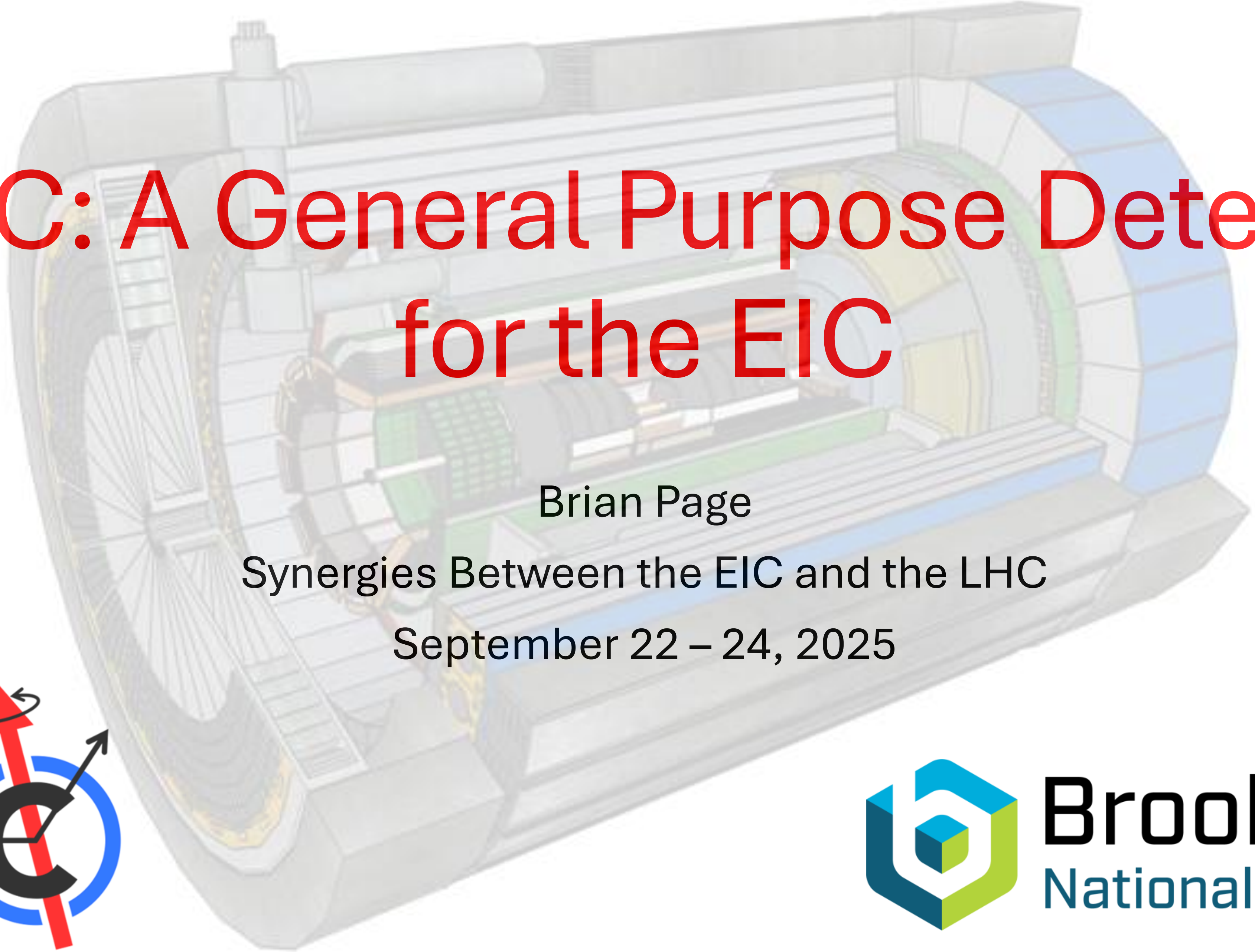


ePIC: A General Purpose Detector for the EIC

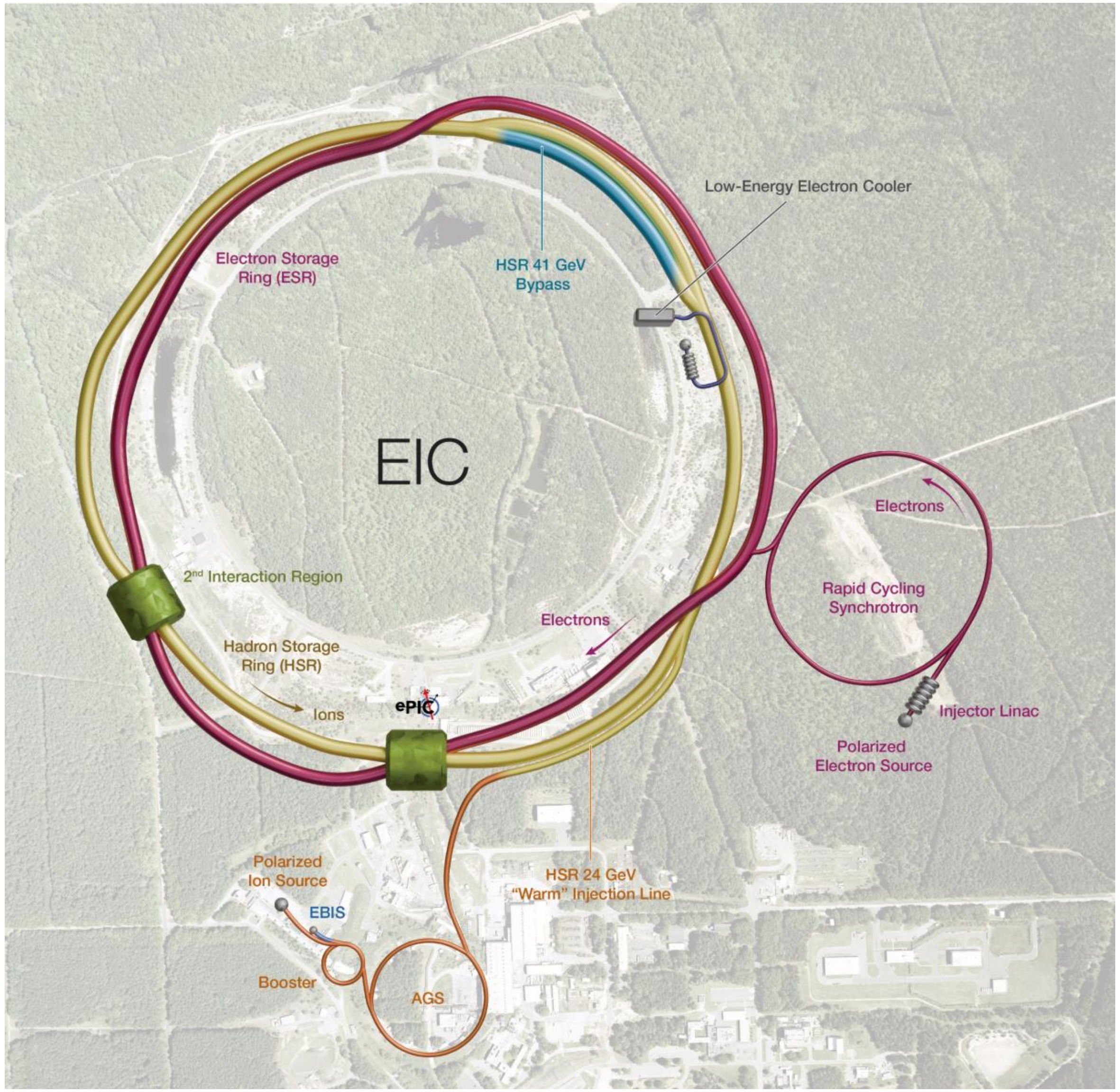
Brian Page

Synergies Between the EIC and the LHC

September 22 – 24, 2025

Brookhaven National Laboratory

The Electron Ion Collider (EIC)



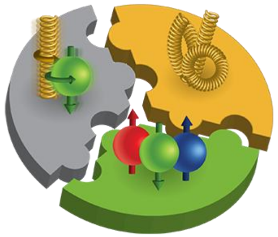
EIC Capabilities

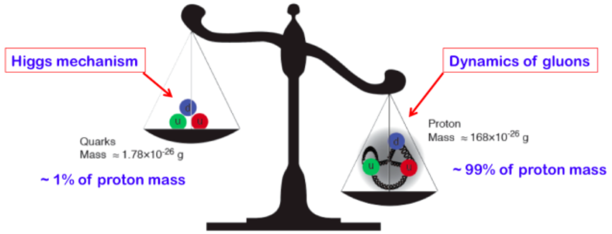
- Large center of mass energy range
  - ep: 28 – 141 GeV
  - eA: 28 – 63 GeV
- High luminosity
  - $10^{33} – 10^{34}$ $cm^{-2}s^{-1}$
  - 10 – 100 fb^{-1} / year
- Electron / proton (and light ion) beam polarization
- Large range in ion species: proton - Uranium

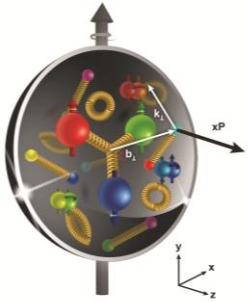
The EIC Physics Pillars

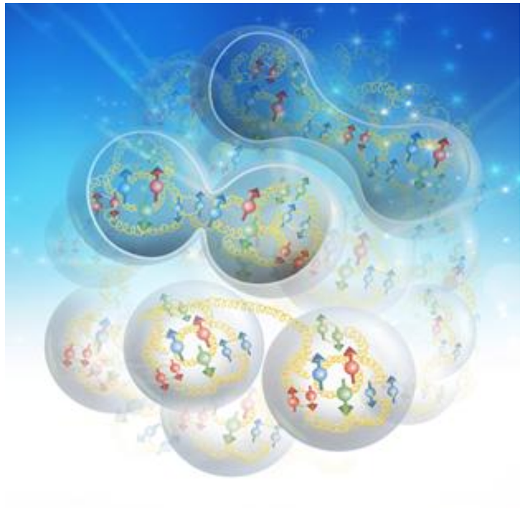
How are the sea quarks and gluons, and their spins, distributed in space and momentum inside the nucleon?

How do the nucleon properties emerge from them and their interactions?









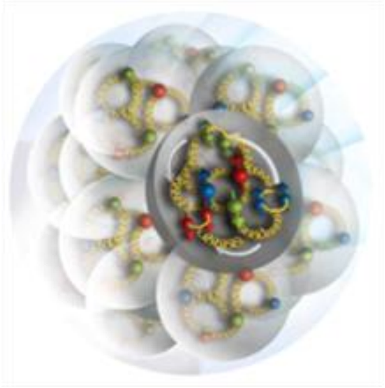
How do color-charged quarks and gluons, and colorless jets, interact with a nuclear medium?

