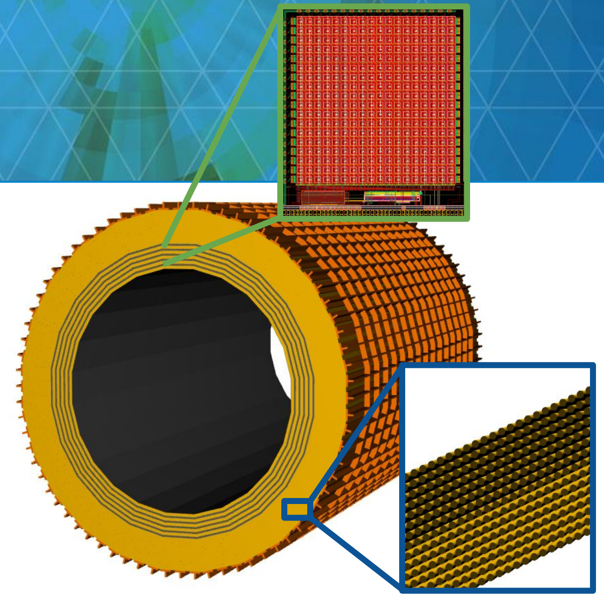
EIC Project R&D - DAC Meeting

Barrel Imaging Calorimeter

Project EIC Detector R&D Program

eRD115 Proposal



08/28/2023

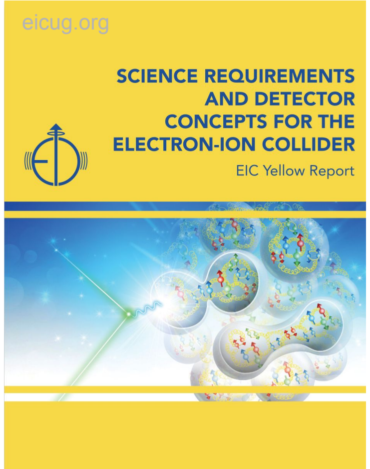
Maria Żurek *for the Barrel Imaging Calorimeter DSC*

EIC Calorimetry Requirements
Barrel ECAL in EIC Yellow Report

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

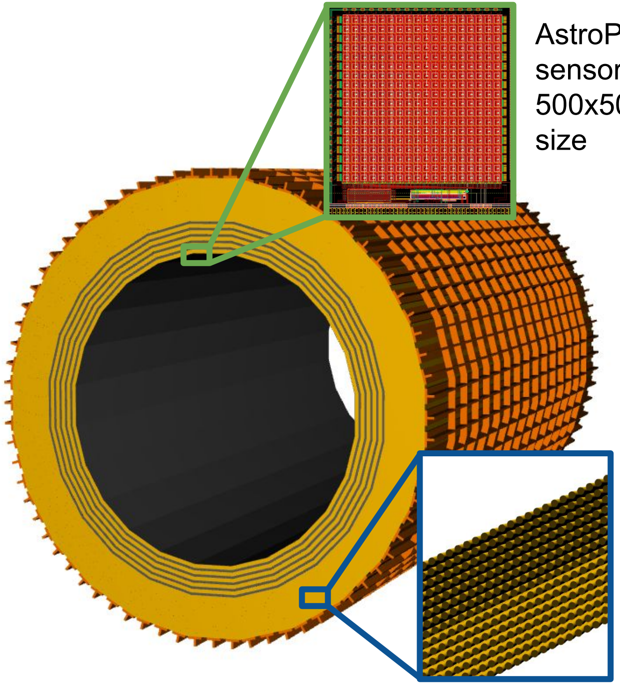
EIC Yellow Report requirements for Barrel EM Calorimeter

- 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 **π^0 decays and single γ up to ~10 GeV**
- **Low energy photon** reconstruction ~100 MeV



Challenges: e/π PID, γ/π^0 discrimination, available space

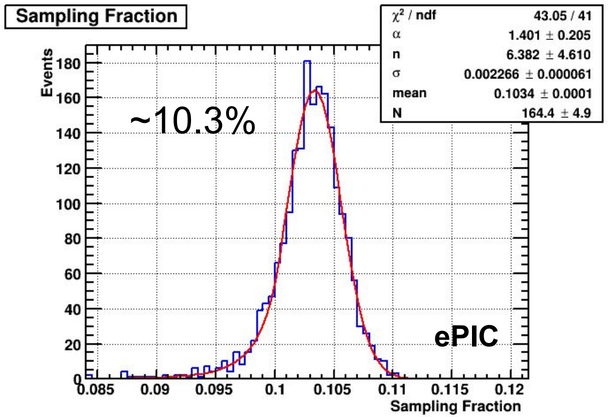
Barrel Imaging ECal: General Overview



AstroPix: silicon sensor with $500\text{x}500\mu m^2$ 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%



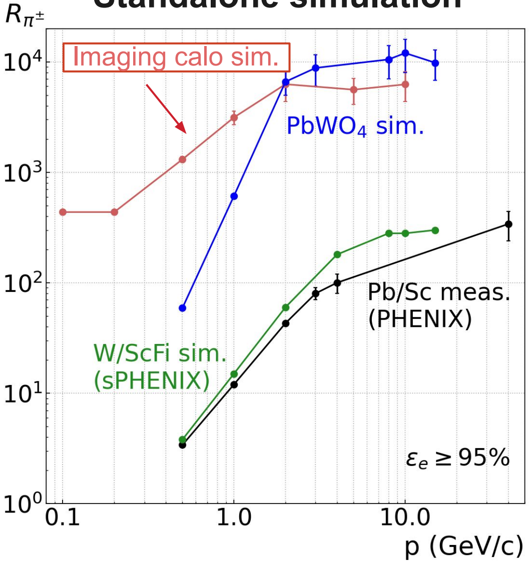
Simulations of **single photons** at η=0 (~17.1 X_0)

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

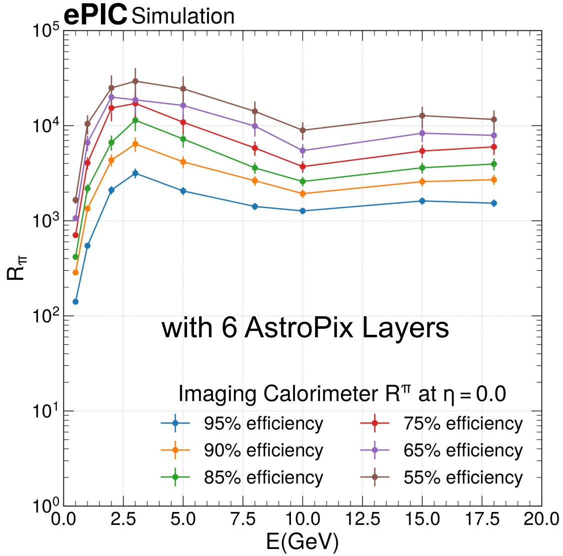
Energy resolution - Primarily from Pb/ScFi layers (+ Imaging pixels energy information)
Position resolution - Primarily from Imaging Layers (+ 2-side Pb/ScFi readout)

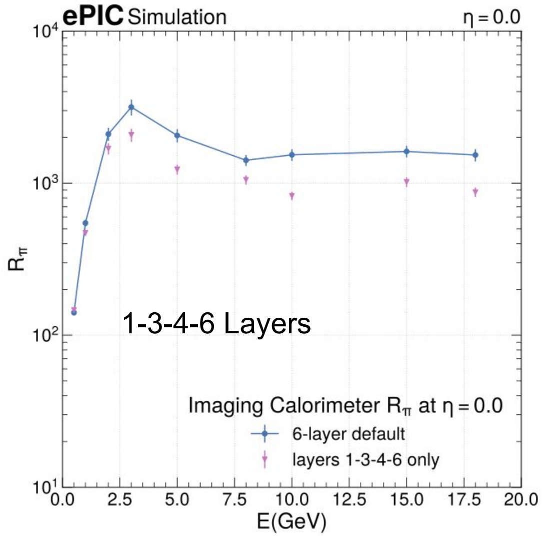
Barrel Imaging ECal: Performance Example

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!

Imaging Barrel ECal: Technology R&D needs

SciFi/Pb Barrel technology:

- Mature: GlueX, KLOE Barrel EMCal
- Tested extensively for electromagnetic response in energies **E_γ < 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:

Feasibility of using in the environment of EIC:

- higher energy particles
- integrated with the AstroPix sensor layers
- benchmarking of high energy simulation performance (e.g., e/π separation)

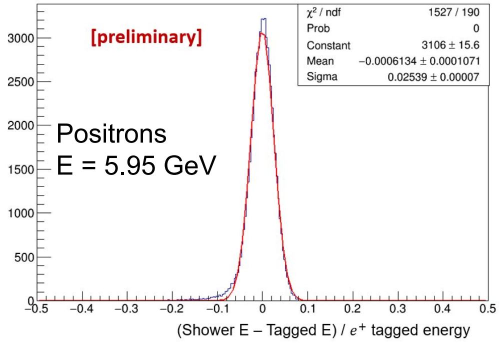
1) GlueX, Nucl. Instrum. Meth. A, vol. 896, pp. 24–42, 2018

Snapshot of FY23 R&D:

Hall D, March 2023
Baby BCAL Test

Measured Resolution: ~ 2.5%

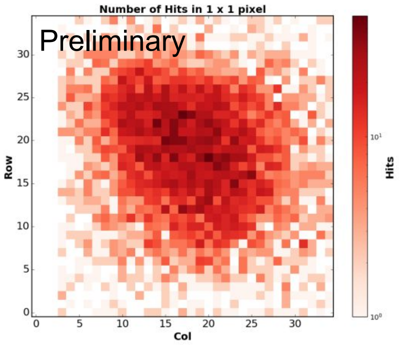
Extrapolated GlueX NIM[1)]: ~4.2%



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: *"**No prototypes** or more detailed engineering test articles **of the hybrid system** are available. (...)"*

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

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

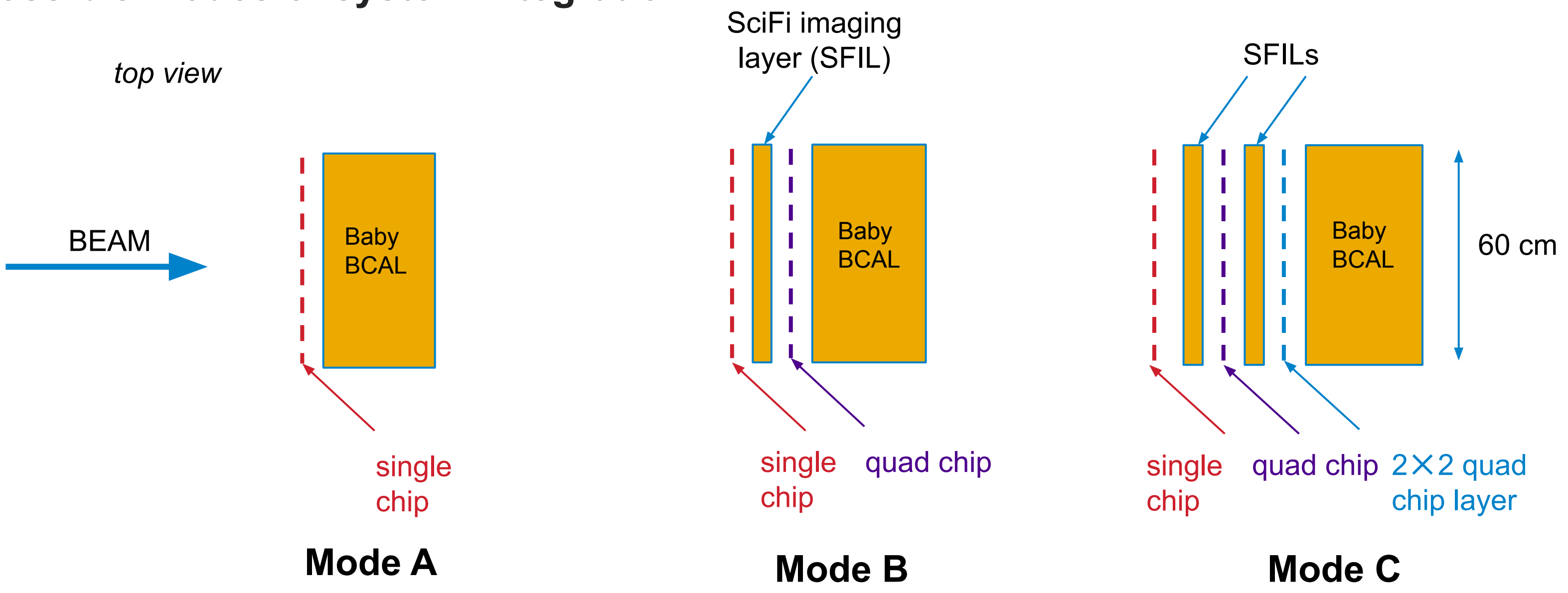
How performance of modern family of SiPMs improves the SciFi/Pb part response wrt the GlueX BCAL response?

