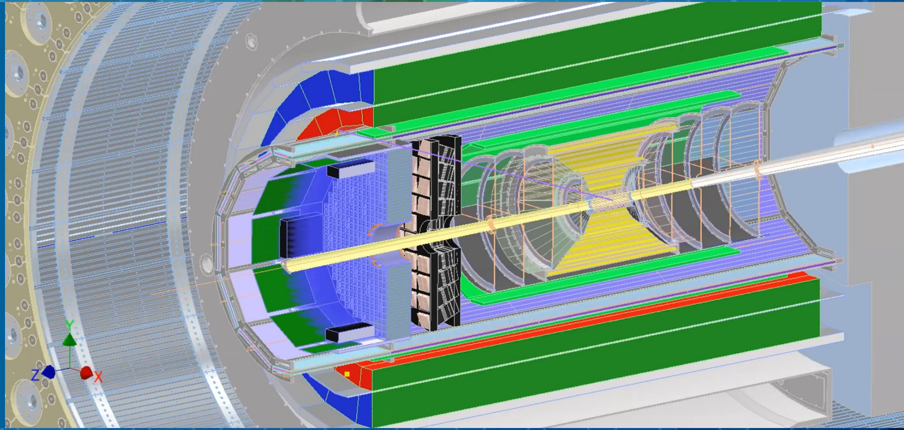
ePIC Barrel ECal Review, March 13-14, 2023

The Imaging Calorimeter for ePIC
Input and Intro



Sylvester Joosten
PHY, Argonne National Laboratory

Why electromagnetic calorimetry at EIC is hard

From the EIC Yellow Report: stringent barrel ECal requirements

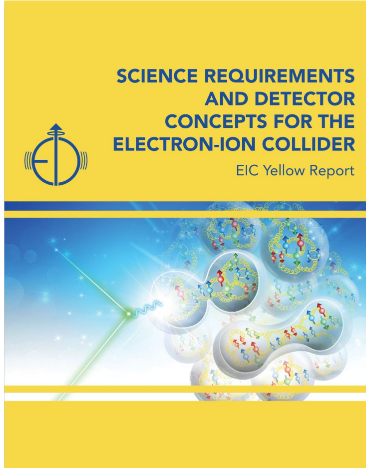
EIC is an **electron scattering** machine and identifying scattered electrons mainly depends on the electromagnetic calorimetry.

The electromagnetic calorimeter is the main detector for **electron-pion separation**. The inclusive physics program requires up to 10^4 pion suppression at low momenta in the barrel.

The exclusive program requires **decent energy resolution** ($< 7\%/\sqrt{E} \oplus 1\%$) **for photon energy reconstruction, and also the fine granularity for good** π^0-γ separation up to 10 GeV.

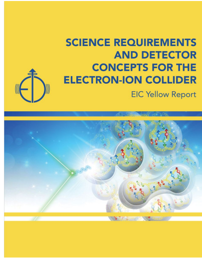
The bECal should be capable of measuring **low energy photons** down to 100 MeV, while having the range to measure energies well above 10 GeV

The system is space-constrained to very **limited space** inside the solenoid.



ECal Technologies in the Yellow Report

None of the discussed technologies meet all requirements for the barrel



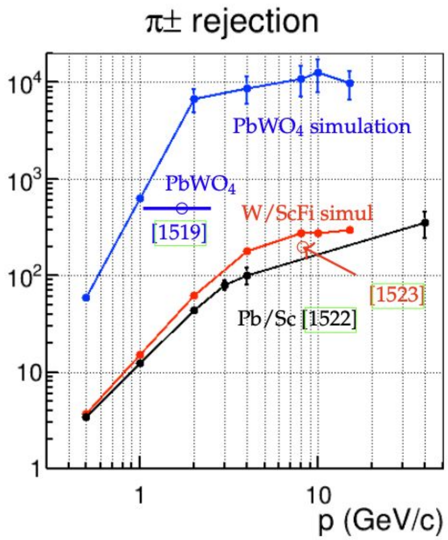
$PbWO_4$ crystal: could hit the marks, impossible to procure enough material (barrel too large), prohibitively expensive, needs precise temperature control.

SciGlass: Larger ratio of radiation length to hadronic interaction length X_0/λ_I leads to suboptimal electron-pion separation, long radiation length in limited space leads to energy leakage, large block size hinders position resolution.

W/ScFi (spacal): Too low electron-pion separation for barrel, even at low efficiencies, energy resolution too low.

Pb/Sc Shashlyk: Cannot meet stringent electron-pion separation requirement

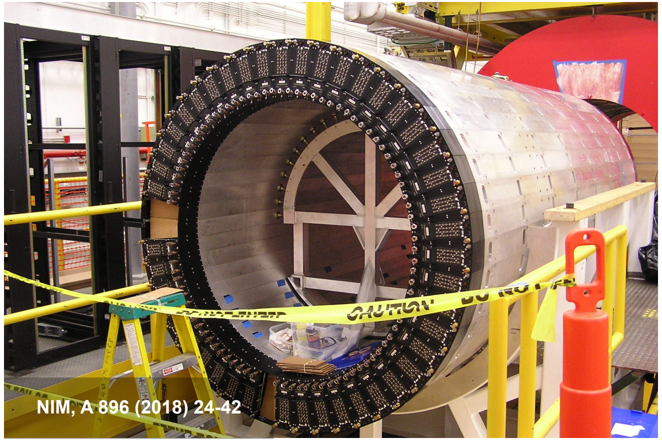
As of YR: No good solution that checks all the boxes. Electron-pion separation requirement in the barrel missed by almost two orders of magnitude risking important parts of the EIC scientific program



Standalone simulations (no field/material) and bench test results from YR.

We can do better!

Let's boost a high-performance sampling calorimeter with inexpensive silicon sensors for shower profiling



Start from mature layered Pb/ScFi technology with side-readout (same as the GlueX calorimeter) for state-of-the-art sampling calorimeter performance

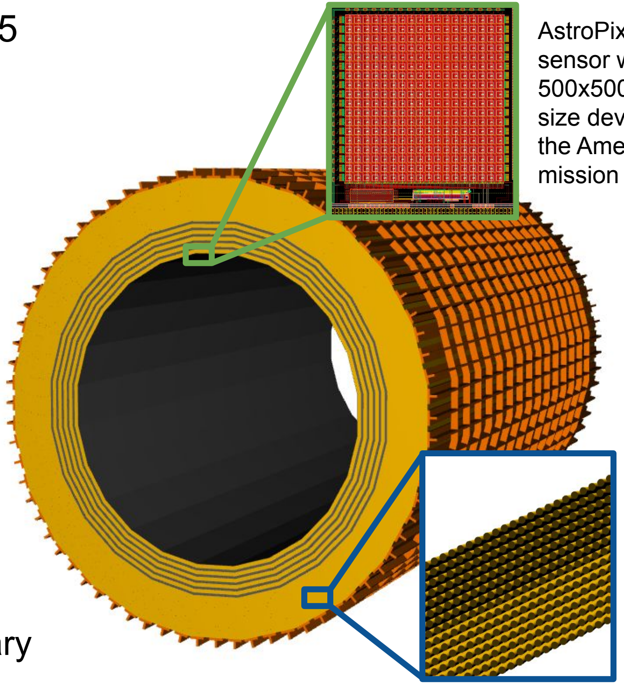
Insert layers of monolithic AstroPix sensors (inexpensive ultra-low-power silicon sensor developed for NASA) in the first half of the calorimeter to capture a 3-D image of the developing shower

Introducing the ePIC Imaging Barrel ECal

Addressing the unique challenges for the barrel region in ePIC

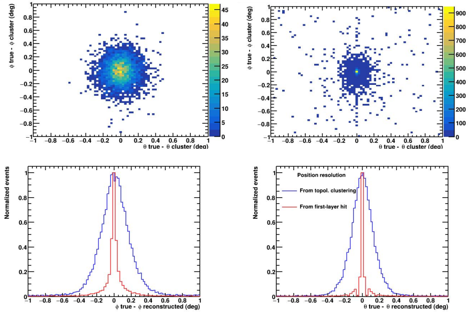
Hybrid concept: 6 layers of Astropix interleaved with the first 5 Pb/ScFi layers, followed by a large volume with the rest of the Pb/ScFi layers