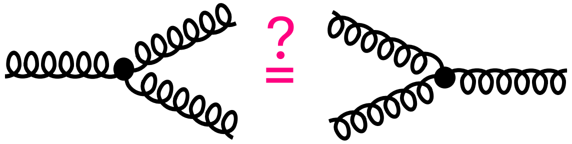
How do the confined hadronic states emerge from these quarks and gluons?

How do the quark-gluon interactions create nuclear binding?

How does a dense nuclear environment affect the quarks and gluons, their correlations, and their interactions?

What happens to the gluon density in nuclei? Does it saturate at high energy, giving rise to a gluonic matter with universal properties in all nuclei, even the proton?





The EIC Physics Pillars

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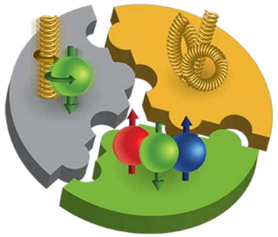

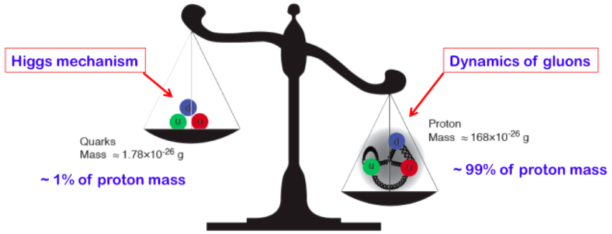

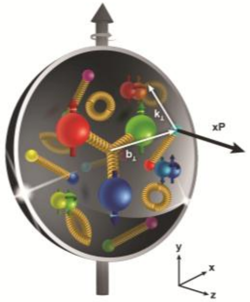

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See upcoming talk by Sal Fazio

How does a dense nuclear environment affect the quarks and gluons, their correlations, and their interactions?

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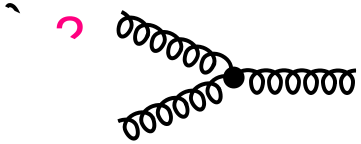
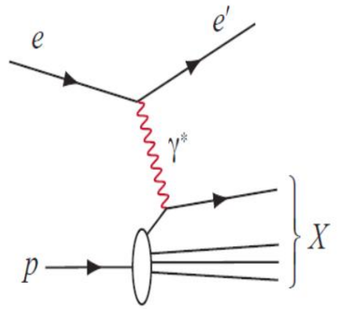
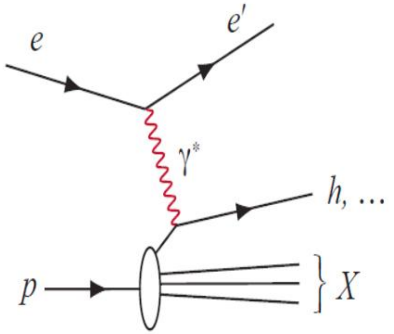


Physics Informs Design



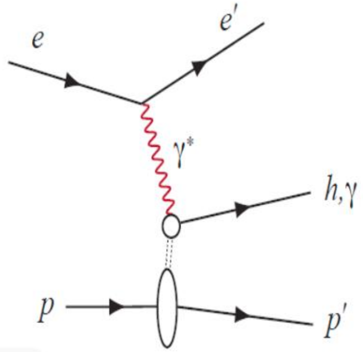
- ❑ Inclusive DIS
  - ➢ Fine binning in x and Q^2

- ❑ Large coverage ($|\eta| < 3.5$) to maximize phase-space reach
- ❑ High-resolution EM calorimetry and PID for e/π separation
- ❑ Low mass, high momentum resolution tracking



- ❑ Semi-inclusive DIS
  - ➢ 5-D binning in x, Q^2, z, p_T, and ϕ_h

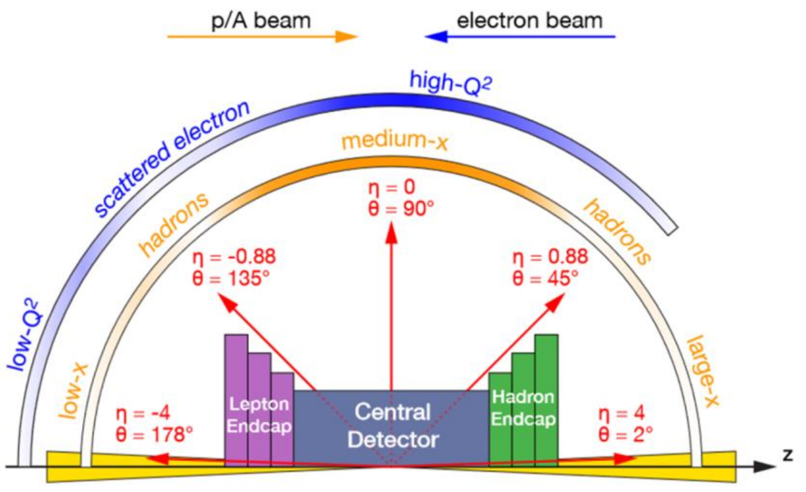
- ❑ Fine p_T (tracking) resolution
- ❑ Extensive PID coverage for hadron identification
- ❑ Hadron calorimetry for jet measurements (neutral hadron ID) and muon ID



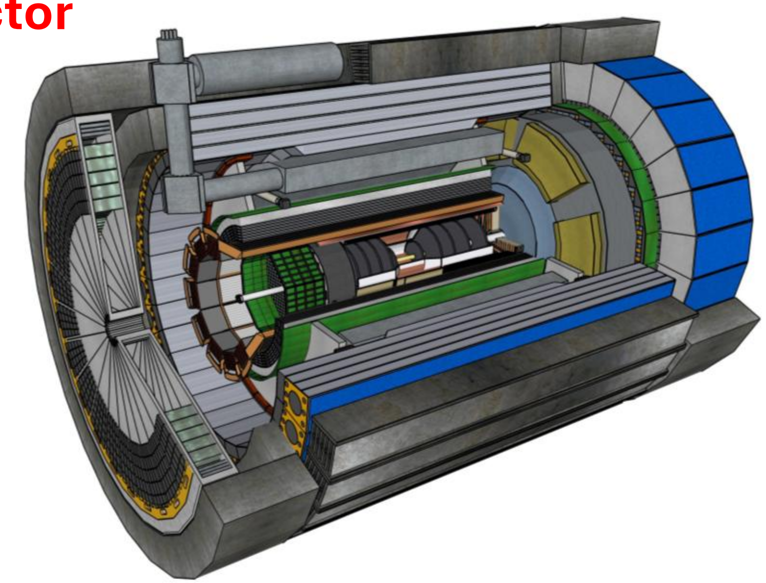
- ❑ Exclusive processes
  - ➢ 4-D binning in x, Q^2, t, and ϕ_h

- ❑ Extended acceptance at very small angles (IR integration and magnet design)
- ❑ Extensive beam-line instrumentation
- ❑ Good vertex resolution
- ❑ EM calorimetry for γ/π^0 separation

