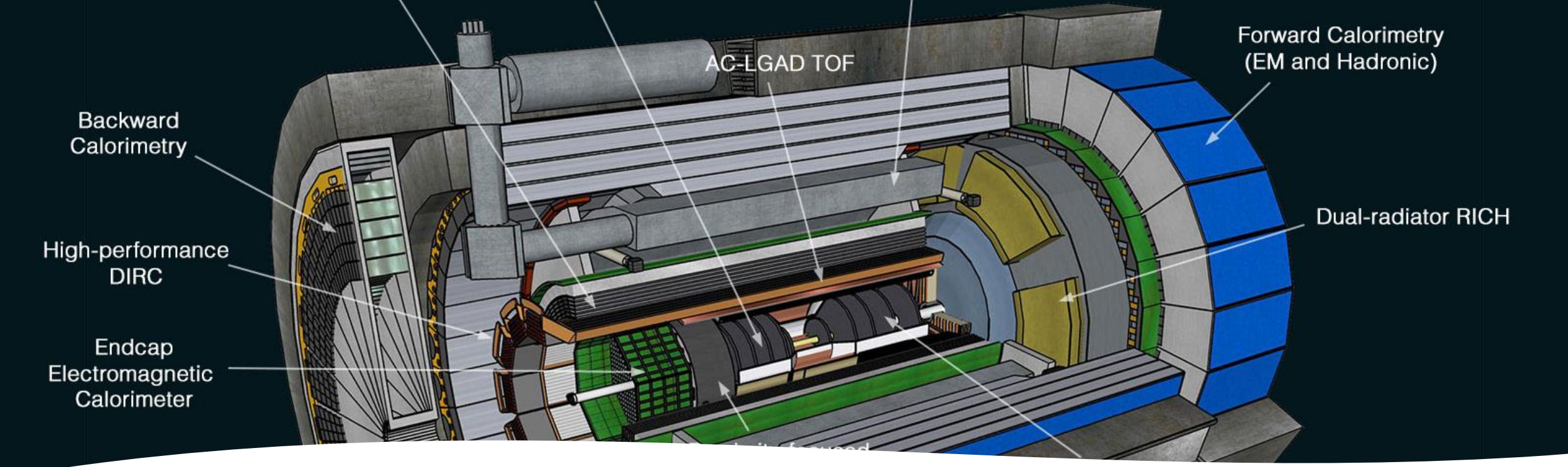


Calorimetry at ePIC

Tristan Protzman for the ePIC Collaboration

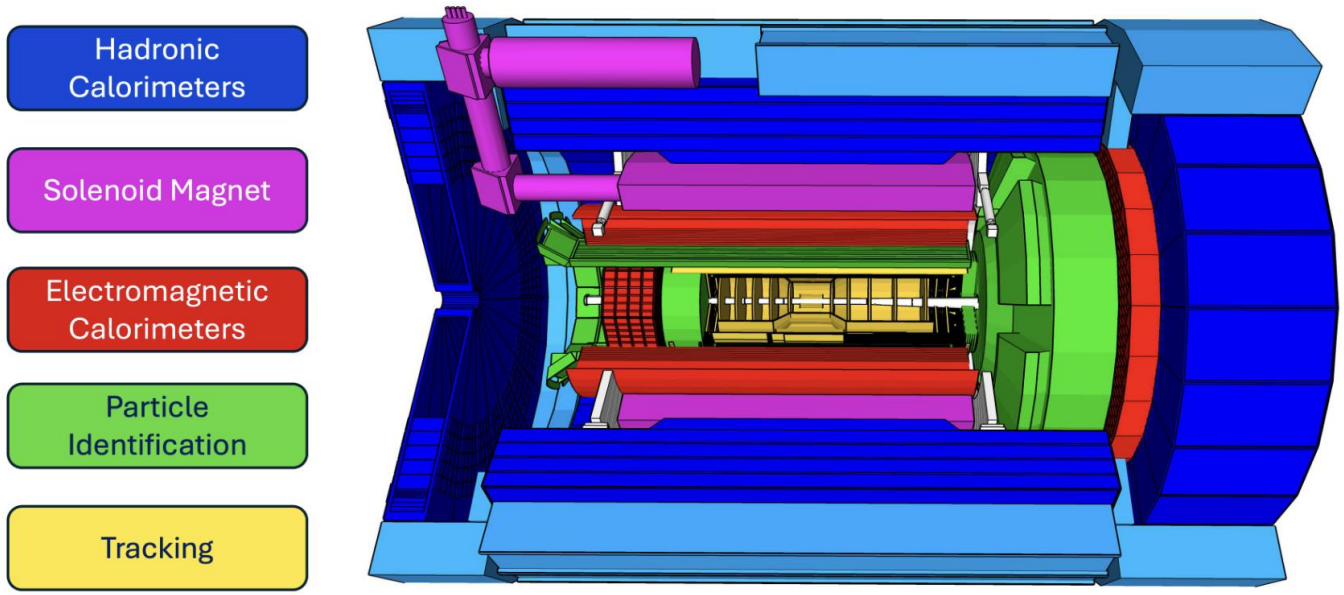
RHIC-AGS Annual Users Meeting

May 20th, 2025

Brookhaven National Lab

The ePIC Detector

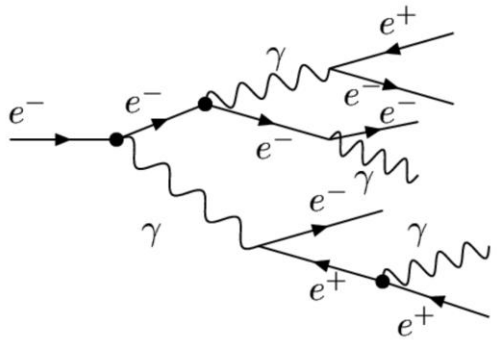
- ePIC is a high precision detector for measuring $e + p$ and $e + \mathrm{A}$ at high luminosities
- ePIC is the sum of several classes of detectors, each with several subsystems
- Each subsystem aids in a holistic, high resolution event reconstruction
- Several calorimeters assist in particle and jet reconstruction

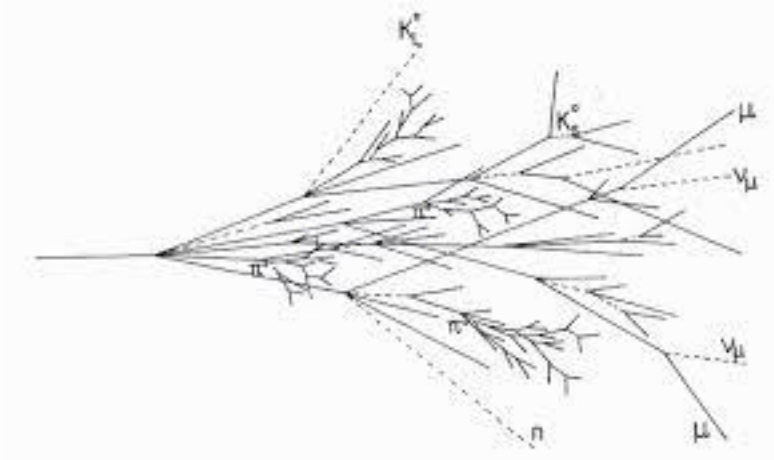


Calorimetry

- Calorimeters measure the energy of particles
  - Convert the particles energy into light or charge, which is measurable
  - Achieved by initiating electromagnetic or hadronic showers
- Electromagnetic and hadronic calorimeters cause showers through different mechanisms

