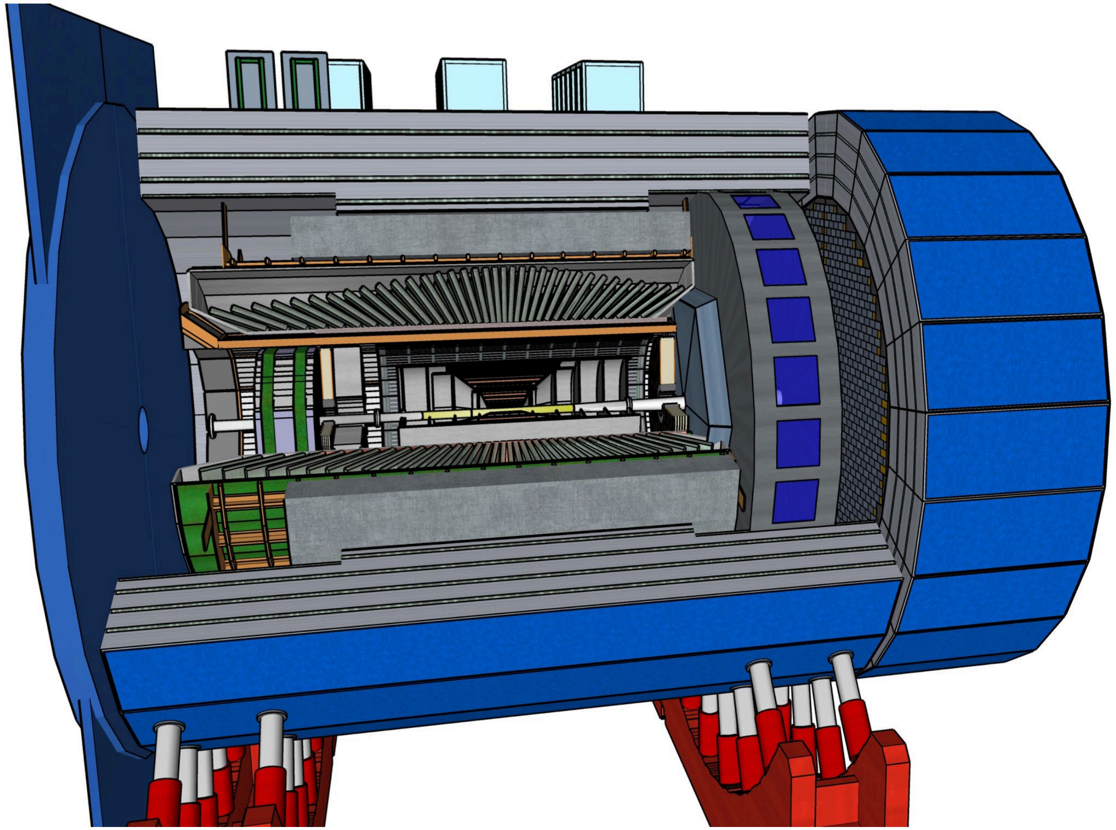
ECCE

EIC Comprehensive Chromodynamics Experiment



ECCE Detector

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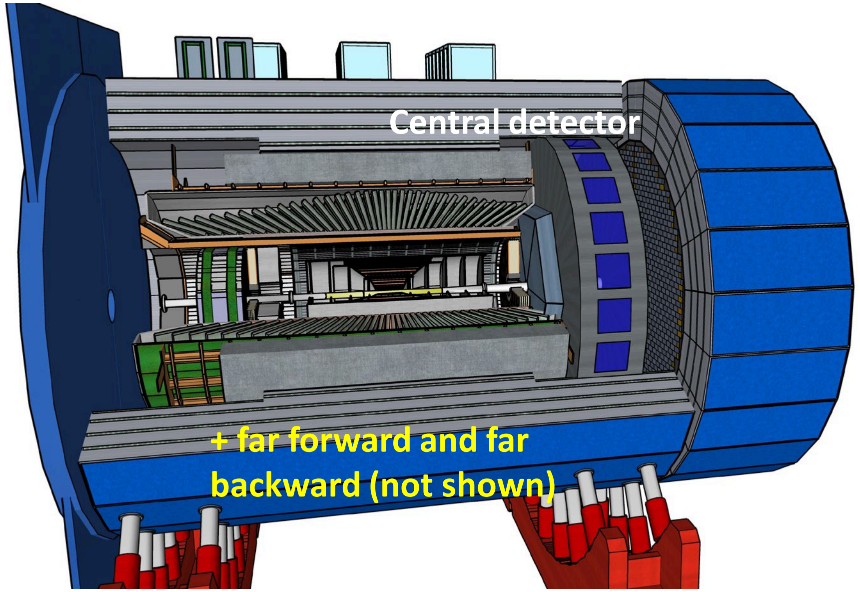
EIC Detector General Requirements

EIC physics measurements require a detector with unique capabilities



- ❑ Large rapidity at least $-3.5 < \eta < 3.5$ (YR) coverage; and far beyond in especially far-forward detector regions
- ❑ High precision low mass tracking
  - small (vertex) and large radius tracking
- ❑ Electromagnetic and Hadronic Calorimetry
  - equal coverage of tracking and EMCal
- ❑ High performance PID to separate π, K, p at 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

➢ **Integration into Interaction Region is critical (done in common with EIC Project)**

The ECCE Magnet

- The BaBar superconducting solenoid will be repurposed for the ECCE detector.
    - The BaBar magnet is already at BNL for use by the sPHENIX experiment (see photo).
- ECCE also plans to reuse the surrounding combined hadronic calorimeter and flux containment system for this magnet
- This provides the 1.4 T field that suffices to do the EIC science with an AI optimized detector

Central Induction	1.5 T* (1.4 T in ECCE flux return)
Conductor Peak Field	2.3 T
Winding structure	Two layers, graded current density
Uniformity in tracking region	±3%
Winding Length	3512 mm *at R.T.*
Winding mean radius	1530 mm *at R.T.*
Operating Current	4596 A (4650 A*)
Inductance	2.57 H (2.56 H*)
Stored Energy	27 MJ
Total Turns	1067
Total Length of Conductor	10,300 m

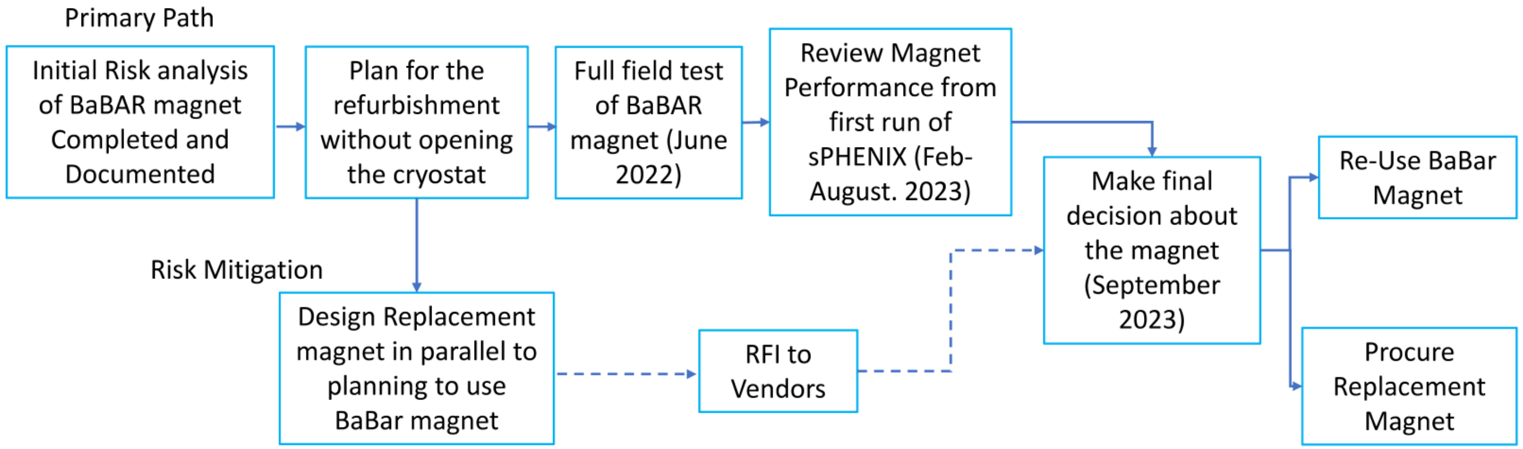
* Design Value

Table 2.3: Design parameters of the BaBar superconducting solenoid.

- *The warm bore diameter of 2.84m and coil length of 3.512 m corresponds to a 39 deg angle, this covers the required region covered by the barrel detectors in the YR (~40 deg angle).*
- *Reuse of a magnet can induce risk, so we plan to mitigate this risk.*

The ECCE Magnet Reuse Plan

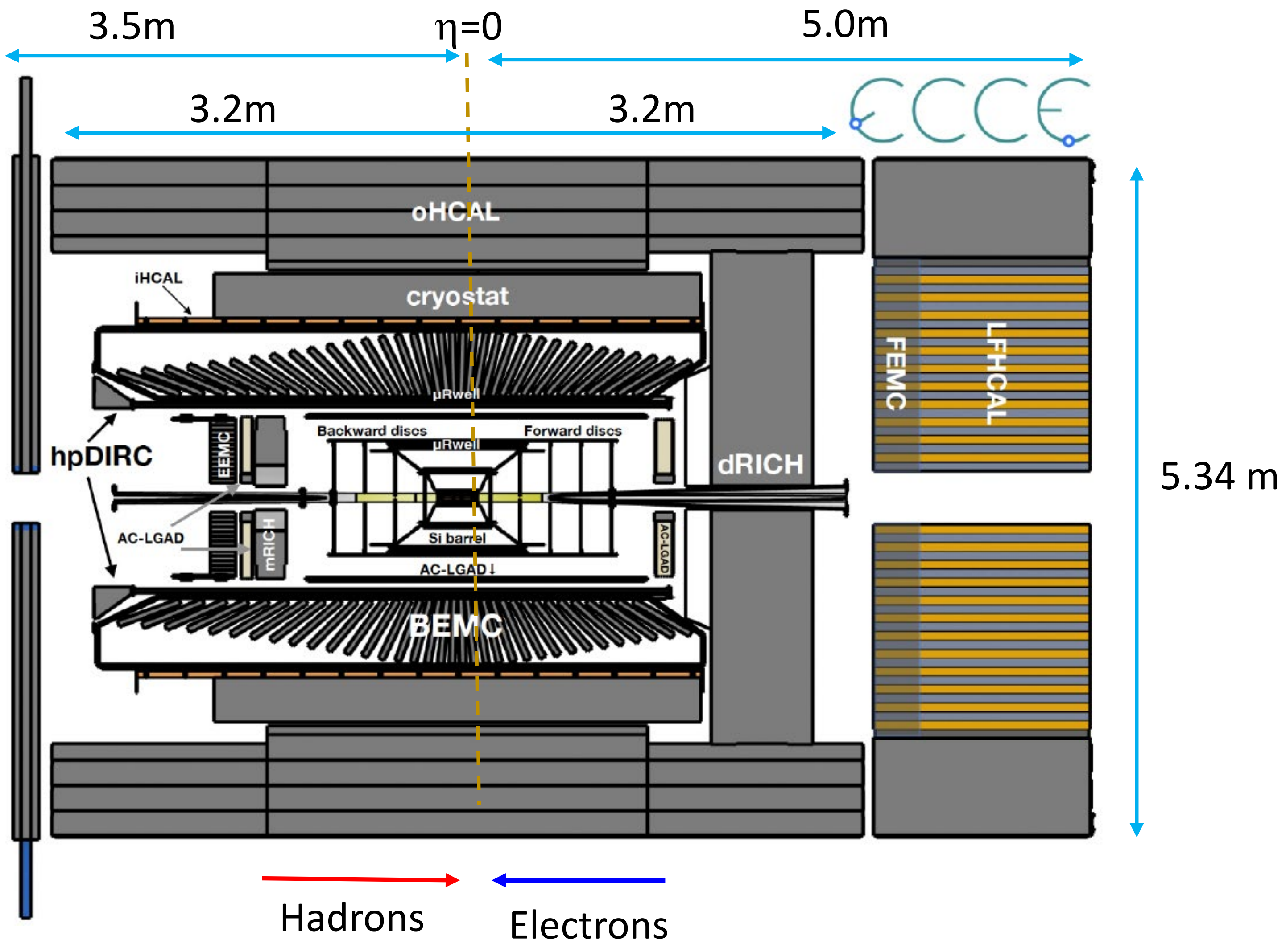
- An engineering study and risk analysis in 2020 concluded that the ***"magnet should be suitable for prolonged use as part of the detector system for the EIC project."***
- The study suggested the implementation of several proactive maintenance and improvement modifications.
- If the magnet continues to operate well throughout a high-field magnet test with the sPHENIX experiment, this refurbishment can be done without opening the cryostat.
- The scope of the reuse of the BaBar solenoid in ECCE includes a review by a panel of experts (following initial sPHENIX running), the disconnect of the magnet in IP-8 and move to IP-6, a new valve box, and assembly and magnet mapping in IP-6.
  - We include E&D for a new BaBar magnet in the scope as schedule risk mitigation – see John Lajoie's talk.