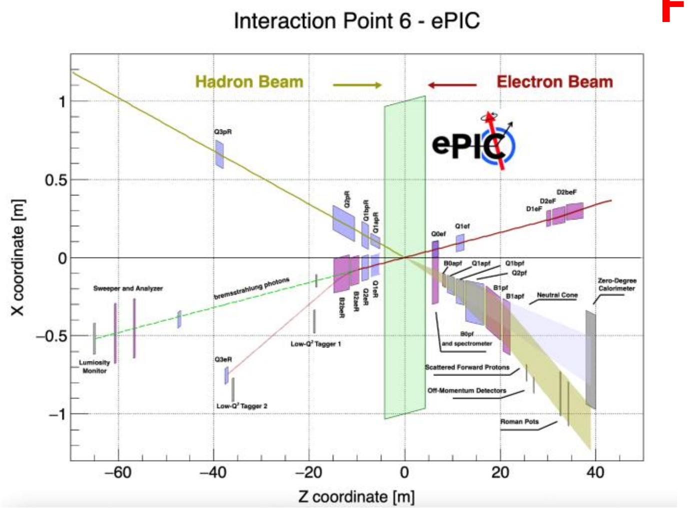
Full Detector Overview

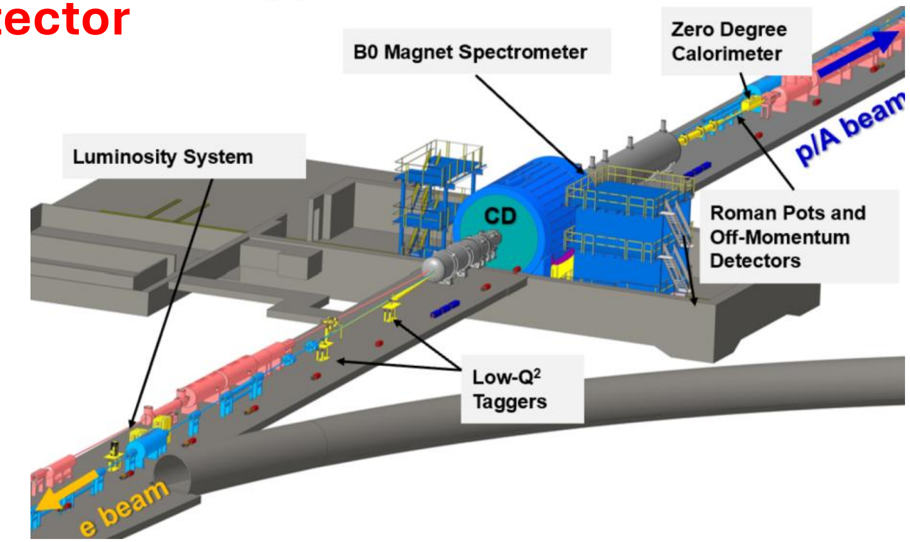


Central Detector



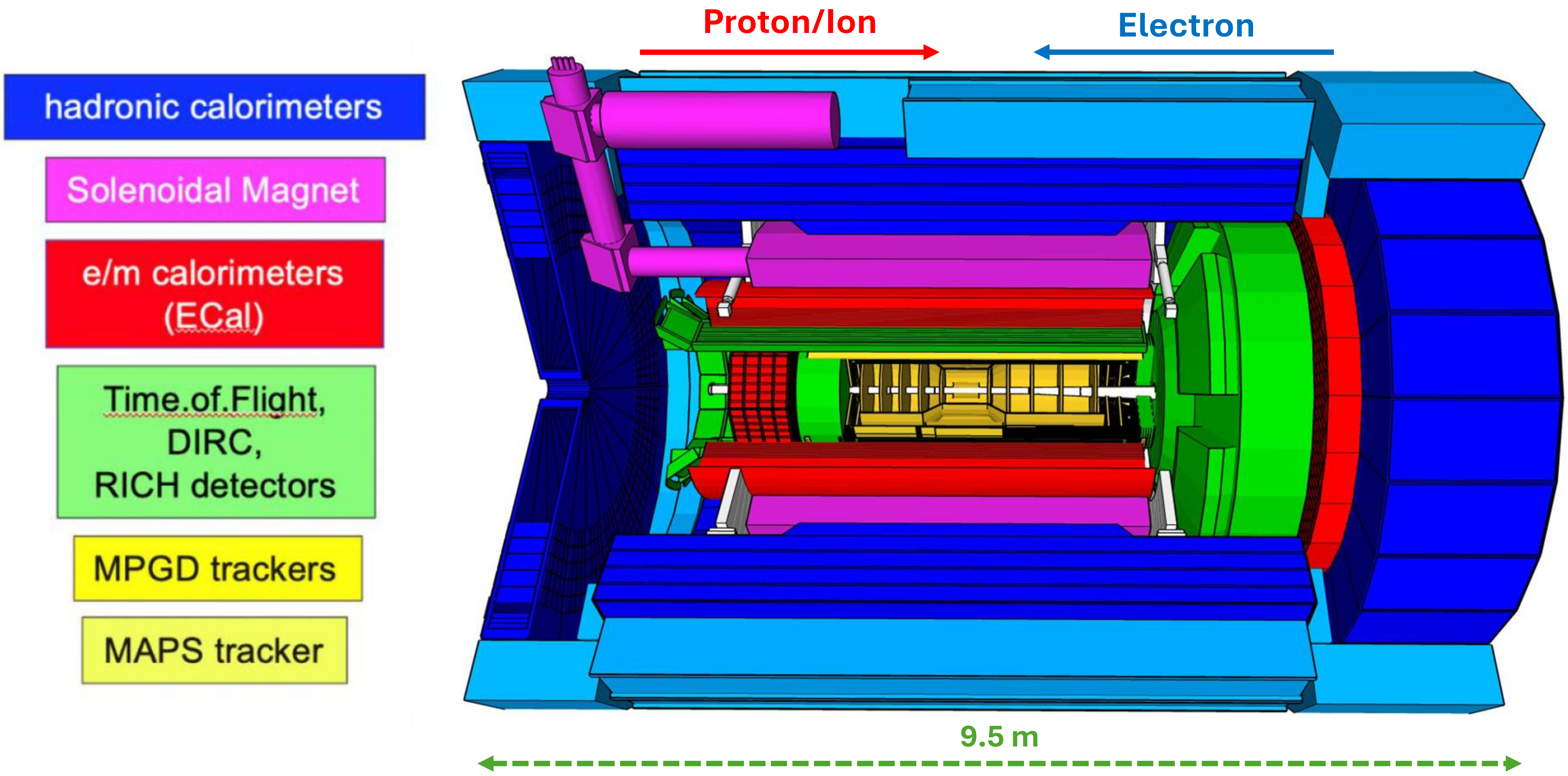
Full Detector



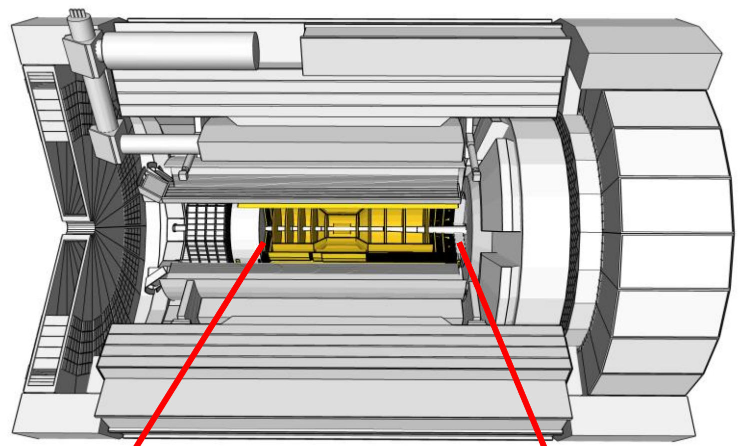


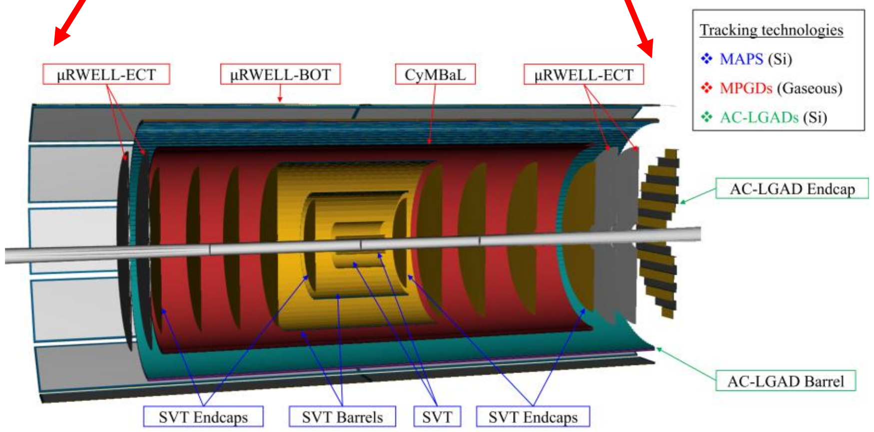
- ❑ Central detector follows familiar HEP detector layout: tracking, PID, EM and hadron calorimetry
- ❑ Asymmetric from forward to backward rapidity reflecting different beam energies
- ❑ Extensive forward and backward instrumentation: lumi, polarimetry, roman pots, ZDC, etc
- ❑ Highly integrated with IR and machine lattice -> full detector is ~90 m

Central Detector Summary



Trackers





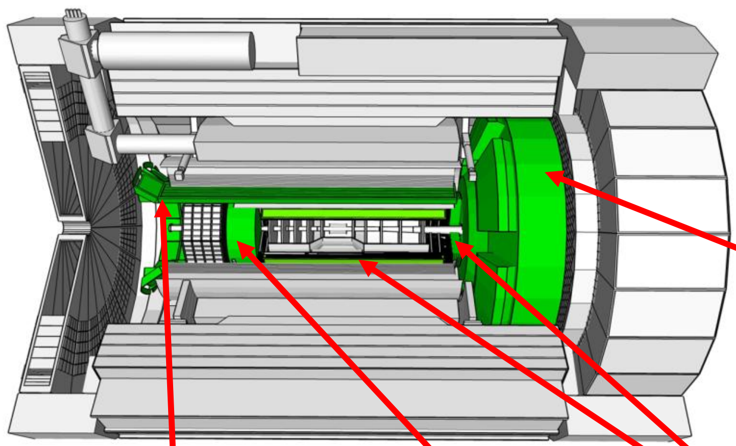
General Requirements for trackers

- Excellent momentum resolution (dp/p(%) up to 0.05*p + 0.5 at mid-rapidity)
- High spatial resolution (20 μm/p_T + 5 μm at mid-rapidity)
- Low material budget
- Timing resolution adequate to resolve 10 ns beam bunch spacing

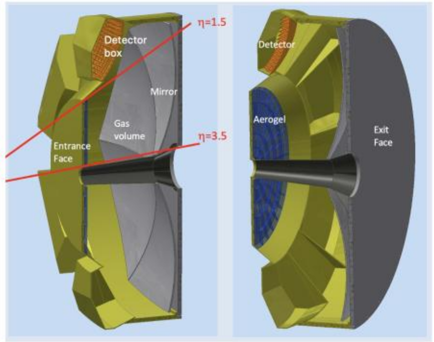
Detector Solutions

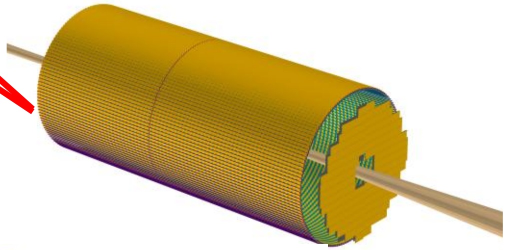
- Silicon Vertex Tracker (Synergy with ALICE ITS3 development)
  - Monolithic Active Pixel Sensors (MAPS) using 65 nm CMOS process
  - 3 inner layers utilizing ALICE ITS3 curved MAPS – 20 μm pixel pitch 0.05% X/X_0
  - 2 outer layers and 5 forward/backward disks using ITS3-based EIC Large Area Sensor <= 0.55% X/X_0
- MPGD – based Trackers
  - Provide additional hit points and fast (O~10 ns) timing capability
  - Cylindrical Micromegas Barrel Layer (CyMBaL) ~1% X/X_0
  - μRWELL Barrel Outer Tracker provides space point directly in front of hpDIRC ~1.5% X/X_0 (central region)
  - GEM-μRWELL endcap disks provide extra hit points where background interference is highest

