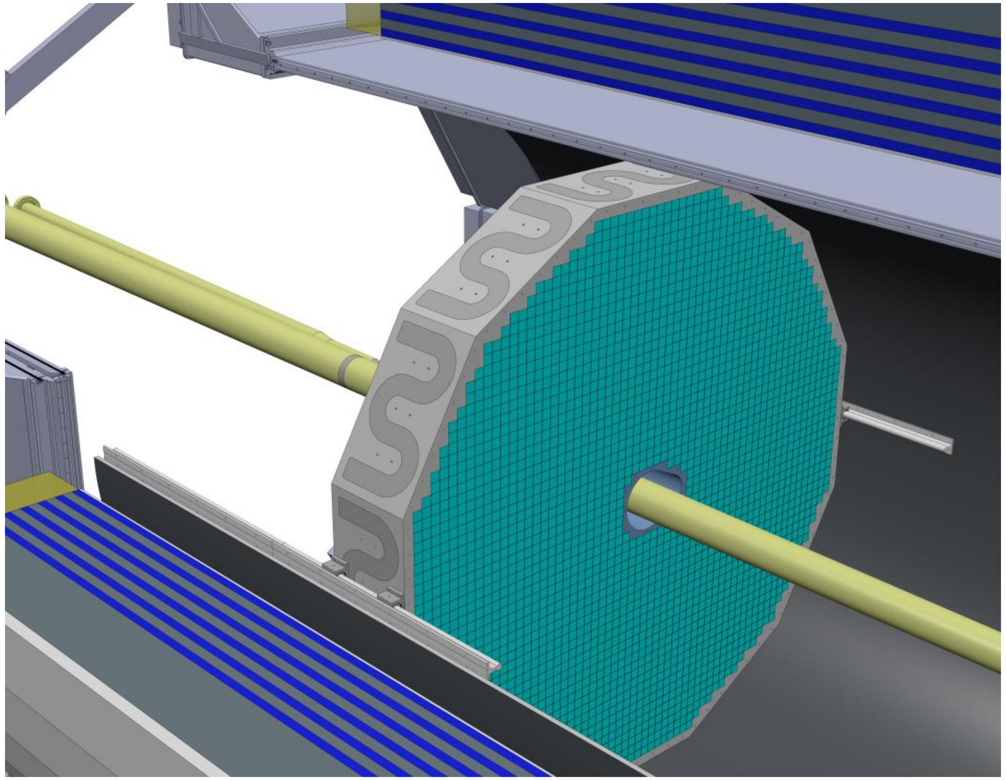


Calorimetry
(Lecture 2)

2nd European EIC School

Carlos Muñoz Camacho

IJCLab

Benicassim, June 25-26 (2025)

With material from E. Chudakov, H. Klest, F. Sefkow, F. Simon and many others..

Conceptual Refinements

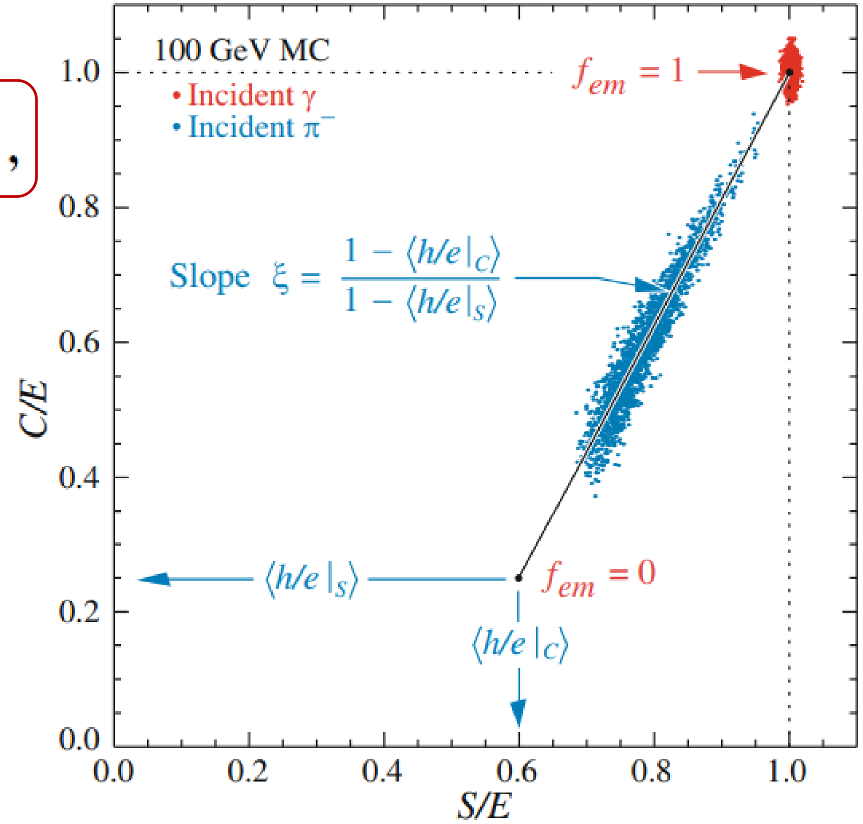
Motivation for Conceptual Advances

- Traditional calorimeters limit jet energy resolution.
- Need for improved particle separation in high-density environments.
- Motivation from future lepton colliders and HL-LHC.
- Explore alternatives: dual-readout, Particle Flow Algorithms (PFA).

Dual Readout Calorimetry

$$C = [f_{\mathrm{em}} + (h/e)_C(1 - f_{\mathrm{em}})]E,$$
$$S = [f_{\mathrm{em}} + (h/e)_S(1 - f_{\mathrm{em}})]E,$$

$$\boxed{E = (\xi S - C)/(\xi - 1),}$$



- Measures both scintillation and Cherenkov signals.
- Allows event-by-event correction for EM fraction (f_{em}).
- Improves hadronic energy resolution.
- Implemented in DREAM and RD52 prototypes.

Dual readout principle:

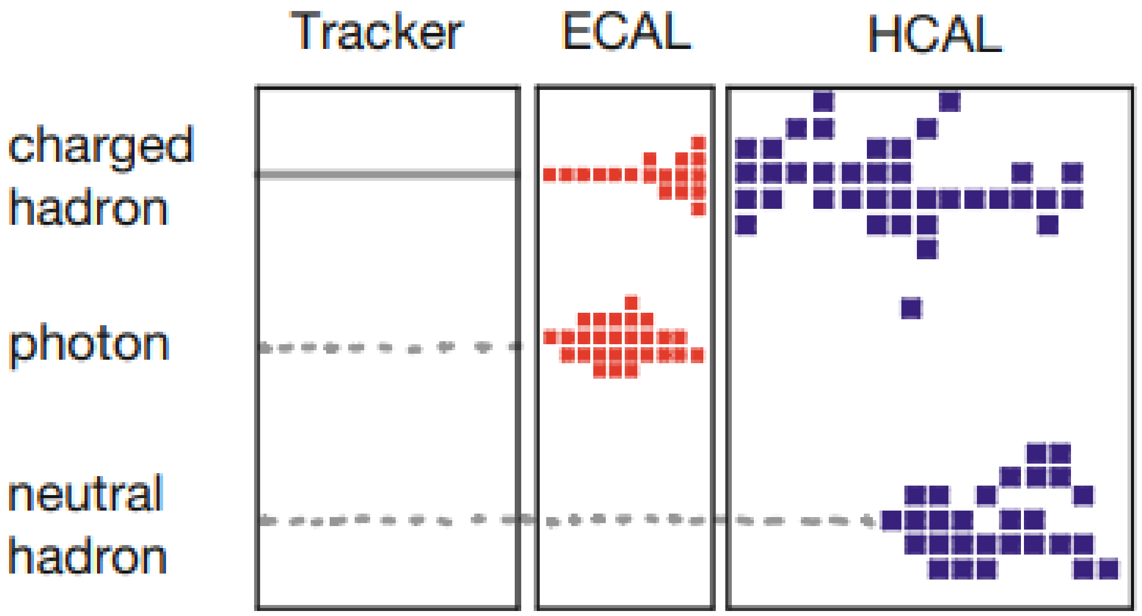
- Cherenkov light from EM component only.
- Scintillation from total energy.
- Ratio determines EM fraction.
- Calorimeter can self-calibrate per event.

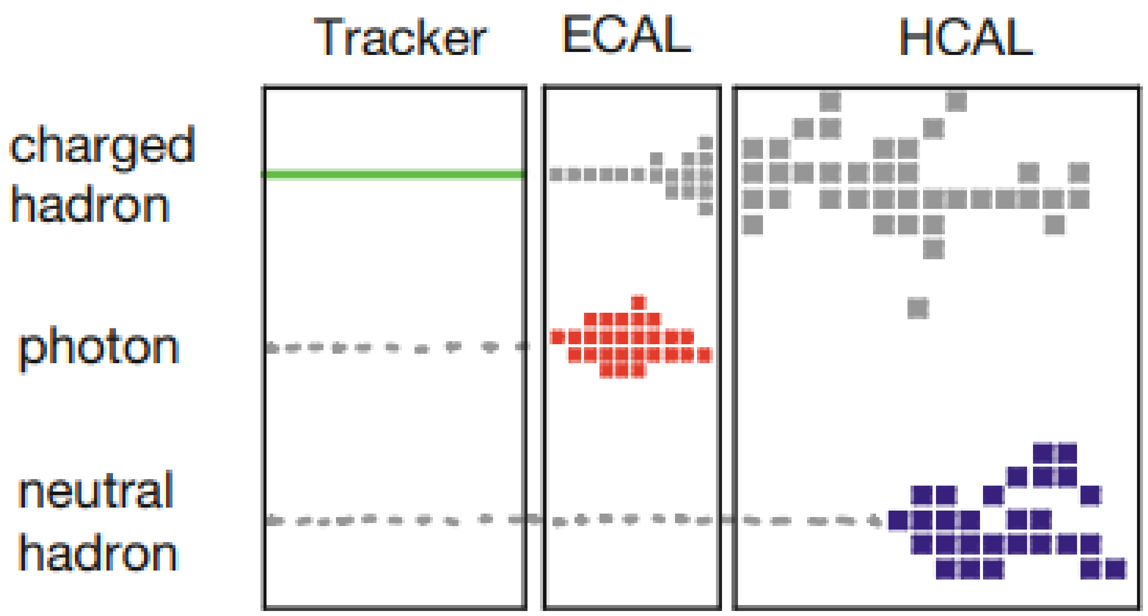
Limitations:

- Complex readout and calibration.
- Low Cherenkov light yield.
- Integration with dense materials is challenging.

Particle Flow Algorithms (PFA)

- Separate particles in jet and measure individually.
- Use tracker for charged particles, ECAL for photons, HCAL for neutrals.
- Requires high granularity and advanced software.

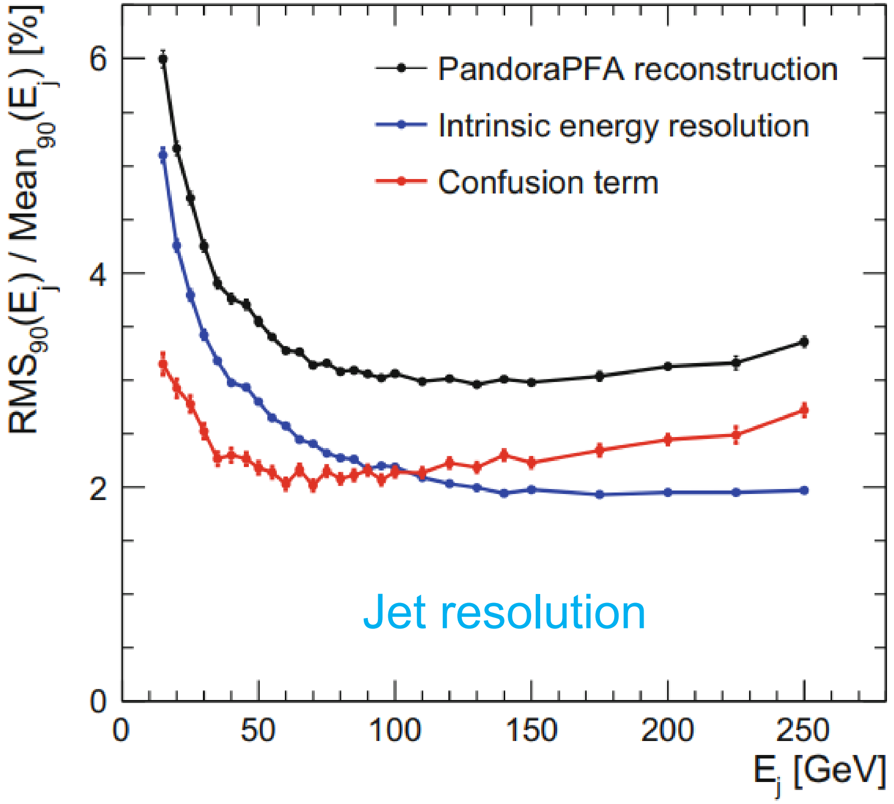




PFA: Detector Requirements and Performance

Requires:

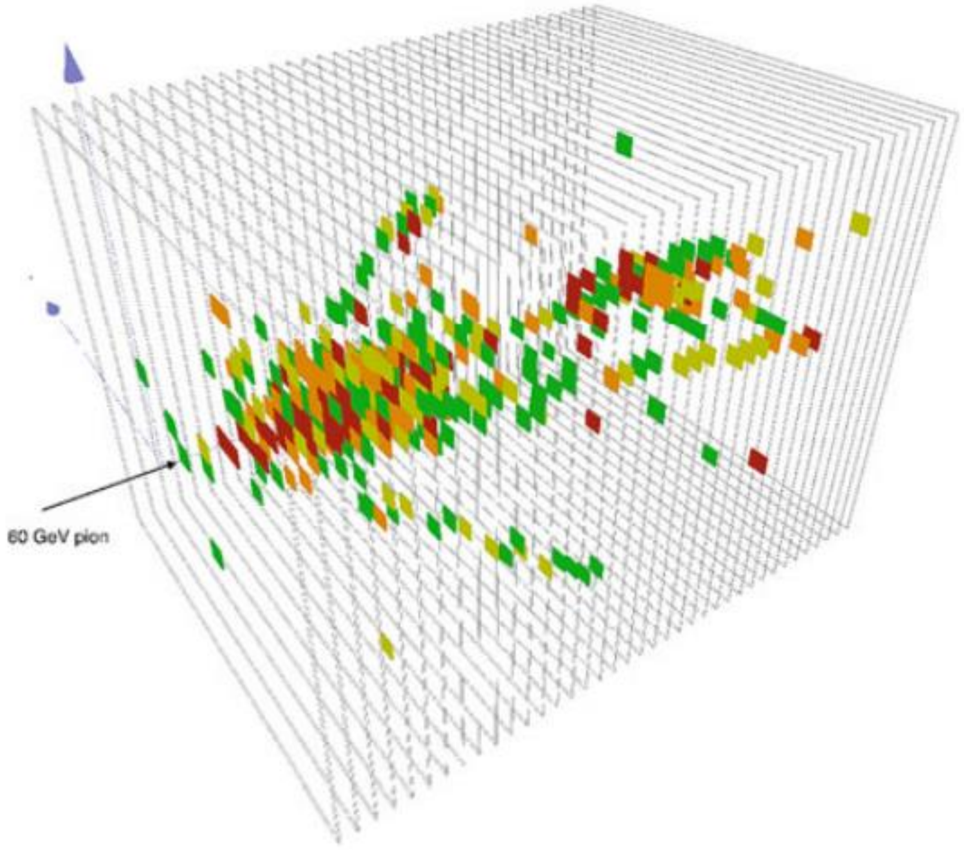
- Fine transverse and longitudinal segmentation.
- Compact showers: minimize overlap.
- Tracker-calorimeter matching.
- Example: ILD, CMS HGCAL.



- Improves resolution especially at low/intermediate energy.
- Confusion term becomes dominant.
- PandoraPFA and others demonstrate performance gains

Timing enhancements

- Picosecond-level timing improves pile-up rejection.
- Can aid in separating overlapping showers.
- Used in ATLAS HGTD, CMS MTD.



60 GeV π− in the CALICE hadron calorimeter prototype
(highly granular calorimeters can resolve shower substructure)

Compensating Calorimeters

- Equalize e/h response to reduce invisible energy effects.
- Typically use high neutron-yield materials (e.g., U, Cu).
- Achieve improved hadronic energy resolution.
- Rare in modern large-scale detectors due to complexity.

Improves linearity and resolution in hadronic calorimeters.

Summary and final remarks

Summary of calorimetry principles

- Calorimeters absorb particle energy to measure it.
- EM and hadronic showers behave differently.
- Different technologies suit different tasks.
- Performance depends on resolution, timing, segmentation.

Performance benchmarks

- ECAL: 1–2% resolution for high-energy electrons/photons.
- HCAL: 5–10% for hadrons and jets.
- Timing: tens of ps for modern calorimeters.
- Granularity and linearity vary by design.

Design tradeoffs

- Cost vs performance: materials, readout.
- Compactness vs segmentation.
- Radiation hardness vs sensitivity.
- Optimized per experiment goals.

Simulation and modeling

- GEANT4 and FLUKA simulate particle-matter interactions.
- Shower shapes and detector response predicted.
- Validation with test beam data.
    - Critical to calibrate and validate models.
    - Compare simulation to experimental data.

