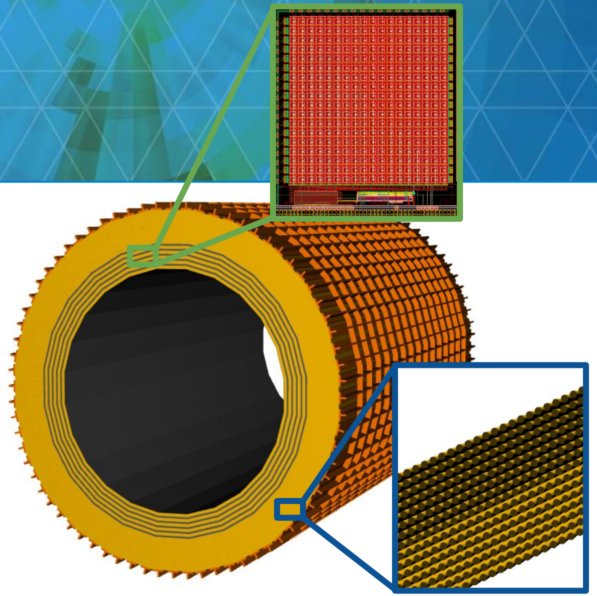
ePIC Collaboration Meeting, July 26-29, 2023

The Imaging Barrel Electromagnetic Calorimeter



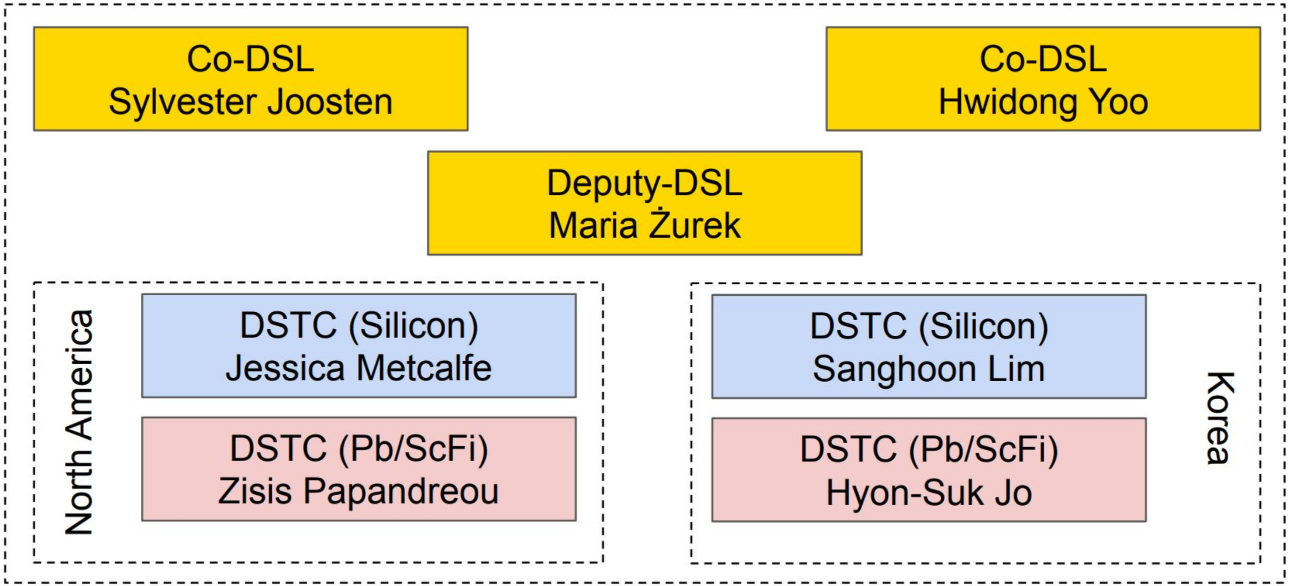
Maria Żurek *for the Barrel ECal DSC*
PHY, Argonne National Laboratory

About the Detector Subsystem Collaboration

Barrel ECal Meetings: https://indico.bnl.gov/category/485/ (See also 12 Jun - 16 Jun Workshop)

Mailing list: https://lists.bnl.gov/mailman/listinfo/epic-bemcal-l

Mattermost channel: det-cal-barrel-imaging



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Performance requirements on the BECal

From the EIC Yellow Report: stringent requirements

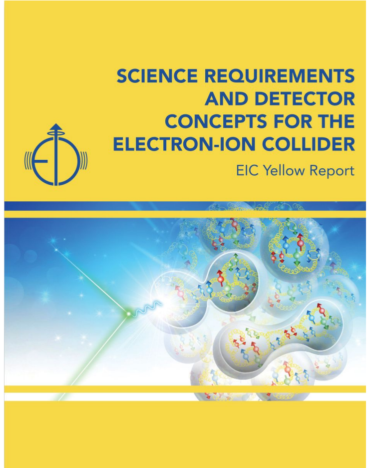
EIC is an **electron scattering** machine and identifying scattered electrons mainly depends on the electromagnetic calorimetry.

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/c.

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.

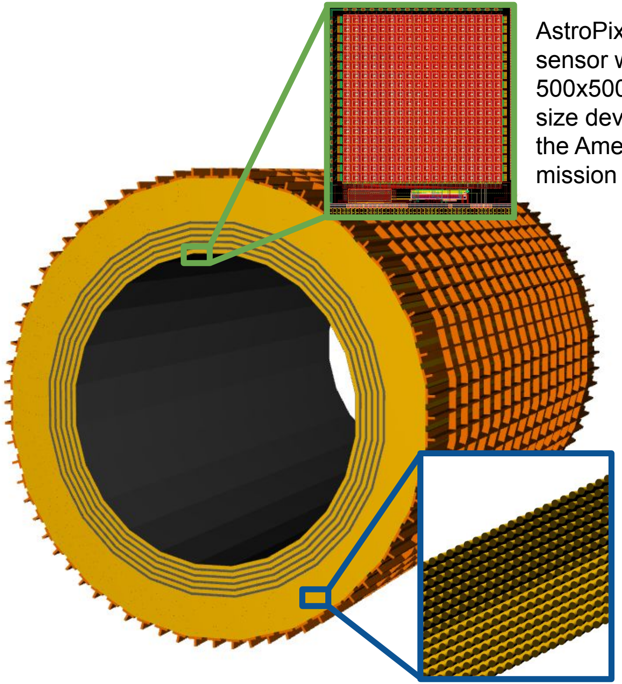


We easily meet the YR requirements

No significant changes in performance compared to the Barrel ECal review

~~6 layers~~ 4(+2) layers of Astropix sensors interleaved with the first 5 Pb/ScFi layers, followed by a large volume of bulk Pb/ScFi layers

- ✅ Deep calorimeter but still very compact at ~ 40 cm (17.1 X_0)
- ✅ 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
- ✅ Longitudinal shower profile from the Pb/ScFi layers
- ✅ Deep enough to serve as inner HCal
- ✅ Very good low-energy performance
- ✅ Wealth of information enables new measurements, ideally suited for particle-flow



AstroPix: silicon sensor with 500x500μm^2 pixel size developed for the Amego-X NASA mission

ScFi Layers with two-sided SiPM readout

Checks all the boxes!

SciFi/Pb layers technology

SciFi/Pb layers follow the **GlueX Barrel Calorimeter**
Energy resolution: $\sigma = 5.2\% / \sqrt{E} \oplus 3.6\%$[1)]

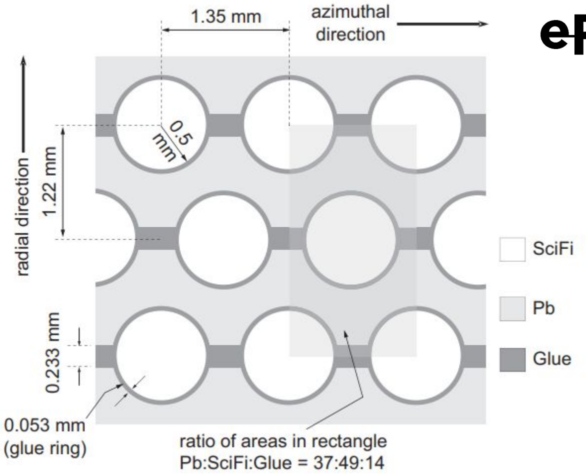
- 15.5 X_0, extracted for low energy photons < ~1 GeV

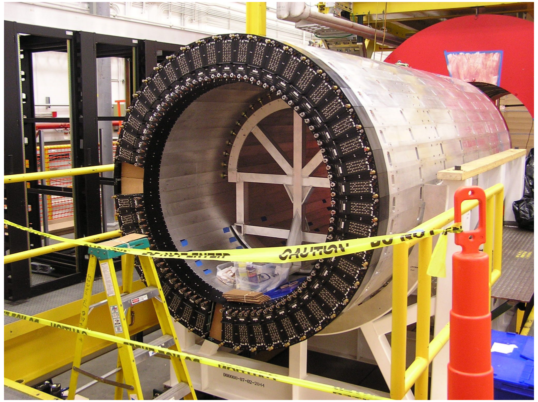
Position resolution in z: 1.1cm/√E [2)]

- 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, SciFi/Pb layers assembly, module machining) fully developed for GlueX
  Z. Papandreou, https://halldweb.jlab.org/DocDB/0031/003164/
    - Previously used equipment still available (swager machine, presses)
- Assembly and installation of self-supporting barrel based on sPHENIX





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

SciFi/Pb calorimetry - R&D

R&D goals with GlueX Baby BCal prototype

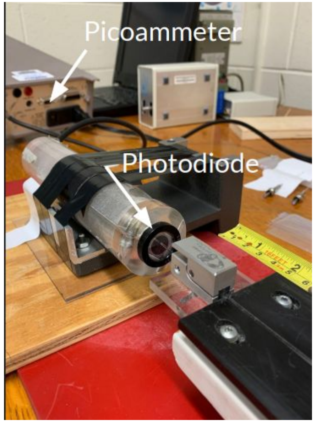
- **SciFi/Pb tested** extensively in for energies **E_γ < 2.5 GeV**
- **Higher-energy data** important to constrain the constant term of energy resolution
- Obtain **responses to EM showers** to benchmark simulations and provide input to realistic **waveform analysis - Hall D, electrons** (up to ~6.2 GeV), Q2 FY23 - analysis ongoing (J. Zarling talk)
- Planned tests in **FY24 with hadronic beams at FNAL** in integrated system with AstroPix sensor and thin SciFi/Pb layers to benchmark response to hadronic showers

R&D goals with fibers

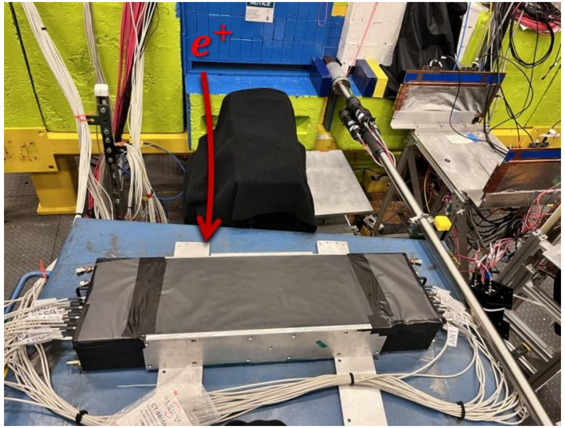
- **Light output and attenuation length** measurements at University of Regina with single- and double-clad fibers from Kuraray and Luxium - ongoing (M. Kerr talk)

Baby BCal ~ 15.5 X_0

Setup at Uni of Regina



Setup at Hall D, JLab



Imaging layers technology

Imaging layers based on AstroPix sensors

- Developed for AMEGOX 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
- Time resolution ~ 3.25 ns (V4)