Particle Identification

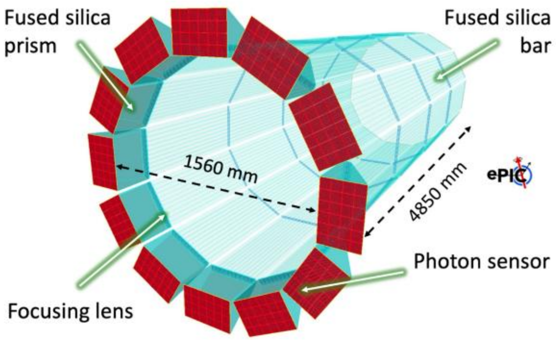


dRICH

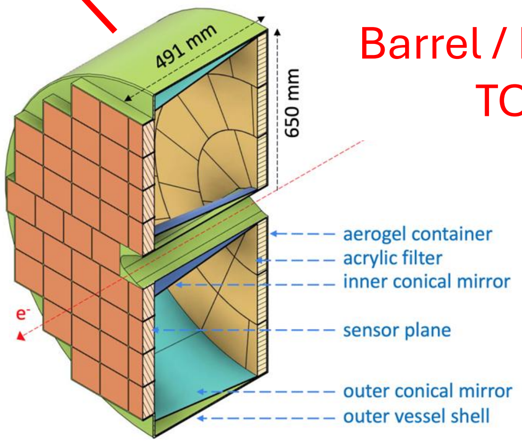




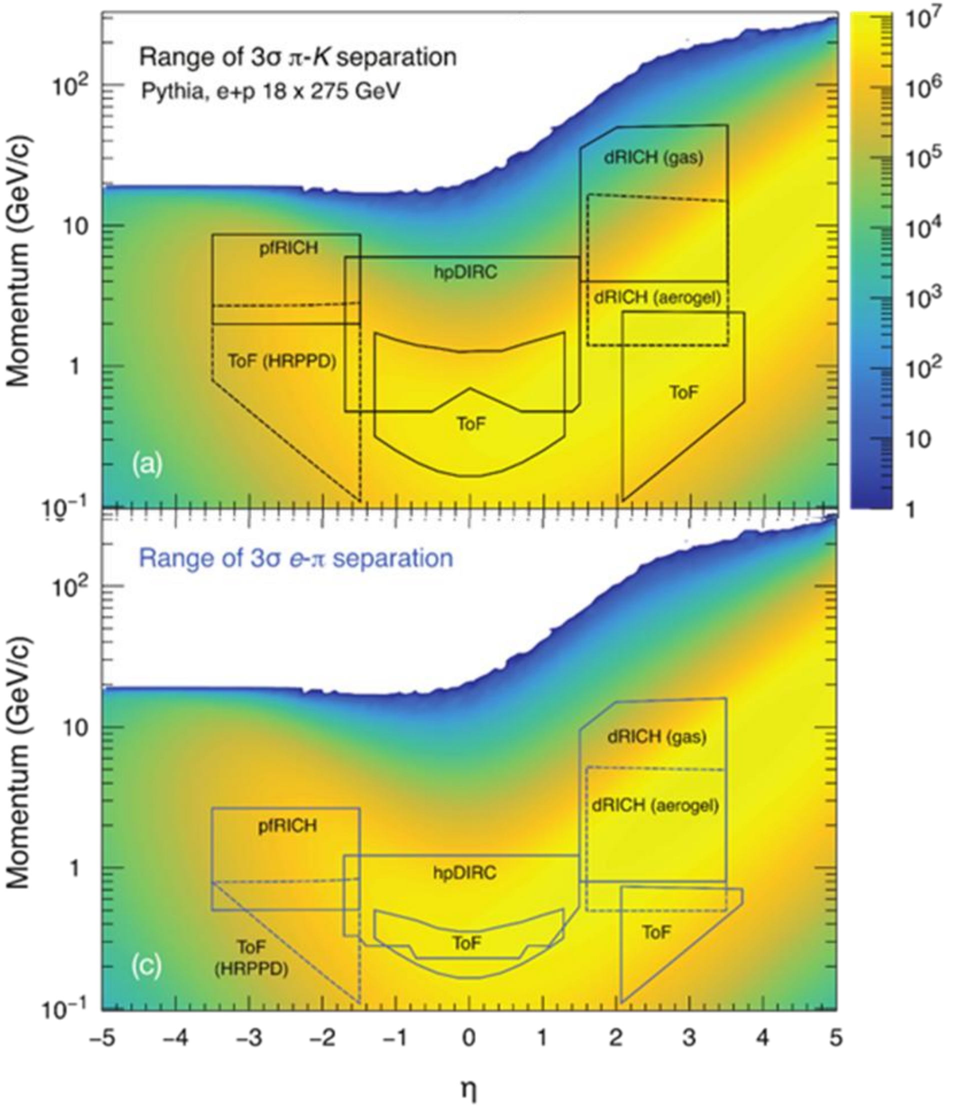
Barrel / Endcap TOF



hpDIRC



pfRICH



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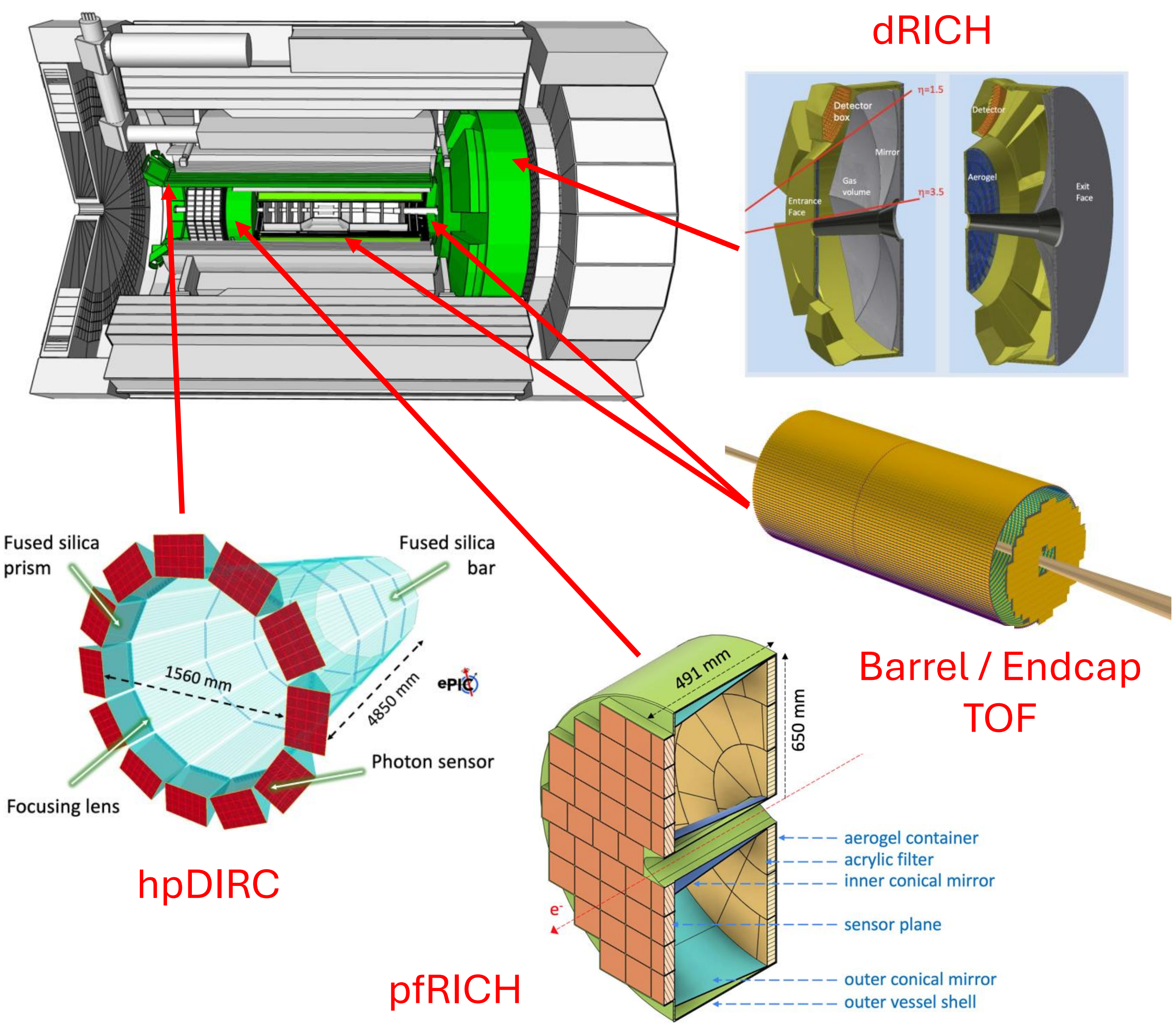


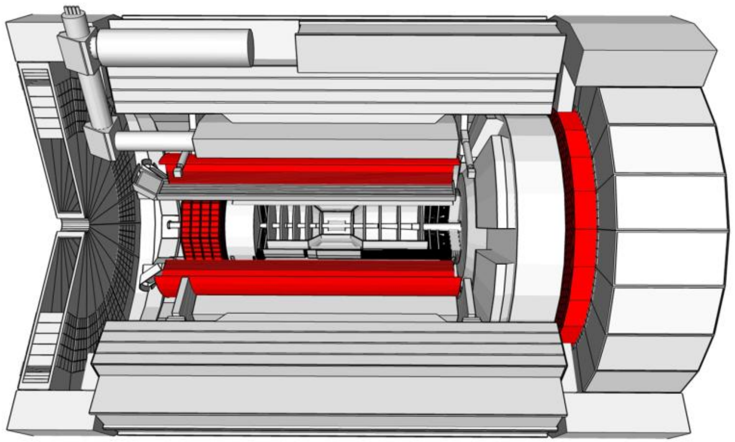
Dual Radiator Ring Imaging Cherenkov (dRICH)
- Aerogel + C_2F_6 gas for PID up to 50 GeV/c
- First-ever use of SiPMs in a RICH (Possible for LHCb)

Proximity Focusing RICH (pfRICH)
- Aerogel radiator for π/k separation up to ~ 8 GeV/c at 3σ
- Novel photosensor solution: HRPPDs (under consideration for LHCb upgrade)
- Excellent time resolution (< 30 ps) allows integrated ToF capability

High-Performance DIRC (hpDIRC)
- Quartz bar radiators running length of ePIC barrel - π/k separation up to 6 GeV/c at 3σ
- 3-layer spherical lens system reduces photon loss between bars and expansion prism
- Pixelized MCP-PMTs as photosensors – possibility to use HRPPDs in synergy with pfRICH

Time-of-Flight Barrel and Forward Endcap (BTOF and FTOF)
- AC-LGAD sensors provide 20-35 ps time resolution
- π/k separation at 3σ for p_T < 1.2 GeV/c and p < 2.5 GeV/c for BTOF and FTOF, respectively

Electromagnetic Calorimetry

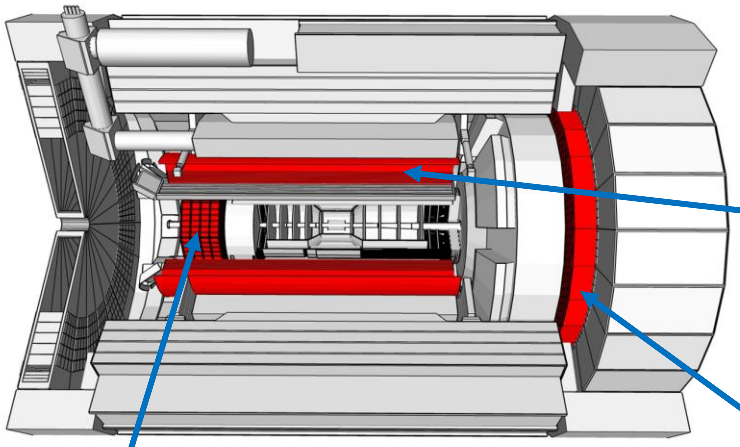


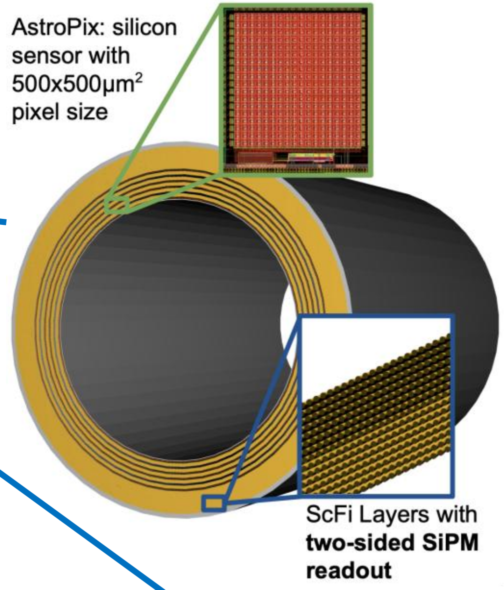
	σ_E/E	E Range [GeV]
E-Endcap	(2-3)%/√E + (1-2)%	0.1 – 18
Barrel	10%/√E + (2-3)%	0.1 – 50
H-Endcap	12%/√E + 2%	0.1 – 100