Summary

- Calorimetry is central to modern HEP.
- Combines physics, engineering, and data science.
- Open problems invite innovation.

The calorimeters are of increasing importance with higher energies. They became the most important/expensive/large detectors in the current big projects (LHC etc).

Summary (continued)

There are various techniques to build calorimeters for different resolution, price, radiation hardness and other requirements.

The typical energy resolutions are:

- EM: from $\frac{\sigma E}{E} \sim \frac{2\%}{\sqrt{E}} \oplus 0.3\%$ for scintillating crystals to about $\frac{\sigma E}{E} \sim \frac{10\%}{\sqrt{E}} \oplus 0.8\%$ for sampling calorimeters.
- HD calorimeters: $\frac{\sigma E}{E} \sim \frac{30-50\%}{\sqrt{E}} \oplus 3\%$

The coordinate resolutions could be about 1-3 mm for EM calorimeters and 20-30 mm for HD ones.

Questions?

Calorimetry at the EIC

The ePIC detector

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

PID:
- Backward pfRICH
- Barrel hpDIRC
- Forward dRICH
- Barrel & Forward TOF (AC-LGAD)

Calorimetry:
- Backward HCal (Steel+scint)
- $PbWO_4$ EMCal in backward direction
- Sampling & Imaging Barrel EMCal
- Outer HCal (sPHENIX re-use)
- Finely segmented EMCal +HCal in forward direction

hadronic calorimeters

Solenoidal Magnet

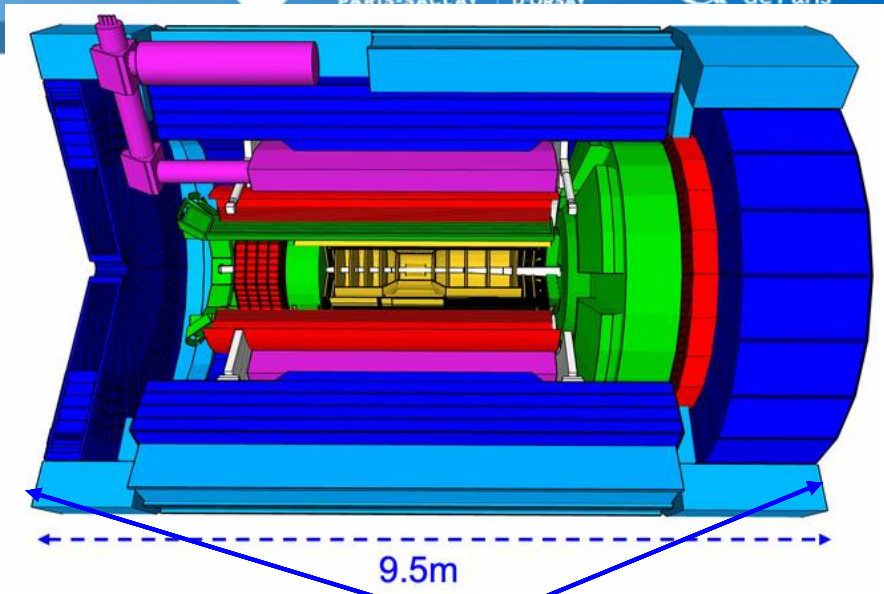
e/m calorimeters

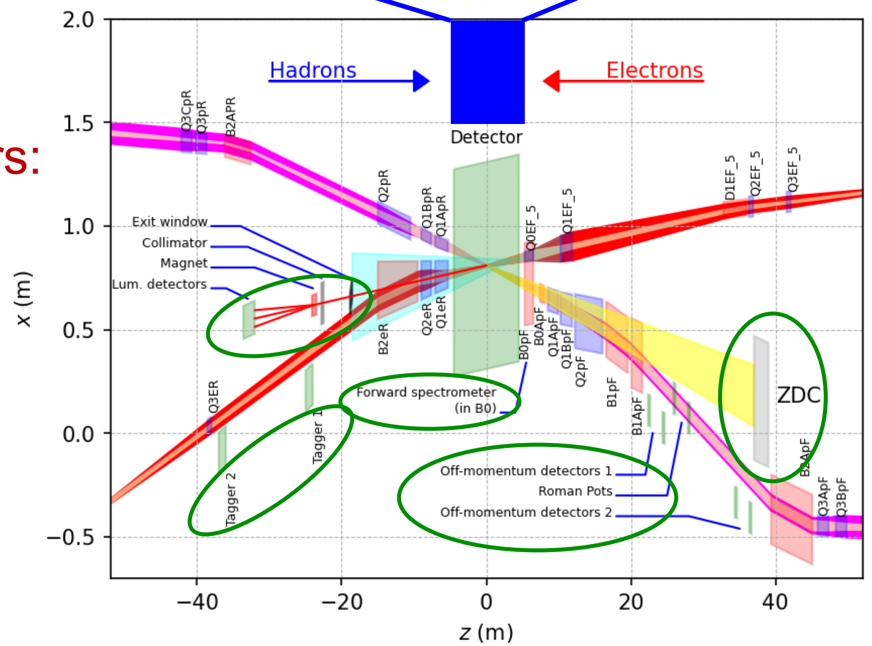
ToF, DIRC, RICH detectors

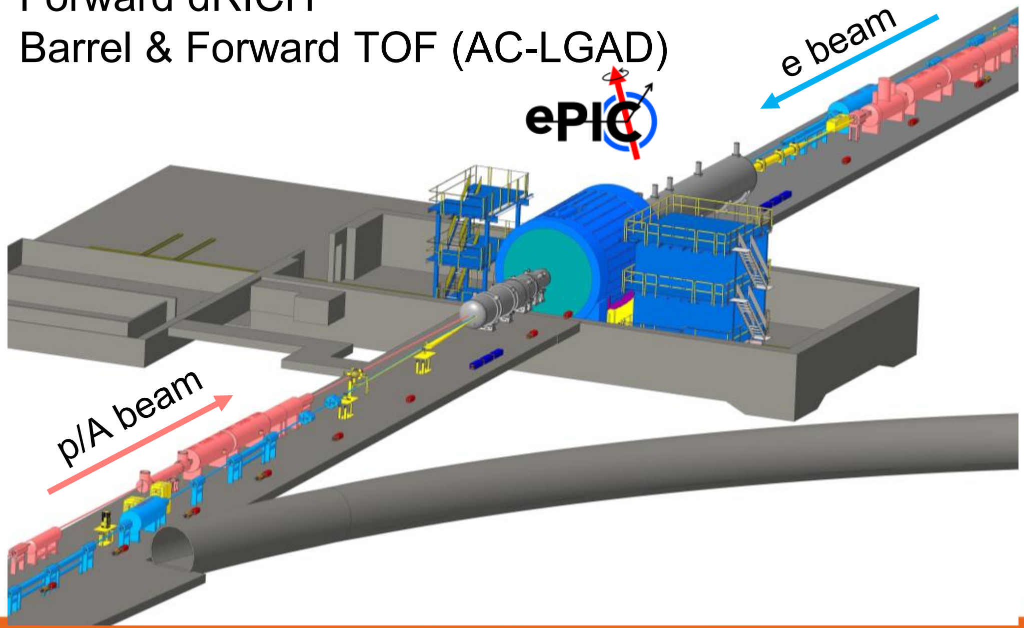
MPG trackers

MAPS tracker

25 subdetectors incl. polarimeters







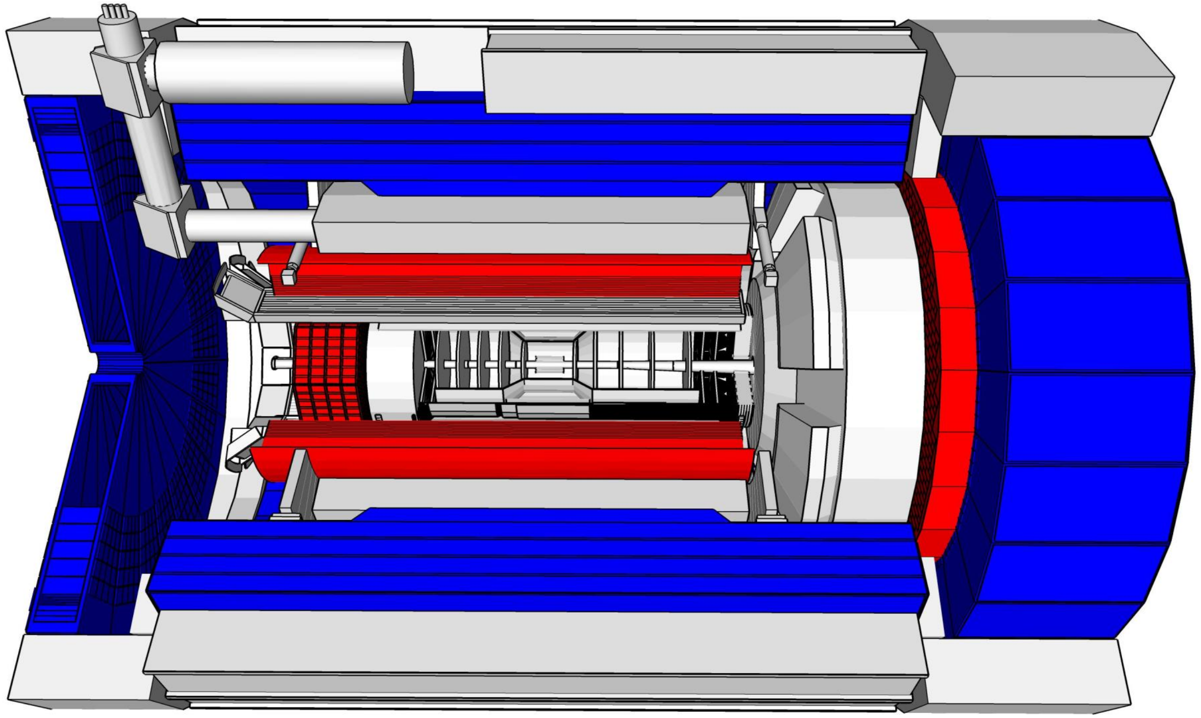
Far-Backward Detectors:
- Luminosity monitor.
- Low-Q^2 Tagger

Far-Forward Detectors:
- B0 Tracking and Photon Detection
- Roman Pots and Off-Momentum Detectors.
- Zero-Degree Calorimeter

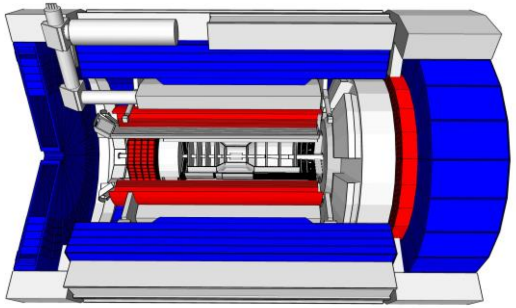
Calorimetry at ePIC

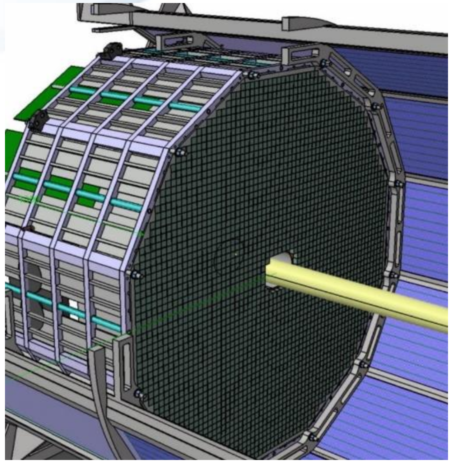
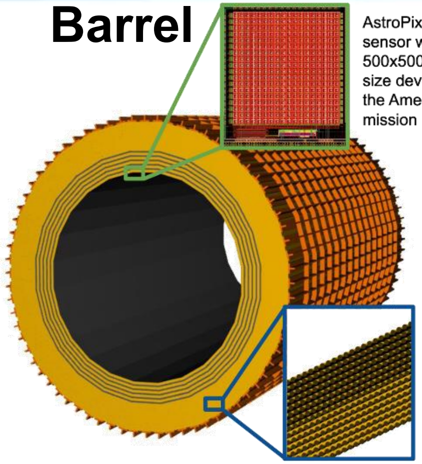
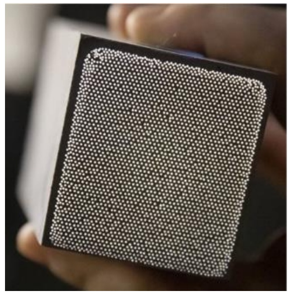
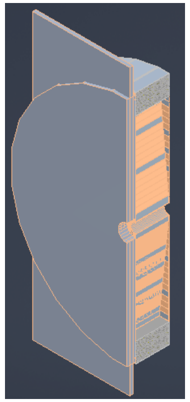
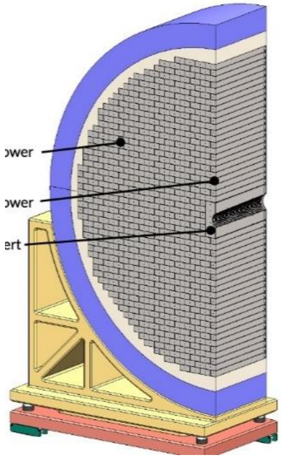
- Calorimetry at the EIC has some unique challenges:
  - Wide variety in CM energy, 5 GeV e^- x 41 GeV p/A to 18 GeV e^- x 275 GeV p
- EIC physics lives at all scales!
  - Large dynamic range required, hundreds of GeV to tens of MeV
  - Most challenging constraint is not always simply measuring energy

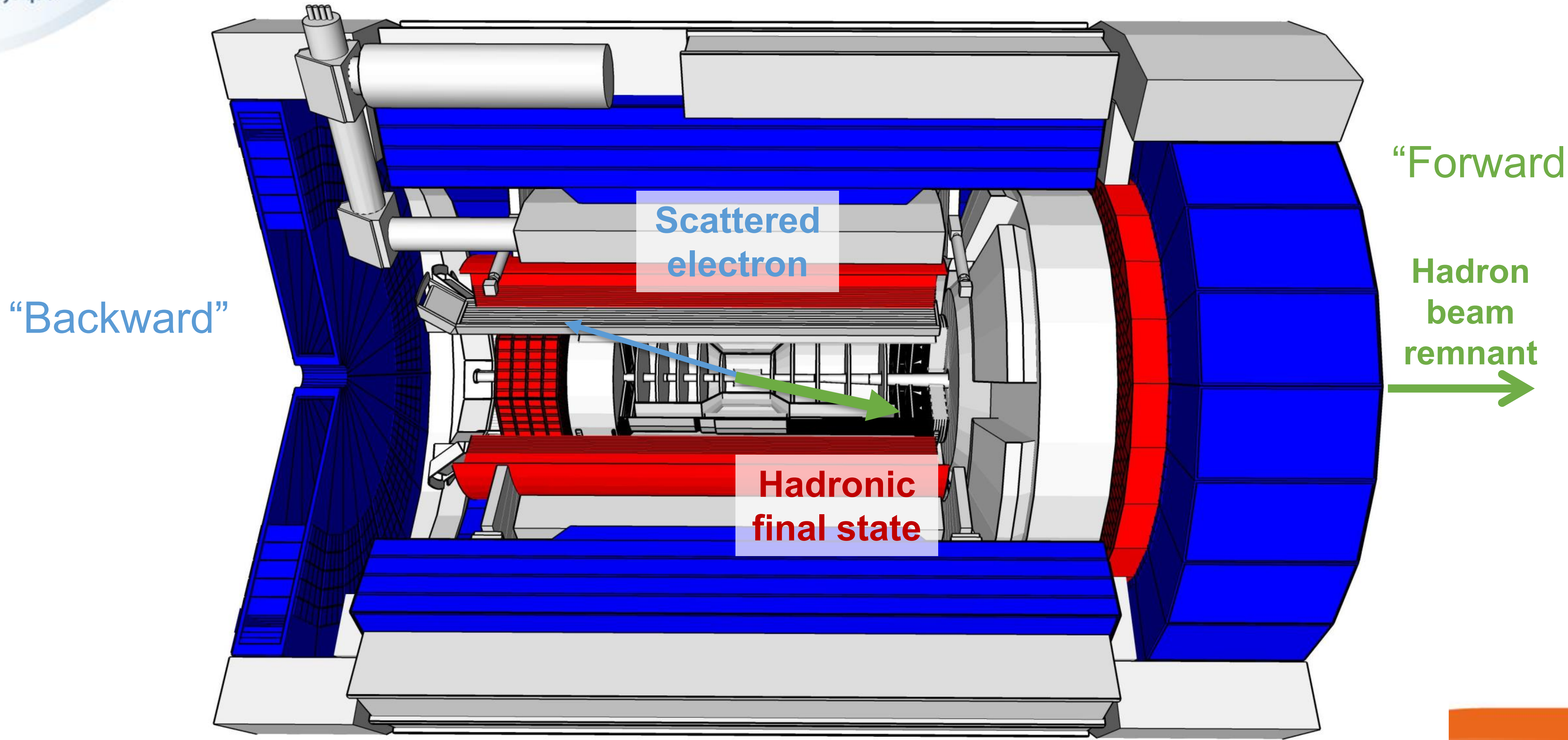
- Electron identification
  - Very stringent requirements on e/h separation to identify DIS events from the much larger photoproduction background
  - 1-in-10000 rejection of pions in the few GeV range!
- Streaming readout
- Integration with PID & tracking detectors



