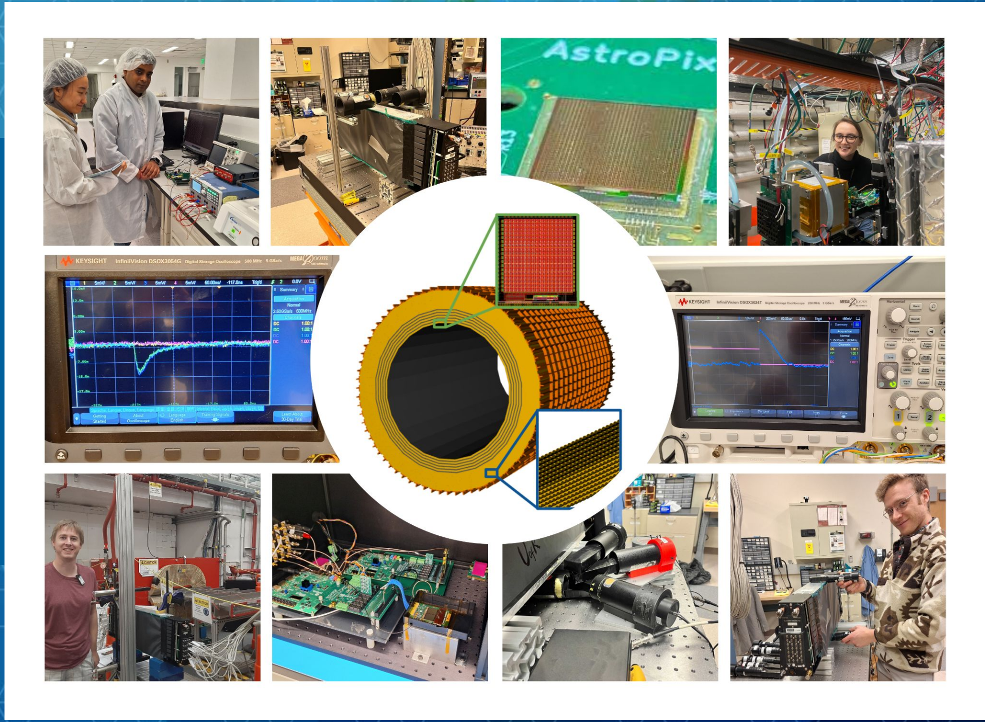
(DNP) T1-4 EIC Physics | Physique EIC (DPN)

CAP Meeting 2024



ePIC Barrel Imaging Calorimeter at the Electron-Ion Collider

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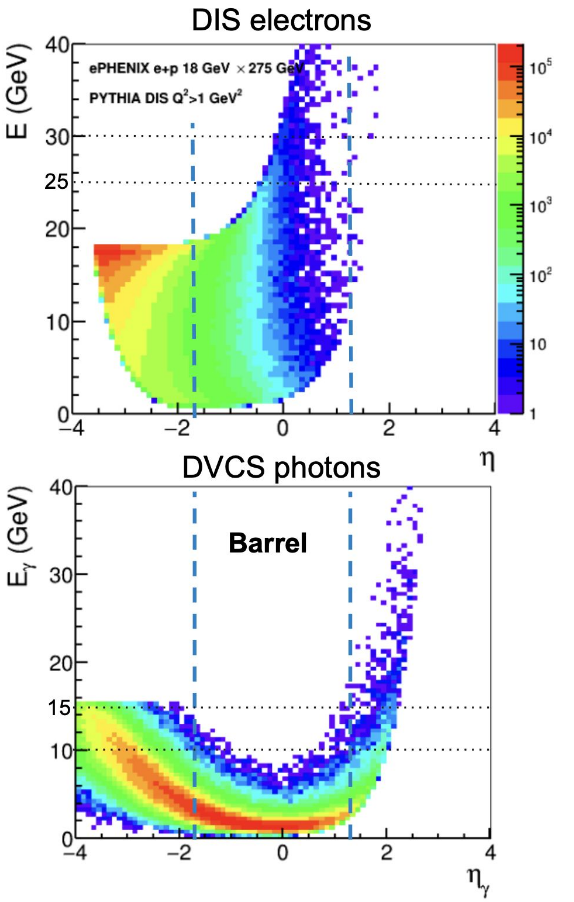
Argonne National Laboratory