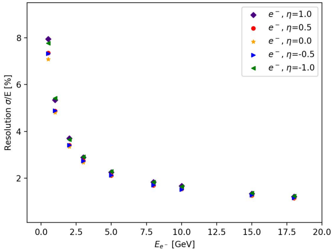
- ✓ Deep calorimeter (21 X_0) but still very compact at ~ 40 cm
- ✓ Excellent energy resolution (5.2% $/\sqrt{E} \oplus$ 1.0%)
- ✓ Unrivaled low-energy electron-pion separation by combining the energy measurement with shower imaging
- ✓ Unrivaled position resolution due to the silicon layers
- ✓ Deep enough to serve as inner HCal
- ✓ Very good low-energy performance
- ✓ Wealth of information enables new measurements, ideally suited for particle-flow
- ✓ Makes the tracking MPGD layer behind the DIRC unnecessary

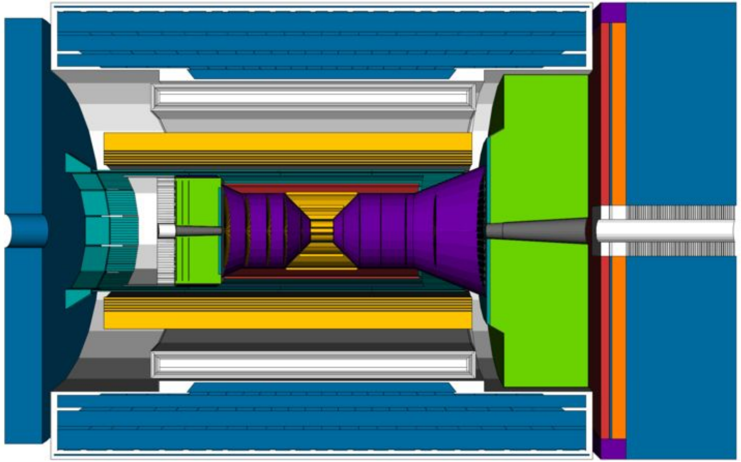


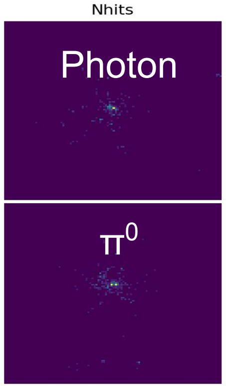
Checks all the boxes!

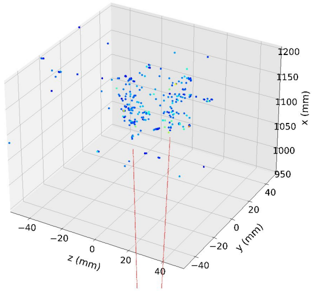
Select Performance Figures

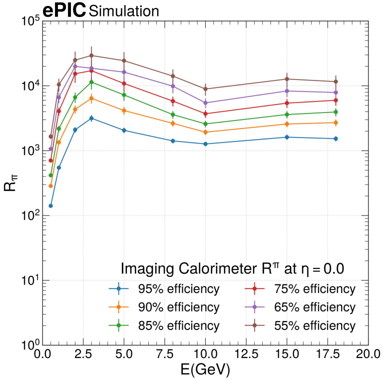


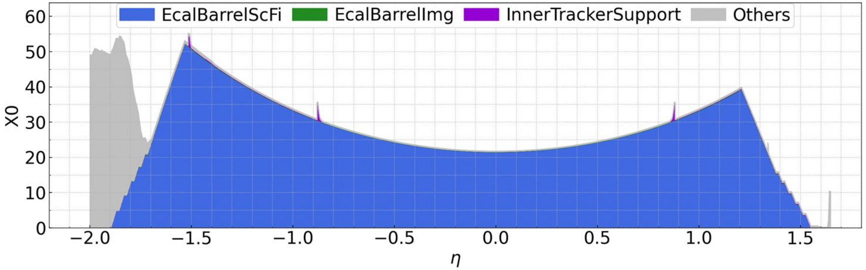












A large, international collaboration with extensive expertise in calorimetry, silicon sensors, and large detector systems

The Imaging Calorimeter for ePIC

EIC-Korea Consortium

EIC-Canada Consortium

European Institutions

US Institutions

INPUT INFORMATION:
Pb/ScFi Layers

Pb/ScFi layer technology

Our Pb/ScFi layers follow the GlueX Design

Energy resolution at GlueX: σ = 5.2% /√*E* ⊕ 3.6%[1)]

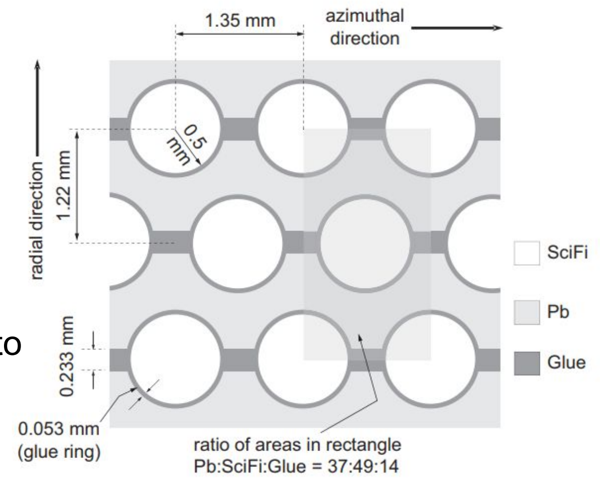
- GlueX has 15.5 X_0, and could not constrain the constant term (due to low energies)

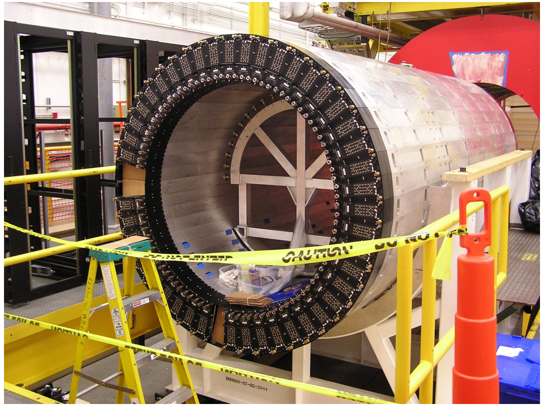
Position resolution in z: 1.1cm/√E [2)]

- 2-side SiPM readout, Δt measurement

Mature technology used in Barrel ECals (GlueX, KLOE)

- Detailed studies on **calorimetry performance**, including the light collection uniformity in fibers, light collection efficiencies, etc.
- **Module construction** (lead handling, swaging, Pb/ScFi layers assembly, module machining) fully developed for GlueX
  Z. Papandreou, https://halldweb.jlab.org/DocDB/0031/003164/
  - Equipment (swager machine, presses) still available for EIC!
- Assembly and installation of self-supporting barrel based on GlueX experience





1) Nucl. Instrum. Meth. A, vol. 896, pp. 24–42, 2018
2) Nucl. Instrum. Meth. A, vol. 596, pp. 327–337, 2008

Pb/ScFi calorimetry - R&D

Testing the layers at higher energies

Pb/ScFi tested extensively in for photon energies **E < 3.2 GeV**

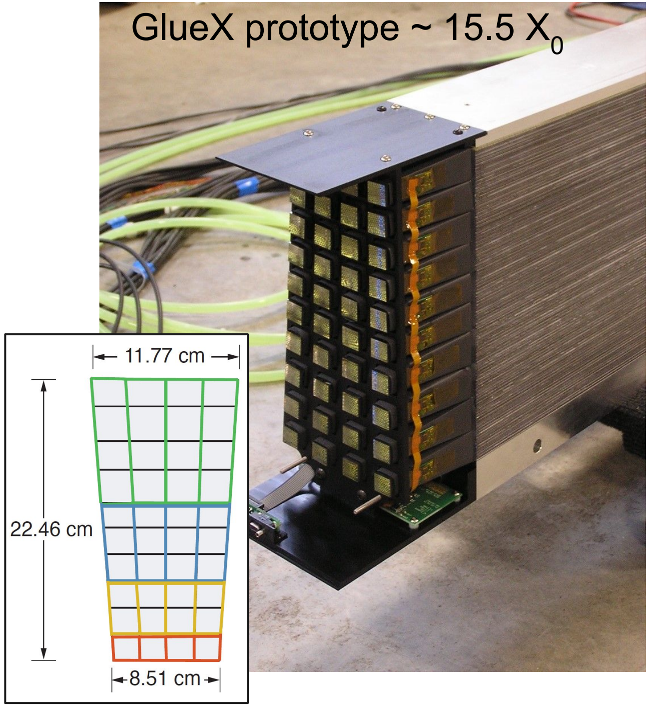
- At EIC we expect energies up to ~10 GeV for photons and up to ~50 GeV for electrons
- Higher-energy data is needed to constrain the energy resolution constant term

