Detector Day, March 25, 2024

# Barrel Imaging Calorimeter

## eRD115



03/25/2024
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Argonne National Laboratory


ePIC

Argonne NATIONAL LABORATORY

# R&D Motivation

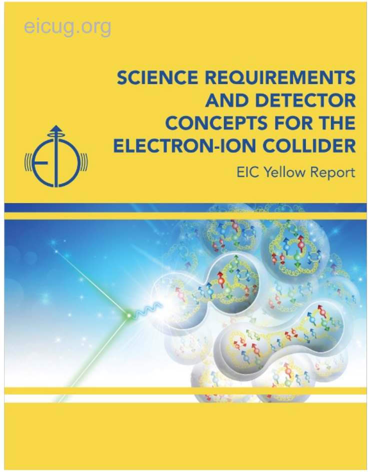
# EIC Calorimetry Requirements

## Barrel ECAL in EIC Yellow Report

EIC Community outlined physics, detector requirements, and evolving detector concepts in the EIC Yellow Report.

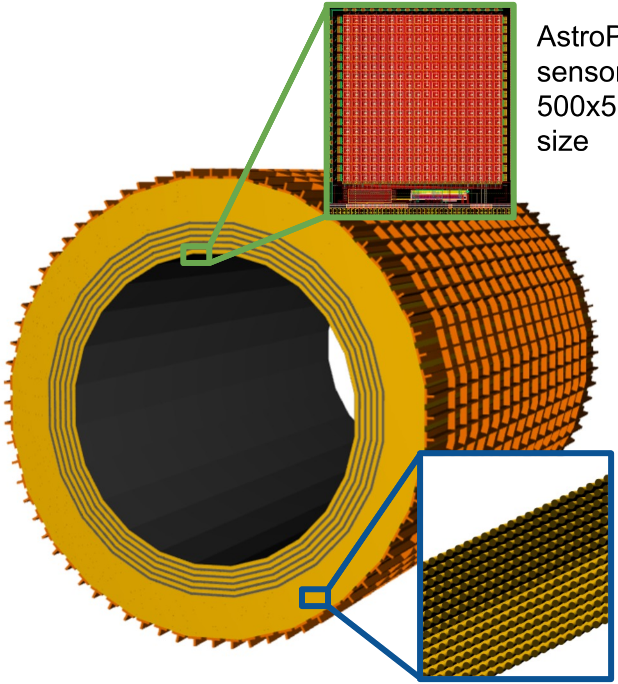
EIC Yellow Report requirements for Barrel EM Calorimeter

- Detection of electrons/photons to measure **energy and position**
- Require **moderate energy resolution** $(7-10)\%/\sqrt{E} \oplus (1-3)\%$
- Require **electron-pion separation up to $10^4$** at low momenta in combination with other detectors
- Discriminate between **$\pi^0$ decays and single ɣ up to ~10 GeV**
- **Low energy photon** reconstruction ~100 MeV




Challenges: e/π PID, ɣ/$\pi^0$ discrimination, available space

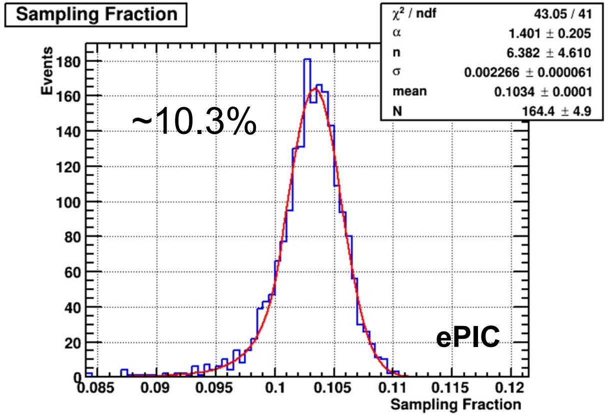
# Barrel Imaging Calorimeter: General Overview



AstroPix: silicon sensor with $500 \times 500 \mu m^2$ pixel size

ScFi Layers with two-sided SiPM readout

- **4(+2) layers of imaging Si sensors** interleaved with **5 Pb/ScFi layers**
- Followed by a **large section of Pb/ScFi section**
- Total radiation thickness ~17.1 $X_0$
- Sampling fraction ~10%



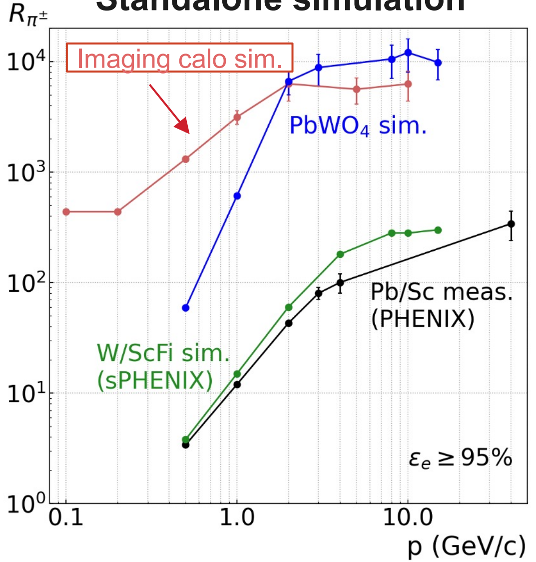

Simulations of **single photons** at η=0 (~17.1 $X_0$)

Sampling fraction = $\Sigma E_{fibers} / E_{thrown}$

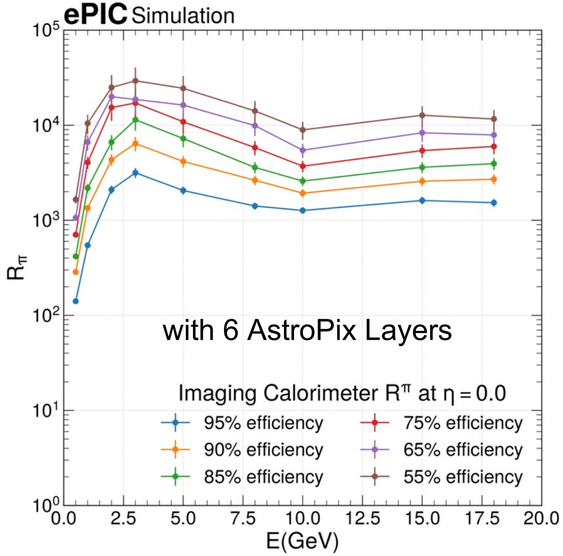
Energy resolution - Primarily from Pb/ScFi layers (+ Imaging pixels energy information)
Position resolution - Primarily from Imaging Layers (+ 2-side Pb/ScFi readout)

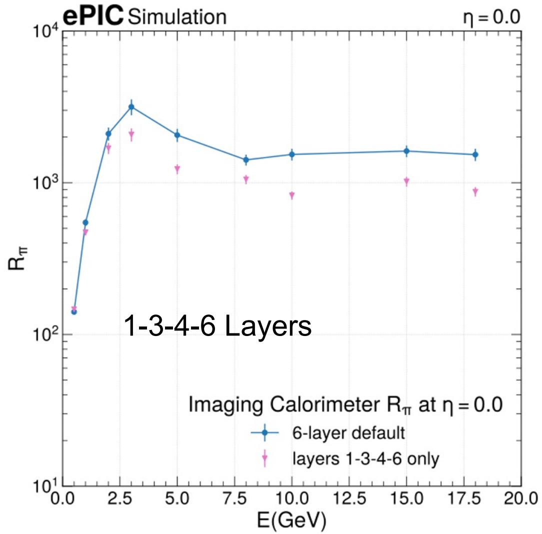
# Barrel Imaging Calorimeter: Performance Example

**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!

# Barrel Imaging Calorimeter: Technology R&D

## SciFi/Pb Barrel technology:

Tested extensively for electromagnetic response in energies **$E_\gamma$ < 2.5 GeV**

**Energy resolution:** $\sigma = 5.2\% / \sqrt{E} \oplus 3.6\%$[1)]

– 15.5 $X_0$, GlueX could not constrain the constant term (due to low energies)

## General direction of R&D:

Test feasibility of using in the environment of EIC:

SciFi/Pb integrated with the AstroPix sensor layers

benchmarking of high energy simulation performance (e.g., e/π separation, response to pions)

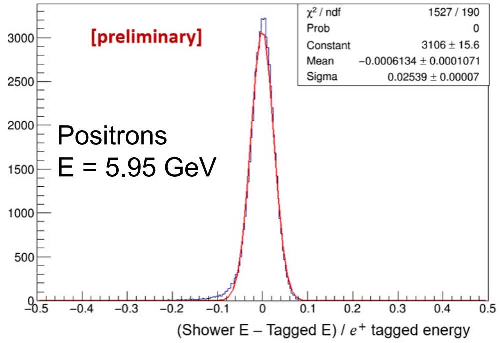
1) GlueX, Nucl. Instrum. Meth. A, vol. 896, pp. 24–42, 2018

## Snapshot of FY23 R&D:

**Hall D, March 2023**
Baby BCAL Test

**Measured Resolution:** ~ 2.5%

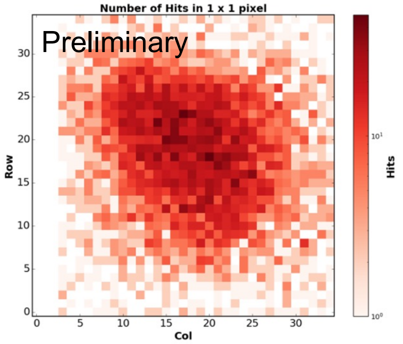
Extrapolated GlueX NIM[1)]: ~4.2%




Trends well below 2% of constant term!