delivered by Z. Papandreou, U of Regina

Electromagnetic Calorimetry at the EIC: Key challenges

From the EIC Yellow Report:
very stringent requirements for Barrel ECal

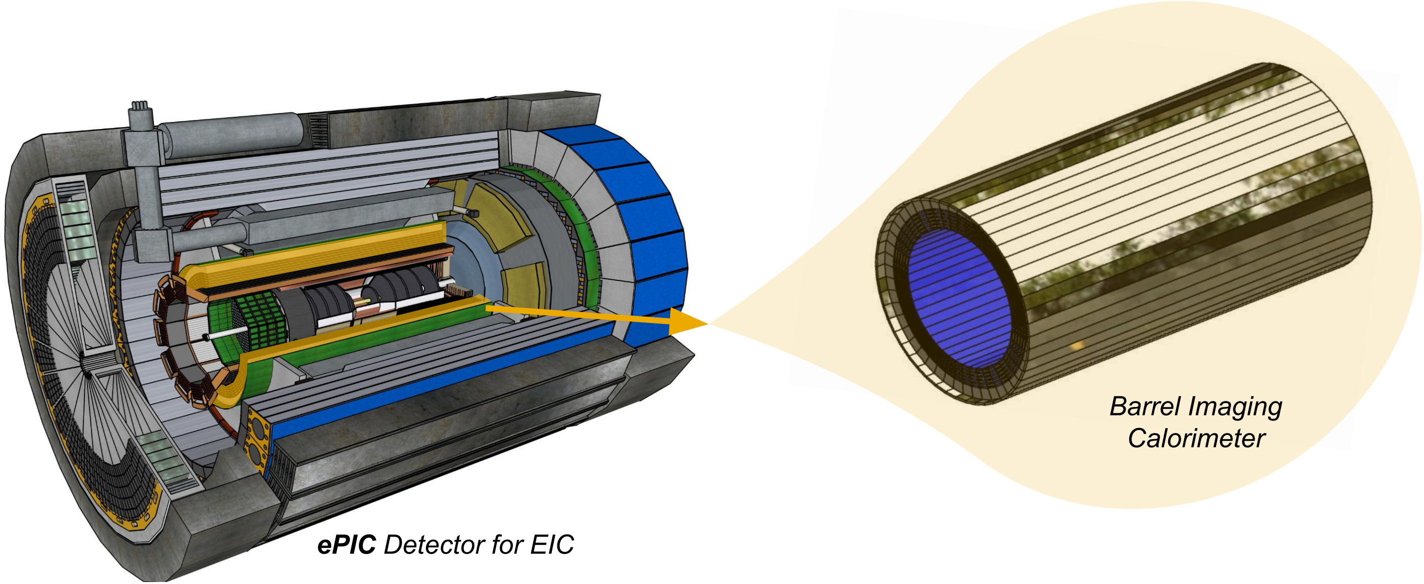
- Electron scattering machine: inclusive physics program requires **up to 10^4 π^- background suppression** at low momenta in the barrel
- The exclusive program requires **good energy resolution** ($< 7\text{-}10\%/\sqrt{E} \oplus 1\%$) for ɣ, and **fine granularity** for **good π^0/ɣ separation up to 10 GeV/c**
- The bECal should be capable of measuring **low energy photons** down to 100 MeV, while having the range to measure energies well above 10 GeV
- The system is very **space-constrained** inside the solenoid