Calorimetry technologies at ePIC



	Backward	Barrel	Forward
EMCals	 ▪ $PbWO_4$ crystals + SiPM readout	 ▪ Pb/SciFi sampling part (SiPMs) ▪ Imaging section (6 layers) interleaving Pb/SciFi with ASTROPIX	 ▪ Tungsten-powder SciFi SPACAL design
HCals	 ▪ Steel + Scintillator ▪ SiPM-on-tile		



“Backward”
Scattered electron
Hadronic final state
“Forward
Hadron beam remnant

Backward calorimeters

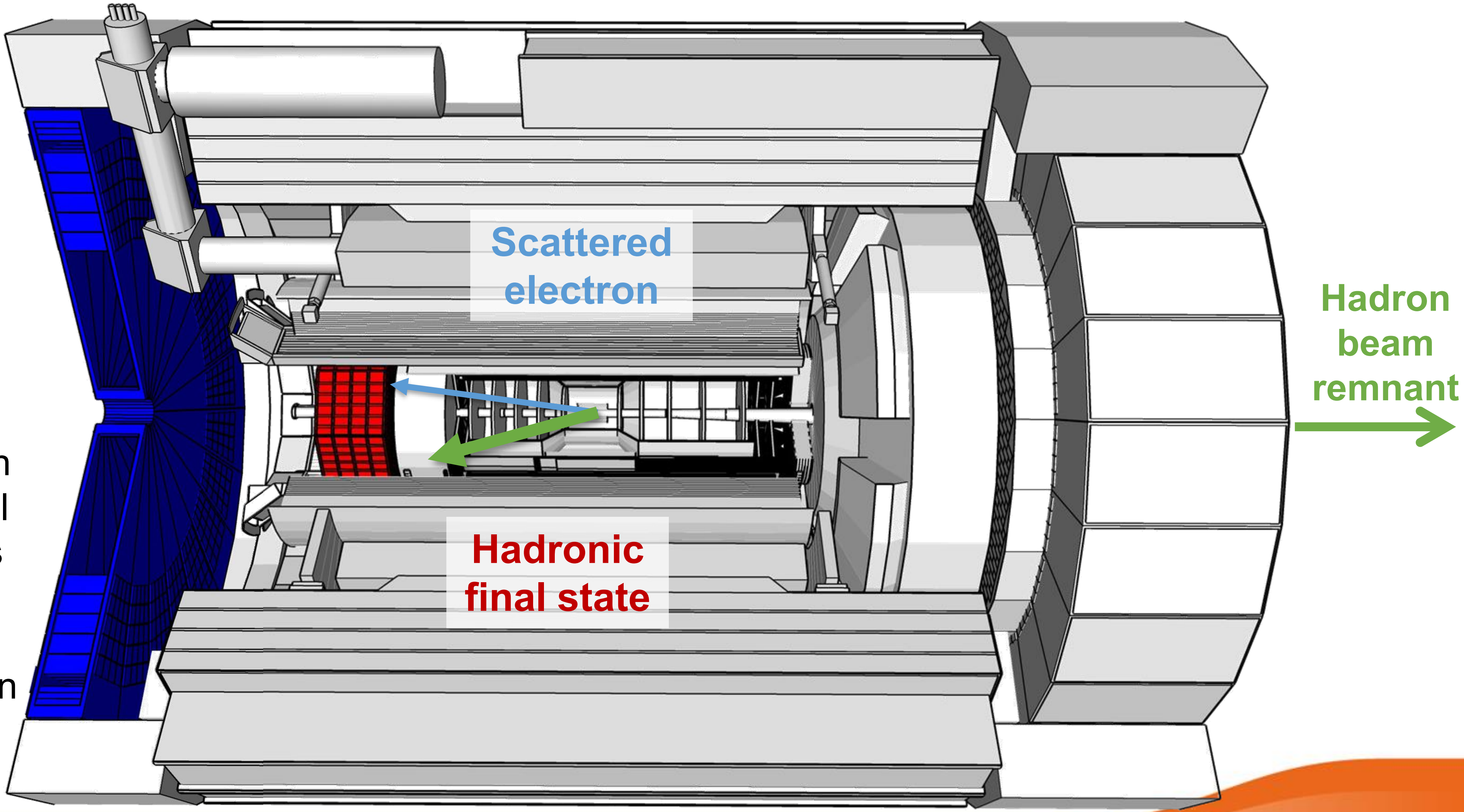
$-3.6 < \eta < -1.7$

Low Q^2, low x

Physics:
gluon saturation, nuclear terra incognita

Challenge:
Measure the electron with high precision at small scattering angles

Separate the scattered electron from the nearby hadrons



Backward calorimeters: requirements

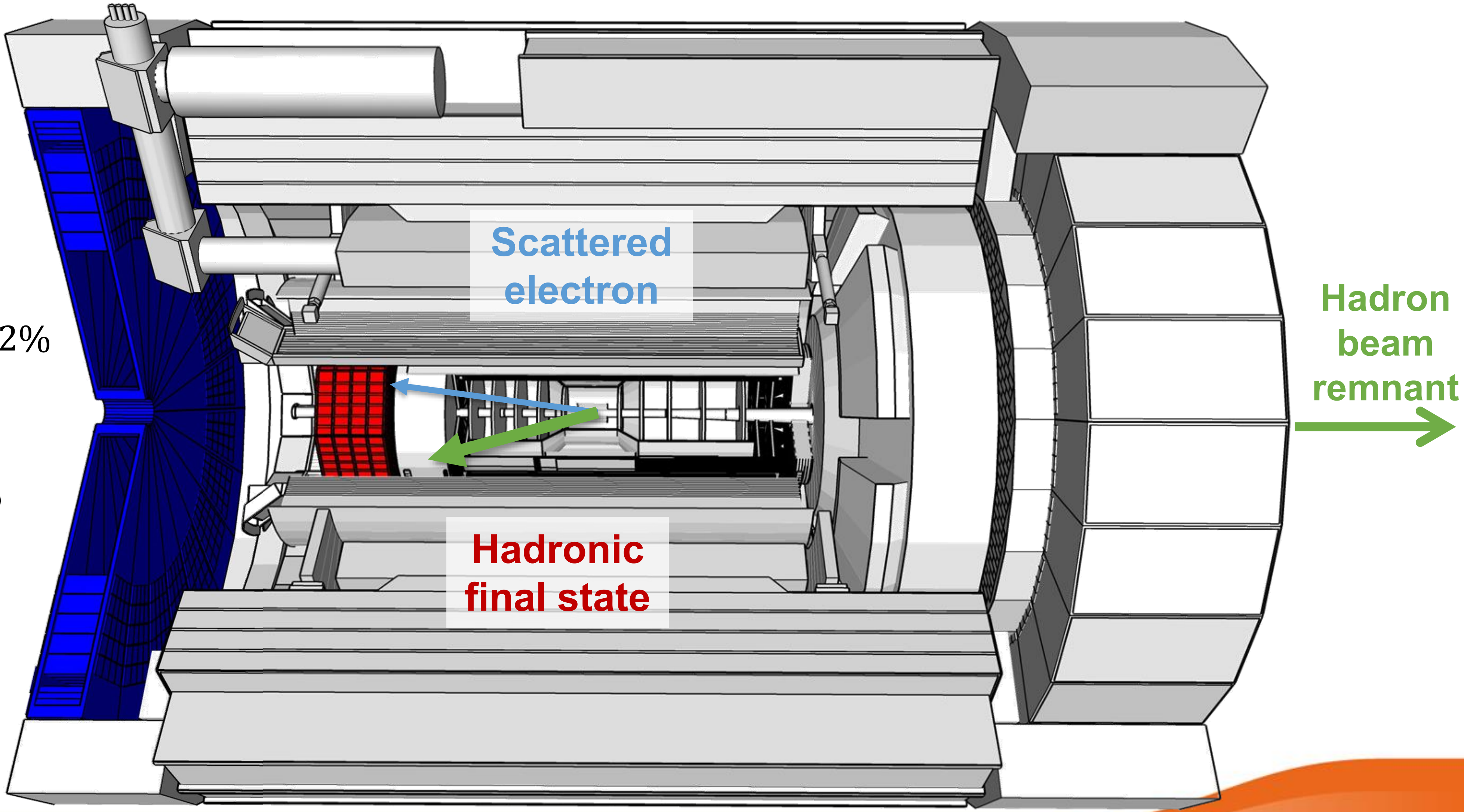
$$-3.6 < \eta < -1.7$$

Low Q^2, low x

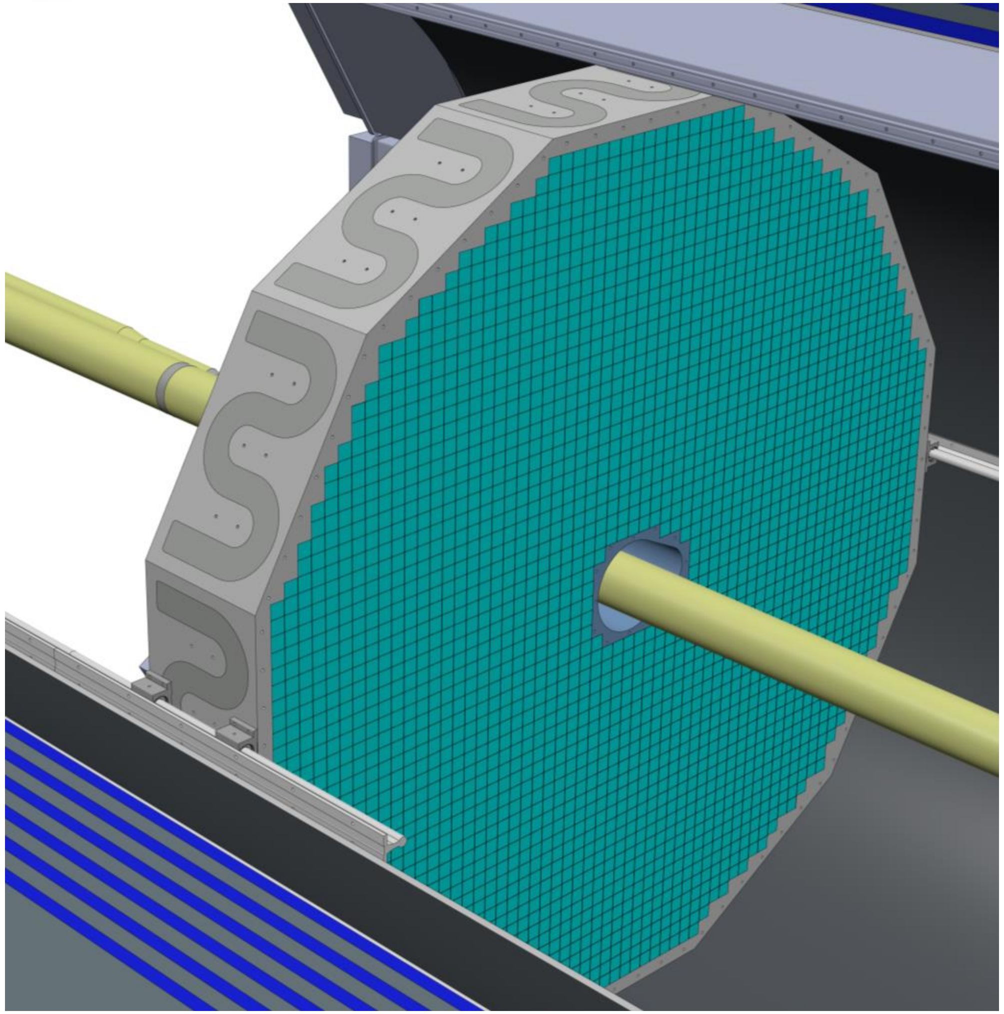
Resolution requirements:

EMCal:
$$\frac{\sigma_E}{E} \sim \frac{2-3\%}{\sqrt{E}} \oplus 1-2\%$$

HCal:
$$\frac{\sigma_E}{E} \sim \frac{100\%}{\sqrt{E}} \oplus 10\%$$

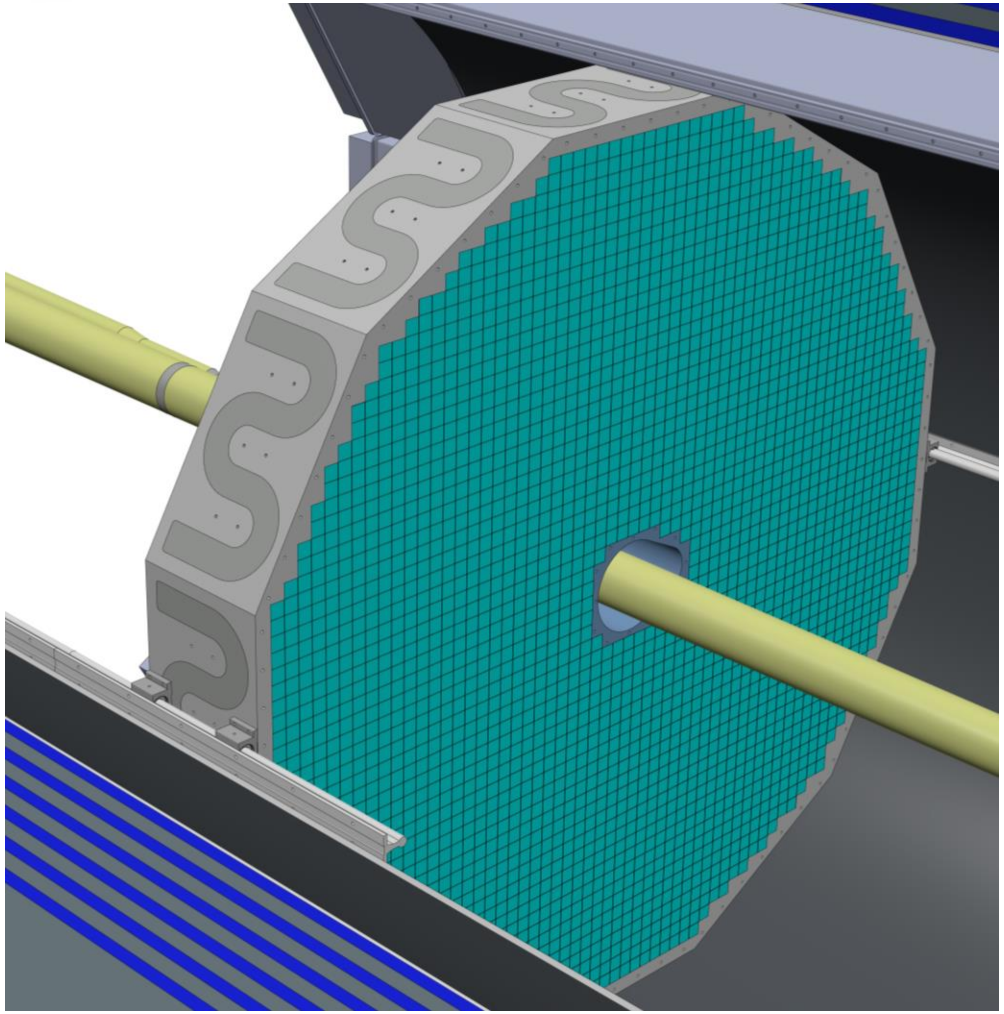


Backward EM calorimeter

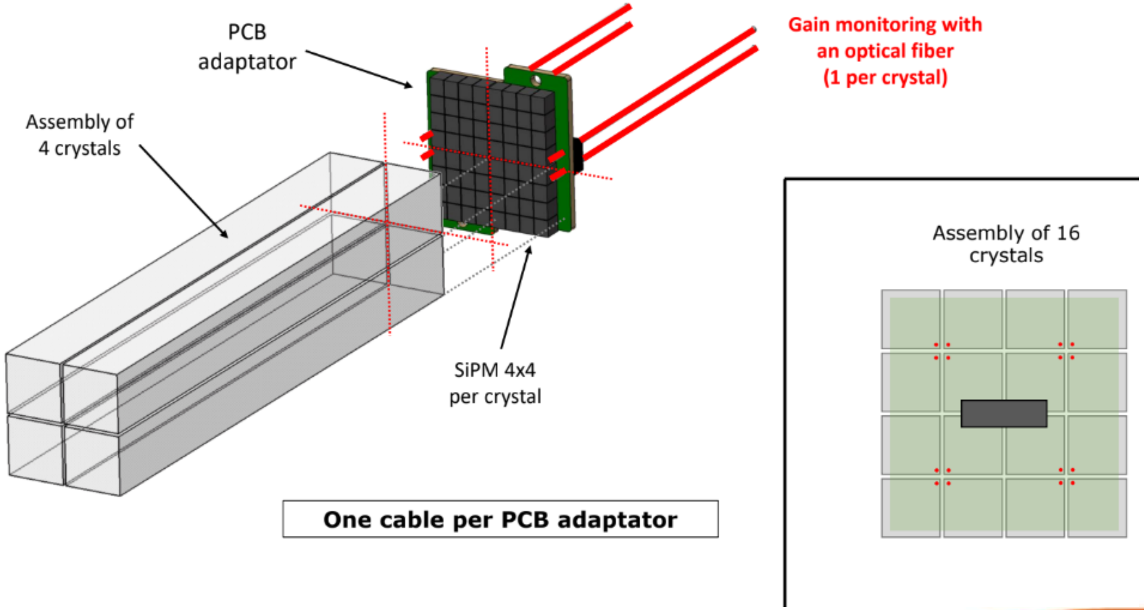


- Largest cross section for small electron scattering angles
  - Captures vast majority of scattered electrons
  - Often better resolution than tracker in this region
- Required energy resolution of $\frac{2\%}{\sqrt{E}} \otimes 1 - 3\%$
  - For most electrons, dominated by constant term
  - Need precise mechanical construction & calibration techniques
- 1 in 10^4 pion suppression
- Detection of photons above 50 MeV
- Radiation hardness

