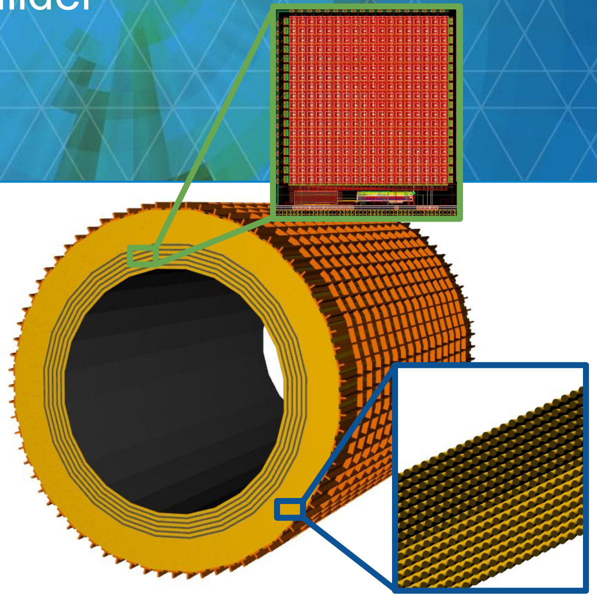
APCTP 2nd Workshop on the Physics of Electron Ion Collider

November 29, 202

The ePIC
Barrel Imaging Calorimeter (BIC)



Sylvester Joosten
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U.S. DEPARTMENT OF ENERGY

ePIC

Argonne NATIONAL LABORATORY

Why electromagnetic calorimetry at EIC is hard

From the EIC Yellow Report: stringent barrel ECal requirements

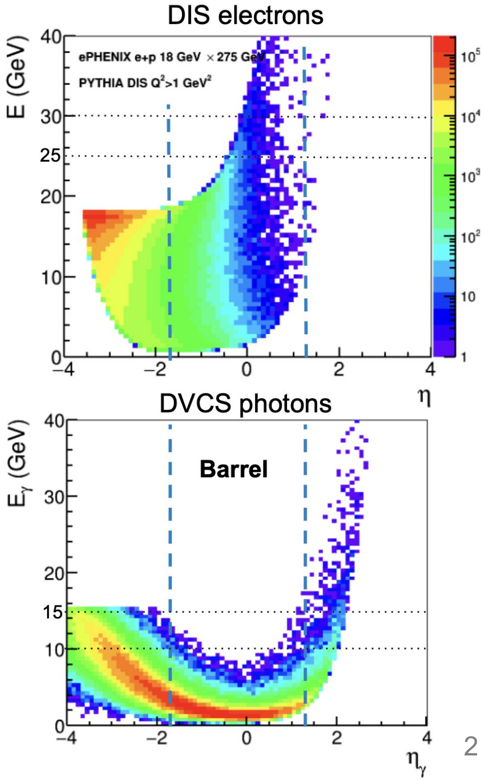
EIC is an **electron scattering** machine and identifying scattered electrons mainly depends on the electromagnetic calorimetry.

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

The exclusive program requires **decent energy resolution** (< $7\%/\sqrt{E} \oplus$ 1-3%) **for photon energy reconstruction, and also the fine granularity for good** π^0-γ separation up to 10 GeV.

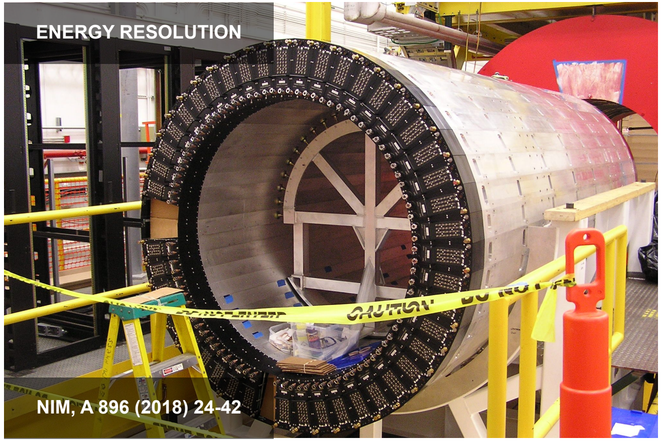
The bECal should be capable of measuring **low energy photons** down to 100 MeV, while having the range to measure energies well above 10 GeV

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

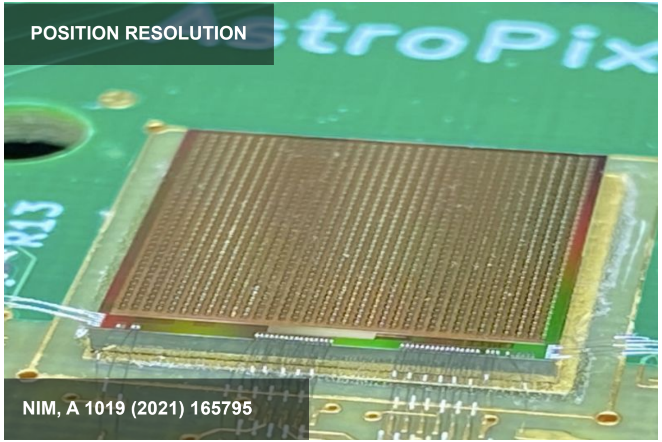


CONCEPT: A HYBRID IMAGING CALORIMETER

Combination of a high-performance sampling calorimeter with inexpensive silicon sensors for shower profiling



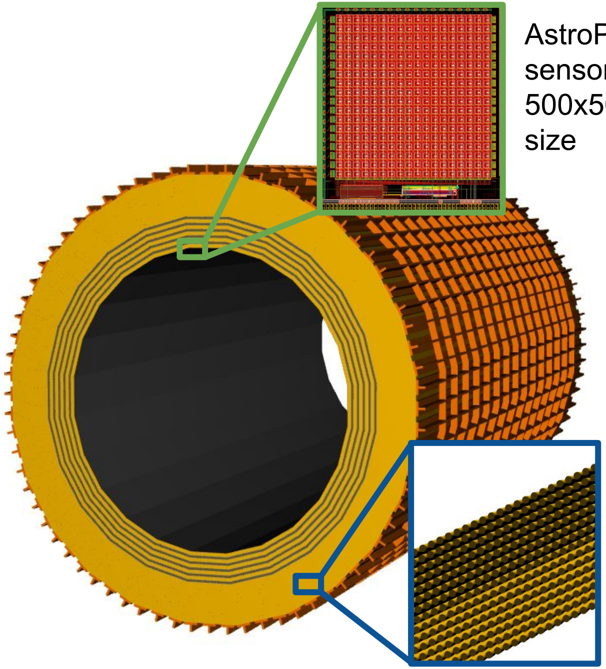
Start from mature layered Pb/ScFi technology with side-readout (same as the GlueX calorimeter) for state-of-the-art sampling calorimeter performance