Electromagnetic Calorimetry at the EIC: Solution

From the EIC Yellow Report: very stringent requirements for Barrel ECal

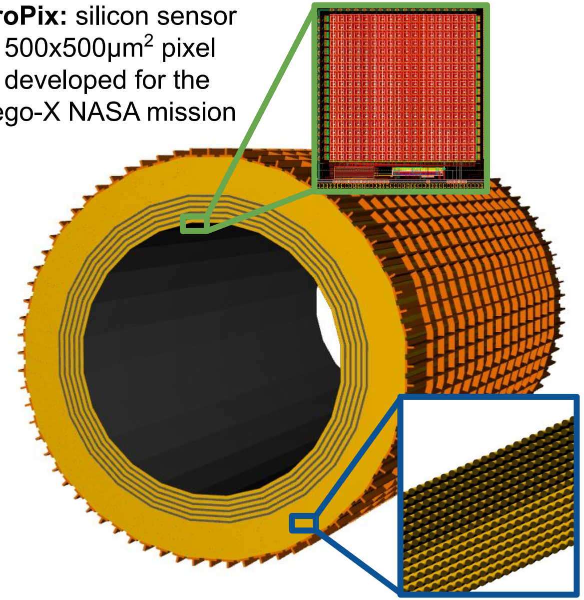
Solution: Hybrid lead/scintillating fiber calorimeter with a silicon tracker to precisely measure 3D image of electromagnetic shower



Barrel Imaging Calorimeter: The Concept

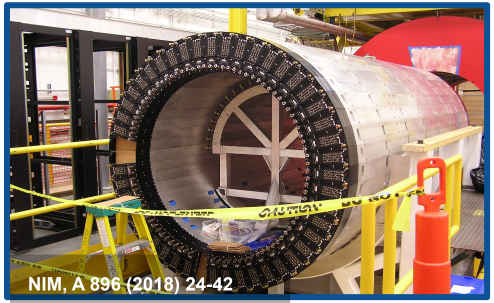
High-performance sampling calorimeter with Si sensors for shower profiling

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



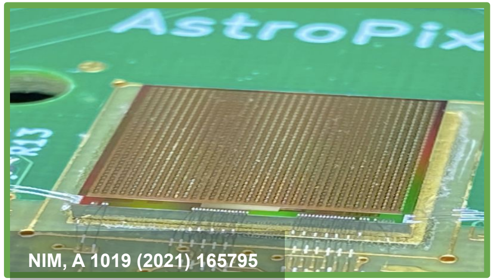
Pb/Scintillating fiber layers with two-sided SiPM readout