Beam spot hit maps
**FNAL, May 2023**
AstroPix v3 Test
120 GeV protons

Performs well in much harsher conditions than EIC



# EiC Calo Review Recommendations

## December 6-7, 2022, Close-Out Report:

***Recommendations***

✅ ***R5*** *Do full physics simulation as soon as possible and demonstrate the added value of the imaging stage.*

The system has been extensively simulated in preparation to the Barrel ECal review and following the design optimisation. See, e.g., review performance talk.

– Based on the simulations it has been demonstrated that integration of imaging layers with SciFi/Pb is crucial in achieving the required e/π separation

🚧 ***R6*** *Move towards tests of prototypes or more detailed engineering test articles as soon as possible.*

Single-technology prototype tests have been performed (SciFi/Pb with e+, AstroPix with p) in FY23, See, e.g. Hall D Baby BCAL Tests, AstroPix FNAL FTBT Tests and Irradiations

The performance, including response to pions, needs to be benchmarked in a prototype of the **hybrid integrated system**.

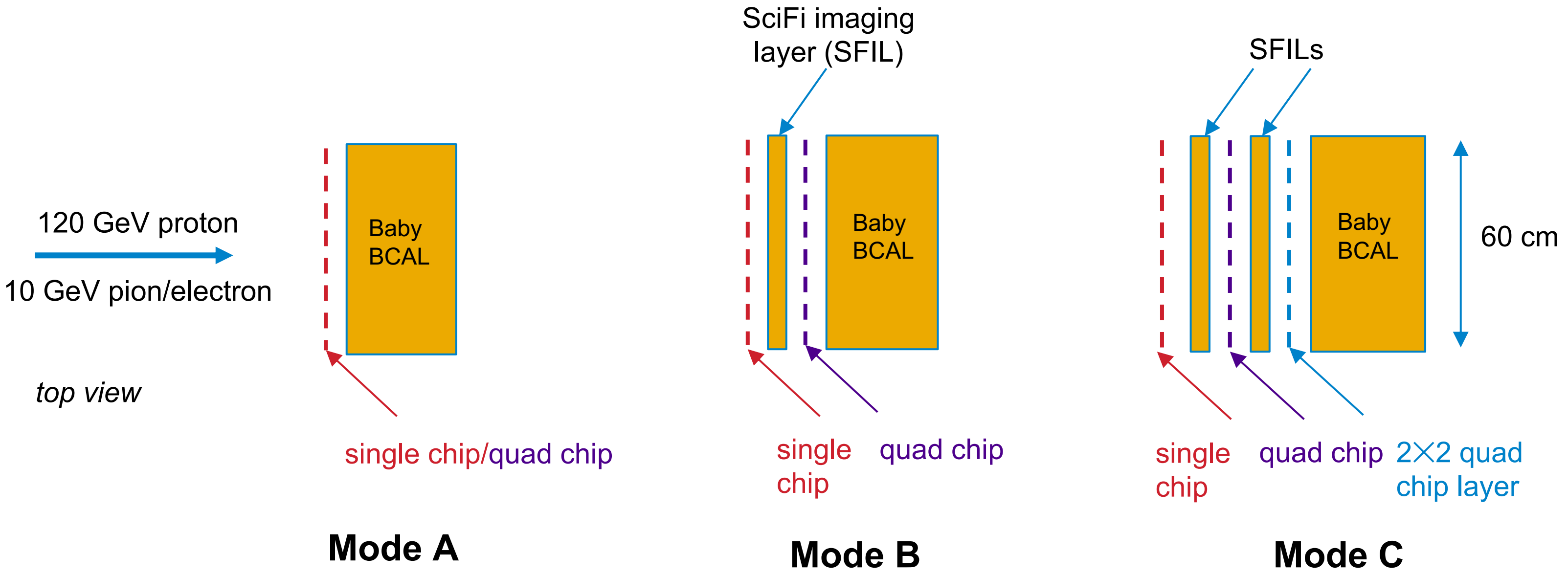
**This R&D program is about addressing the R6 Recommendation**

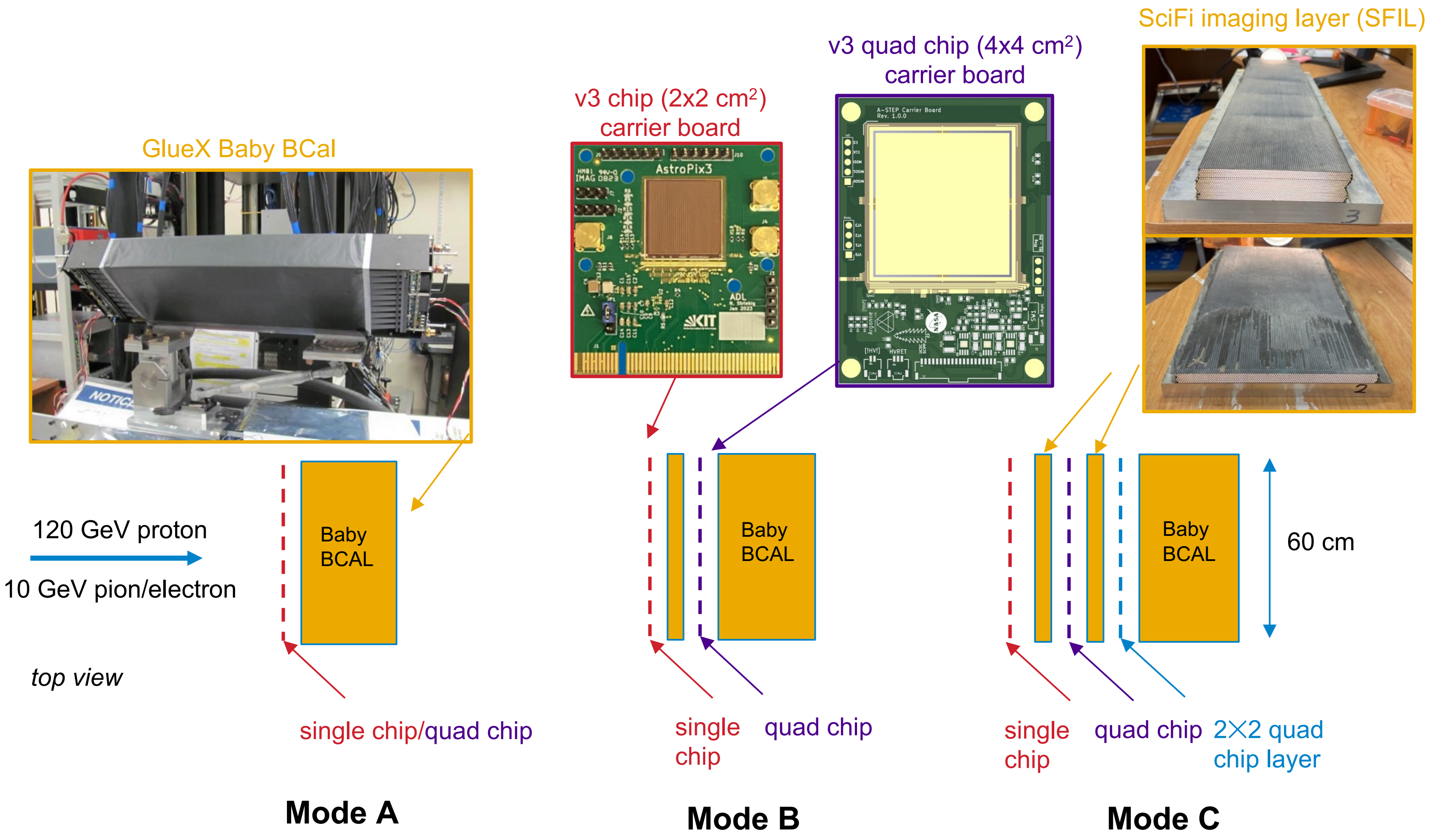
# FY24 Goals

# FY24 R&D Goals

**Goal:** Characterize the integrated AstroPix and SciFi/Pb system with a mixed e/π beam and mips, benchmarking the response to charged pions, benchmarking the electron-pion separation capability, and testing the new generation SiPMs.