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 ɣ,β sources and in 120 GeV proton beam
- See results in arXiv:2209.02631 [astro-ph.IM]

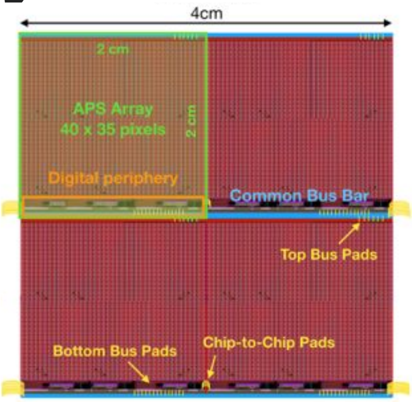
v3 (2×2 cm^2, 500 µm pixel, **quad chip**)

- Ongoing bench and beam test
- Main prototyping with this chip version

v4 (1×1 cm^2, 500 µm pixel)

- Engineering run submitted in April 2023

Quad chip v3



v3 carrier board

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

Targeted AstroPix performance goals

Pixel size	500 μm × 500 μm
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 μm

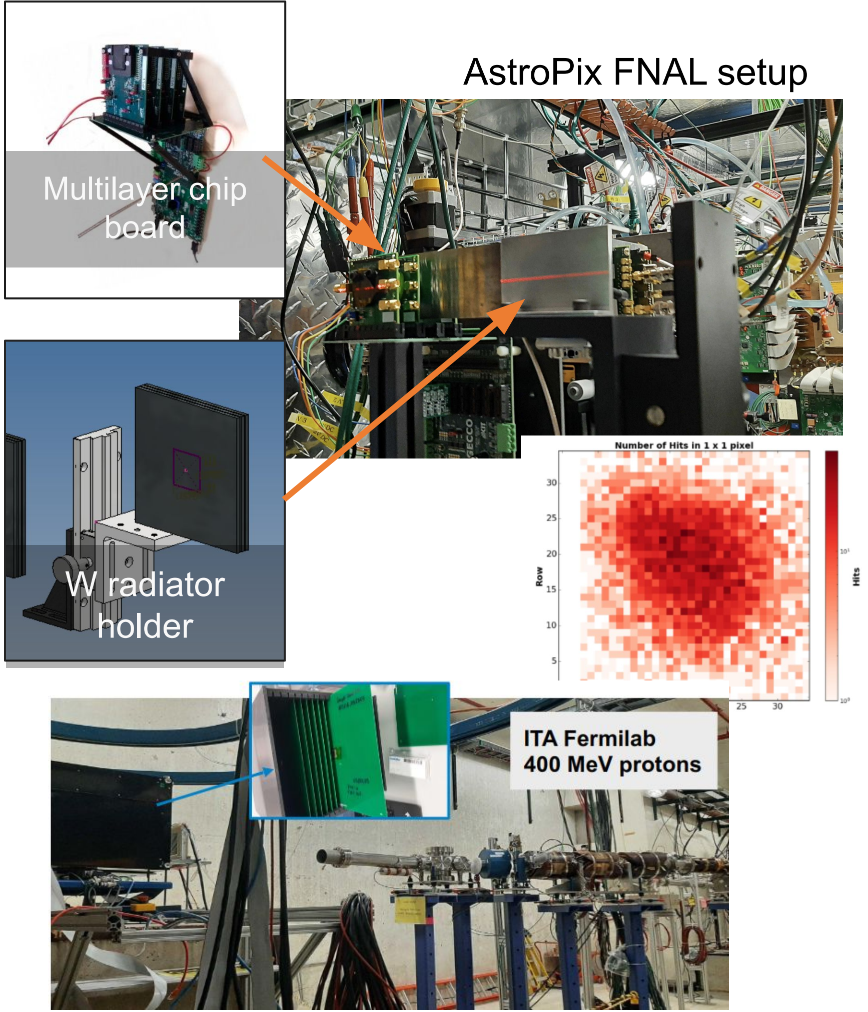
Imaging layers - R&D

R&D program in FY23

- Tests of **AstroPix v2/v3 sensor** in the EM calorimetry environment
    - **Multilayer chip tests** in FNAL with protons, pions and electrons, tests with tungsten radiator, readout aspects (ANL LDRD)
        - Beam tests in February and May 2023
    - **Irradiation test** in the FNAL ITA Facility (ANL LDRD)
        - 9 v2 and 3 v3 samples (passive) + 3 v3 samples (active)

FY24 Plan

- Response to electromagnetic/hadronic shower with multilayer AstroPix v3 prototype integrated with the SciFi/Pb layers and Baby BCal



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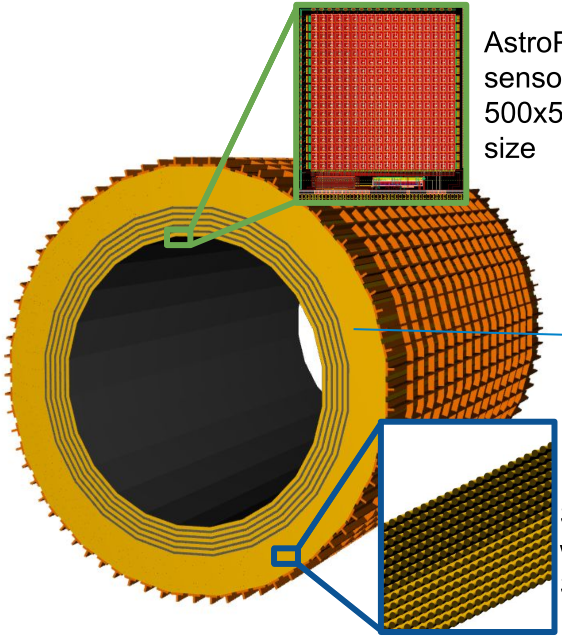
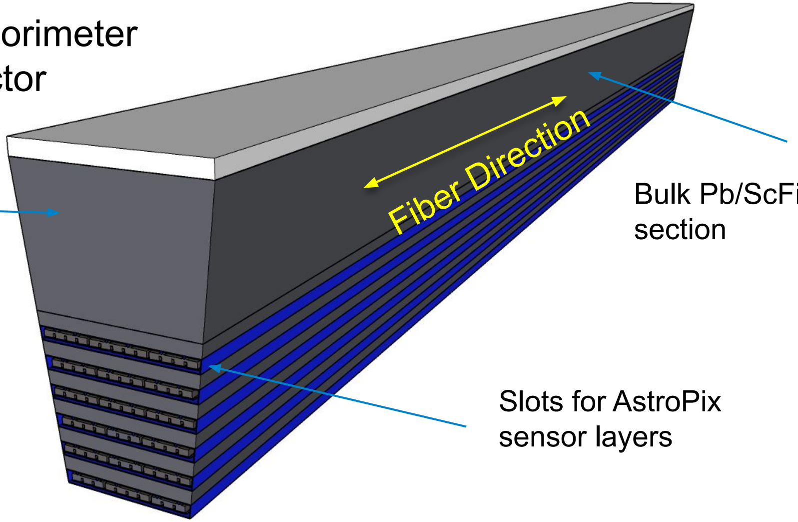
Geometry

- **4(+2) layers of imaging Si sensors** interleaved with **5 Pb/ScFi layers**
- Followed by a **bulk section of Pb/ScFi section**

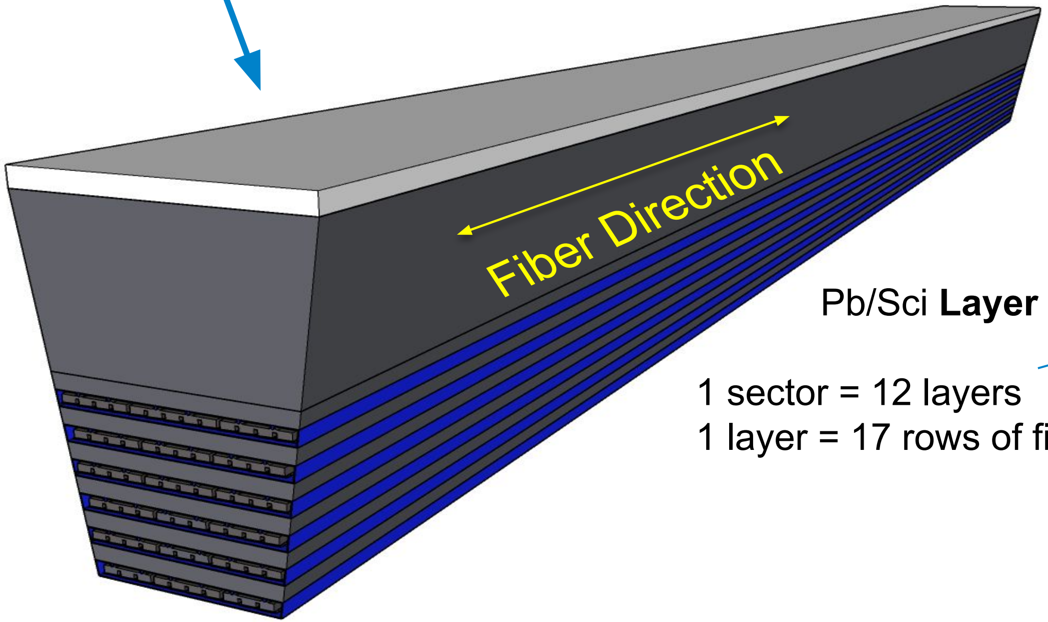




Energy resolution - Primarily from Pb/ScFi layers (+ Imaging pixels energy information)
Position resolution - Primarily from Imaging Layers (+ 2-side Pb/ScFi readout and radial segmentation)

Geometry and Naming Scheme

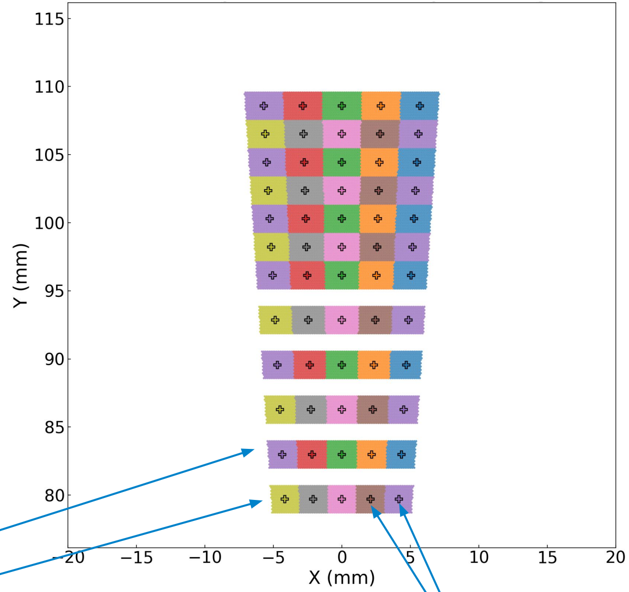
Sector
Whole Barrel: 48 Sectors



Pb/Sci **Layer**

1 sector = 12 layers
1 layer = 17 rows of fiber

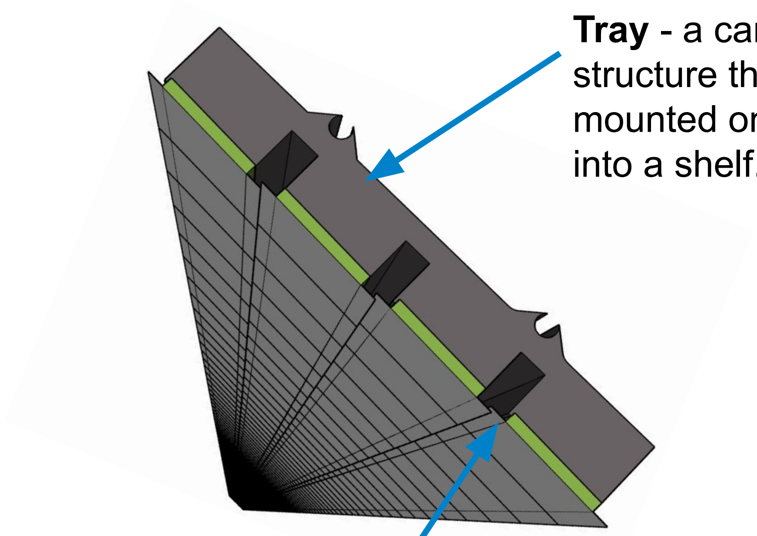
Sector End View
(x-y plane view)



