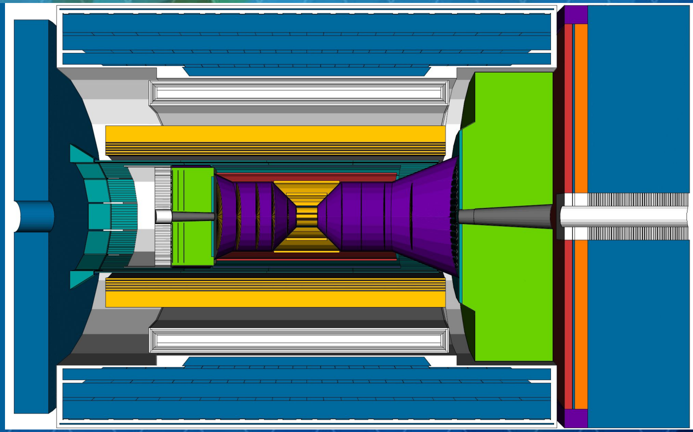
May 18, 2023

1st International Workshop on a 2nd Detector for the Electron-Ion Collider

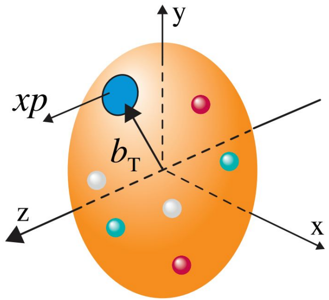
ePIC Detector Overview



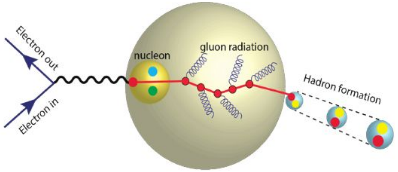
Maria ŻUREK, Argonne National Laboratory

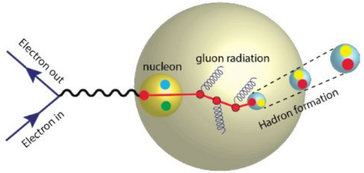
The Physics Quest of the EIC

- How do the **nucleon properties like mass and spin emerge** from their partonic structure?



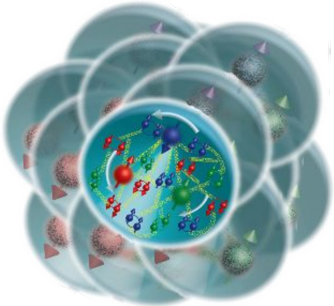
- How are the sea quarks and gluons, and their spins, distributed in space and momentum inside the nucleon?





- In what manner do color-charged quarks and gluons, along with colorless jets, interact with the nuclear medium? And how do the confined hadronic states emerge from these quarks and gluons?

- What is the mechanism through which quark-gluon interactions give rise to nuclear binding?

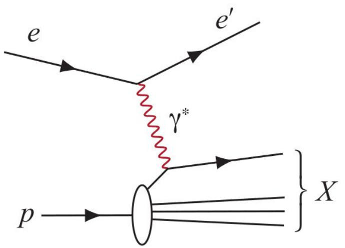


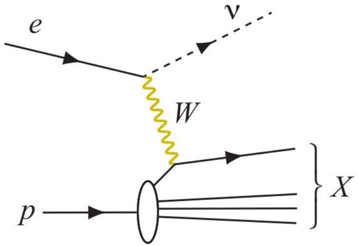
- What impact does a high-density nuclear environment have on the interactions, correlations, and behaviors of quarks and gluons?

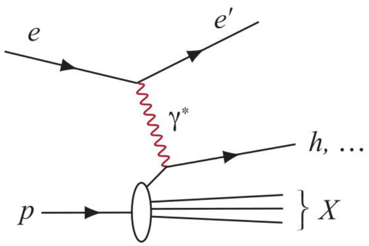
- Is there a **saturation point** for the density of gluons in nuclei at high energies, and does this lead to the **formation of gluonic matter** with universal properties across all nuclei, including the proton?

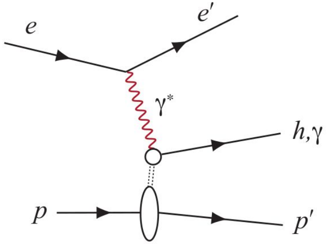
Experimental Processes to Access EIC Physics

DIS event kinematics - scattered electron or final state particles (CC DIS, low y)









Neutral Current DIS

- Detection of scattered electron with high precision - event kinematics

Parton Distributions in nucleons and nuclei

Charged Current DIS

- Event kinematics from the final state particles (Jacquet-Blondel method)

Semi-Inclusive DIS

- Precise detection of scattered electron in coincidence with at least 1 hadron

Spin and Flavor structure of nucleons and nuclei

Tomography Transverse Momentum Dist.

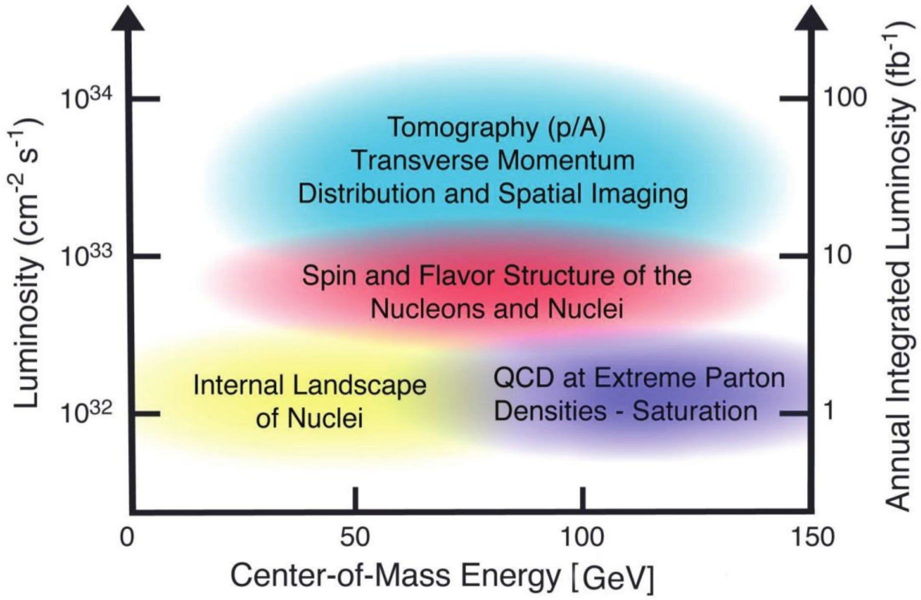
Deep Exclusive Processes

- Detection of all particles in event

QCD at Extreme Parton Densities - Saturation

Tomography Spatial Imaging

Experimental Access to EIC Physics



Access to EIC Physics through

- Large kinematic coverage
- Polarized electron and hadron beams and unpolarized nuclear beams with high luminosities
- Detector setup fulfilling specific requirements of the polarized e-p/A collider

EIC Detector Requirements

Vertex detector → Identify primary and secondary vertices,
- Low material budget: 0.05% X/X_0 per layer
- High spatial resolution: 10µm pitch CMOS Monolithic Active Pixel Sensor

Central and Endcap tracker → High precision low mass tracking
- MAPS – tracking layers in combination with micro pattern gas detectors

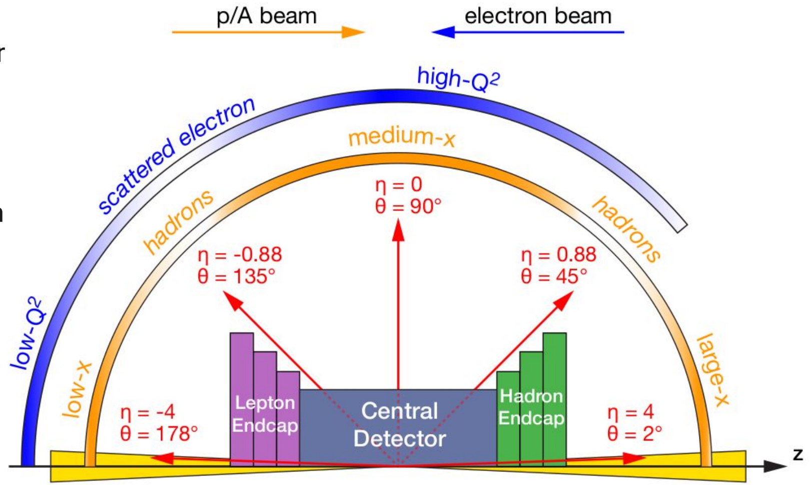
Particle Identification → High performance single track PID for π, K, p separation
- RICH detectors (RICH, DIRC)*
- Time-of-Flight high resolution timing detectors (LAPPDs, LGAD)
- Novel photon sensors: MCP-PMT / LAPPD

Electromagnetic calorimetry → Measure photons (E, angle), identify electrons
- $PbWO_4$ Crystals (backward), W/ScFi (forward)
- Barrel Imaging Calorimeter (Si + Pb/ScFi)*

Hadron calorimetry → Measure charged hadrons, neutrons and K_L^0
- Challenge achieve ~50%/√E + 10% for low E hadrons (~ 20 GeV)
- Fe/Sc sandwich with longitudinal segmentation

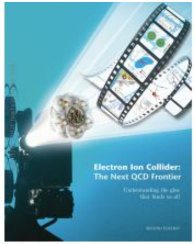
DAQ & Readout Electronics → trigger-less / streaming DAQ, Integrate AI into DAQ

Very forward and backward detectors → Large acceptance for diffraction, tagging, neutrons from nuclear breakup
- Silicon tracking layers in lepton and hadron beam vacuum
- Zero-degree high resolution electromagnetic and hadronic calorimeters

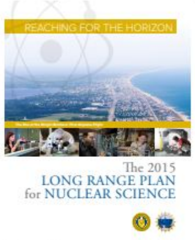


*Motion to initiate the change control process endorsed by ePIC Collaboration Council, April 23