The ECCE Reference Detector

The ECCE detector size is determined by the reuse of the BaBar magnet and sPHENIX HCAL, and further EIC detector needs:

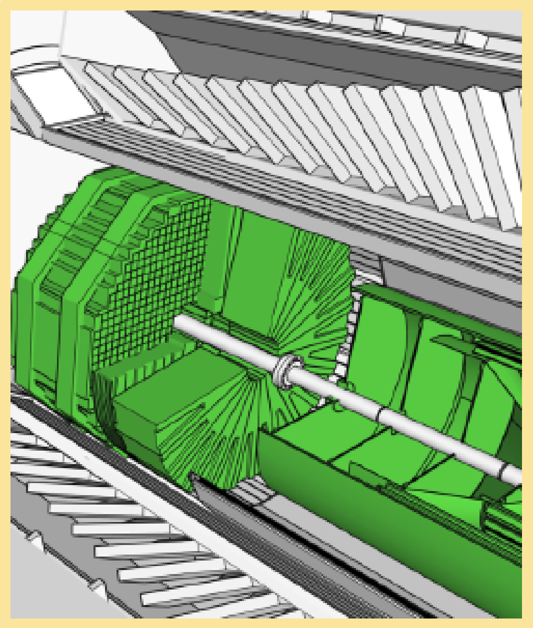
- Needs +5 m on proton/ion side.
- Needs less space (-3.5 m) on electron side.
- The detector radius is 2.7 meter, with the RCS beam at 3.35 meter.



- ❑ -4.5 /+5.0 m machine-element-free region available for central EIC detector
- ❑ 25 mrad crossing angle (IP6 design)
- ❑ Detector rotated by 8 mrad in horizontal plane to account for e-beam angle

The ECCE Reference Technologies

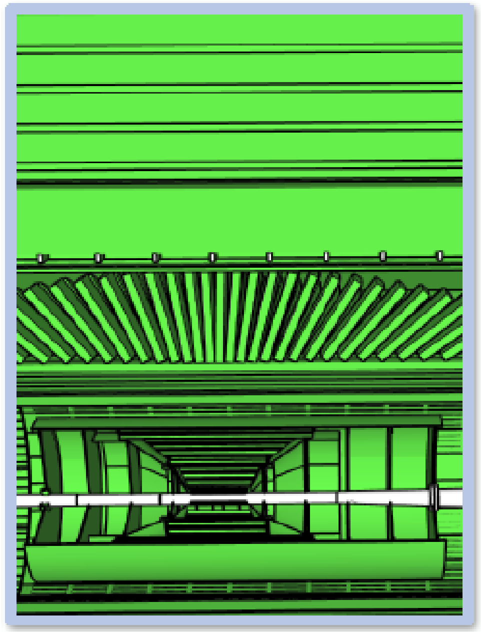
For additional technical details if desired please see the ECCE technical notes: https://www.ecce-eic.org/ecce-internal-notes (PW: ECCEprop)



Backward Endcap

Tracking:
- ITS3 MAPS Si discs (x4)
- AC-LGAD

PID:
- mRICH
- AC-LGAD TOF
- $PbWO_4$ EM Calorimeter (EEMC)



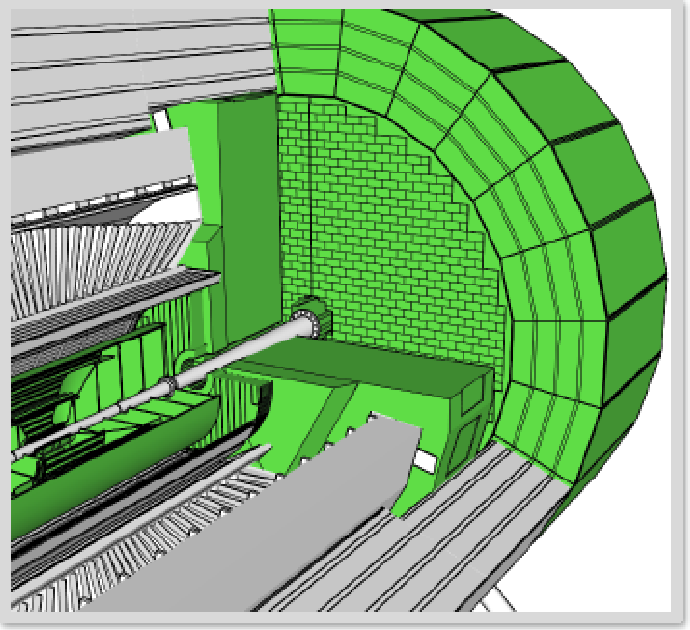
Barrel

Tracking:
- ITS3 MAPS Si (vertex x3; sagitta x2)
- μRWell outer layer (x2)
- AC-LGAD (before hpDIRC)
- μRWell (after hpDIRC)

h-PID:
- AC-LGAD TOF
- hpDIRC

Electron ID:
- SciGlass EM Cal (BEMC)

Hadron calorimetry:
- Outer Fe/Sc Calorimeter (oHCAL)
- Instrumented frame (iHCAL)



Forward Endcap

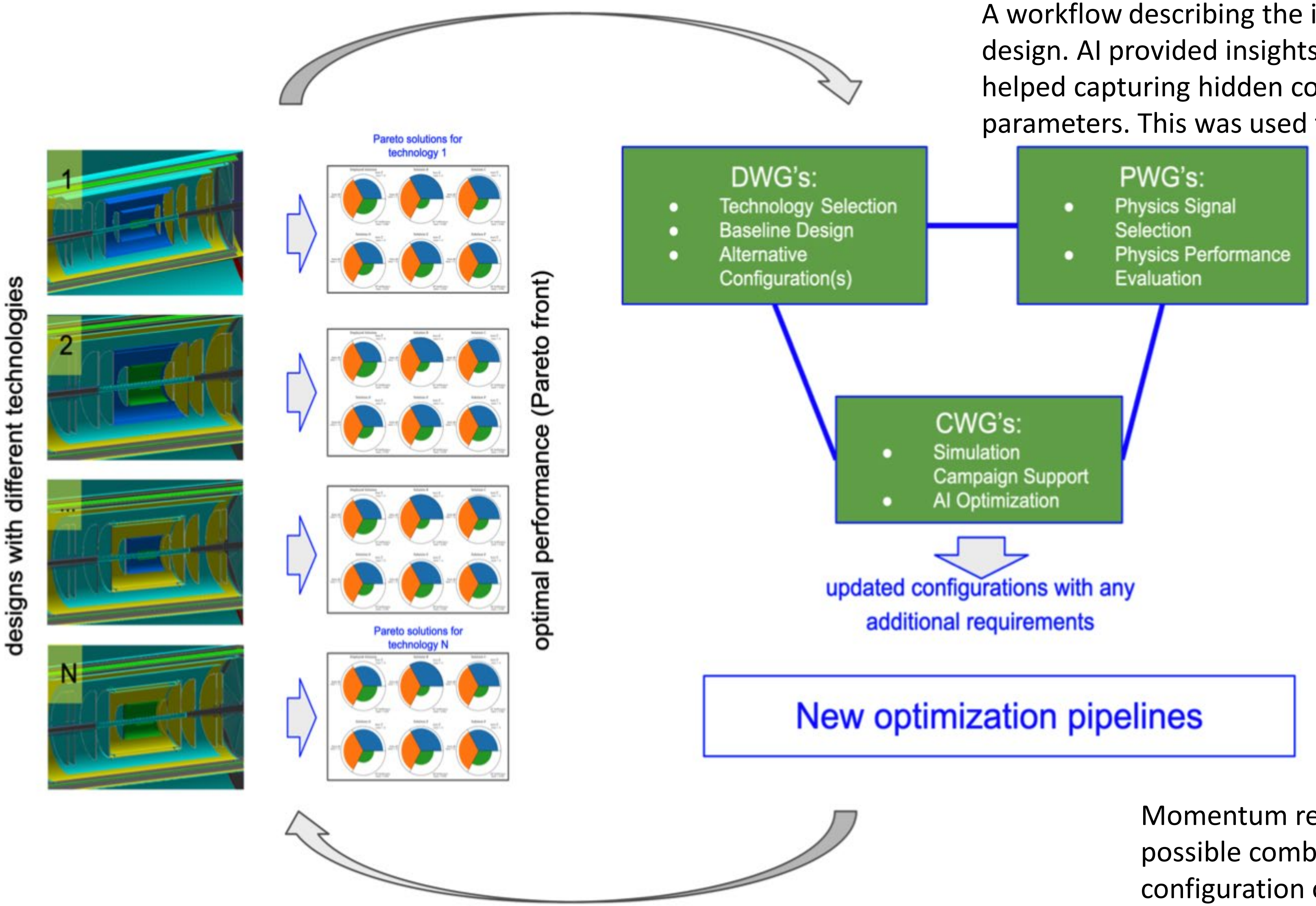
Tracking:
- ITS3 MAPS Si discs (x5)
- AC-LGAD

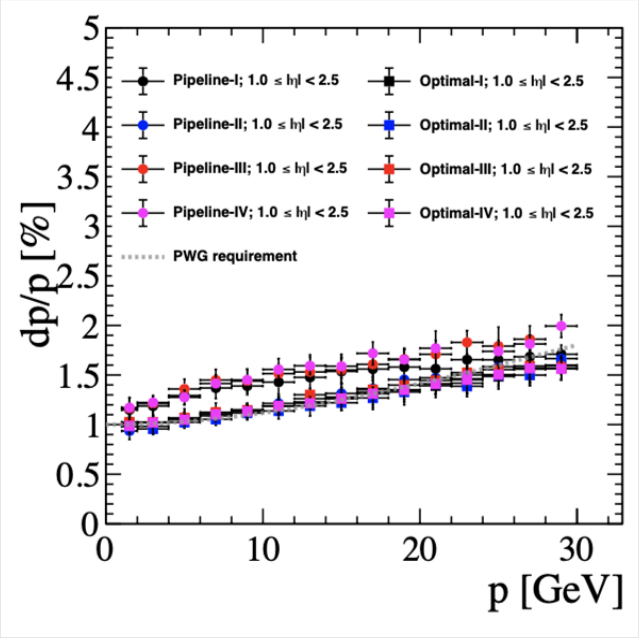
PID:
- dRICH
- AC-LGAD TOF

Calorimetry:
- Pb/ScFi shashlik (FEMC)
- Longitudinally separated hadronic calorimeter (LHFCAL)

AI-Assisted Optimization during the ECCE Proposal

A workflow describing the iterative process of detector design. AI provided insights for technology choices and helped capturing hidden correlations among the design parameters. This was used to steer the design

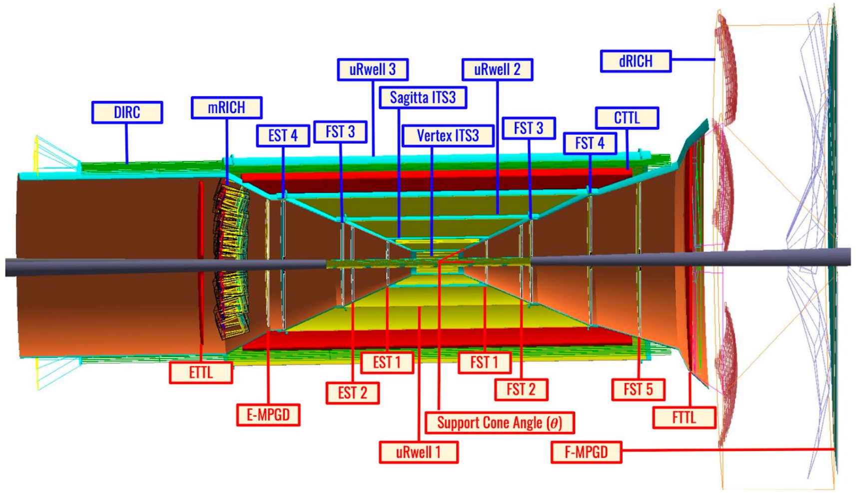


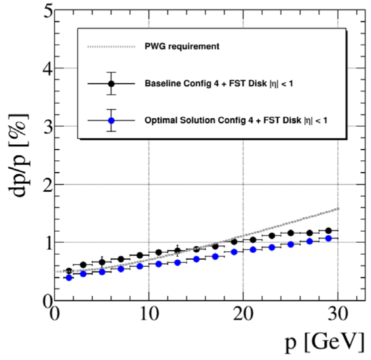


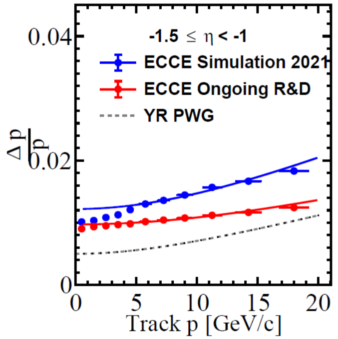
Momentum resolution of different pipelines corresponding to different possible combinations of technology optimized with AI. The AI-optimized configuration outperformed the original designs in all η bins.

