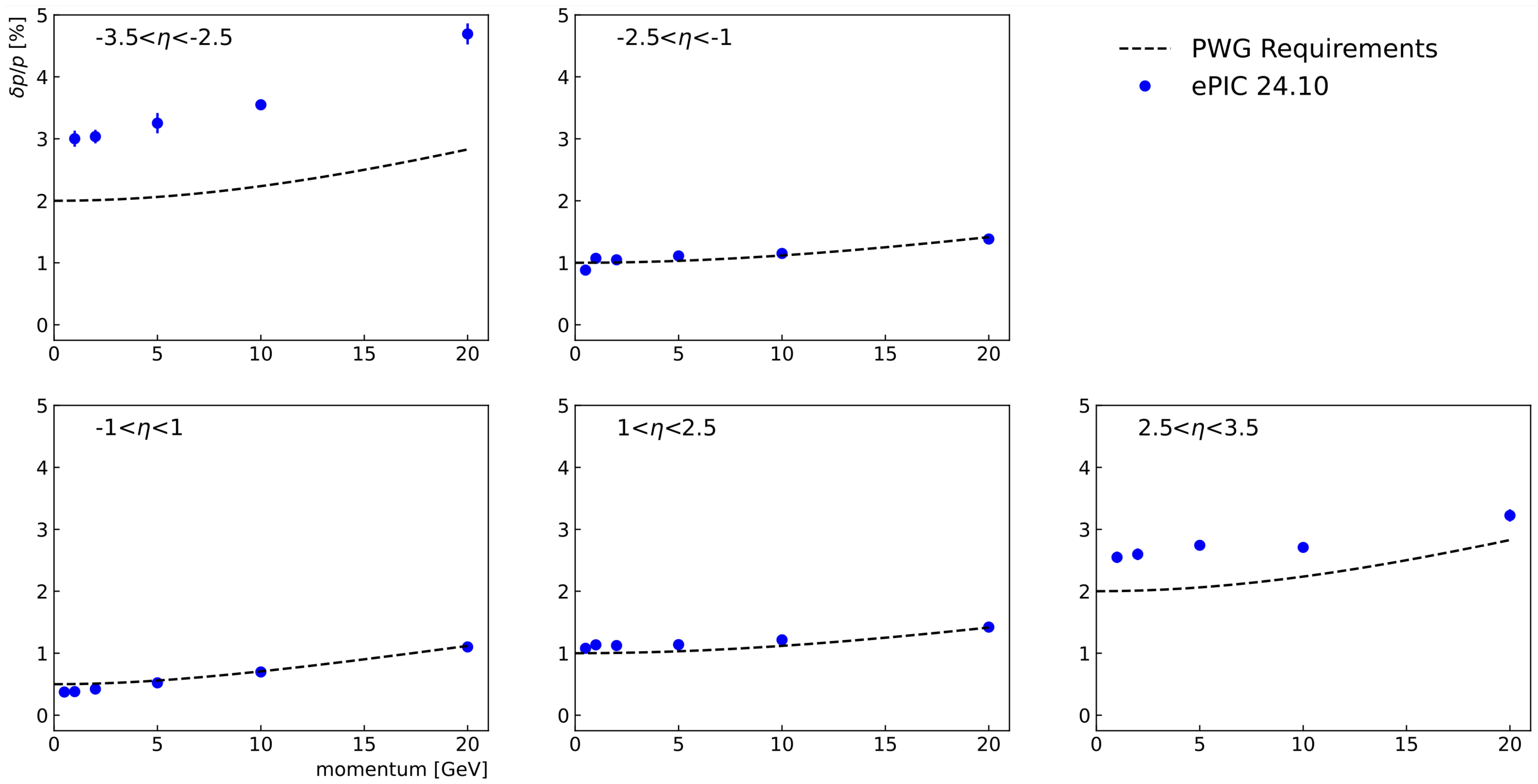
µRWELL disks

- Provide redundancy and pattern recognition for tracking.
- Aid in background rejection