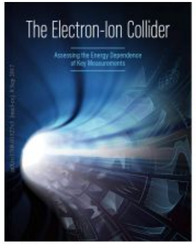
Detector Design Process Timeline



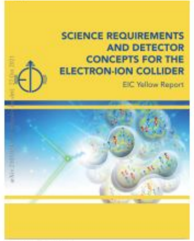
2012



2015



2017

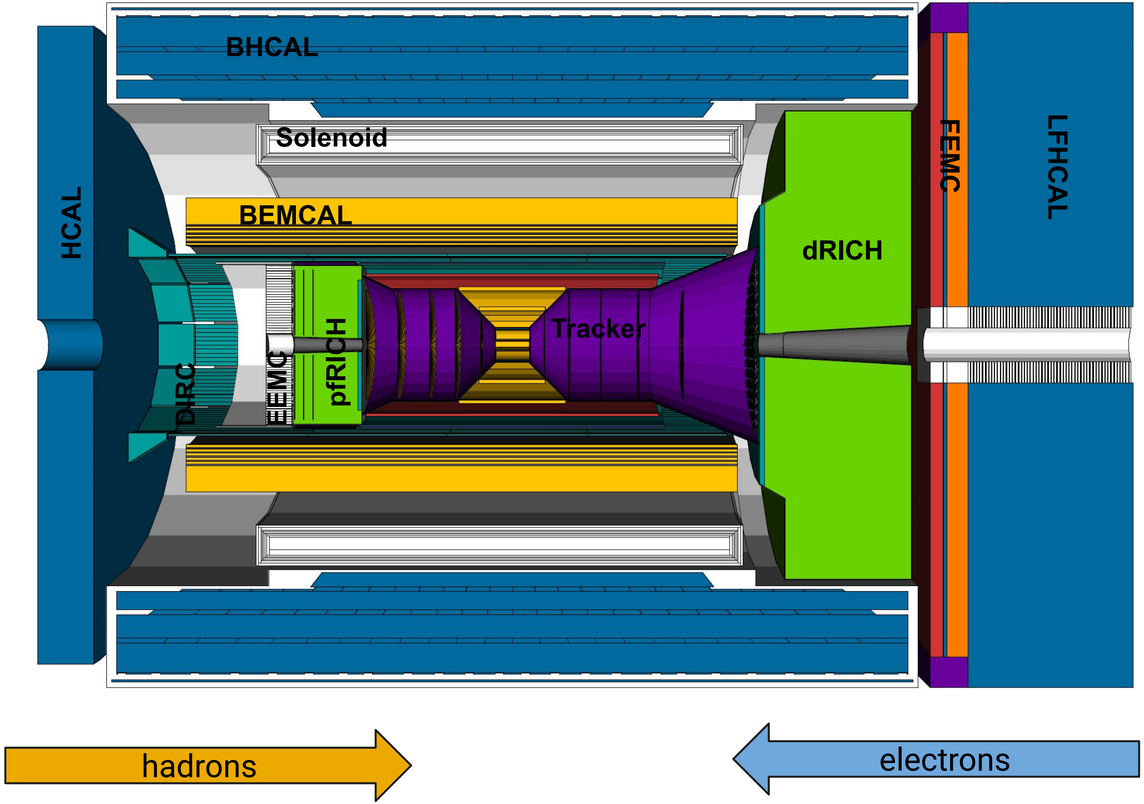


2020

Detector and machine design parameters driven by physics objectives

- Call for proposals issued jointly by BNL and JLab in **March 2021** (Due Dec 2021)
  - ATHENA, CORE and ECCE proposals submitted
- DPAP closeout **March 2022**
  - ECCE proposal chosen as basis for first EIC detector reference design
- **Spring/Summer 2022** – ATHENA and ECCE form joint leadership team
  - Joint WG’s formed and consolidation process undertaken
  - Coordination with EIC project on development of technical design
- Collaboration formation process started **July 2022**
- Charter ratified & elected ePIC Leadership Team **February 2023**
- Technology selections for ePIC and the implementation of the new management structure endorsed by the Collaboration Council **April 2024** (Technology Reviews took place in March 2023)
  - Motions to initiate the change control process for the barrel EMCal and for the backward RICH
- **Working towards TDR and CD-3A and CD-2/3**

ePIC Detector Design

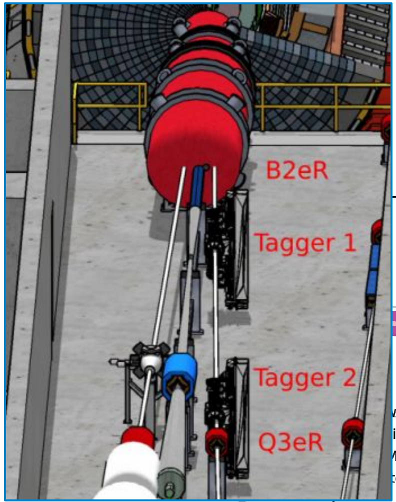


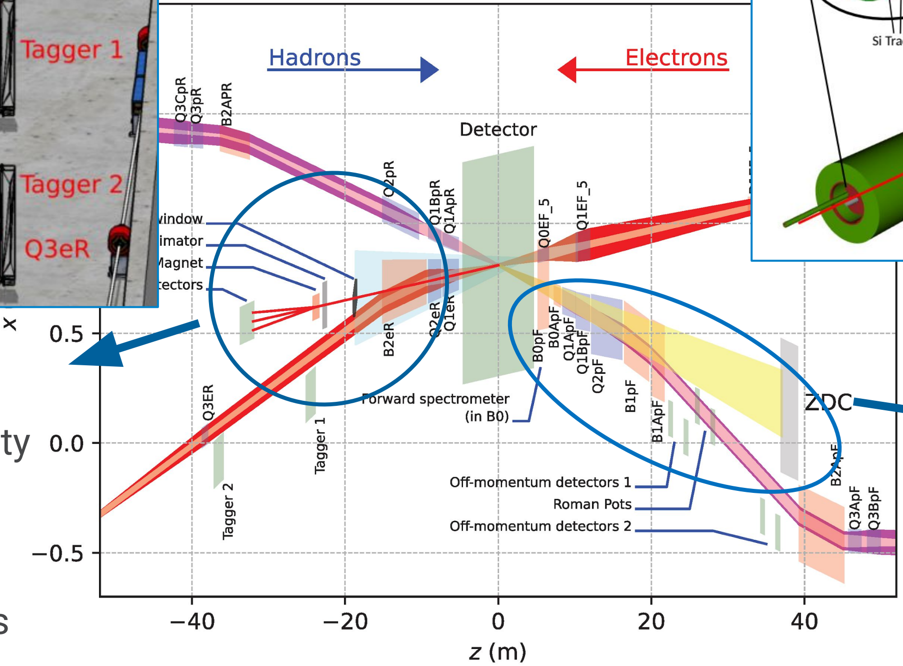
Tracking:
- New 1.7 T solenoid
  See talk by Renuka Rajput-Ghoshal
- Si MAPS Trackers
- MPGD layer before DIRC

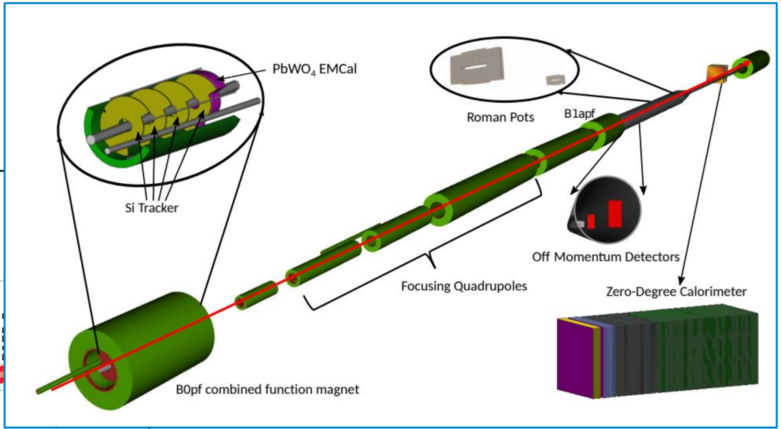
Particle ID:
- DIRC
- pfRICH
- dRICH
- AC-LGAD (~30ps TOF)

Calorimetry:
- Si and Pb/ScFi Barrel EMCal
- PbWO4 EMCal in backward direction
- Finely segmented EMCal + HCal in forward direction
- Outer HCal (sPHENIX re-use)
- Backwards HCal (tail-catcher)

Far-Forward and Far-Backward Detectors







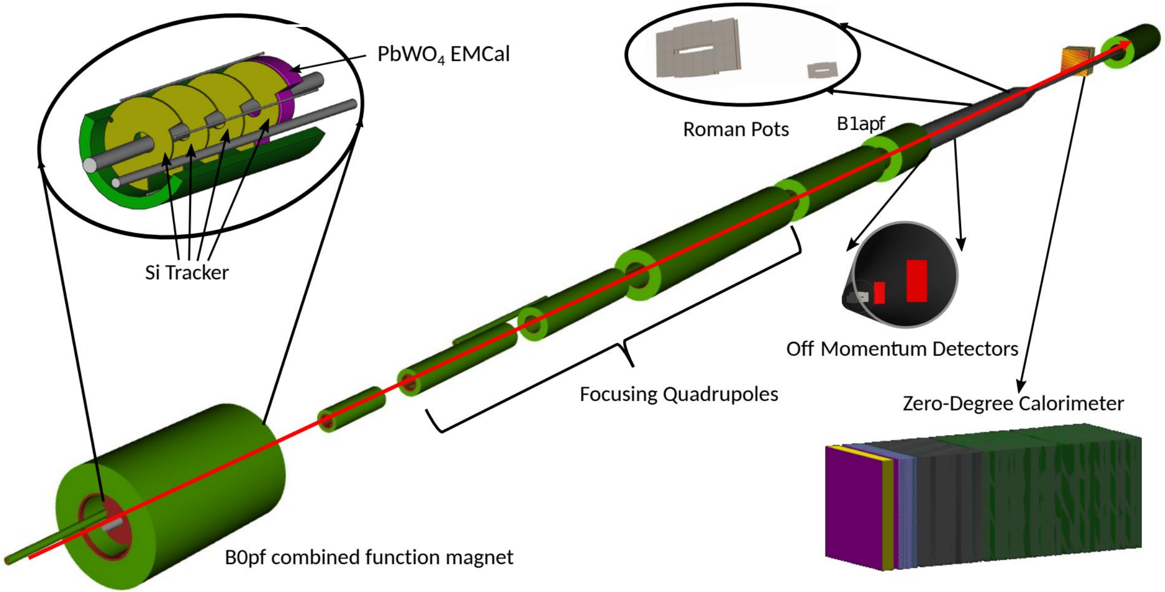
Far-Backward Detectors

- Luminosity monitor
- Low-Q^2 Tagging Detectors

Far-Forward Detectors

- B0 Tracking and Photon Detection
- Roman Pots and Off-Momentum Detectors
- Zero-Degree Calorimeter

Far-Forward Detectors

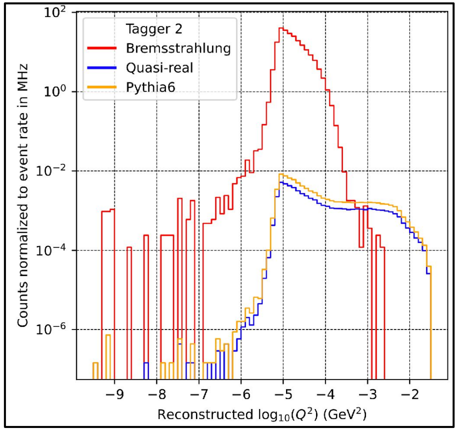


Detector	Acceptance
Zero-Degree Calorimeter (ZDC)	θ < 5.5 mrad (η > 6)
Roman Pots (2 stations)	0.0 < θ < 5.0 mrad (η > 6)
Off-Momentum Detectors (2 stations)	θ < 5.0 mrad (η > 6)
B0 Detector	5.5 < θ < 20.0 mrad (4.6 < η < 5.9)