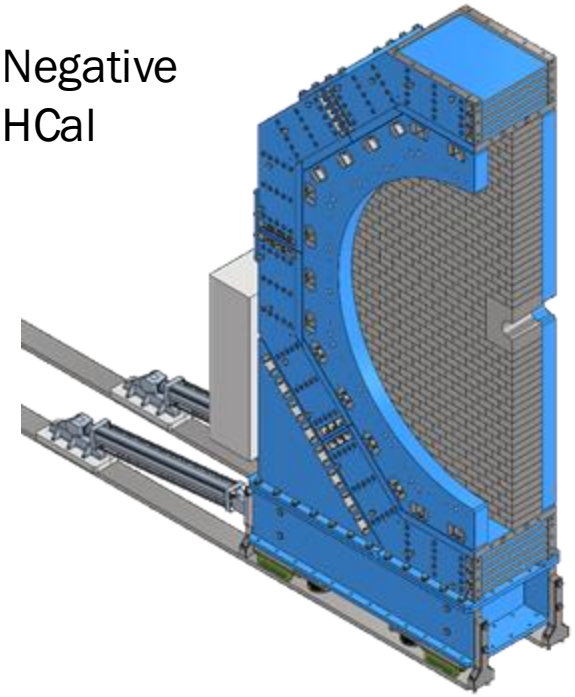
- Electromagnetic
  - Showers through Bremsstrahlung radiation and pair production
  - Produces compact, well described showers
- Hadronic
  - Showers through nuclear interactions
  - Much larger fluctuations in shower size, shape, and electromagnetic fraction