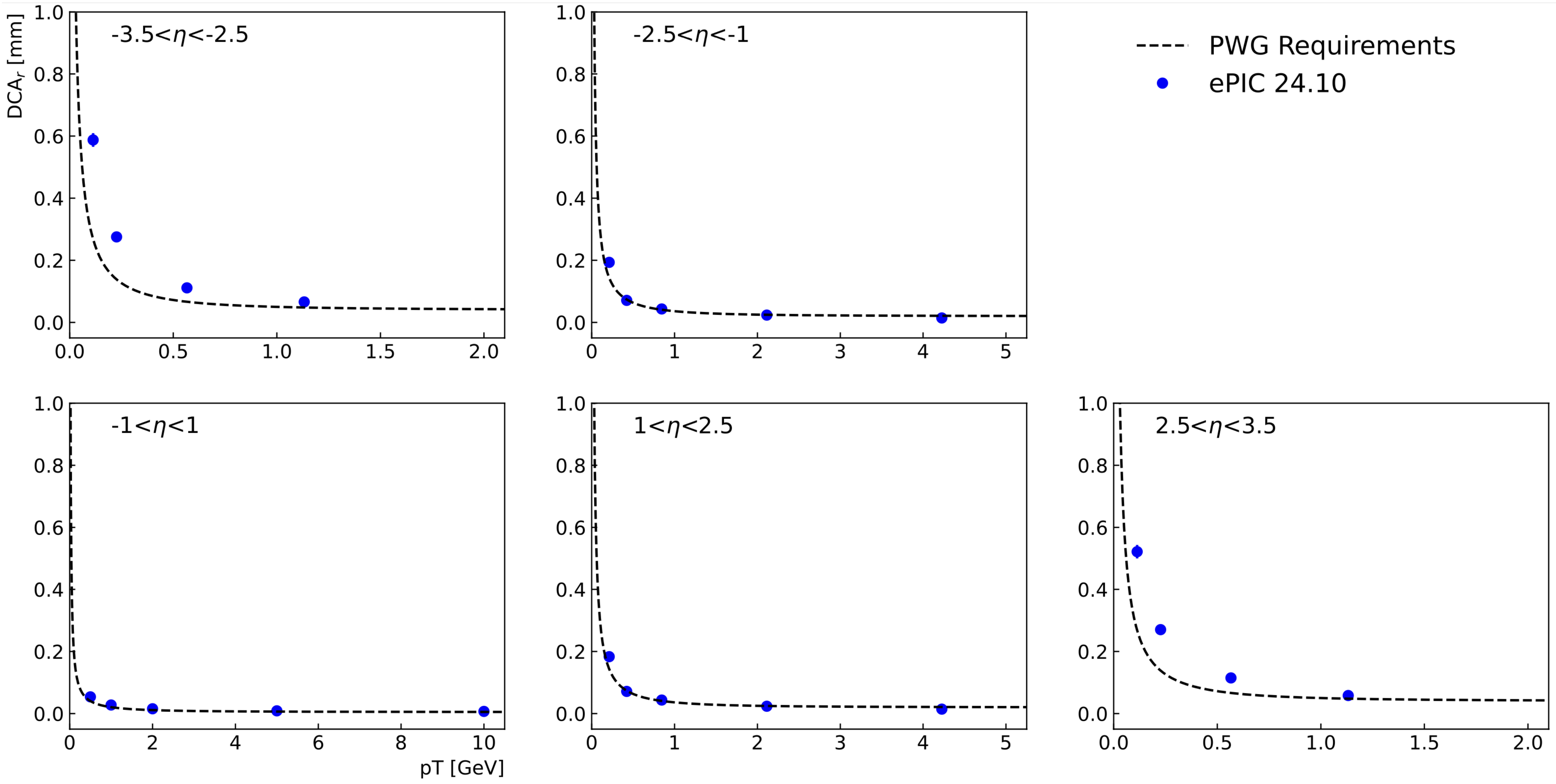
Tracking subsystems at ePIC

Track finding and reconstruction performed using the **ePIC software stack with ACTS-based algorithms**

- Reconstruction parameters optimized with **tuned ACTS settings**
- Results from **full GEANT simulations** of the ePIC central tracking system (SVT + MPGD + AC-LGAD)