ePIC Simulations: Barrel ECal Geometry Rendering



NIM, A 896 (2018) 24-42

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

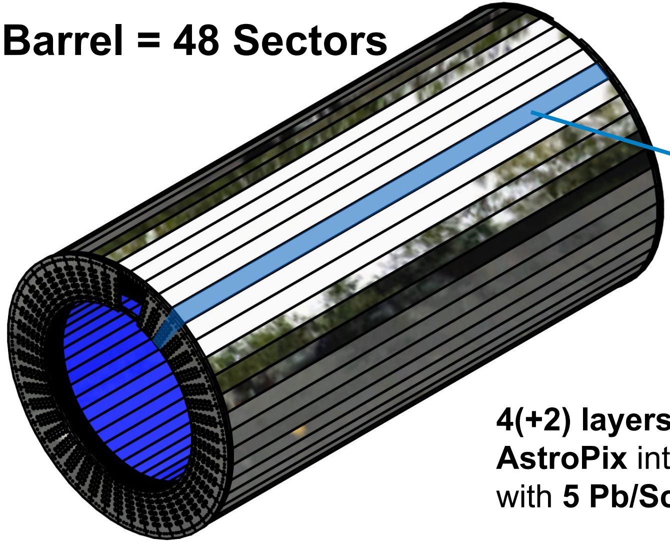


NIM, A 1019 (2021) 165795

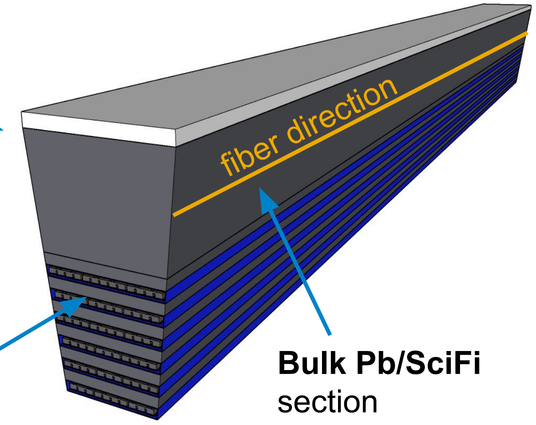
Insert layers of monolithic AstroPix silicon sensors (ultra-low-power, developed for NASA at ANL) to capture a **3D image of the shower**

Detector Structure

Barrel = 48 Sectors



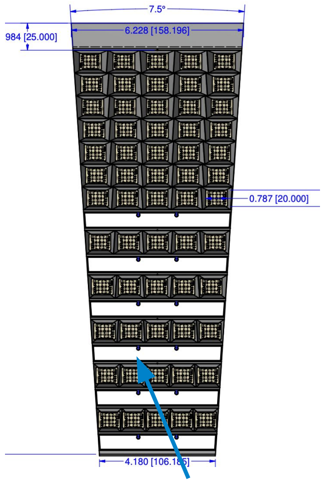
Sector



4(+2) layers of AstroPix interleaved with **5 Pb/ScFi layers**

Bulk Pb/SciFi section

Sector End View



Length: ~435 cm

Radius: ~ 82 cm

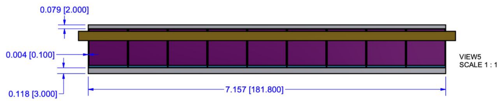
η Coverage: -1.71 < η < 1.31

Depth: 17.1X0 at η = 0

Sampling fraction ~ 10%

AstroPix layers built from

Modules



Module - 9 AstroPix chips daisy chained together

Pb/SciFi Layer (1.4X0)

- 5 readout cells per layers
- 1 light-guide per cell

Barrel Imaging Calorimeter Technical Drawings
T. O'Connor, K. Bailey

SciFi/Pb Layers Technology

Mature technology

SciFi/Pb layers follow the **GlueX Barrel Calorimeter** (built at URegina)

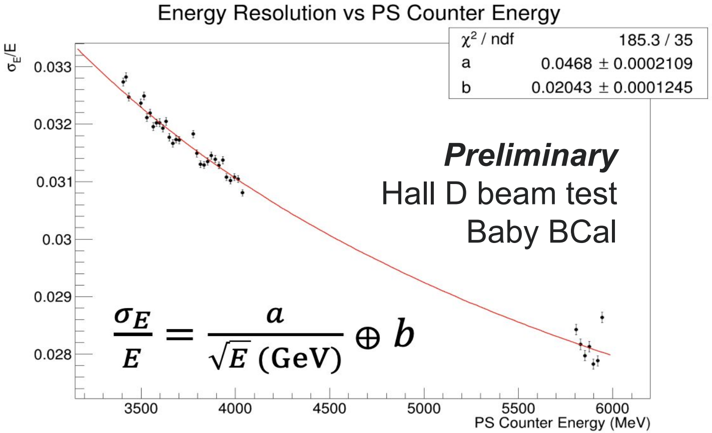
Energy resolution: σ = 5.2% /$\sqrt{E}$ ⊕ 3.6%[1)]

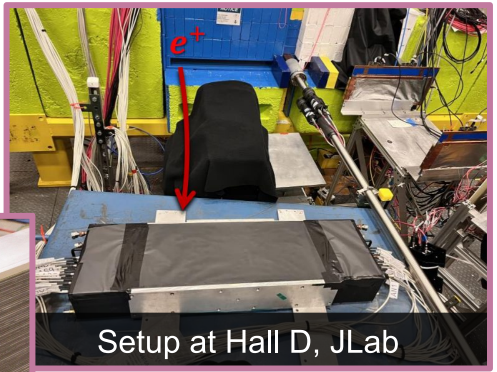
- 15.5 X_0, extracted for low energy γ < ~2.5 GeV