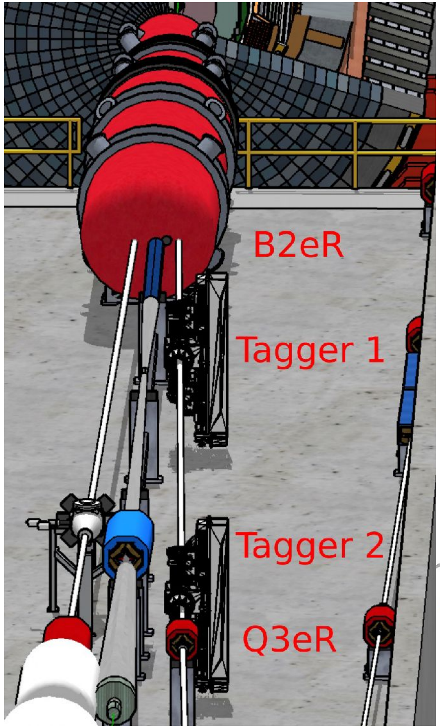
- **B0 system:** Measures charged particles in the forward direction and tags neutral particles
- **Off-momentum detectors:** Measure charged particles resulting from, e.g., decays and fission
- **Roman pot detectors:** Measure charged particles near the beam
- **Zero-degree calorimeter:** Measures neutral particles at small angles

Far-Backward Detectors

Low-Q^2 tagger



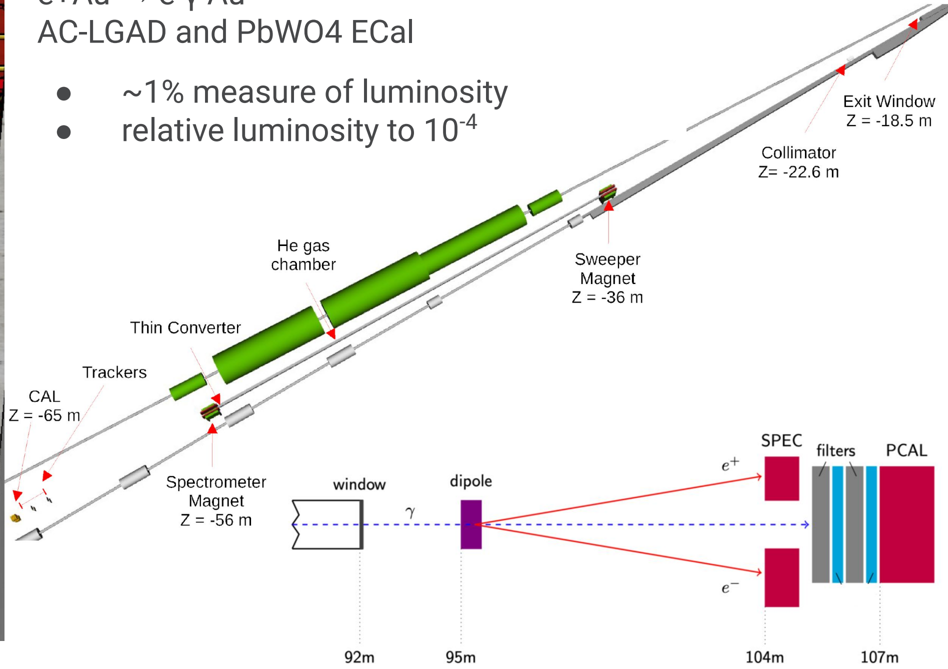
- Double-layer AC-LGAD tracker and PbWO4 ECal
- Clean photoproduction signal for $10^{-3} < Q^2 < 10^{-1}$



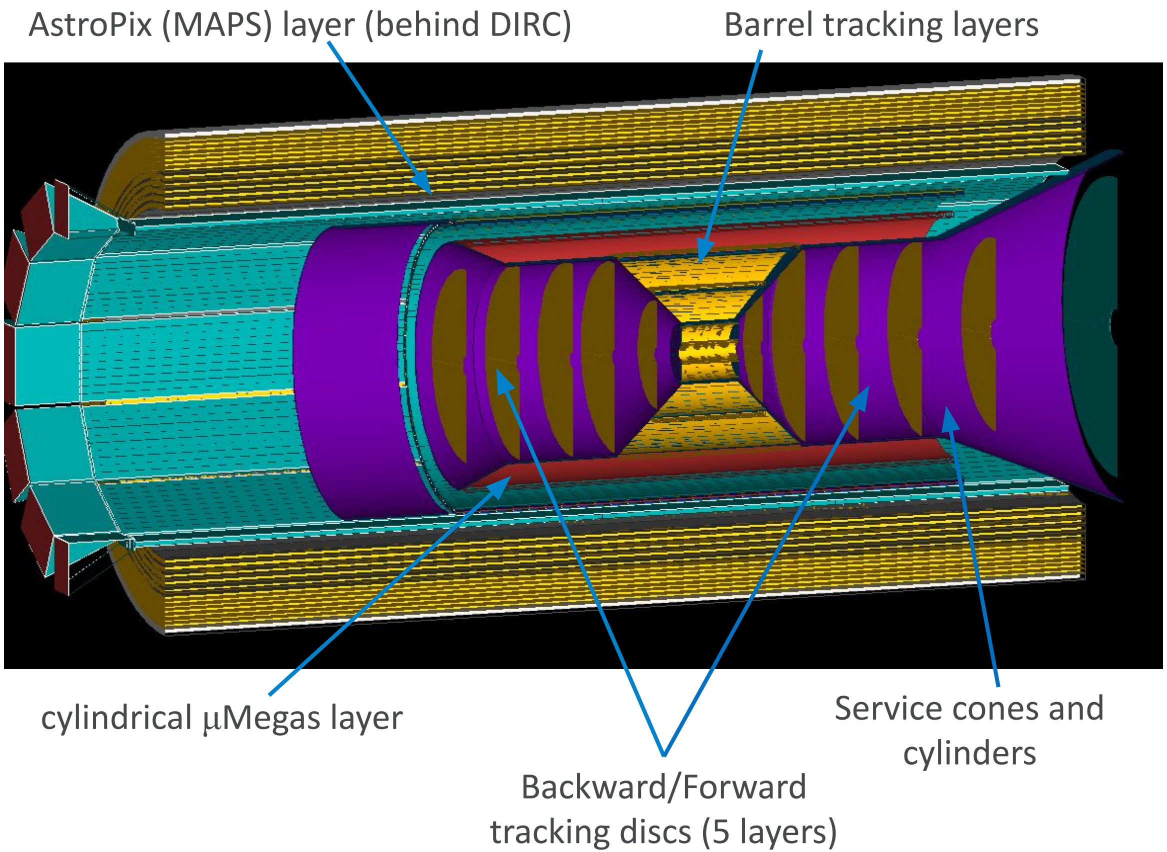
Luminosity Spectrometer

e+p → e γ p
e+Au → e γ Au
AC-LGAD and PbWO4 ECal

- ~1% measure of luminosity
- relative luminosity to 10^{-4}



Tracking



- **Inner two vertex layers** optimized for beam pipe bakeout and ITS-3 sensor size
- Third layer dual-purpose (vertex + sagitta) - **5 layers total**
- **Five discs in forward/backwards** direction (ITS-3 based large area sensor design)
- **Cylindrical μMega** provide pattern recognition redundancy
- **1st AstroPix layer of Barrel ECal** provides ring seed direction, space point for pattern recognition

Tracking

Technology

ITS3 MAPS based Si-detectors:

- O(10μm) pitch, X/X^0 ~ 0.05 – 0.55%/ layer

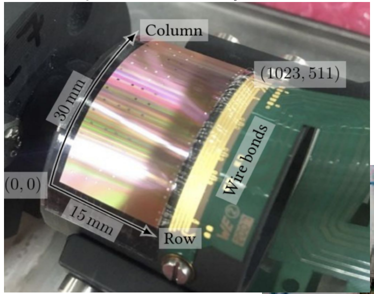
Gaseous tracker:

- σ = 55 μm, X/X_0 ~ 0.2%/layer

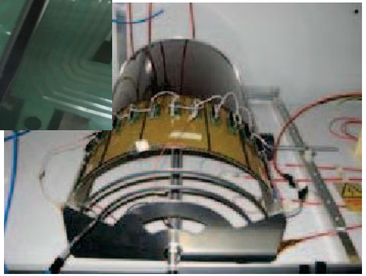
AstroPix outer tracker layer:

- 500μm pixel pitch (σ = 144 μm)

First "μITS3" assembly at CERN

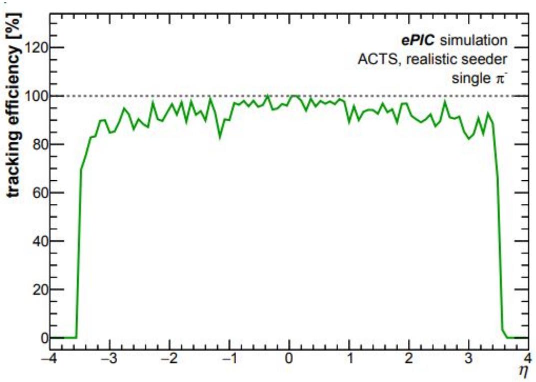


Cylindrical μMega



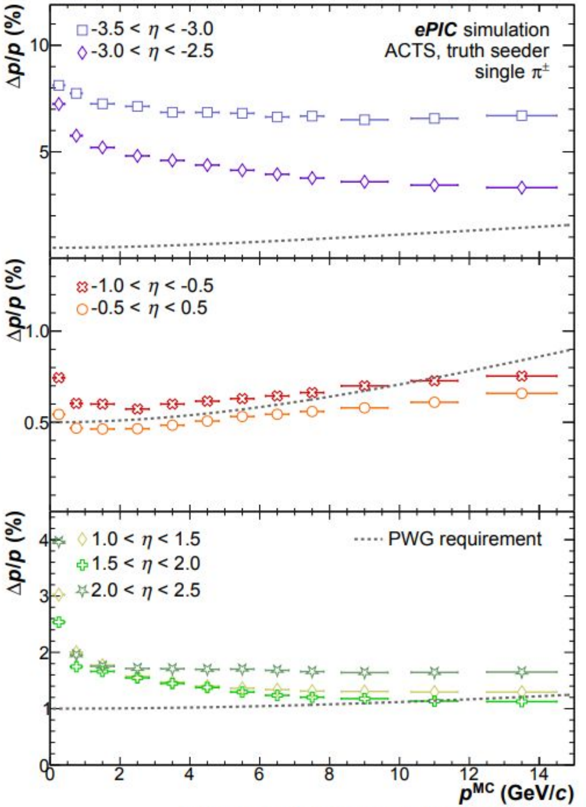
Simulated performance

F. Bock, Hard Probes 2023



- Meets EICUG Yellow Report design requirements
- Backward momentum resolution complemented by calorimetric resolution