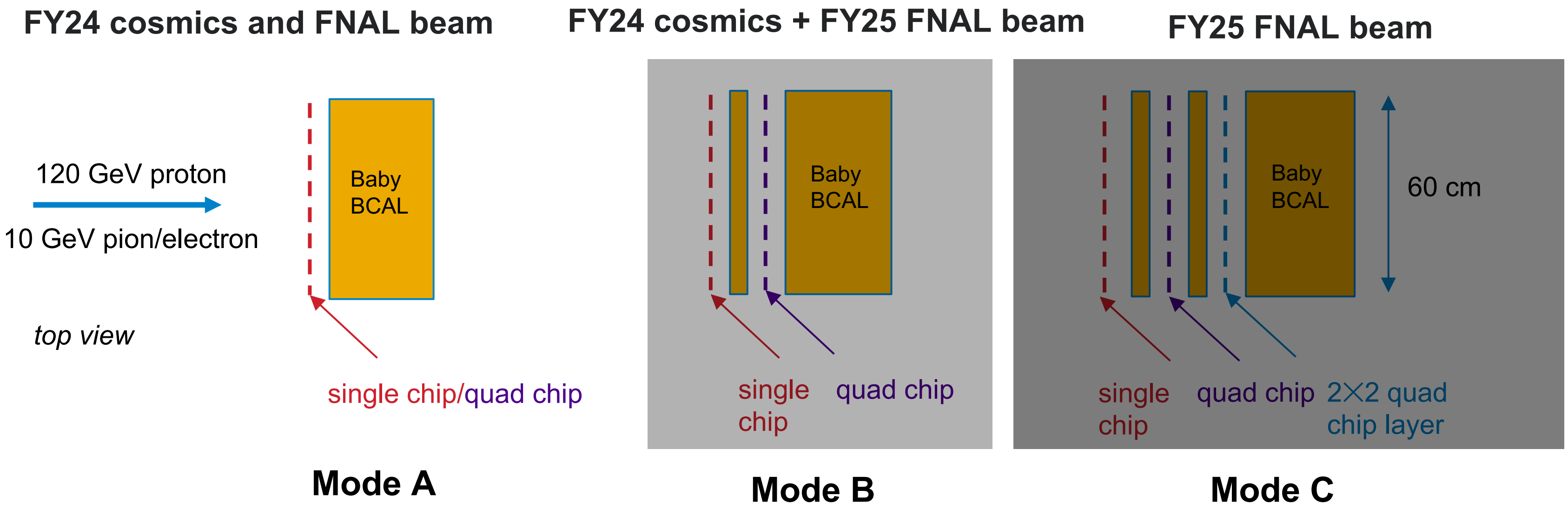
**Possible modes of system integration:**




SciFi imaging layer (SFIL)
v3 quad chip (4x4 cm²)
carrier board
v3 chip (2x2 cm²)
carrier board
GlueX Baby BCal
AstroPix3
120 GeV proton
10 GeV pion/electron
top view
Baby BCAL
Baby BCAL
Baby BCAL
60 cm
single chip/quad chip
single chip
quad chip
single chip
quad chip
2×2 quad chip layer
Mode A
Mode B
Mode C

# FY24 Situation

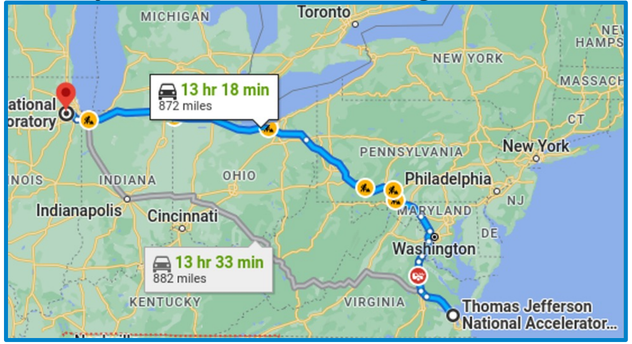
- Due to significant delays in start of the FTBF Beam facility in FY24, **(possibly) only spring ‘24 1 half-week is available -** originally estimated schedule **- 3 full weeks total together with T1224 experiment (ATLAS)**
- **Delays in receiving R&D funds** (Uni of Regina - mid March 2024, Argonne - last Wed)
    - Use cosmics, as much as possible, for integrations. However, readout system needs to be also commissioned in high-occupancy environment of the beam (MIPs/pion-electron).
    - Test SciFi/Pb response to pions (to fold it in the simulation and benchmark e/π response).



# Deliverables and Intermediate Results

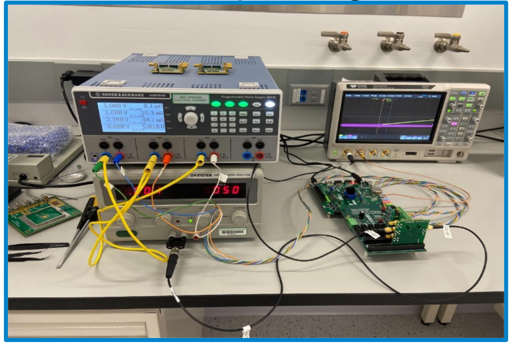
# FY24 R&D Phase I - Preparations

Baby BCal moved to Argonne

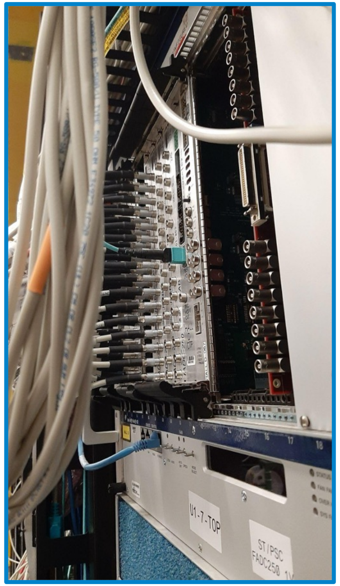



- Shipment of Baby BCAL, SiPM wedges, voltage distribution system, and cables ✅
- Final design of the system fixture ✅
- AstroPix telescope and Baby BCAL assembly ✅

AstroPix set up at Argonne



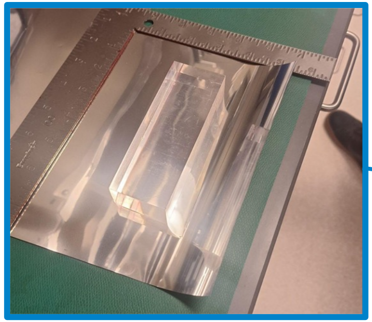
- Performance of chip v3 QA and noise threshold scans ✅
- Calibration with sources 🚧



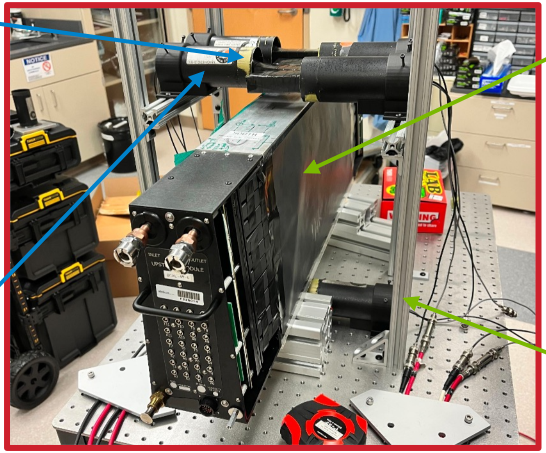
- Tests of the readout with the FADCs and the CODA-based DAQ system 🚧
- Tests of the AstroPix readout system with and without an external trigger 🚧
- Synchronization of both systems 🚧