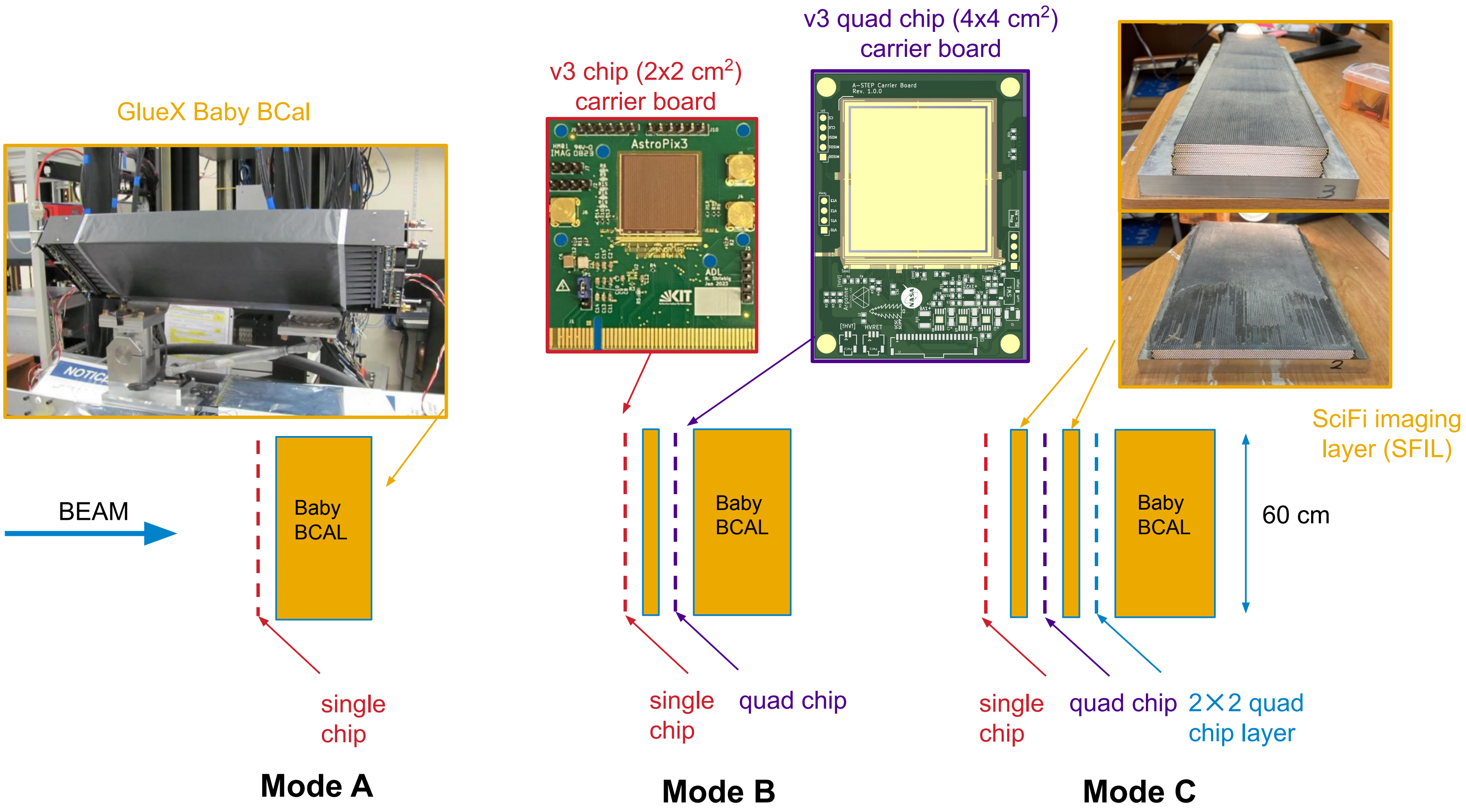
- Benchmark light response and calibrate simulations
- Impact on future design studies related to usage of optical cookies, shape of lightguides, etc.
  - **Photon Detection Efficiency** for GlueX SiPMs (Hamamatsu S12045(X)): ~33%
  - Modern family of SiPMs (e.g. s14160/14161): ~50% (see backup slides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

FY24 R&D Goals

Goal: Characterize the integrated system with a mixed e/π beam and mips, benchmarking the response to charged pions, testing the electron-pion separation capability, and extracting the No of phe with new generation SiPMs.

Possible modes of system integration:




GlueX Baby BCal
v3 chip (2x2 cm^2) carrier board
v3 quad chip (4x4 cm^2) carrier board
AstroPix3
SciFi imaging layer (SFIL)
BEAM
Baby BCAL
single chip
Mode A
Baby BCAL
single chip
quad chip
Mode B
Baby BCAL
60 cm
single chip
quad chip
2×2 quad chip layer
Mode C

FY24 R&D Milestones

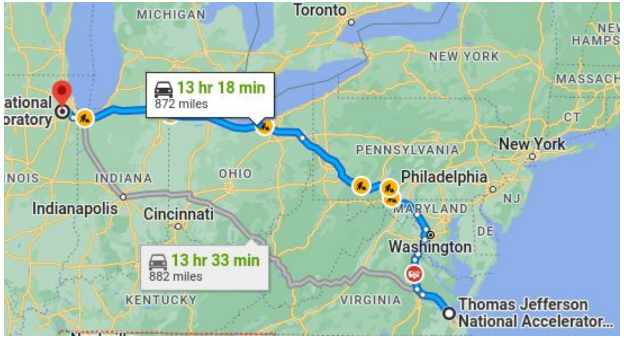
Milestone	Timeline	Experimental condition
M1: Baby BCAL setup complete in FNAL	Q1 FY24	-
M2: AstroPix chip v3 bench preparations completed	Q1 FY24	bench, source
M3: DAQ for the integrated system of Baby BCal and AstroPix chip ready	Q1 FY24	bench, source, cosmics
M4: Integrated system (Baby BCAL + AstroPix chip) commissioned in FNAL - Mode A	Q1 FY24	cosmics, p, e/π beam
M5: Energy spectrum for e/π measured and benchmarked	Q1-Q2 FY 24	e/π beam

FY24 R&D Milestones

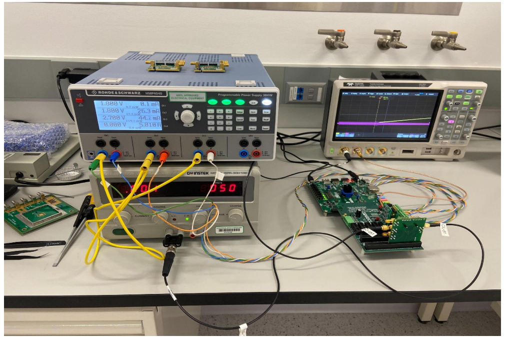
Milestone	Timeline	Experimental condition
M6: SFILs readout with SiPMs installed	Q2 FY24	bench, source, cosmics
M7: SFILs integrated into DAQ	Q2 FY24	bench, source, cosmics
M8: System with SFILs commissioned at FNAL	Q2-Q3 FY24	cosmics, p, e/π beam
M9: Electron/Pion separation benchmarked against FNAL Cherenkov threshold counter	Q2-Q4 FY24	e/π beam
M10: Performance with new generation SiPM compared (SFILs)	Q2-Q4 FY24	e/π beam

FY24 R&D Plan and Deliverables

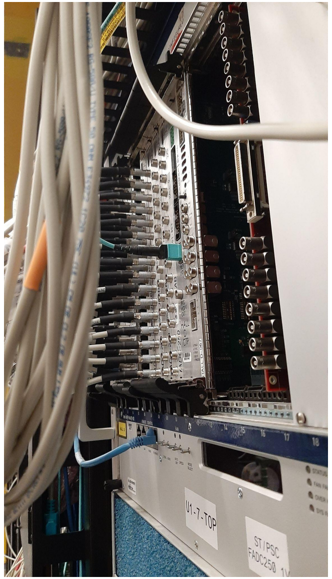
Phase I - Preparations - Q1 FY24



- Shipment of Baby BCAL, SiPM wedges, voltage distribution system, and cables to ANL/FNAL
- Final design of the system fixture
- AstroPix telescope and Baby BCAL assembly at FNAL



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



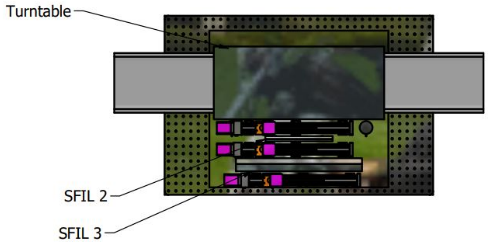
- Tests of the readout with the FADCs and the CODA-based DAQ system with and without an external trigger
- Tests of the AstroPix readout system with and without an external trigger
- Synchronization of both systems