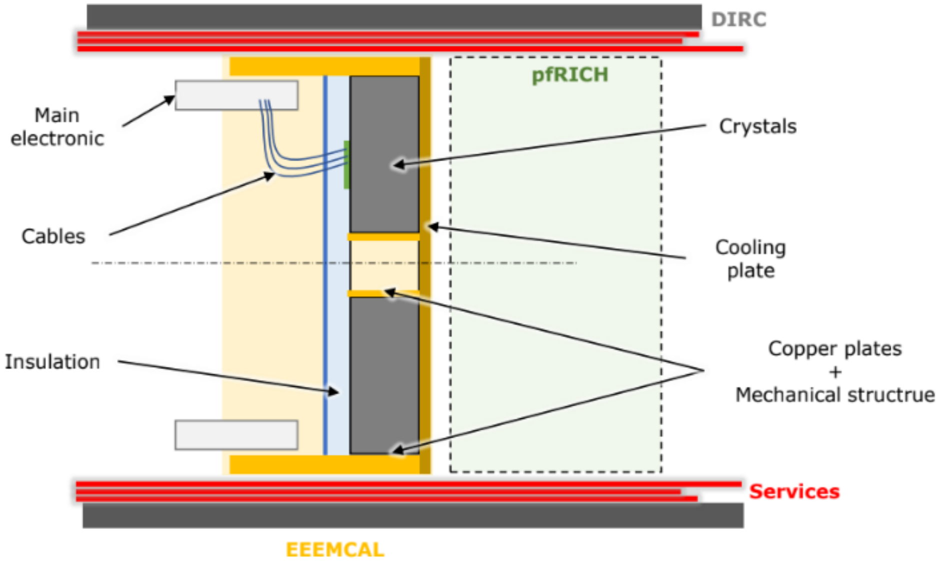
Backward EM calorimeter

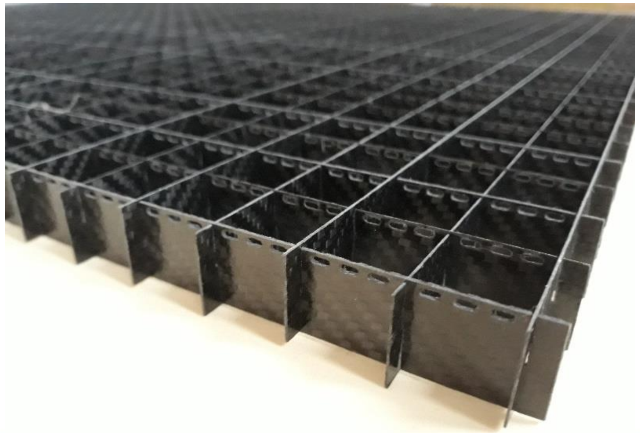


- Only realistic option to meet all of these requirements is $PbWO_4$
  - High density (small Molière radius), high scintillation light yield, fast scintillation, rad hard
  - Readout via HPK S14160-3010/5PS SiPMs



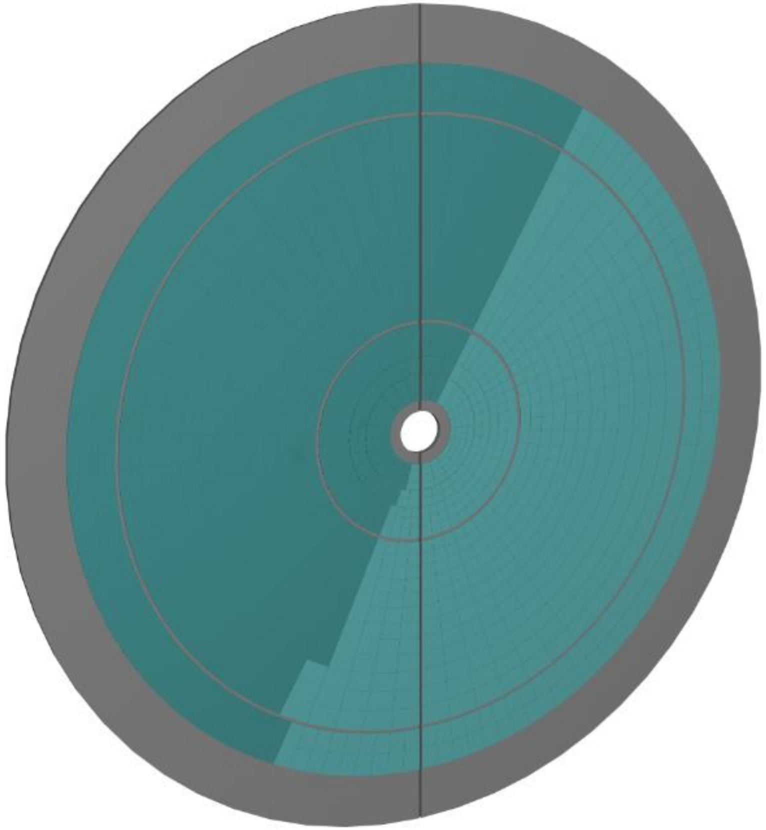
Backward EM calorimeter





- $PbWO_4$ light yield is a strong function of temperature, ~2% per C°
  - Big integration challenge, pfRICH electronics sits nearby
  - Needs temperature stability & monitoring to reach resolution goals
- Non-trivial interplay between achieving temperature stability and reducing dead material between the crystals
  - Crystals held by two 0.5 mm thick carbon fiber frames
  - One in front 2 cm of a block, one in back 2 cm
  - Air gap in-between

Backward hadronic calorimeter



- Experience from H1 & ZEUS, backward HCal useful for improving e/h separation at low-x
  - Electron & hadrons go in the same direction, substantial overlap in the EMCal
- Low-x hadronic final state important for studying gluon saturation, typically backward-going
- Hadron energies are low, serves in part as a tail-catcher for the EMCal
  - Energy resolution requirements not stringent
  - Position resolution should be good enough to match Hcal clusters to energy deposits in Emcal
- Exact design still in progress, some combination of steel + large scintillator tiles & SiPM readout
  - Similar to BELLE KLM

Barrel calorimeters

$-1.7 < \eta < 1.4$

High Q^2, Mid x

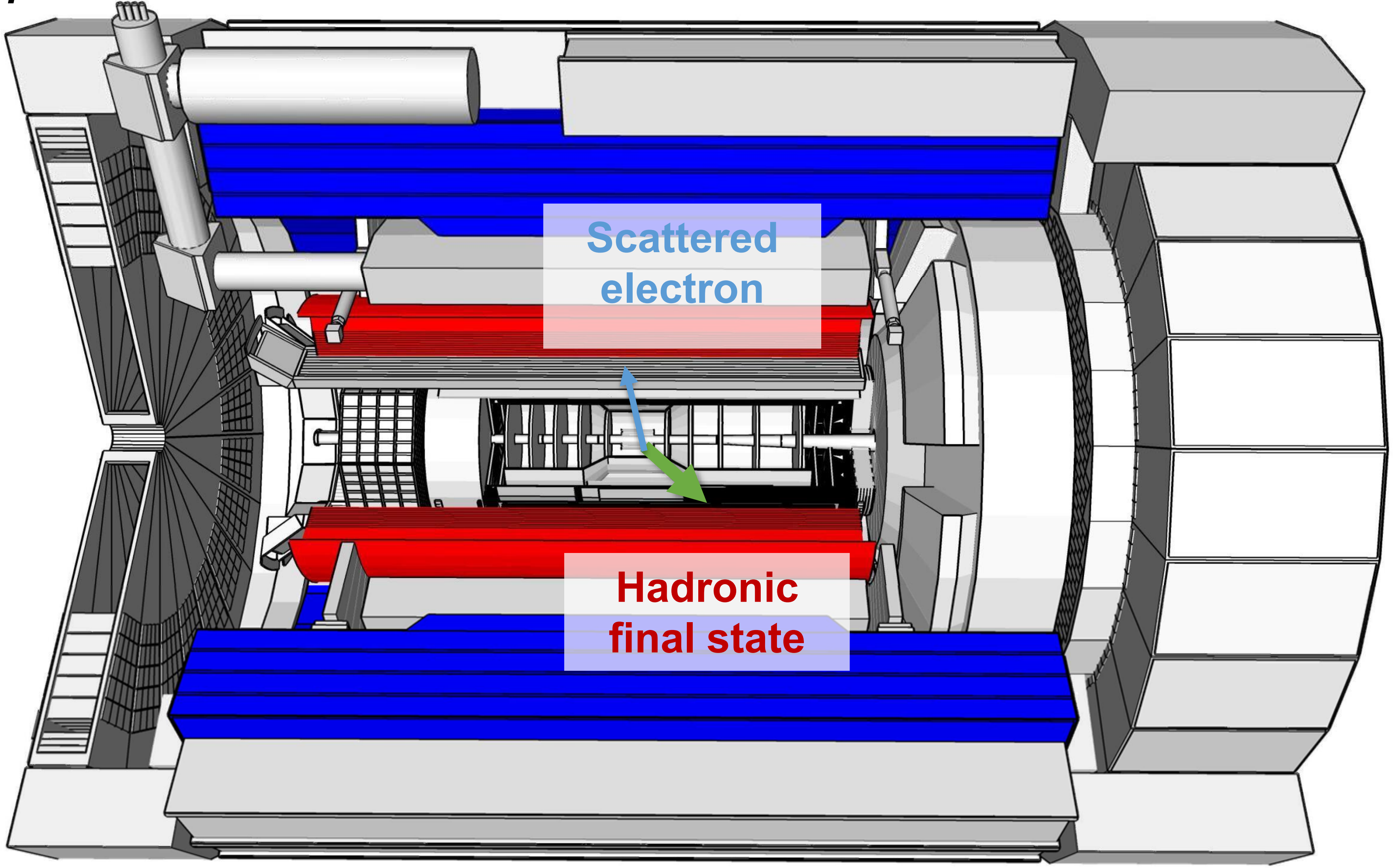
Example Physics: DVCS, DVMP

Challenges:
Identify components of hadronic final state, e.g. separate π^0 from ɣ

Identify low energy e^- from high *y* DIS

Contain 30+ GeV energy e^- from high Q^2

Measure low energy ɣ



Barrel calorimeters: requirements

$$-1.7 < \eta < 1.4$$

High Q^2, Mid x

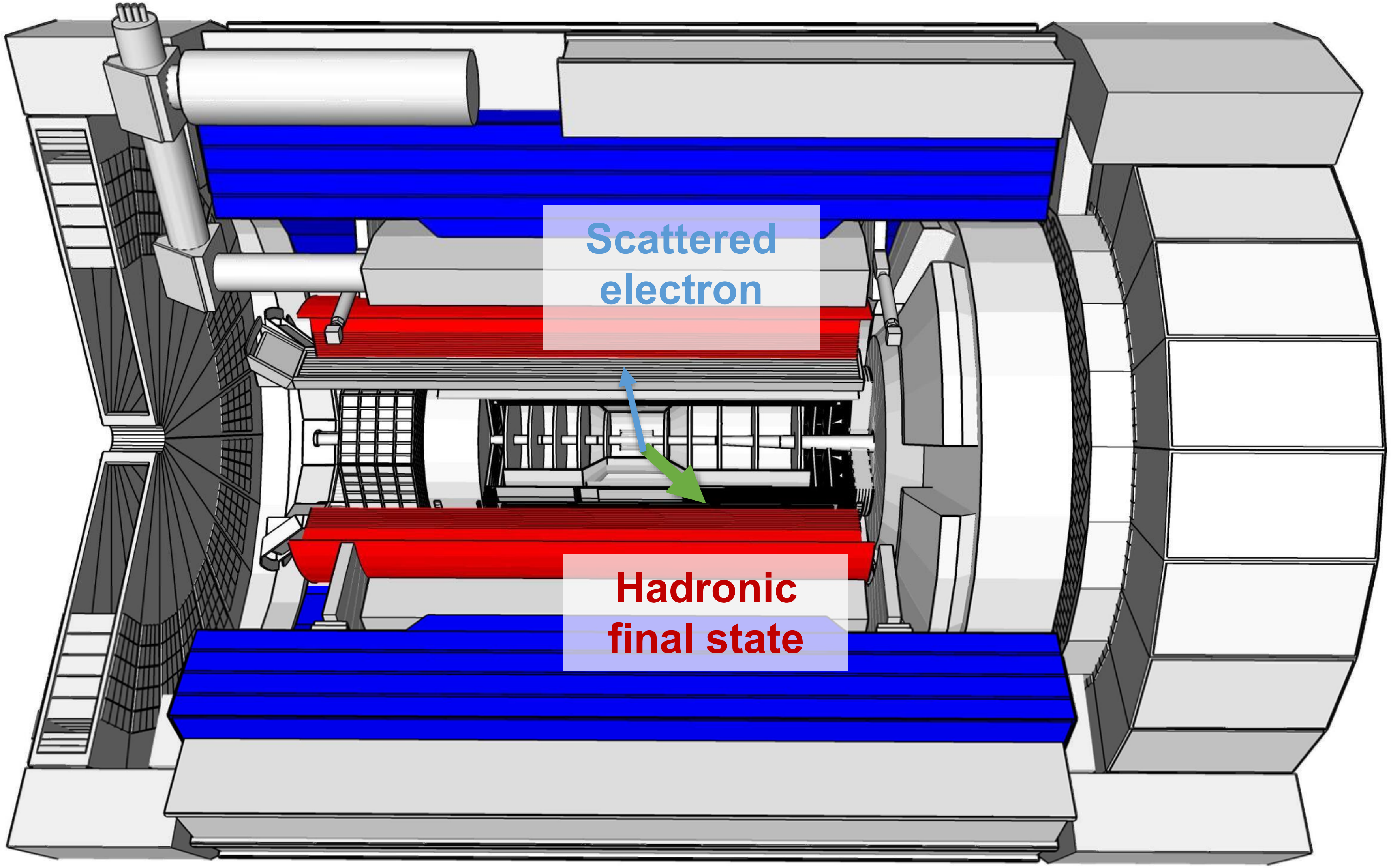
Resolution requirements:

EMCal:

$$\frac{\sigma_E}{E} \sim \frac{10\%}{\sqrt{E}} \oplus 2-3\%$$

HCal:

$$\frac{\sigma_E}{E} \sim \frac{100\%}{\sqrt{E}} \oplus 10\%$$

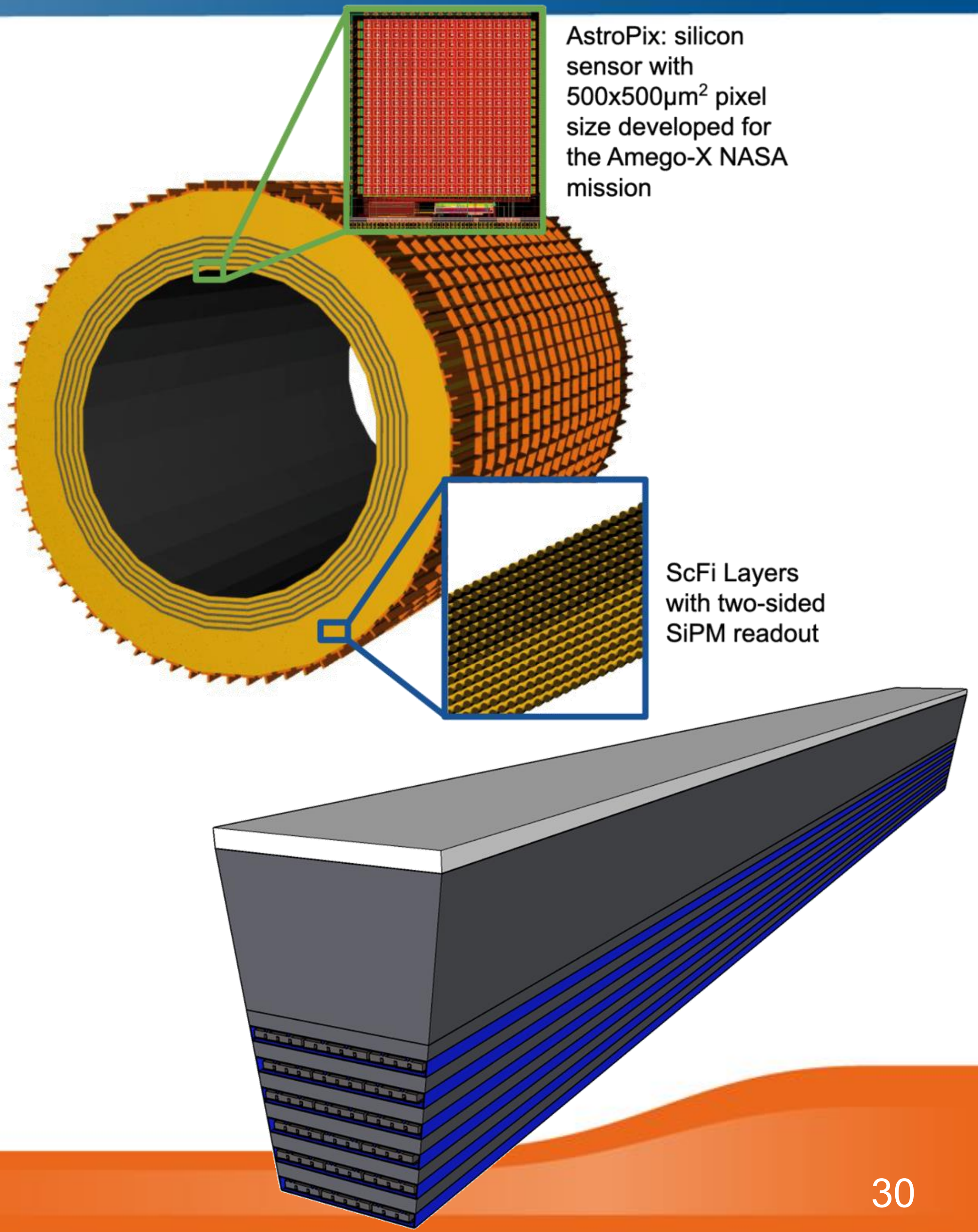


Barrel EM calorimeter

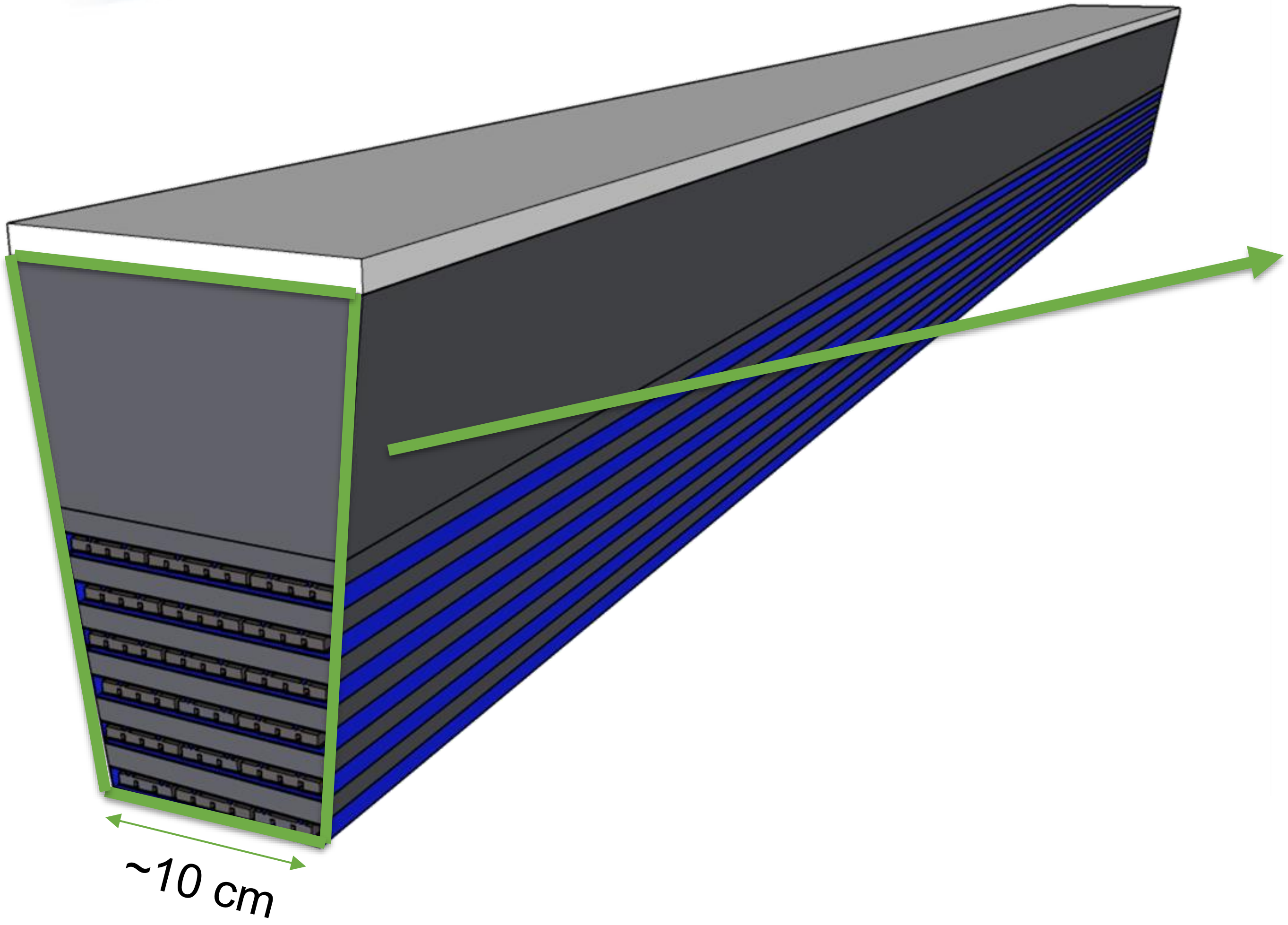
- Hybrid sampling Pb/SciFi + Silicon pixel sensor

- 4.4 m long scintillating fibers, SiPM readout on both ends
  - Longitudinally segmented
  - Similar to KLOE & GlueX
  - "Time-Projection" calorimeter - $\Delta t \rightarrow z$
  - HGCROC for front-end electronics

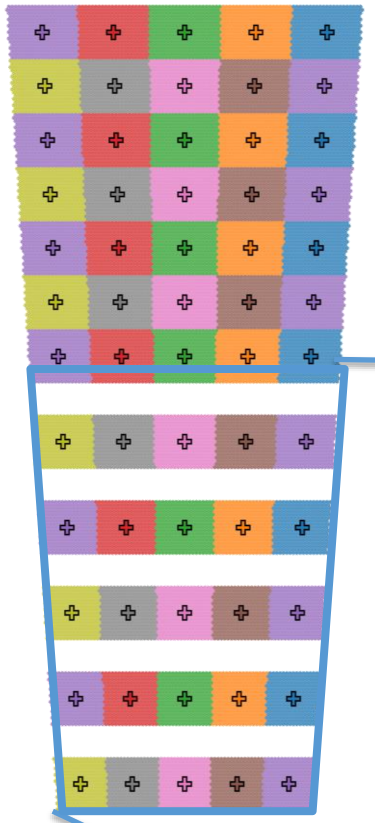
- Interleaved with layers of AstroPix MAPS silicon pixel sensors
  - Very low power consumption (few mW/cm^2)
  - 500 µm "cube" pixels
  - Good resolution (~7%) on energy deposited in pixel



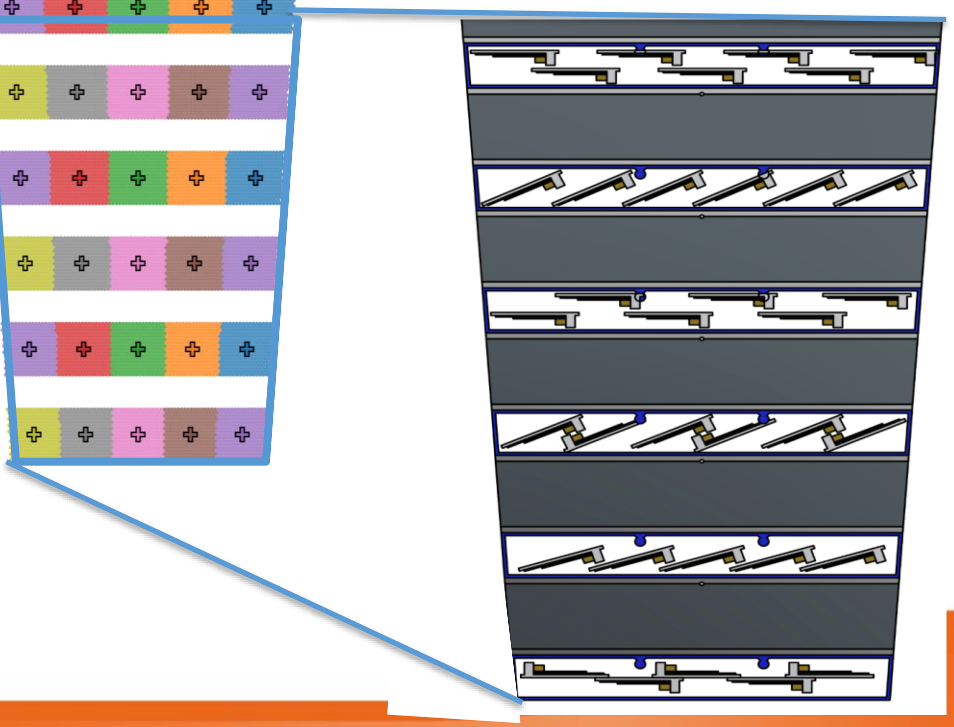
Barrel EM calorimeter



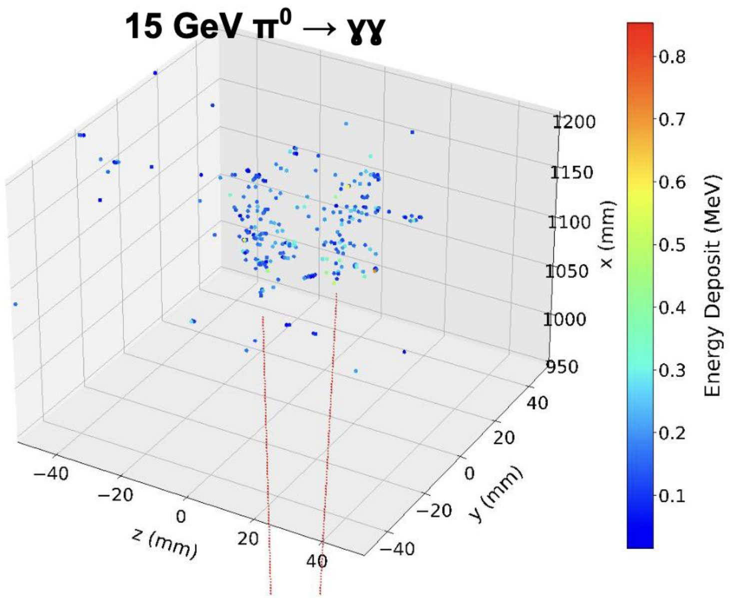
SiPM Readout Scheme
Light guides to 1.2x1.2 cm SiPMs

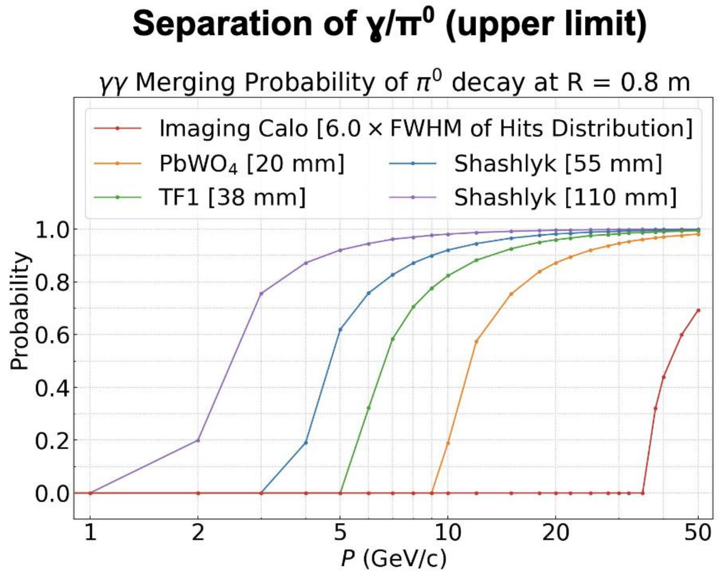


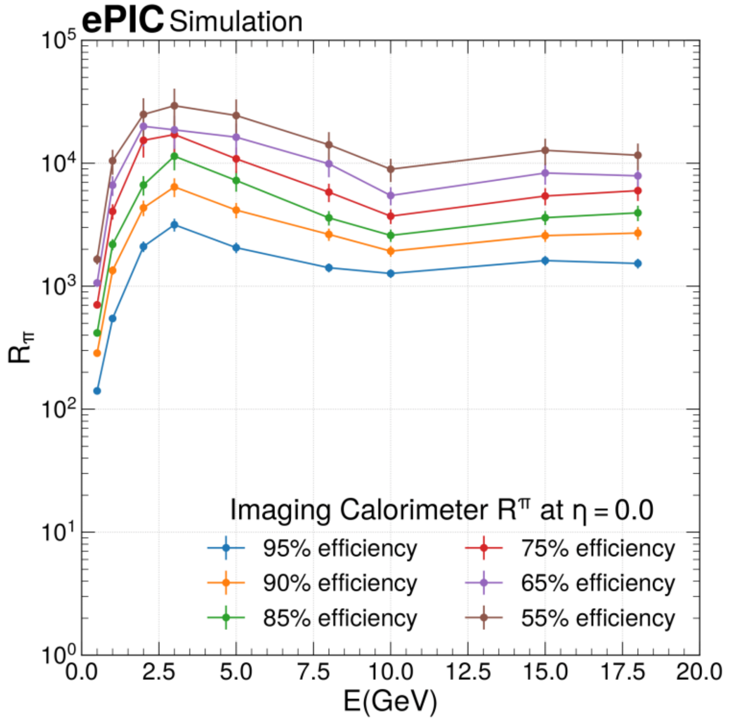
AstroPix Tiling Options



Barrel EM calorimeter: performance



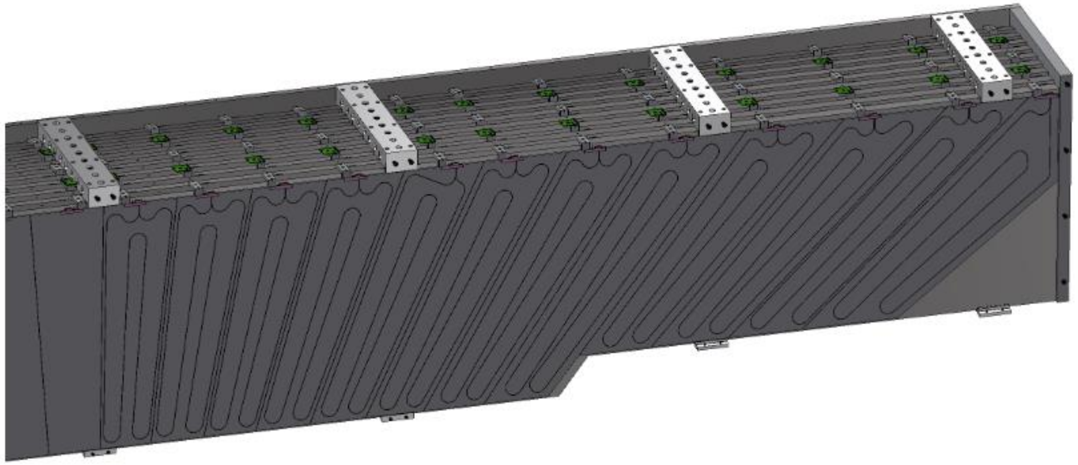


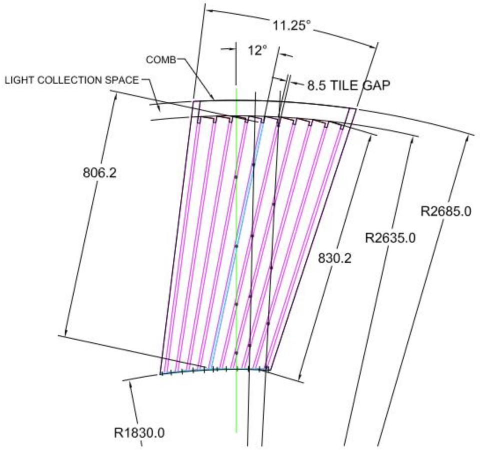


- Interleaving of AstroPix sensors allow for excellent position resolution
  - Angular resolution on the order of 0.1 degree
  - Separate π^0 from ɣ beyond 30 GeV
  - Can do vertexing on photons!
- Very effective separation of electrons from hadrons based on shower shape discrimination
  - Still quite effective at ~1 GeV & below

Barrel hadronic calorimeter

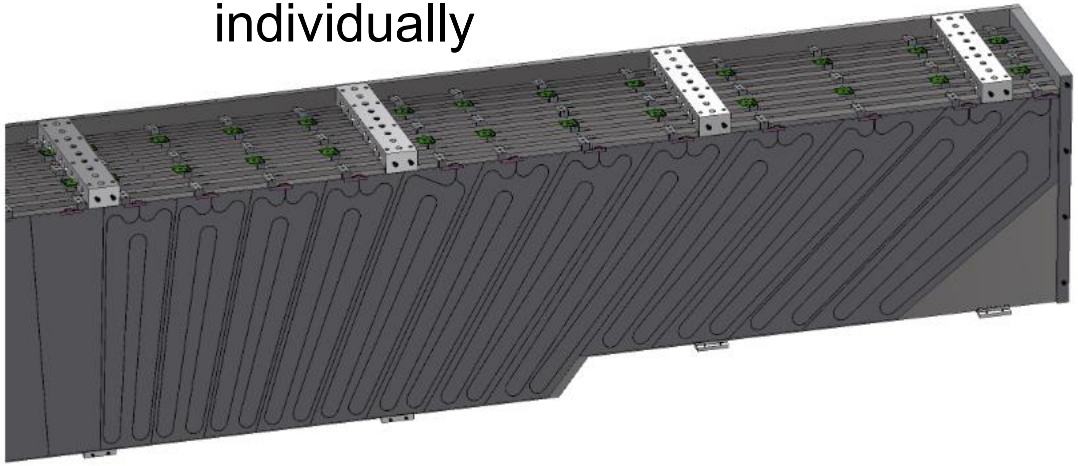
- Modest requirements on energy resolution
  - ~ $100\%/\sqrt{E}$
  - Hadrons in barrel typically low energy (<5 GeV), better measured by tracking
  - Tag jets with large neutral hadron component
- Measure muons from e.g. $J/\psi \rightarrow \mu\mu$
- Reuse from sPHENIX