**Deliverable (M1-M4): Integrated system with DAQ tested with cosmics/sources**

# FY24 R&D Phase I - Cosmic Setup



Baby BCal Setup for
Cosmics at Argonne

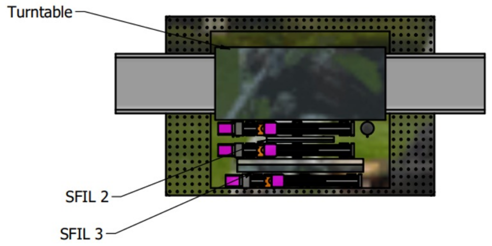


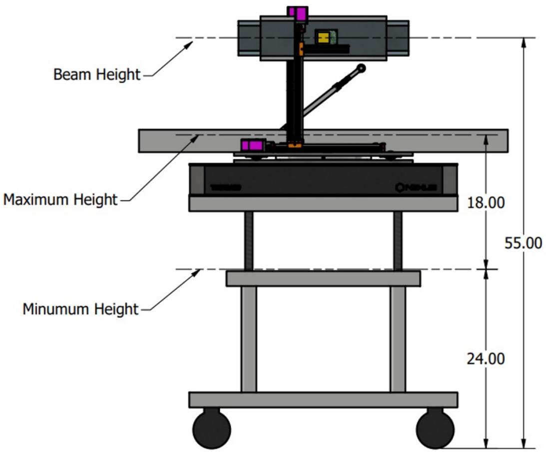

Preparation
and testing of
trigger paddles

Shipment and
assembly of
the setup

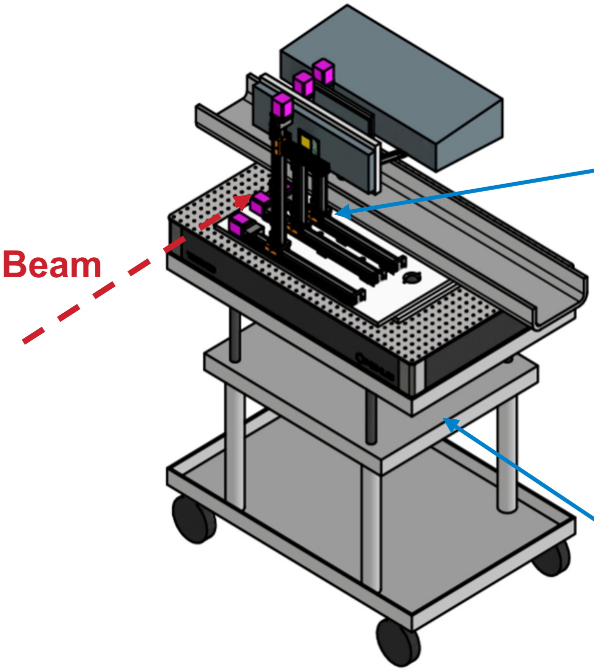
# FY24 R&D Phase I - Beam Test Setup

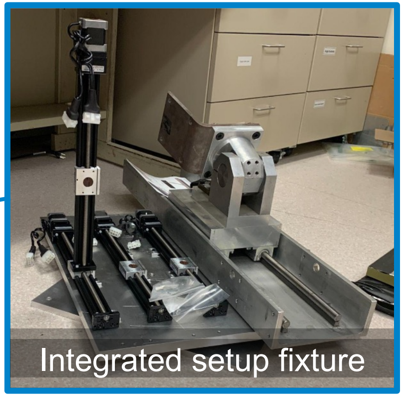
top view




side view



Integrated setup fixture

Baby BCal on a lift table

# FY24 R&D Phase I - Baby BCal Cosmic Tests

All channels tested on oscilloscope: Upstream (U) and Downstream (D) channels in coincidence

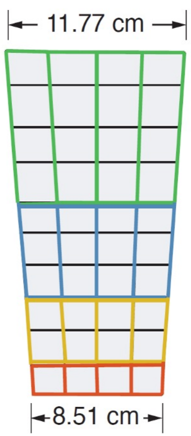
- S12045(X) SiPMs signal summed as shown below
- Only S10 channel has output (known) issue

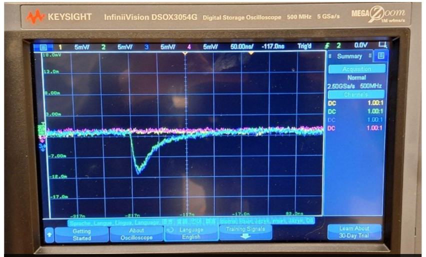
Work in progress on integration within JLab DAQ with fADC

*Baby BCal testing and data analysis: Henry Klest, Jonathan Zarling*

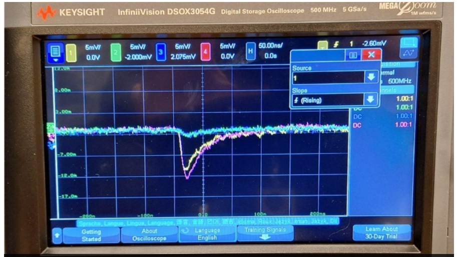
Example fADC amplitudes from a cosmic in Baby BCal

Channel numbering

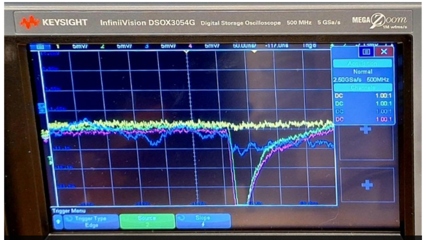


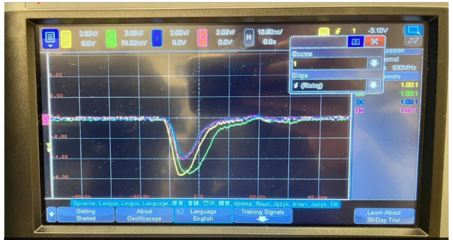
A0 U and D

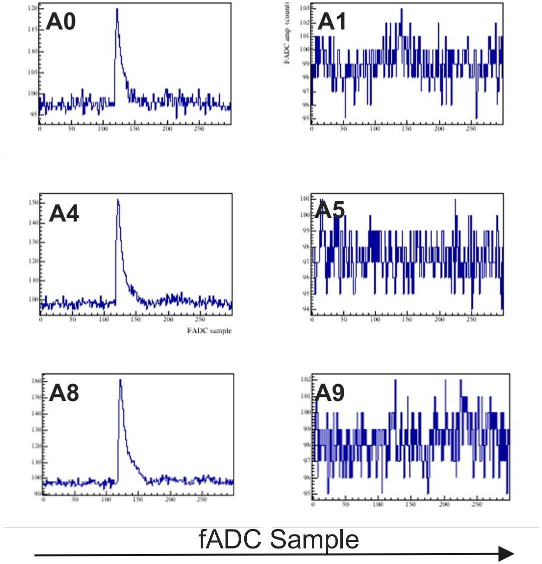


A1 U and D



A11 U and D + A10 issue

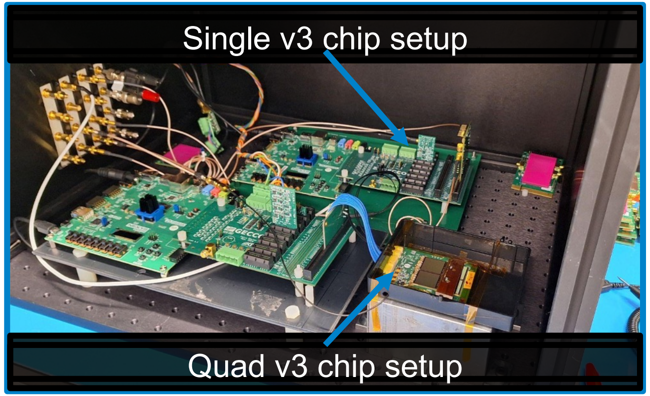

Trigger paddles in coincidence



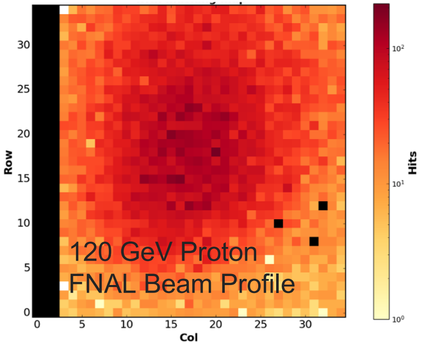
# FY24 R&D Phase I - AstroPix Preparations

- AstroPix v3 chips preparation: masking maps and optimal threshold studies
- Calibration with sources in progress and initial tests for the quad chip

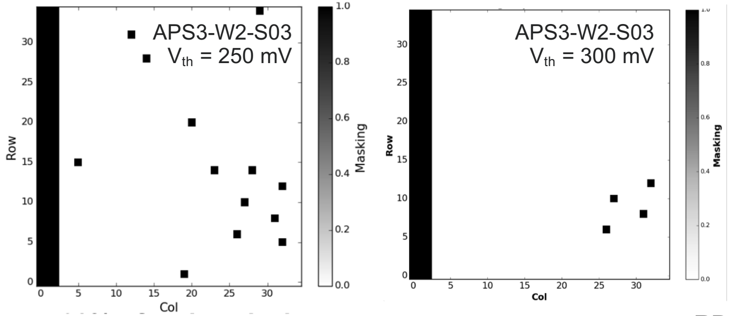
*Beam Test FY23 Results: Jihee Kim*
*Bench Tests FY24: Bobae Kim*