General Electromagnetic Calorimetry Considerations

- Electron-Going Endcap Calorimeter
  - Excellent energy resolution for precision determination of kinematics from scattered electron
  - Electron-hadron discrimination (with other subsystems) up to 10^4
- Barrel Calorimeter
  - Electron identification and hadron suppression for high Q^2 events and electrons from vector meson decay
  - Excellent spatial resolution to discriminate DVCS photons from π^0 decays
  - Large dynamic range to measure MIPs initiated from muons
- Hadron-Going Endcap Calorimeter
  - Large area coverage for jet measurements
  - Spatial resolution to discriminate DVCS photons and π^0s
  - Performance to high energies for particles boosted by hadron beam

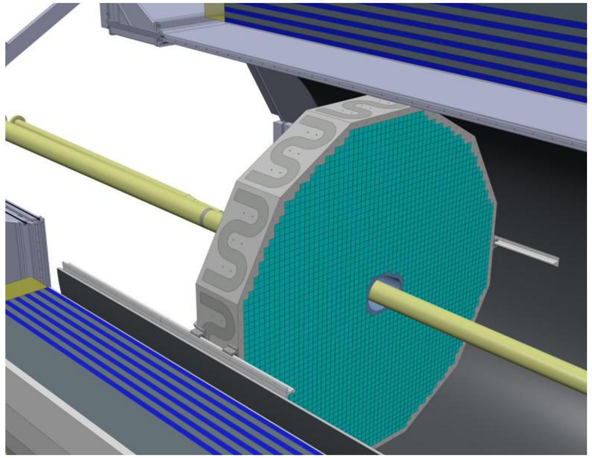
Electromagnetic Calorimetry





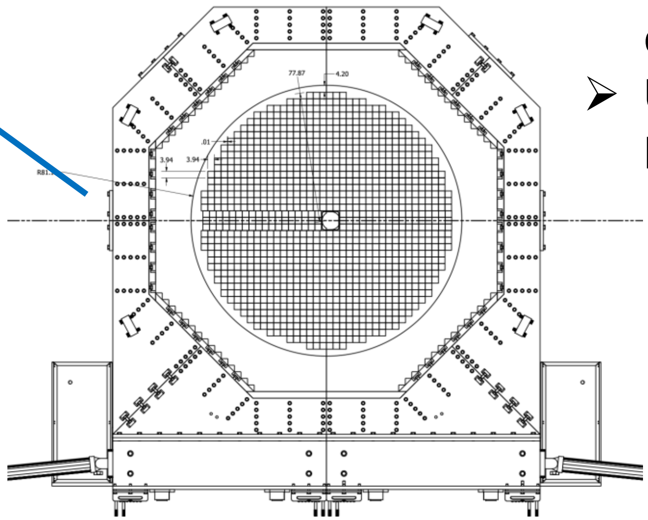
Barrel Imaging Calorimeter (BIC)

- Hybrid calorimeter: 6 layers of AstroPix (4 instrumented) interleaved with 5 Pb/ScFi layers, followed by bulk Pb/ScFi
- Pb/ScFi sections based on GlueX design – SiPM readout at either end of barrel
- AstroPix: MAPS sensors with 500 μm pixel pitch and ~3.2 ns time resolution



EEEMCAL

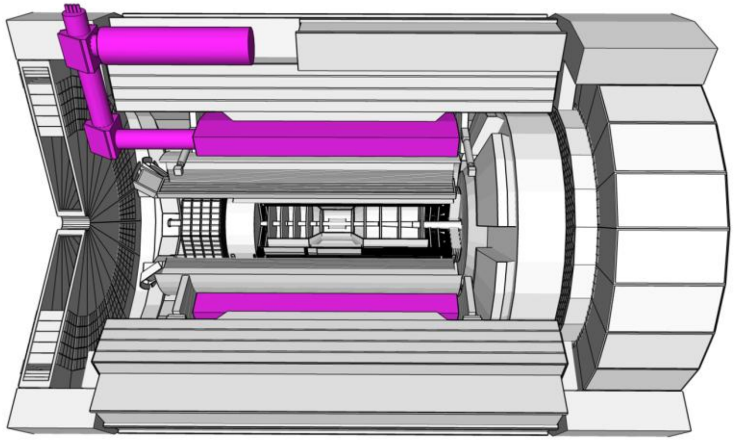
- High-precision $PbW0_4$ crystal calorimeter
- First use of SiPMs in a crystal calorimeter



Hadron-Endcap Ecal

- Tungsten/SciFi SPACAL design with SiPMs
- Utilized in sPHENIX barrel EMCal

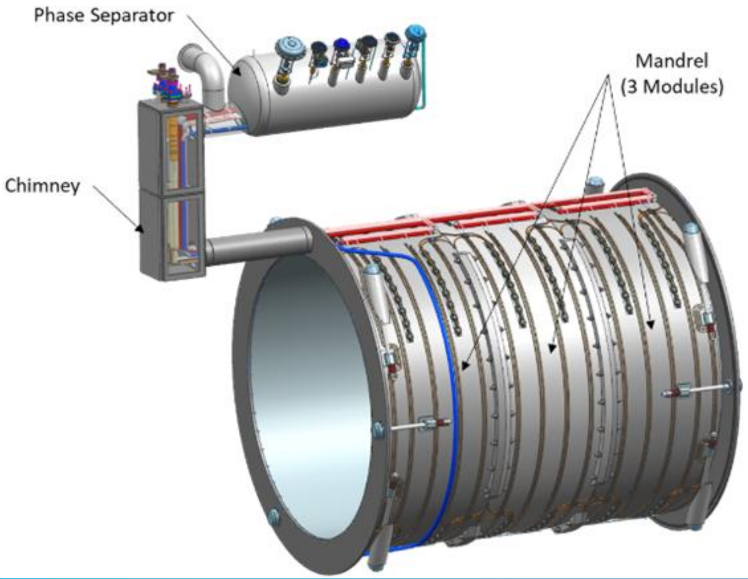
MARCO Magnet

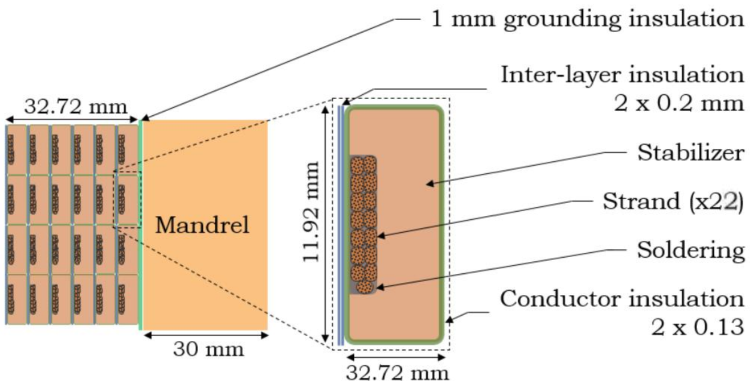


Magnet with Renewed Coils (MARCO)

B_0	1.5 T	1.7 T	2.0 T	Units
Current	2942	3335	3924	A
T_{op}	4.7	4.7	4.7	K
B_{peak}	2.00	2.27	2.67	T
Temp. margin	3.06	2.82	2.45	K
Load line margin	59.6	54.2	46.1	%
$I / I_c(T, B_{peak})$	17.9	22.1	29.3	%

1.7 T nominal field
2.0 T possible

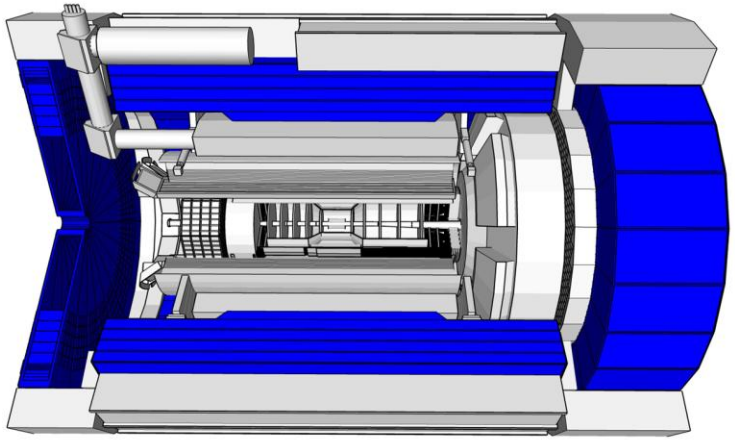




Rutherford In Copper Channel (RICC) Conductor

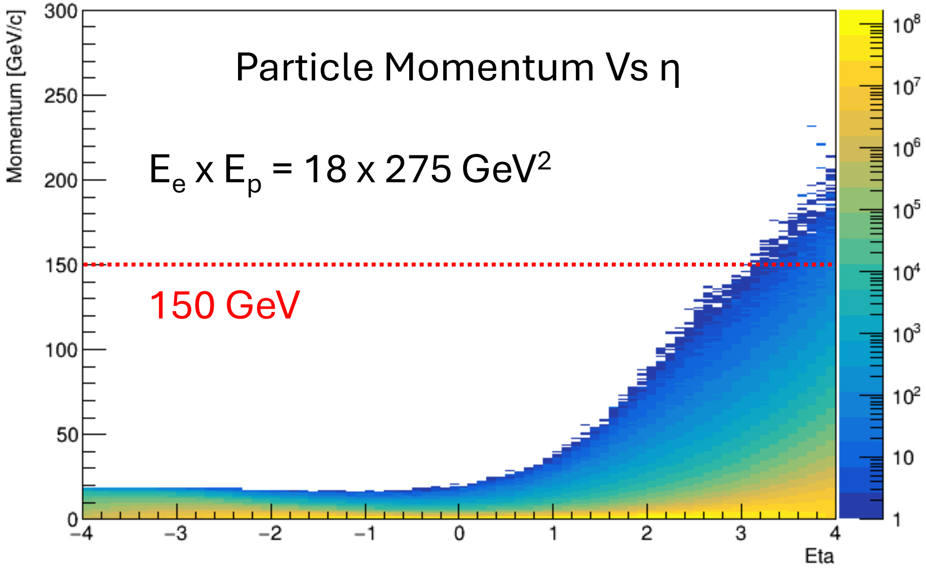
- ❑ Solenoidal field supplied by new large-bore MARCO magnet
  - ➢ Bore Radius = 1420 mm
  - ➢ Cryostat OR = 1770 mm
  - ➢ Cryostat Length = 3850 mm
- ❑ 3 modules with 6 conductor layers each
- ❑ Steel return yoke designed to reduce fringe fields and provide projectivity in RICH region
- ❑ 2 and 3D mechanical analysis done on all components – all stresses and displacements within acceptable limits