Readout **Cell**
Layer = 5 cells

The area 1 light guide is attached

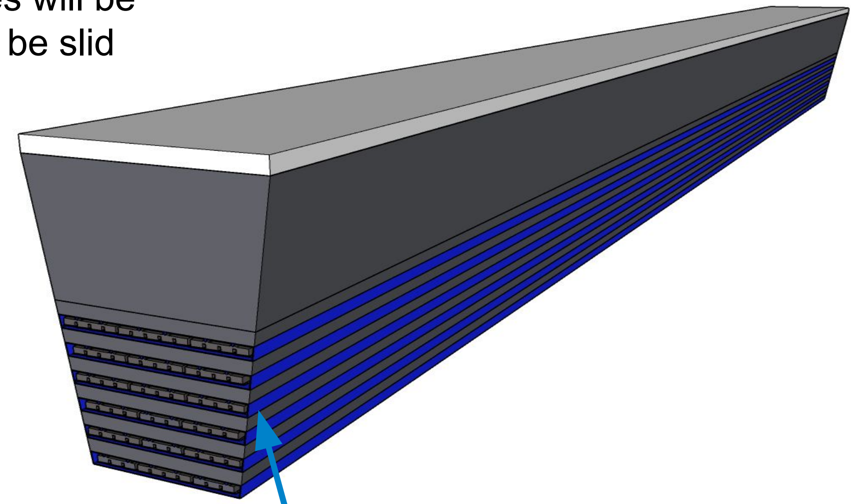
Geometry and Naming Scheme



Tray - a carbon fiber structure the staves will be mounted on. It will be slid into a shelf.

AstroPix **Stave**
Consists of 1 x 100 chips with the support structure

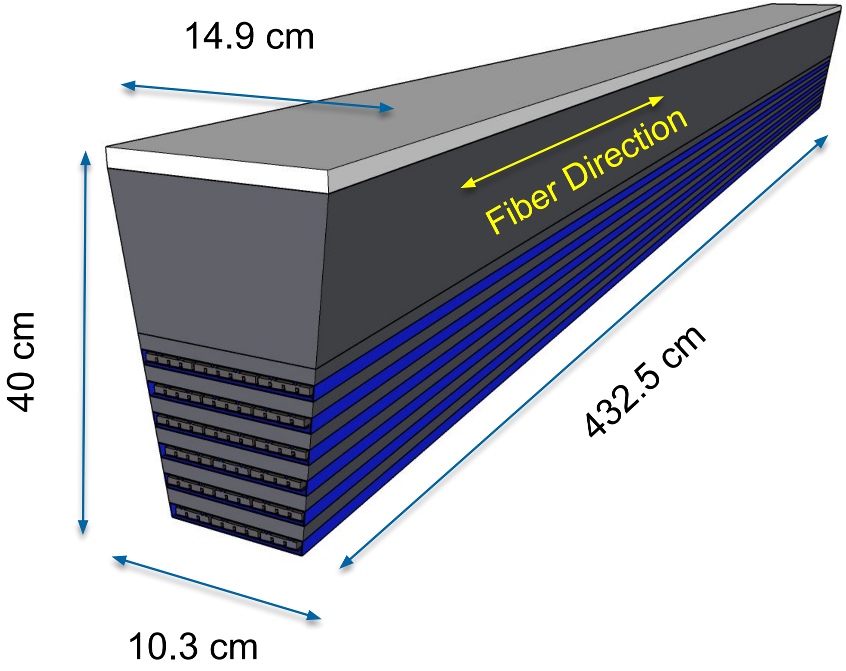
AstroPix **Module**
Subset of 10 chips that will be mounted on one stave support structure



Shelf - a carbon fiber structure that is glued to the Pb/ScFi layers, that we will slide trays with AstroPix staves on.

*The designs presented on these slides are not final but for illustration only

Dimensions

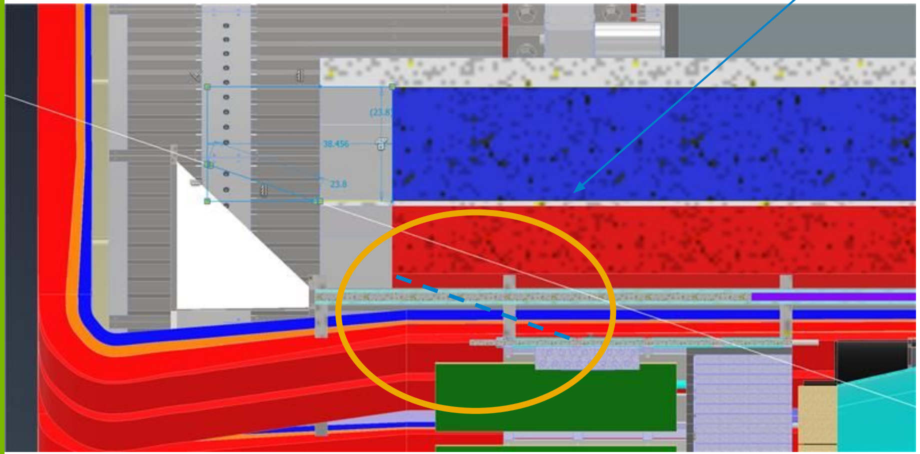


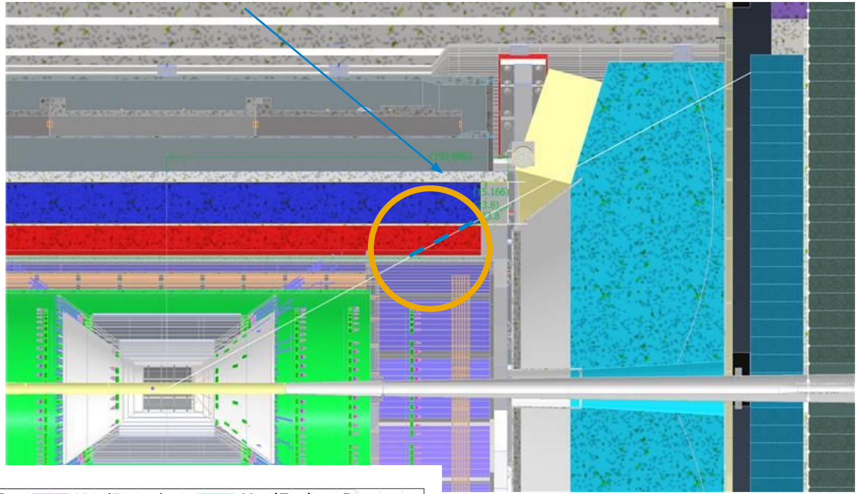
Dimensions a the current stage of the design

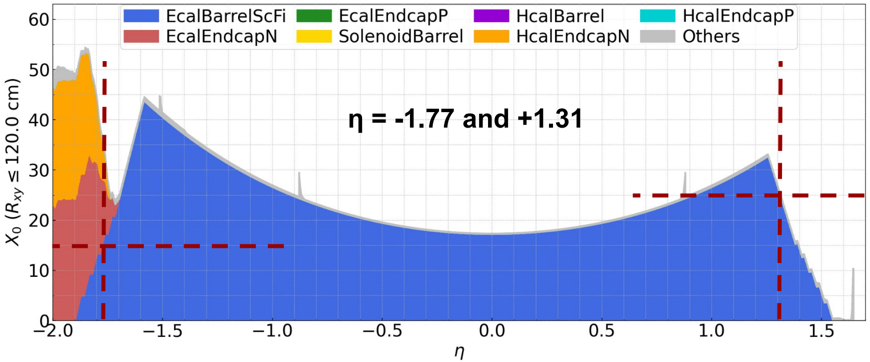
inner barrel radius	78.3 cm
nb of sectors	48
length	432.5 cm
AstroPix slot thickness	1.5 cm
SciFi/Pb Layer 1-5 thickness	2 cm
Total weight	~36 t
1 sector weight	~750 kg

Integration

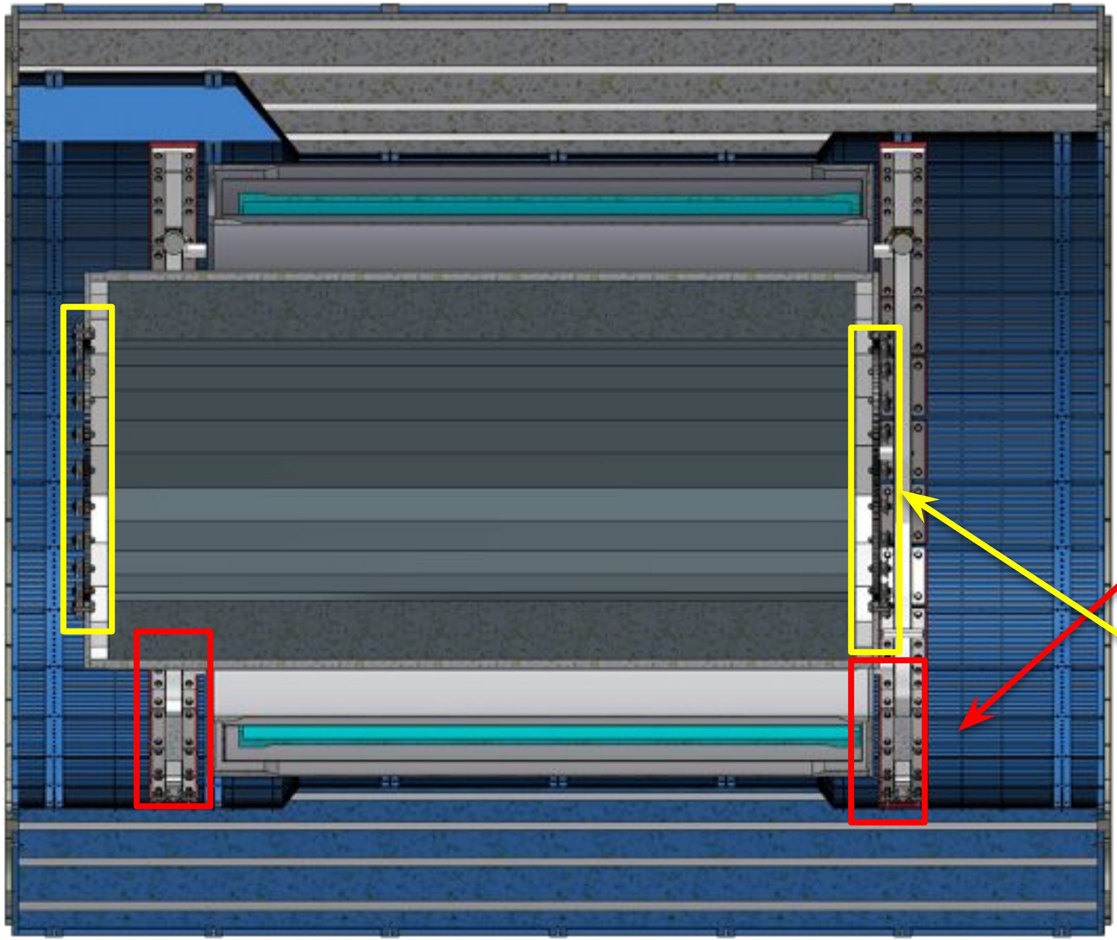
η = -1.77 and +1.31 for those lines assuming *one block size less than maximum radius*