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

- 2-side SiPM readout, Δt measurement

Snapshot of FY23 R&D:





Setup at Hall D, JLab


Baby BCal


GlueX BCal

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

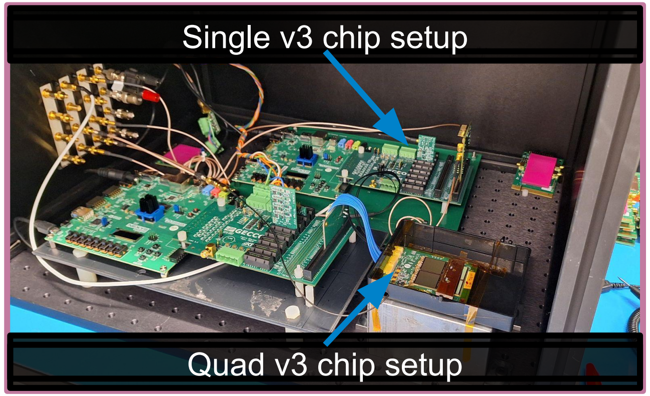
Imaging Layers Technology

AstroPix sensors

- HV-CMOS MAPS based on ATLASPix3 [1]
- designed for the AMEGO-X NASA mission

Key features:

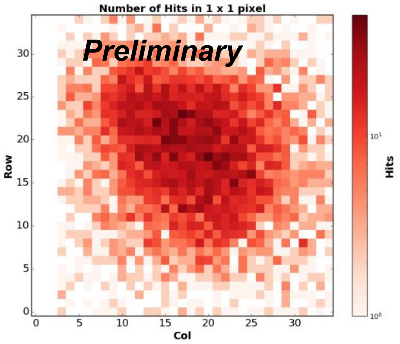
- Very low power dissipation
- Good energy resolution
- 500 µm pixel size
- Time resolution ~ 3.25 ns (v4)



Snapshot of FY23 R&D:

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

Performs well in much harsher conditions than EIC



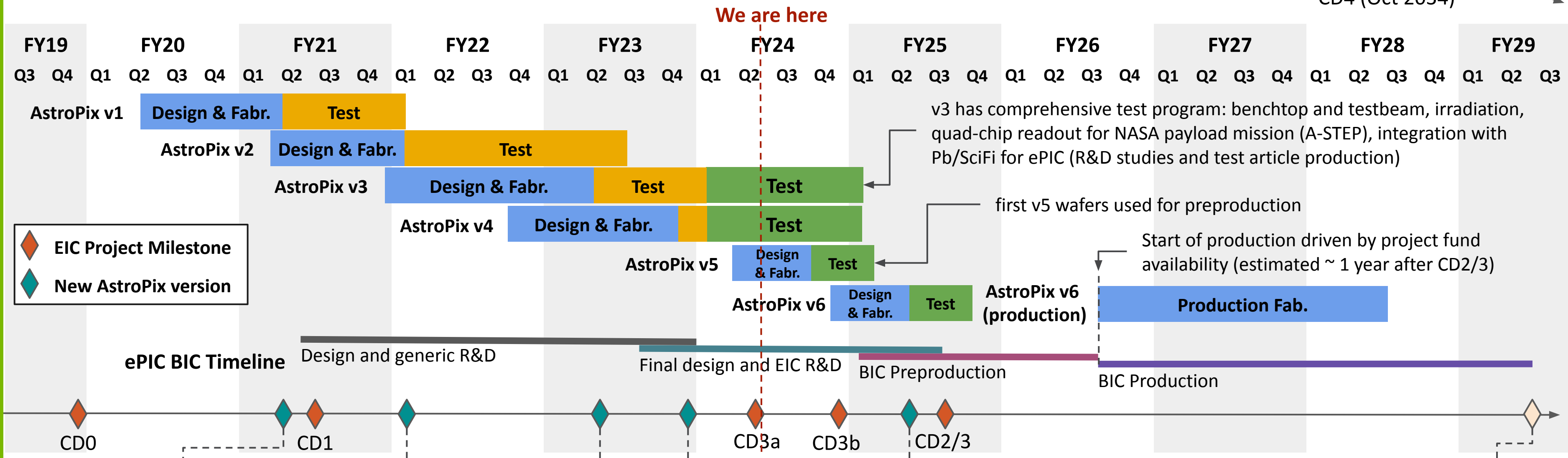
Targeted AstroPix v3 performance goals [2]