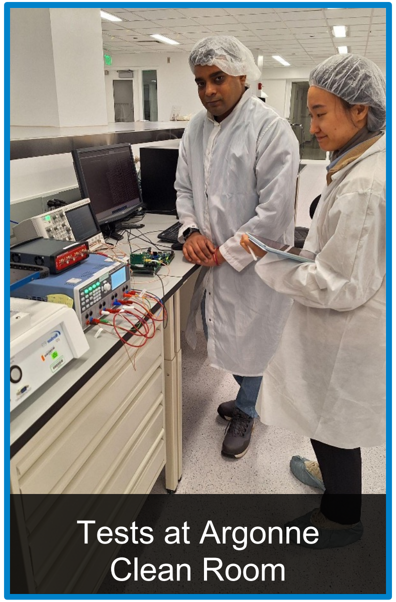

Example Beam Profile
FY23 Beam Test




Example Noise Scans




Analog Signal with Injection

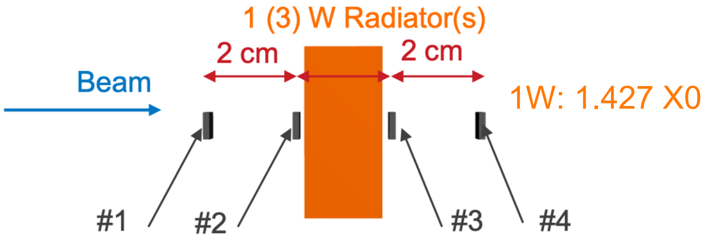



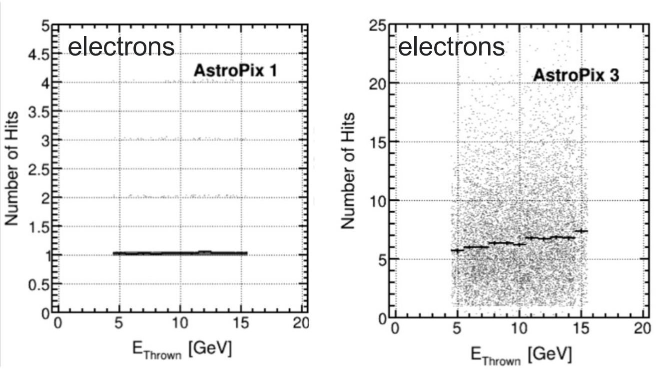
# FY24 R&D Phase I - Simulations

*AstroPix Simulations: Jihee Kim*
*Baby BCal Simulations: Jared Richards*

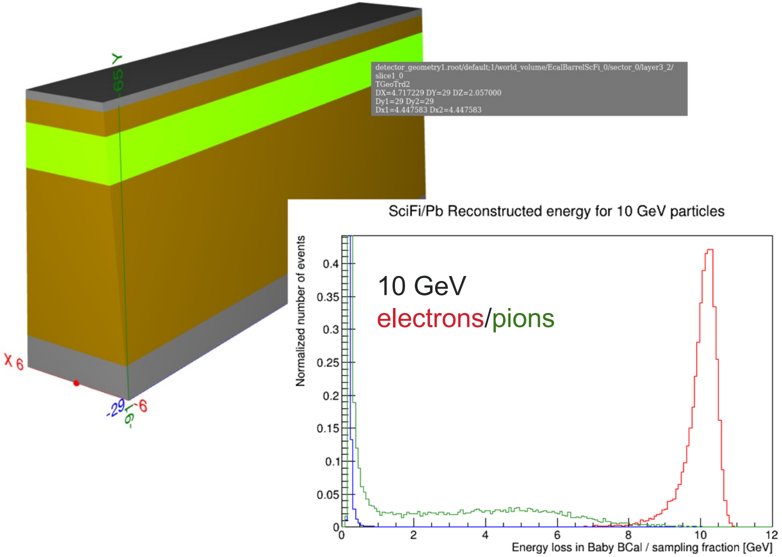
- **Full simulation of AstroPix and SciFi/Pb** matrix implemented for **ePIC**
- Simulation of effective response **including light attenuation and SiPMs responses** implemented
    - Based on measured phe statistics from FY23 Baby BCal beamtest in Hall D
- Current effort on implementing the **Baby BCal and AstroPix Prototype geometry**

AstroPix telescope simulations w/ and w/o radiator




Baby BCal geometry implementation

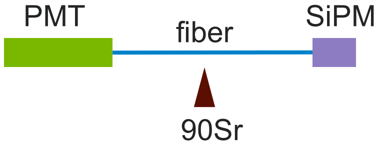


# FY24 R&D - Outlook on SFILs @URegina

## Phase III - beam and bench tests with SFILs (SciFi/Pb Imaging Layers)

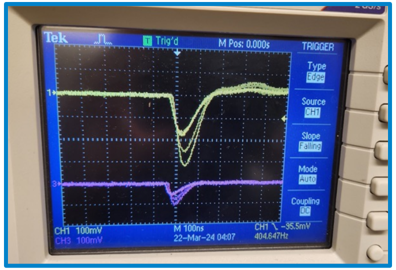
First prototype of custom SiPM readout board

- SensL/onsemi 3x3mm2 SiPM (26V)
- Two-stage amplification
- Initial tests with 90Sr source and scintillating fiber
- Next step: tests with S13360 & S14160 SiPMs with modified board

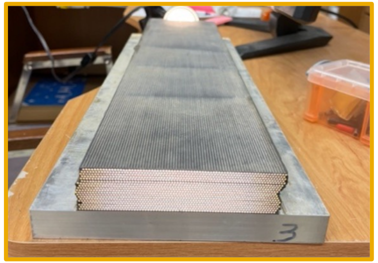


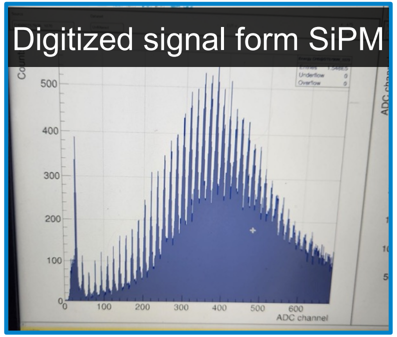

Aiming for 2 SFILs with 1-2 lightguides and SiPMs per side for initial bench and (maybe) beam tests ca. April 29

Prototype readout board tests with 90Sr



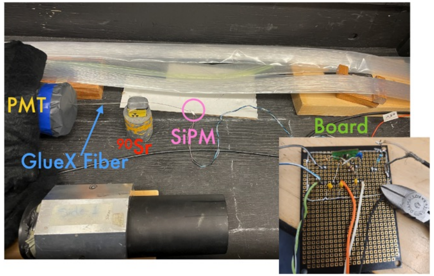

SciFi/Pb Imaging Layer





Digitized signal form SiPM

Test setup for the board



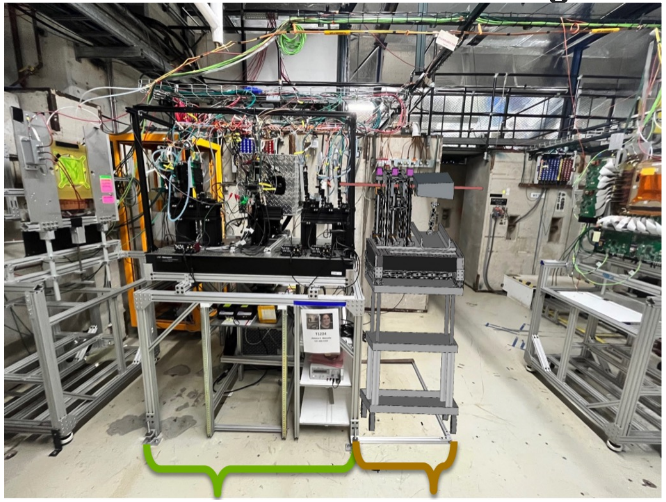

**Deliverables:**

**Commissioned system with SFILs DAQ (with cosmics FY24)**

**Comparison of light output with GlueX and new generation SiPMs**

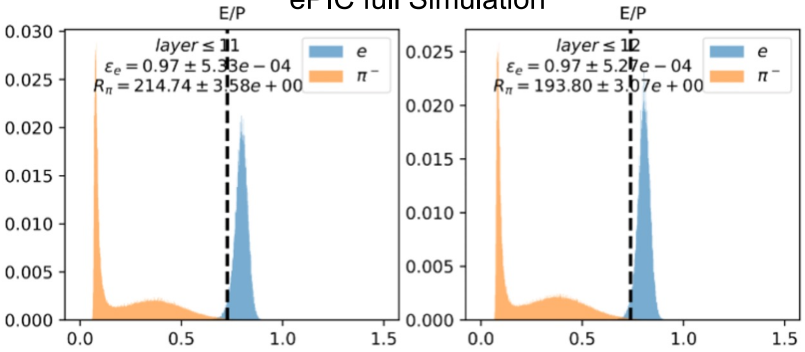
# FY24 R&D - Outlook on Possible FBTF Beam

Phase II - Commission integrated setup at the beam and collect pion/electron data



ATLAS Telescope    BIC Setup

ePIC full Simulation




Example sum dE in SciFi/Pb layers [GeV]

System commissioning:

- Test of DAQ with cosmics and in beam
- Relative gain calibration of photosensor

Energy spectrum for e/pi measured in Baby BCal:

- Detector system calibration
- Detector simulation of the e/π response
- Data analysis for E/p response

**Deliverable (M6-M7): Commissioned (Mode 1) system with DAQ in FNAL and energy response to π benchmarked**

# Milestones Summary

# FY24 R&D Milestones

| Milestone | Original Timeline* | Status |
|---|---|---|
| M1: Integrated setup with Baby BCal and AstroPix chip designed and built at Argonne | t0 + 3 months<br>Q1 FY24* | Done ✅ |
| M2: AstroPix chips prepared at the bench for integrated tests with Baby BCal - Q1 FY24 | t0 + 3 months<br>Q1 FY24* | Done ✅ |
| M3: Data Acquisition (DAQ) for the integrated system of Baby BCal and AstroPix chip designed and tested | t0 + 5 months<br>Q1-Q2 FY24* | In progress 🚧 |
| M4: Integrated prototype system tested at the bench with cosmics and/or source | t0 + 6 months<br>Q2 FY24* | In progress 🚧 |
| M5: SciFi Imaging Layer (SFIL) delivered by the University of Regina, integrated, and tested at the bench | t0 + 7 months<br>Q2-Q3 FY 24* | Not done ✖<br>Work on SFILs started in Regina |
| M6: Integrated system commissioned at the beam test facility with protons | t0 + 9 months<br>Q3 FY24* | Dependent on the FBTF beam availability ✖ |
| M7: Response to pions tested in the beam environment and e/pi separation benchmarked in the simulations | t0 + 12 months<br>Q3-Q4 FY24* | Dependent on the FBTF beam availability ✖ |