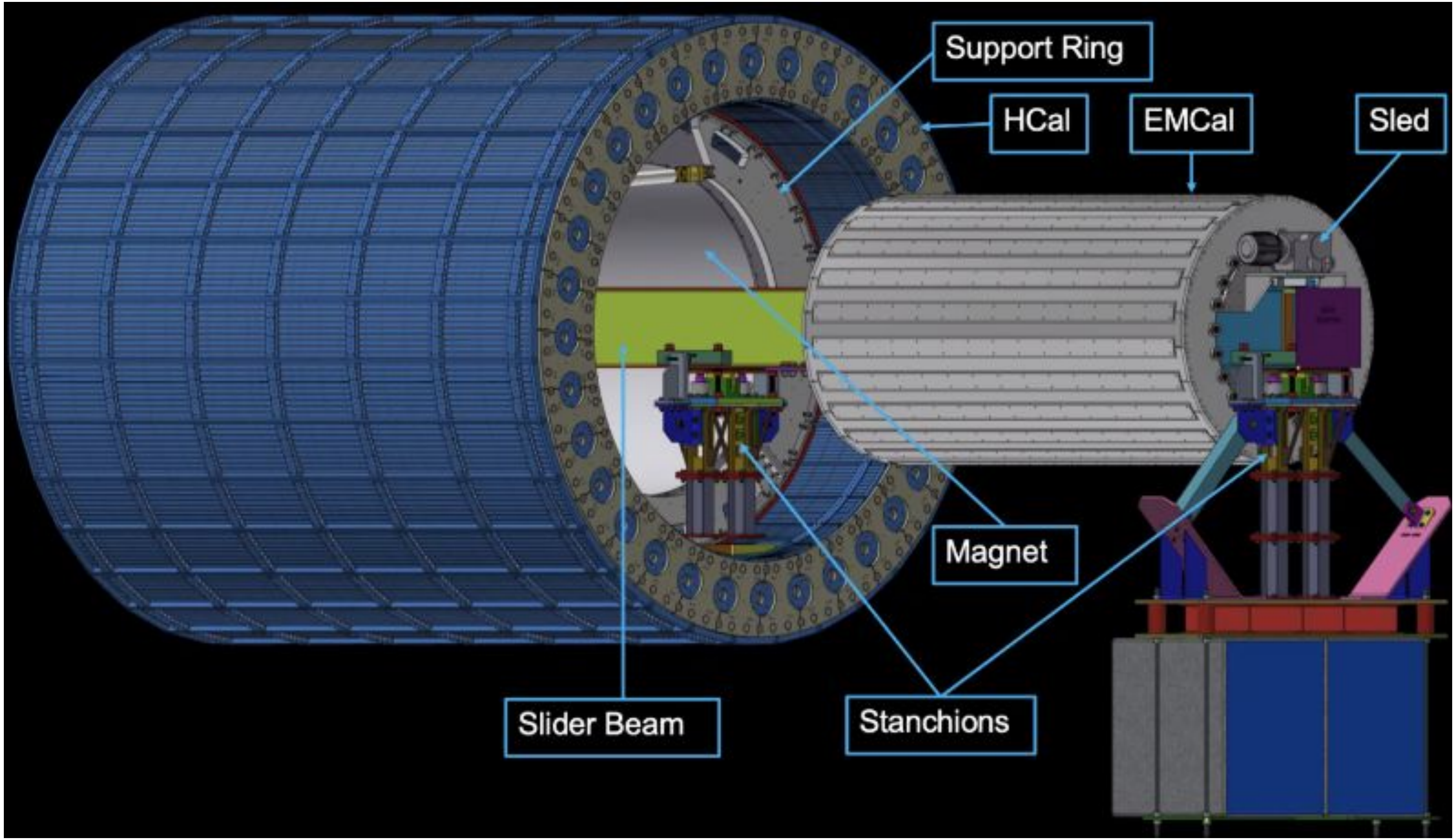


Support structure



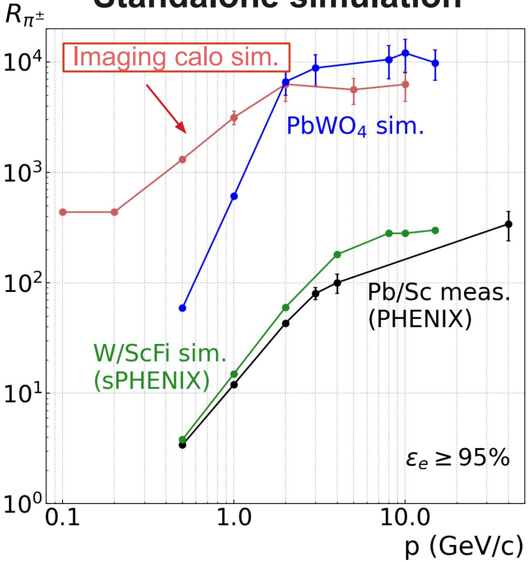
- Support strategy still being evaluated, tightly coupled whole system integration
  - Barrel EMCal may need to support the whole inner detector!
- **Design rapidly evolving**
- Current iteration:
  - Barrel EMCal rests on Barrel HCal support rings
  - Only two points of contact (versus rails in GlueX) requires a bit more work to evaluate rigidity and need for outside support
  - Inner detector suspended off inner support rings at the end of the Barrel EMCal

Assembly tooling

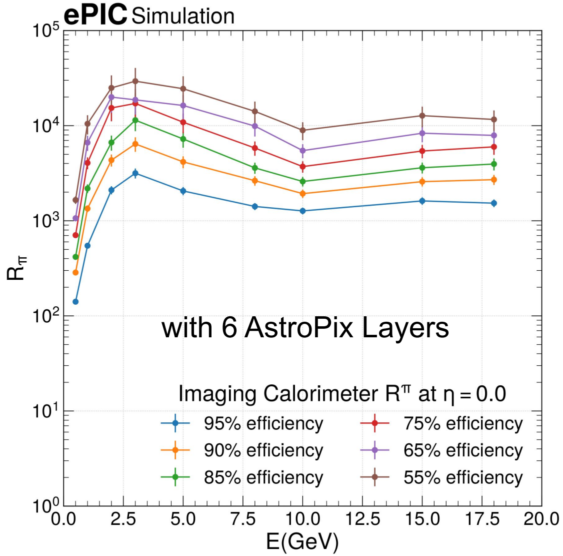


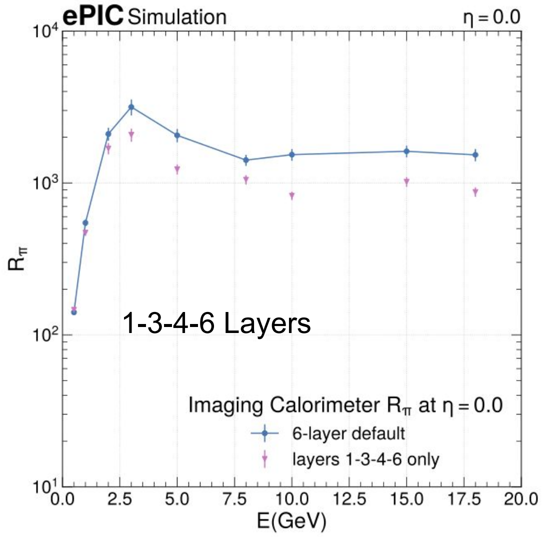
Electron Identification

Standalone simulation



Realistic ePIC simulation





- **Goal:** Separation of electrons from background in Deep Inelastic Scattering (DIS) processes
- Method: **E/p cut (Pb/ScFi) + Neural Network** using 3D position and energy info from imaging layers

- e-π separation exceeds **10^3** in pion suppression at **95% efficiency** above 1 GeV in realistic conditions!

Summary and Outlook

Hybrid Imaging calorimeter - combination of Pb/SciFi calorimeter with a silicon tracker to precisely measure the energy profile and exact position of each particle inside electromagnetic showers - 3D shower imaging

- **SciFi/Pb:** mature technology, design and assembly procedures based on GlueX ECAL
- **Imaging layers:** based on MAPS AstroPix sensors, developed for NASA, planned to be used off-the-shelf

Ongoing tests for both technologies in the EIC-like conditions in FY23+

- Multilayer AstroPix chip tests with p/e/π beam with W radiator at FNAL
- SciFi/Pb prototype test with electromagnetic (JLab) and hadronic (FNAL) showers
- Fiber tests in Uni of Regina to conclude the fiber choice (Aram Teymurazyan and Zisis Papandreou labs)
- Integrated system (SciFi/Pb + AstroPix) testing at FNAL in FY24 in electron/pion beam

Mechanical structure and readout design under development based on experience from GlueX and AMEGO-X mission designs. **Assembly** scheme similar to sPHENIX Calo procedure.

Detailed **bottom up budget and schedule** developed with our collaborators: towards work packages.

Realistic simulations show that design meets the EIC YR requirements and offers new opportunities:

- Design provides considerably more information compared to traditional 2D calorimeters which synergizes particularly well with event reconstruction approaches based on ML/AI

Collaborators

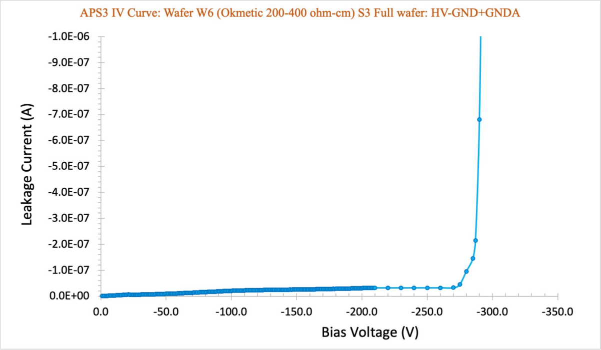
Thank you

Snapshots from the Sensor Irradiations

400 MeV protons

- **9 samples of AstroPix v2 chips prepared for the passive irradiation in the FNAL MTA Facility**

- IV and CV measurements performed for the v2 and v3 chips before irradiations
  - Same measurements will be repeated post irradiation

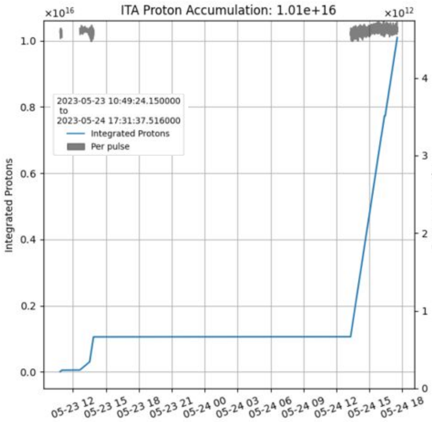


V2 Irradiation

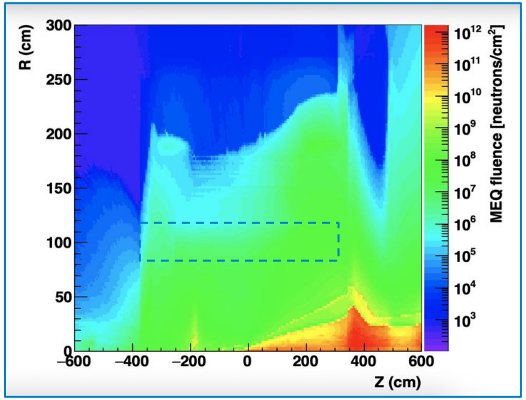
Nb of samples	Doses (400 MeV protons)
3	4.50E+13
3	1.08E+15
2	1.01E+16
1	5.02E+16