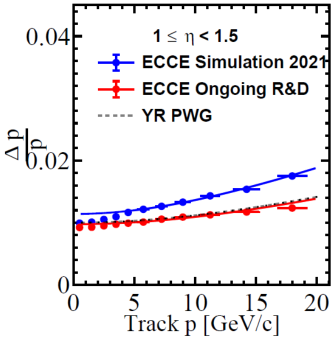
ECCE AI-Assisted Design Solutions

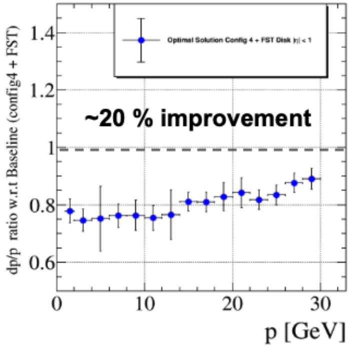
- **Tracking:** technology choice, ordering of detectors,…





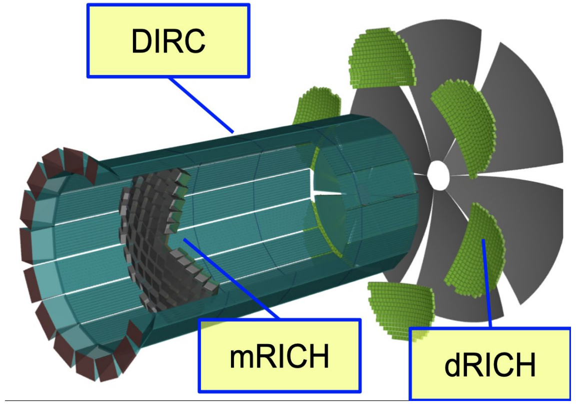


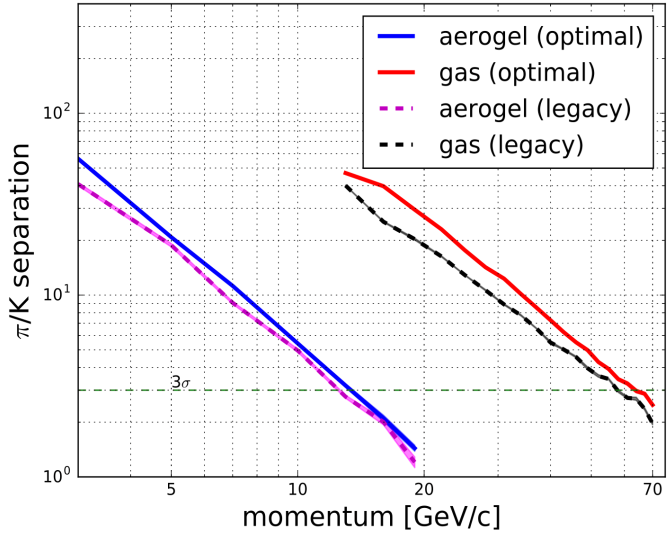




- **Support structure optimization** to reduce impact of readout and services on tracking resolution

- **PID:** material choice, ordering of components,…



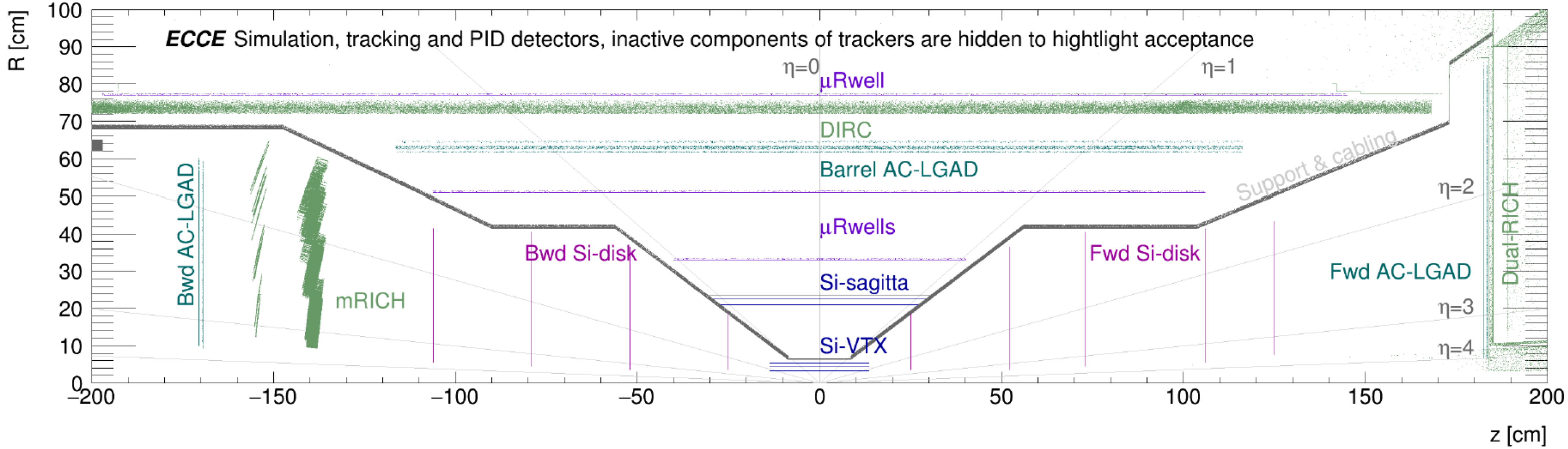


E. Cisbani, A. Del Dotto, C. Fanelli, M. Williams et al. *JINST* 15.05 (2020): P05009.

- Bayesian optimization of the dRICH Design
- Improvement of dRICH performance for ECCE expected from AI-based optimization completed
- Ongoing efforts on reconstruction algorithms

- **Calorimetry:** using ML for pion rejection

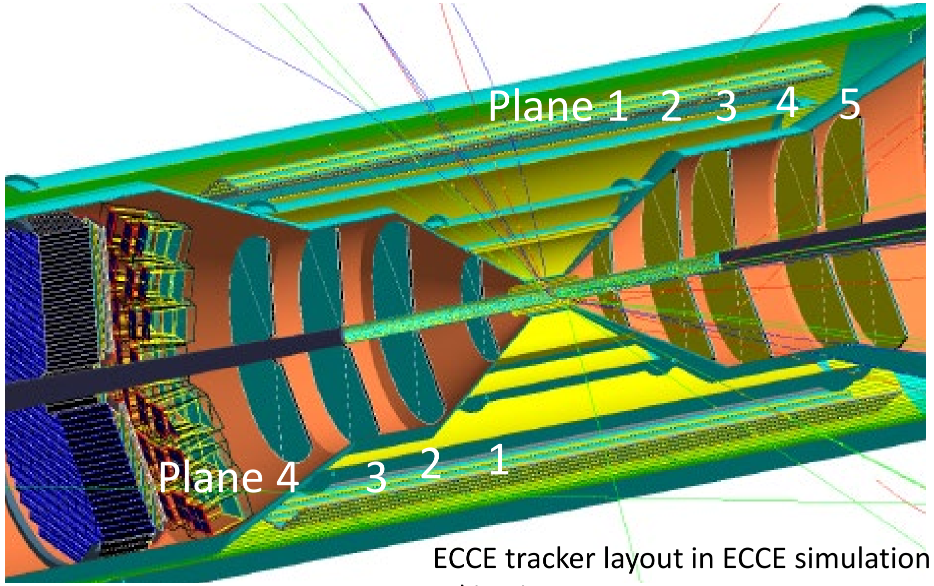
ECCE Tracking System



- Hybrid tracking detector design: Monolithic Active Pixel Sensor (**MAPS**) based silicon vertex/tracking subsystem, the **muRWELL** tracking subsystem and the **AC-LGAD** outer tracker, which also serves as the ToF detector. Ordering and resolution optimization were driven by AI.
  - MAPS 3-layer silicon vertex, 2-layer silicon sagitta layers, five disks in the hadron endcap, four disks in the electron endcap for primary and secondary vertex reconstruction
  - muRWell 2 layers in the barrel following silicon and cylindrical muRWell gas trackers at large radii providing a tracking layer after the DIRC – integrated with PID/DIRC performance
  - AC-LGAD ToF layer provides precision space-time measurement on each track – integrated with PID

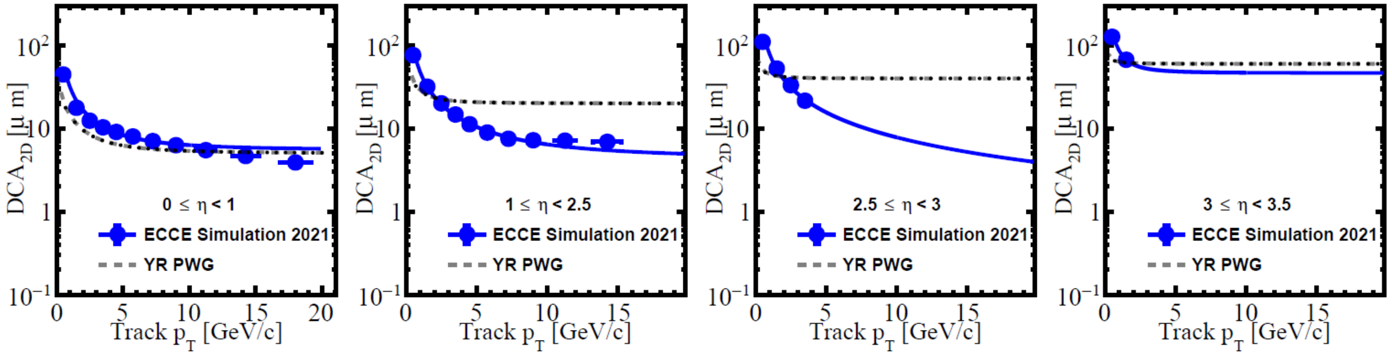
MAPS Vertex

- ❑ For primary and secondary vertex reconstruction
- ❑ Low material budget: 0.05% X/X_0 per layer
- ❑ High spatial resolution: 10 μm pitch MAPS (Alice ITS3)
- ❑ TowerJazz 65nm technology (ongoing R&D Si Consortium)
- ❑ Configuration: Barrel + Disks for endcaps

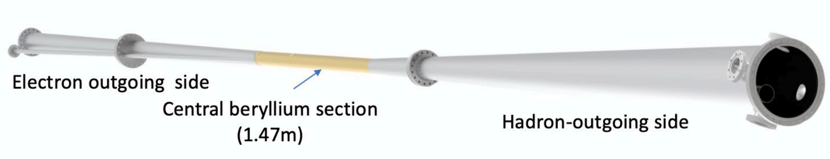


ECCE tracker layout in ECCE simulation taking into account support structures

ECCE achieves high precision primary and decay vertex determination, fine tracking momentum and distance of closest approach resolution in |η|<3.5 with full azimuth coverage