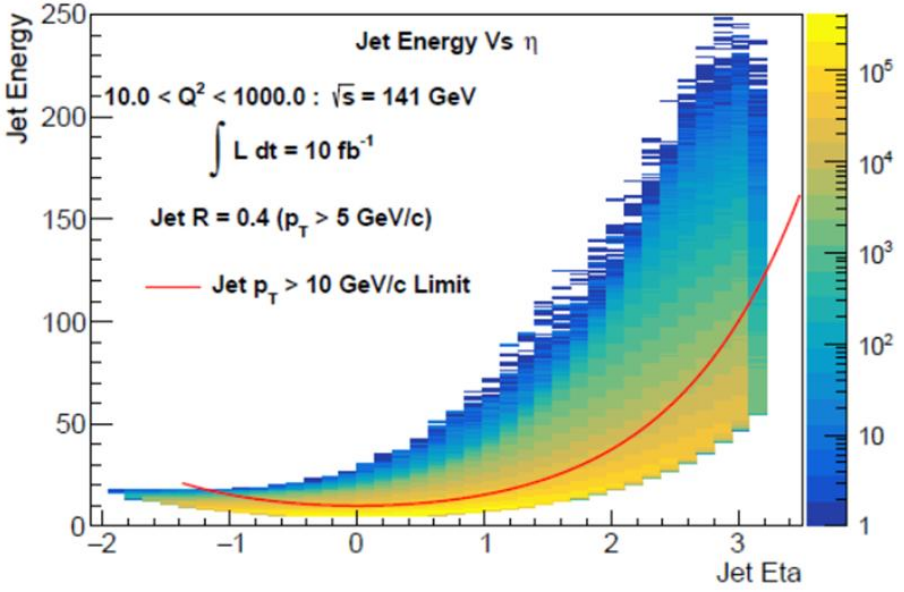
Hadronic Calorimetry



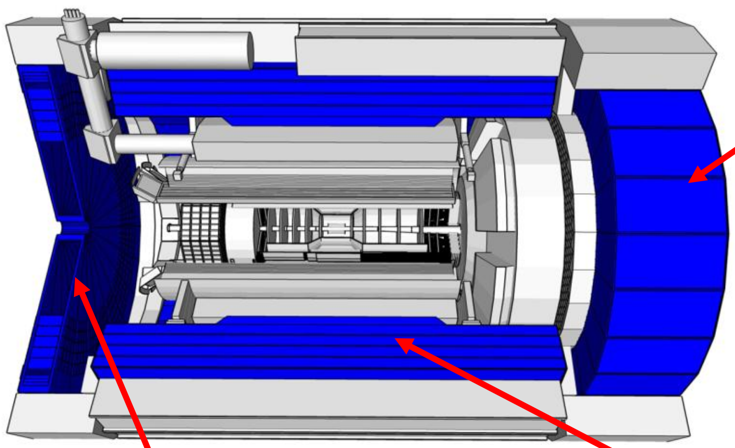
General Hadronic Calorimetry Considerations

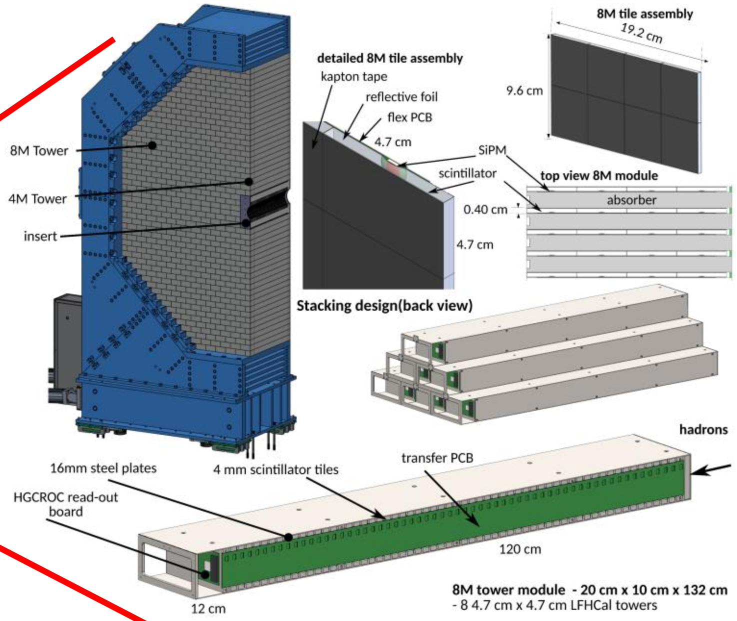
- Particles in forward direction boosted to high energies (up to ~150 GeV) by hadron beam energy
- Tracking momentum and angular resolution degrades for η > 3 so finely segmented good resolution hadronic calorimetry needed for jet measurements and kinematics determinations
- Calorimetry in mid and backward rapidity needed for neutrals detection, tail catching, and muon identification





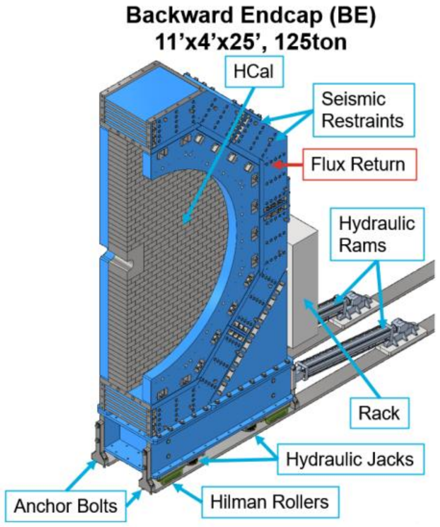
Hadronic Calorimetry





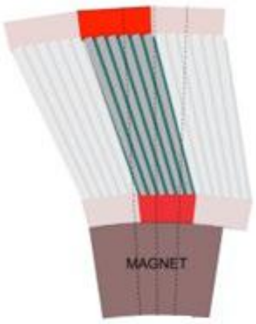
Forward HCal (LFHCal)

- Longitudinally segmented steel + scintillator SiPM-on-tile design
- 8752 towers x 7 individual longitudinal readout groupings ~6 interaction lengths
- High-granularity insert close to beam pipe
- CALICE-like design optimized for particle flow reconstruction



Negative HCal

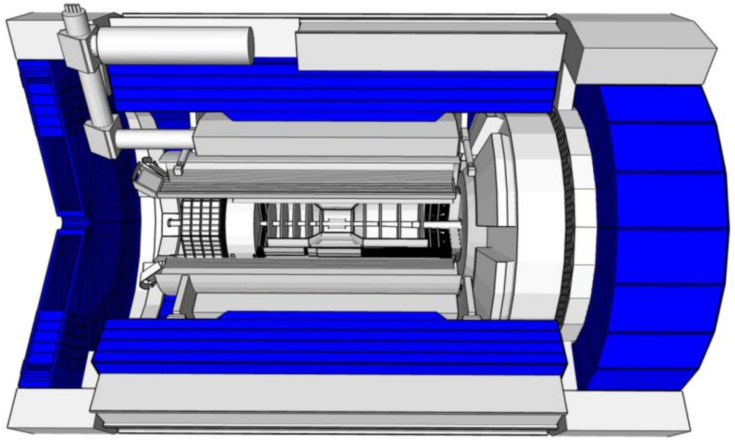
- Similar layout to forward HCal
- Tail catcher for identifying neutral components of jets
- Muon ID

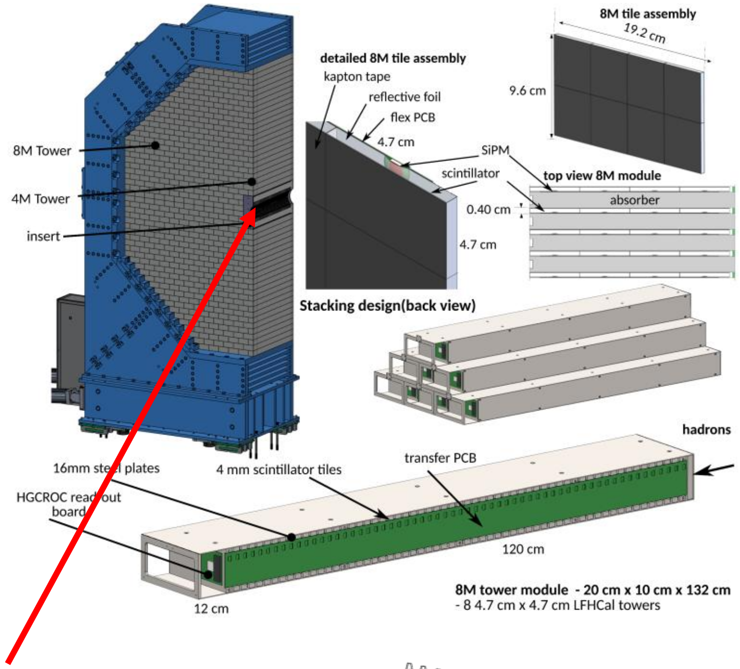


Barrel HCal

- Steel + scintillator design – tilted vertical plates
- Reuse of sPHENIX calorimeter
- Tail catcher and muon ID

Hadronic Calorimetry





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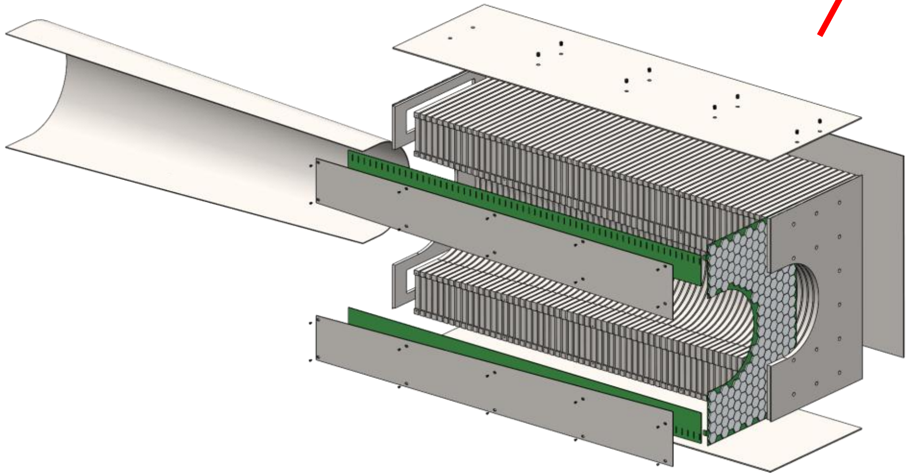
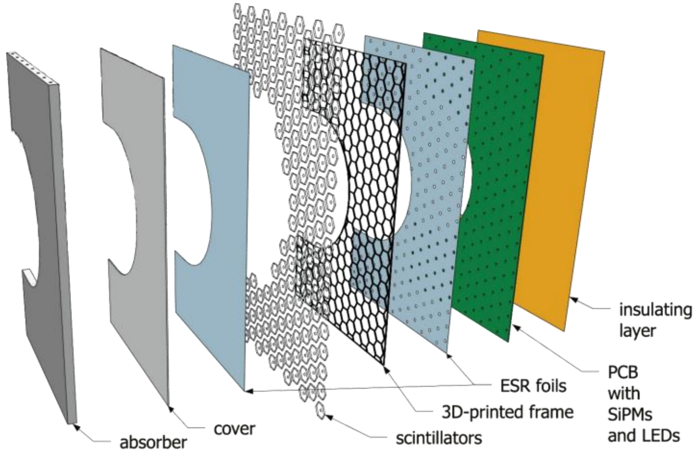
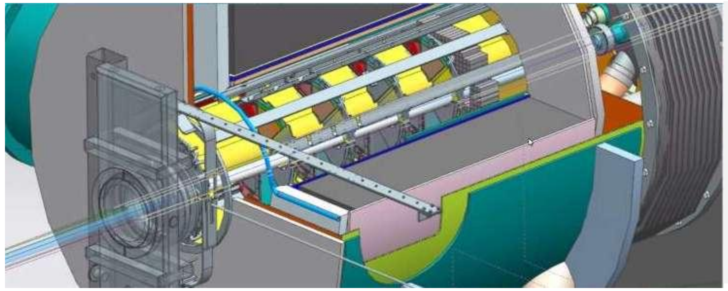