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

General Overview

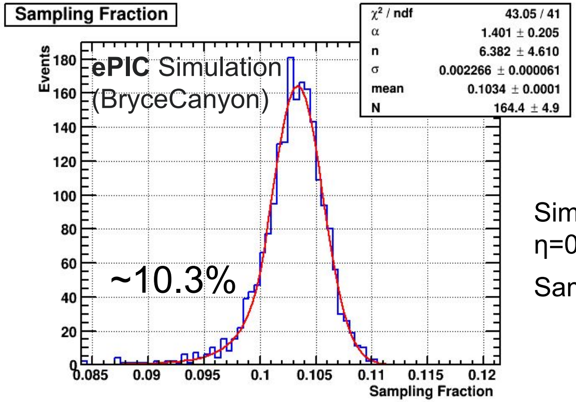
BARREL IMAGING CALORIMETER (BIC)



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%



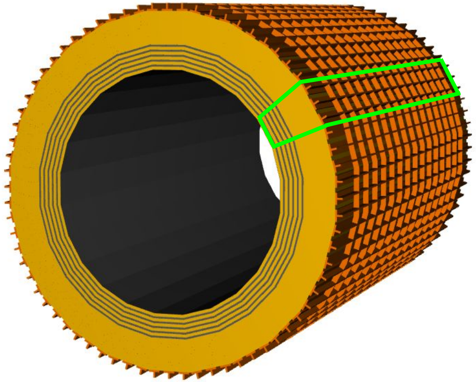
Simulation of **single photons** at $\eta=0$ (~17.1 X_0)

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)

Detector Structure

BARREL IMAGING CALORIMETER (BIC)

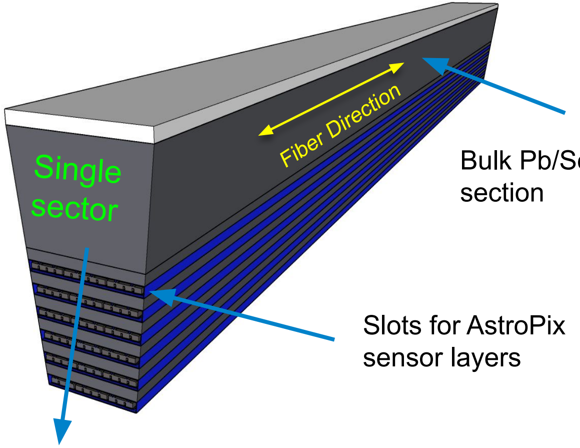


Length: 432.5 cm

Radius: ~ 80 cm radius,

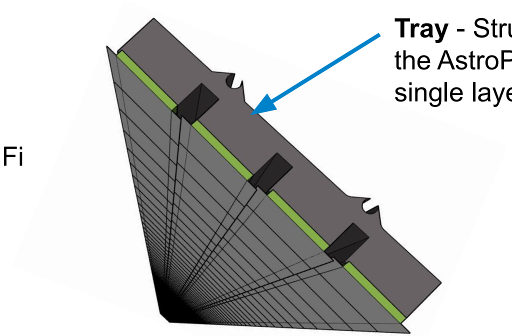
Structure: 48 sectors

η Range: -1.71 < η < 1.31



Bulk Pb/SciFi section

Slots for AstroPix sensor layers

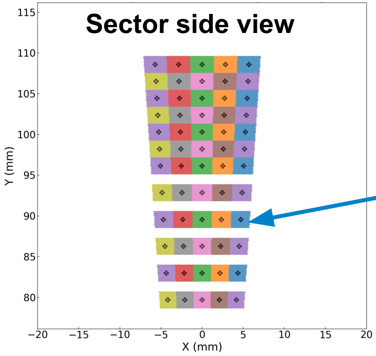


Tray - Structure holding the AstroPix staves for a single layer

Length: ~ 200 cm (half length)

Structure: 6-7 "turbofanned" staves per tray

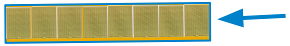
Stave Structure: ~ 13 **Modules** per stave



Pb/SciFi **Layer** - 12 layers per sector

Structure: 5 readout cells (one light-guide per readout cell)

Construction: 17 rows of fiber



Length: ~ 16 cm

Width: ~ 2 cm

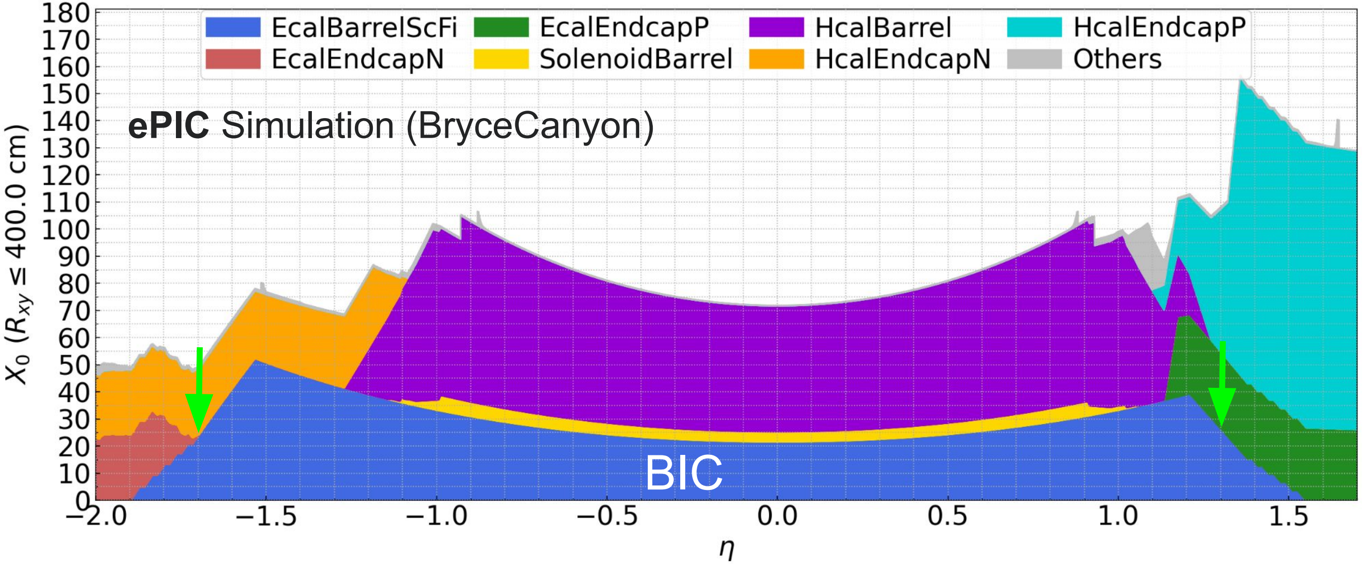
Gaps: < 200 μm

Structure: ~ 8 chips/module

Module - Several AstroPix chips daisy-chained together on Flex PCB

CALORIMETER COVERAGE AT EPIC

- Non-projective "continuous" design
- Particles passing at steeps angle pass through *much* more material than at central rapidities (up to 45 X0 at negative η)
- BIC is responsible for -1.7 < η < 1.3
- Continuous transition between backward-barrel-forward calorimeters