***Assuming Start of Funds in Q1 FY24 (funds available from March 2024)**

# Thank you

**More details:**

BIC Meeting on R&D, Wed March 6

https://indico.bnl.gov/event/22591/

# Backup

# Budget FY24

| Item | Units | Price per unit (USD) | Total price (USD) | Institution |
|---|---|---|---|---|
| Materials: SiPMs | 20 | $50 | $1,000 | ANL |
| Materials: Mechanical fixture for SIFLs | 1 | $2,000 | $2,000 | ANL |
| Materials: HV supply | 1 | $10,500 | $10,500 | ANL |
| Overhead on Materials | 18% | $13,500 | $2,400 | ANL |
| Postdoc - AstroPix + DAQ | 30% FTE | $150,000 | $45,000 | ANL |
| SFIL boards - design (industry contract) | 1 | $2,000 | $2,000 | Regina |
| SFIL boards - fab and assembly (industry contract) | 1 | $3,000 | $3,000 | Regina |
| Postdoc - Baby BCAL + SFILs | 25% FTE | $80,000 | $20,000 | Regina |
| Travel 7 days | 3 persons | $2,500 | $7,500 | Regina |
| **TOTAL:** | | | $93,400 | |

Materials to instrument, mount and readout SFILs

Postdoc FTEs for design and integration of DAQ, AstroPix tests, and beamtest

Design and fabrication of SiPM boards for SFILs

Postdoc FTEs for the installation and commissioning of the Baby BCAL and SFILs at FNAL, related bench tests, simulation and data analysis, travel for beamtests at FNAL

The R&D program is planned to be accomplished in FY24 (before the CD-2/3 stage)

# Open R&D questions

## To be completed with the R&D program before CD-3

**How detector performance obtained from detailed simulations compare with the measurements in the integrated SciFi/Pb and AstroPix prototype system?**

- Physics benchmark of energy response to pions
- Physics benchmark of e/π separation
- Technical benchmark of streaming readout of both technologies

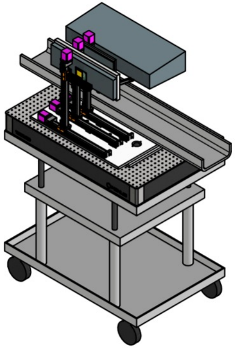
**How performance of modern family of SiPMs improves the SciFi/Pb part response wrt the GlueX BCAL response?**

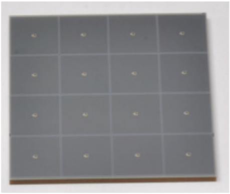
- Benchmark light response and calibrate simulations
- Impact on future design studies related to usage of optical cookies, shape of lightguides, etc.
  - **Photon Detection Efficiency** for GlueX SiPMs (Hamamatsu S12045(X)): ~33%
  - Modern family of SiPMs (e.g. s14160/14161): ~50% (see backup slides 18-20)

# FY24 R&D Plan and Deliverables

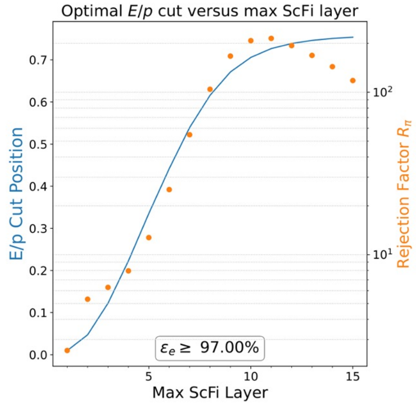
## Phase III - FNAL with Mode B/C setup

SFILs





14161-3050-04 array from Hamamatsu




Integration with SFILs and multi AstroPix Layers

- Design, production and assembly of the SiPMs boards for the SFILs
- Development of mechanical fixture of SFILs modules
- Integration of SFILs into DAQ

Electron/Pion separation benchmarking

- Detector system simulation
- Detector system calibration
- FNAL Cherenkov measurement of beam composition
- Data analysis from the integrated system

**Deliverables:**
**Commissioned system with SFILs DAQ in FNAL**
**Benchmarked electron/pion separation**
**Comparison of light output with GlueX and new generation SiMPs**

# SciFi/Pb - R&D FY23

### R&D goals with GlueX Baby BCal prototype

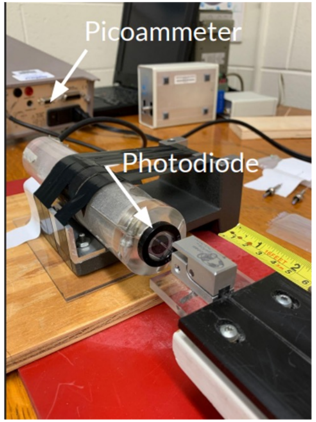
- **SciFi/Pb tested** extensively in for energies **$E_\gamma$ < 2.5 GeV**
- **Higher-energy data** important to constrain the constant term of energy resolution
- Obtain **responses to EM showers** to benchmark simulations and provide input to realistic **waveform analysis - Hall D, electrons** (up 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

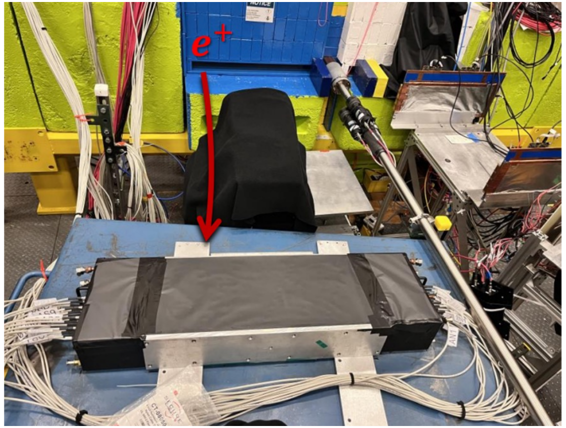
- **Light output and attenuation length** measurements at University of Regina with single- and double-clad fibers from Kuraray and Luxium - ongoing (M. Kerr talk)