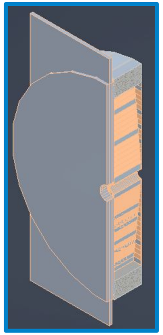
F. Bock, Hard Probes 2023



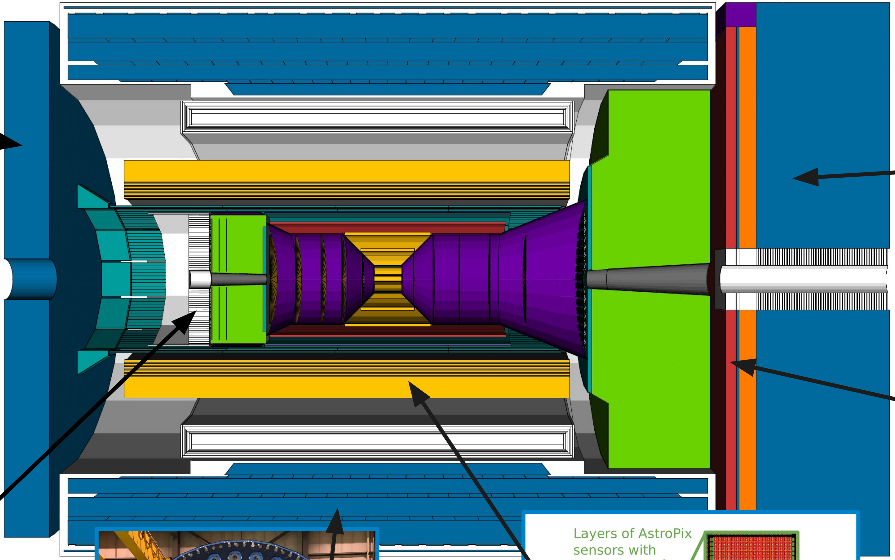
E. Yeats, R. Cruz-Torres, N. Schmidt, S. Maple

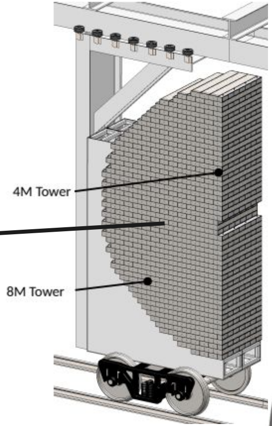
Calorimetry

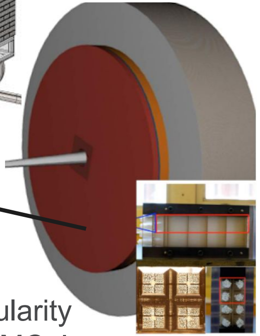
See talks by N. Schmidt and B. Page



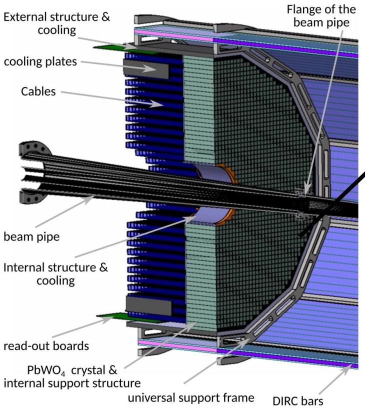
Backwards HCal
Steel/Sc
Sandwich
tail catcher



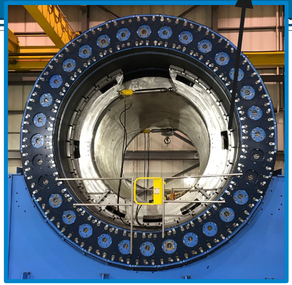




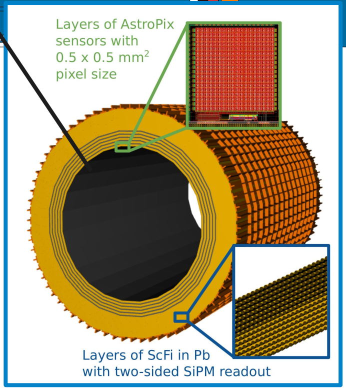
High granularity
W/SciFi EMCal
Longitudinally separated
HCAL with high-η insert



Backwards EMCal
$PbWO_4$ crystals



Barrel HCAL
(sPHENIX re-use)



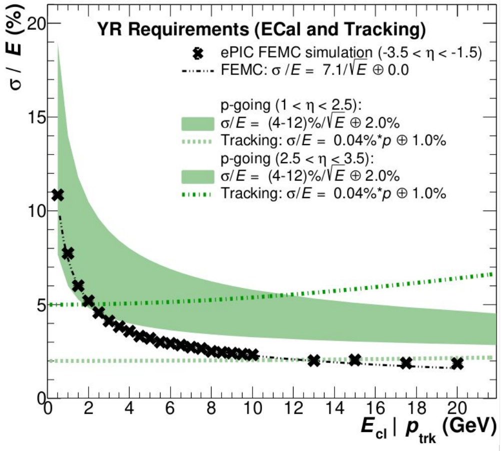
Imaging Barrel ECAL*

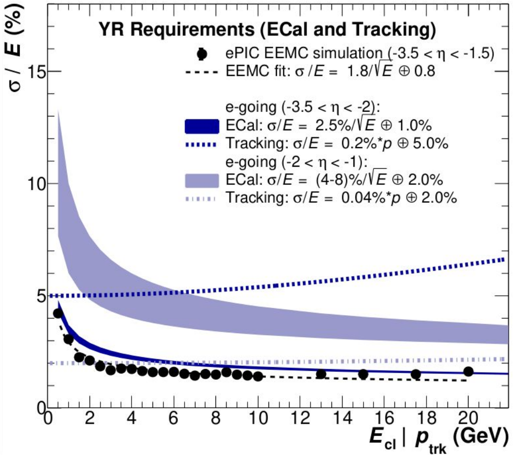
*Motion to initiate the change control process (from Sci-Glass ECal) endorsed by ePIC CC, April 23

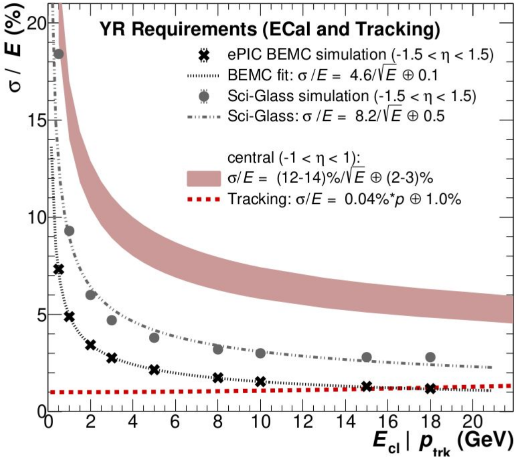
Calorimetry

See talks by N. Schmidt and B. Page

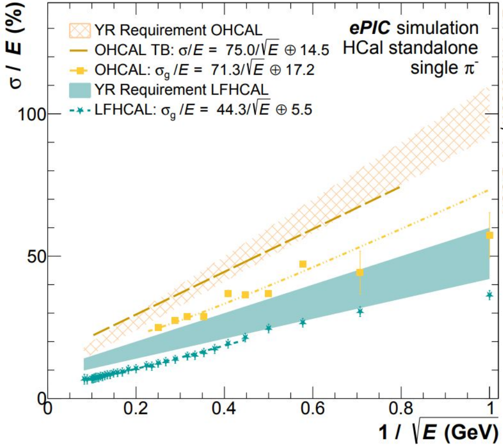
plots by N. Schmidt







F. Bock, Hard Probes 2023



D. Anderson, F. Bock

Performance on energy resolution and matching

- Technologies fulfill YR requirements on energy resolution
- Ongoing simulation studies related to overlaps between different η regions for calorimetry and reconstruction algorithms

Ongoing work on Monte-Carlo validation

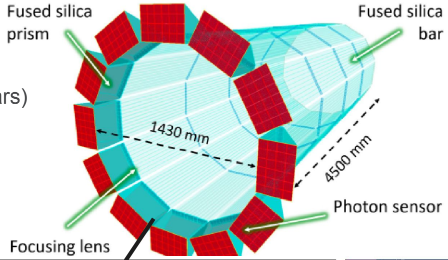
- Validation for high Z absorbers

Particle ID

See talks by Z. Ye, G. Kalicy, P. Garg, Y. Ilieva, A. Lyashenko

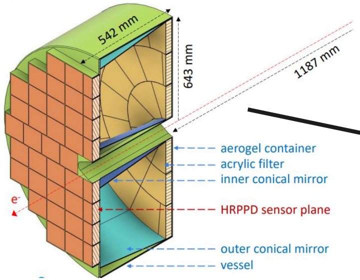
High-Performance DIRC

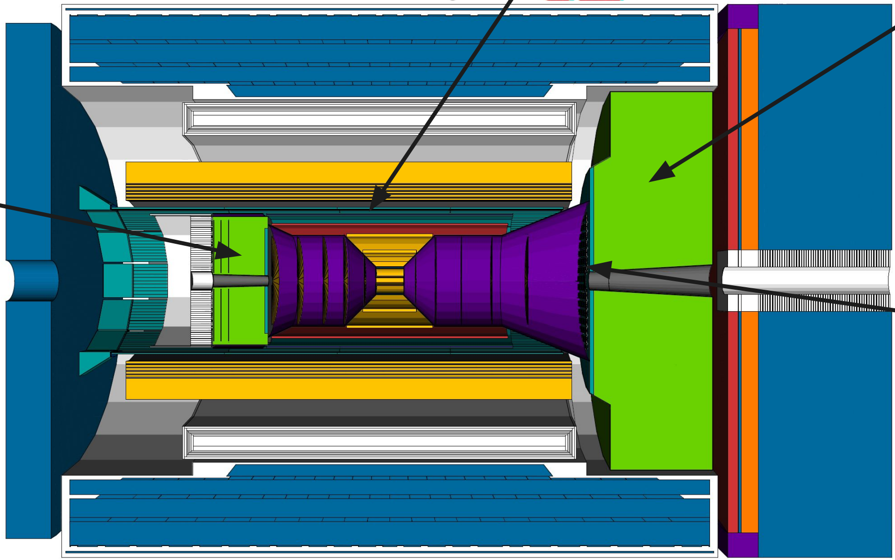
- Quartz bar radiator (BaBAR bars)
- light detection with MCP-PMTs
- Fully focused
- π/K 3б separation at 6 GeV/c



Proximity Focused (pfRICH)*

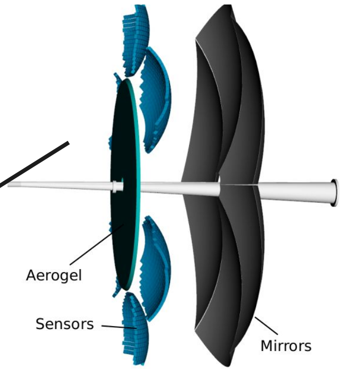
- Proximity gap >40 cm
- Sensor: LAPPDs
- up to 9 GeV/c 3б π/K sep.