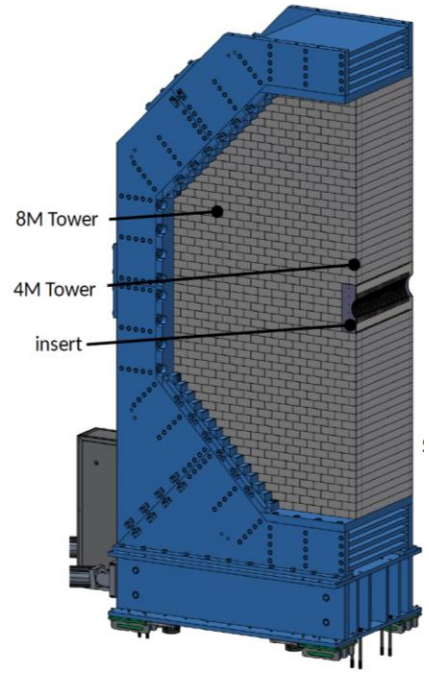


ePIC's calorimeters

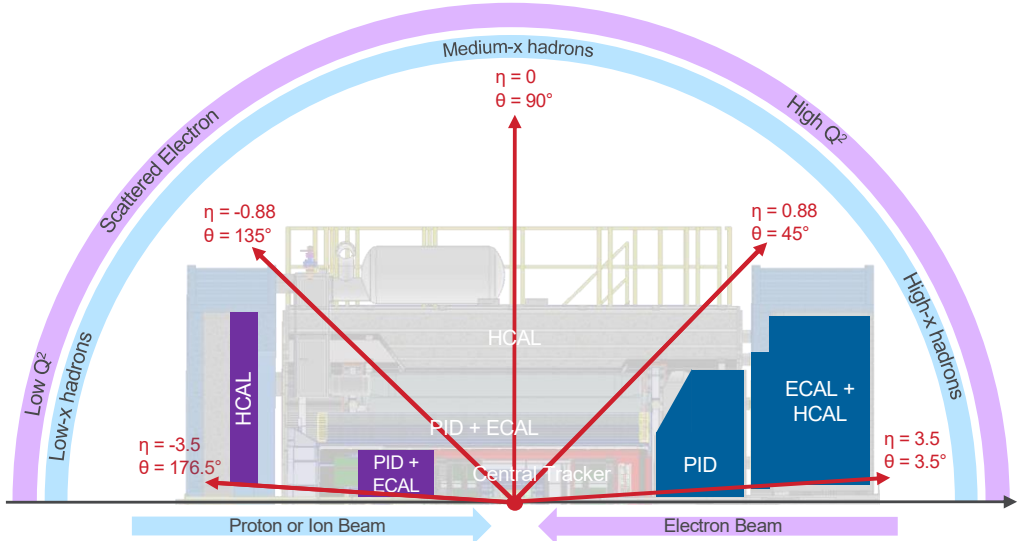
Negative HCal



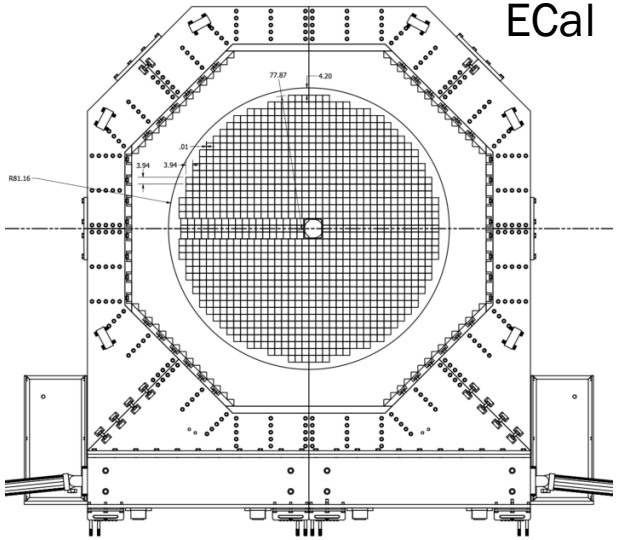
Barrel HCal



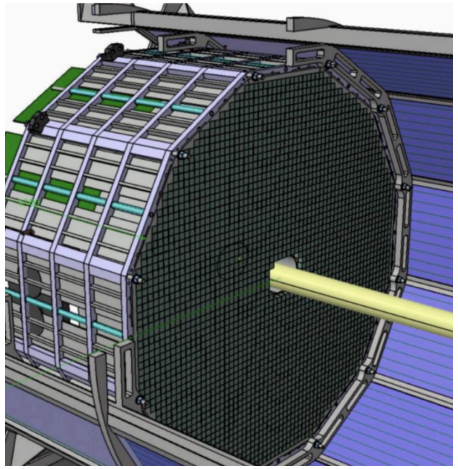
LFHCal

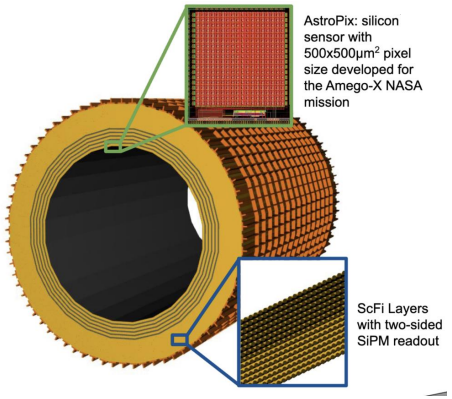


Forward ECal



Electron Endcap EMCal



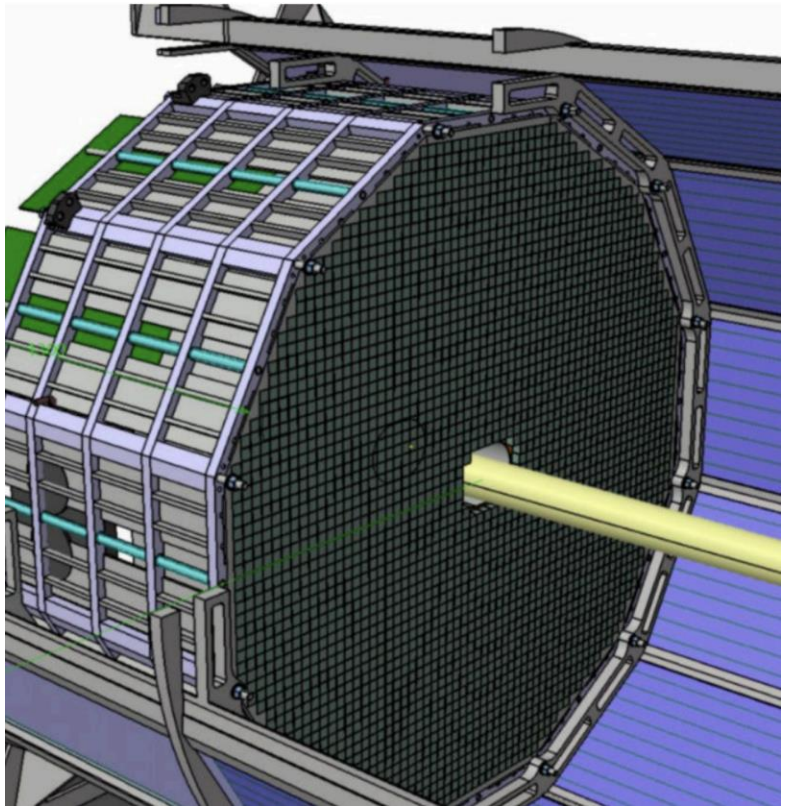


Barrel Imaging Calorimeter

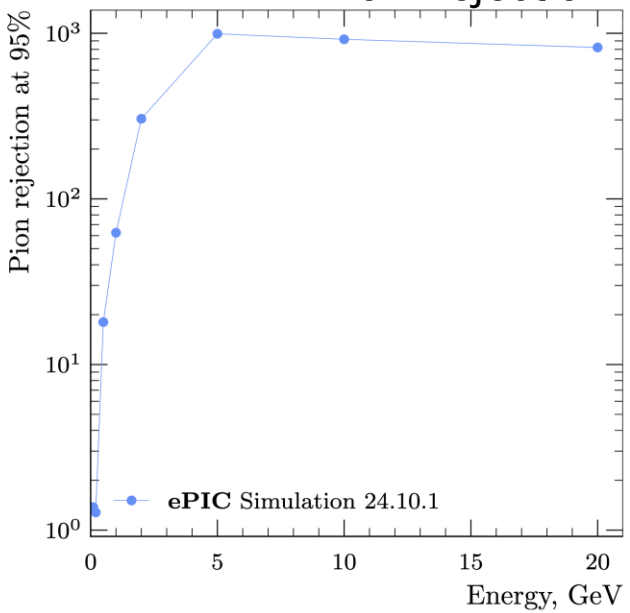
Electron Endcap Electromagnetic Calorimeter

- Captures the scattered electron in low Q^2 events
  - Electron at very small angle to beam line
  - Crucial for defining kinematics in DIS events
  - Requires excellent energy and position resolution
    0.5 - 18 GeV dynamic range
  - Target resolution: $\frac{\sigma_E}{E} \approx \frac{2-3\%}{\sqrt{E}} \oplus 1-2\%$

- Separate electrons and pions
  - In low x events, the final hadronic state is in the backwards direction as well as the scattered electron
  - Excellent pion rejection at high energy to identify DIS electron

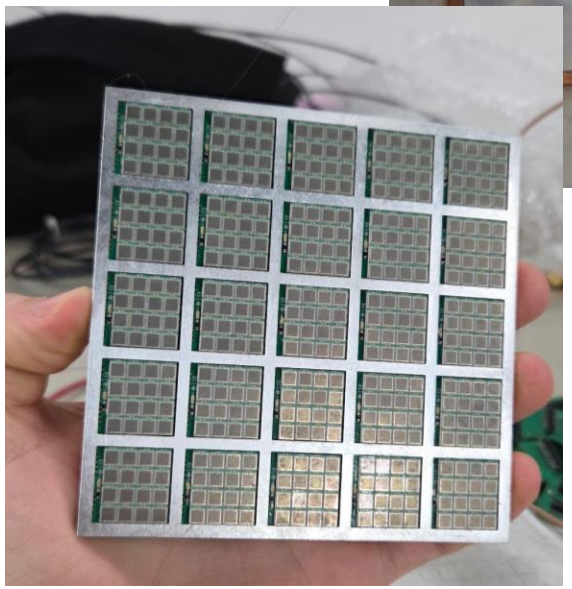


Pion Rejection



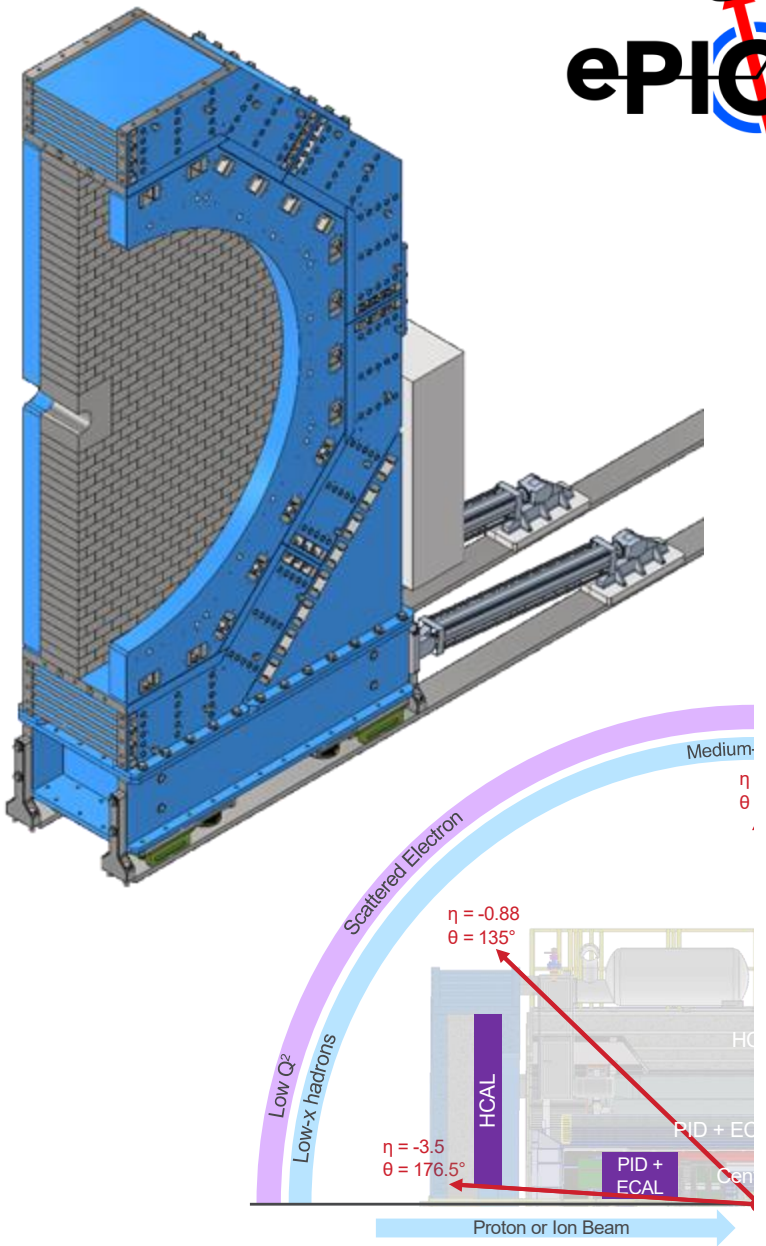
Electron Endcap Electromagnetic Calorimeter