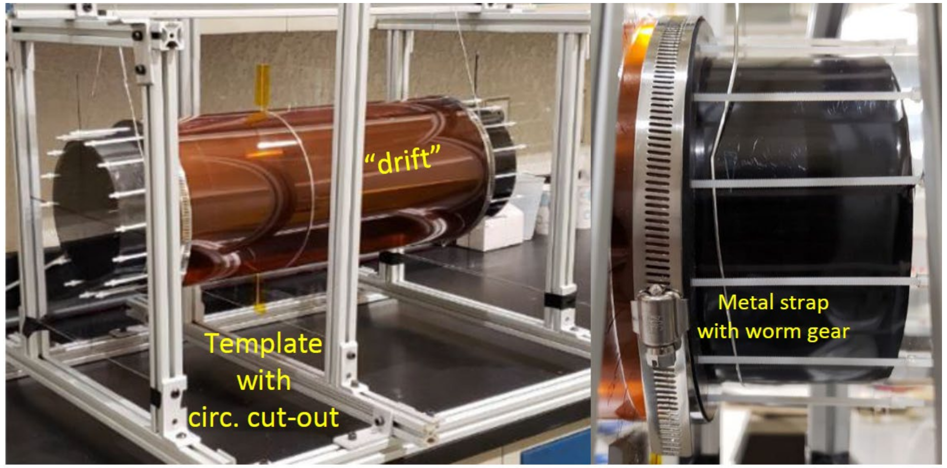
ECCE simulations

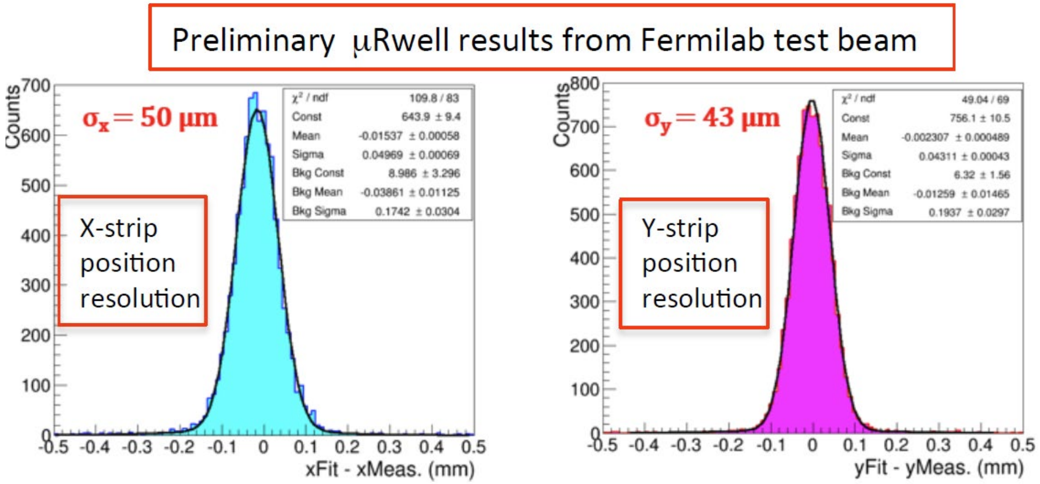


- ❑ Central area of beampipe (around IP):
  ~1.5m of beryllium to minimize multiple scattering for low P_T particles
- ❑ ECCE studies also include a Synchrotron shielding coating in the Be-section of the beam pipe (2 μm Au coating)
- ❑ Low-mass exit window for far-forward particles

muRWell

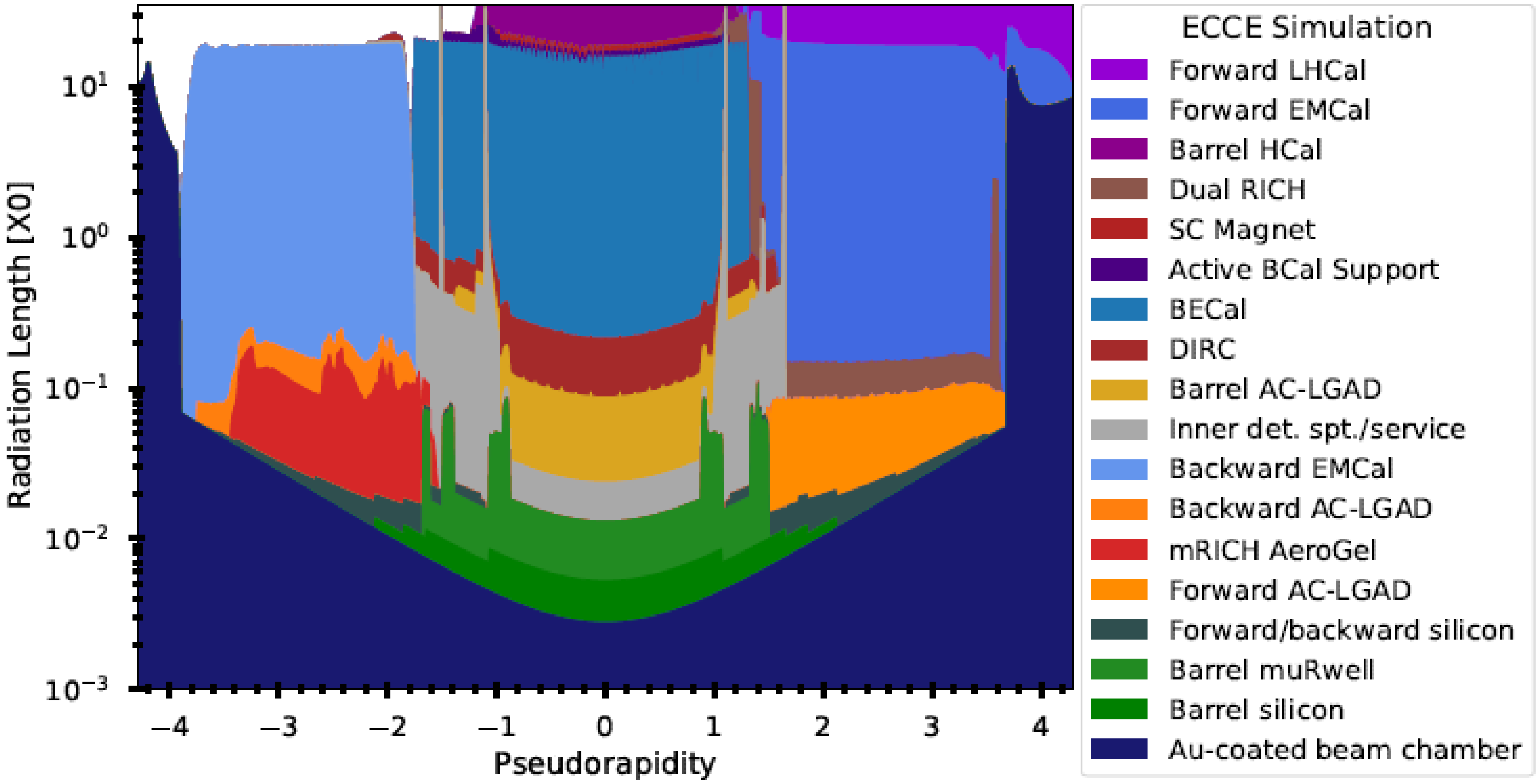
- The ECCE muRWell technology is based on the outcome of the EIC generic R&D (eRD6) and in line with the reference EIC detector concept in the Yellow Report.
- Geometries and ordering of layers were optimized with AI assistance to fit the ECCE baseline design while maintaining performance and also being integrated with PID
- The muRWell technology is expected to provide spatial resolution well below 100 um for curved geometry estimated based on recent beam tests (ongoing R&D eRD108)
- Large-area detectors possible - cost efficient compared to silicon large surface detectors
    - Expertise in the ECCE consortium - a Korean manufacturer (Mecaro) has demonstrated that they can produce high quality large MPGD foils for the CMS detector at the LHC





ECCE Material Budget

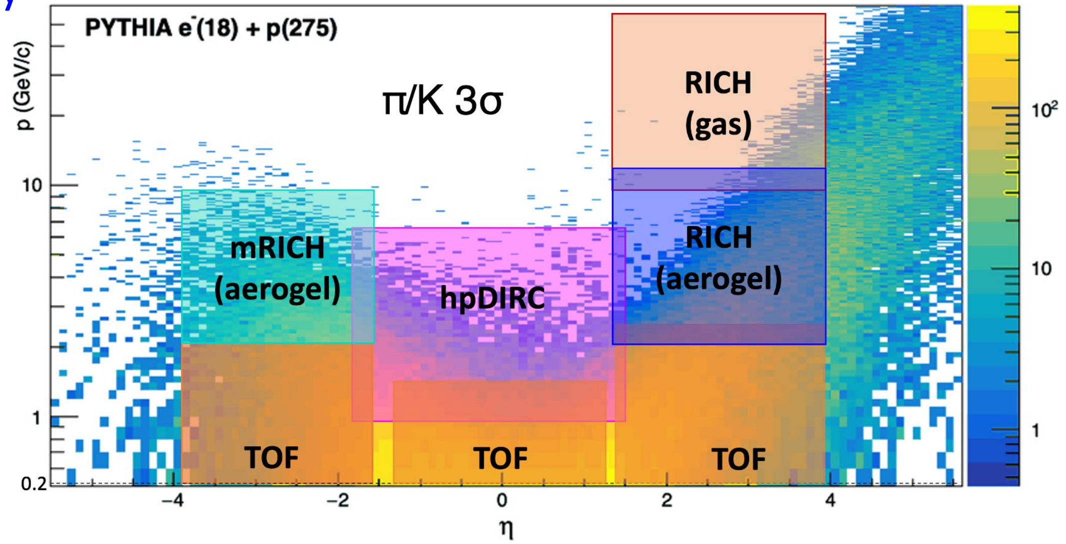
- Low material budget
  - Minimize bremsstrahlung and conversions for primary particles
  - Improve tracking performance at large |η| by minimizing multiple Coulomb scattering
  - Minimize the dead material in front of the high-resolution EM calorimeters



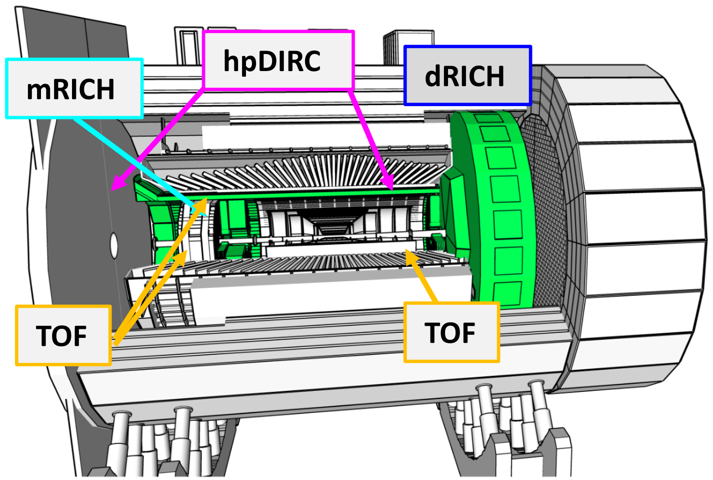
Charged Particle Identification

- In general, need to separate:
  - Electrons from photons
  - Electrons from charged hadrons -> mostly provided by calorimetry
  - Charged pions, kaons and protons from each other -> **Cherenkov**

Cherenkov detectors, complemented by other technologies at lower momenta



- **ECCE PID technologies are based on** the outcome of the **EIC generic R&D** (eRD14) and **in line with the reference EIC detector concept in the Yellow Report.**
  - Backward: Short, modular RICH **(mRICH)**
  - Barrel: Radially compact with flexible design high-performance DIRC **(hpDIRC)**
  - Forward: Double-radiator RICH **(dRICH)**
  - AC-LGAD based time-of-flight (TOF) system for hadronic PID in momentum range below the thresholds of the Cherenkov detectors