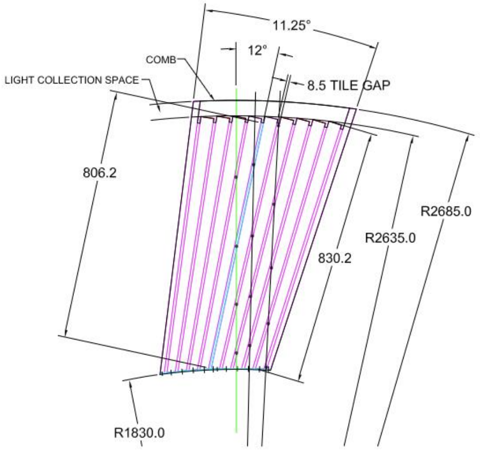




Barrel hadronic calorimeter

- Steel/Scintillator design
  - Steel plates tiled at an angle to prevent channeling
  - Straight tracks have a sizable path length through scintillator, good for MIP detection
  - Readout via HPK S12572 series SiPMs
- Refurbish for EIC
  - Expect minor radiation damage from sPHENIX, can replace SiPMs with HPK S14 series
  - Upgrade electronics to HGCROC
  - Increase segmentation by reading out each tile individually





Forward calorimeters

$1.4 < \eta < 4$

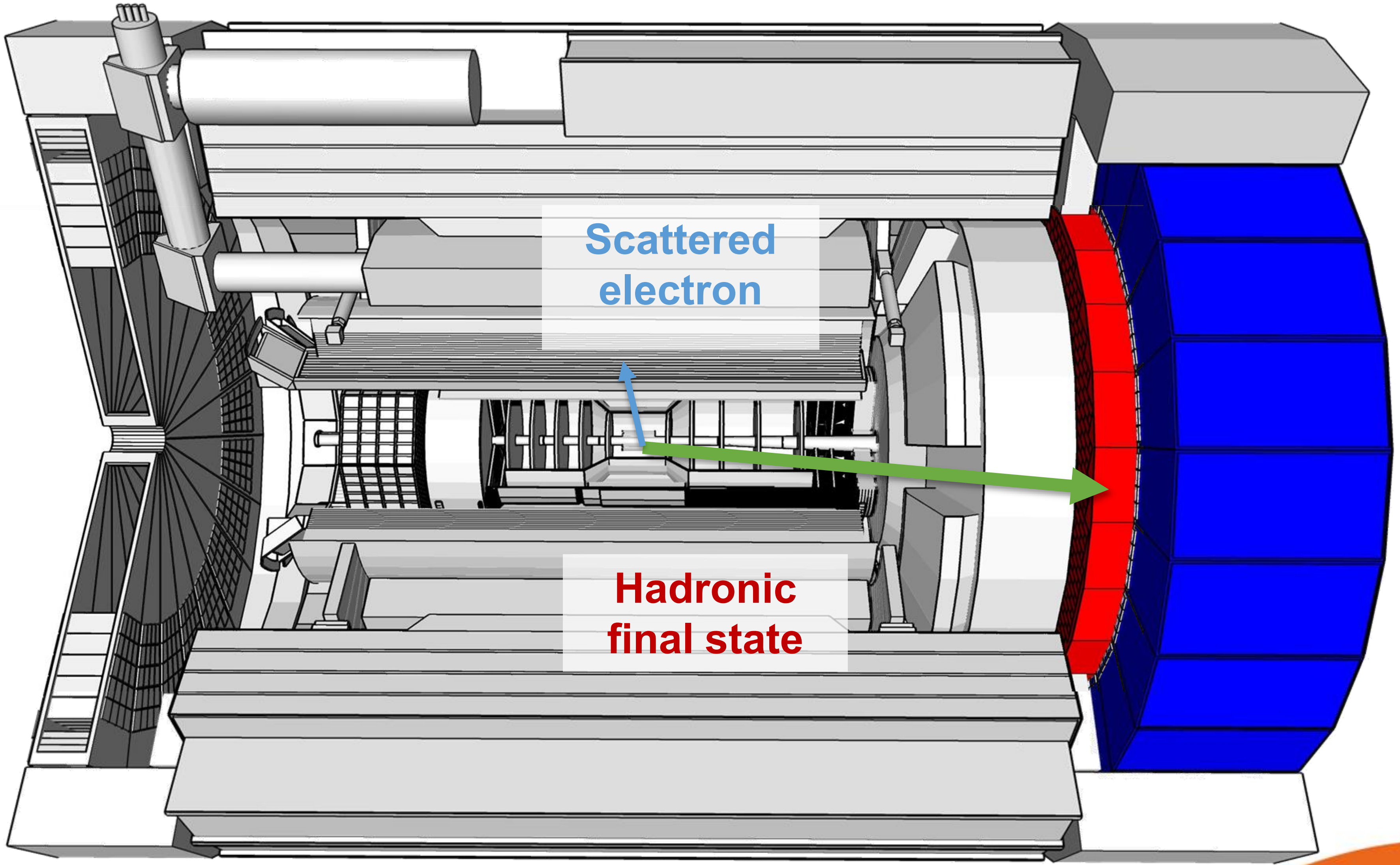
High Q[2], High x

Example Physics:
TMDs, Jets, SIDIS

Challenges:
Contain the highly energetic hadronic final state

Separate clusters in a dense hadronic environment

Highest radiation load near hadron beam



Forward calorimeters: requirements

$1.4 < \eta < 4$

High Q^2, High x

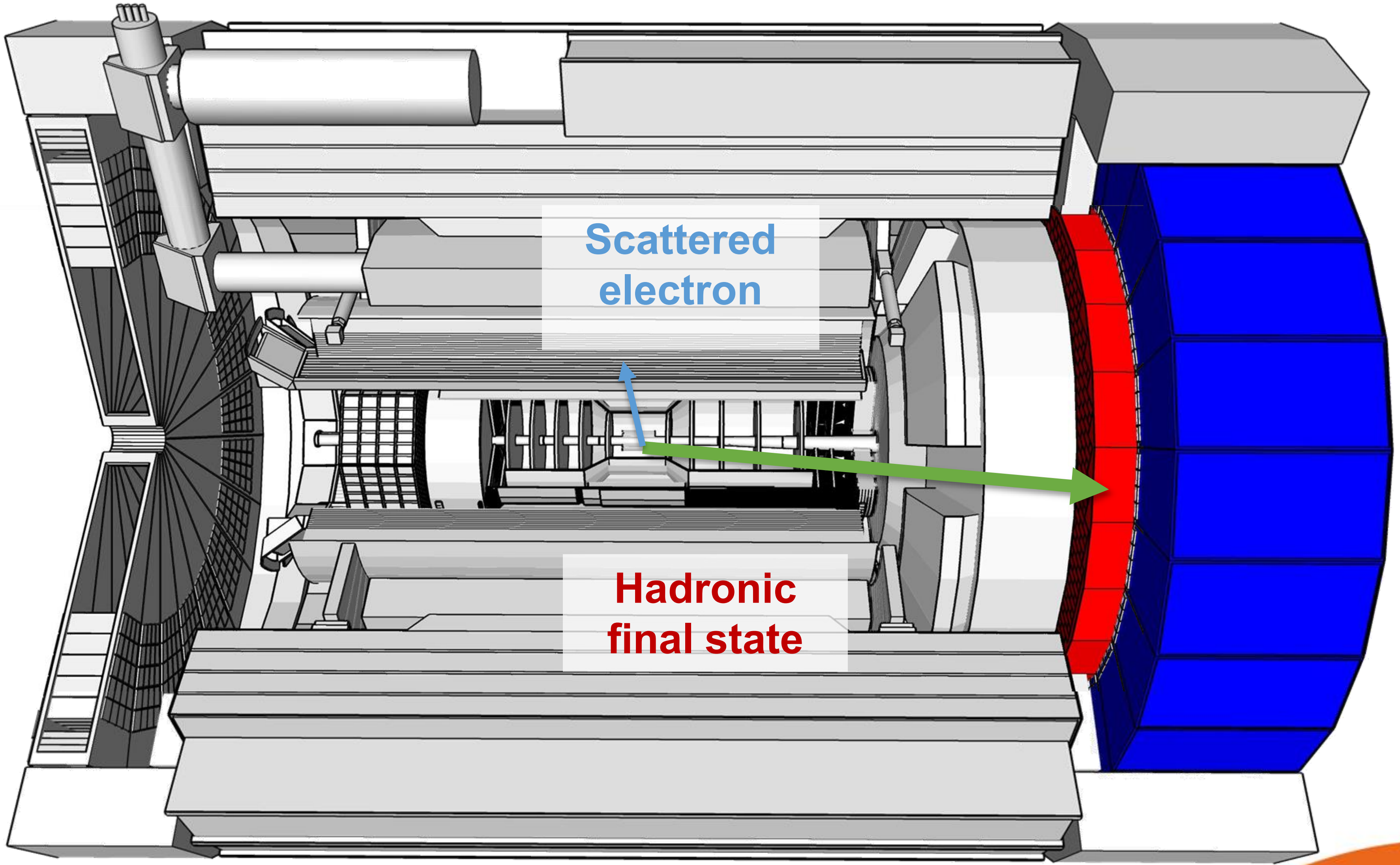
Resolution requirements:

EMCal:

$$\frac{\sigma_E}{E} \sim \frac{10\%}{\sqrt{E}} \oplus 2-3\%$$

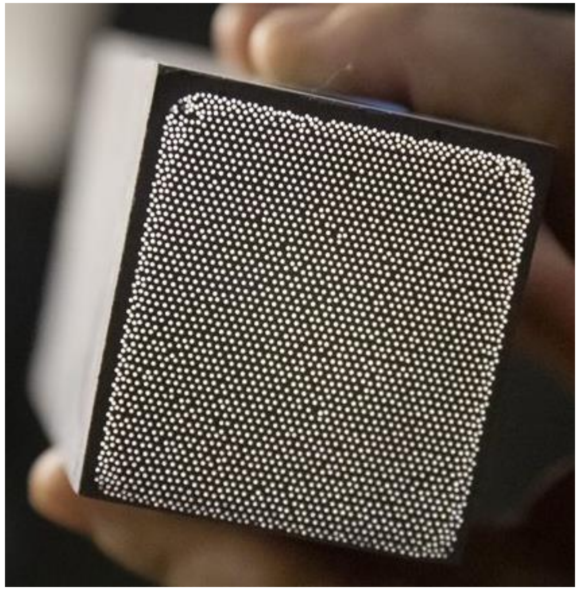
HCal:

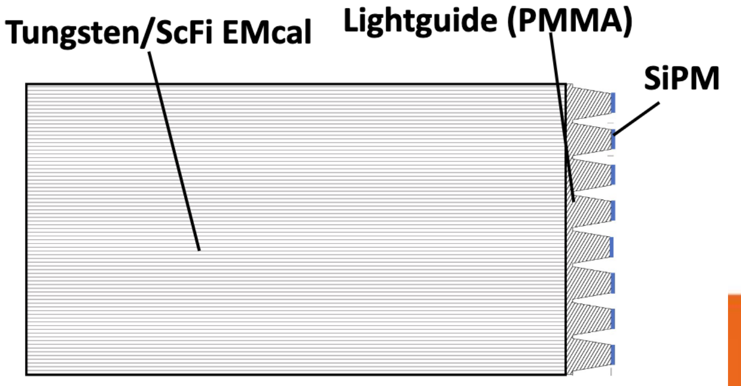
$$\frac{\sigma_E}{E} \sim \frac{50\%}{\sqrt{E}} \oplus 10\%$$



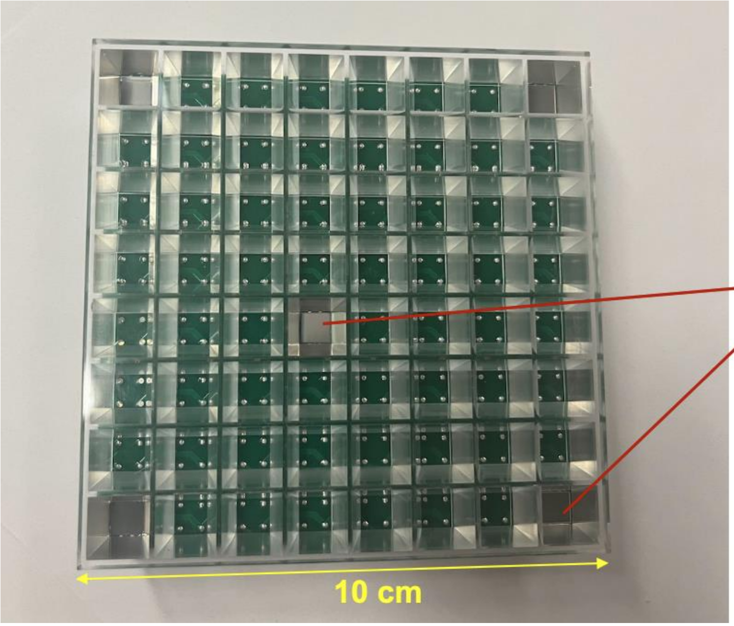
Forward EM calorimeter

- Tungsten + SciFi SPACAL design
  - Developed through EIC R&D and applied successfully in sPHENIX EMCal
  - Tungsten powder mixed with epoxy
- Position resolution vital to separate π^0 from ɣ at high energy
  - Dense absorber (~10 g/cm^3)
  - Readout with many SiPMs to create a small tower size
- Uniformity of construction important to reduce constant term
  - Dominates at high energy
  - Powder + epoxy enables fine control over spatial distribution of scintillator