High-Granularity Insert

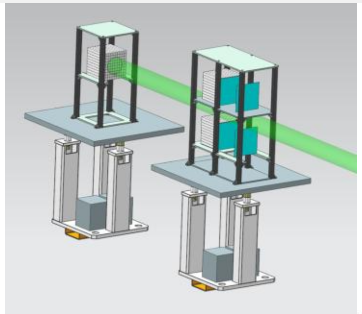
- Beam pipe shape is non-trivial in forward endcap region
- Machine each layer to match beam pipe envelope to maximize acceptance
- SiPM-on-tile with hexagonal segmentation
- Hexagons offset layer-to-layer to improve shower reconstruction

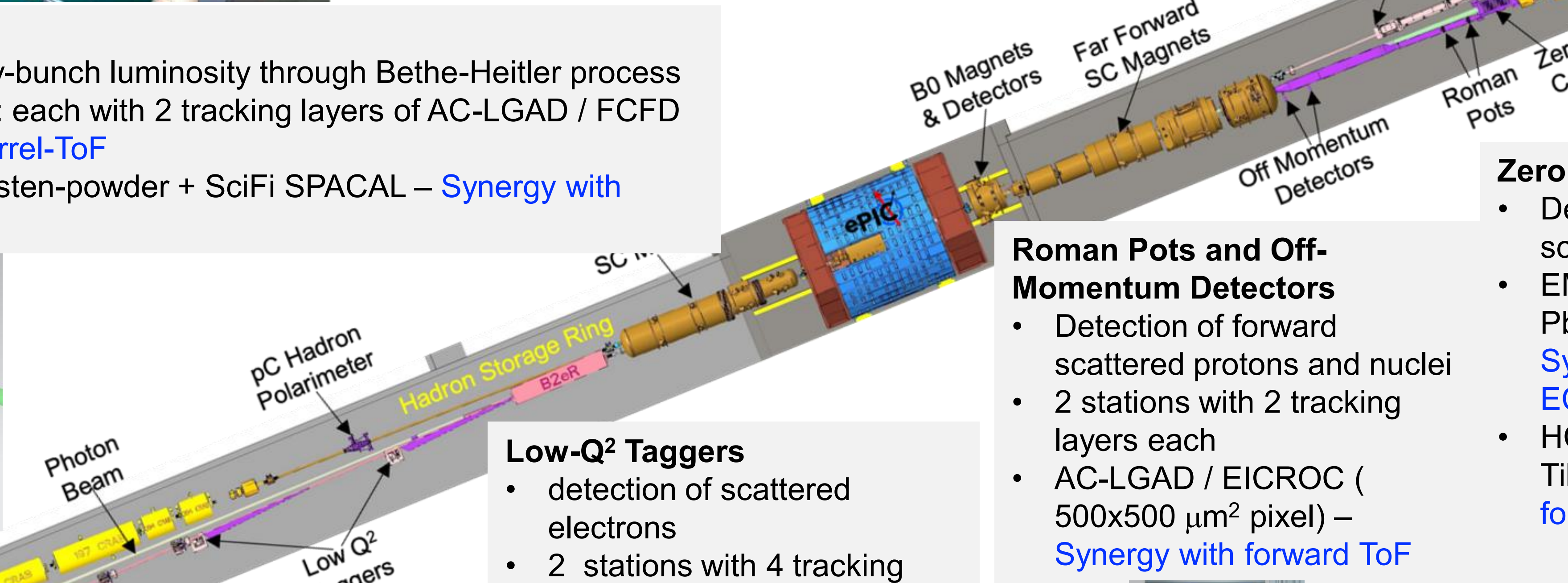
Far-Forward & Far-Backward Instrumentation



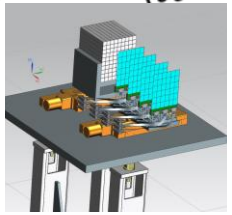
B0 Magnet Spectrometer
- detection of forward scattered protons and and γ
- 4 tracking layers each of AC-LGAD / EICROC (500x500 μm^2 pixel) – Synergy with forward ToF
- EMCAL: 2x2x20 cm^3 $PbWO_4$ calorimeter – Synergy with backward ECal

Luminosity System
- Measure bunch-by-bunch luminosity through Bethe-Heitler process
- Pair-spectrometer: each with 2 tracking layers of AC-LGAD / FCFD – Synergy with Barrel-ToF
- Calorimeter: Tungsten-powder + SciFi SPACAL – Synergy with forward ECal

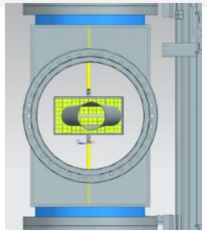




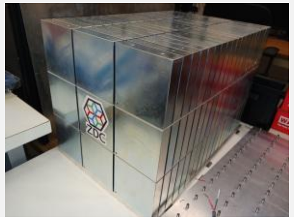
Low-Q² Taggers
- detection of scattered electrons
- 2 stations with 4 tracking layers each (16x18cm^2) Si / Timepix4
- Calorimeter: Tungsten-powder + SciFi SPACAL – Synergy with forward ECal



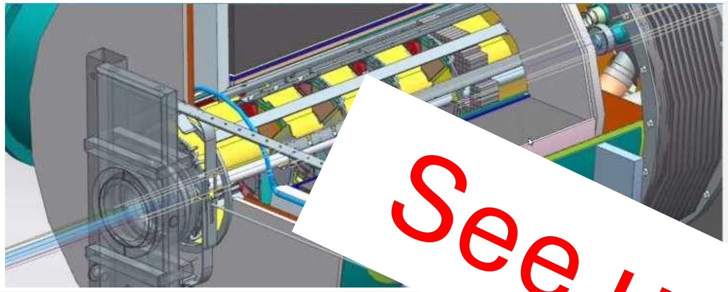
Roman Pots and Off-Momentum Detectors
- Detection of forward scattered protons and nuclei
- 2 stations with 2 tracking layers each
- AC-LGAD / EICROC (500x500 μm^2 pixel) – Synergy with forward ToF



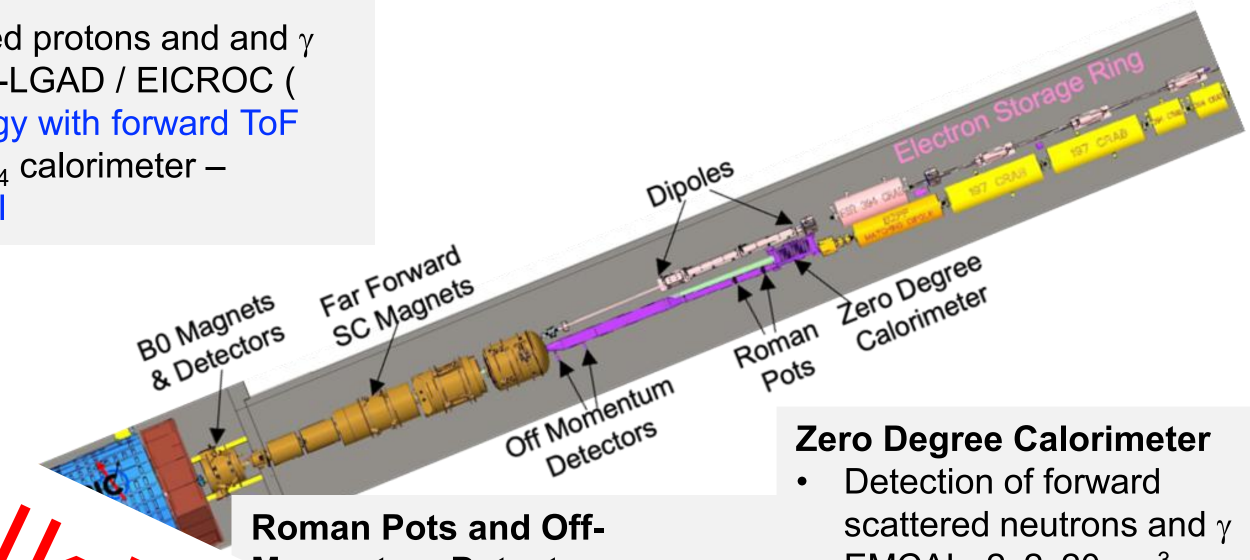
Zero Degree Calorimeter
- Detection of forward scattered neutrons and γ
- EMCAL: 2x2x20 cm^3 $PbWO_4$ calorimeter – Synergy with backward ECal
- HCAL: Steel-SiPM-on-Tile – Synergy with forward HCal