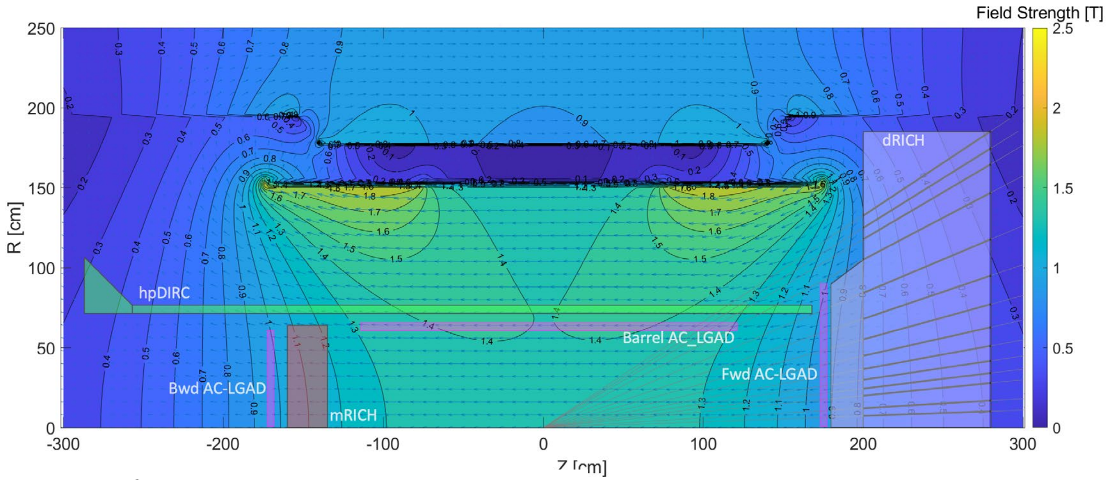
Charged Particle Identification

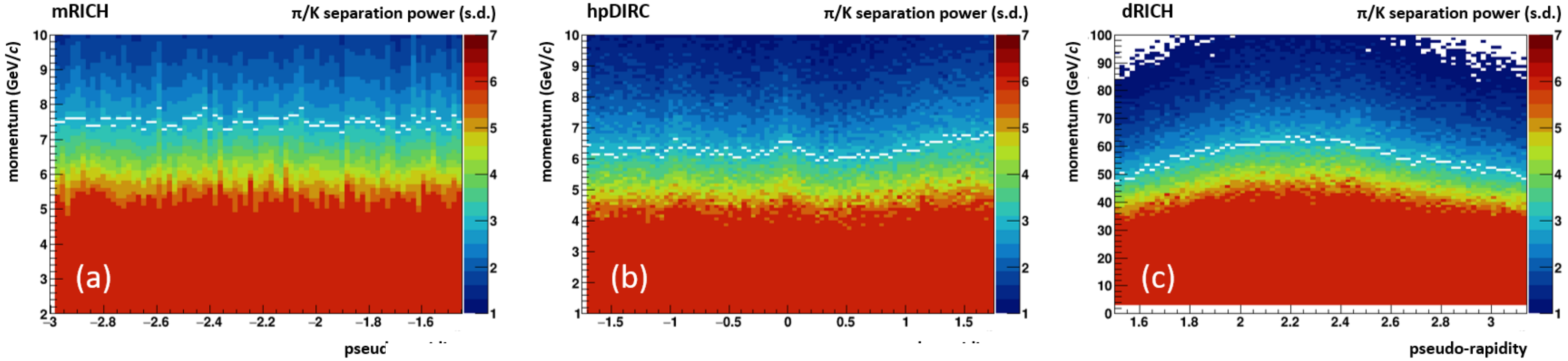
- ❑ In general, need to separate:
  - ➢ Electrons from photons
  - ➢ Electrons from charged hadrons -> mostly provided by calorimetry
  - ➢ Charged pions, kaons and protons from each other -> **Cherenkov**

Cherenkov detectors, complemented by other technologies at lower momenta

- ❑ **Geometries were optimized to fit the ECCE baseline design while maintaining the required performance** to assure wide momentum coverage across the full phase space.

- ❑ **Magnetic field in ECCE provides a large safety margin in terms of the selected photosensors field tolerance!**
  - ○ For ECCE we have alternate choices beyond SiPM sensors, which could be advantageous for single photon detection

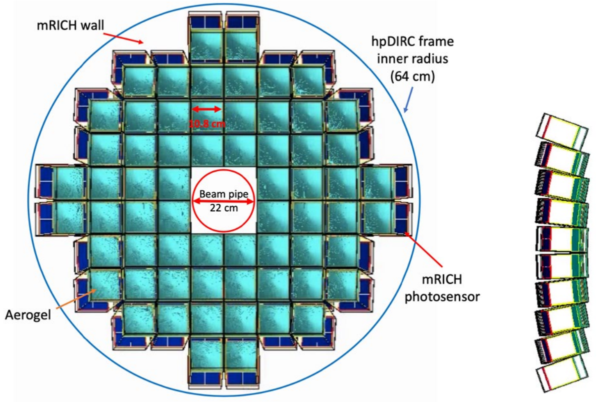


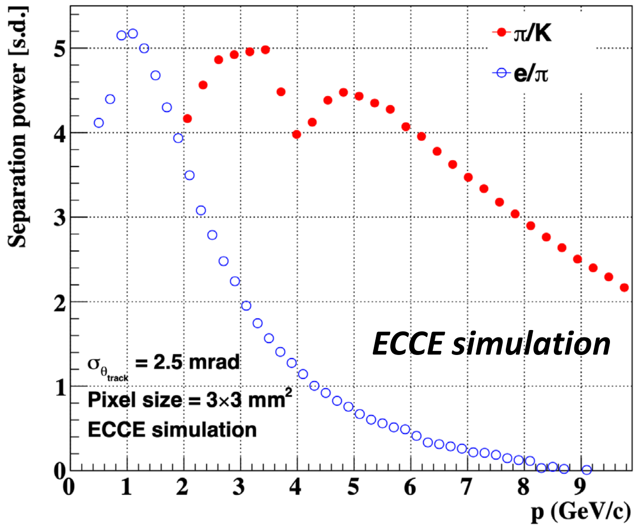


ECCE Simulation: PID Detector Coverage

Backward PID

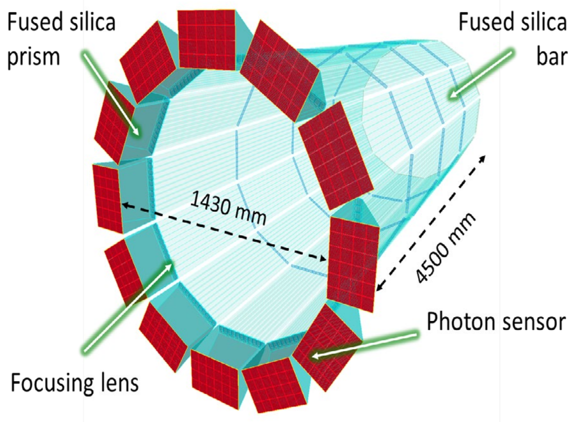
Compact version of a conventional aerogel-based proximity focusing RICH

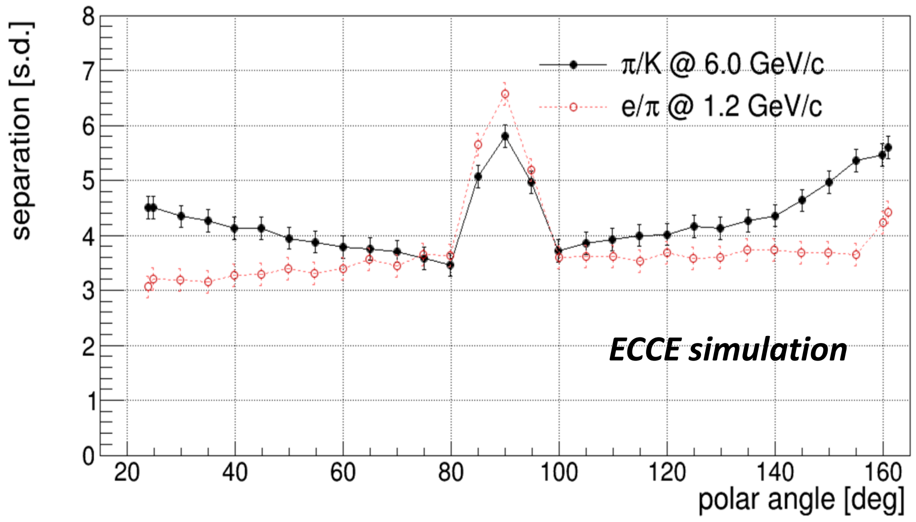




Barrel PID

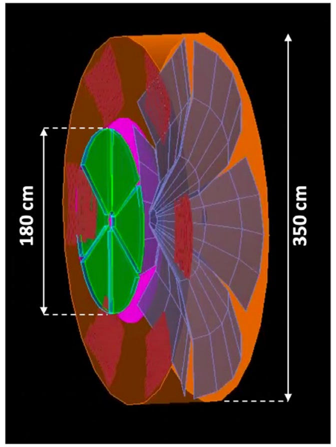
- Radially compact (~ 5cm)
- hpDIRC with better optics and <100 ps timing (π/K up to ~6 GeV/c)

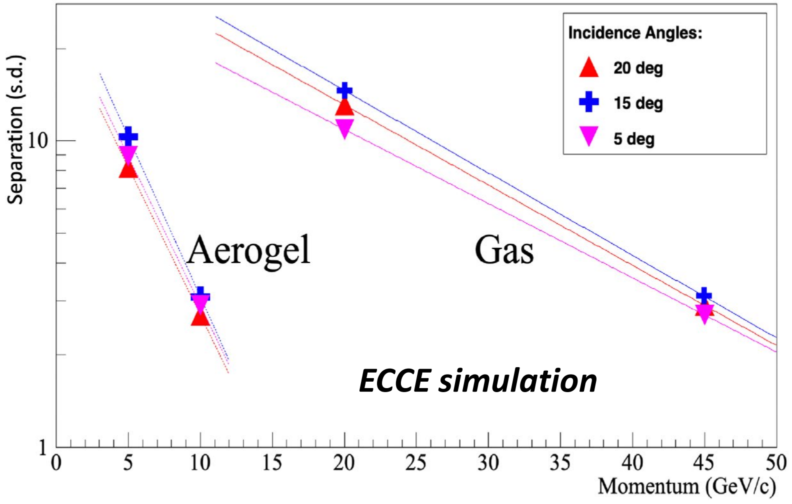




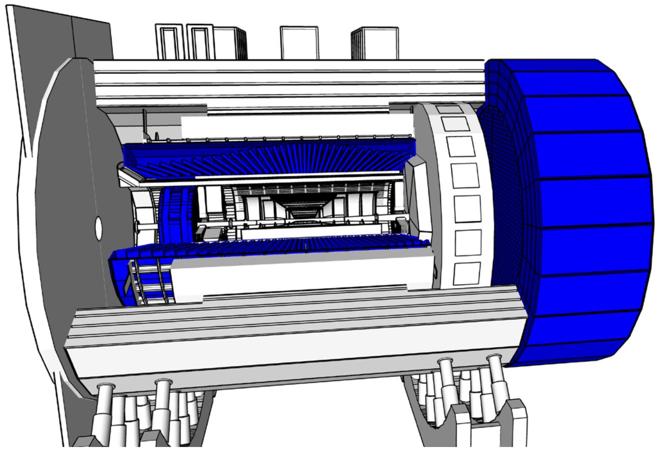
Forward PID

Use a combination of aerogel and C_mF_n with indices of refraction matching EIC momentum range in the forward endcap. Similar to LHC-b, HERMES, JLAB/Hall-B, …