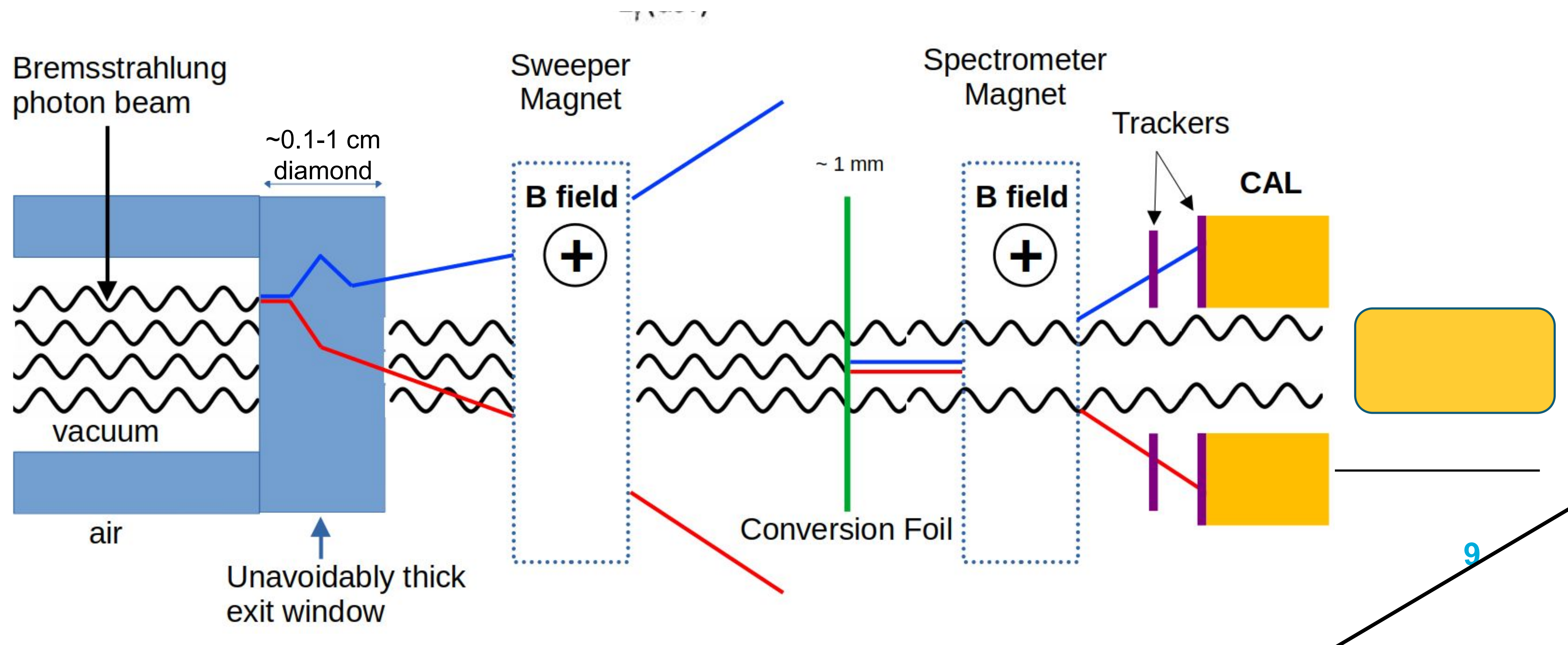


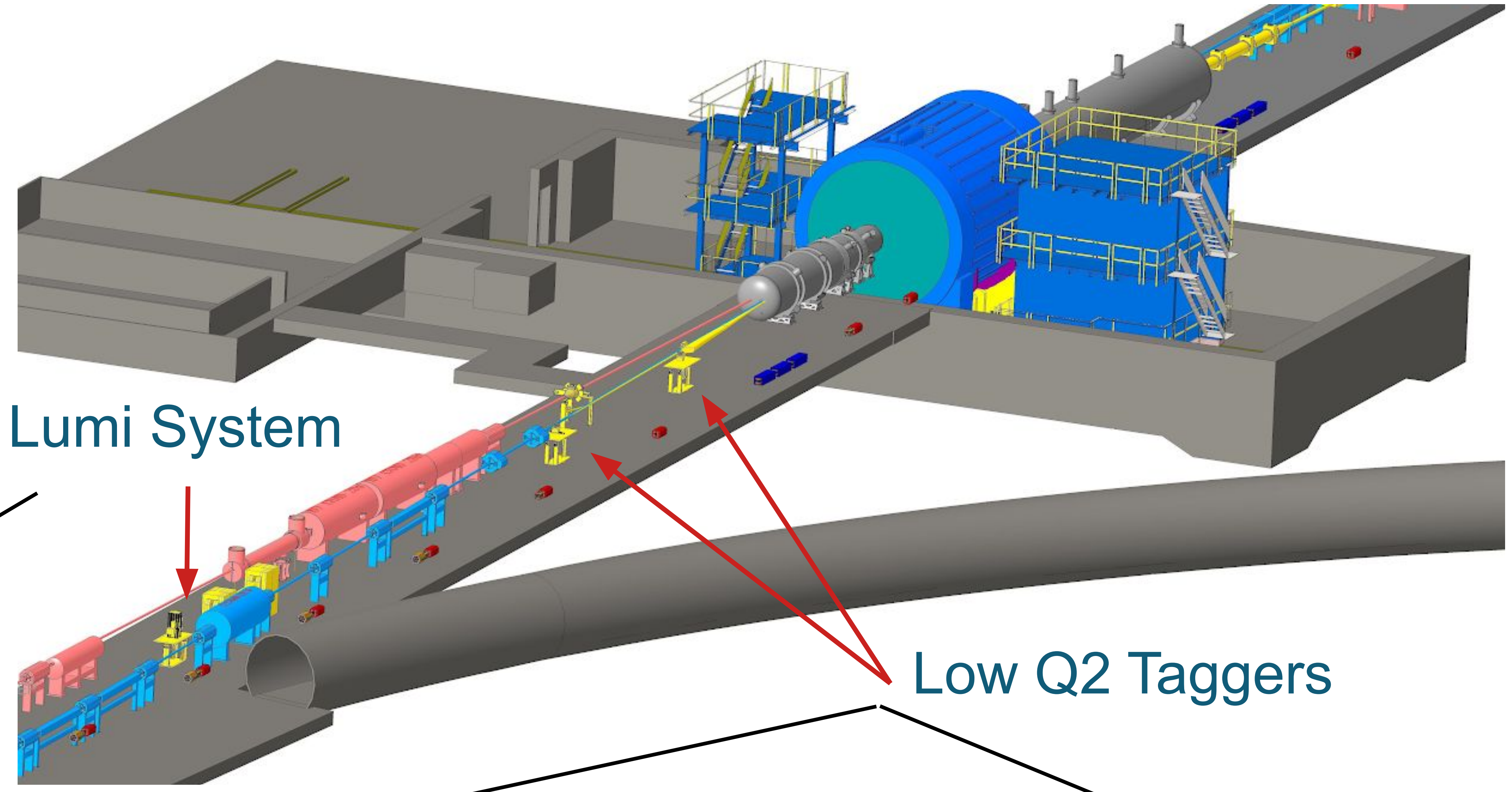
Relative Momentum Resolution for Charged Pions



Distance of Closest Approach (DCA) Resolution for reconstructed charged pion tracks