Baby BCal ~ 15.5 $X_0$

Setup at Uni of Regina




Setup at Hall D, JLab



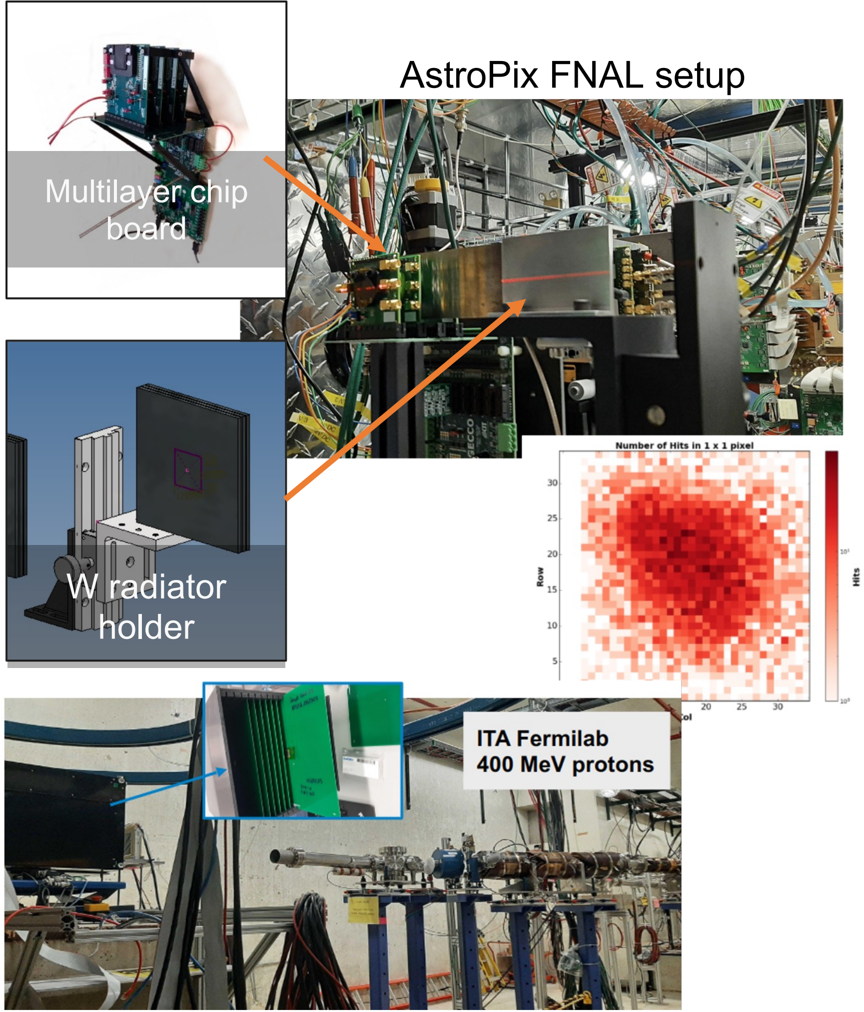
# Imaging layers - R&D FY23

**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

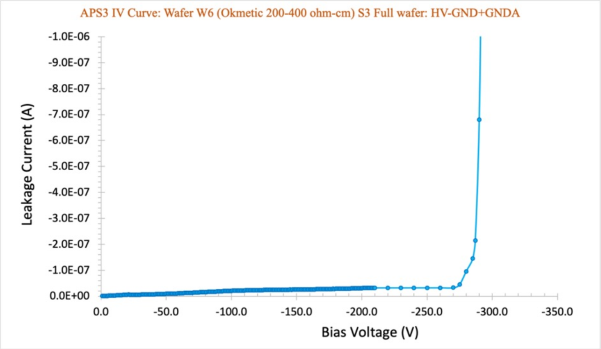


# Snapshots from the Sensor Irradiations

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

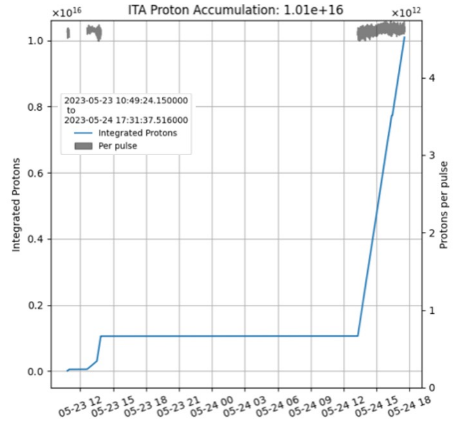



## V2 Irradiation

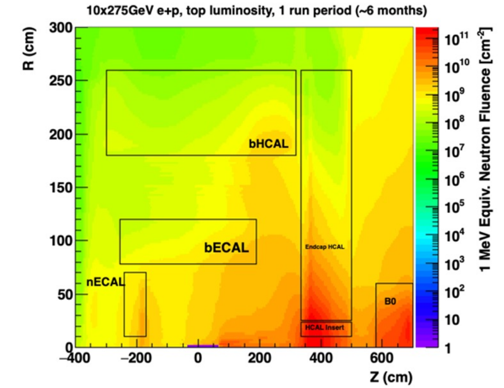
| Nb of samples | Doses (400 MeV protons) |
|---|---|
| 3 | 4.50E+13 |
| 3 | 1.08E+15 |
| 2 | 1.01E+16 |
| 1 | 5.02E+16 |

## 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




# SciFi/Pb layers technology

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

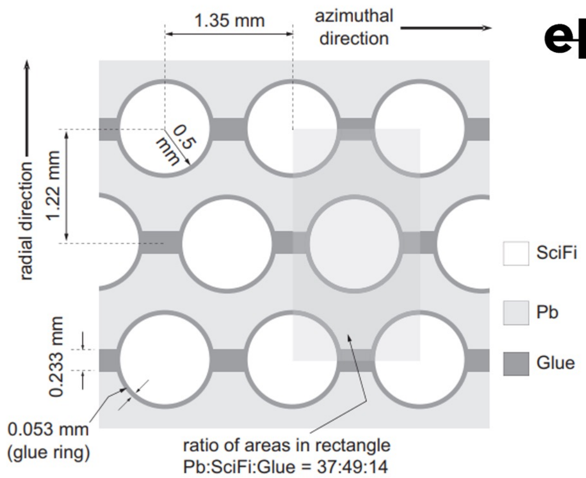
- 15.5 $X_0$, extracted for low energy photons < ~2.5 GeV

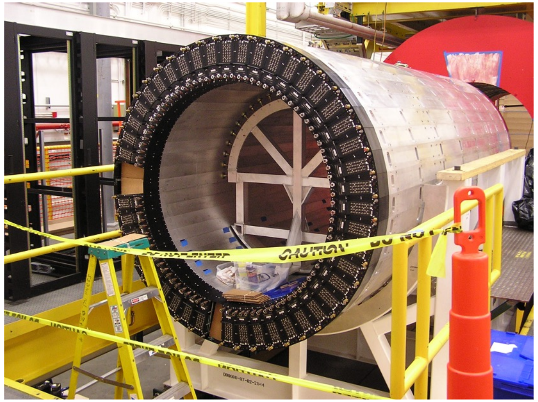
**Position resolution in z:** $1.1\text{cm}/\sqrt{E}$ [2)]

- 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

# 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]

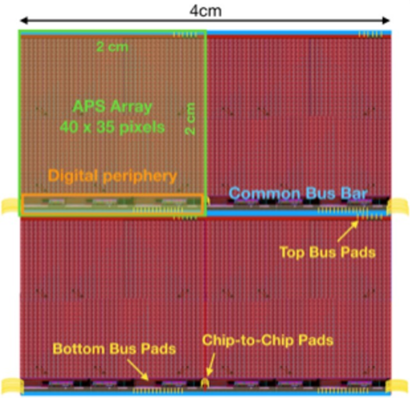
**v3** (2×2 $cm^2$, 500 μm pixel, **quad chip**)

- 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 v3 performance goals

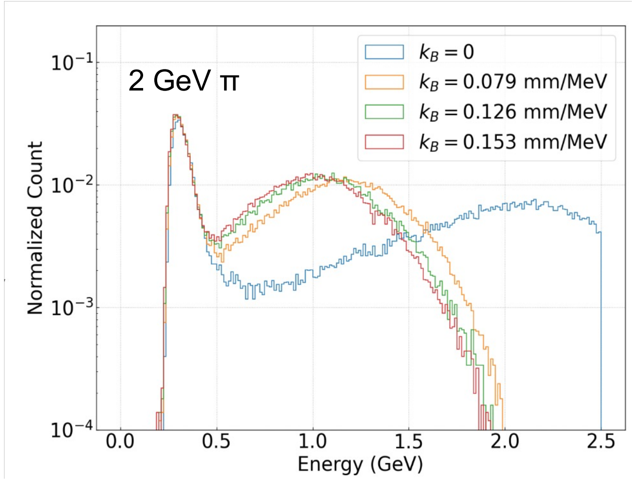
| | |
|---|---|
| Pixel size | $500\,\mu m \times 500\,\mu m$ |
| Power usage | $< 1$ mW/$cm^2$ |
| Energy resolution | 10% @ 60 keV (based on the noise floor of 5 keV) |
| Dynamic range | $\sim 700$ keV |
| Passive material | $< 5\%$ on the active area of Si |
| Time resolution | 25 ns |
| Si Thickness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

# Pb/ScFi

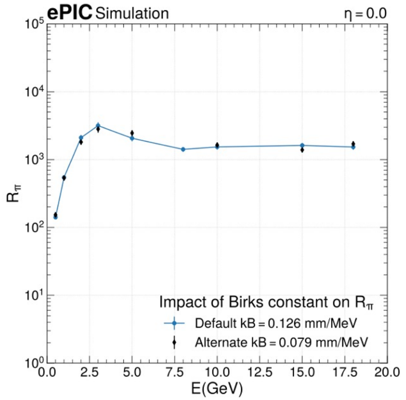
## Confidence in the hadron rejection simulation

**Birk's constant**

- FTFP_BERT physics list and 0.126 mm/MeV Birks constant
  - **The response to pions** in Barrel ECal changes slightly while changing the Birks constant ~38%
  - The larger the Birks constant the better E/p separation (pion responses are more "squished", see the plot)
  - We have shown that **the e/π response leans heavily on imaging layers** (tested with kB = 0.079 mm/MeV with current geometry and stand alone simulations with extreme kB = 0)




| Material | kB [mm/MeV] | Source link |
|---|---|---|
| SCSF-78 | 0.132 ± 0.004 | arXiv:2007.08366 |
| BC-408 | 0.155 ± 0.005 | arXiv:2007.08366 |
| Polystyrene fiber, Kuraray SCSF– 81SJ | 0.126 | arXiv:1106.5649 |
| SCSN-38 | 0.079 | DOI: 10.1109/23.159657 |