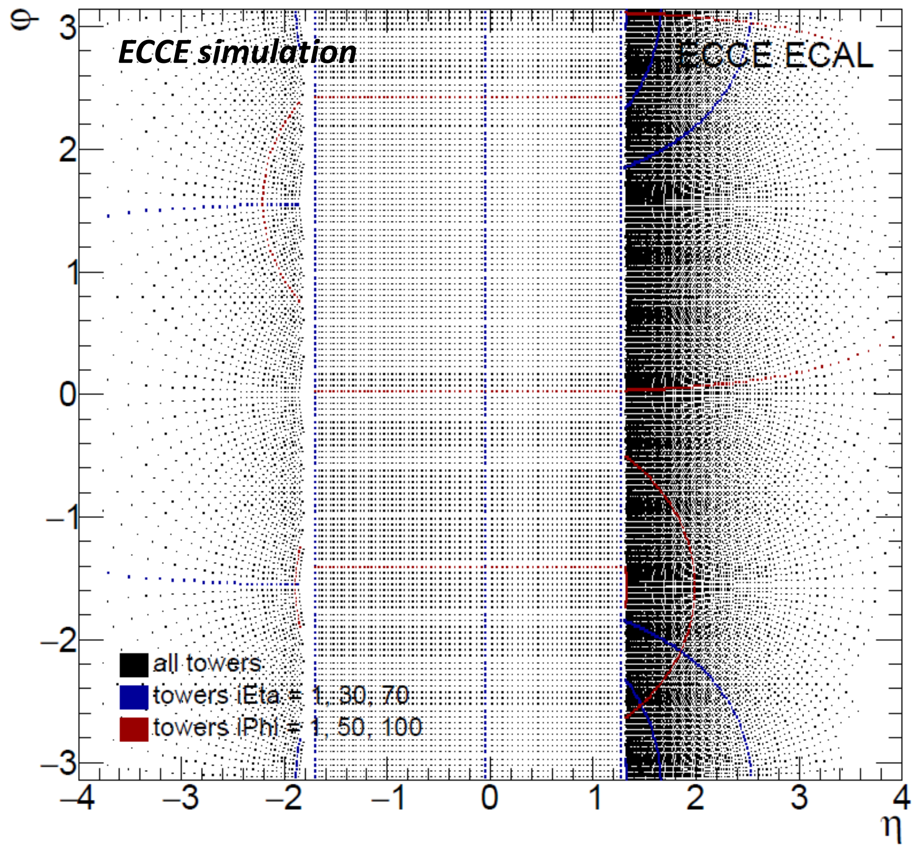




Electromagnetic Calorimeters



- In general, calorimeters need to perform
  - Scattered electron kinematics measurement at large |η| in the e-endcap – most stringent
  - Photon detection and energy measurement
  - e/h separation (via E/p & cluster topology)
  - π^0/γ separation



- **ECCE EMCAL technologies are based on** the outcome of the **EIC generic R&D** (eRD1) and **in line with the reference EIC detector concept in the Yellow Report.**
- **Geometries were optimized to fit the ECCE baseline design with focus on excellent electron detection with the broadest electron detection coverage** across the full phase space.

η	[-4 .. -1.8]	[-1.7 .. 1.3]	[1.3 .. 4]
Material	$PbWO_4$	SciGlass	Pb/Sc
X_0 (mm)	8.9	24-28	16.4
R_M (mm)	19.6	35	35
Cell (mm)	20	40	40
X/X_0	22.5	17.5	19
Δz (mm)	60	56	48

Backward ECAL (EEMC)

Homogeneous calorimeter based on high-resolution $PbWO_4$ crystals

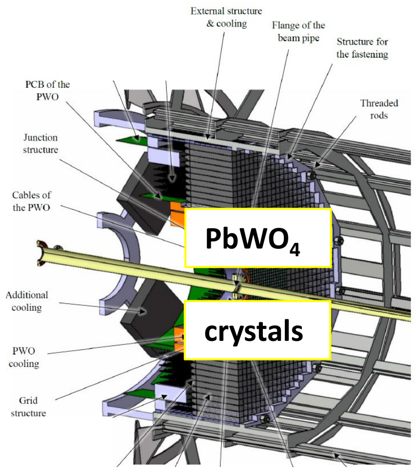


Figure from the EIC EEEMCAL Consortium design report

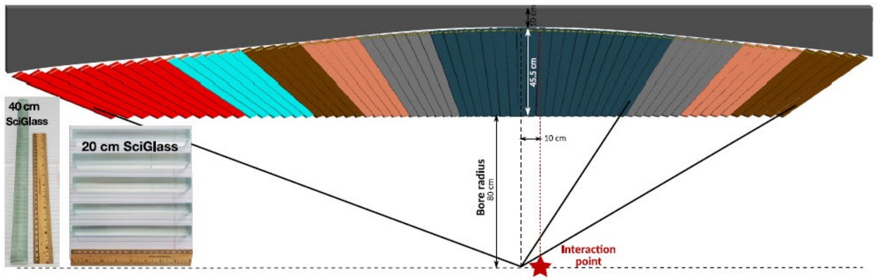
Backward ECAL

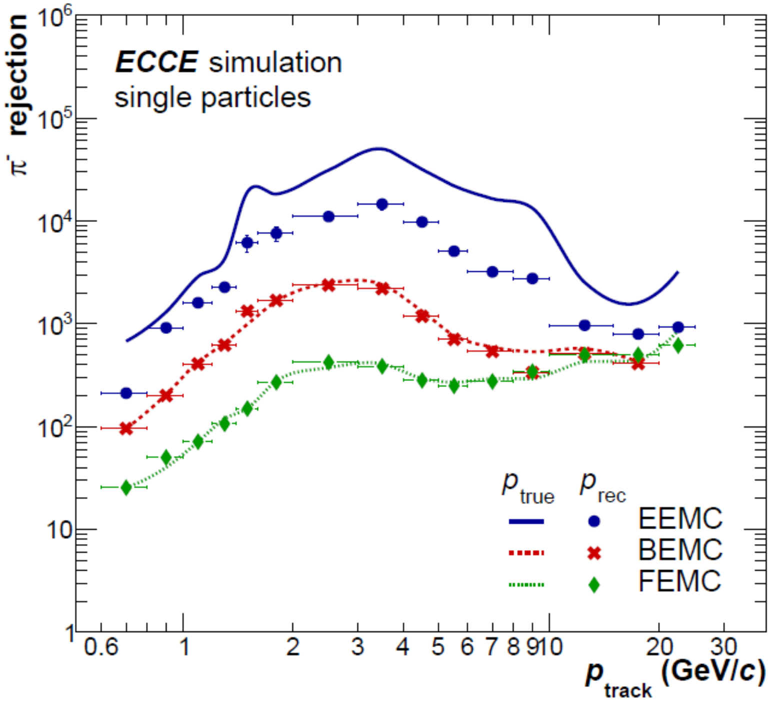
η	[-4 .. -1.8]
σ_E/E	2%/√E+1%*

*Based on prototype beam tests and earlier experiments

Barrel ECAL (BEMC)

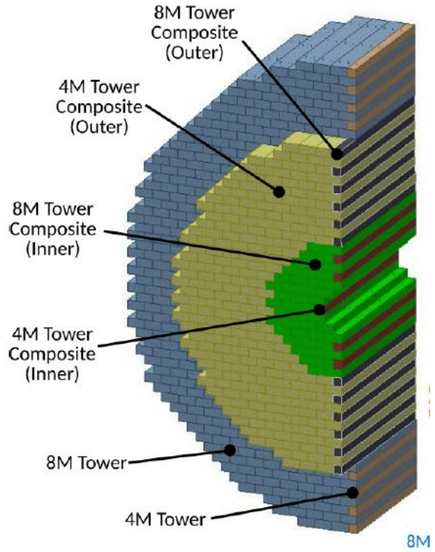
Homogeneous, projective calorimeter based on SciGlass, cost-effective alternative to crystals





Forward ECAL (FEMC)

Highly-granular shashlik sampling calorimeter based on Pb/SC



	Barrel ECAL	Forward ECAL
η	[-1.7 .. 1.3]	[1.3 .. 4]
σ_E/E	2.5%/√E+1.6%*	7.1%/√E+0.3%

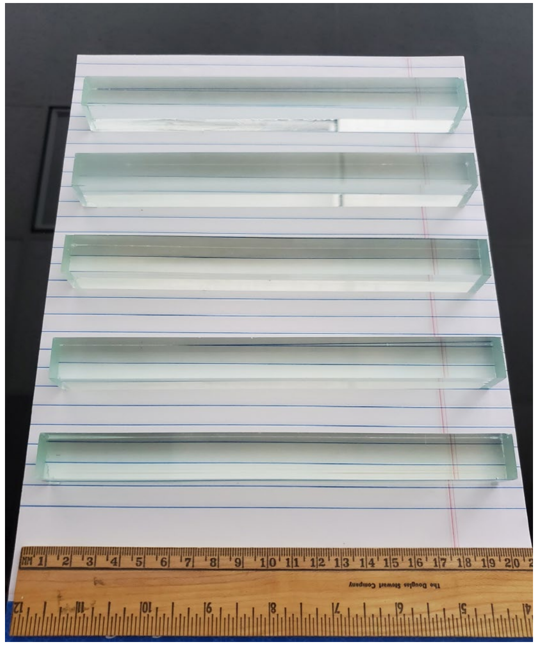
*Based on prototype beam tests and earlier experiments

ECCE EM calorimeters provide the required coverage, meet the physics energy resolution, and pion suppression in all three regions (endcaps, barrel)

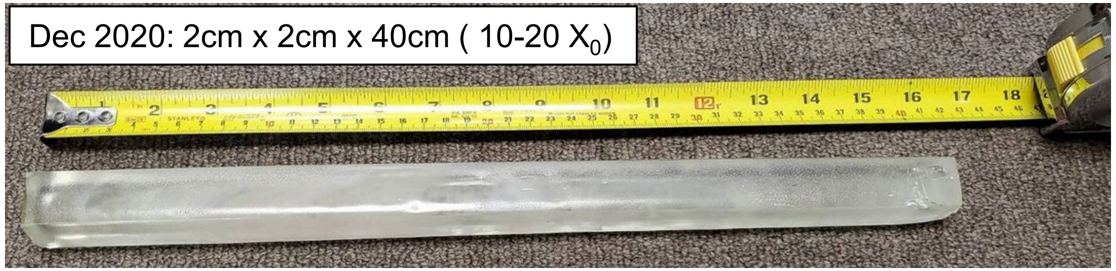
Homogeneous materials: Crystals and Glass

- High-resolution $PbWO_4$ (PWO) crystals are available from two vendors
- SciGlass 20cm has been produced reliably; We tested a 3x3 20 cm SciGlass prototype detector in beam and measured its performance as per simulation (ongoing R&D EEEMCAL consortium, eRD105)
- Received the first polished 40 cm SciGlass with more on the way
- We have an SBIR phase-II to start large-scale production (40+ cm, rectangular and projective shapes)

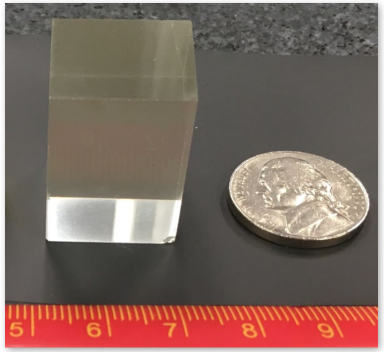
Example: G4 glass



Feb 2021: 2cm x 2cm x 20cm (7 X_0)



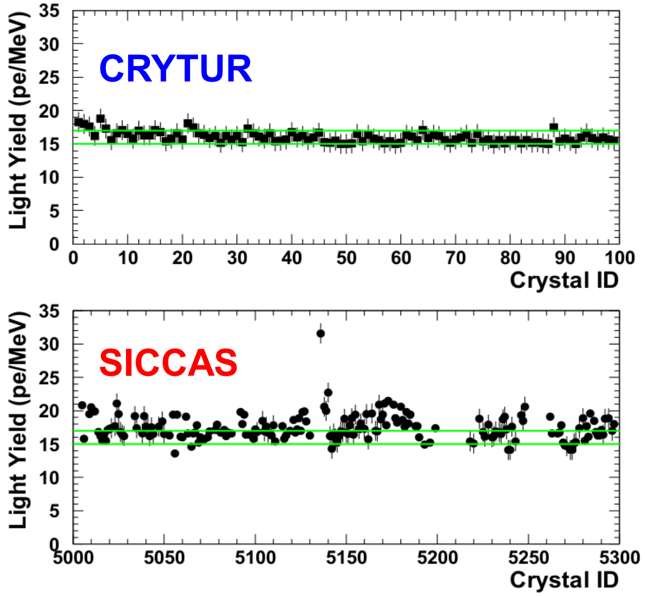
Dec 2020: 2cm x 2cm x 40cm (10-20 X_0)