Deliverable (M1-M3): Integrated system (Mode A) with DAQ in FNAL

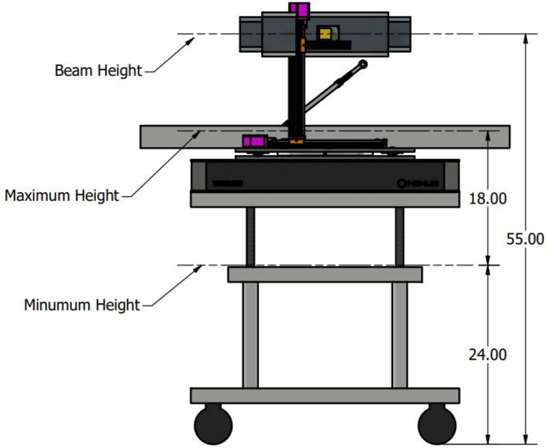
FY24 R&D Plan and Deliverables

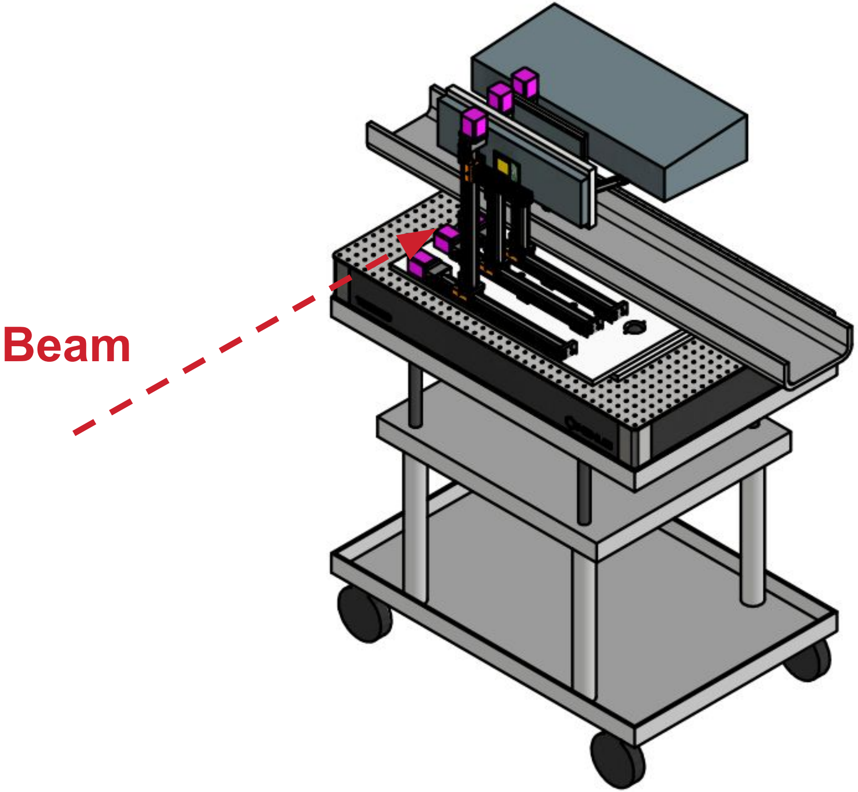
Phase I - Preparations - Q1 FY24

top view



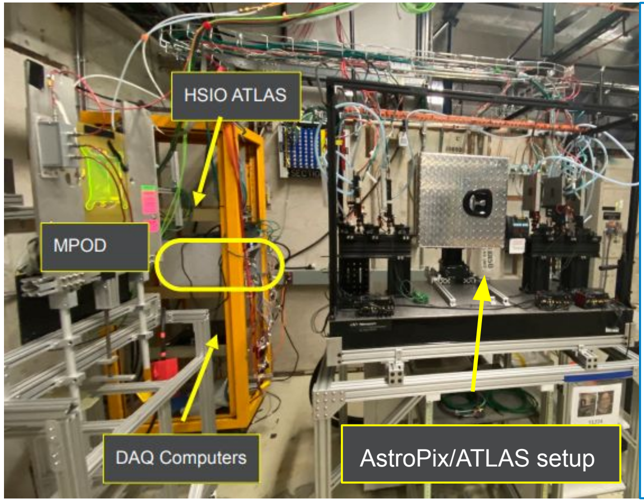
side view





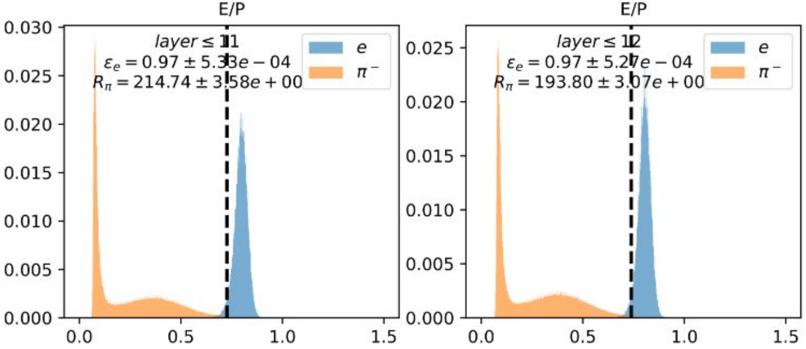
FY24 R&D Plan and Deliverables

Phase II - Commissioning at FNAL with Mode A setup (1st beamtime Q1)



Space for Baby BCal 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:

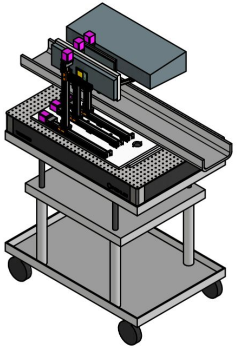
- Detector system calibration
- Detector simulation of the e/π response
- Data analysis for E/p response

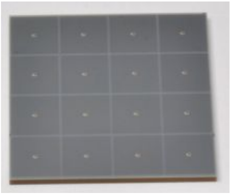
Deliverable (M4-M5): Commissioned system with DAQ in FNAL and energy response to π benchmarked

FY24 R&D Plan and Deliverables

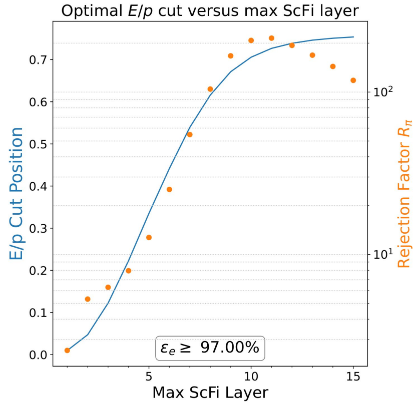
Phase III - FNAL with Mode B/C setup (2nd and 3rd beamtime Q2-Q3)

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 (Q4)

Deliverables (M6-M10):

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

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)

Backup

Photon Detection Efficiency: GlueX SiPM Parameters

Methodology for the Determination of the Photon Detection Efficiency of Large-Area Multi-Pixel Photon Counters

T. Beattie, G. J. Lolos, Z. Papandreou, A. Yu. Semenov, and L. A. Teigrob

***Abstract*—Large-area, multi-pixel photon counters will be used for the electromagnetic Barrel Calorimeter of the GlueX experiment at Jefferson Lab. These photo sensors are based on a 3×3 mm^2 cell populated by 50 μm pixels, with 16 such cells tiled in a 4×4 arrangement in the array. The 16 cells are summed electronically and the signals are amplified. The photon detection efficiency of a group of first-article units at room temperature under conditions similar to those of the experiment was extracted to be $(28 \pm 2(stat) \pm 2(syst))\%$, by employing an analysis methodology based on Poisson statistics carried out on the summed energy signals from the units.**

***Index Terms*—Multi-photon pixel counters, photon detection efficiency, silicon photomultipliers.**

I. Introduction

MODERN particle physics experiments and medical applications have placed technical demands that cannot often be met by photomultipliers (PMTs). Indeed, there has been a flurry of activity in the development and application of silicon photomultipliers (SiPMs). These offer immunity to Tesla-level magnetic fields, compactness, high ($\approx 20\%$) photon detection efficiency (PDE) and operation below 100 V, while preserving many of the PMT's other attributes. In addition, SiPMs provide excellent photoelectron peak separation provided that dark current is kept low, the latter reduced either by using mm^2-sized or by cooling cm^2-sized devices. The evolution of the field, including large-scale applications of SiPMs in particle physics detectors and applications to related fields, is available in a comprehensive review [1].

SiPMs are known by other acronyms with a common one being Hamamatsu's (Hamamatsu Corporation, Bridgewater, NJ 08807, USA (sales.hamamatsu.com)) Multi-Pixel Photon Counters (MPPCs). These devices are comprised of an array of limited Geiger-mode avalanche photodiodes on a silicon substrate. The electronic circuit of an MPPC is the parallel sum of its individual pixels/diodes. Each pixel is a silicon Avalanche Photo Diode (APD) typically based on "n on p" structure. The avalanche in these APDs is quenched by a silicon resistor that is in series with the pixel [2]. A common inverse bias voltage is provided to all APDs, so as to operate the device at a few volts above the break down point, V_{br} and the signals may include after-pulsing and cross talk [3].

II. Large-Area MPPCs for the GlueX BCAL

The GlueX Experiment aims to elucidate the confinement property of quantum chromodynamics by mapping out the spectrum of exotic hybrid mesons [4], [5]. A hermetic detector is needed for this task, a key sub-system of which is the electromagnetic barrel calorimeter (BCAL) [6]. The BCAL is a lead-scintillating-fibre sampling calorimeter that will reside inside a 2 T superconducting solenoid.

Our collaboration investigated various solutions for the BCAL readout, among them hybrid photodiodes [7]. None of those, however, could satisfy the simultaneous requirements of magnetic field tolerance, minimization of light losses from calorimeter to sensor, high gain and compactness. In addition, the BCAL readout granularity demanded readout cell areas of ≈ 1.3 cm^2. To this end, we focused our attention on SiPMs and embarked on a multi-year collaboration with a photonics firm (SensL - Ireland, 6800 Airport Business Park Cork, Ireland (sensl.com)) that eventually led to the development of the very first large-area tiling based on a 3×3 mm^2 cell with 35 μm pixel size [8]. The potential of such a device in particle physics applications and in related fields was apparent, as evidenced by other companies eventually producing similar devices. The GlueX configuration is one of the standards now available commercially from several firms.

In the end, Hamamatsu was selected to produce MPPC arrays for the BCAL. The chosen S12045(X) units were configured in 4×4 array of 3×3 mm^2 cells based on a 50 μm pixel, which yields 57,600 pixels per array. These devices deliver a nominal gain of 6×10^5 at 25°C; a schematic is reproduced in Fig. 1. The BCAL's 3840 units are fully operational and are currently being gain-calibrated using cosmic rays and high-energy photons from π° decays.

III. Evaluation and Quality Control

A detailed description of "first-article" (first 80 units from the production) MPPC arrays and initial evaluation tests on gain, dark noise, cross talk, temperature dependence and radiation hardness have been published by our colleagues at Jefferson Lab [9]. The devices will be cooled to $+5^\circ$ in order to reduce their

Manuscript received December 27, 2014; revised March 20, 2015; accepted May 27, 2015. Date of publication July 17, 2015; date of current version August 14, 2015. This work was supported by NSERC grant SAPJ-326516 and by Jefferson Science Associates, LLC, who operate Jefferson Lab under U.S. DOE Contract DE-AC05-06OR23177.
The authors are with the Department of Physics, University of Regina, Regina, SK S4S 0A2, Canada (e-mail: semenov@jlab.org).
Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.
Digital Object Identifier 10.1109/TNS.2015.2442262

PDE value for 11 SiPM units from our measurements of 28% ± 2% (stat) ± 2% (syst), for these Hamamatsu large-area arrays for 0.9 V and at 460 nm.