PB/SCFI TECHNOLOGY

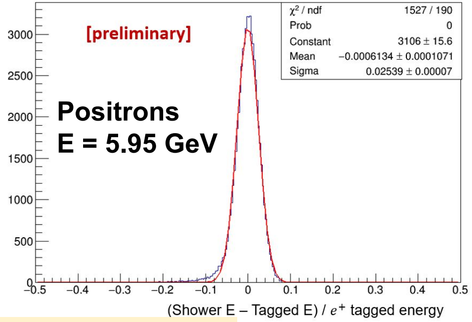
Our Pb/ScFi layers follow the GlueX Design

- Mature Technology: **GlueX**, KLOE electromagnetic calorimeters
  - Detailed studies on **calorimetry performance**, including the light collection uniformity in fibers, light collection efficiencies, etc.
  - **Module construction** (lead handling, swaging, Pb/ScFi layers assembly, module machining) fully developed for GlueX
    Z. Papandreou, https://halldweb.jlab.org/DocDB/0031/003164/
  - Assembly and installation of self-supporting barrel based on GlueX experience
- 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
  - New results from Hall D beam tests show that constant term < 2%

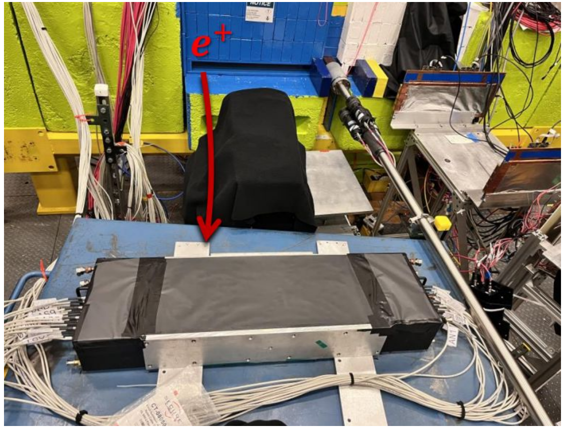
March 2023 beam test

Measured Resolution: ~ 2.5%

Extrapolated GlueX NIM[1)]: ~4.2%



Trends well below a 2% constant term!



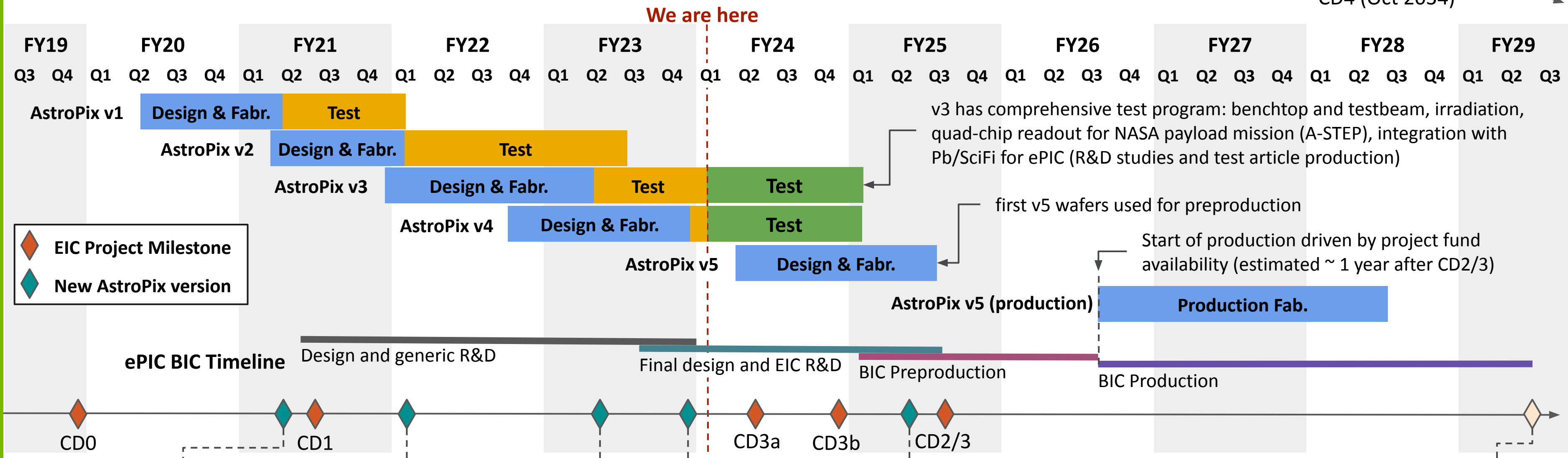
Baby BCAL
60 cm long
15.5 X0

tested with e+
E ~ 3.6-6 GeV

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

ASTROPIX TECHNOLOGY

Not shown:
Early CD4 (Oct 2032)
CD4 (Oct 2034)

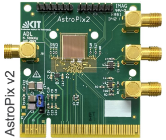


AstroPix v1

HV-CMOS MAPS based on ATLASPix3, designed for the AMEGO-X NASA mission, optimized for power dissipation and energy resolution

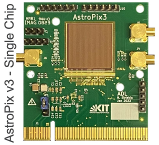
Nucl.Instrum.Meth.A 1019 (2021) 165795

0.45 x 0.45 cm^2 chip, 175 µm pixel pitch
18 x 18 pixel matrix
Power dissipation 14.7 mW/cm^2



AstroPix v2

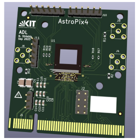
1 x 1 cm^2 chip, 250 µm pixel pitch
35 x 35 pixel matrix
Row/column readout
Power dissipation 3.4 mW/cm^2



AstroPix v3

First full-size chip

2 x 2 cm^2 chip, 500 µm pixel pitch
Row/column readout
Power dissipation <1 mW/cm^2
2.5 MHz timestamp, 200 MHz ToT



AstroPix v4

Final design but smaller size

1 x 1 cm^2 chip, 500 µm pixel pitch
Individual pixel readout
3 timestamps, 3.25ns time resolution
TuneDAC for pixel-by-pixel thresholds

AstroPix v5

Full-size production chip

2 x 2 cm^2 chip, 500 µm pixel pitch
Design identical to v4 (with bug fixes)

ASTROPIX LAYER SIZE

The BIC will be a large silicon detector:

- 4 (+2) layers in the ePIC barrel will cover **-1.7 < |eta| < 1.3**
- The Astropix sensor area will be about **100 m^2 (+40 m^2)**
- ~ 250,000 (+125,000) chips

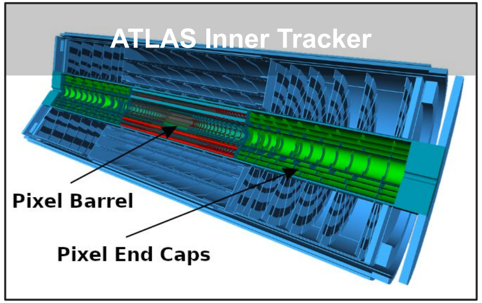
Other comparable Si detector arrays in advanced stage

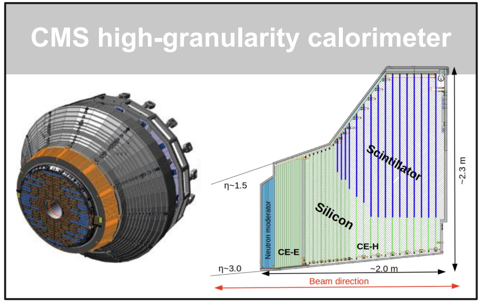
- ATLAS Inner Tracker - silicon strips[1] (ITk pixel) 160 m^2 (50 million channels)
- CMS high granularity calorimeter [2] ~ 600 m^2 (6.5 million channels)
- **AMEGO-X NASA mission**:
  - Will use a 40 m^2 AstroPix-based tracker, to be sent into space
  - We plan to use chips off-the-shelf: **no design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

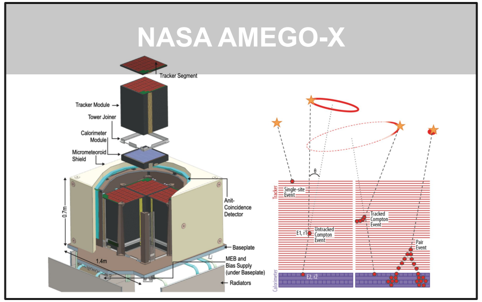
Advantages of AstroPix with respect to pixels used in e.g. ATLAS

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

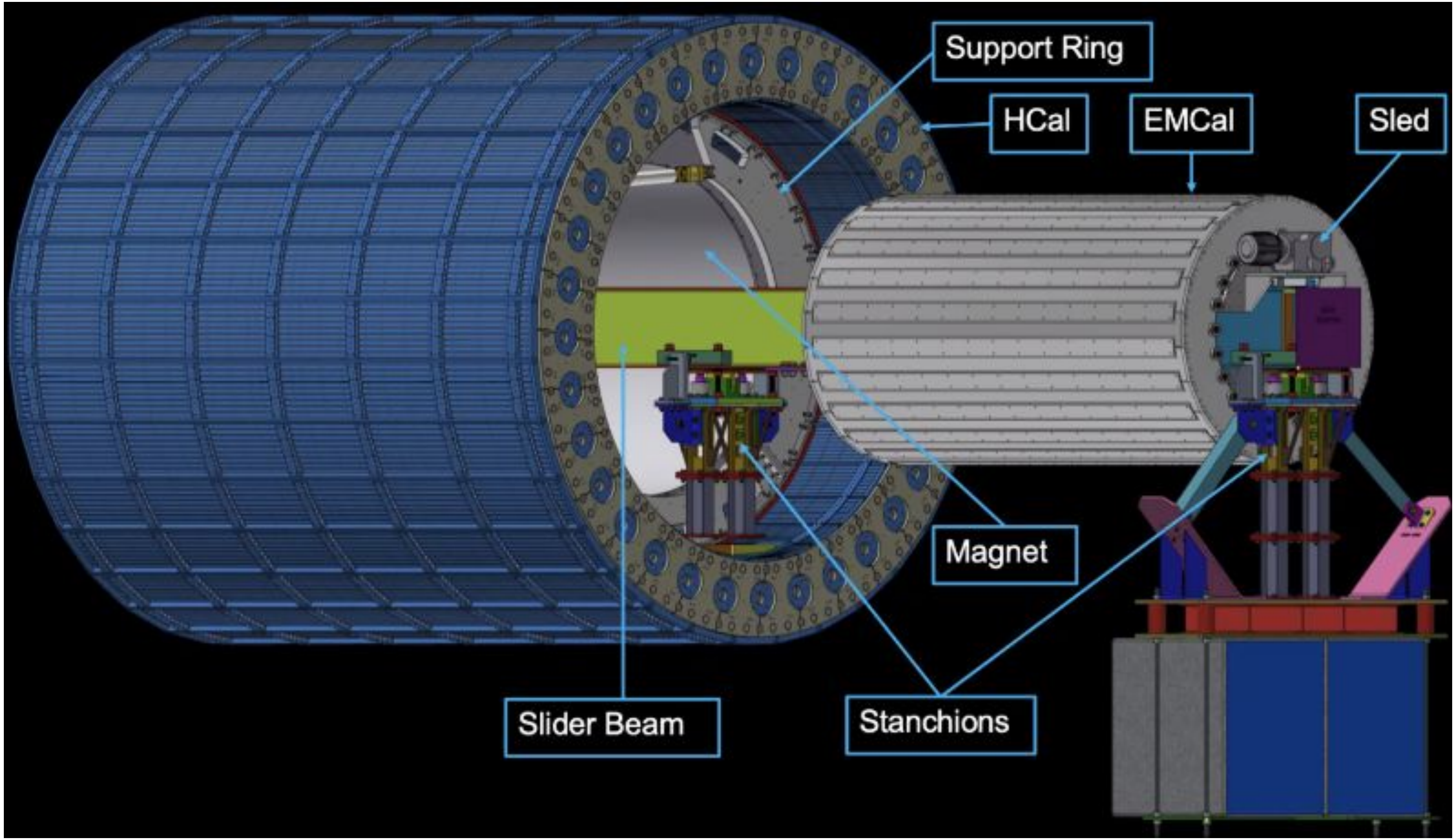
[1] arXiv:2105.10367, ATLAS ITk Pixel Detector Overview
[2] arXiv:1802.05987, The CMS High-Granularity Calorimeter for Operation at the High-Luminosity LHC2