- Constructed from lead tungstate crystals
  - Homogenous calorimeter, absorber and sampling material are the same
  - Short radiation length and small Moliere radius enables a relatively compact detector
  - High light yield, but sensitive to thermal changes
    Light yield varies ~2% per degree Celsius
- 16 SiPMs directly attached to the face of each crystal
  - Investigating reading out individually, groups of 2, 4 or all 16
  - Fewer readout channels needed, but increased capacitance
- Tested in DESY II electron beam, February 2025



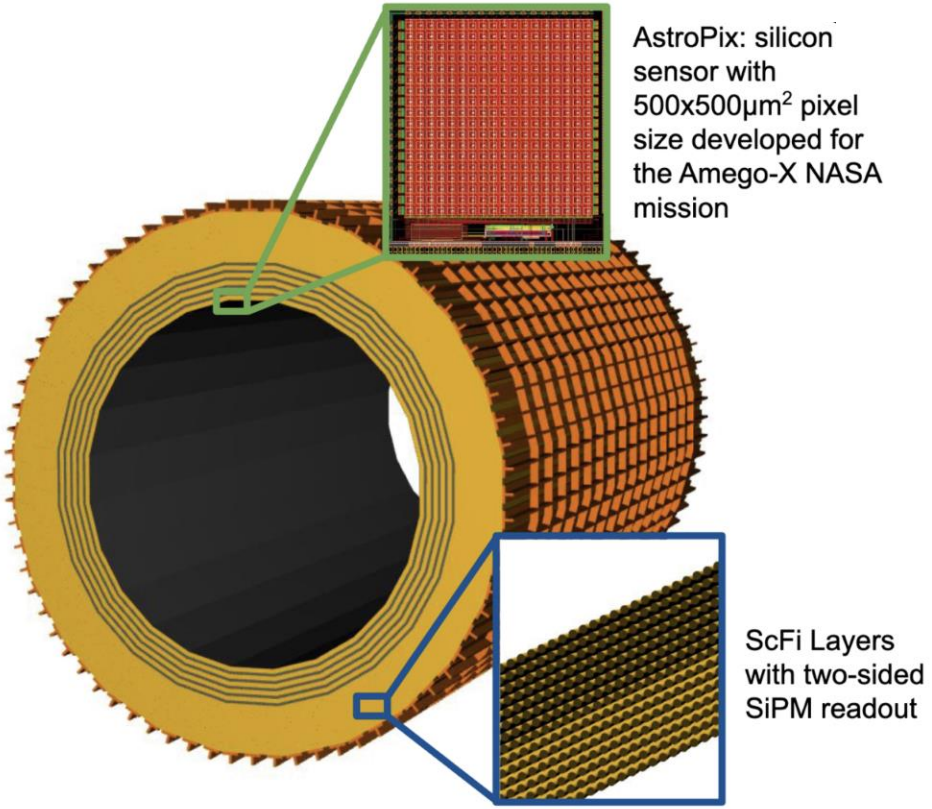
Negative Hadronic Calorimeter

- Low x events result in low momentum hadrons in the backwards direction
  - Vector meson production, diffractive dijets
- A hadronic calorimeter serves as a tail-catcher for the EEEMCal
- Improves discrimination between hadronic final state and scattered electron
  - Separation of vector meson –> e^+e^- and $\mu^+\mu^-$ states
- Modest energy resolution requirements, but good low energy neutron detection efficiency
  - Used for neutral tagging/veto
  - Position resolution to match hadronic clusters to electromagnetic clusters
- Alternating steel and scintillator design, similar to LFHCal