The average PDE of (24 ± 2)% for 3000 units measured by USM at 0.9 V was extracted at a wavelength of 518 nm. The PDE varies as a function of wavelength, with it being larger by a factor of 1.11 in going from 518 nm to 460 nm according to the manufacturer. This correction increases the USM number to ~27% at 460 nm, consistent with the result reported herin.

https://ieeexplore.ieee.org/document/7161418

Measurements at USM:

Characterization of novel Hamamatsu Multi Pixel Photon Counter (MPPC) arrays for the GlueX experiment:
https://www.sciencedirect.com/science/article/pii/S0168900213009042

Novel Hamamatsu Multi-Pixel Photon Counter (MPPC) array studies for the GlueX experiment: New results
https://www.sciencedirect.com/science/article/pii/S0168900213017233

Photon Detection Efficiency: GlueX SiPM Parameters

PDE ~33%

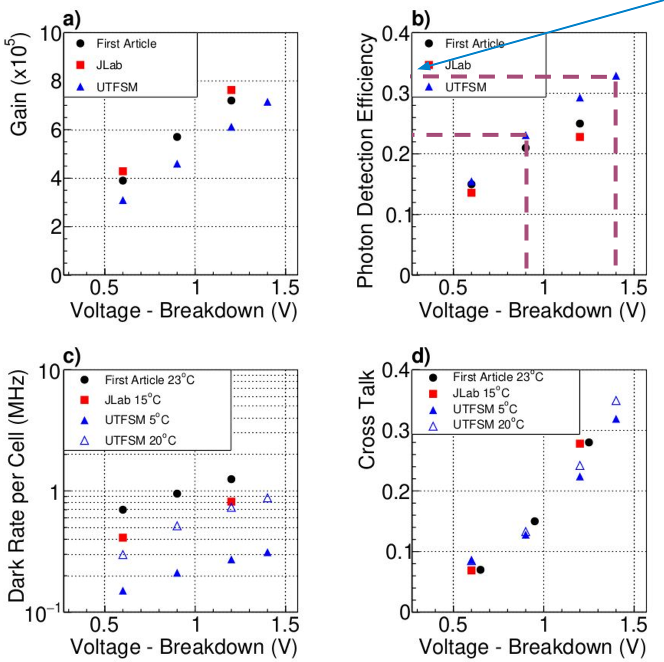


Figure 4: Measurements of the first-article samples (black circles) [20, 25], production samples at JLab (red squares) and production samples at UTFSM (triangles) [21, 22] of four basic SiPM parameters as a function of the voltage over breakdown. a) gain, b) photon detection efficiency, c) dark rate per tile (the dark rate for the array is 16 times higher) and d) cross talk determined from deviations of the single-pixel distributions from a pure Poisson function. As long as the voltage over breakdown is kept constant, the dark rate is the only parameter that has a significant temperature dependence. The nominal operating voltage for the GlueX experiment is 1.4 V above breakdown. (Color online)

The Hamamatsu specification sheets provide the recommended operating voltage for a nominal gain of 7.5 × 10^5 , although our measurements indicate lower gains (Fig. 4a). We determined that this operational voltage on average corresponds to 0.9 V above breakdown; to obtain our setting at an overvoltage of 1.4 V, we added 0.5 V and then adjusted for temperature.

Hamamatsu Multi-Pixel Photon Counter (MPPC) S12045(X):
16 x 3600 pixels (50 um)

arXiv:1801.03088v2 [physics.ins-det] 20 Apr 2018

Construction and Performance
of the Barrel Electromagnetic Calorimeter
for the GlueX Experiment

T.D. Beattie[a], A.M. Foda[a], C.L. Henschel[a], S. Katsaganis[a], S.T. Krueger[a], G.J. Lolos[a], Z. Papandreou[a,*], E.L. Plummer[a], I.A. Semenova[a], A.Yu. Semenov[a], F. Barbosa[b], E. Chudakov[b], M.M. Dalton[b], D. Lawrence[b], Y. Qiang[b,1], N. Sandoval[b], E.S. Smith[b,*], C. Stanislav[b], J.R. Stevens[b,2], S. Taylor[b], T. Whitlatch[b], B. Zihlmann[b], W. Levine[c], W. McGinley[c], C.A. Meyer[c], M.J. Staib[c], E.G. Anassontzis[d], C. Kourkoumelis[d], G. Vasileiadis[d], G. Voulgaris[d], W.K. Brooks[e], H. Hakobyan[e], S. Kuleshov[e], R. Rojas[e], C. Romero[e], O. Soto[e], A. Toro[e], I. Vega[e], M.R. Shepherd[f]

[a]*Department of Physics, University of Regina, Regina, Saskatchewan, Canada S4S 0A2*
[b]*Jefferson Laboratory, Newport News, Virginia 23606, USA*
[c]*Carnegie Mellon University, Pittsburgh, Pennsylvania 15213, USA*
[d]*National and Kapodistrian University of Athens, 15771 Athens, Greece*
[e]*Universidad Técnica Federico Santa María, Casilla 110-V Valparaíso, Chile*
[f]*Indiana University, Bloomington, Indiana 47405, USA*

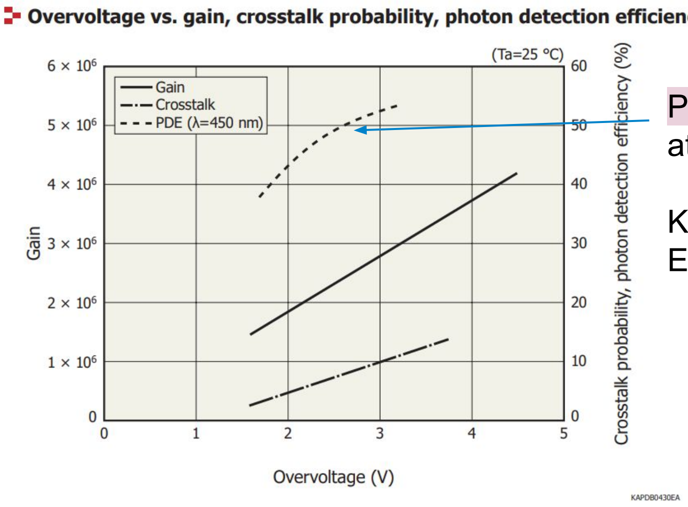
Abstract

The barrel calorimeter is part of the new spectrometer installed in Hall D at Jefferson Lab for the GlueX experiment. The calorimeter was installed in 2013, commissioned in 2014 and has been operating routinely since early 2015. The detector configuration, associated Monte Carlo simulations, calibration and operational performance are described herein. The calorimeter records the time and energy deposited by charged and neutral particles created by a multi-GeV photon beam. It is constructed as a lead and scintillating-fiber calorimeter and read out with 3840 large-area silicon photomultiplier arrays. Particles impinge on the detector over a wide range of angles, from normal incidence at 90 degrees down to 11.5 degrees, which defines a geometry that is fairly unique among calorimeters. The response of the calorimeter has been measured during a running experiment and performs as expected for electromagnetic showers below 2.5 GeV. We characterize the performance of the BCAL using the energy resolution integrated over typical angular distributions for π^0 and η production of $\sigma_E/E = 5.2\%/\sqrt{E(\mathrm{GeV})} \oplus 3.6\%$ and a timing resolution of $\sigma = 150$ ps at 1 GeV.

https://arxiv.org/abs/1801.03088

Photon Detection Efficiency: Hamamatsu: s14160/14161

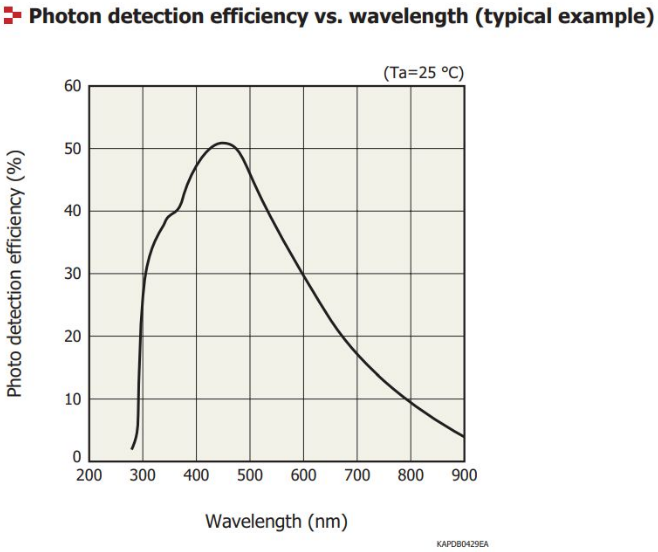
50 um pixel pitch



PDE = ~50%
at 2.7 V, λ = 450 nm

Kuraray SCSF-78
Emission peak = 450 nm

MPPC characteristics vary with the operating voltage. Although increasing the operating voltage improves the photon detection efficiency and time resolution, it also increases the dark count and crosstalk at the same time, so an optimum operating voltage must be selected to match the application.



Photon detection efficiency does not include crosstalk and afterpulses.

50%/33% = ~1.51

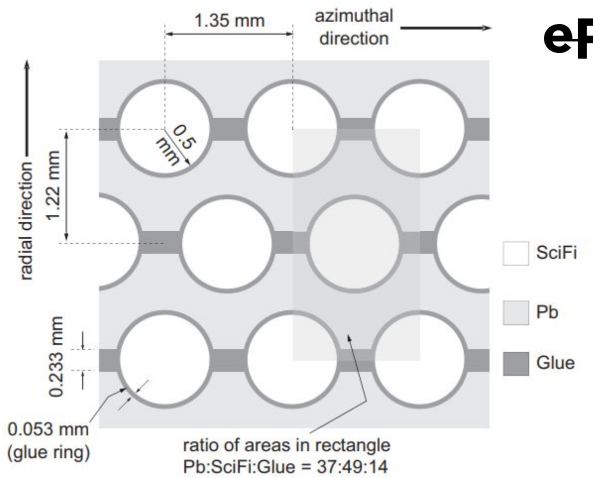
- https://www.hamamatsu.com/content/dam/hamamatsu-photonics/sites/documents/99_SALES_LIBRARY/ssd/s14160_s14161_series_kapd1064e.pdf
- https://www.kuraray.com/uploads/5a717515df6f5/PR0150_psf01.pdf

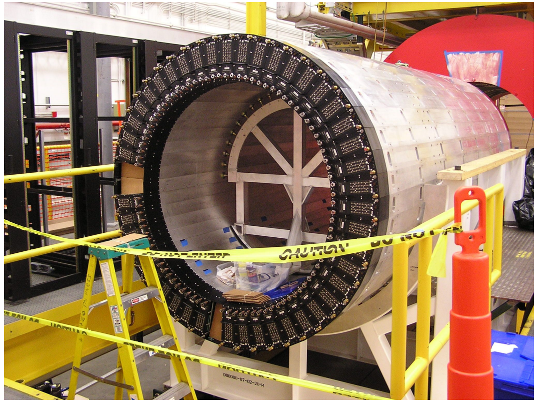
SciFi/Pb layers technology

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: 1.1cm/√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 - R&D FY23

R&D goals with GlueX Baby BCal prototype

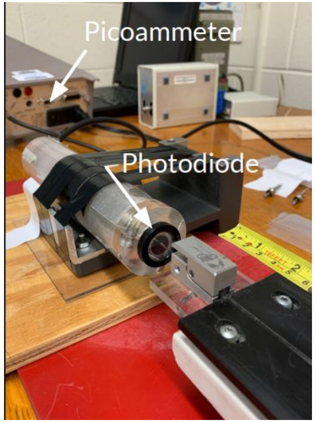
- **SciFi/Pb tested** extensively in for energies **E_γ < 2.5 GeV**
- **Higher-energy data** important to constrain the constant term of energy resolution
- Obtain **responses to EM showers** to benchmark simulations and provide input to realistic **waveform analysis - Hall D, electrons** (up to ~6.2 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

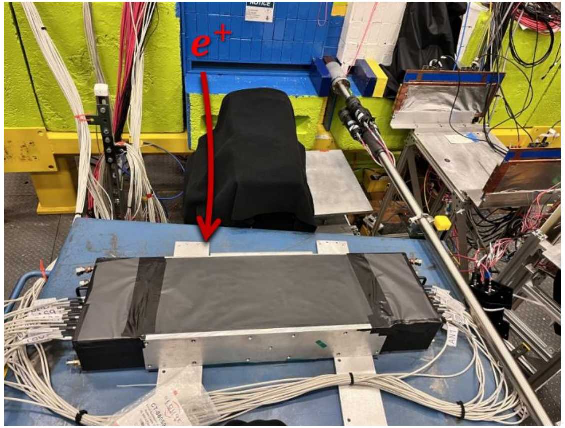
- **Light output and attenuation length** measurements at University of Regina with single- and double-clad fibers from Kuraray and Luxium - ongoing (M. Kerr talk)

Baby BCal ~ 15.5 X_0

Setup at Uni of Regina



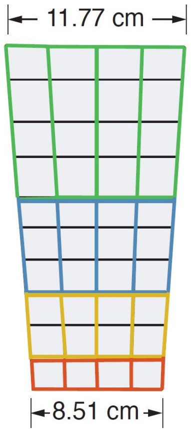
Setup at Hall D, JLab



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, 50×50μm^2 pixels)
- 12 layers x 5 cells x 2 sides x 48 sectors = 5760 channels