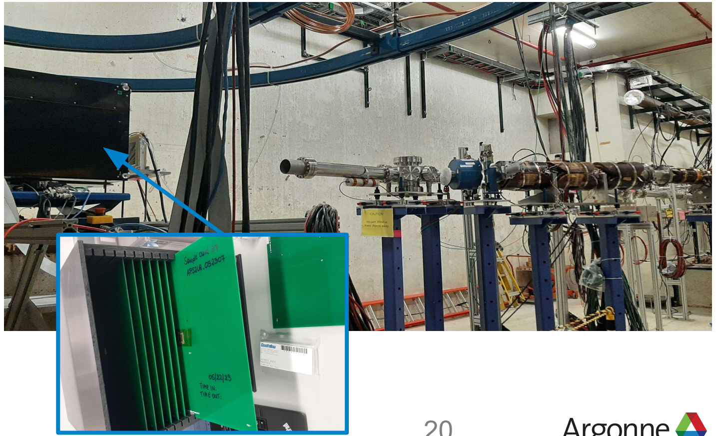
V3 Irradiation (low and high ResChips)

Nb of samples	Doses (400 MeV protons)
2	4.50E+13
1	5.04E+15



1-MeV neutron equivalent fluences at EIC





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SiFi/Pb Discussions

GlueX Production (Zisis): https://indico.bnl.gov/event/19689/contributions/77399/
HGCROC Readout (Norbert): https://indico.bnl.gov/event/19689/contributions/77418/

Selected Discussion Items

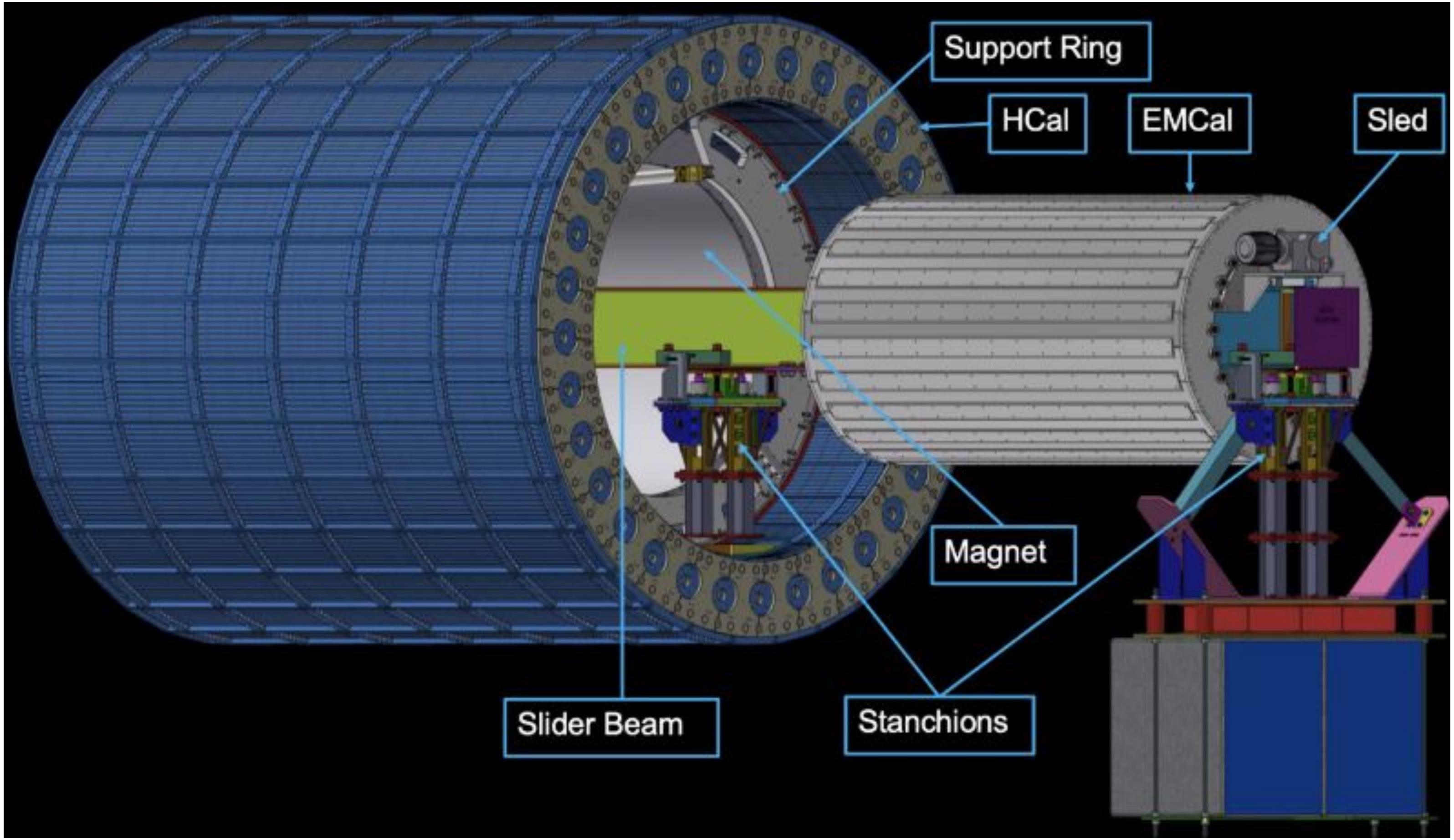
Realistic production strategy and workforce requirements discussed

- Production rates estimated in the bottom up schedule

Strategy for prototyping

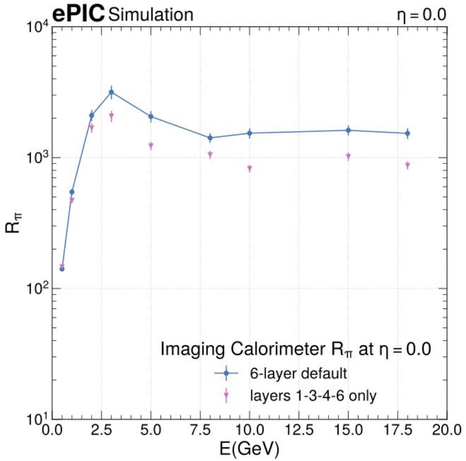
- Short term R&D (testing of fibers light output in Regina, small scale prototype in FNAL)
- Engineering test article (mechanical properties testing, readout testing, shelf-SiFi/Pb integration)
- First article

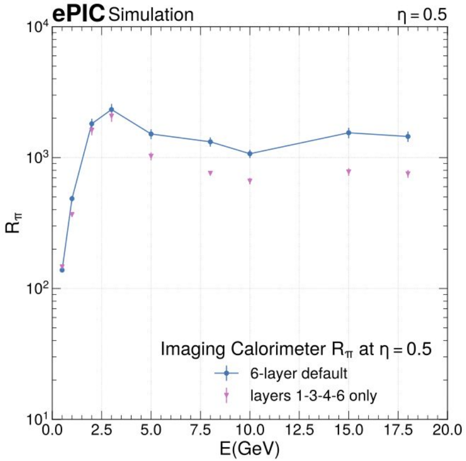
Possible strategy of reading out SiPMs with HGCROC

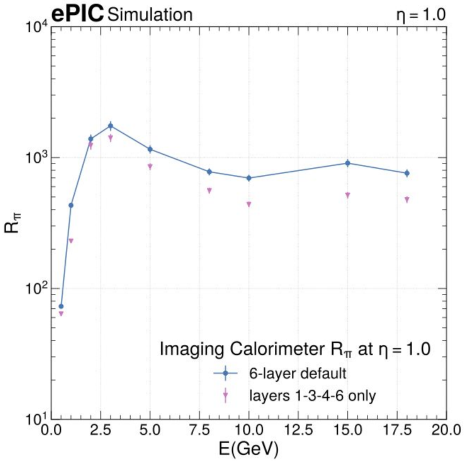

Support Ring
HCal
EMCal
Sled
Magnet
Slider Beam
Stanchions

Performance with reduced number of layers

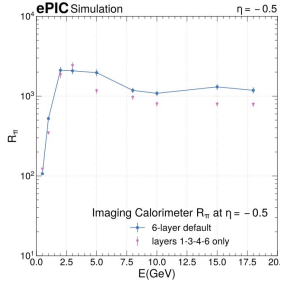
e/π separation at 95% efficiency

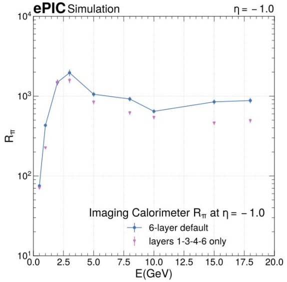






4-layer alternate: layers 1-3-4-6



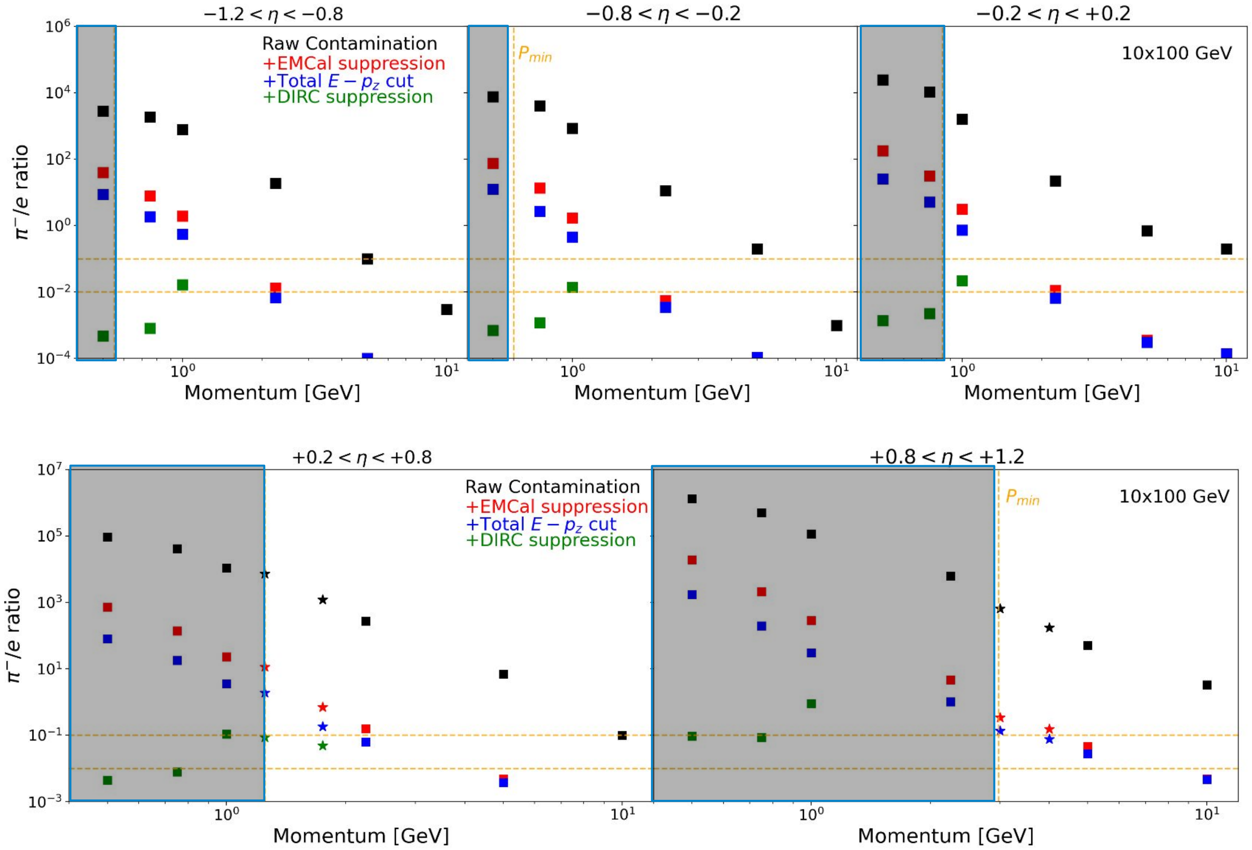


Default configuration exceeds 10^3 pion rejection almost everywhere

4-layer alternate still performs relatively well at lower energies (where most rejection is needed), larger degradation at higher energies

4-layer alternate seems workable compromise.