Far-Backward subsystems at ePIC



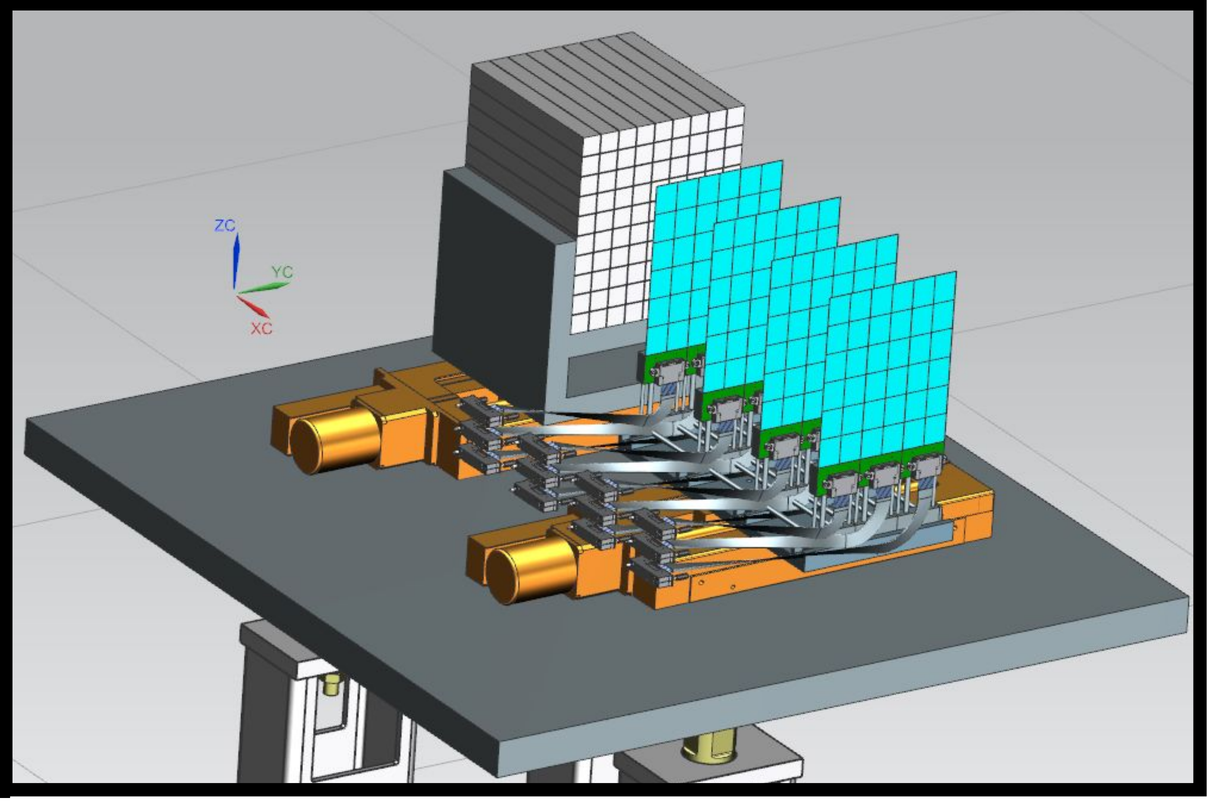


Main Function:
measure bunch-by-bunch luminosity through Bethe-Heitler process

Technology:
Pair-spectrometer: each with