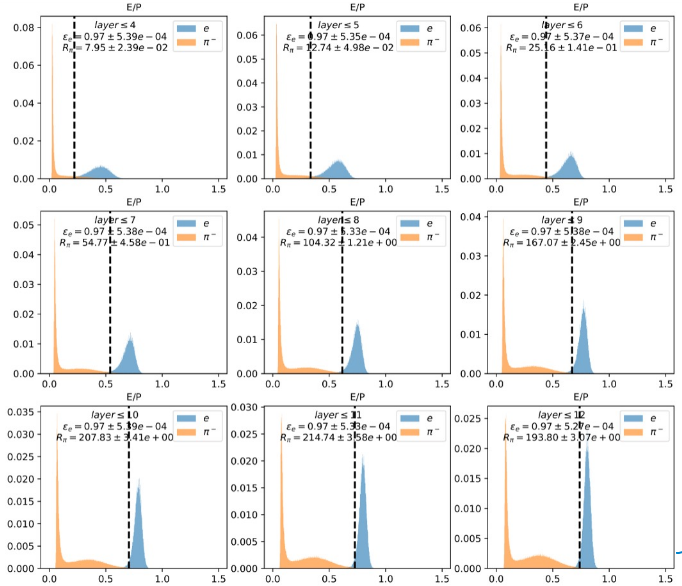


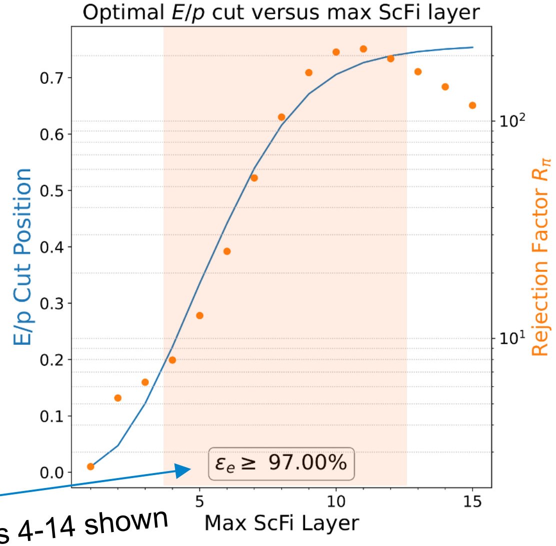
# e/π Separation in Barrel ECal - Method

**Steps:**

1. **Optimized cut on E/p** from different depth of Pb/ScFi layers at very high electron efficiency
2. **Convolutional neural network** utilizing energy and spatial information for shower (see backup slides for details)

Example for 2 GeV e/π

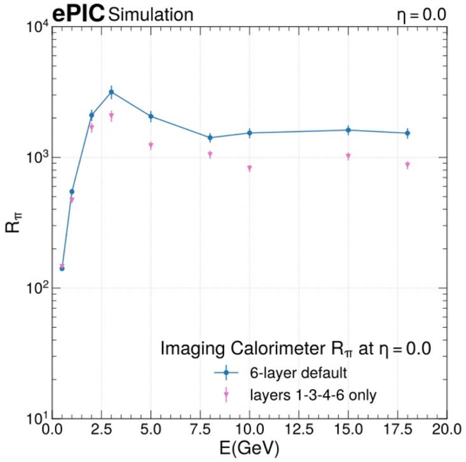


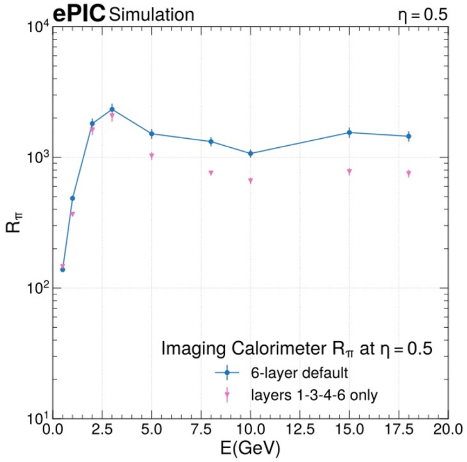



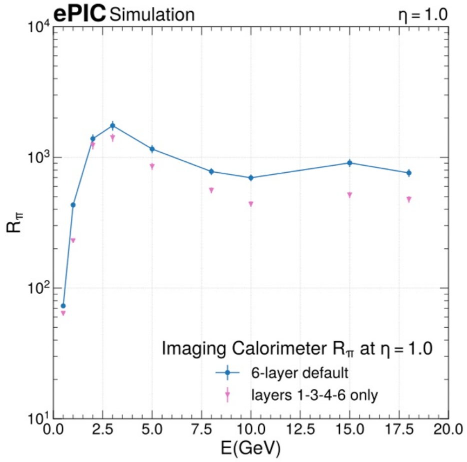

ScFi layers 4-14 shown

# Performance with reduced number of layers

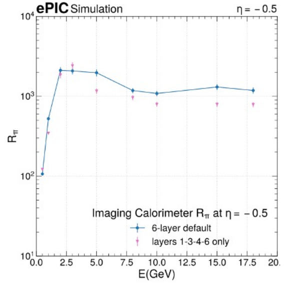
## e/π separation at 95% efficiency

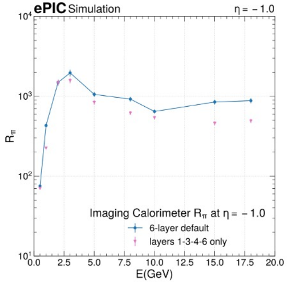



**4-layer alternate**: layers 1-3-4-6




**Default configuration** exceeds $10^3$ pion rejection almost everywhere

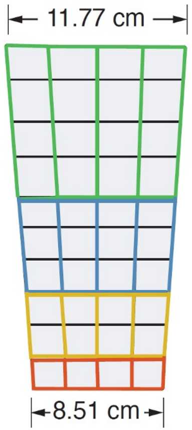
**4-layer alternate** still performs relatively well at lower energies (where most rejection is needed), larger degradation at higher energies

**4-layer alternate seems workable compromise.**

# SiPM Readout

- **2-side SiPM readout**
- **Lightguides** attached to the sector sides
  - inner surface ~2×2 $cm^2$
  - output face 1.3×1.3 $cm^2$
- SiPMs: S14161-6050-04 array (4x4 array of 3×3 $mm^2$, 50×50$\mu m^2$ pixels)
- 12 layers x 5 cells x 2 sides x 48 sectors = 5760 channels

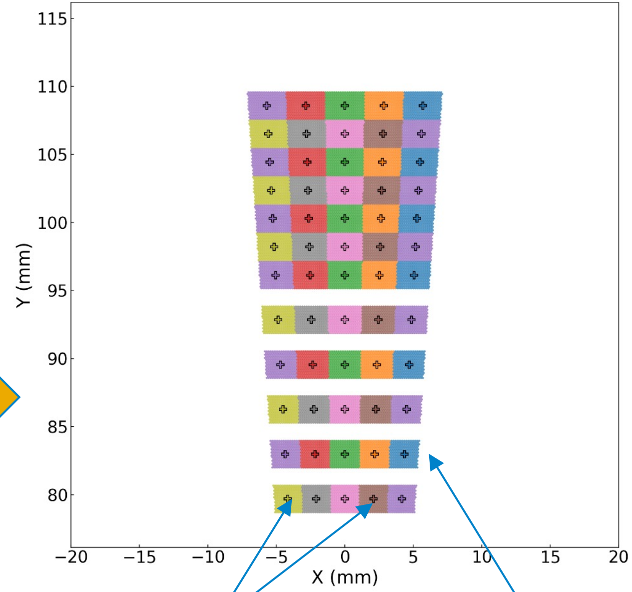
**GlueX**
1/48$^{th}$ of the barrel end view




Hamamatsu S12045(X)
4×4 array of 3×3 $mm^2$
50×50$\mu m^2$ pixels

16 FADC per side
12 TDC per side

**ePIC** Sector End View
(x-y plane view)




Readout **Cell**
Layer = 5 cells

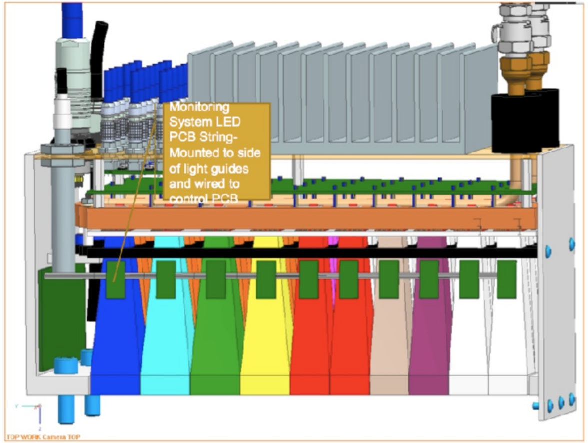
*The area 1 light guide is attached*

Pb/Sci **Layer**

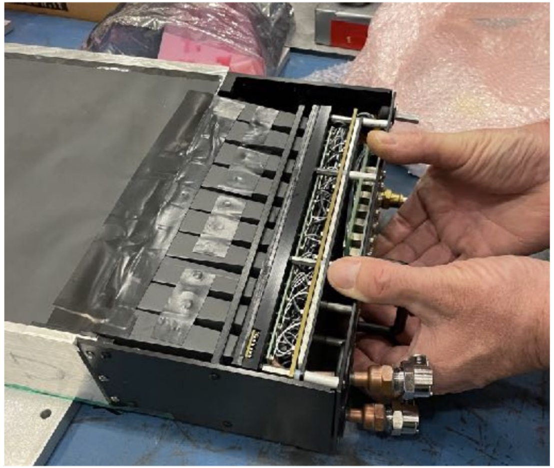
1 sector = 12 layers
1 layer = 17 rows of fiber

# 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



Baby BCAL prototype readout box