Performance for 10 x 100 GeV



Studies on π contamination performed by B. Schmookler (UCR)

- See ePIC Collaboration Meeting contribution (link)

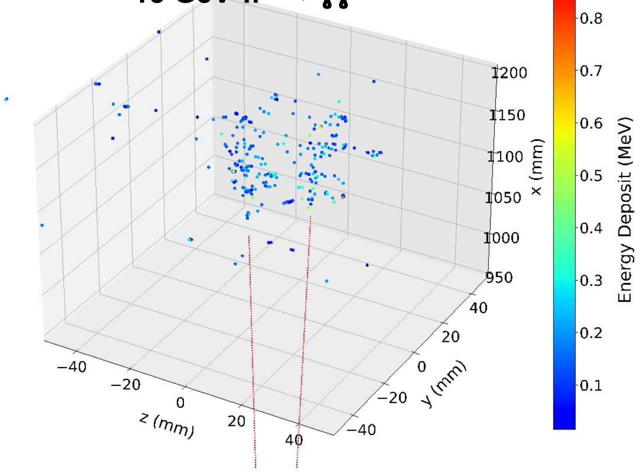
Challenging goal: Achieve 90% electron purity from the combined detector performance (ECAL + DIRC)

- To keep pion contamination systematic uncertainty to required 1% level

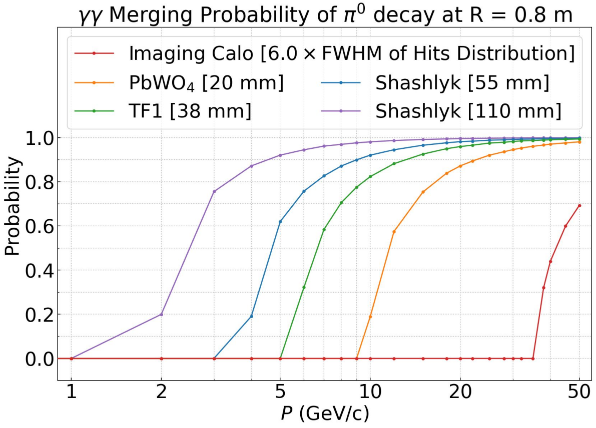
Imaging calorimeter fulfills the requirement in all η ranges

Neutral Pion Identification

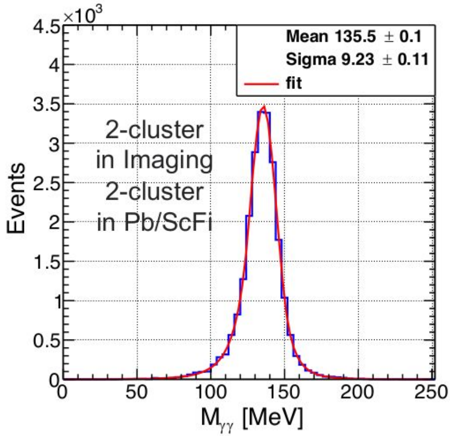
15 GeV $\pi^0 \rightarrow \gamma\gamma$



Separation of γ/π^0 (upper limit)



M_{inv} reconstruction 2 GeV π^0



- **Goal:** Discriminate between π^0 decays and single γ from DVCS, neutral pion identification
- Precise position resolution allow for excellent separation of γ/π^0 **based on the 3D shower profile**
- Reconstruction of 2 GeV π^0 invariant mass as a testing ground for cluster energy splitting

Separation of two gammas from neutral pion well above required 10 GeV

γ/π^0 Separation - Exploratory Studies

Convolutional neural network utilizing energy and spatial information from AstroPix layers

- Started from **10 GeV/c at η = 0** - the upper limit for γ/π^0 from YR

No proper **topological clustering algorithm** in the ePIC reconstruction yet

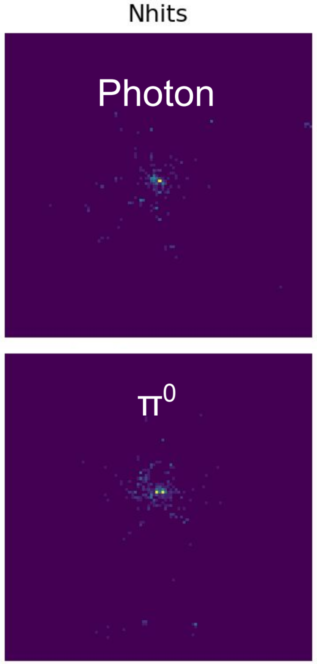
With a quick study we easily achieved

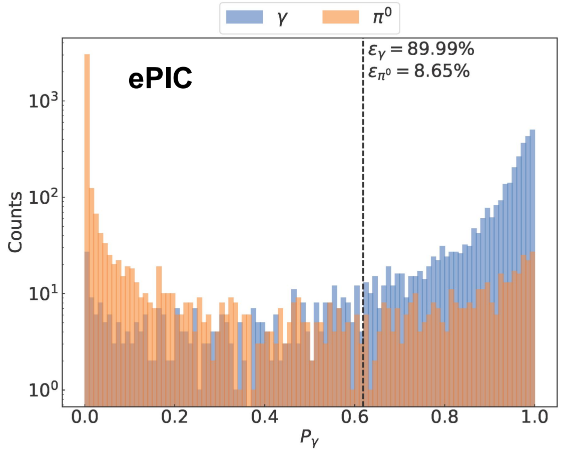
10 GeV/c particles - **91.4%** rejection of π^0 at **90%** efficiency of γ (better than $PbWO_4$ crystal with 20mm block size)

4-layer alternate is workable (still better than theoretical limit on a crystal calorimeter!), but reduced π^0

Full study is ongoing:

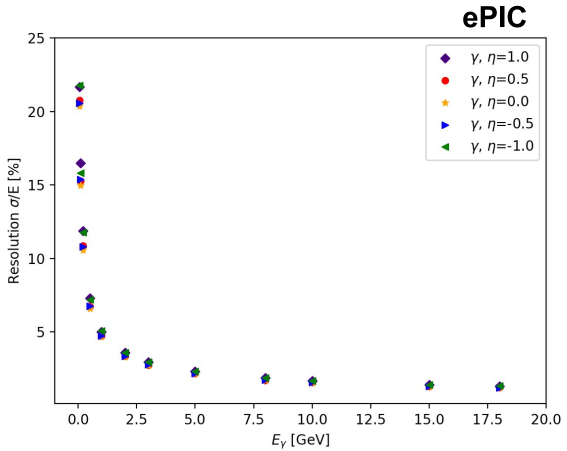
- Implementing optimized topological clustering for AstroPix layers
- Significant improvements expected

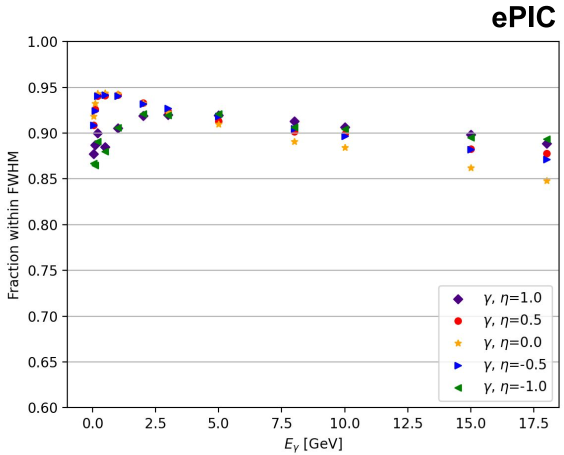


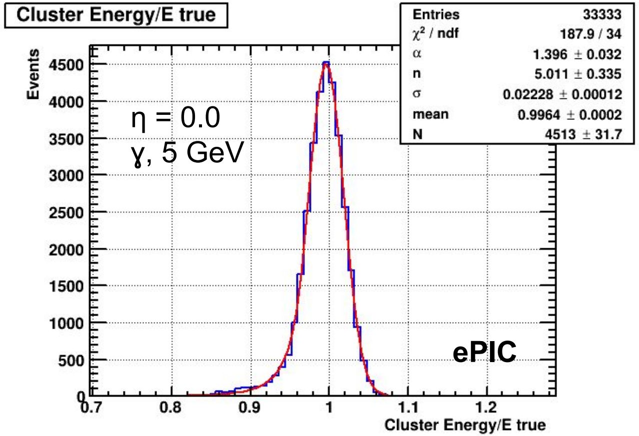


Configuration	γ efficiency	π^0 rejection at 10 GeV/c
6-layer default	90%	11.5
4-layer alternate	90%	5.4

Energy Resolution - Photons







Fit parameters

η	$a/\sqrt{E}$ [%]	b [%]
-1	5.1(0.01)	0.47(0.03)
-0.5	4.77(0.01)	0.38(0.02)
0	4.67(0.01)	0.40(0.02)
0.5	4.75(0.01)	0.39(0.02)
1	5.1(0.01)	0.41(0.02)

- Based of Pb/ScFi part of the calorimeter
- Resolution extracted from a Crystal Ball fit σ

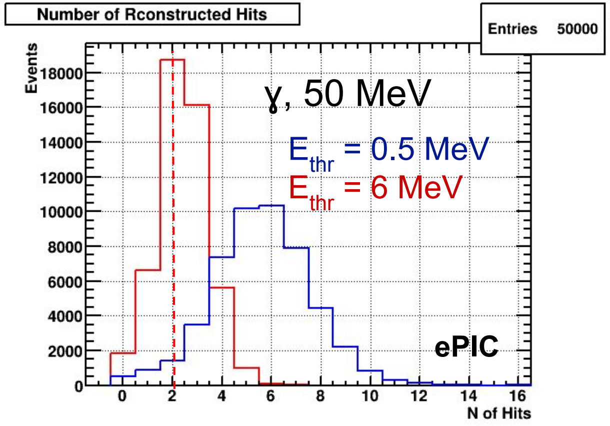
GlueX Pb/ScFi ECal: σ = 5.2% $/\sqrt{E} \oplus$ 3.6% NIM, A 896 (2018) 24-42

- 15.5 X_0, extracted for integrated range over the angular distributions for π^0 and η production at GlueX (E_γ = 0.5 - 2.5 GeV)
- Measured energies not able to fully constrain the constant term