2 tracking layers of AC-LGAD / FCFD
Synergy with Barrel-ToF
Calorimeter: Tungsten-powder + SciFi SPACAL
Synergy with forward ECal

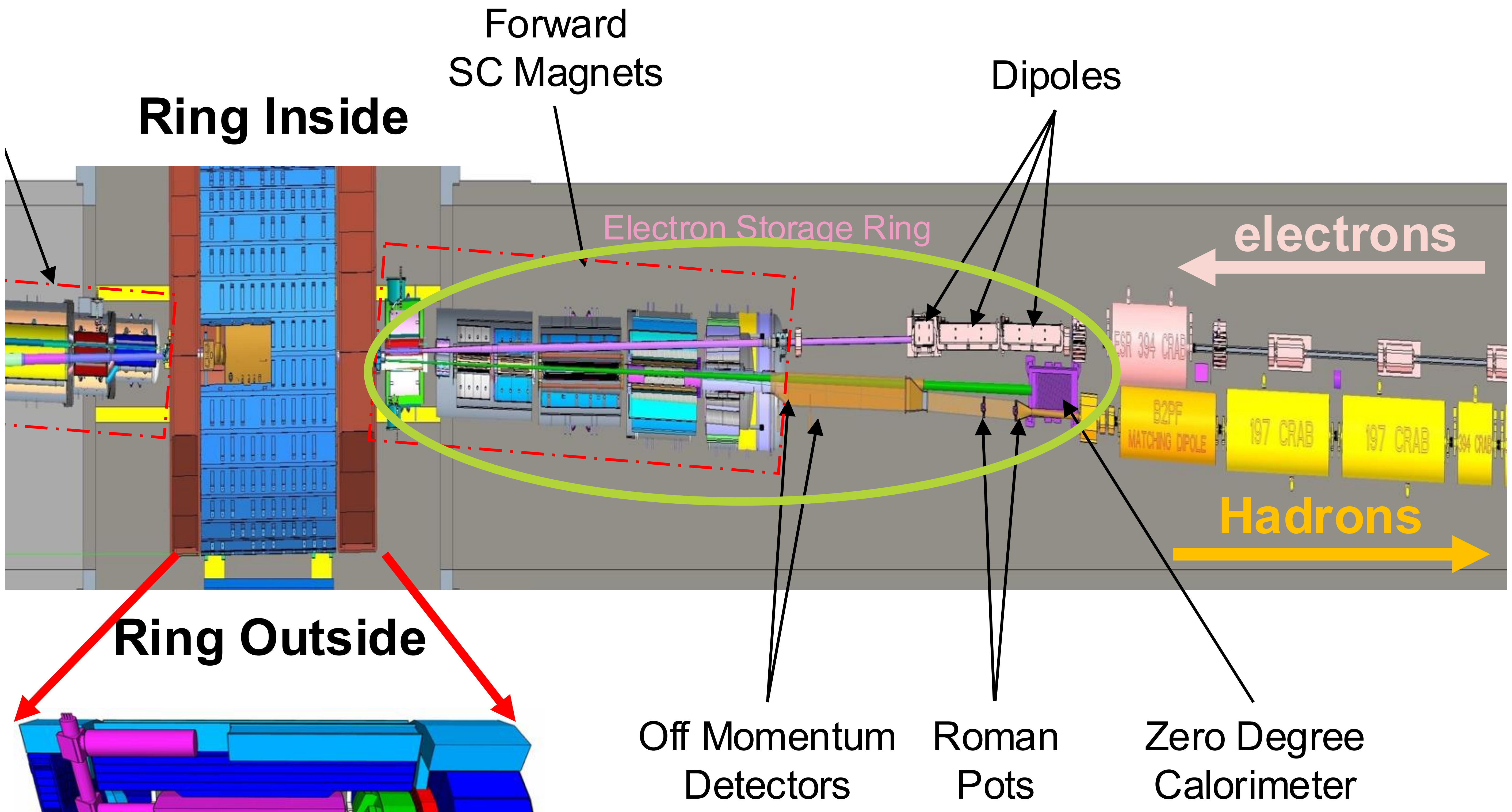
Main Function:
detection of scattered electrons