R&D goals with GlueX prototype

- Obtain **responses to electromagnetic and hadronic showers** to benchmark simulations and provide input to realistic **waveform analysis**
- This will be further used to optimize the detector design

Beam tests program

1. **Hall D, electrons** (energies up to ~6.2 GeV), happening right now (March 2023)!
2. Next phase: benchmark hadronic response at **FNAL with pion/electron** beams



- 60-cm long prototype
- 40 light guides on either side
- 40 SiPMs per side

Supported by EICGENR&D 2022 #25

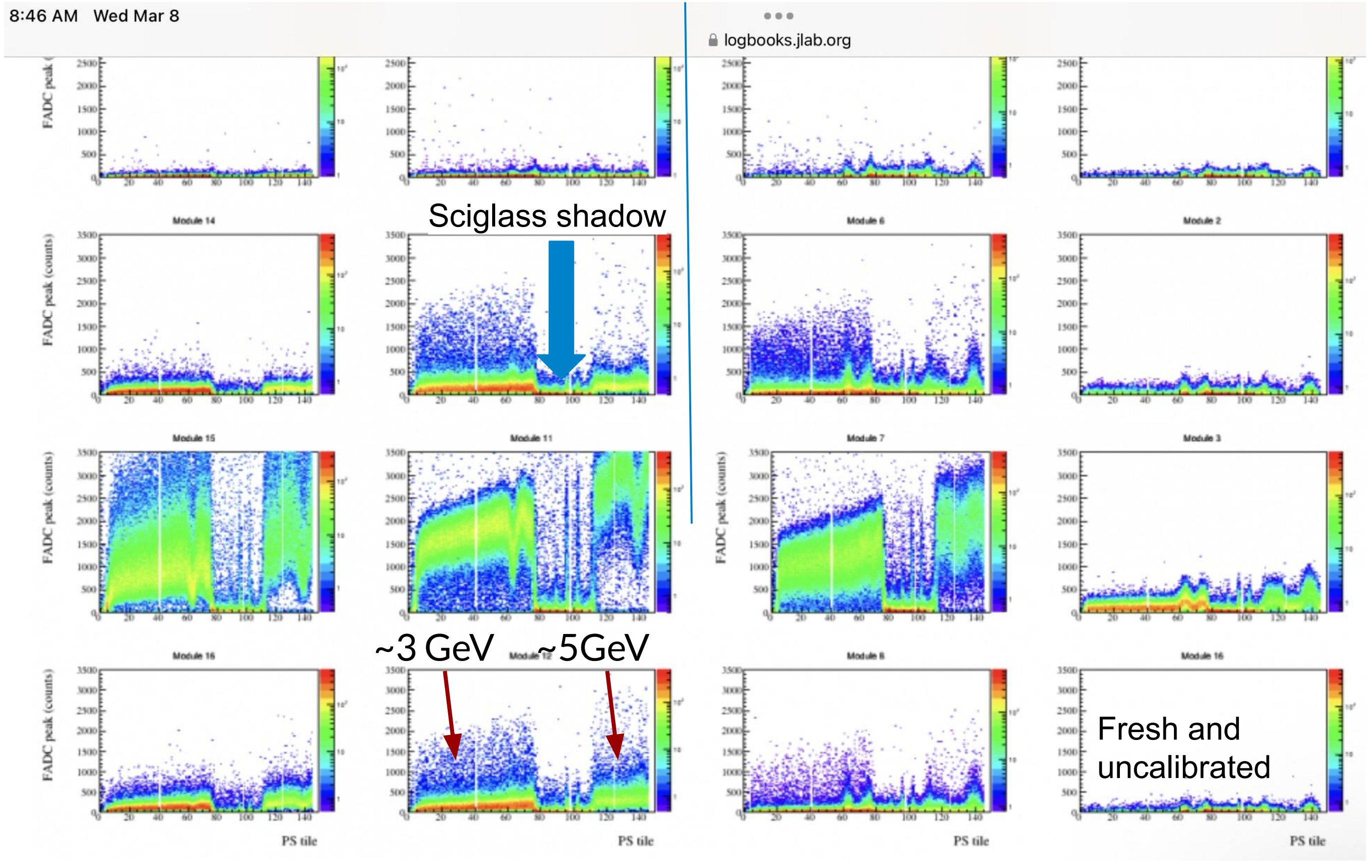
Mini BCAL test setup in Hall D

- Detector being cabled by Regina students, behind the GlueX Pair Spectrometer on upstream platform
- Can view 3-6 GeV positrons
- 70-cm-long prototype, $16X_0$
- 74-75 V bias on SiPMs
- No cooling of SiPMs (21 C ambient)
- 40 SiPMs per side
- 16 FADC readouts per side

University of Regina

Argonne NATIONAL LABORATORY

Mini BCAL test going well



3-6 GeV positrons

INPUT INFORMATION:
AstroPix layers

Imaging layers technology

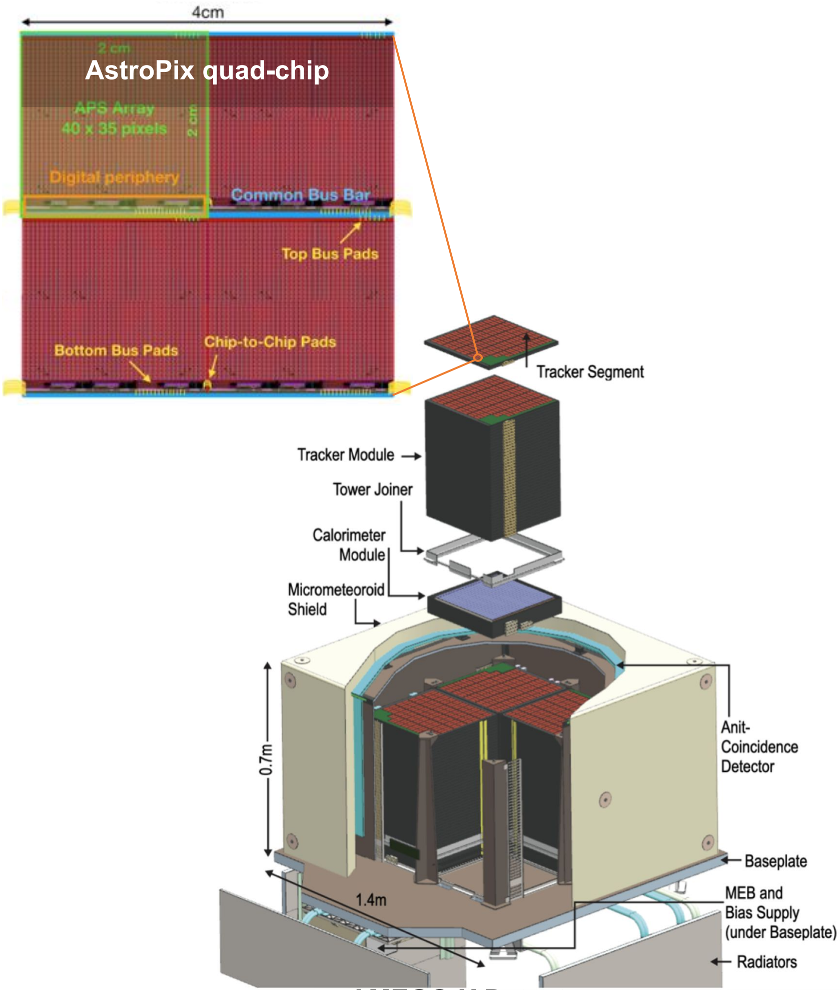
Leveraging an existing sensor

Imaging layers will use the AstroPix sensors

- Developed for NASA AMEGO-X space mission
- CMOS sensor based on ATLASpix3
  arXiv:2109.13409 [astro-ph.IM]