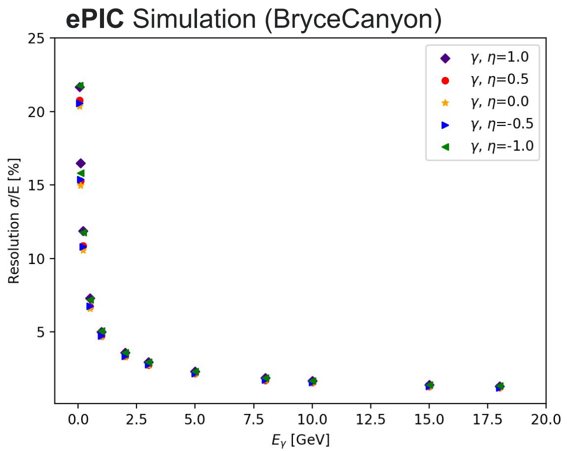


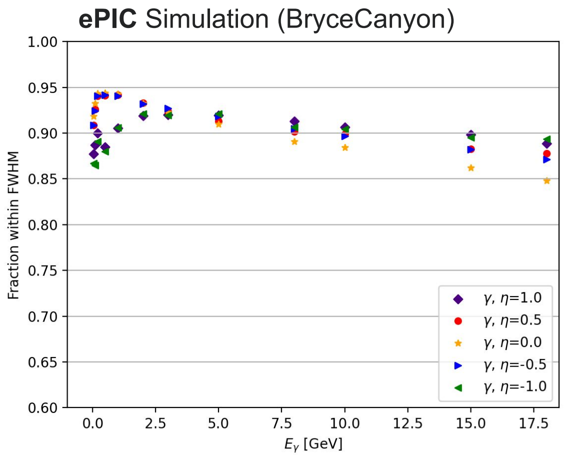


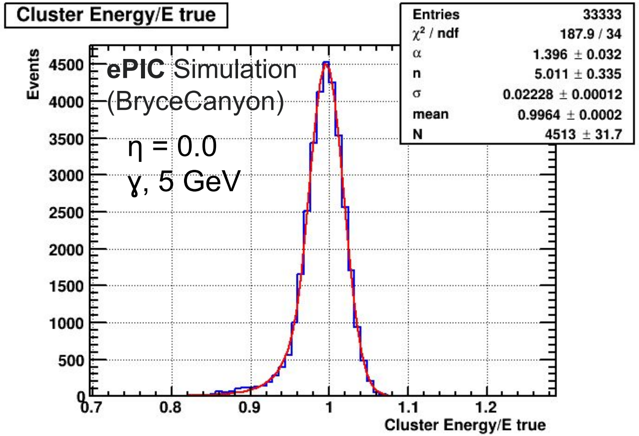
ASSEMBLY TOOLING



ENERGY RESOLUTION - PHOTONS







Fit parameters

η	a/√(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)

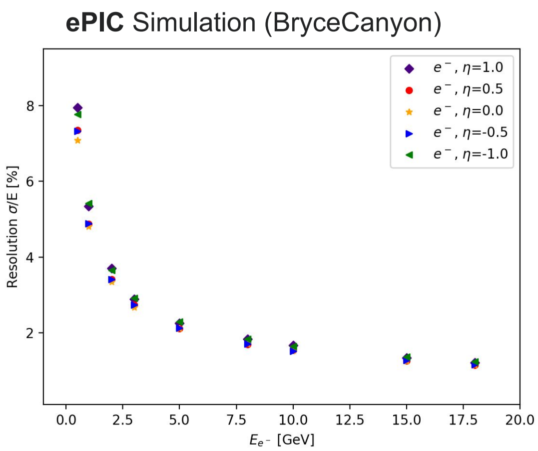
- Based of Pb/ScFi part of the calorimeter
- Resolution extracted from a Crystal Ball fit σ

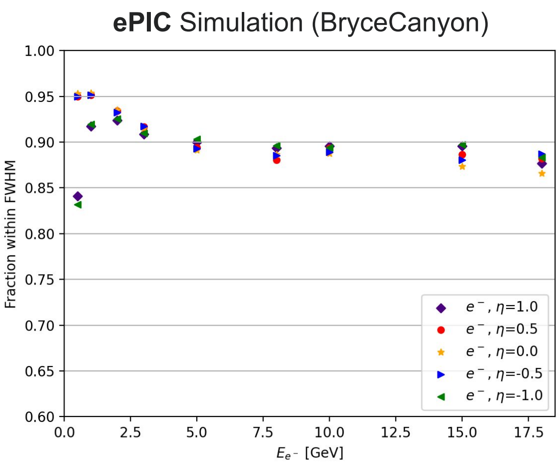
GlueX Pb/ScFi ECal: $\sigma = 5.2\% / \sqrt{E} \oplus 3.6\%$ NIM, A 896 (2018) 24-42

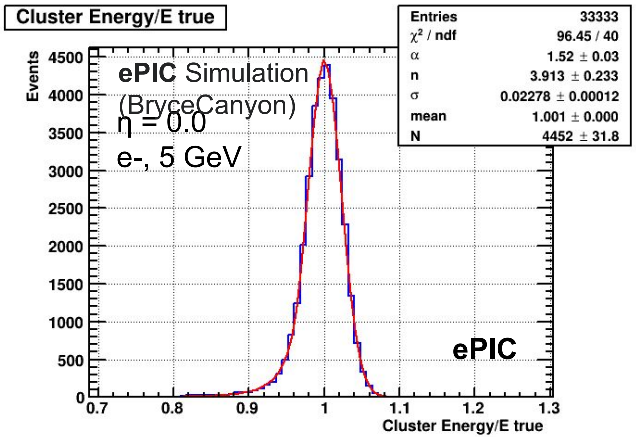
- 15.5 X_0, extracted for integrated range over the angular distributions for π^0 and η production at GlueX (E_γ = 0.5 - 2.5 GeV)
- Measured energies not able to fully constrain the constant term

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

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

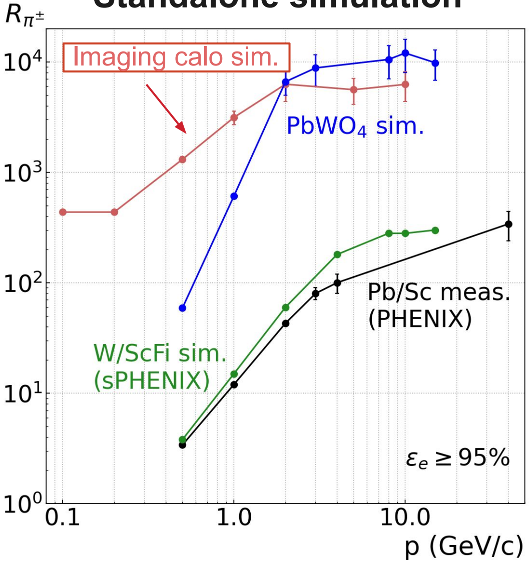
- 15.5 X_0, extracted for integrated range over the angular distributions for π^0 and η production at GlueX (E_γ = 0.5 - 2.5 GeV)
- Measured energies not able to fully constrain the constant term