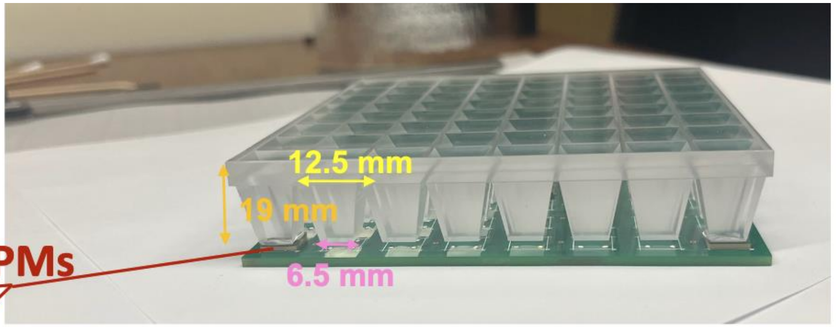


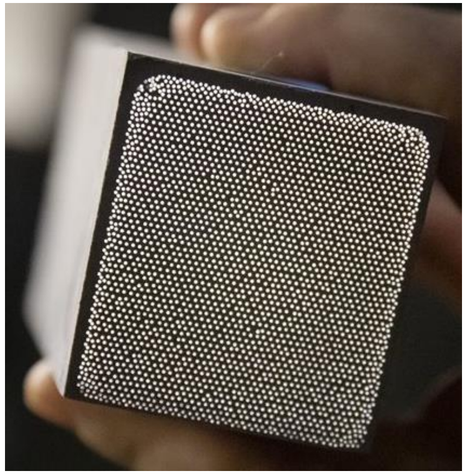


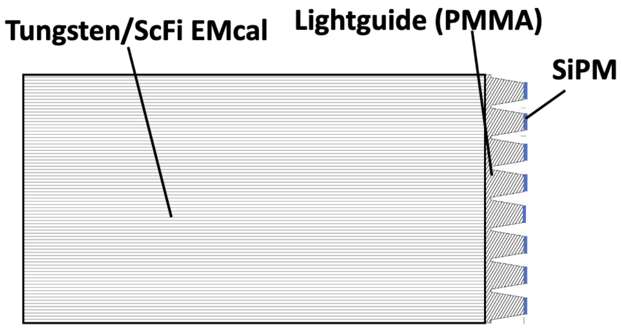
Forward EM calorimeter



SiPMs



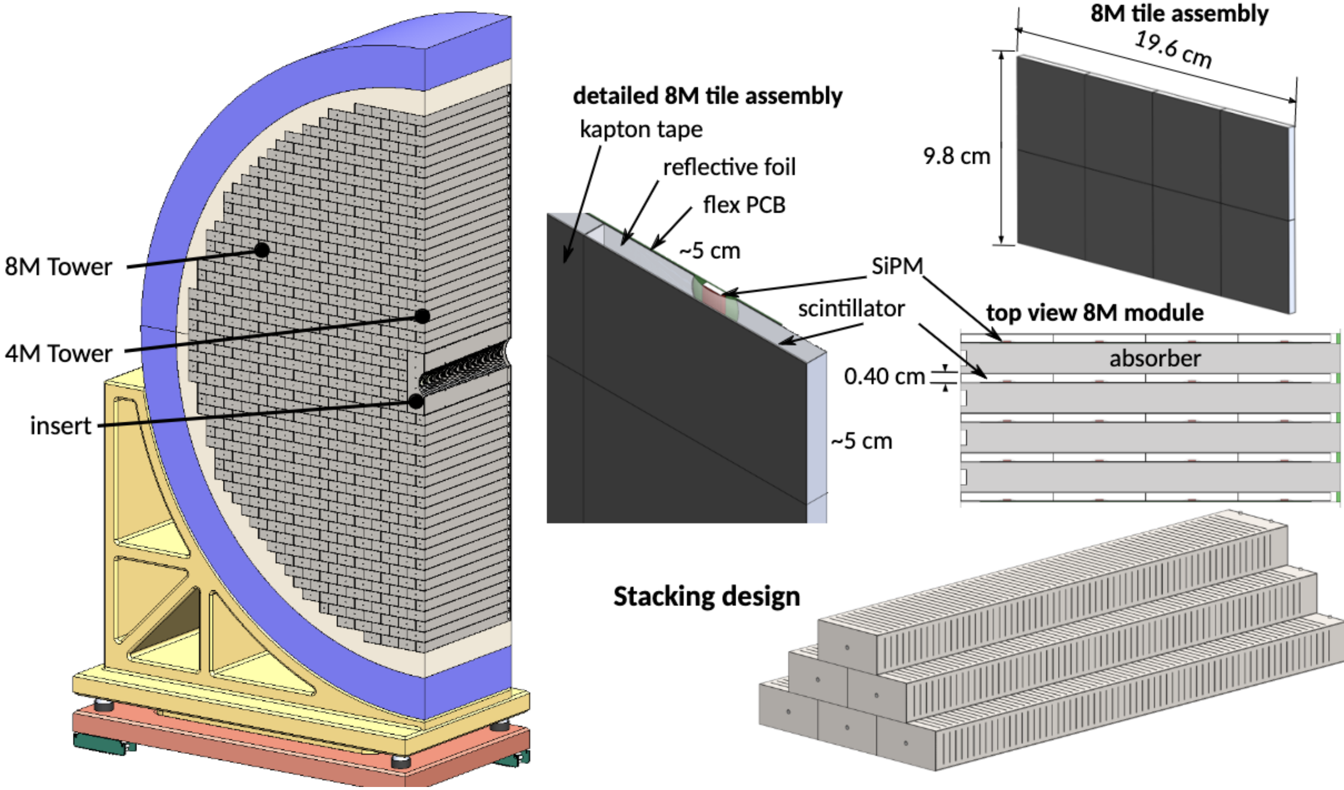




- 5 cm x 5 cm x 17 cm blocks of absorber + fibers
  - Four independent towers per block
- Each 2.5 x 2.5 cm tower is readout by four 6x6mm HPK S14 series SiPMs
- Expected energy resolution ~ $\frac{10\%}{\sqrt{E}} \oplus 1-3\%$

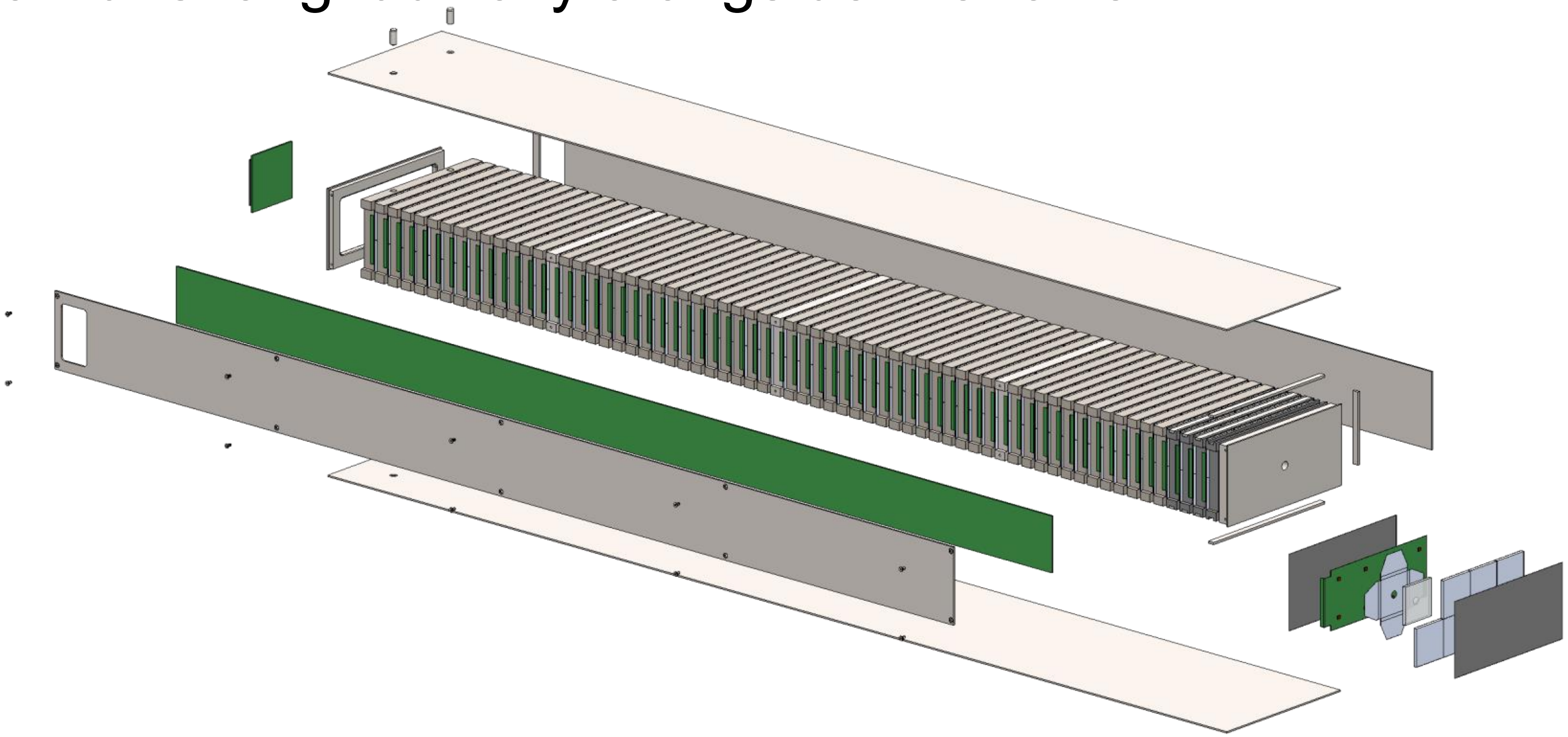
Forward hadronic calorimeter

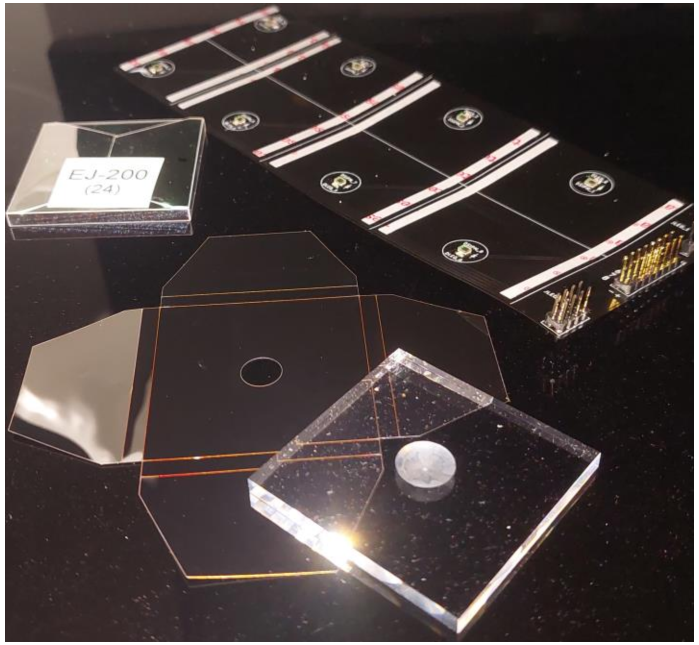
- Steel + Scintillator SiPM-on-tile
  - Pioneered by CALICE analog HCal
  - Ideal for particle-flow measurements!
- Highly segmented longitudinally, 65 layers per tower
  - 565,760 SiPMs
  - 65 layers ganged into 7 readout channels
- Stackable for “easy” construction
  - Steel as absorber significantly simplifies design, improves material uniformity
  - Achieves ~6.5 λ_0
- Expected resolution ~ $\frac{45\%}{\sqrt{E}} \oplus 5\%$
  - Exceeds requirements defined by Yellow Report!



Forward hadronic calorimeter

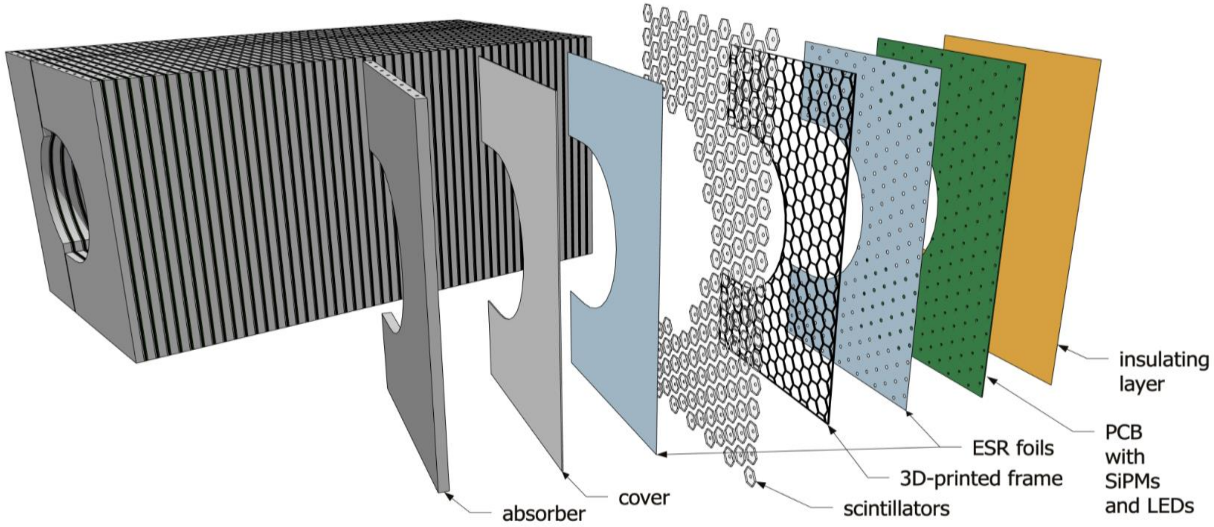
- SiPMs mounted to thin flex PCBs
  - Signals routed along PCB to periphery
- Signals brought to HGCROC at back by a thin flex PCB that runs longitudinally alongside the tower

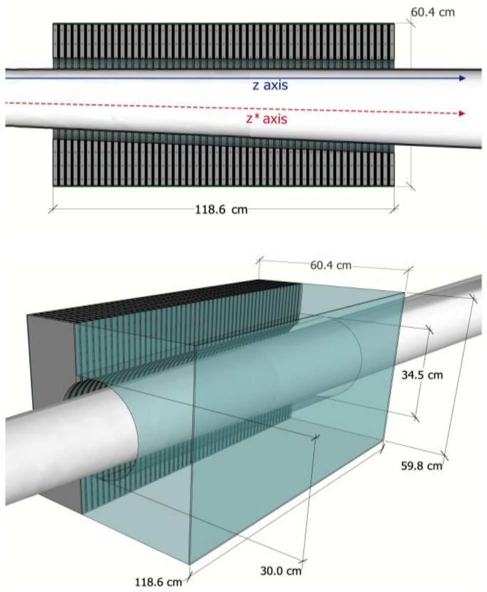


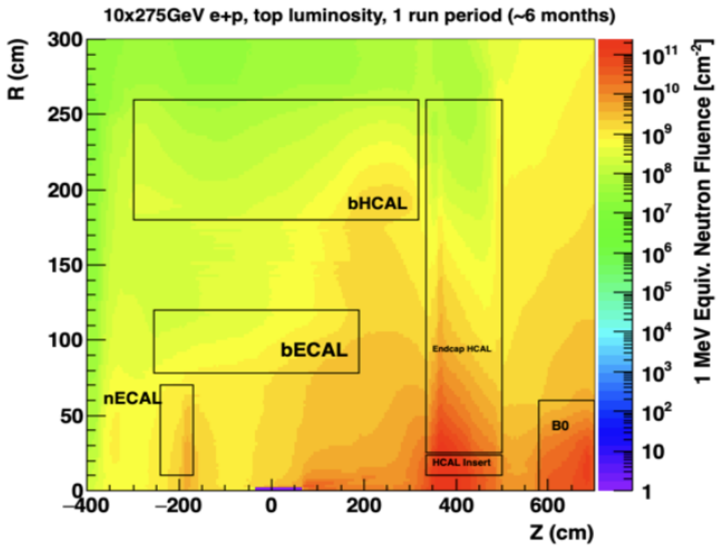


Forward insert calorimeter

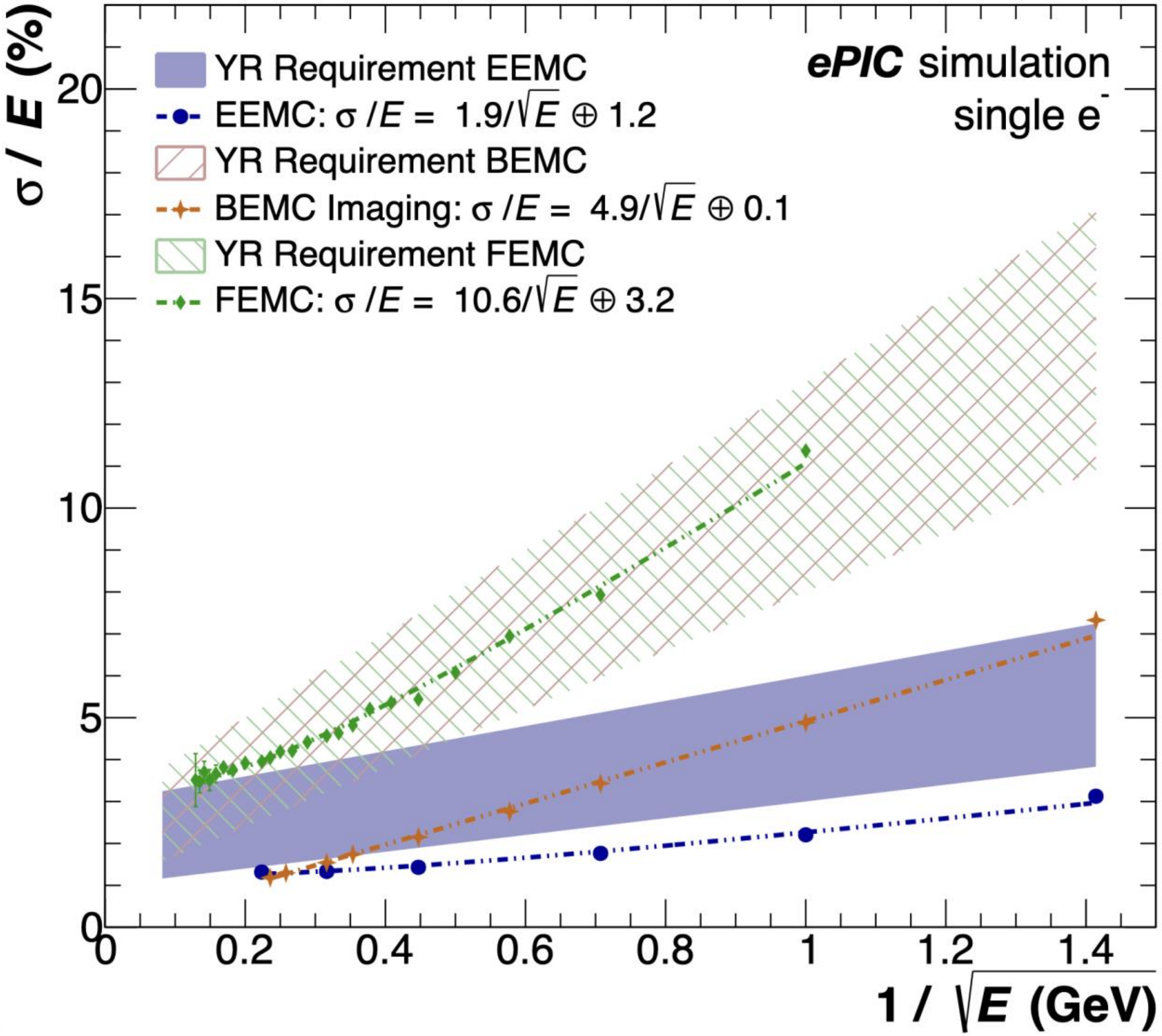
- Insert to extend central detector acceptance as much as possible in the forward direction
  - Crucial for containment of hadronic final state for inclusive kinematic reconstruction and rapidity gap diffractive measurements
  - $3.2 < \eta < 4$
  - Needs to accommodate complex beam pipe geometry
- Small hexagonal scintillator tiles for better spatial uniformity & increased light yield
- High radiation load
  - SiPMs will be serviceable
  - $\sim 10^{12}$ neq/cm^2/year