Key features:

- Very low power dissipation (will be used in space!)
- Good energy resolution (thick silicon sensor)
- 500 μm pixel size (~144μm resolution)
- Perfect for use in calorimetry!
- First silicon layer has sufficient resolution to be used as tracking layer behind the DIRC (replacing the MPGD layer)



AMEGO-X Detector
arXiv:2208.04990 [astro-ph.IM]

AstroPix Sensor Layer Size

The Imaging Barrel ECal will be a large silicon detector:

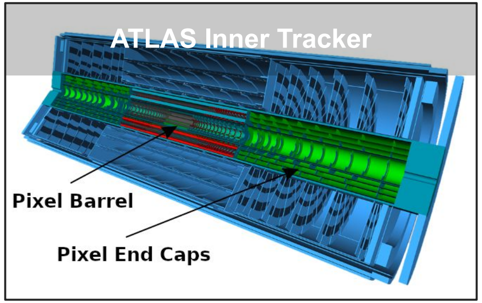
- 6 layers in the ePIC barrel will cover **-1.5 < |eta| < 1.2**
- The Astropix sensor area will be about **140 m^2**
- 24 staves: ~2.5×10^3 sensors per stave, ~3.7×10^6 pixels per stave, ~4.6×10^5 pixels per aggregator area (numbers per layer of AstroPix)

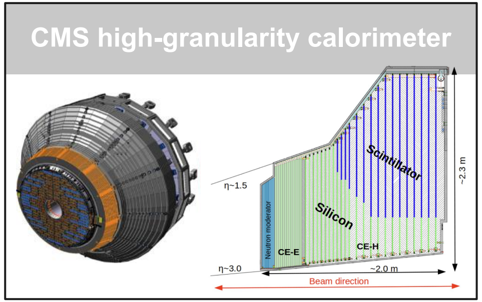
Other comparable Si detector arrays in advanced stage (large scale prototypes)

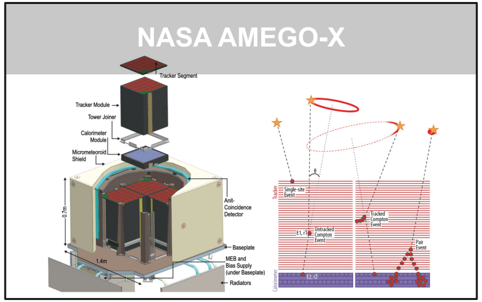
- ATLAS Inner Tracker - silicon strips[1] (ITk pixel) 160 m^2 (50 million channels)
- CMS high granularity calorimeter [2] ~ 600 m^2 (6.5 million channels)
- **AMEGO-X NASA mission**:
  - Will use a 40 m^2 AstroPix-based tracker, to be sent into space
  - We plan to use chips off-the-shelf: **no design modifications**.

Advantages of AstroPix with respect to pixels used in e.g. ATLAS

- AstroPix has very low power consumption (used in space)
  - 100 times smaller power consumption per cm^2 than ATLASPix pixels
  - AstroPix is a monolithic sensor - less complicated structure
  - No bump bonding - less risk of damaging sensors







[1] arXiv:2105.10367, ATLAS ITk Pixel Detector Overview
[2] arXiv:1802.05987, The CMS High-Granularity Calorimeter for Operation at the High-Luminosity LHC2

Imaging layers - R&D

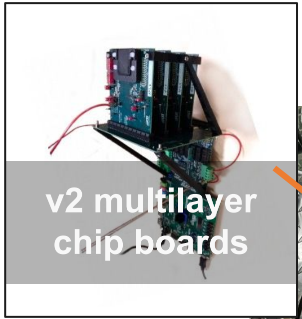
Extensive R&D program in FY23/24

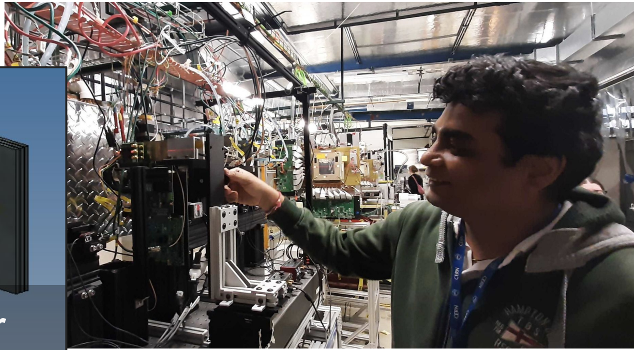
Benchmark **AstroPix v2/v3 sensor** in an electromagnetic calorimeter environment

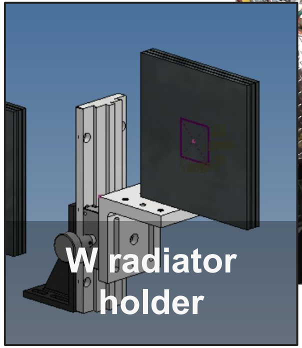
1. **Multilayer chip tests** in FNAL with protons, pions and electrons, tests with tungsten radiator, readout aspects (ANL LDRD grant)
   - ➢ Ongoing (February and May 2023)
2. **Irradiation test** in the FNAL ITA Facility (ANL LDRD grant)
3. Readout of multilayer chips with the **Felix board** (collaborative effort with the ANL HEP and NASA community)

FY24 Plan

1. Response to electromagnetic/hadronic shower with multilayer AstroPix v3 prototype







INPUT INFORMATION:
Simulation Studies

Realism of simulation studies

All simulation studies used the **official ePIC simulation productions (13.03.00)**

AstroPix simulation conditions:

- Digitization on the level of AstroPix pixel with 4σ threshold cut
- No cracks/non-sensitive regions in the sensor coverage assumed in simulations
- In simulations we explore the possibility of using the AstroPix sensor off-the-shelf
- Layer thickness 0.155 cm + 1 cm of air (cooling):

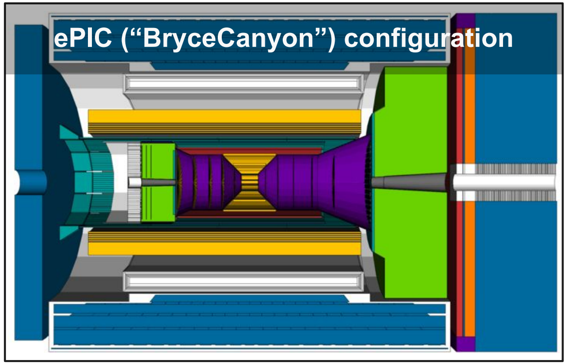
Pb/ScFi simulation conditions

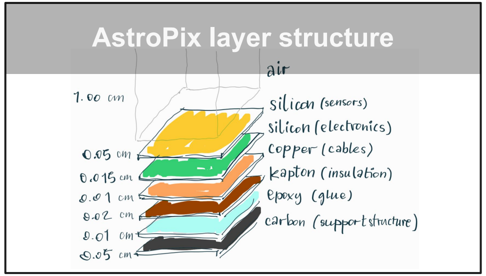
- Digitization on the level of SiPM grid, with dynamic range and pedestal subtraction
- Assumed ~ 2 cm x 2 cm grid size
- While we plan for a 2-side readout for spatial resolution, we currently use one-sided energy response for island clustering[1], adding effective z-segmentation through the DD4hep description.
- Birks constant for ScFi kB = 0.126 mm/MeV in GEANT4

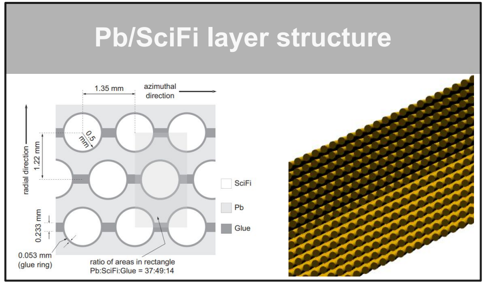
Background hits and noise are still missing[2]:

- Background event merging (effect expected to be small)
- Realistic detector noise integration at the digitization level

Detector geometry includes full material details (fiber cladding, glue, silicon services, …), except for the carbon-fiber trays holding the silicon







[1] Description of clustering algorithms in backup slide

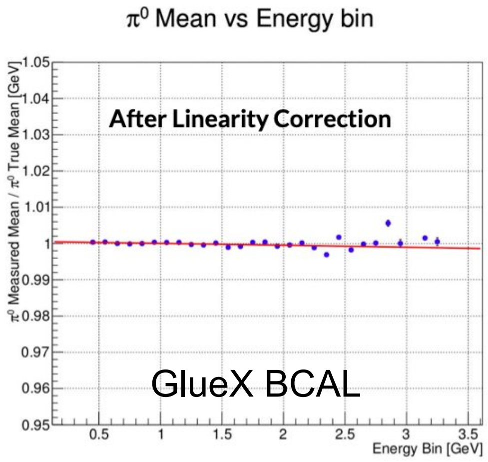
[2] This is true for all ePIC detector subsystems, and a high priority item of the a collaboration-wide background Task Force

Pb/ScFi

Effect of light collection uniformity in the Pb/ScFi layers

The impact of light collection uniformity has been extensively studied at GlueX (a running experiment!)

- Naked fibers were random-tested for each shipment, performance agreed with the manufacturer numbers
- Attenuation length is 385 cm (RMS 7%), light-yield measured with a ^{90}Sr source
- Cosmics tests in the prototype consistent with the naked fibers
- Small fluctuations in light yield in GlueX BCAL **are easily calibrated away** (bootstrap π^0 gain calibration) - see the picture

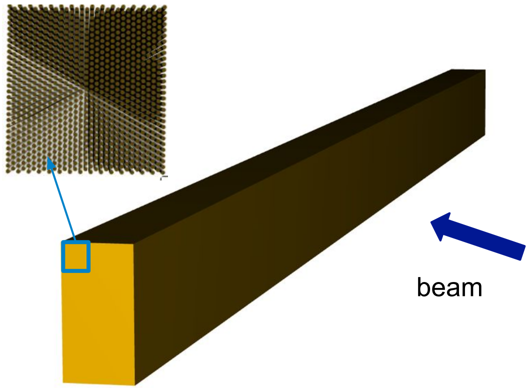


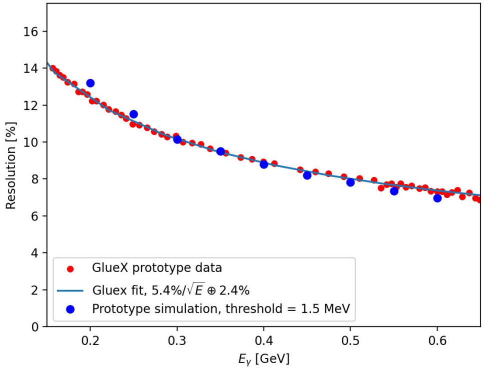
Bottom-line: System well understood, has been in production for years. **Effects from light collection uniformity minor** in an almost identical setup.

- We will verify this through full simulations with light propagation, and can include effects + corrections in the digitization and (future) calibration steps.

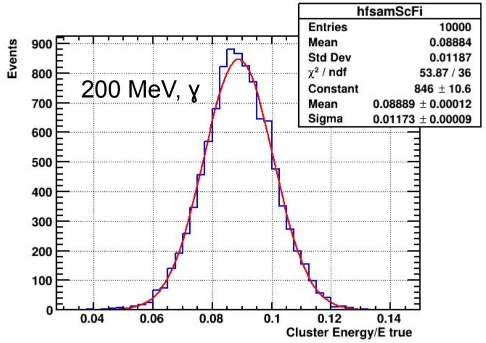
Comparison with GlueX prototype data

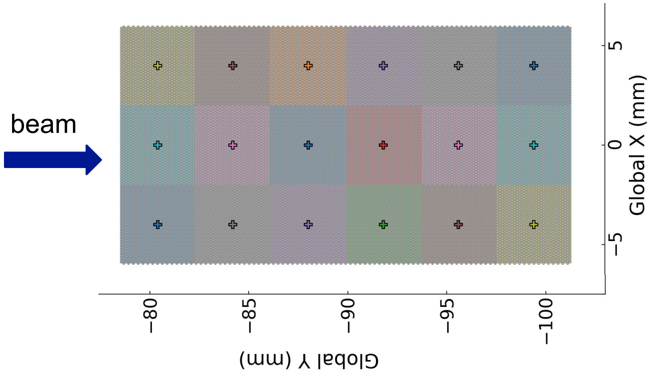
Simulation of GlueX prototype and readout scheme in ePIC simulation environment





Reconstructed Energy/True energy





- Data from test in Hall B with full size one stave prototype
- Realistic geometry implementation and simulation of the prototype with readout

- Low energy data described quite well by the simulation
- Energies up to ~6 GeV being tested in the ongoing test at Hall D

Pb/ScFi

Confidence in the hadron rejection simulation?

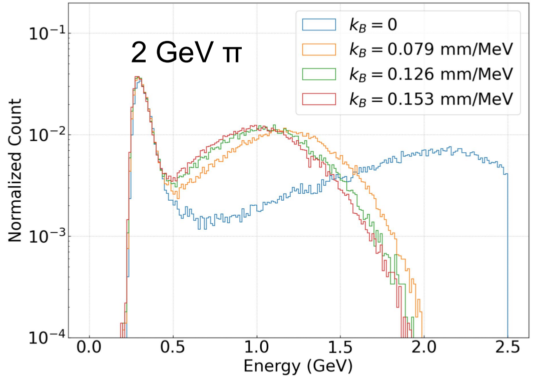
Realistic Pb/SciFi matrix implementation (SciFi, glue, cladding), digitization and reconstruction included

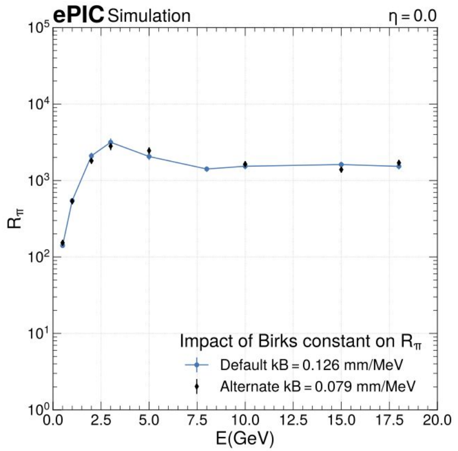
- Have additional stand-alone implementations of geometry: Regina group (exact), Argonne group (near-exact)

FTFP_BERT physics list and 0.126 mm/MeV Birks constant

- The energy response to pions in Barrel ECal changes ~38% when changing the Birks constant to (too low) value of 0.079 mm/MeV
- Our pion rejection results on rejection are resilient: the e/π separation is **strongly driven by the imaging layers** (shower topology)
    - AstroPix beamtime ongoing (Feb and May at FNAL)

Ongoing R&D program at JLab and FNAL will help benchmark our simulation to ensure maximal realism.