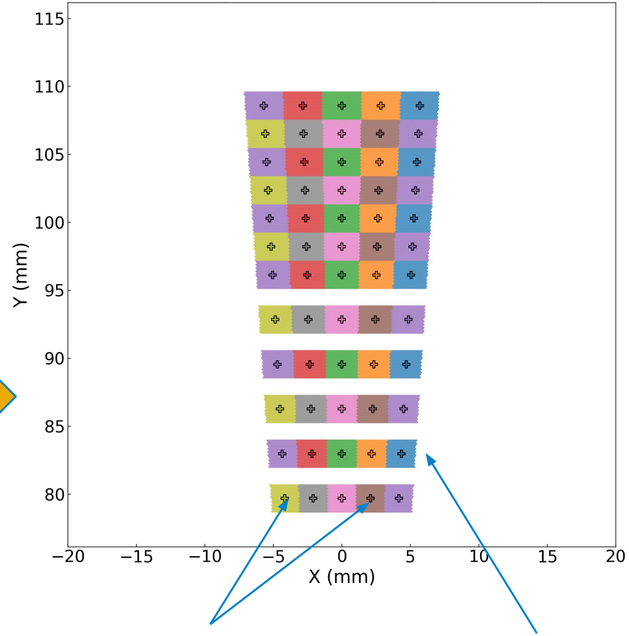
GlueX
1/48th of the barrel
end view



Hamamatsu S12045(X)
4×4 array of 3×3 mm^2
50×50μm^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

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

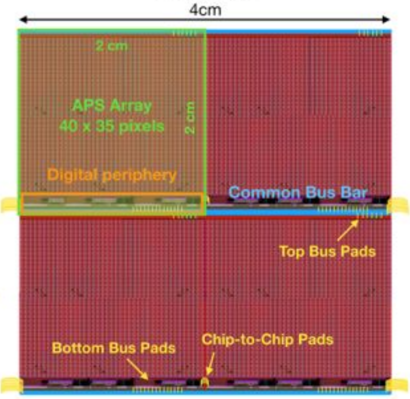
v3 (2×2 cm^2, 500 µm pixel, **quad chip**)

- 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	$500\,\mu m \times 500\,\mu m$
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	$500\,\mu m$

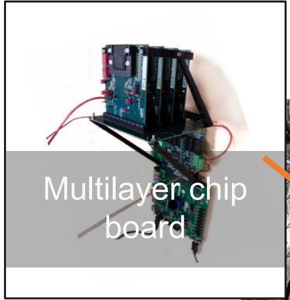
Imaging layers - R&D FY23

R&D program in FY23

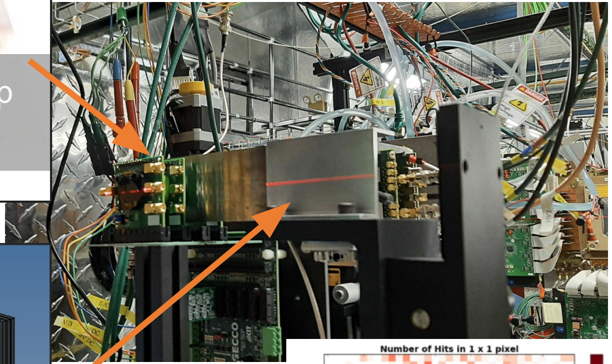
- Tests of **AstroPix v2/v3 sensor** in the EM calorimetry environment
  - **Multilayer chip tests** in FNAL with protons, pions and electrons, tests with tungsten radiator, readout aspects (ANL LDRD)
    - Beam tests in February and May 2023
  - **Irradiation test** in the FNAL ITA Facility (ANL LDRD)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

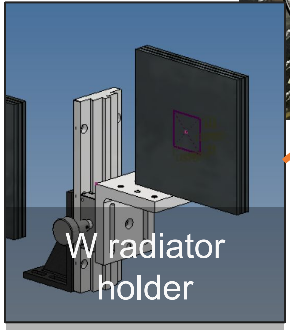
FY24 Plan

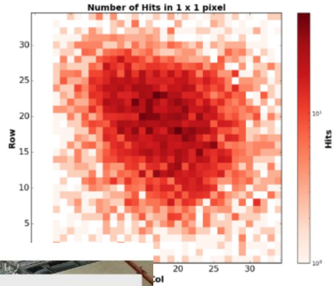
- Response to electromagnetic/hadronic shower with multilayer AstroPix v3 prototype integrated with the SciFi/Pb layers and Baby BCal

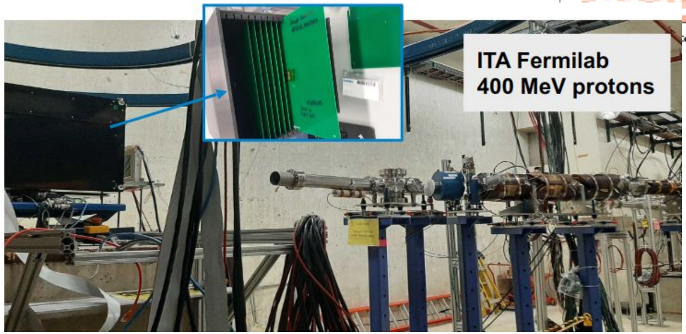


AstroPix FNAL setup







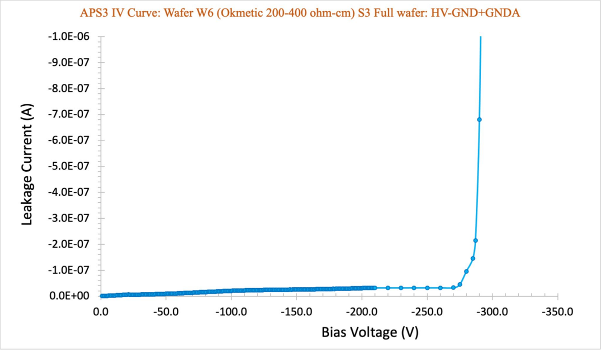


Snapshots from the Sensor Irradiations

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

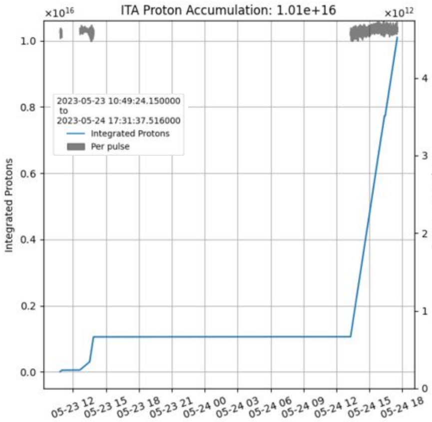


V2 Irradiation

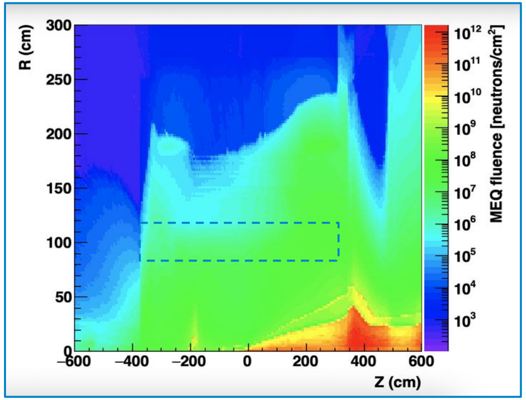
Nb of samples	Doses (400 MeV protons)
3	4.50E+13
3	1.08E+15
2	1.01E+16
1	5.02E+16

V3 Irradiation (low and high ResChips)

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



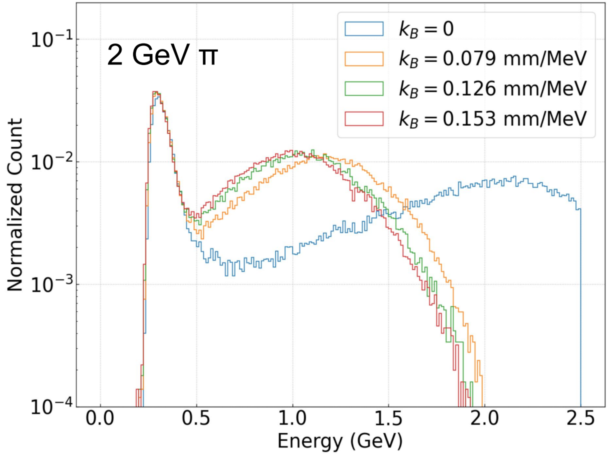
1-MeV neutron equivalent fluences at EIC



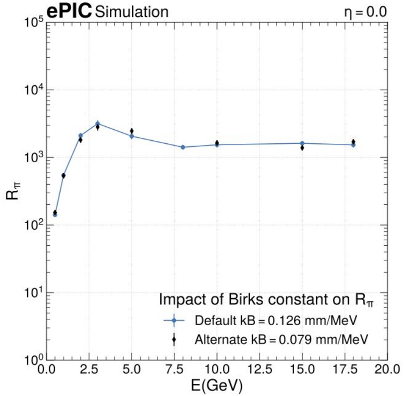
Pb/ScFi
Confidence in the hadron rejection simulation