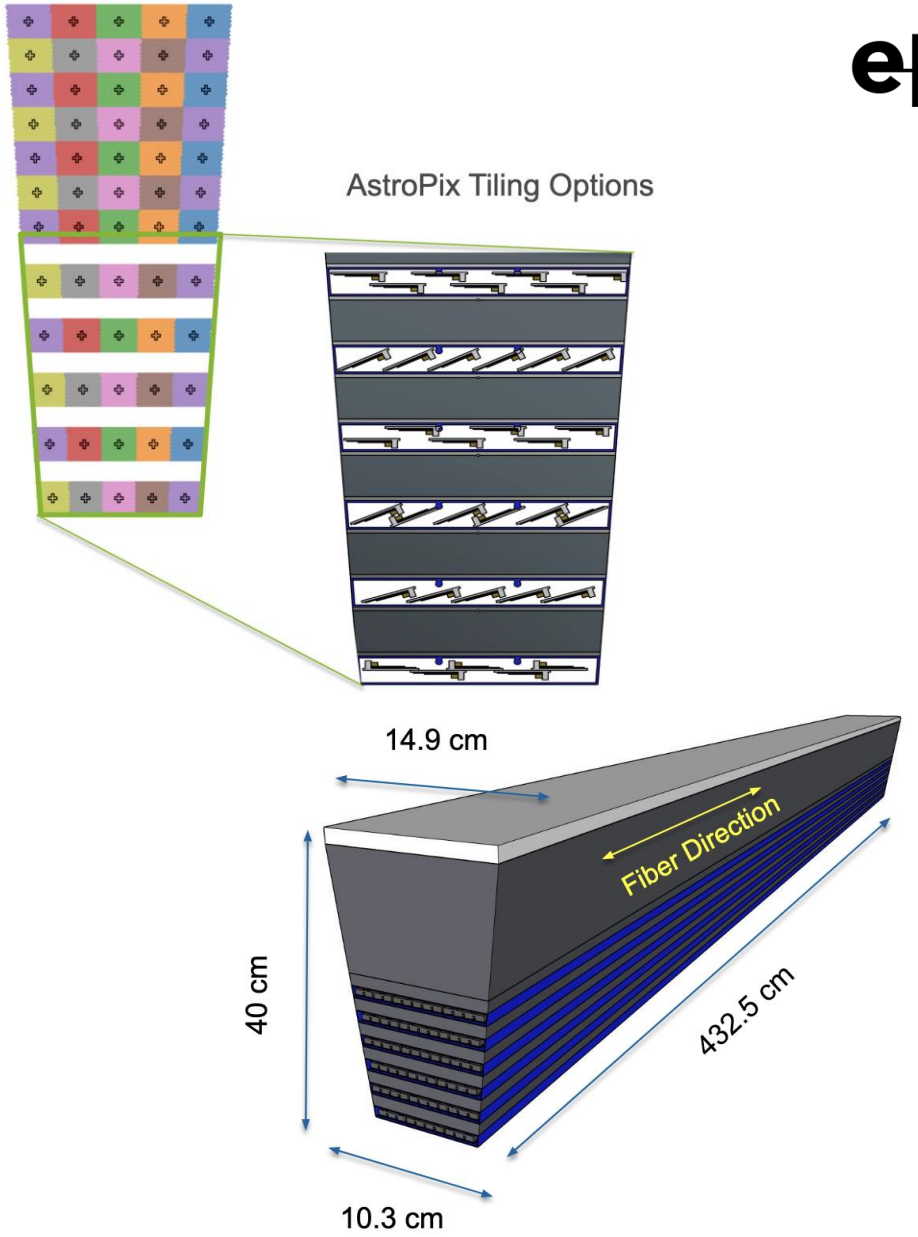
Barrel Imaging Calorimeter

- Measures scattered electron in high Q^2 events
- Aid in reconstruction of final hadronic state
- Good energy resolution
  - $\frac{\sigma_E}{E} \leq \frac{10\%}{\sqrt{E}}$
- Enables electron identification from 1 to 50 GeV
  - Requires strong electron/pion separation!
- Able to separate photons and neutral pions up to 10 GeV
- Combination of two technologies
  - Lead-scintillating fiber sampling calorimeter
  - MAPS based silicon tracking layers interleaved with Pb/SciFi layers
  - Up to 6 layers at various depths, with 4 layers as the baseline



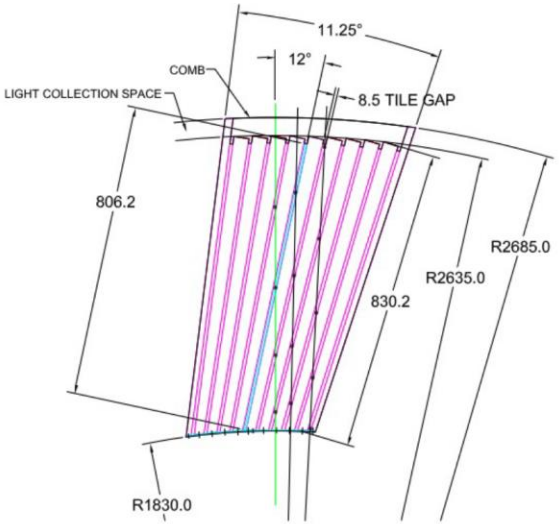
Barrel Imaging Calorimeter

- Imaging layers
  - AstroPix MAPS pixel sensor enables a detailed view of the shower development
  - Developed for NASA AMEGO-X project
  - Enables the strong $e^-/\pi^\pm$ and γ/π^0 separation required
- Sampling portion
  - Scintillating fibers embedded in lead absorber
  - SiPM readout at either end of the detector
  - z coordinate determined by Δt between the arrival of signals
- Components of the BIC have been studied in multiple test beams



Barrel Hadronic Calorimeter

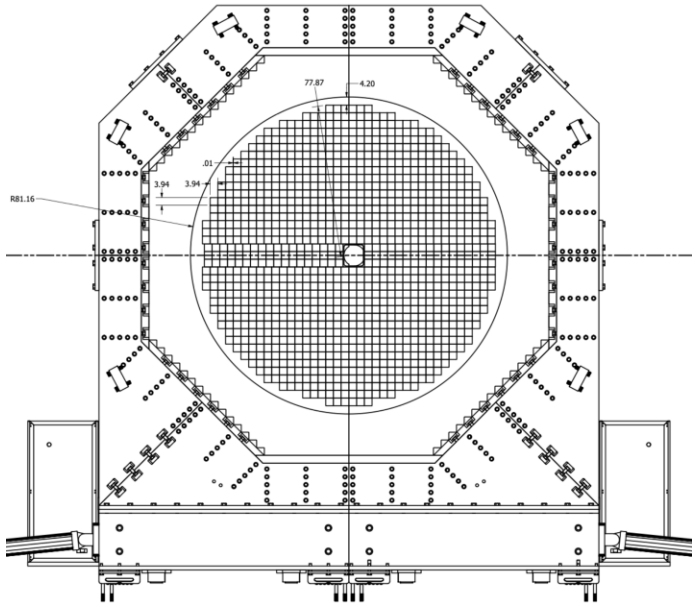
- Helps the reconstruction of jets, charged-current DIS, identification of the hadronic final state, and muon identification
- Steel and scintillator sampling calorimeter
  - Modest resolution: $\frac{\sigma_E}{E} \approx \frac{75\%}{\sqrt{E}} \oplus 14.5\%$
  - Plates parallel to beam direction to use as magnet flux return
  - Tilted to avoid particles passing through without interacting
- Refurbishment of sPHENIX Outer Hadronic Calorimeter
  - New SiPMs
  - Individual readout channels

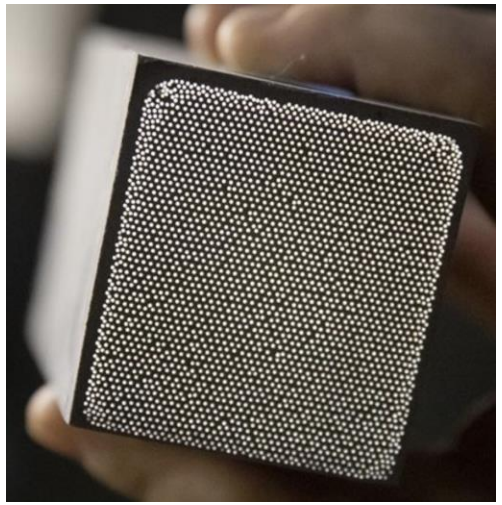


Forward Electromagnetic Calorimeter

- Jets, TMD, SIDIS events
  - Needed to accurately construct highly energetic hadronic final states
  - High segmentation needed to separate π^0 decay photons at high p_{T}

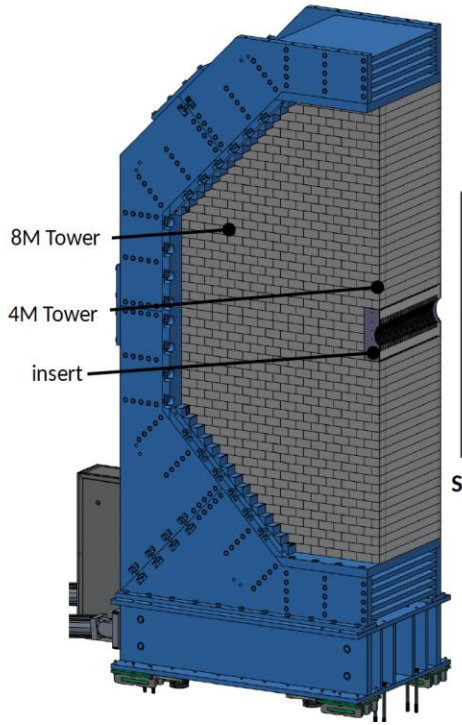
- Based on tungsten powered embedded with scintillating fibers – SPACAL design
  - Developed through EIC R&D efforts
  - Demonstrated in sPHENIX EMCal
  - Very short radiation length and Moliere radius allows for a compact, high granularity detector
  - $\frac{\sigma_E}{E} \approx \frac{12\%}{\sqrt{E}} \oplus 2\%$
  - γ/π^0 separation up to 50 GeV!