Simulation plans

Next priorities for simulations (rough timeline), if selected

1. Detailed simulation with light propagation in the ScFi (can be standalone)
2. Background studies
3. More complete implementation of the silicon sensor staves and CF drawers
4. Impact of non-sensitive areas around AstroPix chips (ongoing)
5. 2-sided readout for the Pb/ScFi
6. Optimization studies on the readout scheme
7. Iteration between simulation and the mechanical model of the calorimeter
8. Reconstruction studies (cluster matching, full event reconstruction, clustering algorithms, cluster merging, …)
9. Benchmark simulation against R&D tests
10. Performance impact of the imaging calorimeter on the hadronic calorimetry
11. Realistic calibration (collaboration-wide)

Spring 23

Summer 23

Fall-Winter 23

Summary

The detector requirements for the Barrel ECal, driven by the EIC physics program, are **extremely stringent.**

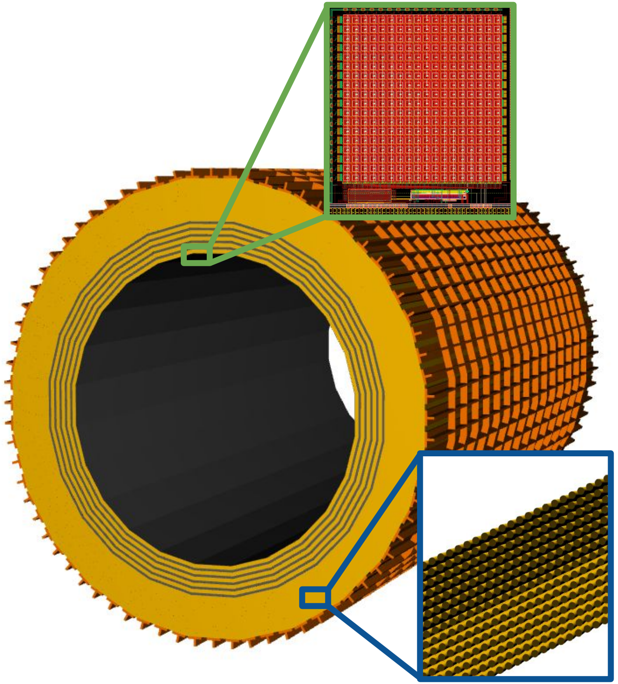
The Imaging Barrel ECal promises **unmatched performance for electron-pion separation and position resolution**, fits in the limited space without compromising on performance, and exceeds all other requirements to enable the EIC physics program.

The detector combines **two mature technologies**, Pb/ScFi and off-the-shelf monolithic silicon sensors, to enable full 3-D shower imaging.

Our team has proven expertise in calorimetry, silicon sensors, and large detector systems.

A multi-faceted R&D program is well underway, to mitigate remaining open questions in our simulation studies.

The proponents of this detector are highly active in the simulation software development for ePIC.



BACKUP

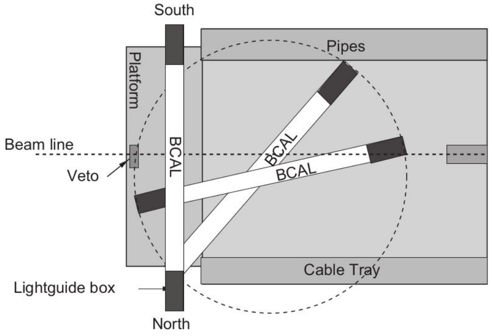
CHARGE

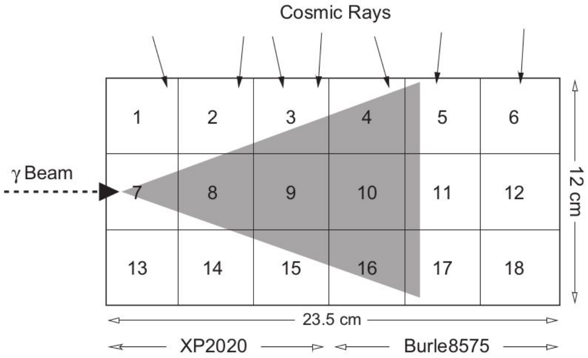
1. *Reminder of the proposed detector configuration for use in the ePIC detector.*
   Slides 2-7, 23
2. *Input information:*
   a. *R&D, prototypes and their tests: done so far, ongoing efforts, future planning (with timelines); results from prototypes and their tests.*
      Slides 10-12, 16
   b. *Pertinent information on similar technology/design that is used by other experiments incl. R&D efforts (literature, conferences).*
      Slides 9, 14-15
   c. *Simulation studies: already performed, ongoing and planned (with timelines); results from the simulations; particular care in*
      Slide 19-22
      i. *showing how realistic the parameters used in simulations are and*
         Slide 18, 20-21
      ii. *reporting what is missing for a fully realistic simulation (backgrounds, specific event categories, ...)*
         Slide 18-19
   d. *Does the simulation take into account the realistic light collection uniformity, response of the selected photosensors and related FEE?*
      Slide 18-20; future plans in slide 22

GlueX full-size prototype test

Test at JLab Hall B with **full size one stave prototype**, secondary **photon beam**, **~0.15-0.6 GeV**, **90º angle**

NIM, 596 (2008) 327–337, Performance of the prototype module of the GlueX electromagnetic barrel calorimeter





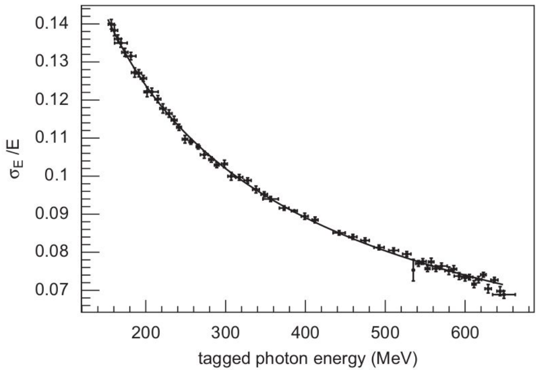


Fig. 11. Energy resolution vs. E_{BEAM} for photons for $\theta = 90^{\circ}$ and $z = 0$ cm. The fit gives $\sigma_E/E = 5.4\%/\sqrt{E(\mathrm{GeV})} \oplus 2.3\%$. The fit of Fig. 10 corresponds to the 40th datum from the right (19th from the left) in this figure.

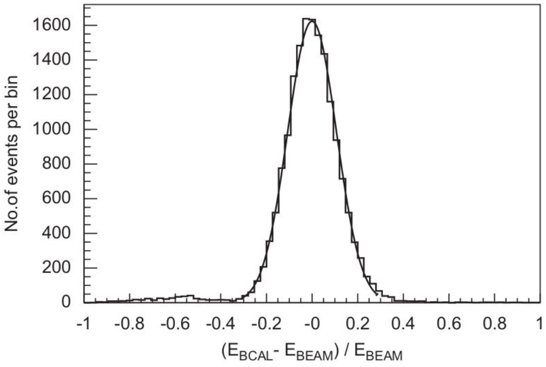


Fig. 10. The calibrated spectrum for D is shown for timing counter 40, corresponding to a beam energy of 273 MeV. The solid line is a Gaussian fit to the data.

Clustering

In the old Juggler analysis framework, the clustering was done by

1. digitization -> simulation hits to readout signals
2. readout reconstruction -> readout signals to energy/timing/position/etc (calibration)
3. proto-clustering -> group hits following certain algorithms
4. cluster reconstruction -> reconstruct position/energy/etc from group of hits

Two clustering algorithms were available now

1. Island clustering for 2D hits (this one is ported to EICRecon)
2. Topo clustering for 3D hits (this one still needs porting)

Island Clustering

Group all neighbouring hits

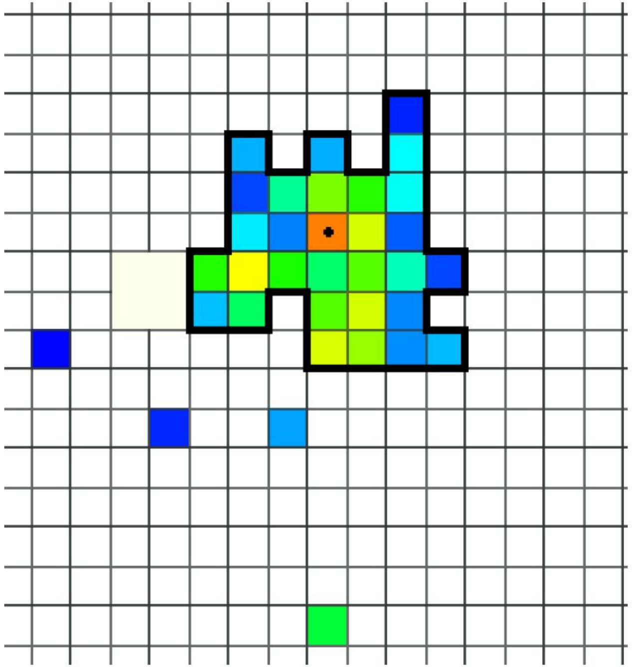
Parameterized conditions for finding neighbors