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

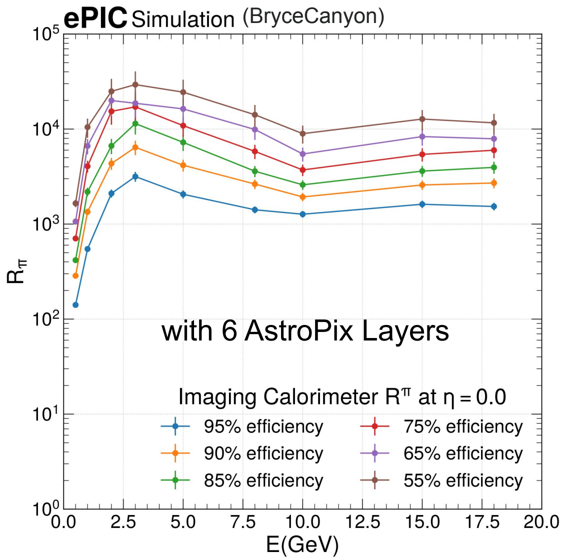
BIC: PERFORMANCE EXAMPLE

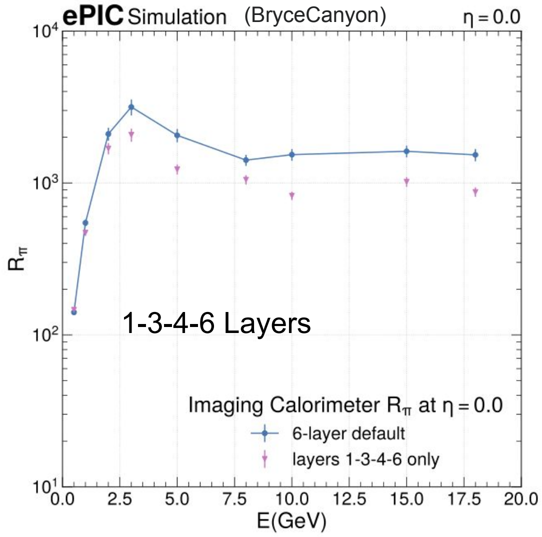
e/π Separation

Standalone simulation



Realistic ePIC simulation



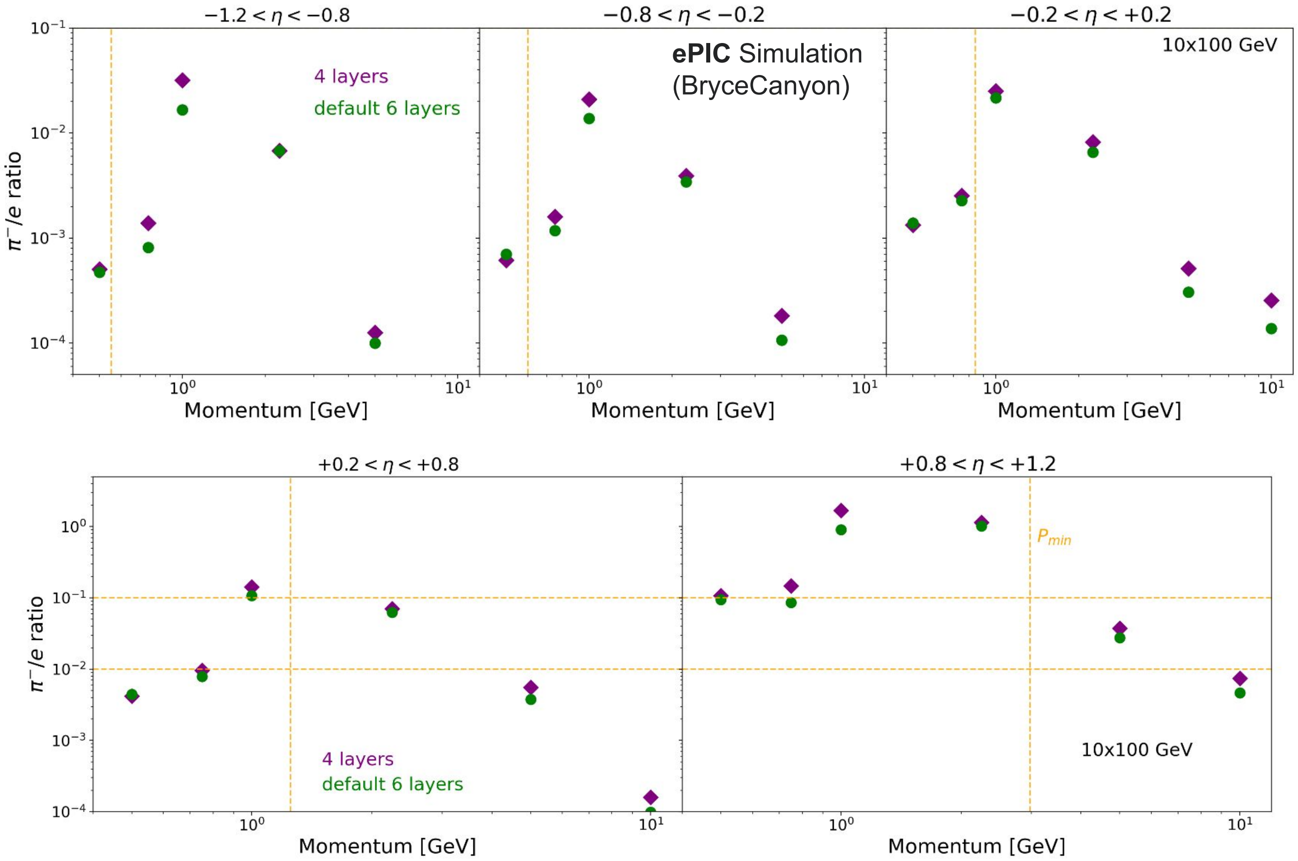


- **Goal:** Separation of electrons from background in Deep Inelastic Scattering (DIS) processes
- Method: **E/p cut (Pb/ScFi) + Neural Network** using 3D position and energy info from imaging layers