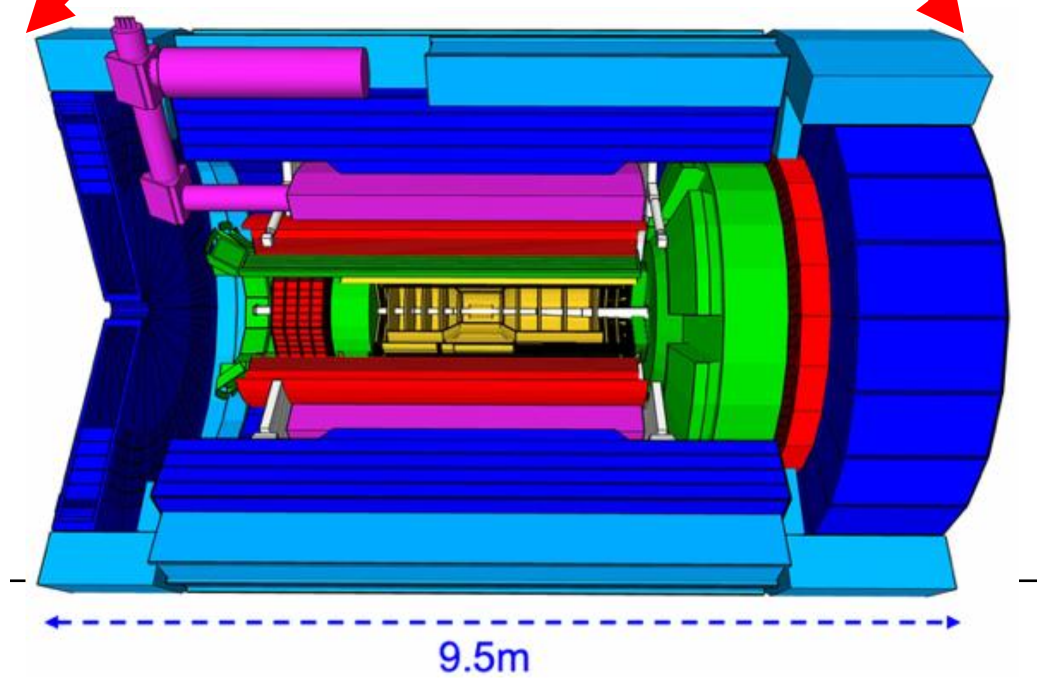
Technology:
2 stations with 4 tracking layers each ($16 \times 18 cm^2$)
Si / Timepix4
Calorimeter: Tungsten-powder + SciFi SPACAL
Synergy with forward ECal



Far-Forward subsystems at ePIC

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





Off Momentum Detectors Function:
detection of forward scattered protons and and γ
Technology:
4 tracking layers each
AC-LGAD / EICROC (500x500 mm^2 pixel)
Synergy with forward ToF
EMCAL: 2x2x20 cm^3 PbWO$_4$ calorimeter
Synergy with backward ECal

detection of forward scattered neutrons and γ

Technology:
EMCAL: 2x2x20 cm^3 PbWO$_4$ calorimeter
Synergy with backward ECal
HCAL: Steel-SiPM-on-Tile
Synergy with forward HCal

Summary

- EIC will be the **first** polarized electron proton/ion and electron nucleus collider providing high luminosity beams with wide range of energies

- EIC will enable opportunities for many important QCD studies

- The ePIC collaboration is dedicated to build the first detector system at IP6 with many world's first technologies to provide high coverage for nuclear physics programs

Exciting times ahead as the construction and operation of EIC & ePIC advances