Distance in local-XY, local-XZ, local-YZ,

local-XY scaled by cell dimensions,

global eta-phi, global R-phi

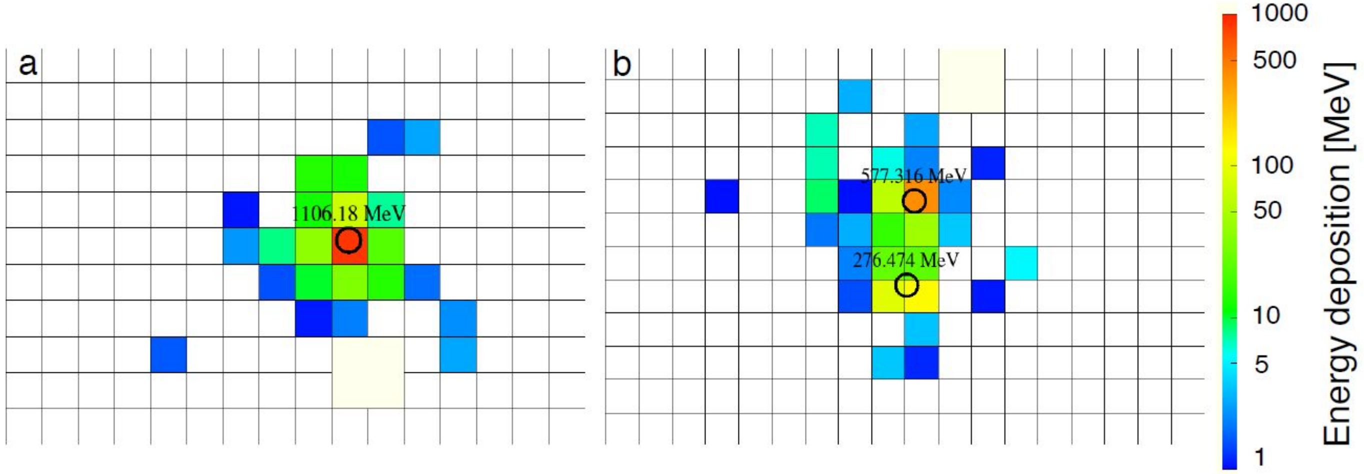
Parameterised minimal energy to be qualified as cluster center, and minimal energy to participate clustering



Island Clustering Splitting

Cluster splitting is available for Island Clustering

- Split based on Local maxima that are qualified as cluster center
- Hits energy split based on local maxima's energies and distances



Topo Clustering

Similar to Island clustering but works for hits from several layers, currently used for imaging layers

Hits at the same layer, local-XY

Hits from different layers, layer id difference and global eta-phi

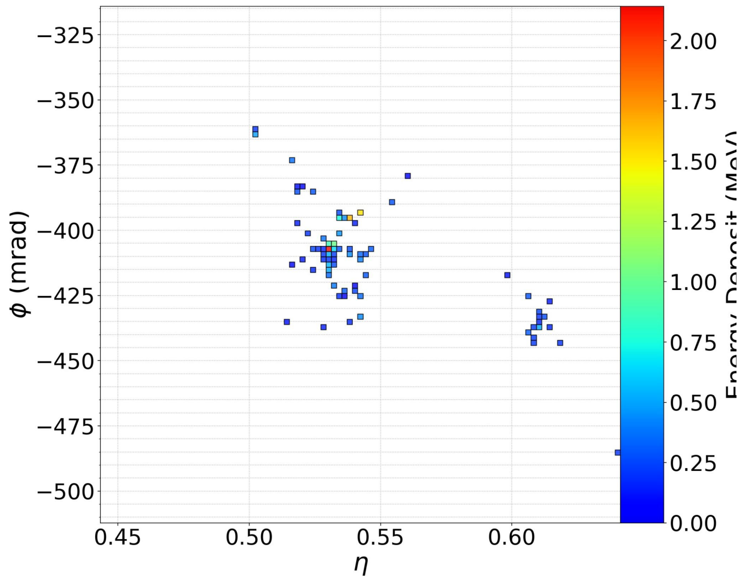
Hits from different sectors, global distance

No splitting implemented currently

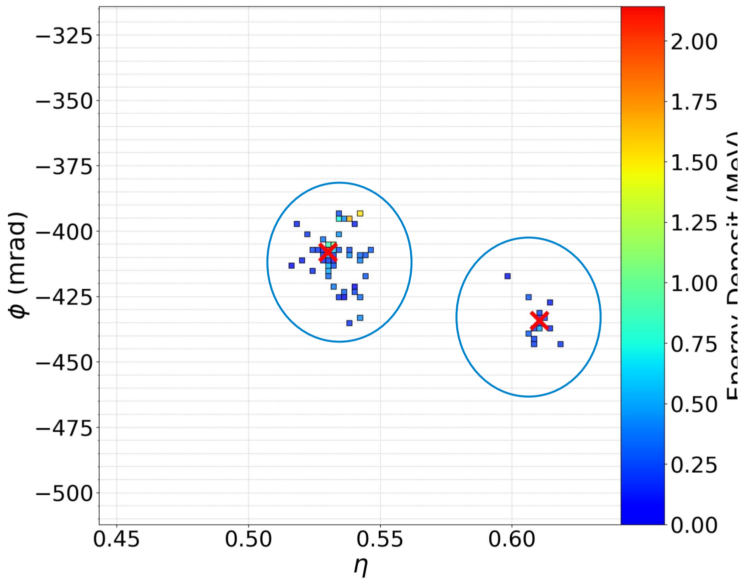
- Mostly MIP signals in imaging pixels

3D Clustering Samples

All Hits

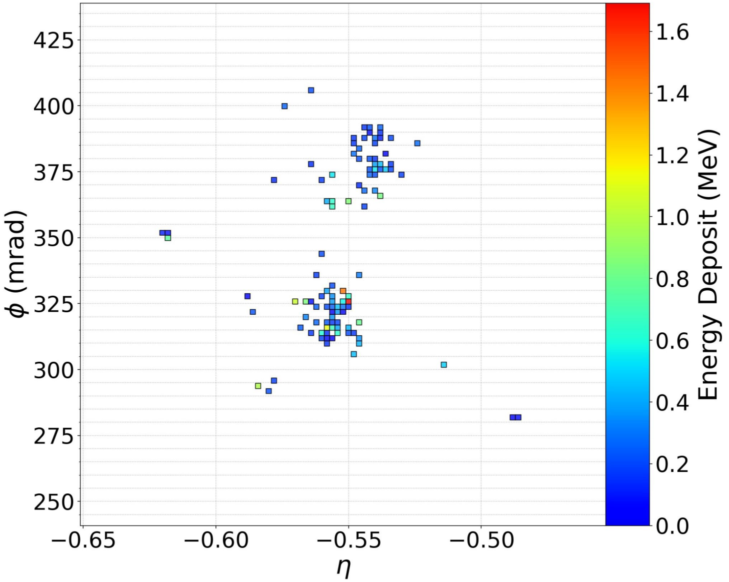


Clusters and True gamma positions

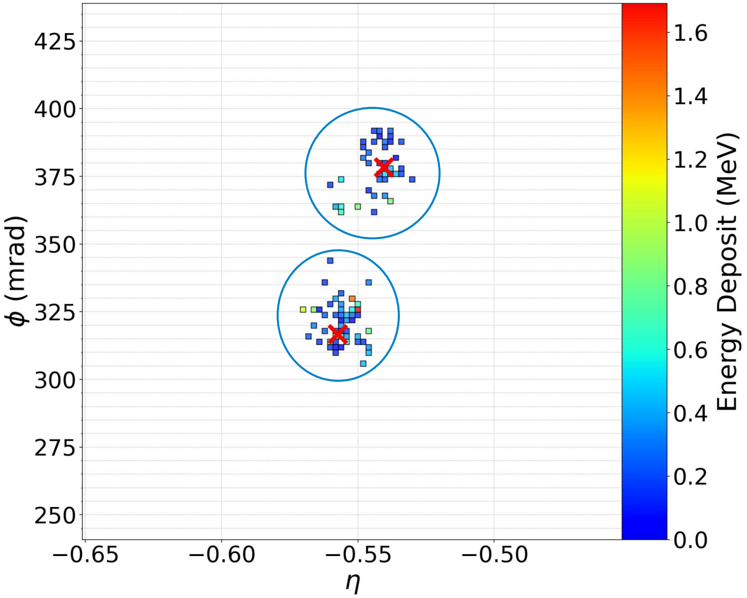


3D Clustering Samples

All Hits



Clusters and True gamma positions



Imaging layers technology

Imaging layers based on AstroPix sensors

- Developed for AMEGO-X NASA mission
- CMOS sensor based on ATLASpix3
  arXiv:2109.13409 [astro-ph.IM]