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	$500\,\mu m$

1) arXiv:2109.13409 [astro-ph.IM]
2) arXiv:2208.04990 [astro-ph.IM]

AstroPix Timeline

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



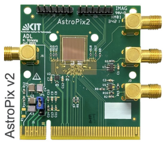
Start of BIC installation at BNL

AstroPix v1

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

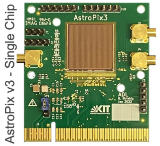
Nucl.Instrum.Meth.A 1019 (2021) 165795

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

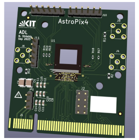
1 x 1 cm^2 chip, 250 µm pixel pitch
35 x 35 pixel matrix
Row/column readout
Power dissipation 3.4 mW/cm^2



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

pre-production chip

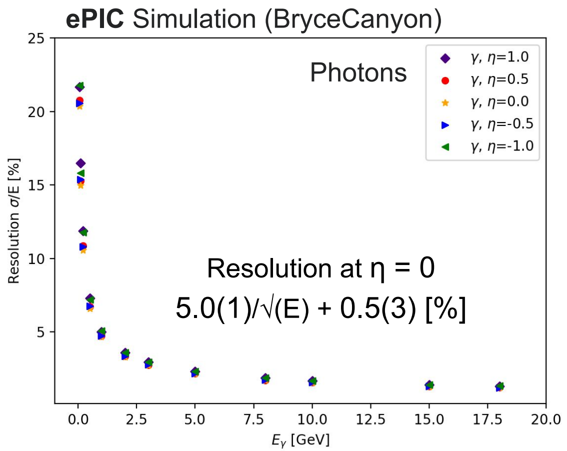
1.87 x 1.9575 cm^2 chip, 500 µm pixel pitch
Design identical to v4 (with bug fixes)

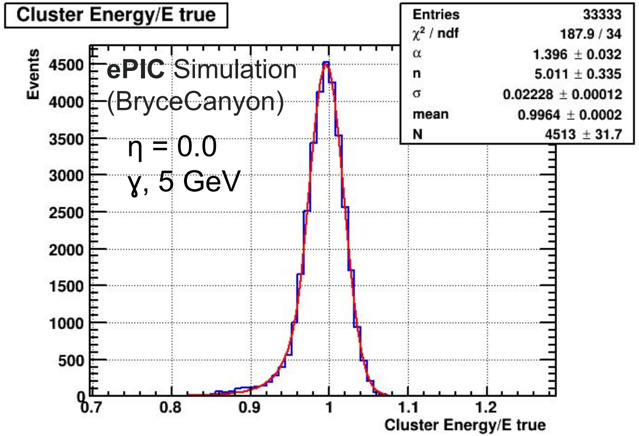
AstroPix v6

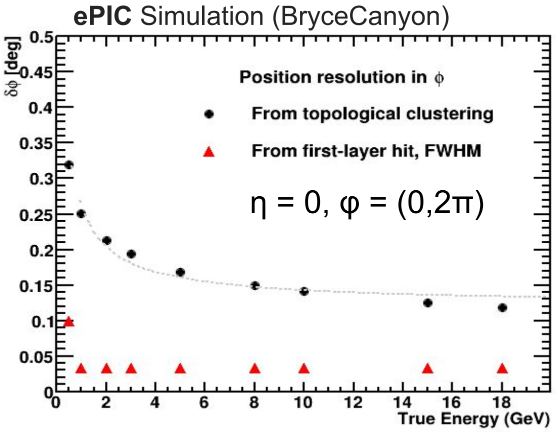
production chip

2 x 2 cm^2 chip, 500 µm pixel pitch
Design identical to v5 (with bug fixes)