Far-Forward & Far-Backward Instrumentation

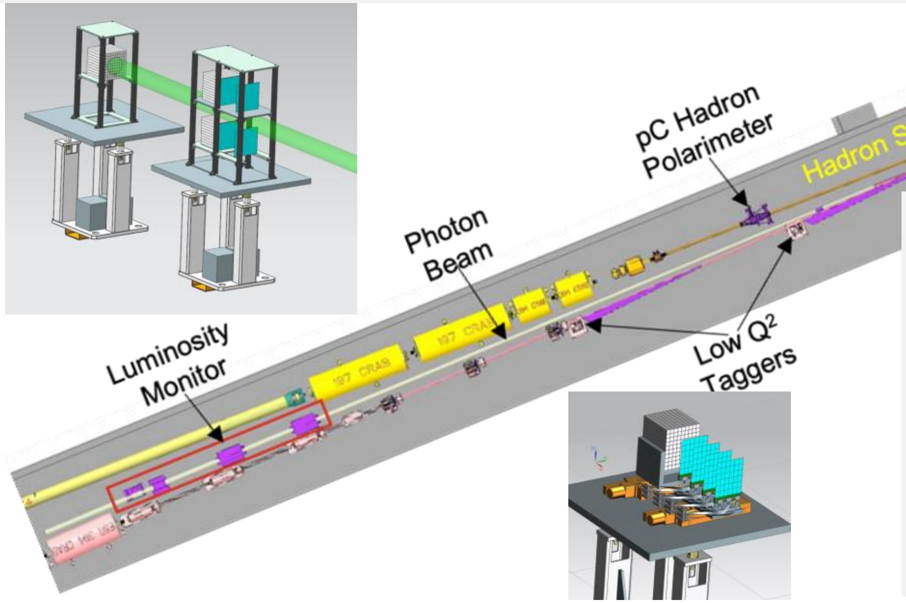


B0 Magnet Spectrometer
- detection of forward scattered protons and and γ
- 4 tracking layers each of AC-LGAD / EICROC (500x500 μm^2 pixel) – Synergy with forward ToF
- EMCAL: 2x2x20 cm^3 $PbWO_4$ calorimeter – Synergy with backward ECal



See upcoming talk by Alex Jentsch

Luminosity System
- Measure bunch-by-bunch lumino… process
- Pair-spectrometer: each with 2 tracking … QED – Synergy with Barrel-ToF
- Calorimeter: Tungsten-powder + SciFi SPACAL – … forward ECal



Low-Q^2 Taggers
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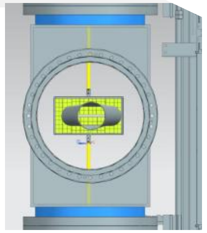
- Calorimeter: Tungsten-powder + SciFi SPACAL – Synergy with forward ECal

Roman Pots and Off-Momentum Detectors
- …tection of forward … protons and nuclei
- … 2 tracking …
- A… 500x5… Synergy with…



Zero Degree Calorimeter
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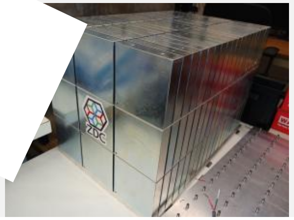
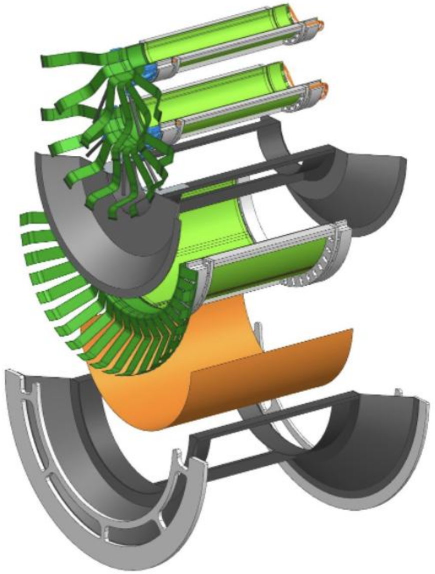


Hardware Synergies with HEP

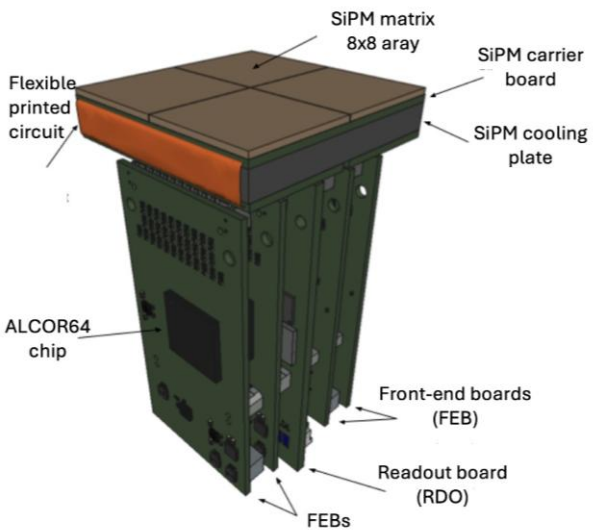
Many of the novel and existing detector technologies needed to fulfill the ePIC science goals have applications in future HEP experiments and upgrades – opportunity for synergistic R&D and exchange of operational expertise

- ❑ Tracking
  - ➢ Collaboration on ITS3 with ALICE
  - ➢ Integrated cooling solutions
- ❑ PID
  - ➢ Use of MCPs and SiPMs as photosensor solutions for RICHs
  - ➢ Low temp operation and annealing of SiPMs for dark count mitigation
  - ➢ Aerogel fabrication and characterization
  - ➢ See RICH 2025 – many overlaps with future LHC upgrades
- ❑ Calorimetry
  - ➢ Implementation of CALICE-like calorimeter with SiPM-on-tile tech
  - ➢ Hybrid Ecal combining silicon and Pb/SciFi
- ❑ Magnet
  - ➢ Maintain crucial expertise and manufacturing capability

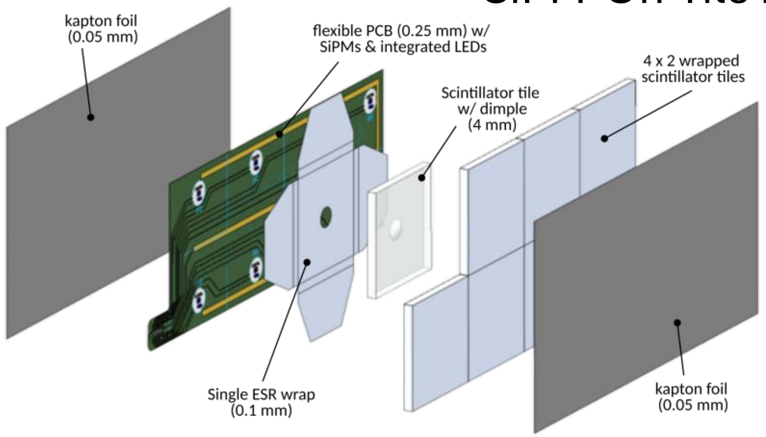
SVT Assembly



dRICH Sensor Modual



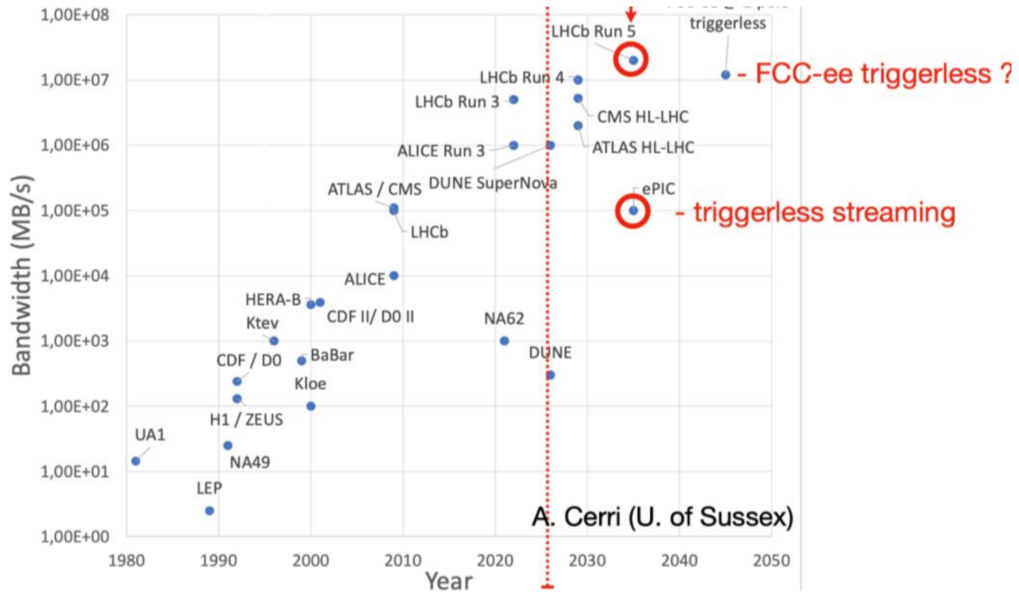
SiPM-On-Tile Layout



Computation Synergies with HEP

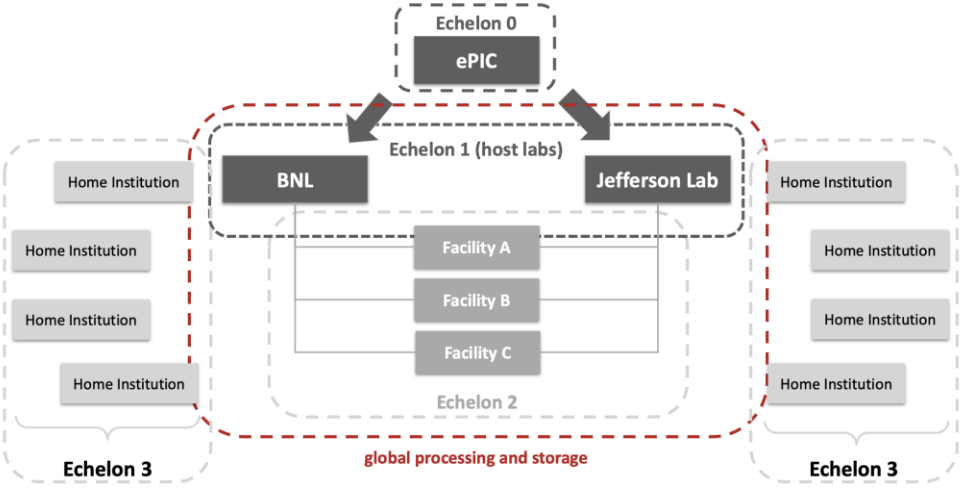
At ePIC, we are advancing detector-compute co-design:

- ❑ Our DAQ is tightly integrated with computing, enabling seamless data processing from detector readout to physics analysis via streaming and AI:
  - ➢ Event selection using full detector readout and unprecedented background/noise characterization enhance precision
  - ➢ Autonomous experimentation enables fast turnaround of physics results



Broader Impact and Synergy with HEP

- ❑ ePIC innovations in AI-driven streaming data and heterogeneous computing will benefit future experiments in NP and HEP
- ❑ Streaming data processing at scale will advance distributed computing across NP and HEP
- ❑ FAIR data and AI-driven science catalyze collaboration across NP, HEP, and related fields



Summary

- The Electron-Ion Collider will be the ultimate machine for the exploration of QCD and will likely be the only novel collider build in the next few decades

- The ePIC detector is designed to be a precision QCD experiment that will fully address the extensive physics program at the EIC

- ePIC is a complex detector with over 20 individual subsystems utilizing both established and novel technologies to provide tracking, PID, EM and hadronic calorimetry and near-beam detection capability over a wide acceptance

- Many opportunities for synergistic development and implementation of detector technologies as well as related needs like streaming readout / DAQ and even magnet construction