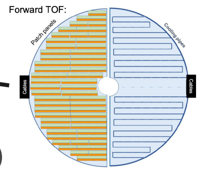


*Motion to initiate the change control process (from Modular RICH mRICH) endorsed by ePIC CC, April 23

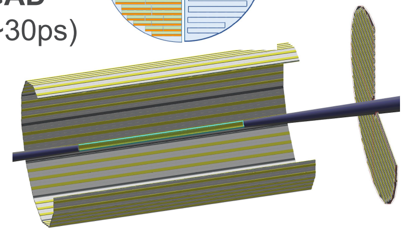
Dual-Radiator RICH(dRICH)



- C_2F_6 Gas Volume and Aerogel
- Sensors tiled on spheres (SiPMs)
- π/K 3б sep. at 50 GeV/c



AC-LGAD TOF (~30ps)



- Accurate space point for tracking
- forward disk and central barrel

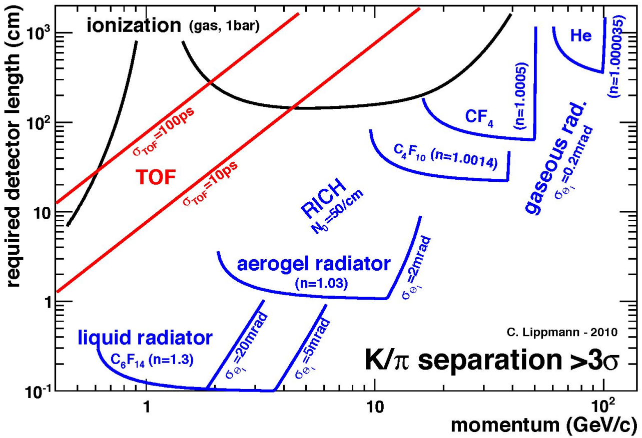
See talks by Z. Ye, G. Kalicy, P. Garg, Y. Ilieva, A. Lyashenko

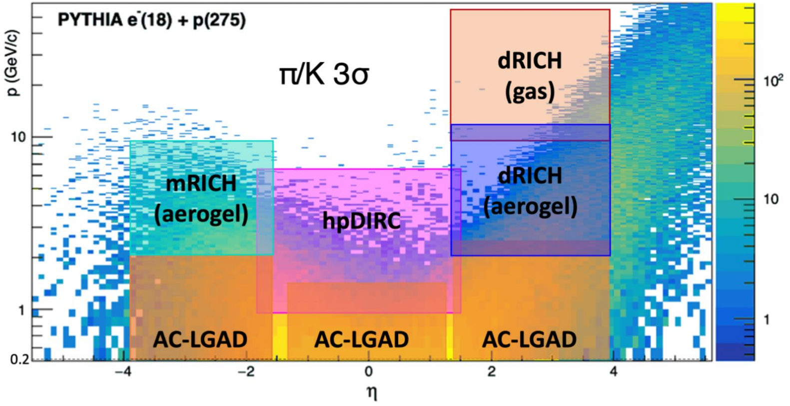
Particle ID

Particle IDentification needs

- Electrons from photons ⟶ **4π coverage in tracking**
- Electrons from charged hadrons ⟶ **mostly provided by calorimetry and tracking**
- Charged pions, kaons and protons from each other on track level ⟶ **Cherenkov detectors**
  - Cherenkov detectors, complemented by other technologies at lower momenta ToF or dE/dx

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



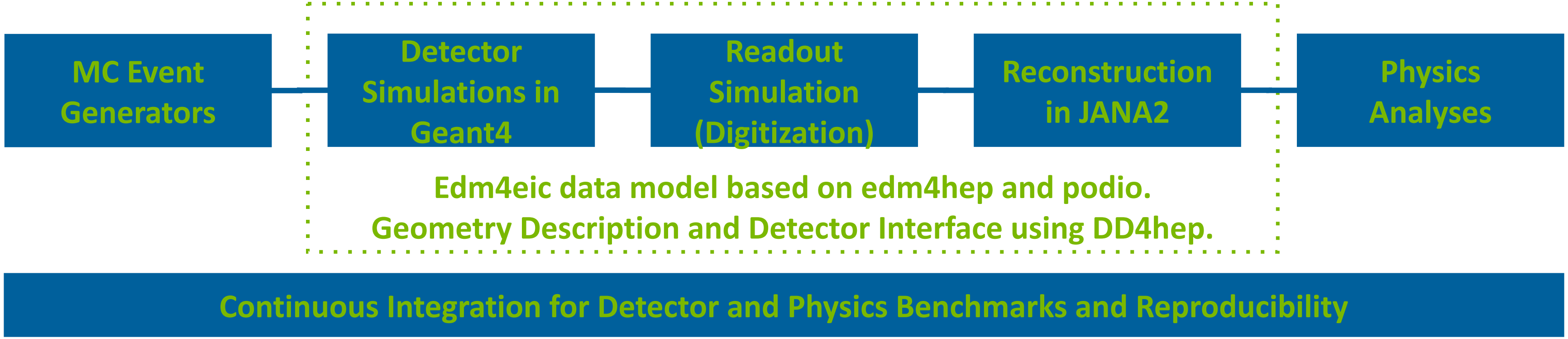


Need more than one technology to cover the entire momentum ranges at different rapidities

ePIC Software

Our software design is based on **lessons learned in the worldwide NP and HEP community** and a **decision-making process** involving the whole community. We will continue to work with the worldwide NP and HEP community.

Modular Simulation, Reconstruction, and Analysis Toolkit using tools from the NP-HEP community



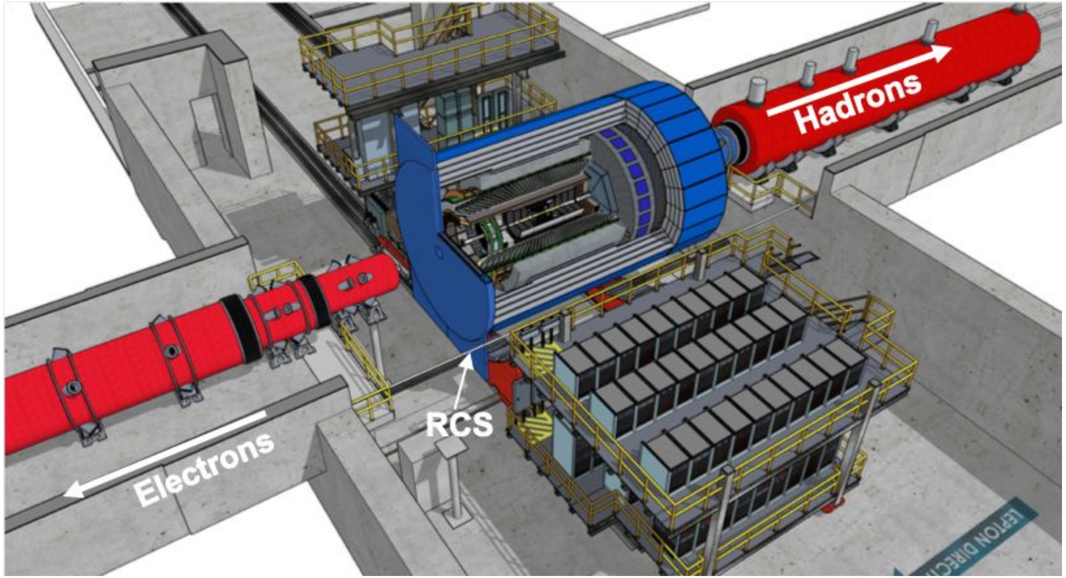
We are providing a production-ready software stack throughout the development:

- **Milestone**: Software enabled first large-scale simulation campaign for ePIC.

We have a good foundation to meet the near-term and long-term software needs for ePIC.

Optimize Physics Reach

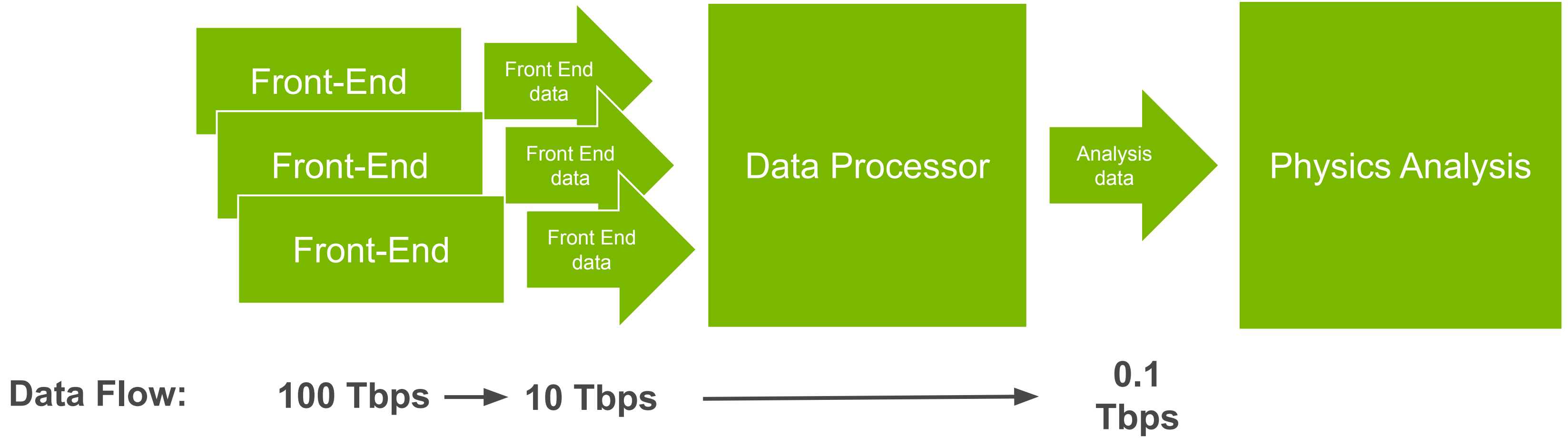
Integrated interaction and detector region (+/- 40 m)
Get ~100% acceptance for all final state particles, and measure them with good resolution. All particles count!



Compute-Detector Integration
Extend integrated interaction and detector region into detector readout (electronics), data acquisition, data processing and reconstruction, and physics analysis.