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

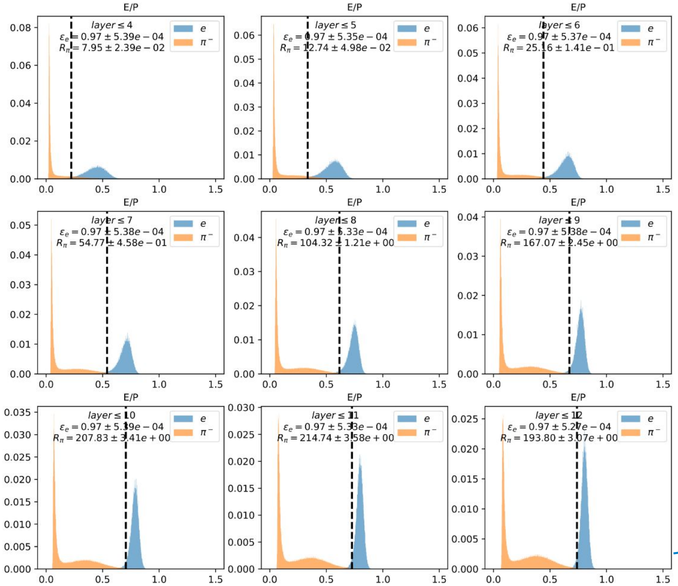


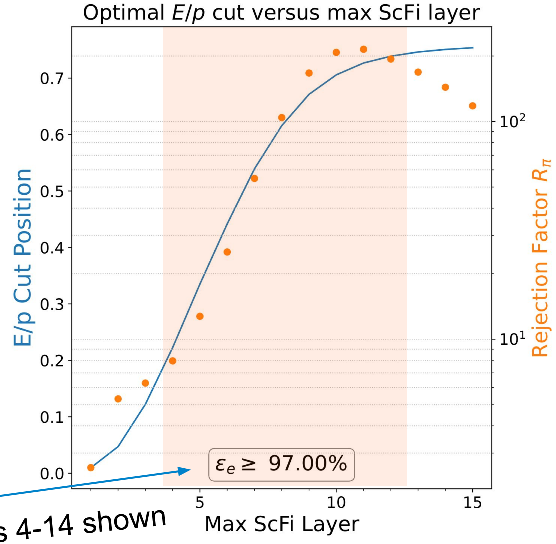
e/π Separation in Barrel ECal - Method

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

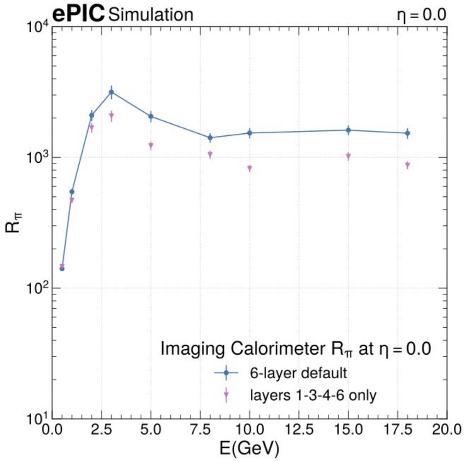


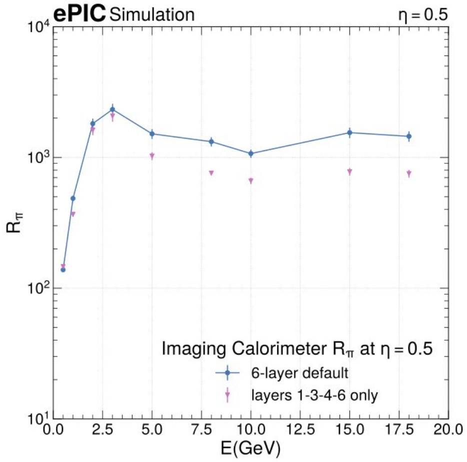


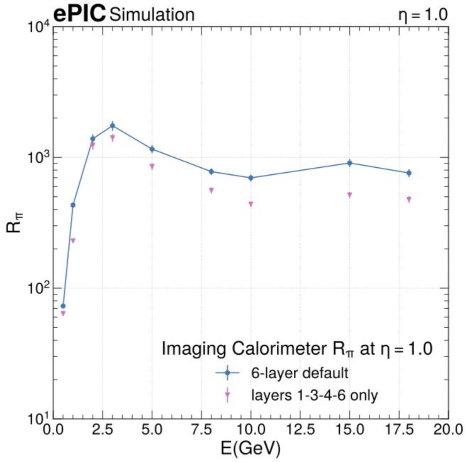
ScFi layers 4-14 shown

Performance with reduced number of layers

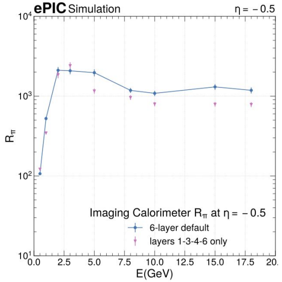
e/π separation at 95% efficiency

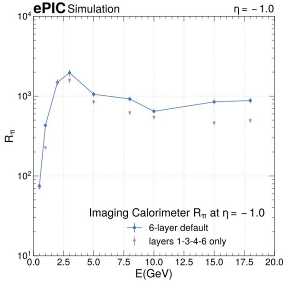






4-layer alternate: layers 1-3-4-6



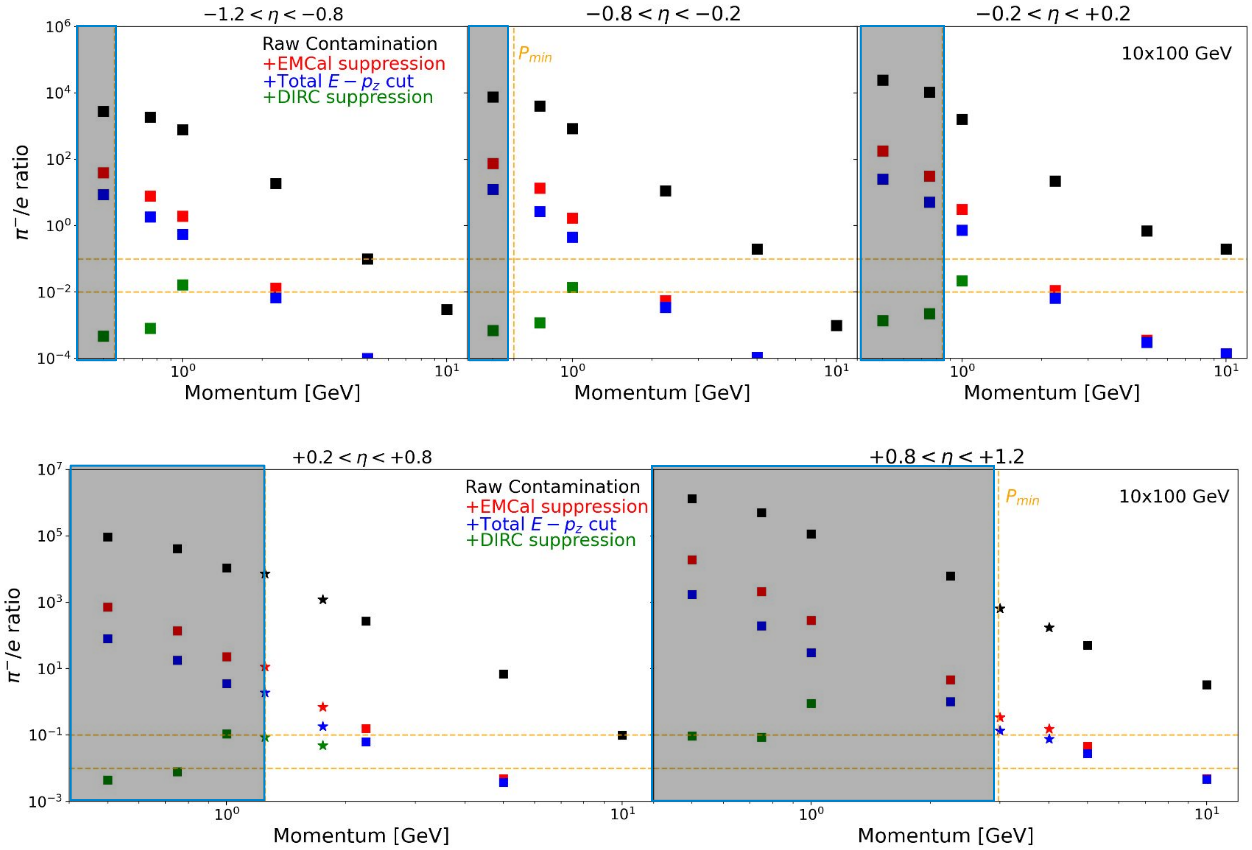


Default configuration exceeds 10^3 pion rejection almost everywhere

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.

Performance for 10 x 100 GeV



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

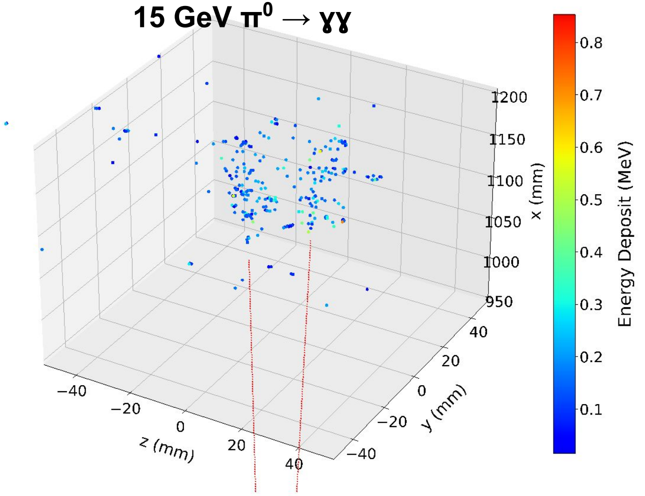
- See ePIC Collaboration Meeting contribution (link)

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

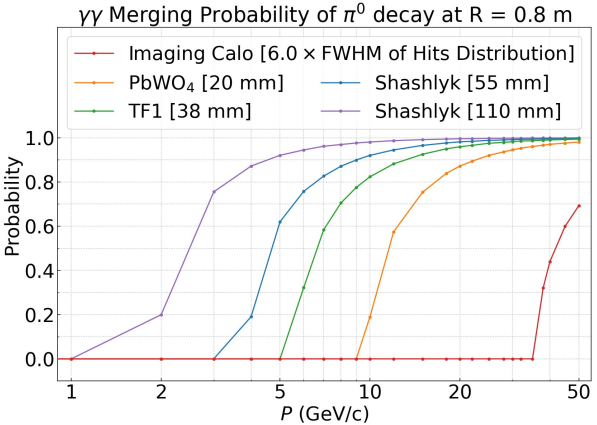
- To keep pion contamination systematic uncertainty to required 1% level

Imaging calorimeter fulfills the requirement in all η ranges

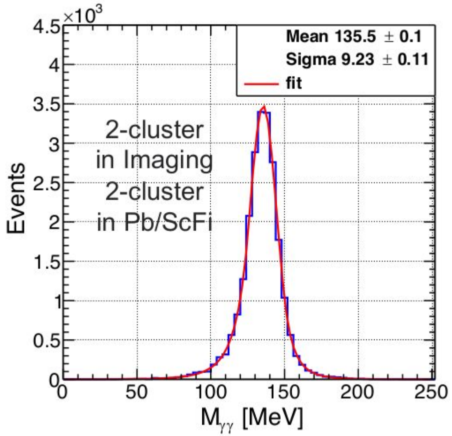
Neutral Pion Identification



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

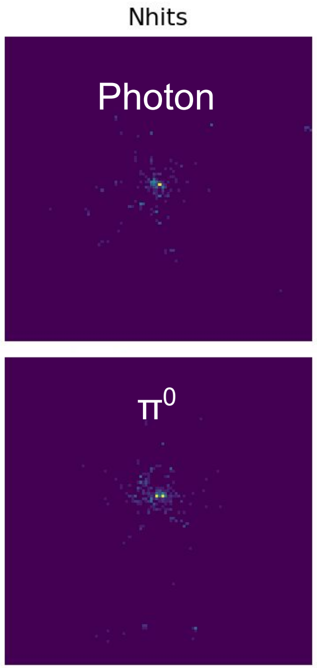
With a quick study we easily achieved

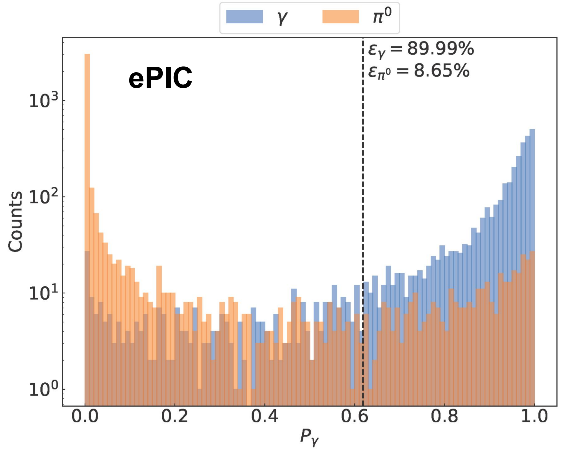
10 GeV/c particles - **91.4%** rejection of π^0 at **90%** efficiency of γ (better than $PbWO_4$ crystal with 20mm block size)

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

Full study is ongoing:

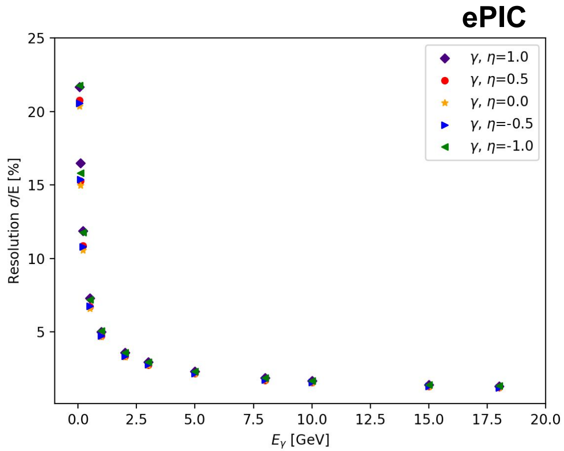
- Implementing optimized topological clustering for AstroPix layers
- Significant improvements expected