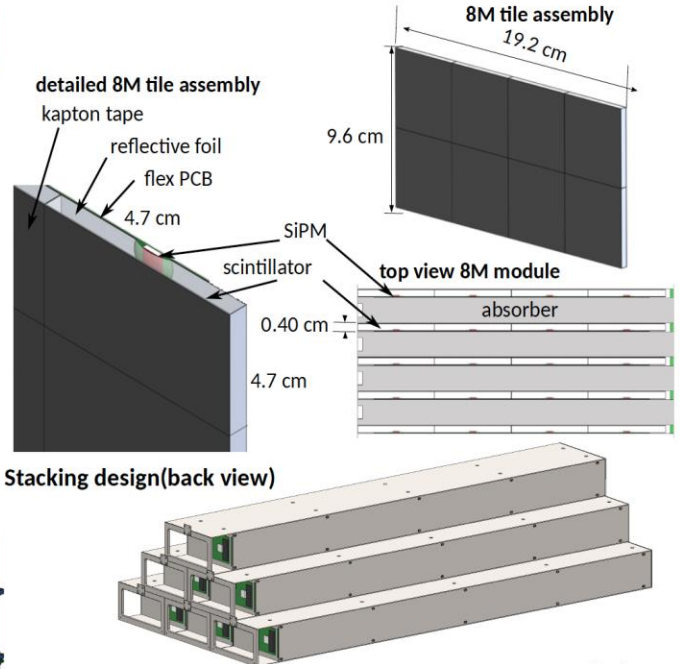


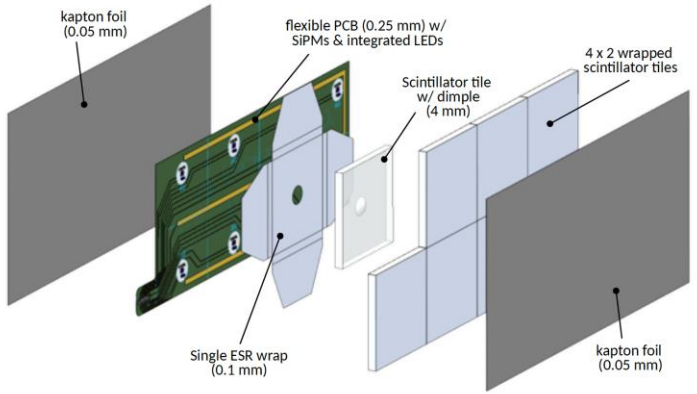


Longitudinal Forward Hadronic Calorimeter

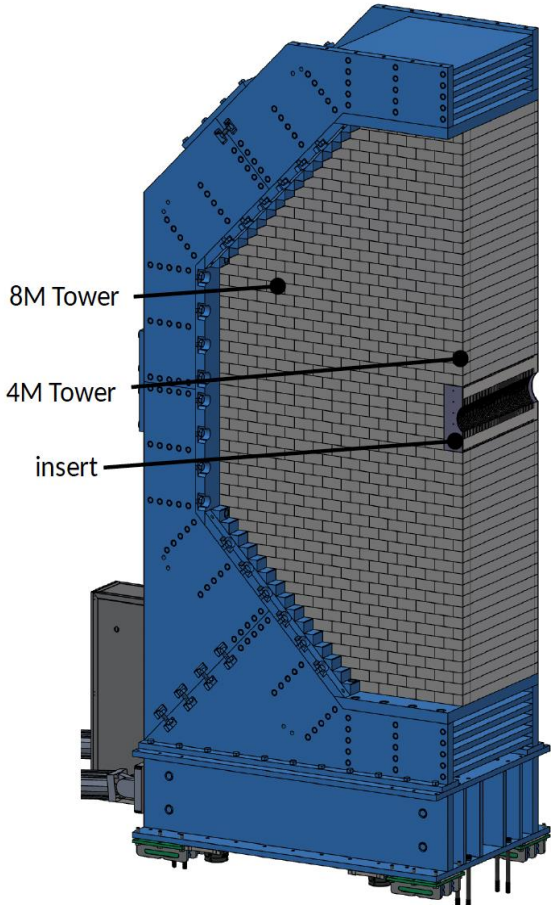
- Improved jet reconstruction at small angles
  - At high rapidity, calorimetry performance can outperform tracking
- Aid in particle flow reconstruction algorithms
- Longitudinally alternating layers of steel and plastic scintillator
  - Allows for measurement of the shower shape
- SiPM on tile design
  - Based on CALICE AHCal design
- Prototype modules and electronics tested at CERN in 2023 and 2024