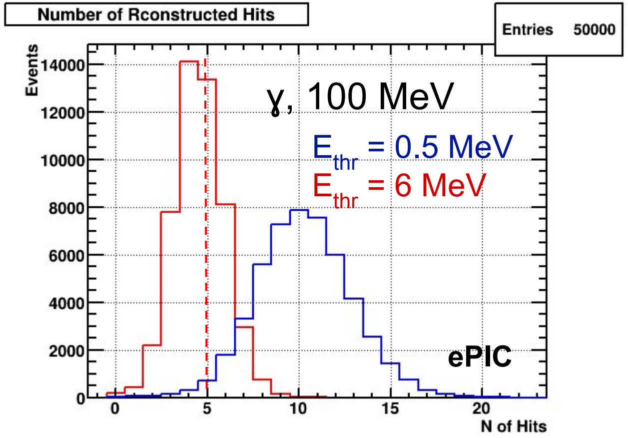
Simulations of **GlueX prototype** in ePIC environment agree with data at E_γ < 0.5 NIM, 596 (2008) 327−337

Low Energy Particles

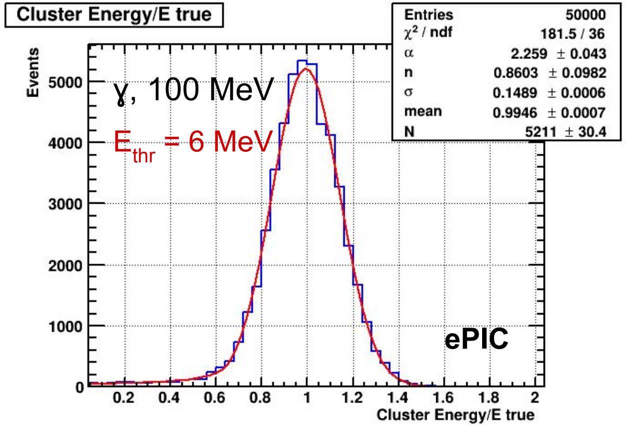
- For electrons: cut out because of the 1.7 T field to reach the calorimeter (p < ~408 MeV)
- For photons shown number of fired readout cells with different thresholds at η = 0



Thresholds corrected for f_{sam}



Blue threshold very low just to illustrate the distribution shape



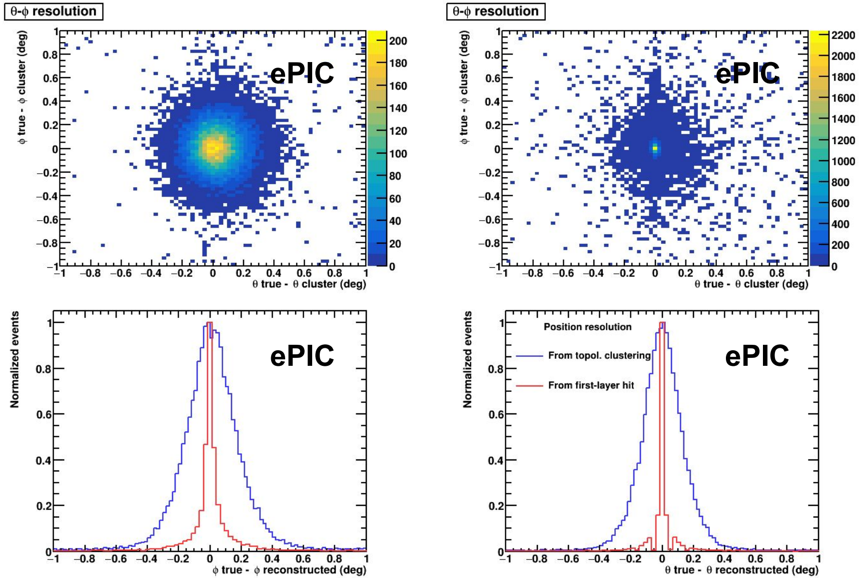
- **From GlueX** studies: cluster/shower threshold is 100 MeV nominal (down to 50 MeV for some analyses, with mostly two cells per event only). Low energy detection threshold studied also with Michel electrons. (NIM, A 896 (2018) 24-42)

Position Resolution

with 6 AstroPix Layers

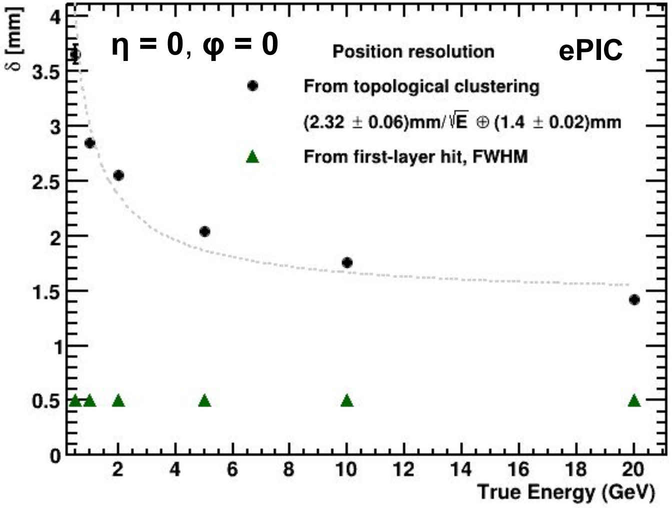
Example of θ - φ resolution for 5 GeV photons

Only information from **clusters** | **Clusters + first-layer hit**



Position resolution for photons

Particles thrown perpendicular to the calo surface



- Clusters from Imaging Si layers reconstructed with 3D topological algorithm
- Cluster level information: $\sigma_{position}$ = (2.32 ± 0.06) mm/√E ⊕ (1.4 ± 0.02) mm at η=0
- First-layer hit information added: $\sigma_{position}$ = **~0.5 mm (pixel size)**

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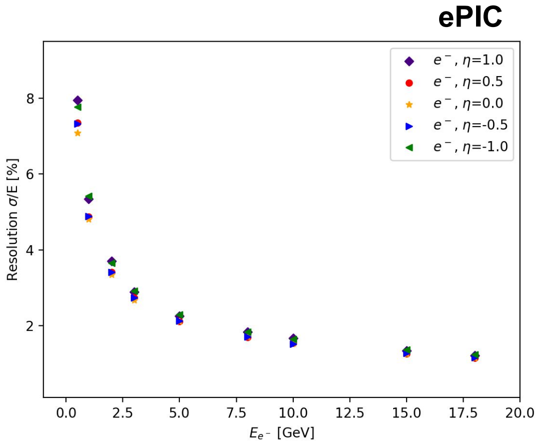
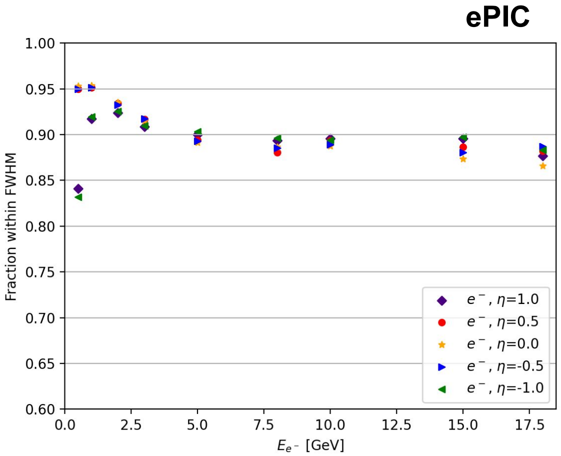
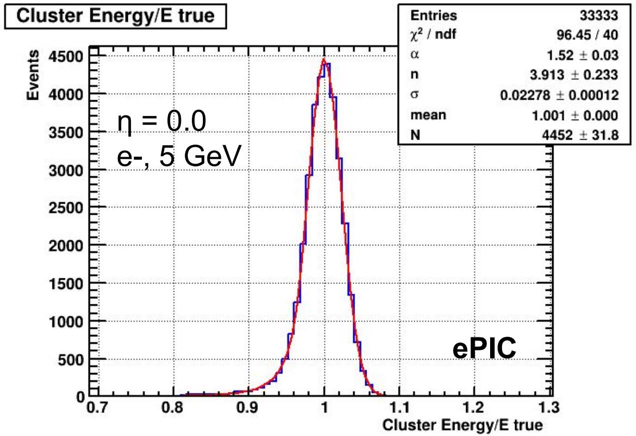
Energy Resolution - Electrons







Fit parameters

η	a/√(E) [%]	b [%]
-1	5.22(0.02)	0(0.08)
-0.5	4.88(0.01)	0(0.04)
0	4.81(0.01)	0(0.08)
0.5	4.88(0.01)	0(0.04)
1	5.19(0.01)	0(0.06)

Resolution extracted from a crystal ball fit σ

GlueX Pb/ScFi ECal: $\sigma = 5.2\% / \sqrt{E} \oplus 3.6\%$ NIM, A 896 (2018) 24-42

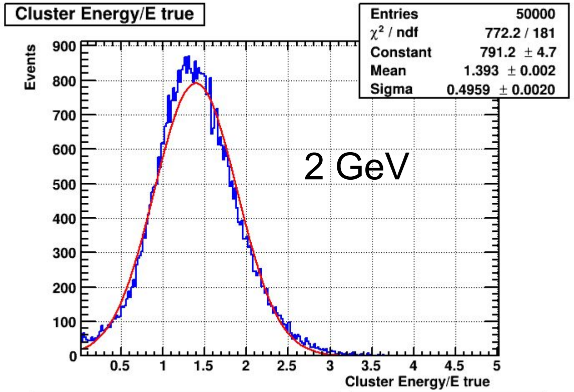
- 15.5 X_0, extracted for integrated range over the angular distributions for π^0 and η production at GlueX (E_γ = 0.5 - 2.5 GeV)
- Measured energies not able to fully constrain the constant term

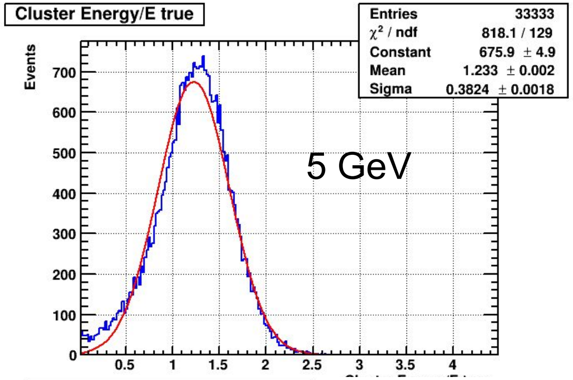
Simulations of **GlueX prototype** in ePIC environment agree with data at E_γ < 0.5 NIM, 596 (2008) 327−337

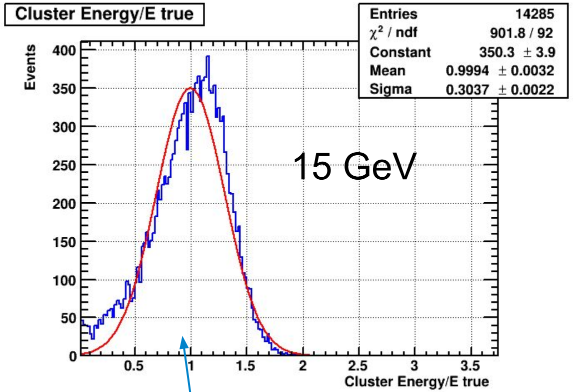
Energy resolution of AstroPix Layers

- **Sampling fraction < 0.5 %**
- Example Energy Lineshapes for photons at $\eta = 0$