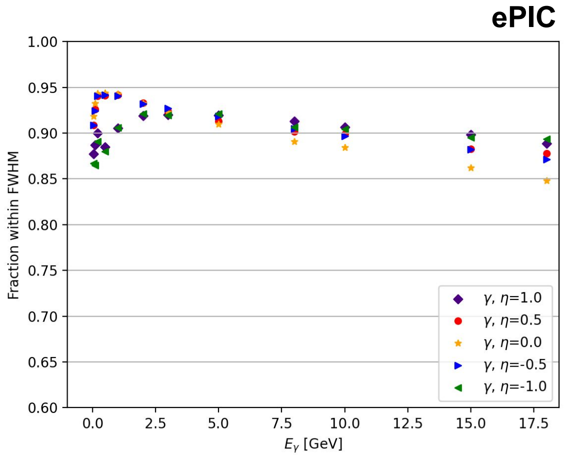


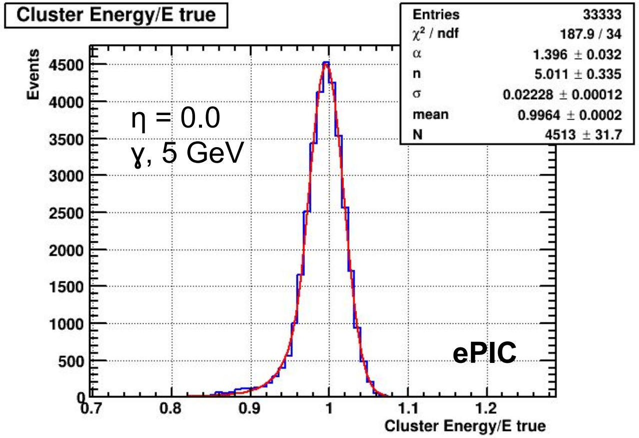


Configuration	γ efficiency	π^0 rejection at 10 GeV/c
6-layer default	90%	11.5
4-layer alternate	90%	5.4

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

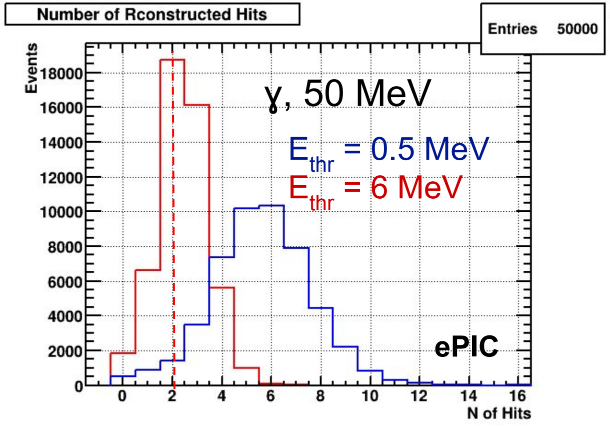
GlueX Pb/ScFi ECal: $\sigma = 5.2\% / \sqrt{E} \oplus 3.6\%$ NIM, A 896 (2018) 24-42

- 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

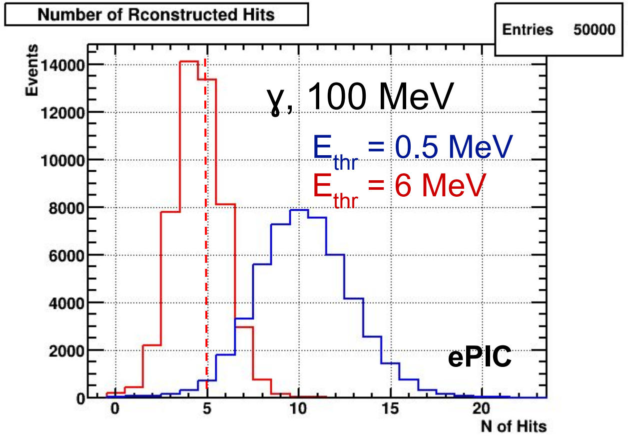
Simulations of **GlueX prototype** in ePIC environment agree with data at E_γ < 0.5 NIM, 596 (2008) 327−337

Low Energy Particles

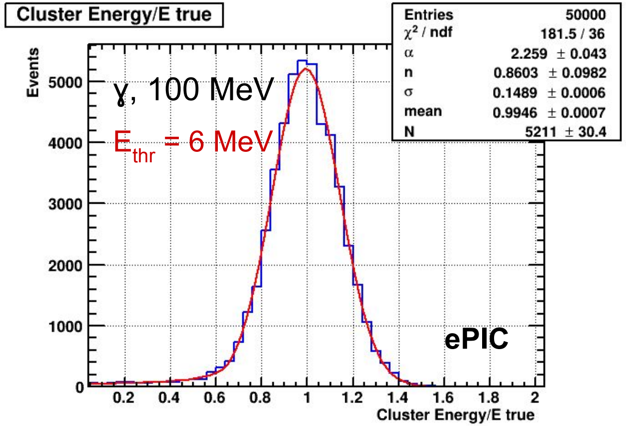
- For electrons: cut out because of the 1.7 T field to reach the calorimeter (p < ~408 MeV)
- For photons shown number of fired readout cells with different thresholds at $\eta = 0$



Thresholds corrected for f_{sam}



Blue threshold very low just to illustrate the distribution shape



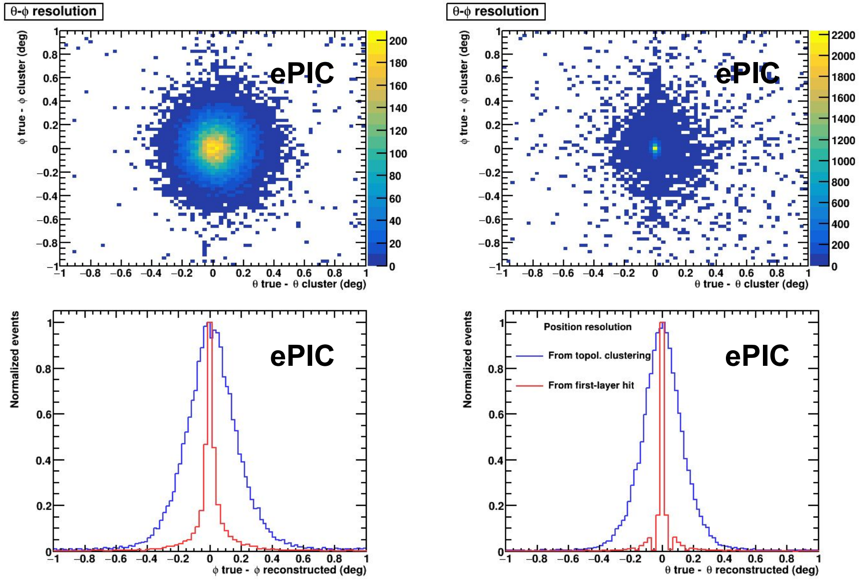
- **From GlueX** studies: cluster/shower threshold is 100 MeV nominal (down to 50 MeV for some analyses, with mostly two cells per event only). Low energy detection threshold studied also with Michel electrons. (NIM, A 896 (2018) 24-42)

Position Resolution

with 6 AstroPix Layers

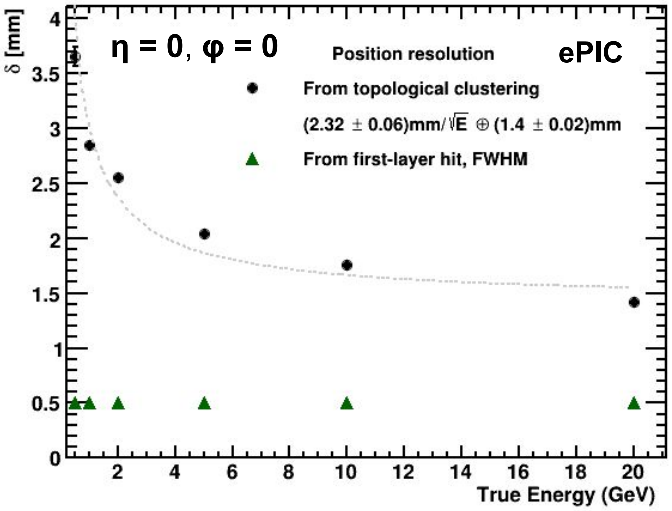
Example of θ - φ resolution for 5 GeV photons

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



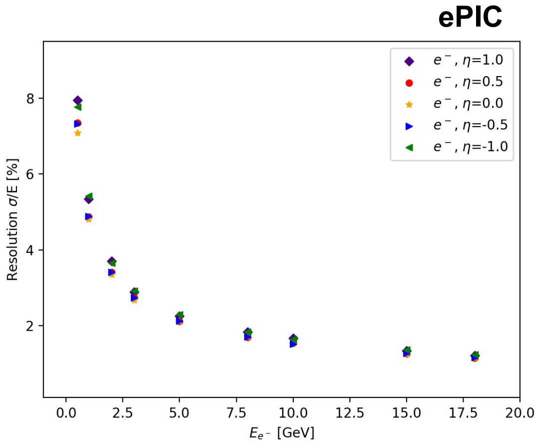
Position resolution for photons

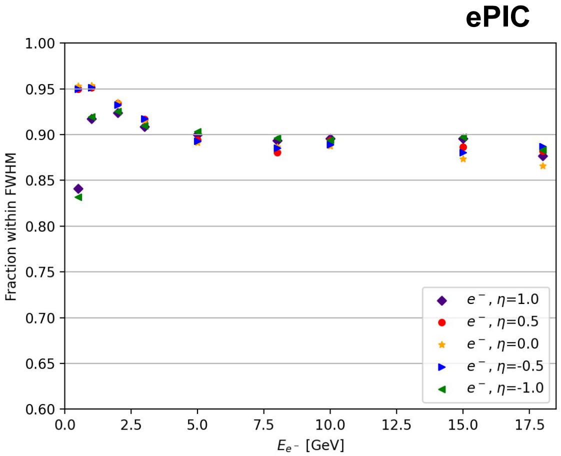
Particles thrown perpendicular to the calo surface

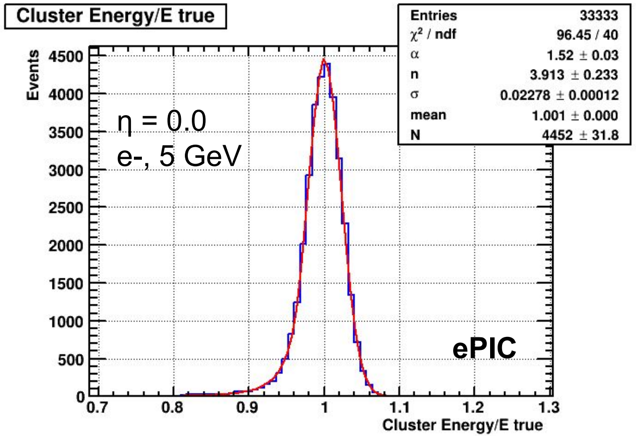


- Clusters from Imaging Si layers reconstructed with 3D topological algorithm
- Cluster level information: $\sigma_{position}$ = (2.32 ± 0.06) mm/√E ⊕ (1.4 ± 0.02) mm at η=0
- First-layer hit information added: $\sigma_{position}$= **~0.5 mm (pixel size)**