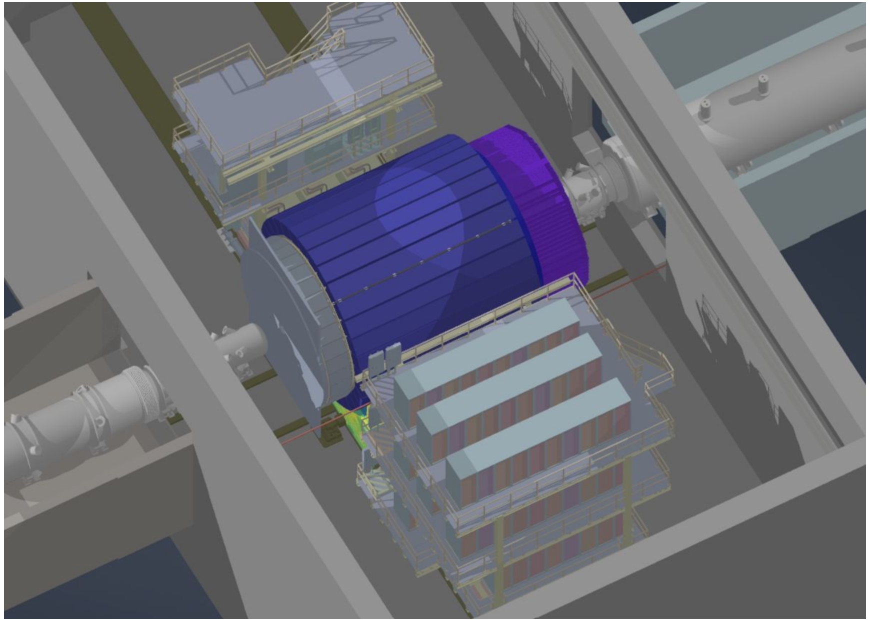
Compute-Detector Integration to Maximize Science

- **Problem** Data for physics analyses and the resulting publications available after O(1year) due to complexity of NP experiments (and their organization).
  - Alignment and calibration of detector as well as reconstruction and validation of events time-consuming.
- **Goal** Rapid turnaround of data for physics analyses.
- **Solution** Compute-detector integration using:
  - AI/ML for autonomous alignment and calibration as well as reconstruction in near real time,
  - Streaming readout for continuous data flow and heterogeneous computing for acceleration.

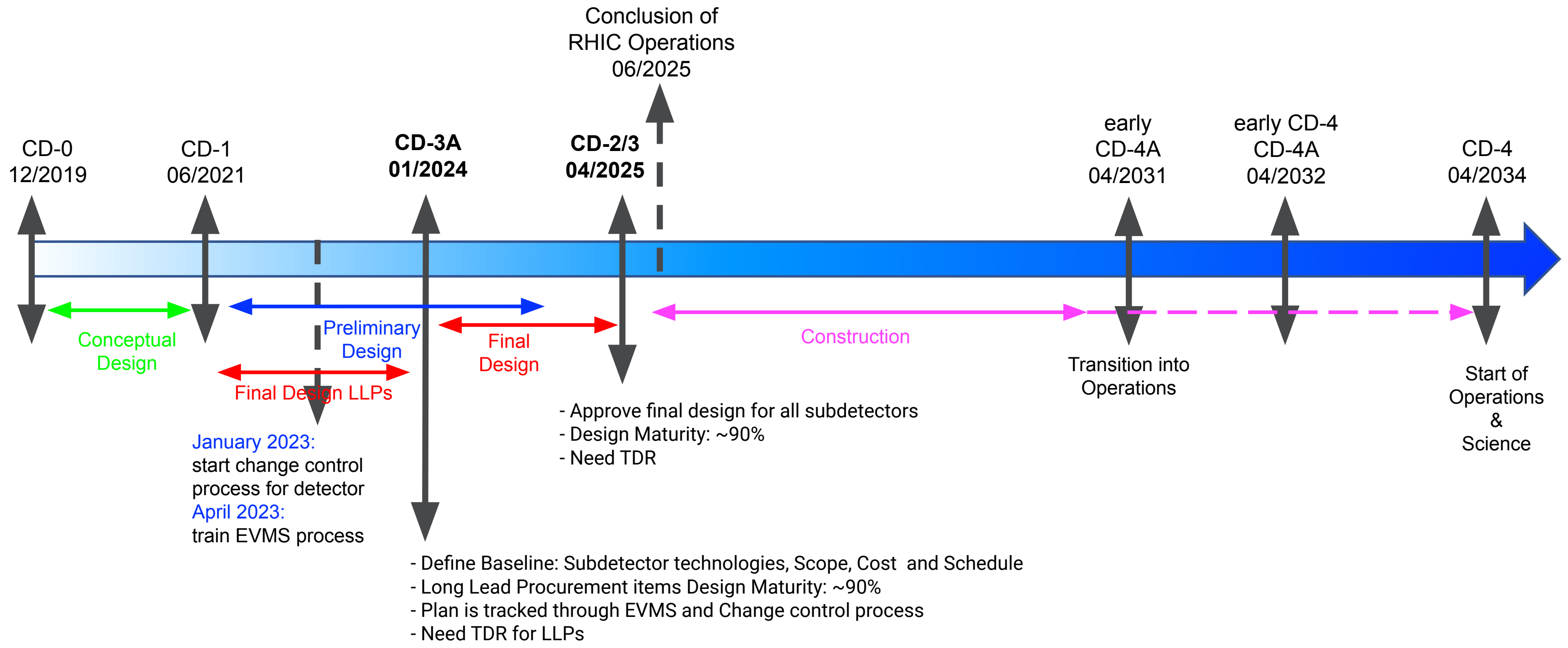


Work Underway on ePIC Design

- Preparations to the **change control process for pfRHIC and Imaging Barrel ECAL**
- **Tracking optimization**
  - Achieve a realistic, low-mass design with good performance
- **Engineering Design**: Full CAD design of ePIC ongoing to facilitate realistic detector integration, including cabling and services
- Preparations to the **CD-3a** (Long Lead Procurement items) - Reviews Summer/Fall 2023
- **CD-2/3 in April 2025** - Approved final design for all subdetectors - Design Maturity: ~90%



EIC Project Schedule



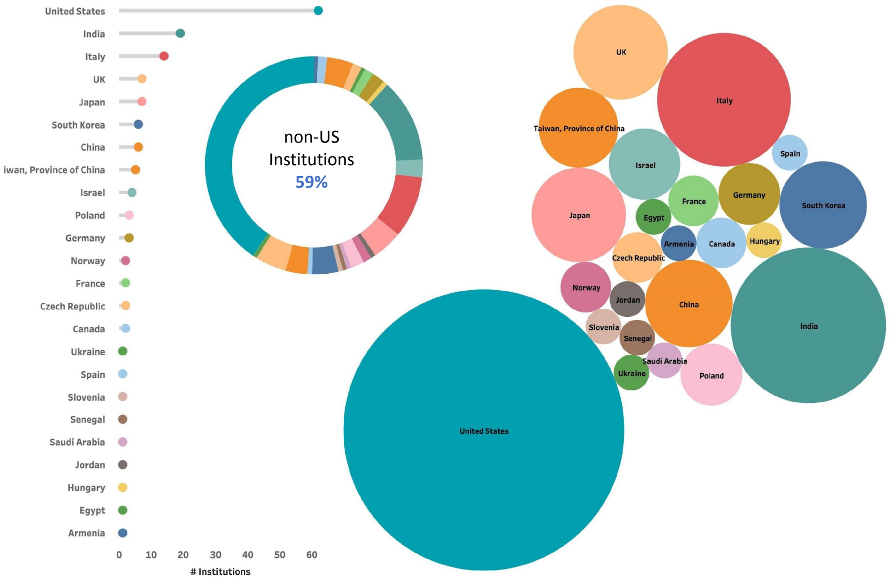
Summary

- **The ePIC Detector is maturing into a detailed technical design**
  - EIC detectors are an enormous undertaking that requires participation and expertise from both the RHIC and JLab communities
  - Motion to initiate the change control process for calorimeter and RICH technologies endorsed by ePIC CC
  - Progress towards DOE milestones: CD-3A reviews start in Summer/Fall 2023!

- Indico Meeting Agenda:
https://indico.bnl.gov/category/402/

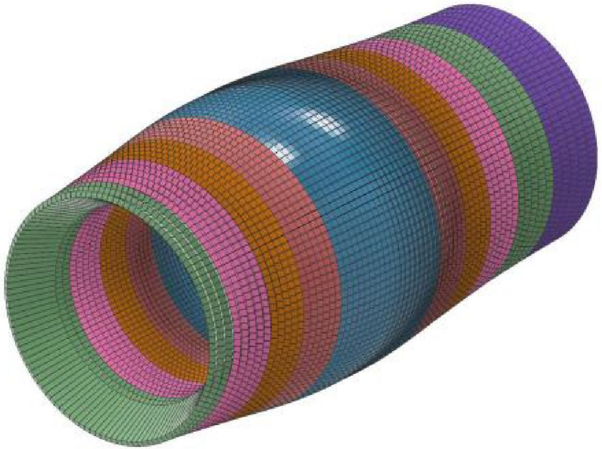
- ePIC Wiki:
https://wiki.bnl.gov/EPIC/index.php?title=Main_Page

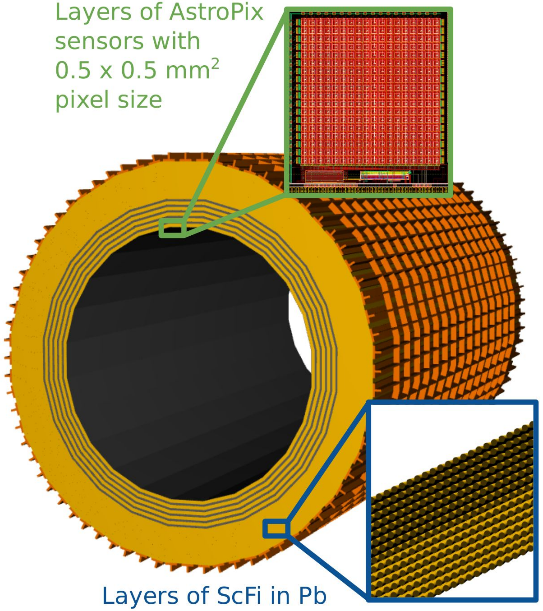
- ePIC Mailing Lists:
https://lists.bnl.gov/mailman/listinfo
  - Look for “eic-projdet-xxx” lists



Backup

Barrel ECal Technology Selection





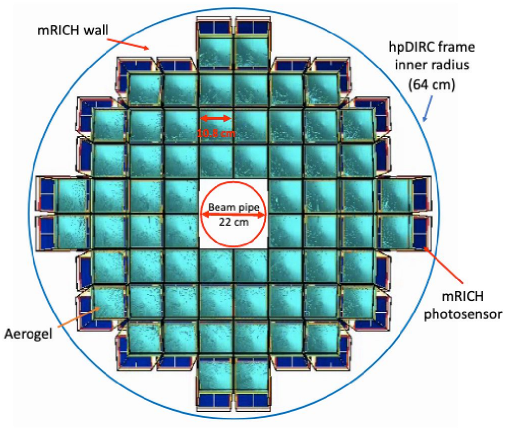
Homogeneous Calorimeter:

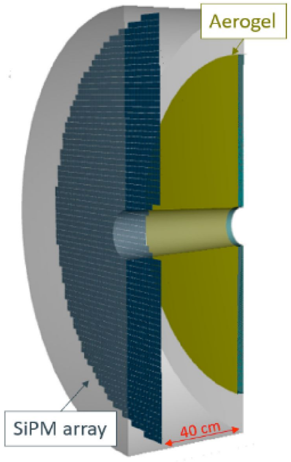
- SciGlass: cost-effective radiator
- Geometry and mechanical design based on PANDA
- Anticipated readout with SiPM matrices

Hybrid Design:

- Imaging calorimetry based on monolithic silicon sensors (AstroPix)
- 6 layers of imaging Si sensors interleaved with 5 SciFi/Pb layers
- Followed by a large section of Pb/ScFi (can serve as inner HCAL)

Backwards PID Technology Selection



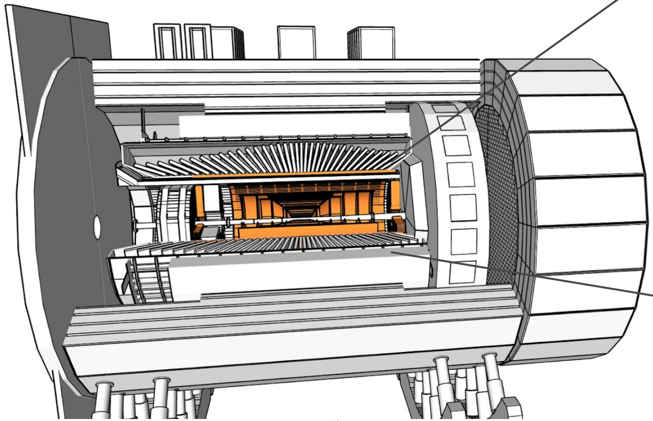


Modular RICH (mRICH)
- Aerogel radiator
- Longitudinally compact due to Fresnel lens focusing
- Modules have dead area

Proximity Focusing RICH (pfRICH)
- Aerogel radiator
- Gas threshold-based electron ID
- Requires expansion volume

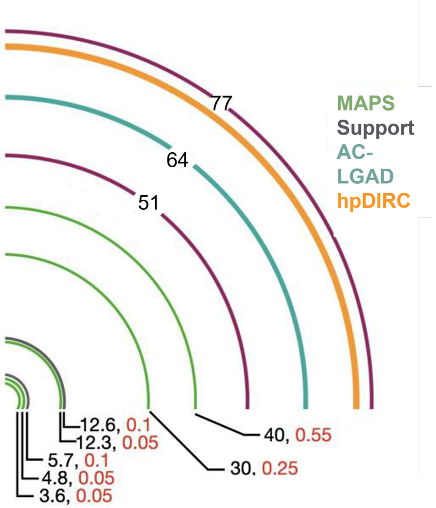
Both with use LAPPD/HRPPD readout to provide additional timing information

Tracking



Black numbers are radii in cm

Red numbers are material in % X0

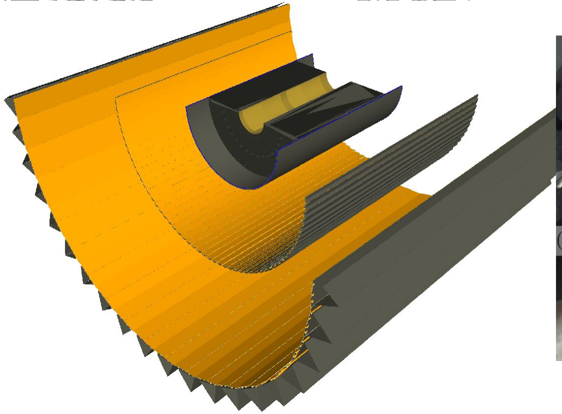


Si Tracker based on ALICE ITS3 65nm MAPS sensors.

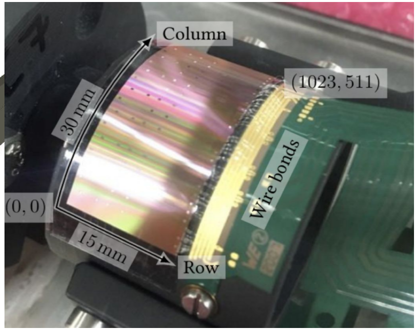
Five layers in barrel, supplemented by MPGDs for pattern recognition.

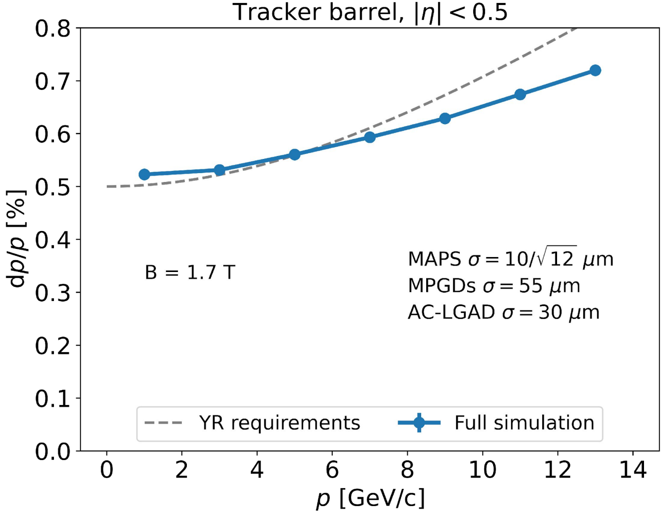
Five discs in forward/backward directions (+MPGD in forward)

Meets EICUG Yellow Report design requirements.

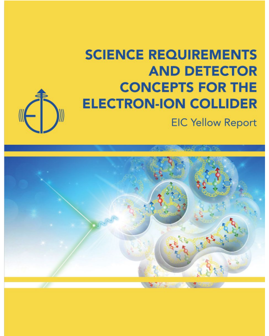


First “μITS3” assembly at CERN





EIC Calorimetry Requirements



EIC Community outlined physics, detector requirements, and evolving detector concepts in the EIC Yellow Report.

Main tasks of the ECAL

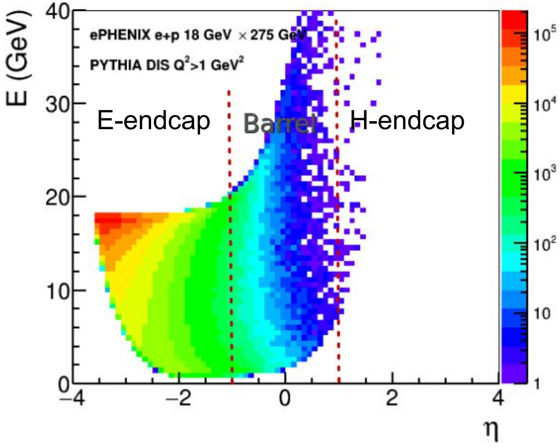
- Detect the scattered **e and separate them from π.**
- Improve the electron **momentum resolution at backward rapidities**.
- **Detect neutral particles (photons, π^0)**, and measure the energy and the coordinates of the impact.
- Separate **secondary electrons and positrons from charged hadrons**.
- Provide **spatial resolution of two photons sufficient to identify decays π^0 → γγ** at high energies.

	$-4 < \eta < -2$	**$-2 < \eta < -1$**	**$\lvert\eta\rvert < 1$**	**$1 < \eta < 4$**
E resolution	$2\%/\sqrt{E} \oplus (1-3)\%$	$7\%/\sqrt{E} \oplus (1-3)\%$	$(10-2)\ \%/\sqrt{E} \oplus (1-3)\%$	$(10\text{-}12)\ \%/\sqrt{E} \oplus (1-3)\%$
e/π separation	up to 10^{-4}	up to 10^{-4}	up to 10^{-4}	3σ e/π
Min E [GeV]	0.1	0.1	0.1	0.1

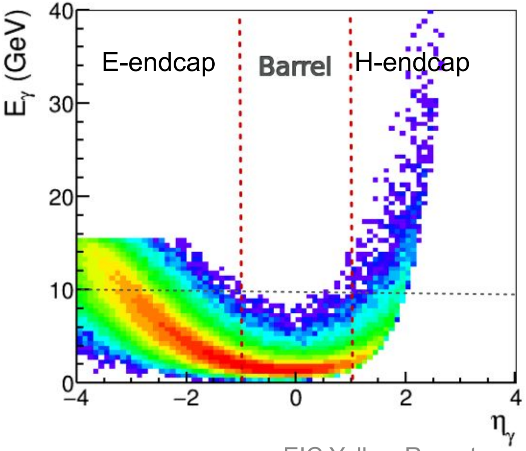
EIC Calorimetry Requirements

EIC Yellow Report

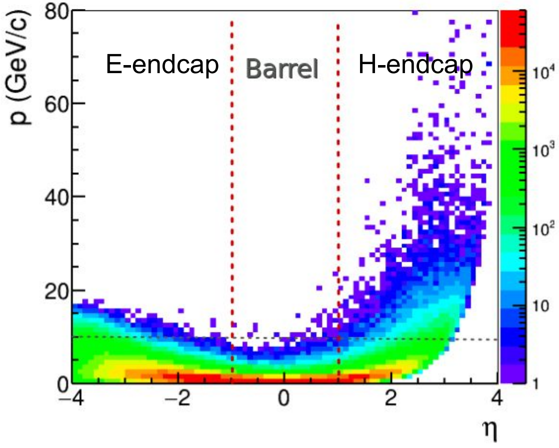
DIS electrons



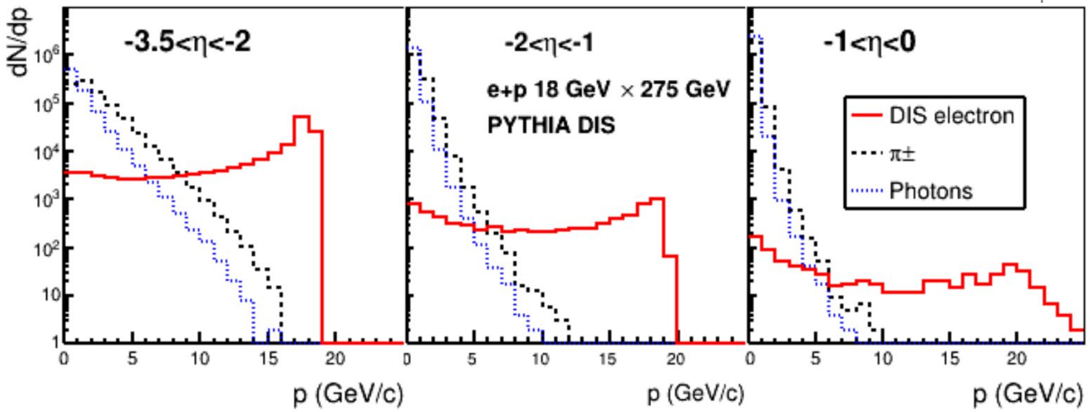
DVCS photons



SIDIS π^0



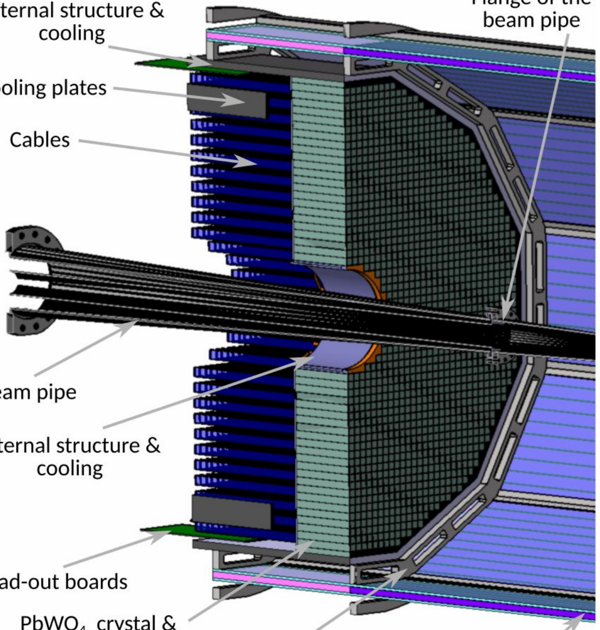
EIC Yellow Report



e/π separation:

- Depends on momentum and η
- Tightest constrain from parity violating asymmetries 10^{-4}
- ΔG requires ~ 10^{-3}

Backward Calorimetry



Backward EMCAL

- Non-projective **$PbWO_4$ calorimeter** (EEEMC-Consortium)
  - 2 × 2 × 20 cm^3 crystals
  - Length ~$20X/X_0$, transverse size ~Molière radius
  - Located inside the inner DIRC frame
  - Preferred readout: SiPMs of pixel size 10μm or 15μm
  - Cooling to keep temperature stable within ± 0.1 °C
- Ongoing efforts advancing the design to increase coverage in η ($-3.7 < \eta < -1.5$) with inlay around beampipe

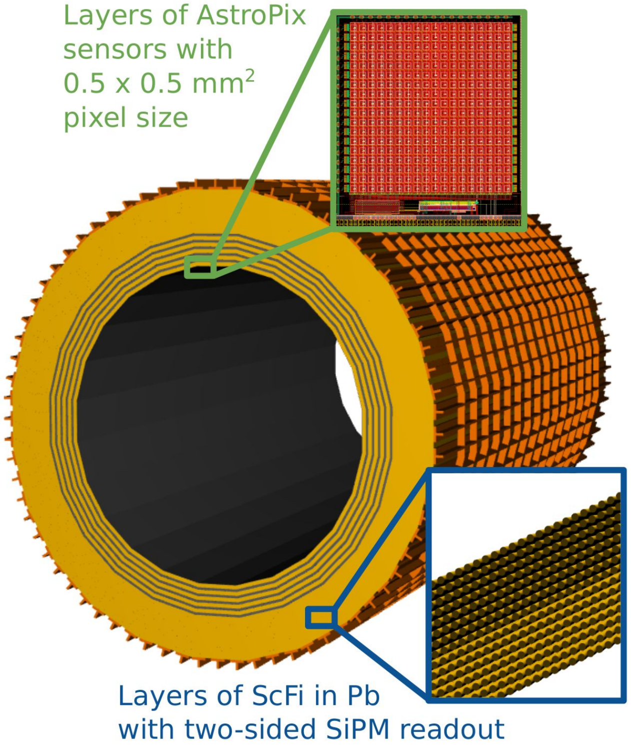
Backward HCAL in consideration

- Possible upgrade path

→ See C. Muñoz Camacho for EEEMCal, https://indico.bnl.gov/event/15493/
→ See B. Page, https://indico.bnl.gov/event/15686/

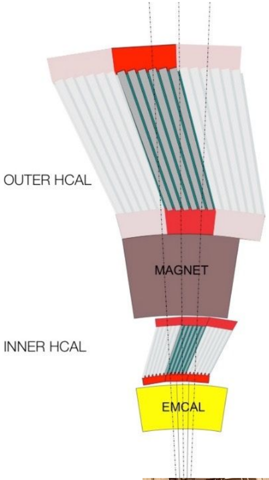
Barrel EM Calorimetry

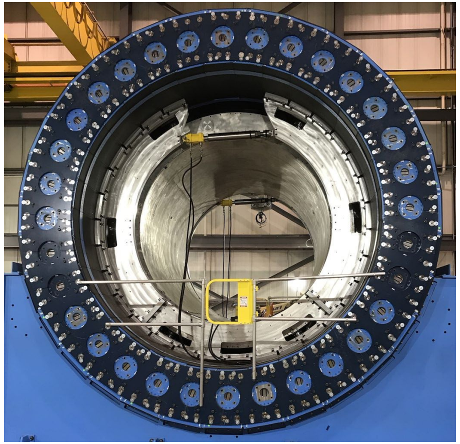
- **Hybrid concept**
  - Imaging calorimetry based on monolithic silicon sensors AstroPix (NASA's AMEGO-X mission) - 500 µm x 500 µm pixels Nuclear Inst. and Methods in Physics Research, A 1019 (2021) 165795
  - Scintillating fibers in Pb (Similar to GlueX Barrel ECal, 2-side readout w/ SiPMs) Nuclear Inst. and Methods in Physics Research, A 896 (2018) 24-42
- 6 layers of imaging Si sensors interleaved with 5 Pb/ScFi layers and followed by a large chunk of Pb/ScFi section (can be extended to inner HCAL)
- Total radiation thickness for EMCAL of ~20 X_0
- Detector coverage: $-1.7 < \eta < 1.3$



Energy resolution - SciFi/Pb Layers: $5.3\% / \sqrt{E} \oplus 1.0\%$
Position resolution - Imaging Layers (+ 2-side SciFi readout): with 1st layer hit information ~ pixel size

Barrel Hadronic Calorimetry

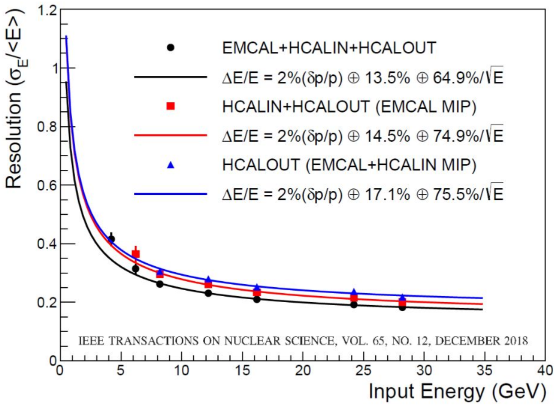




Reuse of sPHENIX outer (outside of the Solenoid) HCal ≈ 3.5λ_I

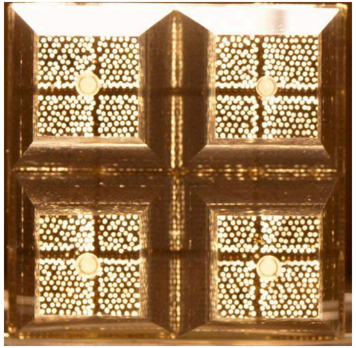
- Steel and scintillating tiles with wavelength shifting fiber
- $\Delta\eta \times \Delta\varphi \approx 0.1 \times 0.1$
  (1,536 readout channels, SiPMs)

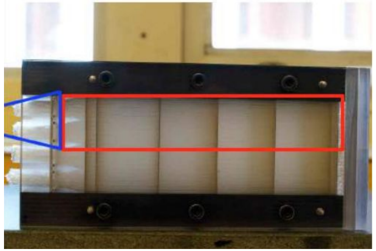
sPHENIX Test Beam



⟶ See: J. Lajoie, https://indico.bnl.gov/event/15493/

Forward EM Calorimetry





4 SiPMs / tower

Sampling EMCal design:

- W/SciFi: scintillating fibers embedded in W/epoxy mix
  - Similar to sPHENIX W/SciFi
  - X/X_0 = 23 (17 cm + 10 cm readout), 2.5 x 2.5 cm towers (R_M=~2.3 cm)
  - Easier construction for WSciFi calorimeter
  - Compactness and higher EM-shower containment

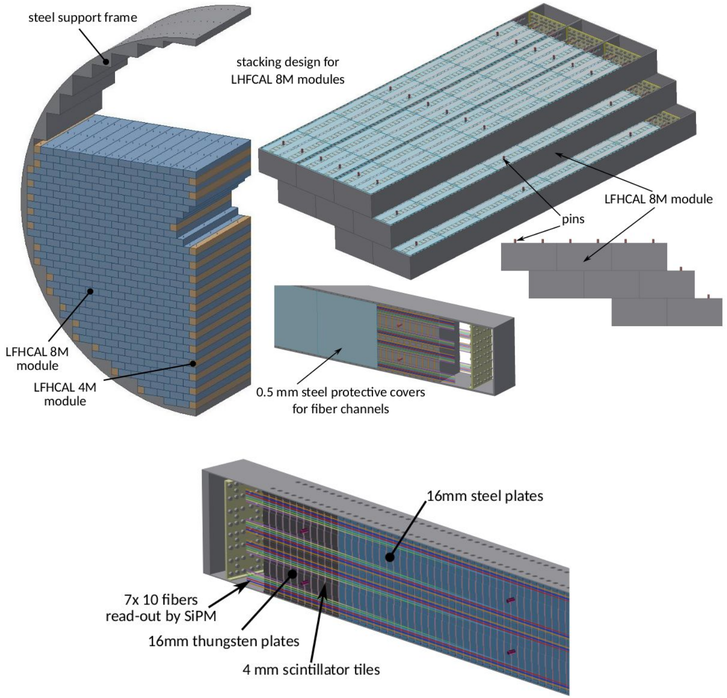
R&D: Improvement of light collection eff. and uniformity

Simulations:

- Expected E resolution ~ $11\%/\sqrt{E} \oplus 2\%$
- Can effectively separate γ/π^0 (z = 3.5 m) with ML methods

→ See O. Tsai, https://indico.bnl.gov/event/15686/

Forward Hadronic Calorimetry



Two design based on longitudinally separated steel and scintillator tiles

- Inspired by Projectile Spectator Detector (CBM)
  - 60 layers of steel-sci plates + 10 layers of W-Sci plates (5 x 5 cm towers)
  - 7 signals per tower (from 10 plates)
  - λ/λ_0 = 6.9 (HCAL only, larger shower containment)

- Ongoing efforts on granular inlay around beampipe

→ See F. Bock, https://indico.bnl.gov/event/15810/
→ See O. Tsai, https://indico.bnl.gov/event/15810/