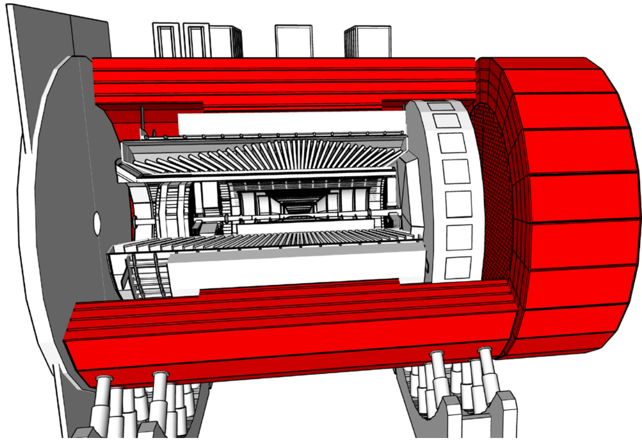
2019: 2cm x 2cm x 4cm

2018: 1cm x 1cm x 1cm

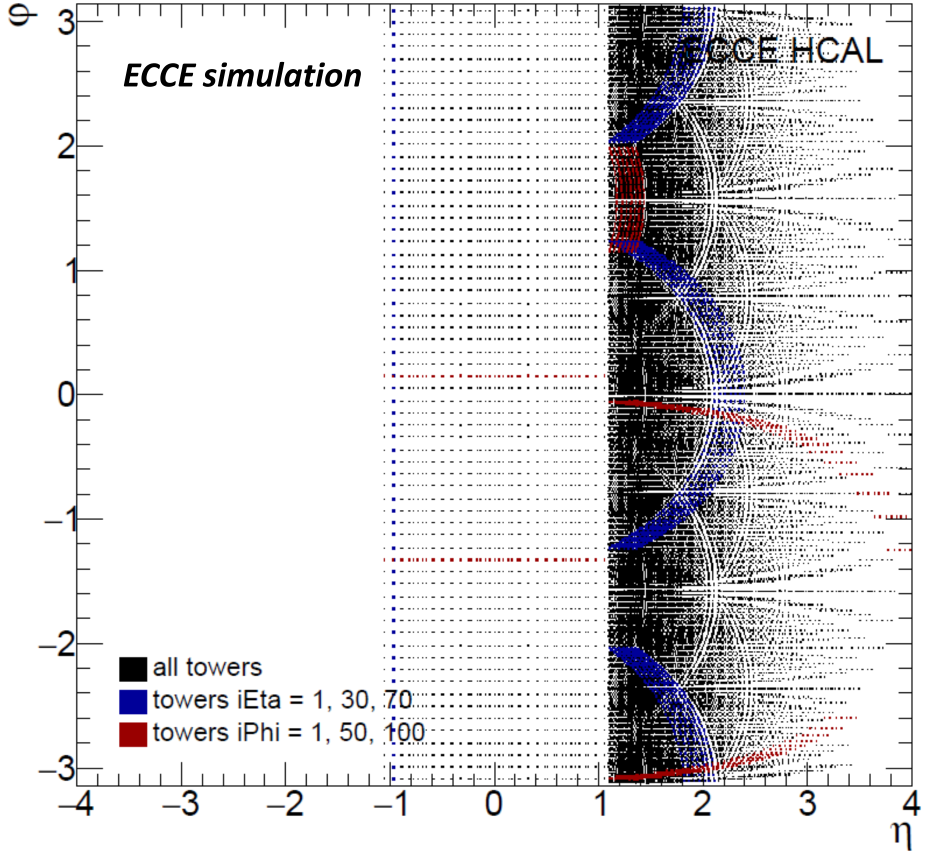
PWO: vendor characterization



Hadronic Calorimeters

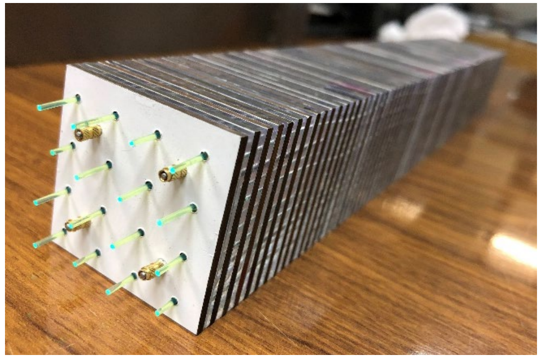


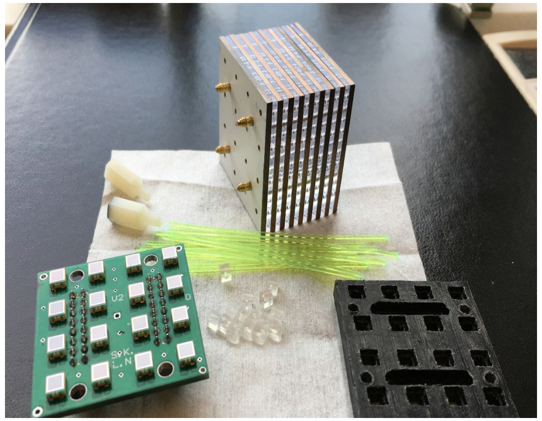
- Main purpose: jet energy measurement
  - Particle Flow Algorithm usage anticipated (where HCal role is identification and energy measurements of the neutral hadrons, namely neutrons and K_L)



- **ECCE HCAL technologies are based on existing hadronic calorimeters** with **components optimized to fit the ECCE baseline design and providing the required performance and coverage**
- The barrel HCAL is a re-use of the hadronic calorimeter from sPHENIX – it has two components
  - Outer HCAL (OHCAL): uniform sampling in azimuth and also serves as barrel flux return
  - Inner HCAL (IHCAL): provides additional longitudinal segment and aids overall calibration of the calorimeter system
- The forward calorimeter is an integrated ECAL+HCAL with longitudinal segmentation and reducing dead material
- The ECCE reference detector includes a flux return in the electron endcap, as no NAS or White Paper EIC science process was found to benefit from a backward hadronic calorimeter within the first years of data taking.

Pb/ScTile shashlyk

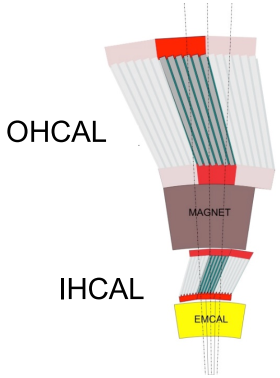


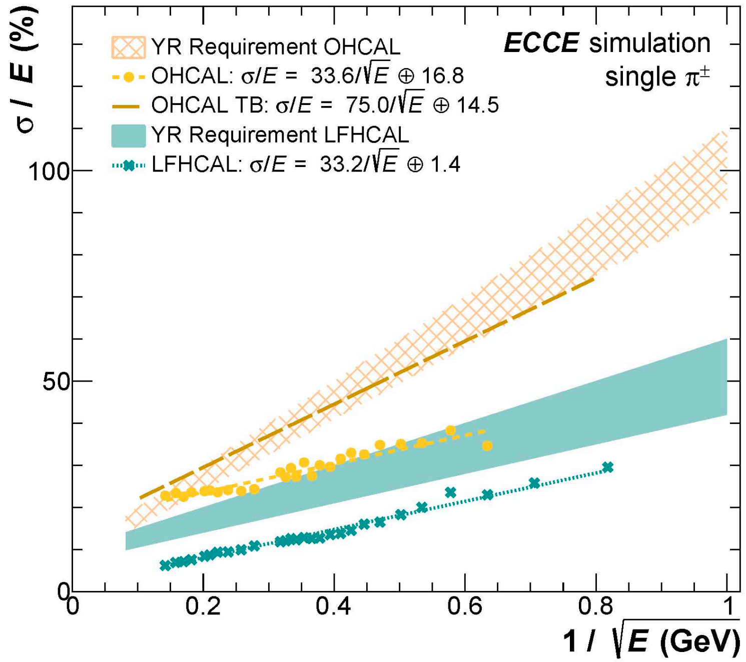


- ❑ Well-established technology
  - ○ ALICE, sPHENIX
- ❑ Medium energy resolution
- ❑ Compact (X_0~7mm or less), cost efficient

Barrel HCAL (OHCAL+IHCAL)

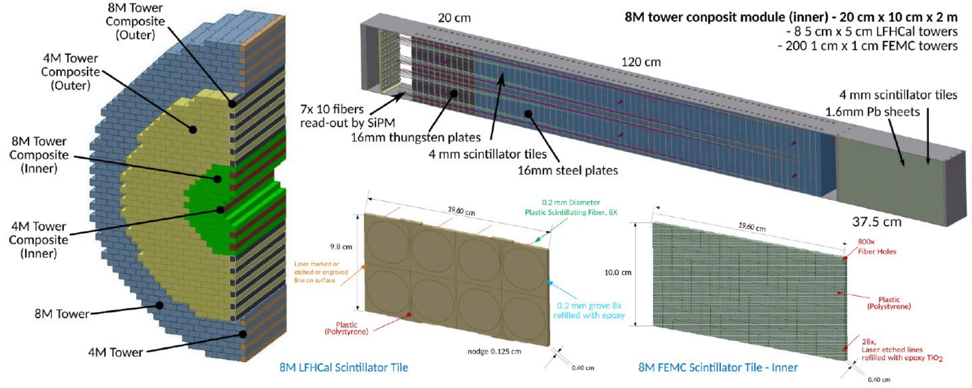
Sampling calorimeter based on Fe/SC tiles





Forward HCAL (LFHCAL)

Integrated ECAL+HCAL longitudinally segmented sampling calorimeter based on Fe/SC, W/Sc and last segment W (tailcatcher)

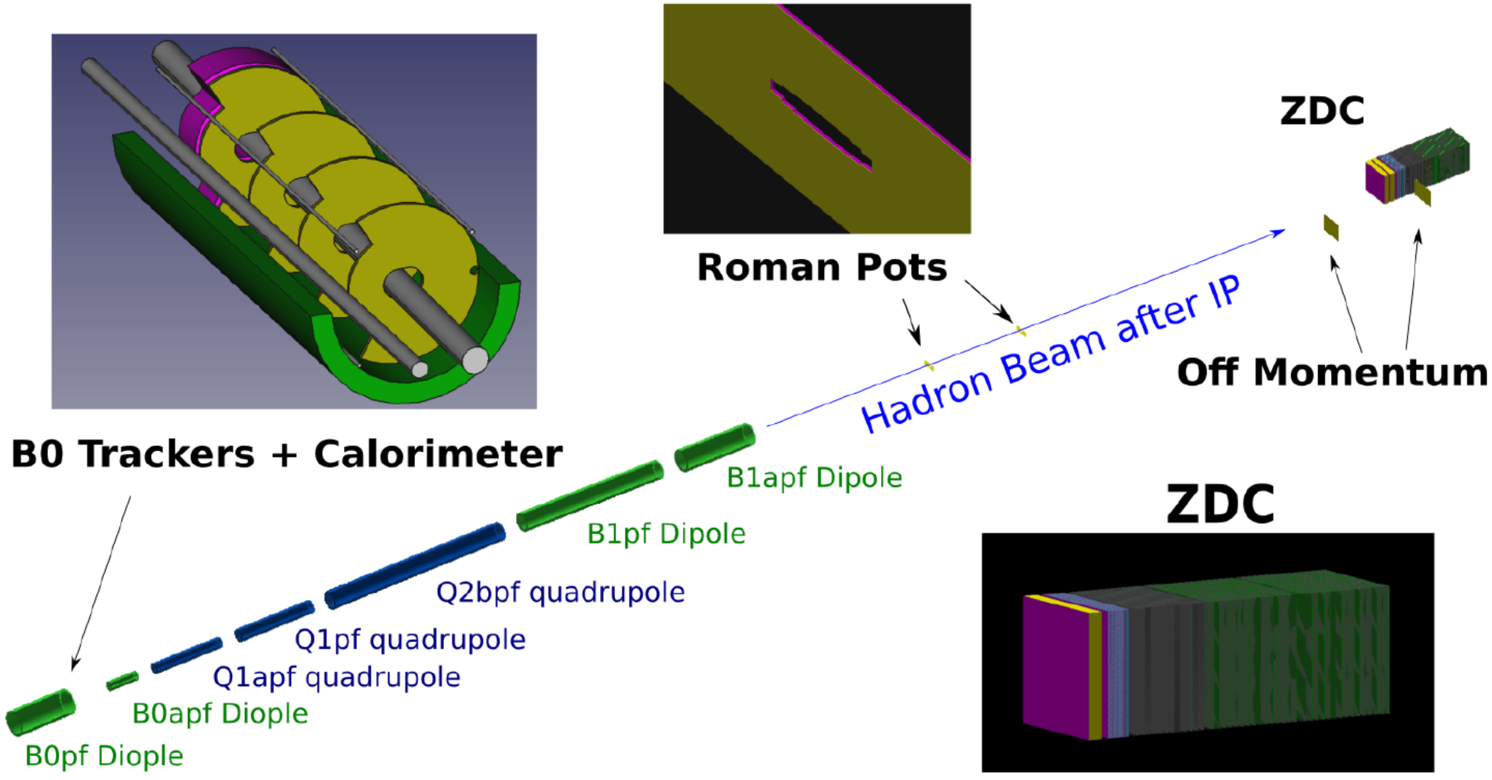


	Barrel HCAL	Forward HCAL
η	[-1 .. 1]	[1 .. 4]
σ_E/E	~75%/√E + 15%*	~33%/√E + 1.4%
depth	~4-5 λ_I	~7-8 λ_I