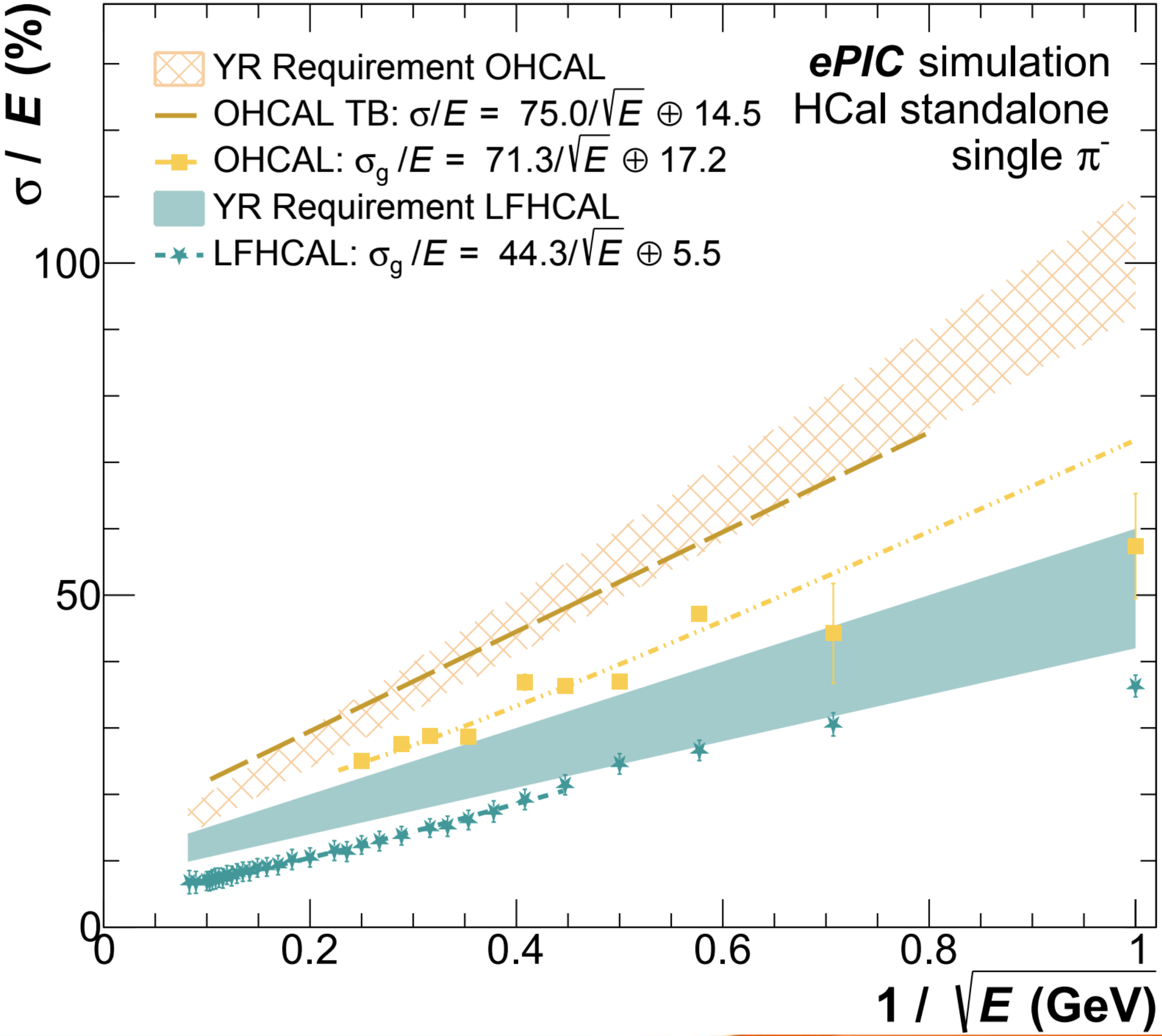






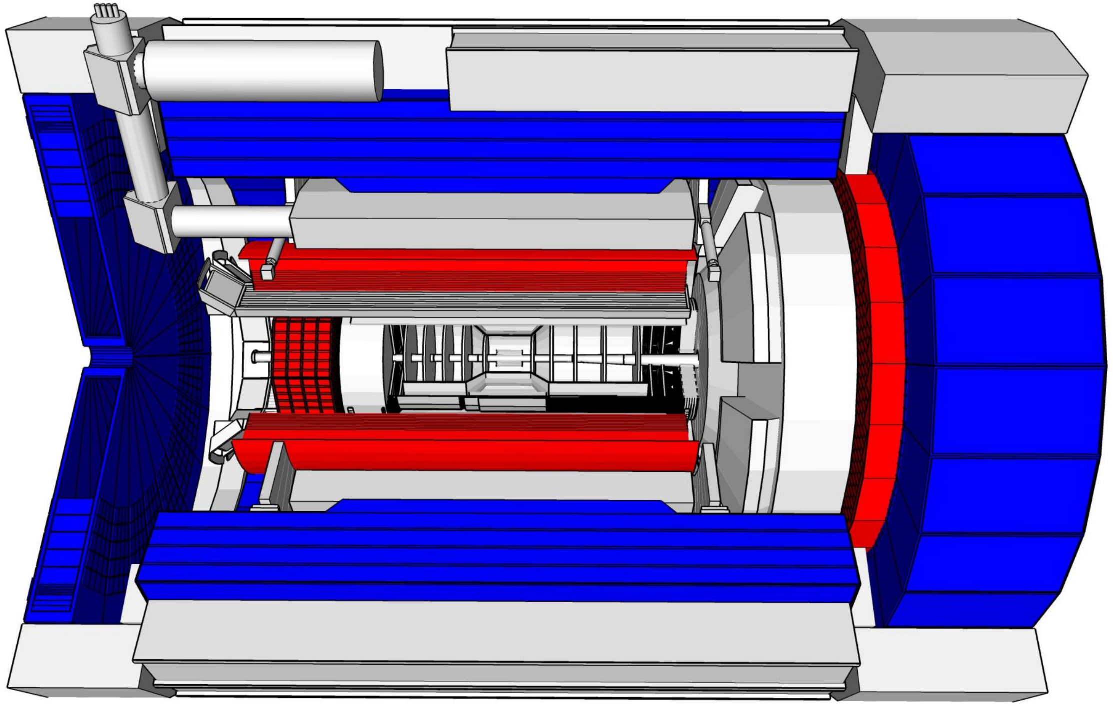
Performance projections





ePIC calorimetry summary

- Calorimetry is a vital component of the EIC detector package
- ePIC employs unique calorimetry designs to meet the varied demands of the different detector regions
  - Designed to meet the multifarious challenges & physics of the EIC!
- The ePIC calorimeter designs meet or exceed their performance requirements'



- EIC is scheduled to begin running in 2034
  - CD3 & Construction to begin in early 2026

- **ePIC TDR coming soon, stay tuned!**

New trends in calorimetry

European Calorimeter R&D Priorities for Future Experiments

Motivation & Objectives

- Align with ECFA's Detector R&D Themes:
- DRDT 6.1: Precision EM calorimeters (radiation-hard, high granularity)
- DRDT 6.2: Imaging calorimeters (PFA-capable, multi-dimensional)
- DRDT 6.3: Calorimetry for extreme environments (radiation, timing, rates)
- Target detectors for future facilities:
  Higgs factories, **muon colliders**, **EIC**, and **intensity frontier experiments**
- Emphasis on **system-level R&D**: materials, mechanics, electronics, and integration

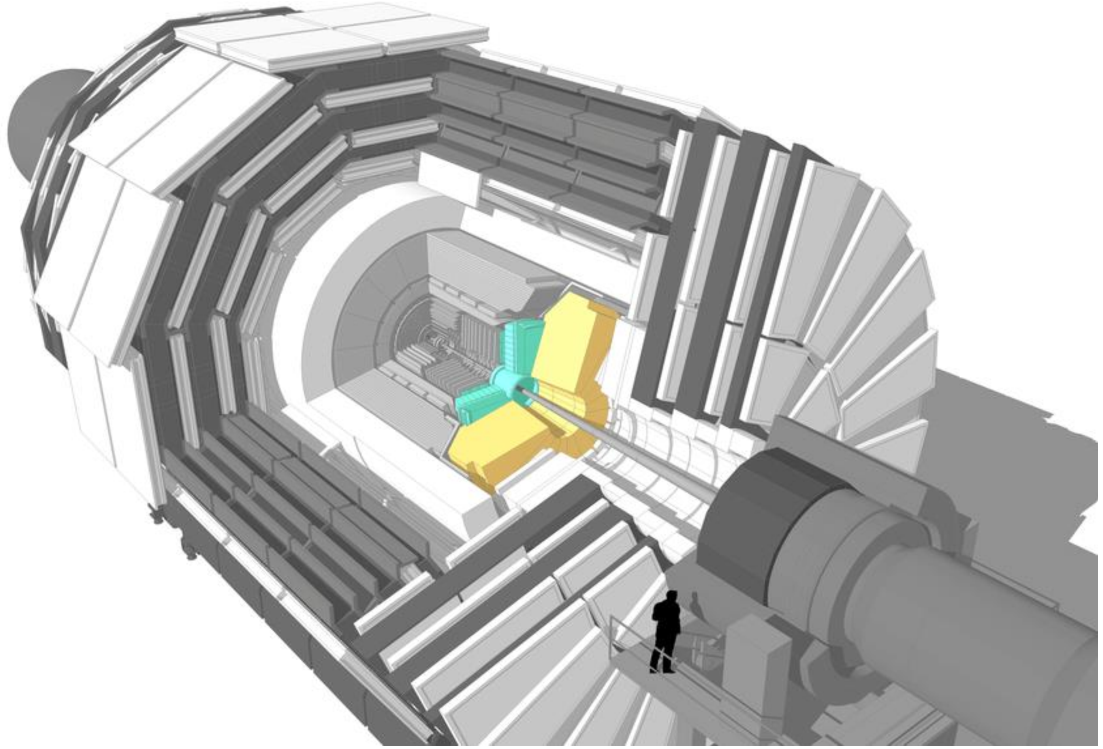
DRD6 Structure

Work Packages (WPs):

1. **WP1:** Imaging sandwich calorimeters
2. **WP2:** Noble liquid calorimeters
3. **WP3:** Optical calorimeters
4. **WP4:** Electronics and readout systems

Cross-Working Groups (WGs):

- Photodetectors (esp. SiPMs)
- Mechanics & thermal management
- Simulation, reconstruction, AI/ML
- Beam test coordination
- Industrial links & production



Close-up view of the HGCAL endcap in CMS endaps

WP1: Imaging sandwich calorimeters

Technologies & Projects:

- **SiW-ECAL:** Analog silicon pads (ILD, CMS HGCAL lineage)
- **DECAL:** CMOS pixel-based digital ECAL (MAPS)
- **Sc-ECAL:** Scintillator strips with SiPMs
- **AHCAL:** Highly segmented hadronic calorimeter
- **MPGD-HCAL:** Micropattern gas detector for HCAL
- **T-SDHCAL:** Semi-digital with timing capability

Common Goals:

- High spatial resolution (cm-scale or better)
- Integration of front-end ASICs in the active layers
- Power pulsing & compact mechanics
- Compatibility with PFA and timing layers

WP2: Nobel liquid calorimeters

Focus:

•Use of **liquid argon** and **liquid xenon** as active media
•Emphasis on **homogeneity, stability**, and **radiation resistance**

Ongoing R&D:

•Electrode design for high granularity (mm-scale)
•Electronics: cryogenic ASICs vs. warm readout options
•Mechanical structures and long-term purity control
•Test module construction (2024–2028)

Applications:

•FCC-ee precision calorimetry
•Background suppression in muon colliders

WP3: Optical calorimeters

Technologies:

- **Crystal calorimeters:** e.g., MAXICC, Crilin (ultra-fast, homogeneous)
- **Scintillator-sampling ECALs:** e.g., SpaCal, GRAiNITA, RADiCAL
- **Dual-readout and timing calorimeters:** e.g., DRCal

Innovations:

- Use of novel crystals (LYSO, BGO, PbF_2) and nanocomposites
- Focus on ultrafast timing (30–50 ps resolution)
- Dual-readout for compensation and resolution improvement
- Compactness and modularity for integration

WP4: Electronics and readout

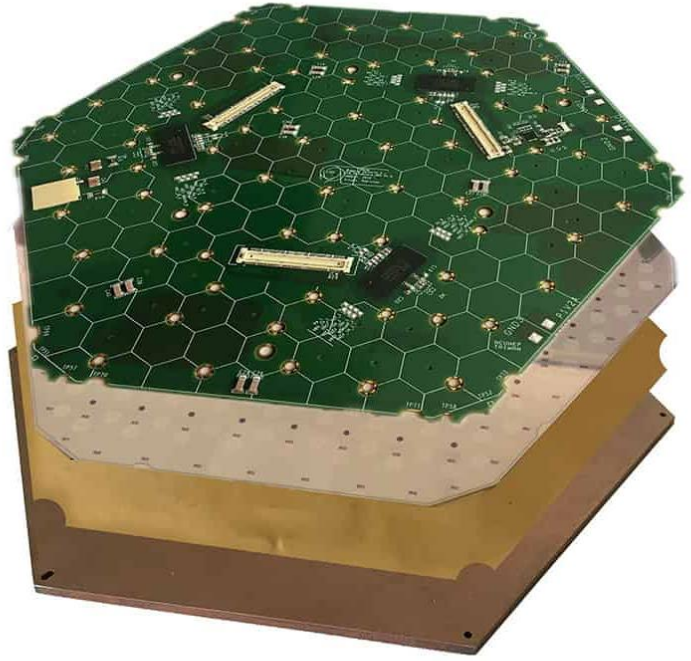
Challenges:

•Front-end ASICs must support:

- **Low power**, **high timing precision**, **radiation tolerance**

•Development of:

- Digitization close to sensor
- Clock distribution and synchronization
- Data compression and trigger integration

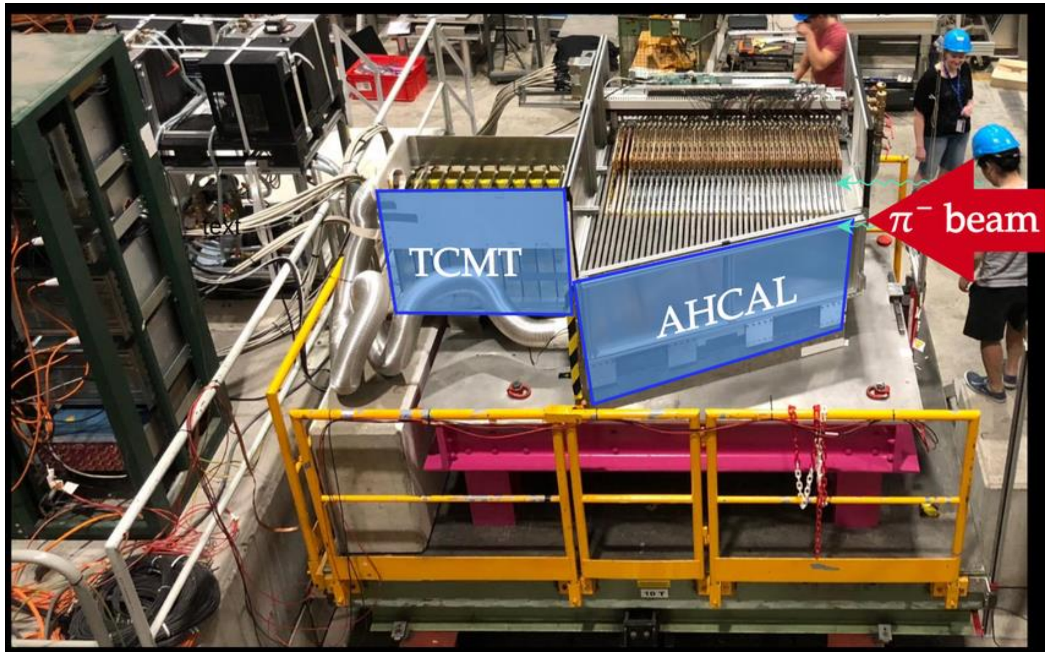


Collaborations:

•Shared designs across WP1–3

Common effort with DRD7 (Electronics)

Cross-Cutting Themes



Photodetectors:

•SiPM characterization, lifetime tests, saturation behavior

Simulation & Software:

•Unified frameworks (e.g., DD4hep, GEANT4)
•ML-enhanced reconstruction (energy regression, clustering)

Beam Test Coordination:

•Shared test campaigns at CERN, DESY, FNAL
•DAQ standardization, infrastructure sharing

Industry Collaboration:

•Scalable production of scintillators, crystals, electro

Roadmap and milestones

Timeline:

- 2024–2026: Small and medium-scale prototype tests
- 2026+: Integrated modules, beam tests with tracking
- 2030+: Design studies for FCC, MuC, ILC, EIC
- Final goal: Deliver validated technologies for TDRs (~2035)

Deliverables:

- Comparative performance benchmarks
- System integration studies
- Technical demonstrators

Conclusions & outlook

Summary:

•DRD6 is central to next-generation calorimeter development in Europe
•Emphasis on imaging, precision, and fast timing
•Strong collaboration between institutions and DRDs
•Positioned to deliver mature technologies for future colliders

Outlook:

•Expect increased beam test activity and prototype scaling
•Cross-fertilization with ongoing LHC and EIC upgrades
•Opportunities for new collaborators, especially in ASICs and ML