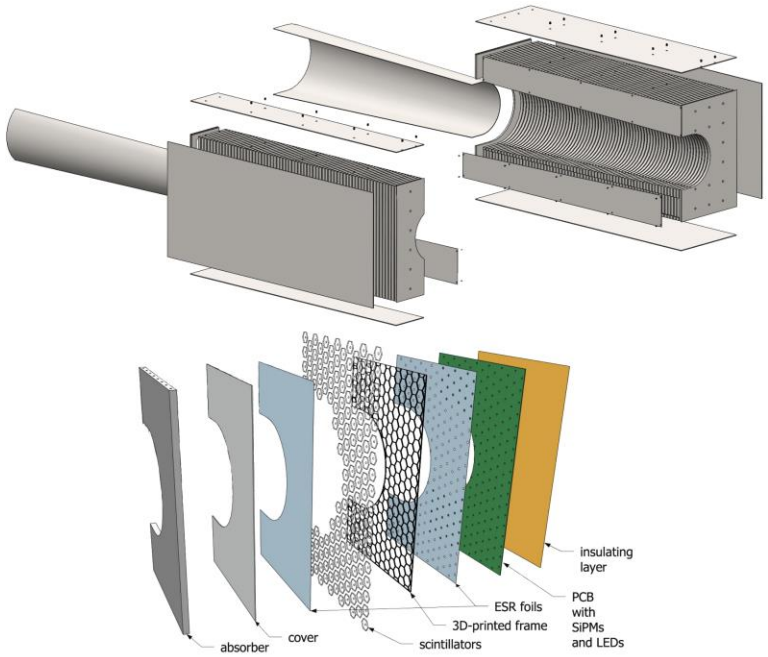


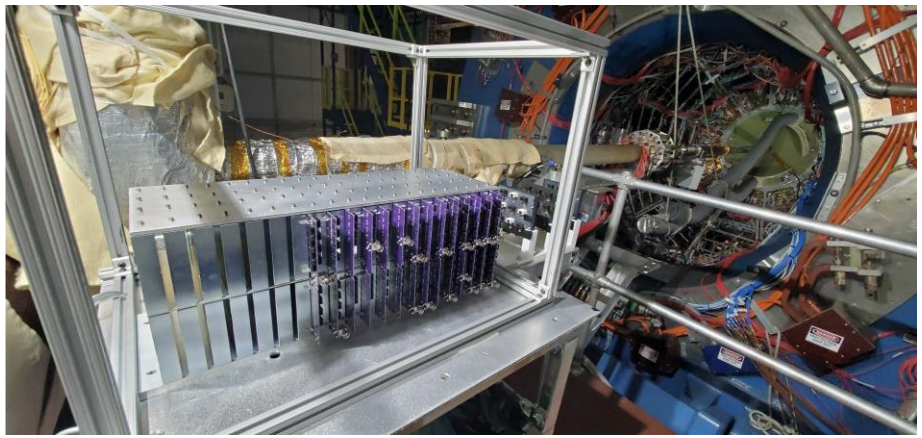




Forward HCal insert







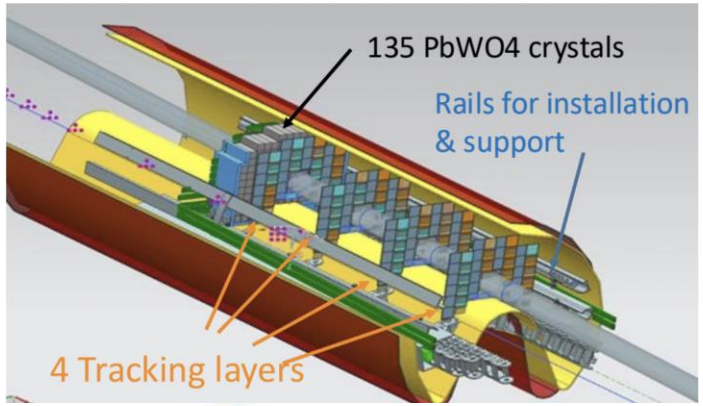
- To maximize performance at small angles, an insert shaped around the beam pipe is being constructed
  - $3.5 \leq \eta \leq 4{,}4$
- SiPM-on-tile with hexagonal tiles
- Each tile individually read out to improve shower shape measurement
- Prototype tested in STAR hall
  - First SiPM-on-tile calorimeter in a collider environment!

Far forward and far backward region

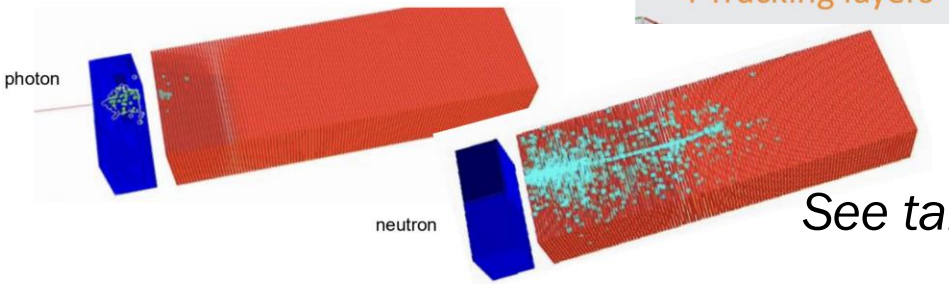
Far Forward Calorimeters

- B0 EMCal
  - Combination tracker and EMCal
  - Lead Tungstate Crystals for photon detection
- Zero-degree calorimeter
  - Combination EMCal and HCal
  - Crystal EMCal for low to medium energy photon detection
  - SiPM-on-tile HCAl for high energy neutron, photon and lambda reconstruction

B0 Detector



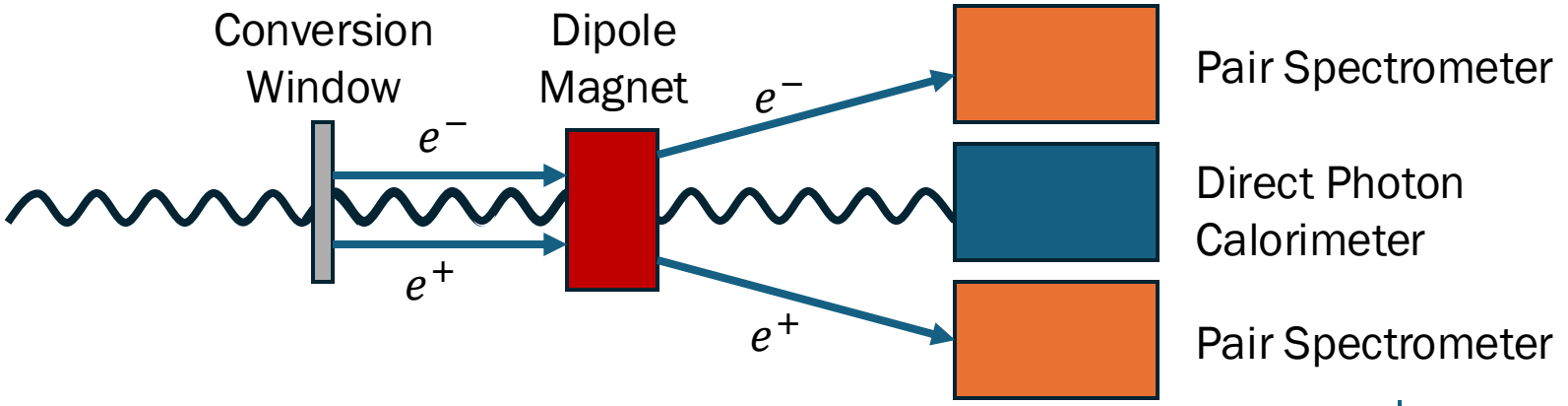
Zero-degree calorimeter



See talk by Alex Jentsch for more detail!

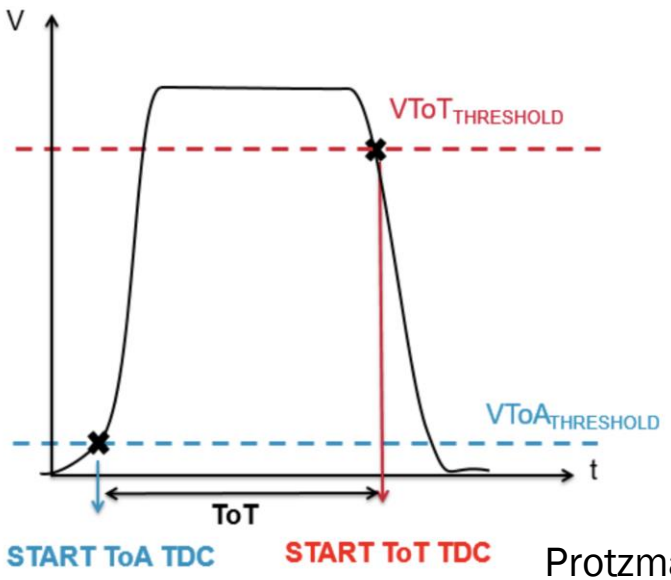
Far Backward Calorimeters

- **Luminosity monitor**
  - Direct photon detector
  - Pair spectrometer
  - Measures luminosity to 1% absolute accuracy