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

BIC: PERFORMANCE EXAMPLE

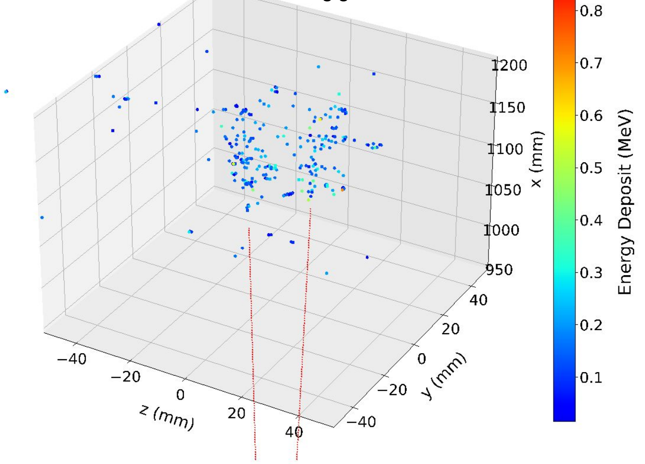
Impact on Inclusive Physics



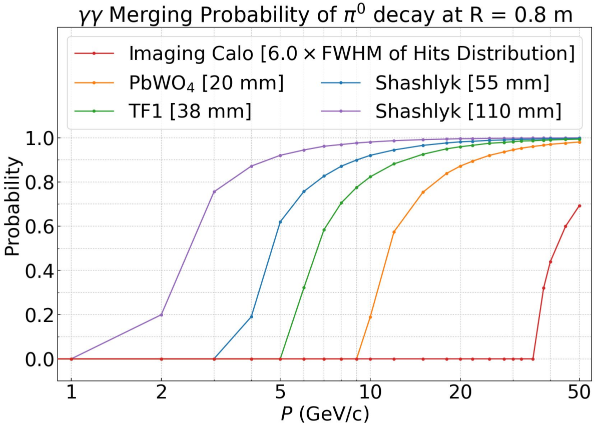
10 x 100 GeV

NEUTRAL PION IDENTIFICATION

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

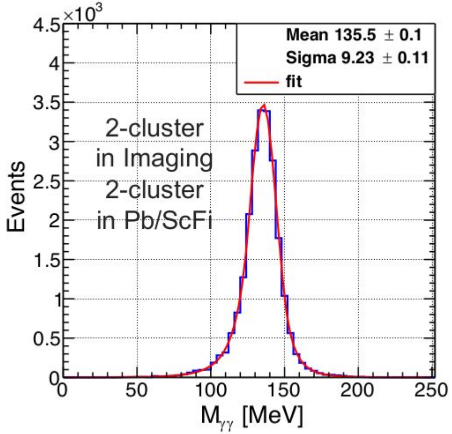


Separation of γ/π^0 (upper limit)



ePIC Simulation (BryceCanyon)

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

EXPLORATORY: γ/π^0 SEPARATION

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

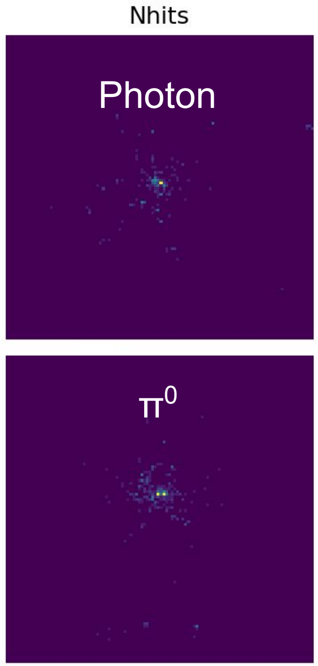
No proper **topological clustering algorithm** in the ePIC reconstruction yet

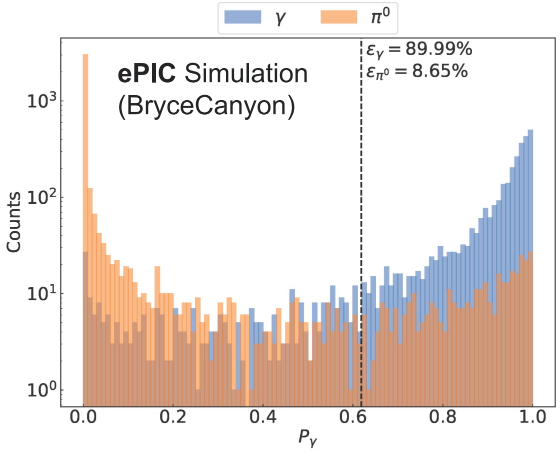
With a quick study we easily achieved

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

Full study is ongoing:

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





ePIC BIC Detector Subsystem Collaboration

ePIC

USA

Argonne National Laboratory

NASA Goddard Space Flight Center

Oklahome State University

University of Connecticut

University of California Santa Cruz

Canada

University of Manitoba

University of Regina

Mount Allison University

NSERC

Canada Fund for Innovation

Korea

Kyungpook National University

Yonsei University

University of Seoul

Pusan National University

Korea University

Sungkyunkwan University

Hanyang University

Gangneung-Wonju National University

Germany

Karlsruhe Institute of Technology

University of Giessen

BIC DETECTOR SUBSYSTEM COLLABORATION

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DSTC (Pb/ScFi)
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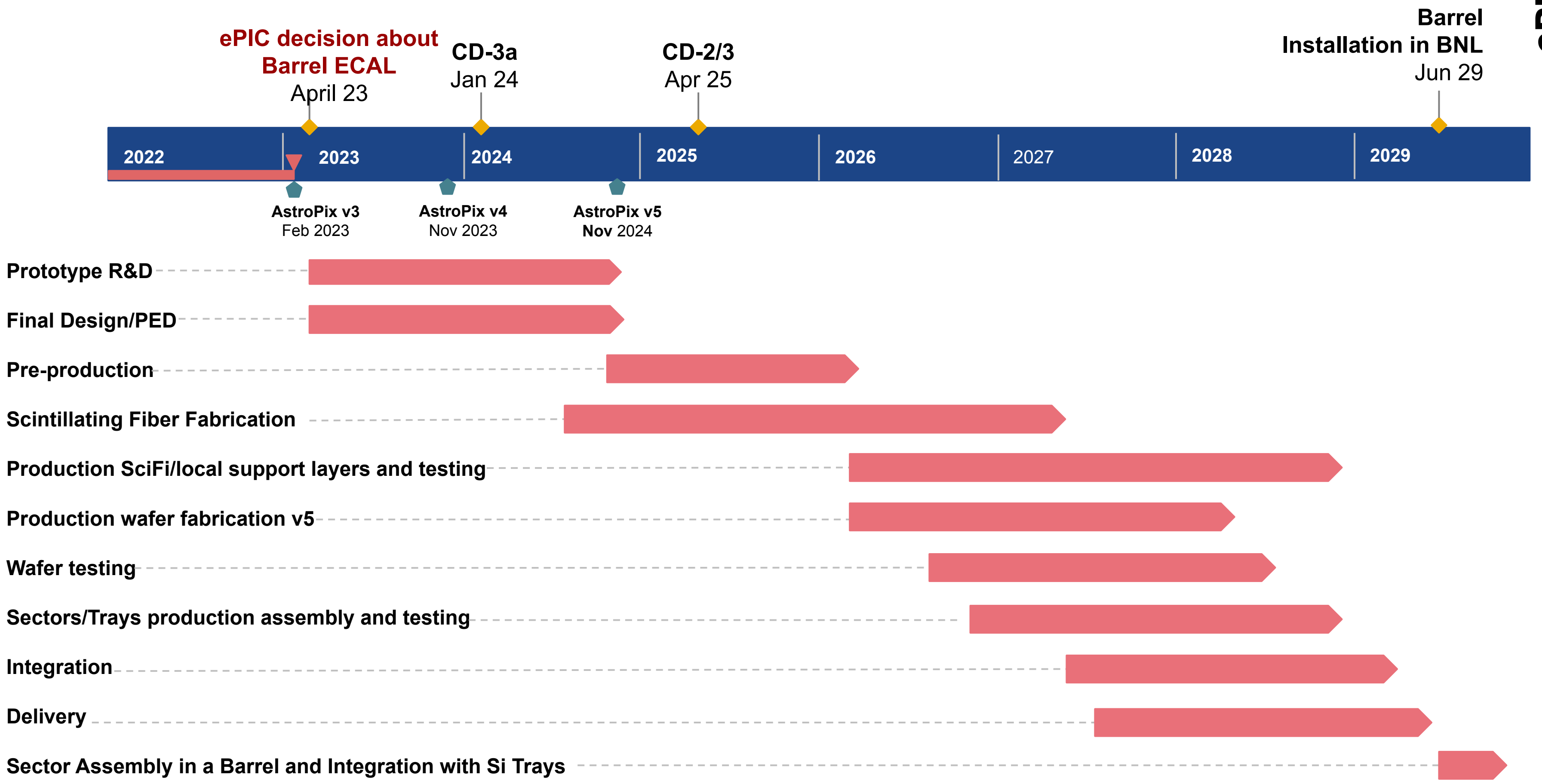
Korea