*Based on prototype beam tests and earlier experiments

ECCE HCALs provide the required coverage, information on hadronic shower development, and energy resolution

Far-Forward Region



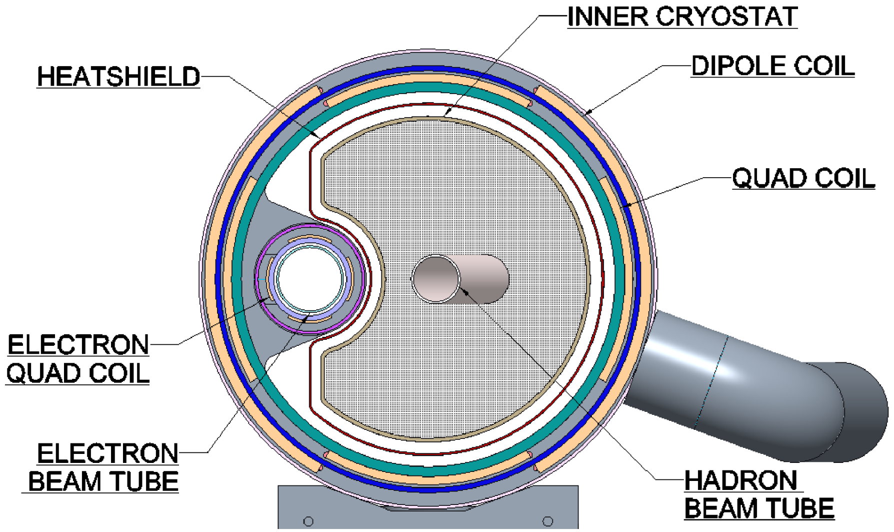
- The **B0 system** measures charged particles in the forward direction and tags neutral particles.
- The **off-momentum detectors** measure charged particles with different rigidity than the beam, e.g., those following decay and fission.
- The **roman pot detectors** measure charged particles close to the beam envelope.
- The **zero-degree calorimeter** measures neutral particles at small angles.

Detector	(x,z) Position [m]	Dimensions	θ [mrad]	Notes
ZDC	(-0.96, 37.5)	(60cm, 60cm, 1.62m)	$\theta < 5.5$	$\sim$4.0 mrad at $\phi = \pi$
Roman Pots (2 stations)	(-0.83, 26.0) (-0.92, 28.0)	(30cm, 10cm)	$0.0 < \theta < 5.5$	$10\,\sigma$ cut.
Off-Momentum Detector	(-1.62, 34.5), (-1.71, 36.5)	(50cm, 35cm)	$0.0 < \theta < 5.0$	$0.4 < x_L < 0.6$
B0 Trackers and Calorimeter	(x = -0.15, 5.8 < z < 7.0)	(32cm, 38m)	$6.0 < \theta < 22.5$	$\sim$20 mrad at ϕ=0

Far-Forward Detectors

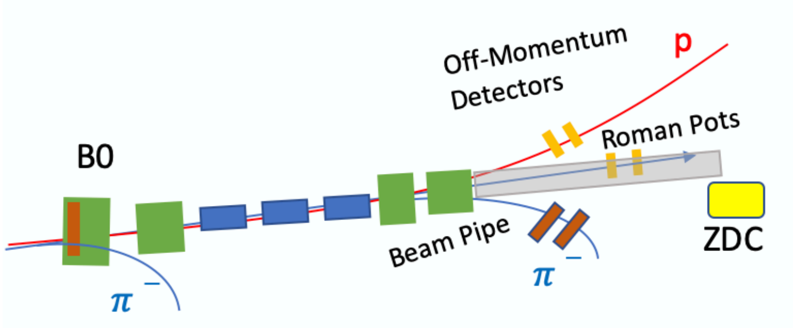
B0-spectrometer

- ❑ Warm space for detector package insert located inside a vacuum vessel to isolate from insulating vacuum.
- ❑ **ECCE: 4 AC-LGAD trackers with 30 cm spacing** between each layer providing **charged particle detection for 6 < θ < 22.5 mrad**.
- ❑ Add a **$PbWO_4$ (11.2 R.L.) calorimeter behind the 4th tracking layer to obtain 100% acceptance** for $\gamma+\gamma$ from π^0 to cleanly isolate u-channel DVCS



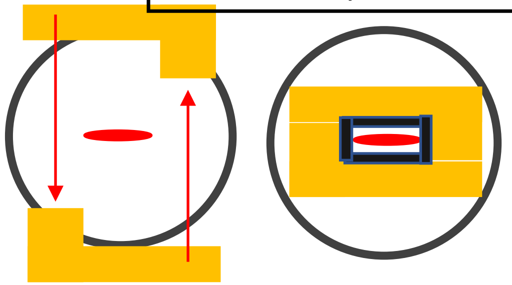
Roman-Pots and Off-momentum detectors

0.0* (10σ cut) < $\boldsymbol{\theta}$ < 5.0 mrad



- ❑ **Roman Pots**: detect protons with high energy and small pT (< 1.3 GeV) particles with with small separation from the hadron beam. They will consist of two double-layer 25x12 cm^2 AC-LGAD stations, located **inside the beam line** and 10σ from the main beam.

$$\sigma(z) = \sqrt{\varepsilon \cdot \beta(z))}$$

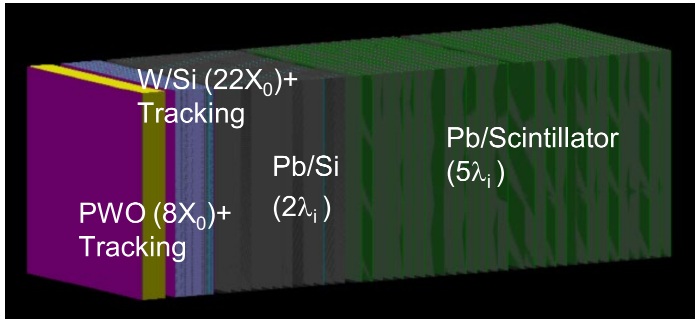


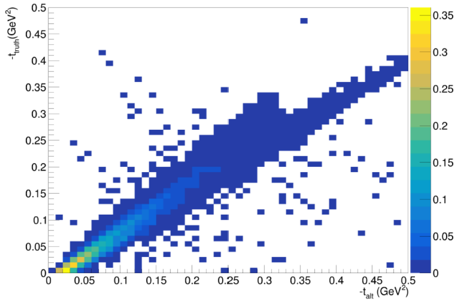
- ❑ **Off-momentum detectors** measure charged particles that have a smaller magnetic rigidity than the main hadron beam. Such particles will be **bent outside the beam pipe**. The detectors consist of tracking planes based on AC-LGAD sensors.
- ❑ Fast Timing to take into account crab crossing

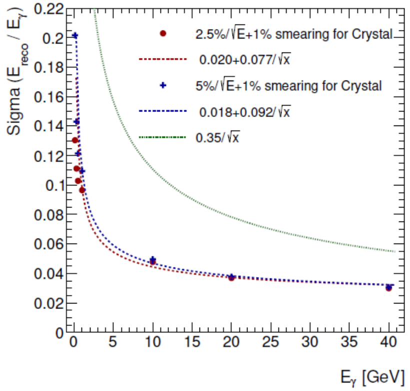
Far-Forward/Backward Detectors

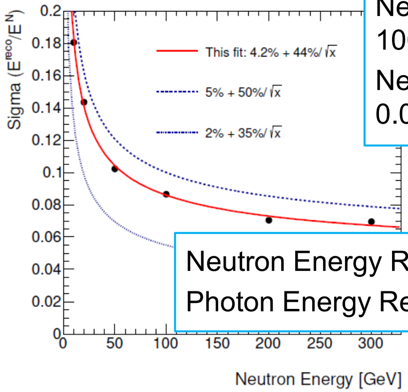
Zero Degree Calorimeter

- ECCE ZDC has dimensions of 60cm x 60cm x 162cm for the needed acceptance (YR) and consists of $PbWO_4$ crystal, W/Si layer, Pb/Si, and Pb/Scintillator layers
- ECCE ZDC **provides detection for photons and neutrons (0<θ<5.5 mrad) with the required performance**





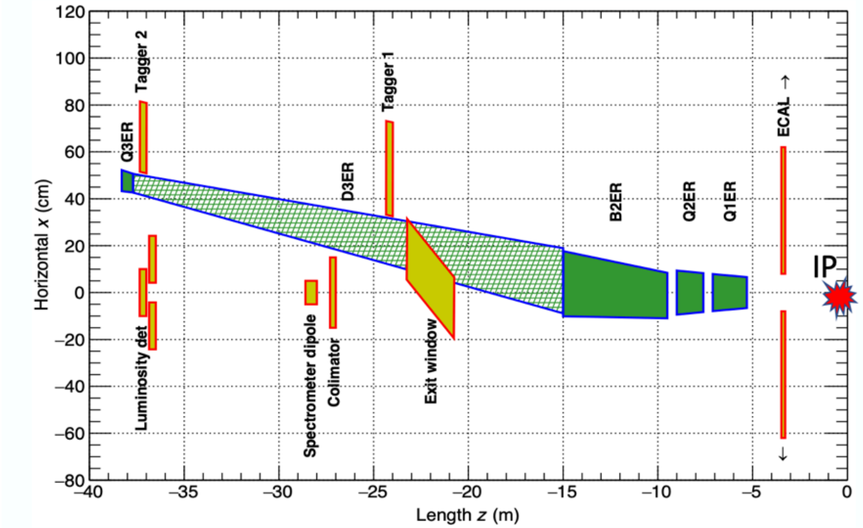




Neutron detection fraction: 100% (59% at 5 on 41 GeV)
Neutron t-resolution: 0.005-0.007 GeV² (0.019 GeV²)

Neutron Energy Resolution: 44%/√E +4.2%
Photon Energy Resolution: 2.5%/√E+1%

Far-backward (electron-going) region



- This area is designed to **measure scattered electrons at small, far-backward angles**
- **Low Q^2-tagger:**
  - Double-layer AC-LGAD tracker, of 40.5cmx40.5 cm at 24m and 30cm x 21cm at 37m from IP
  - $PbWO_4$ EMCAL (20cm x 2cm² crystals)
- **Luminosity Monitor**:
  - AC-LGAD and PbWO4 to provide accuracy of the order of 1% or relative luminosity determination exceeding 10^{-4} precision.

Summary

- The ECCE detector is a physics-driven balance of
  - the reuse of equipment
  - the use of mature detector technologies where possible, and
  - the use of detector technologies that are at the near-end of an extensive R&D effort and were judged absolutely essential for the EIC science.
- The ECCE detector is complex due to the high demand on detector/interaction region integration and the many different detector technologies.
  - This led to several detector technologies with multi-purpose use, and use of AI to optimize detector choices, locations, and materials.
  - The integration of detector with electronics and computing → next talk by D. Lawrence
- The ECCE detector can be ready at an *early CD-4A*!
- The ECCE detector can do the EIC white paper and NAS science, and more!

Backup