Key features:

- Very low power dissipation
- Good energy resolution
- 500 µm pixel size

AstroPix chip R&D:

v1 (4.5×4.5 mm^2, 200 µm pixel)

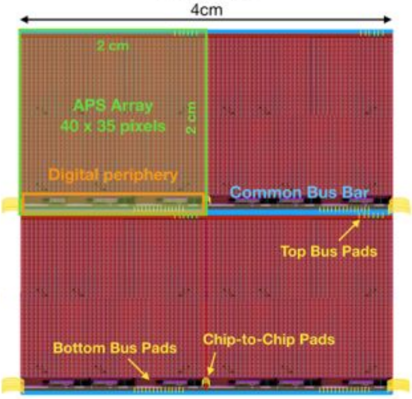
v2 (1×1 cm^2, 250 µm pixel)

- Both chips tested with γ,β sources and in 120 GeV proton beam
- See results in arXiv:2209.02631 [astro-ph.IM]

v3 (2×2 cm^2, 500 µm pixel, **quad chip**)

- Expected ready for tests in **January 2023**

Quad chip v3



v2 carrier board

arXiv:2208.04990 **[astro-ph.IM]**

Targeted AstroPix performance goals

Pixel size	$500\,\mu m \times 500\,\mu m$
Power usage	< 1 mW/cm^2
Energy resolution	10% @ 60 keV (based on the noise floor of 5 keV)
Dynamic range	~ 700 keV
Passive material	$< 5\%$ on the active area of Si
Time resolution	25 ns
Si Thickness	$500\,\mu m$

Planned choice of the foundry TSI (v1-v3). With a large production order, AMS as a backup.

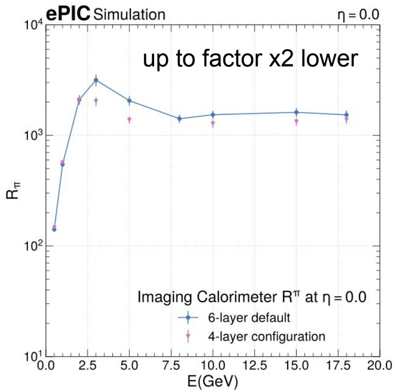
The case for 6 imaging layers

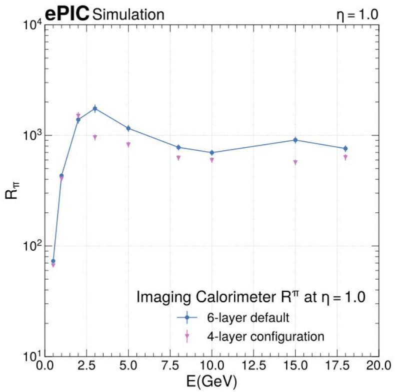
Default 6-layer configuration vs an equidistant 4-layer configuration

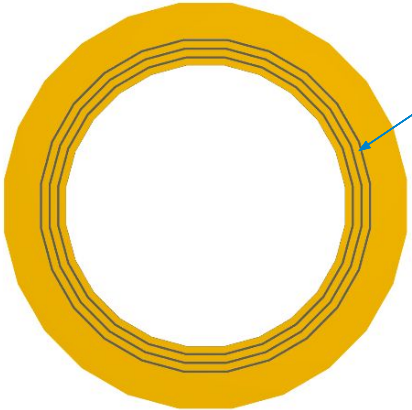
- Most pion rejection performance loss in **middle energy range**, where the barrel **ECal is the most crucial**
- **Exaggerated reduction at larger *η*** due to inflated radiation length between layers. Lose much of the shower imaging capabilities, impacting also photon-pion separation
- **Impacts Pb/ScFi energy splitting**, which relies on the cluster topology and energy resolution for nearby clusters in the same azimuthal region
- **Impacts the energy resolution** of the imaging part of the calorimeter, and **position resolution of gammas**

Bottom-line:

- Removing 2 layers reduces performance and redundancy for relatively small cost savings
- A staged approach to installing the imaging layers could be a possible risk mitigation strategy







2.52 X_0 separation between imaging layers at η = 0 (1.45 X_0 separation in default geometry)

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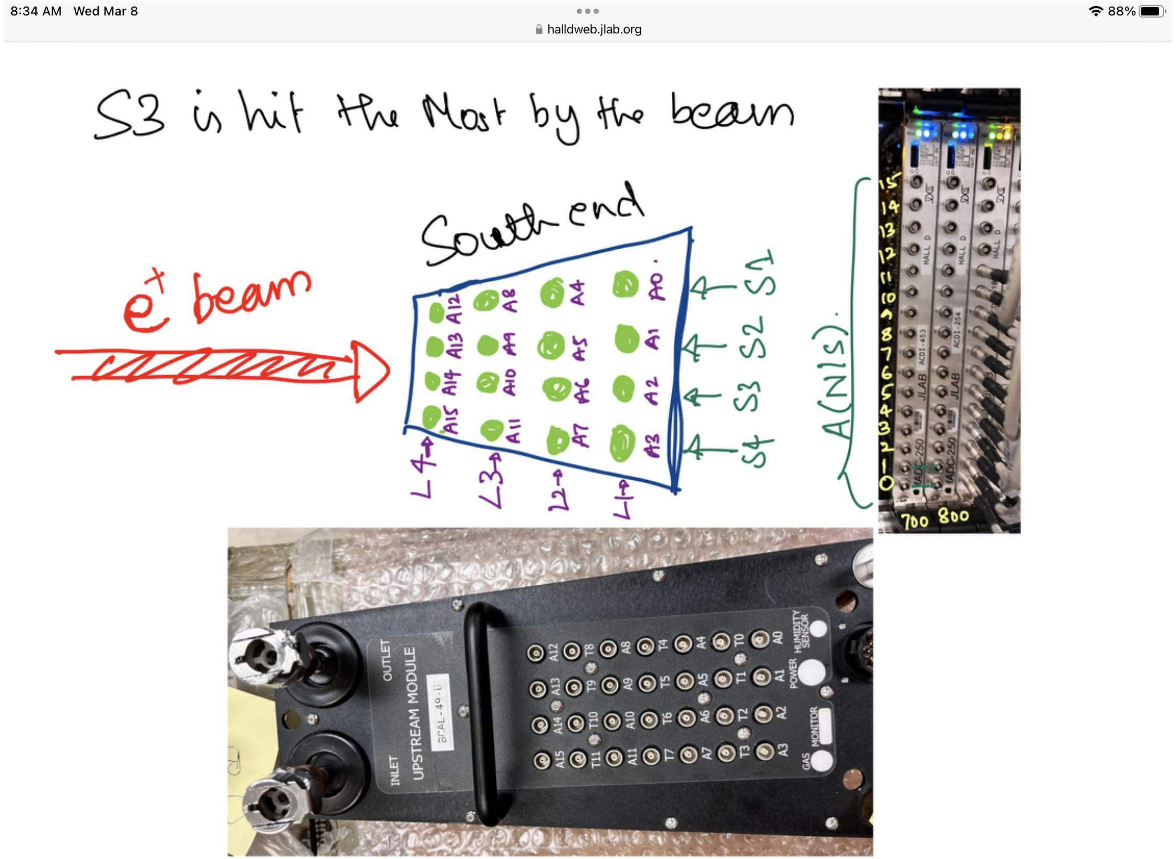
Mini BCAL Channel Assignment



Mini BCAL Scalers

3rd bin in each group of 4, mostly intercepts the positrons