DSTC (Silicon)
Sanghoon Lim

DSTC (Pb/ScFi)
Hyon-Suk Jo

BIC HIGH-LEVEL SCHEDULE



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?

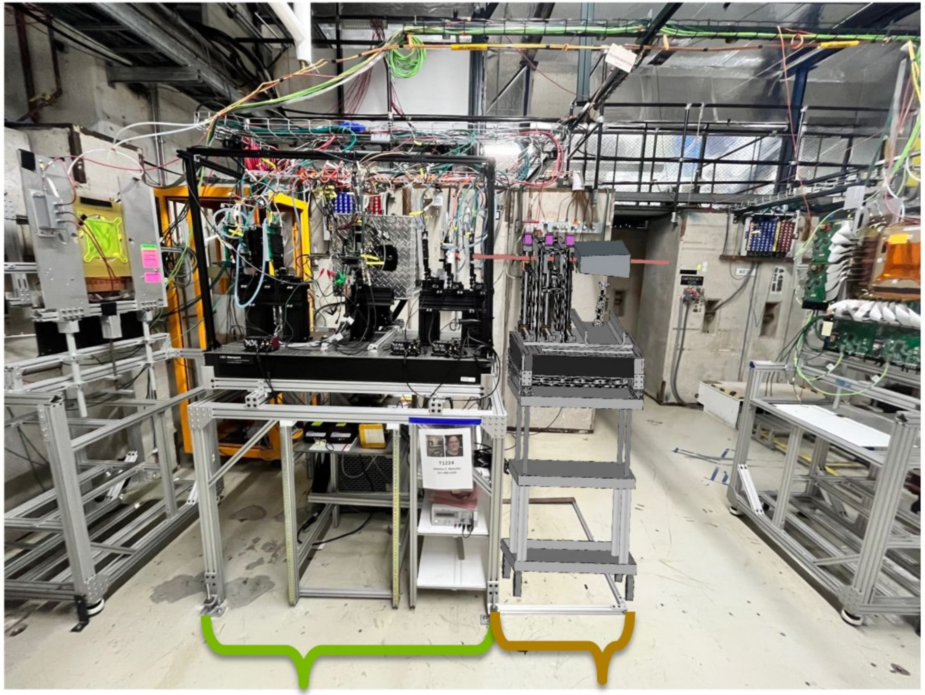
- Physics benchmark of energy response to pions
- Physics benchmark of e/π separation
- Technical benchmark of streaming readout of both technologies

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)

GENERAL R&D SETUP AT FNAL

- Add BIC prototype calorimeter behind existing Argonne ATLAS Pixel telescope with AstroPix setup at MTest
- Rotating stage to simulate particles incident at angles up to 45° ($\eta \sim 1$)
- Ability to lower BIC setup out of the beam, no need to uninstall for other experiments to run
  - Proximity to Argonne enables occasional opportunistic running



Current ANL AstroPix Telescope Setup

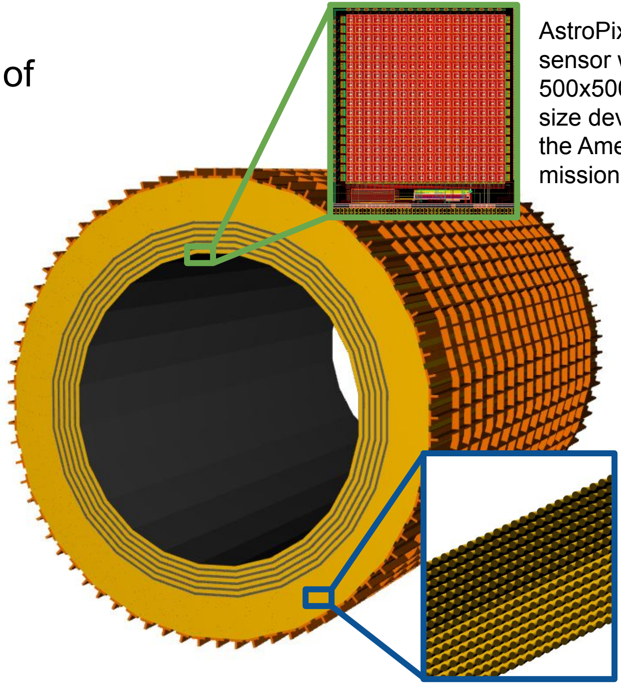
Planned BIC Setup

SUMMARY

Addressing the unique challenges for the barrel region in ePIC

Hybrid concept: 4 (+2) layers of Astropix interleaved with the first 5 Pb/ScFi layers, followed by a large volume with the rest of the Pb/ScFi layers

- ✓ Deep calorimeter (η = 0 ~17.1 X_0) while compact at ~ 40 cm
- ✓ Excellent energy resolution ($5.2\% / \sqrt{E} \oplus 1.0\%$)
- ✓ Unrivaled low-energy electron-pion separation by combining the energy measurement with shower imaging
- ✓ Unrivaled position resolution due to the silicon layers
- ✓ Deep enough to serve as inner HCal
- ✓ Very good low-energy performance
- ✓ Wealth of information enables new measurements, ideally suited for particle-flow
- ✓ Serves as tracking layer behind the DIRC



Checks all the boxes!

This work is supported by the U.S. Department of Energy, Office of Science, Office of Nuclear Physics, under contract DE-AC02-06CH11357.