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

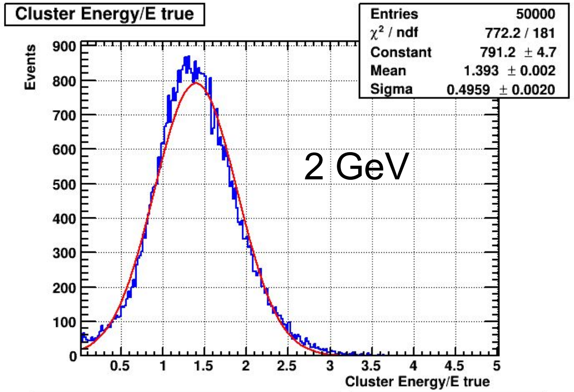
- 15.5 X_0, extracted for integrated range over the angular distributions for π^0 and η production at GlueX (E_γ = 0.5 - 2.5 GeV)
- Measured energies not able to fully constrain the constant term

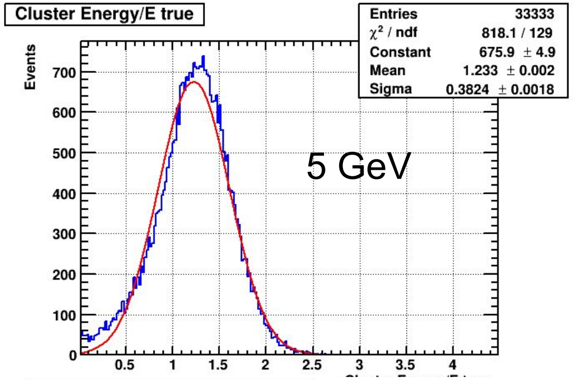
Simulations of **GlueX prototype** in ePIC environment agree with data at E_γ < 0.5 NIM, 596 (2008) 327−337

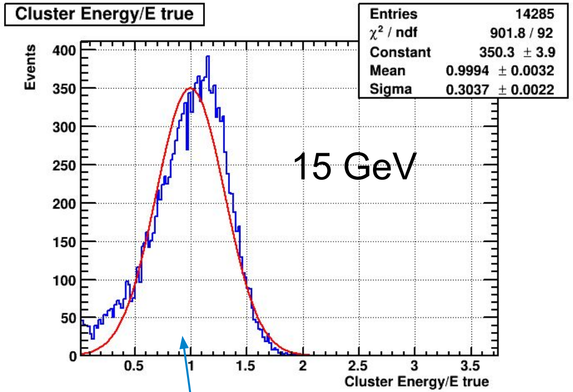
Energy resolution of AstroPix Layers

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

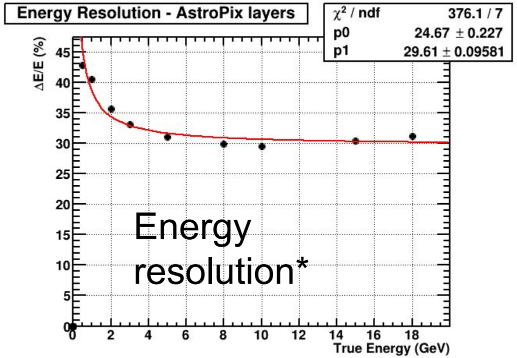
with 6 AstroPix Layers

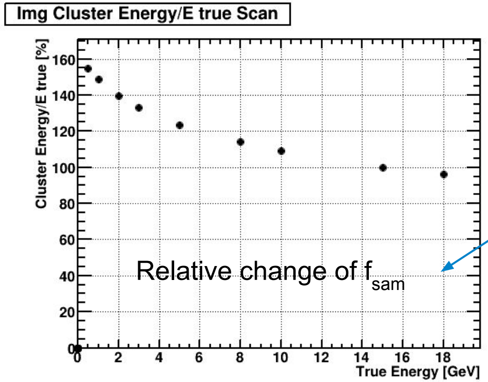






non-gaussian





strong dependence in this geometry

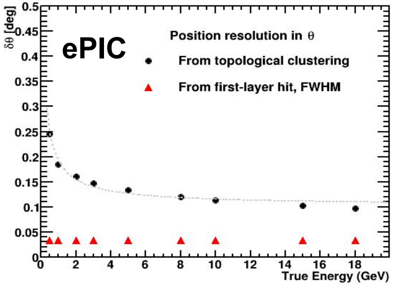
*Assuming perfect calibration (but! huge sampling fraction energy dependence)

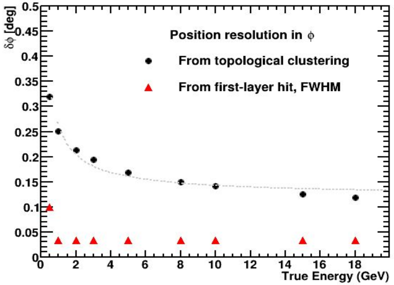
Position resolution studies

with 6 AstroPix Layers

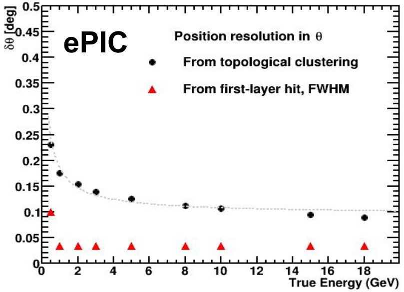
Angular resolution for different η

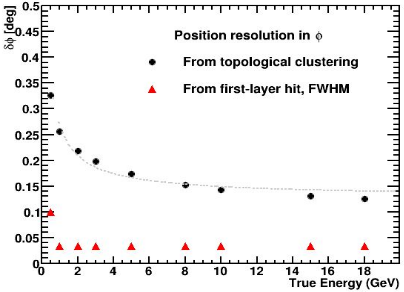
η = 0, φ = (0,2π)



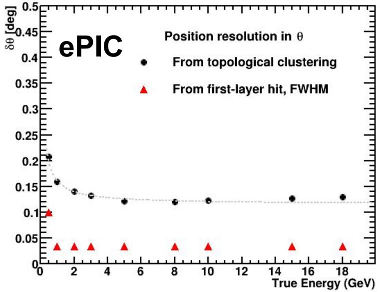


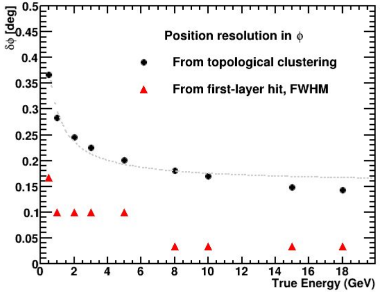
η = 0.5, φ = (0,2π)





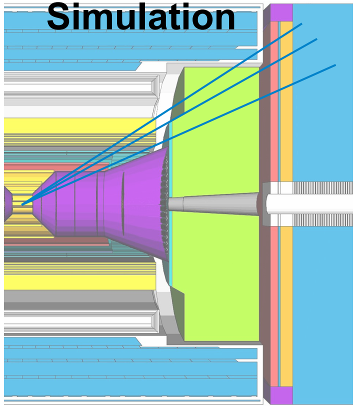
η = 1, φ = (0,2π)

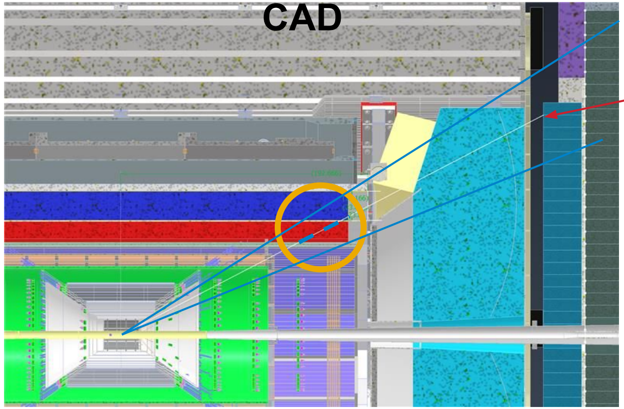




- Small dependence seen with changing η
- Angular resolution in all regions well below 0.1 deg (in majority regions on the level of single pixel resolution)
- Results well below any tower-like calorimetry

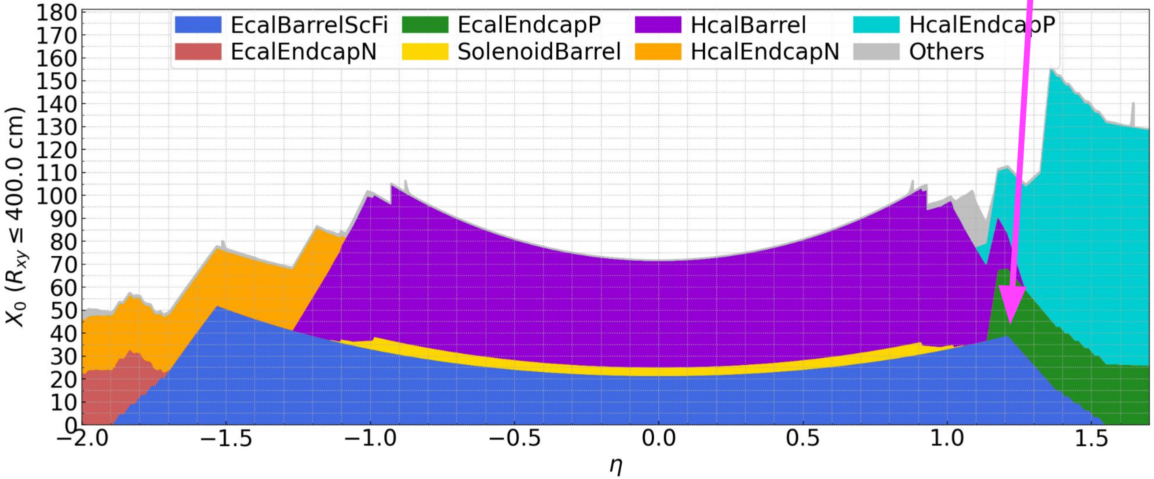
Forward integration





η = 1.31

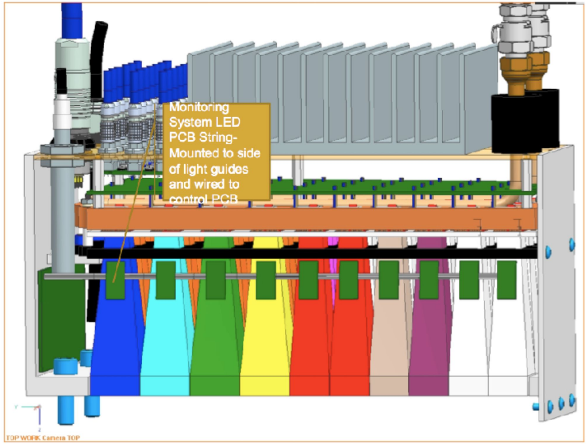
Very good continuous coverage in the forward region, up to ~ 33 X0



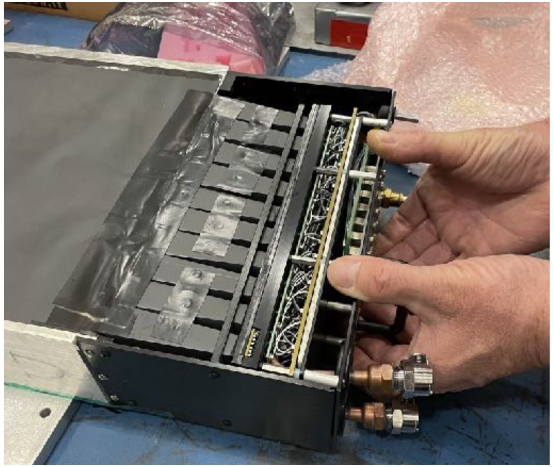
at η = 1.31
~25 X_0

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