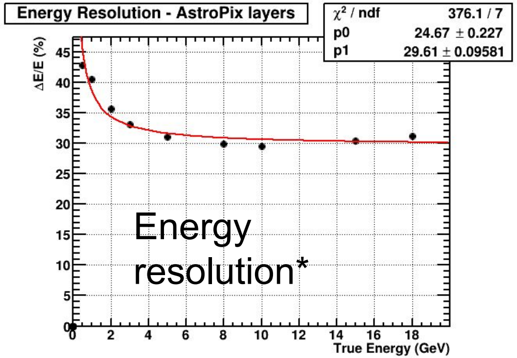
with 6 AstroPix Layers

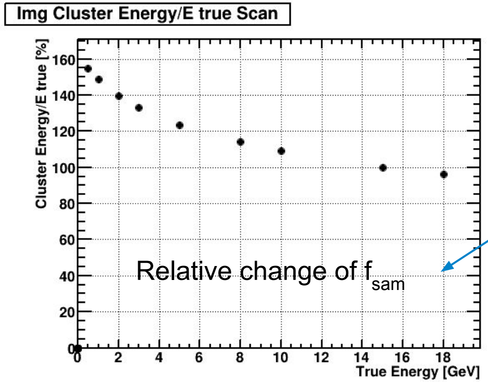






non-gaussian





strong dependence in this geometry

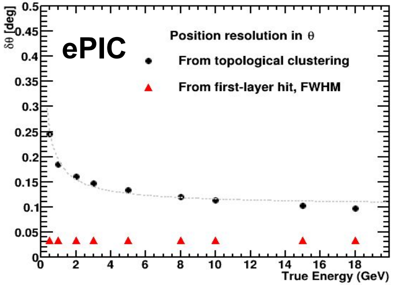
*Assuming perfect calibration (but! huge sampling fraction energy dependence)

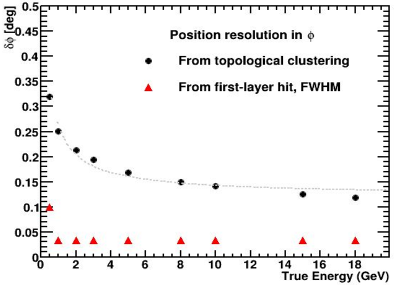
Position resolution studies

with 6 AstroPix Layers

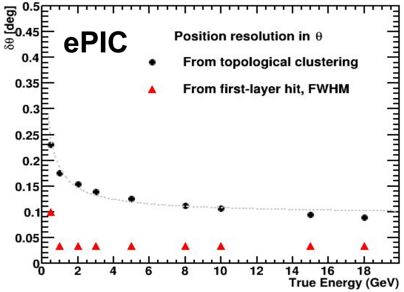
Angular resolution for different η

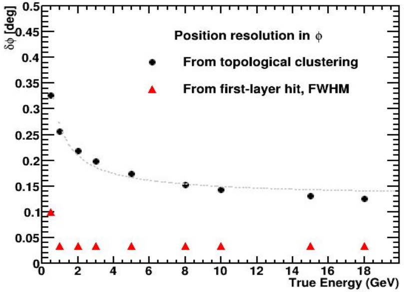
η = 0, φ = (0,2π)



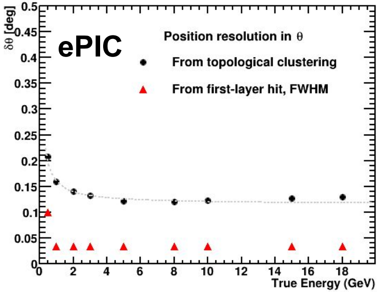


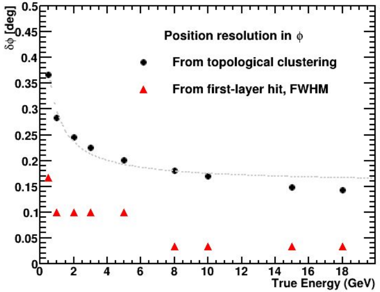
η = 0.5, φ = (0,2π)





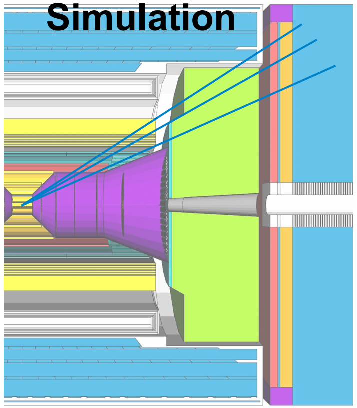
η = 1, φ = (0,2π)

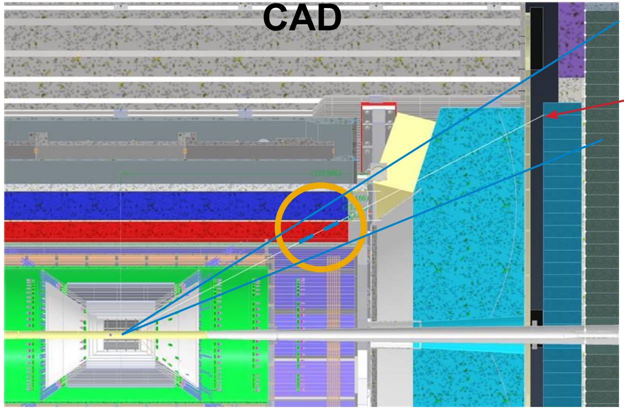




- Small dependence seen with changing η
- Angular resolution in all regions well below 0.1 deg (in majority regions on the level of single pixel resolution)
- Results well below any tower-like calorimetry

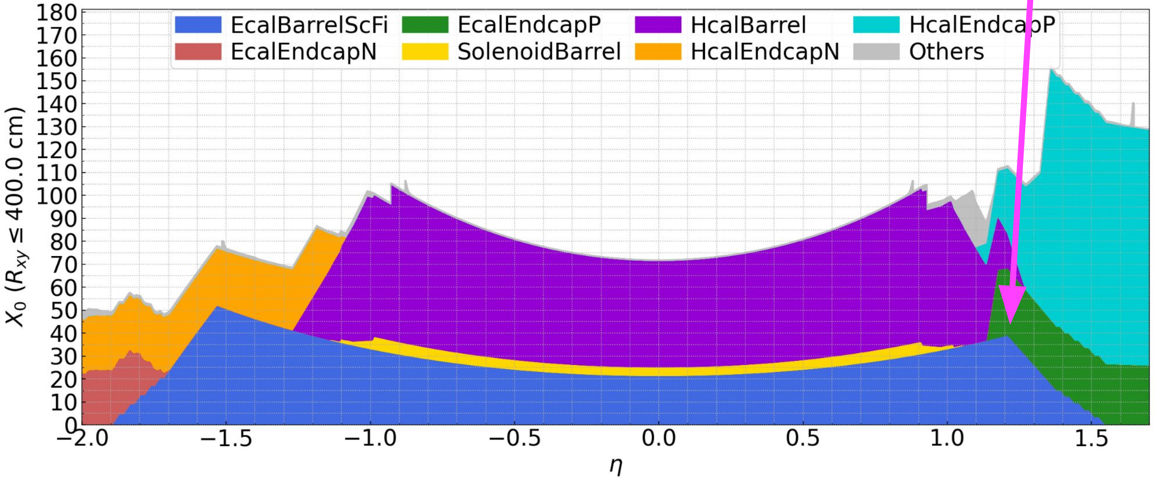
Forward integration





η = 1.31

Very good continuous coverage in the forward region, up to ~ 33 X0



at η = 1.31
~25 X_0

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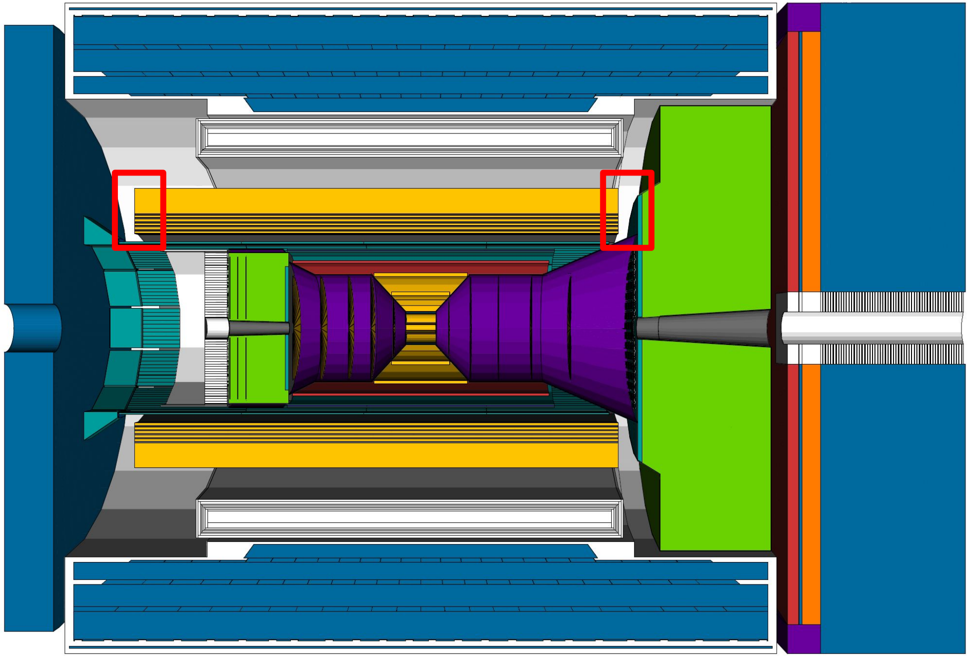
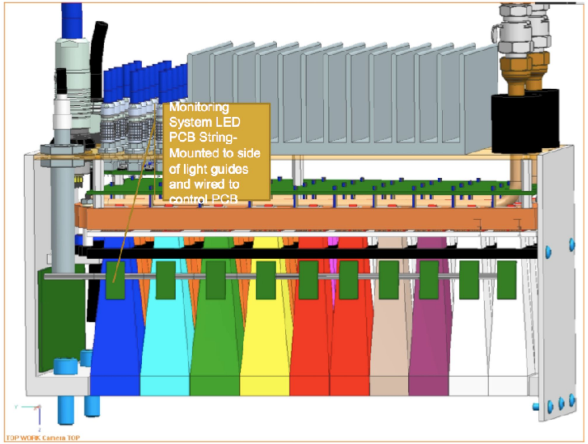
Barrel ECal Readout & Services



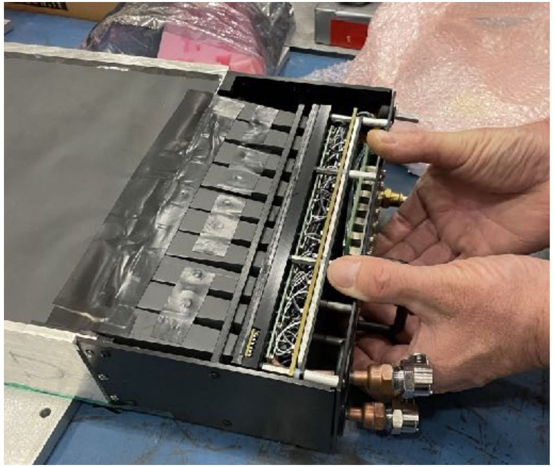
- Nominal 10cm service box at the end of each sector, may have to grow slightly
  - This would put (more) space pressure in the hadron-going direction.
  - May need to shorten calorimeter by a few cm to compensate
- Readout box includes:
  - Pb/ScFi readout components based on the GlueX design (including light-monitoring system)
  - 4 6x6mm2 SiPMs with 50 um pixel per lightguide (“project” Hamatsu meets the performance requirements)
  - 1 x HGCROC per sector-end for SiPM readout
  - End-of-tray FPGAs for each of the silicon layers
- Readout boxes at both sides of the calorimeter are identical.

GlueX BCAL Readout Design

- Pb/ScFi readout based on the GlueX BCAL readout
- Footprint excluding external connectors of GlueX BCAL readout box about 14cm
  - Dominated by light guides (~ 8 cm)
- We will likely be able to shrink this somewhat to < 12 cm
  - Space pressure in the forward direction, where space is limited.



CAD drawing of GlueX readout box



“BabyBCAL” prototype readout box