Detector readout

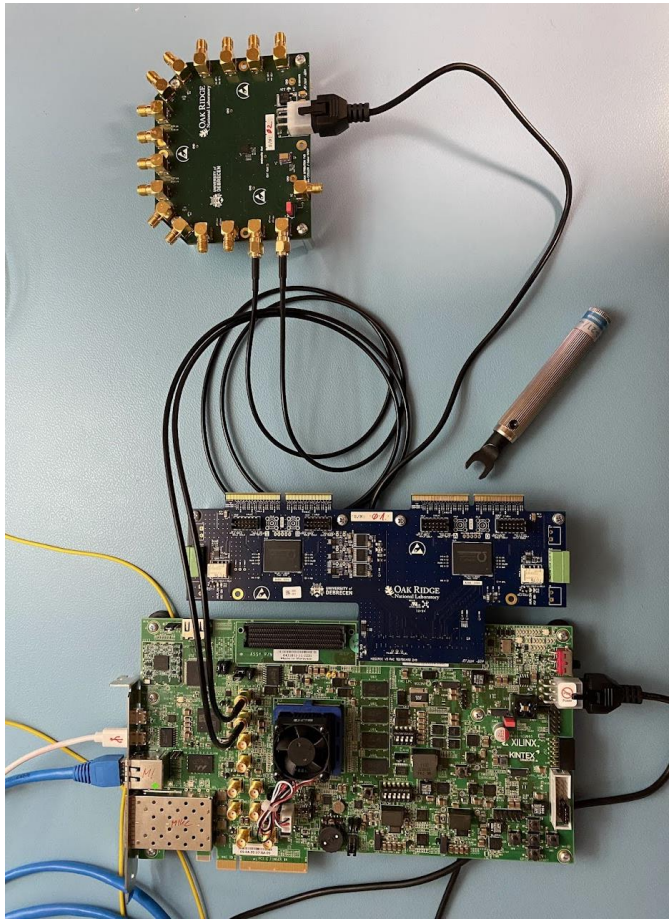
- ePIC digitization is based around the streaming readout concept
  - Recording constantly, not triggered!
- Many calorimeters will use the CALOROC readout
  - ePIC specific implementation of HGCROC developed for CMS HGCal
  - 40 MHz digitization
  - Large dynamic range through through combination of ADC and time-over-threshold measurement
- Used in multiple test beams, results in progress



Common clock

Protoboard 2.0 with two H2GROC3A

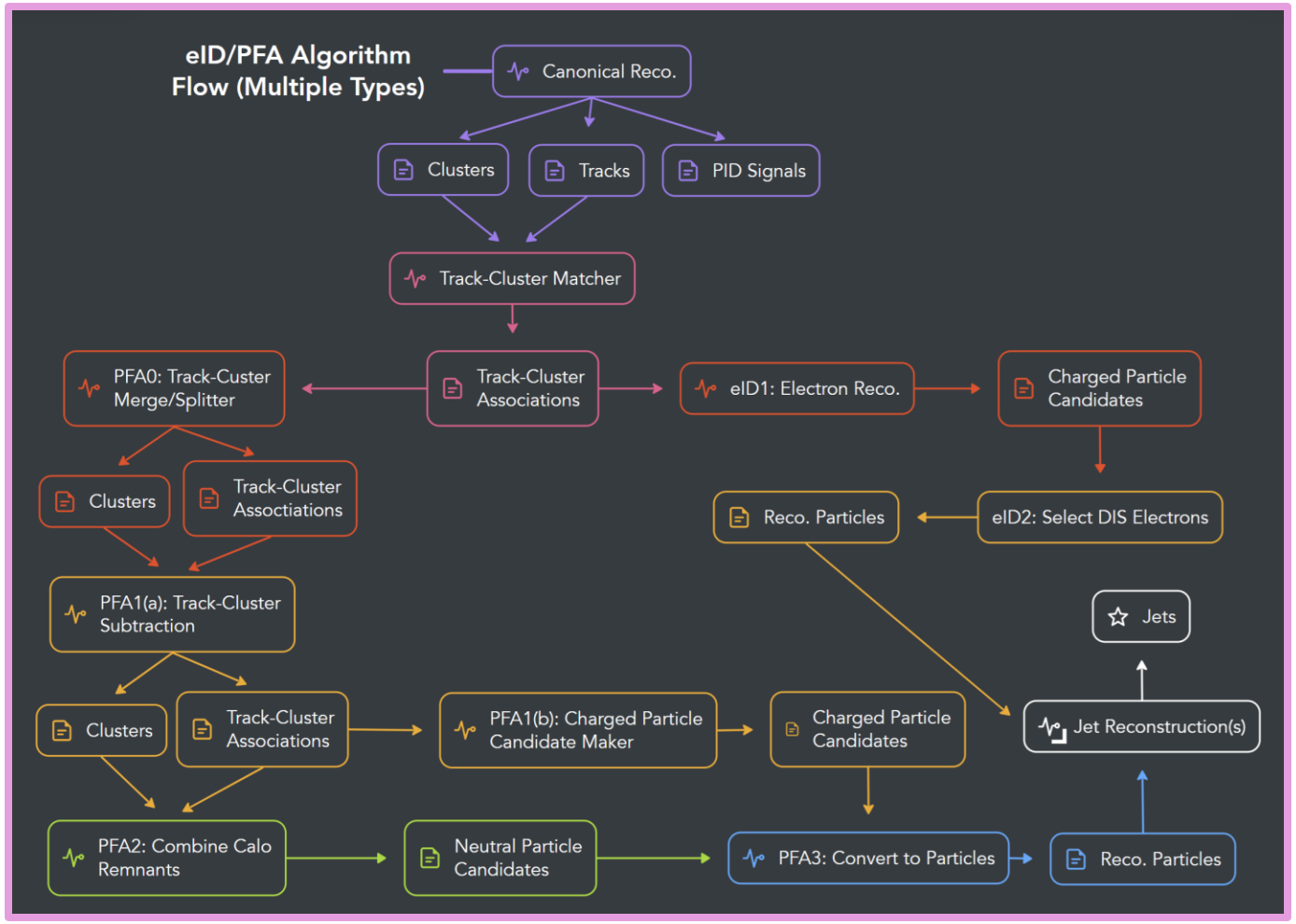
Xilinx KCU



Test beam prototype

Integration with ePIC reconstruction

- Calorimetry is a critical component of the ePIC reconstruction process
- Tracks and clusters are matched to identify electrons through E/p measurements
  - Used to select DIS electron – crucial to many EIC measurements!
- Used in particle flow to holistically reconstruct particle energy and identification



Conclusions

- A successful ePIC detector requires several calorimeter systems to form a hermetic barrel
- Each tuned to specific strengths demanded by that region's physics
- All calorimeters **meet or exceed** the performance requirements!
- Design and testing is well underway, with several test beams completed