Detector Performance: Energy and Position





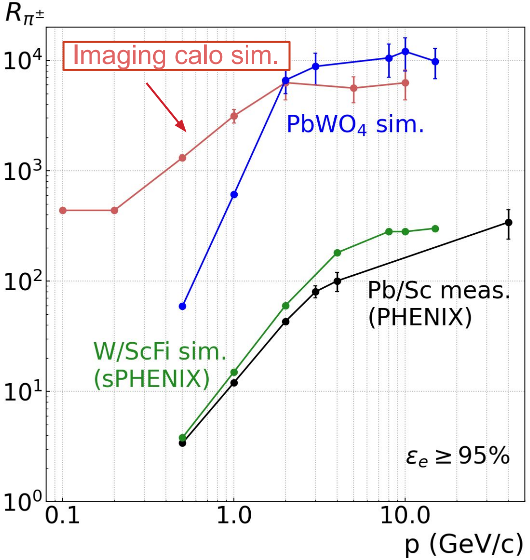


- **Simulated resolution for photons** at η = 0: 5.0(1)/√(E) + 0.5(3) [%]
- **GlueX Pb/ScFi ECal:** $\sigma = 5.2\% / \sqrt{E} \oplus 3.6\%$ NIM, A 896 (2018) 24-42
  - 15.5 X_0, E_γ = 0.5 - 2.5 GeV, measured energies not able to fully constrain the constant term
- **Angular resolution** in all regions well below 0.1 deg in majority regions on the level of single pixel resolution

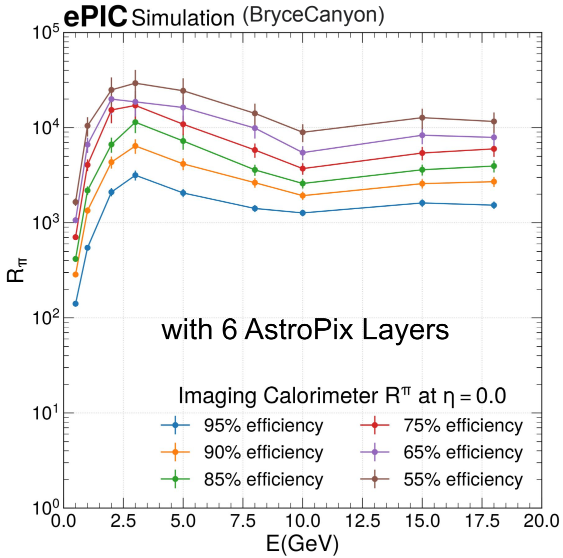
Energy resolution - Primarily from Pb/ScFi layers (+ Imaging pixels energy information)
Position resolution - Primarily from Imaging Layers (+ 2-side Pb/ScFi readout)

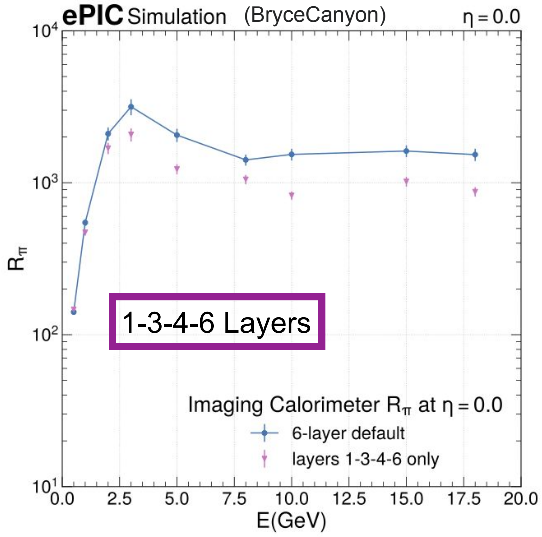
Detector Performance: e/π Separation

Standalone simulation



Realistic ePIC simulation

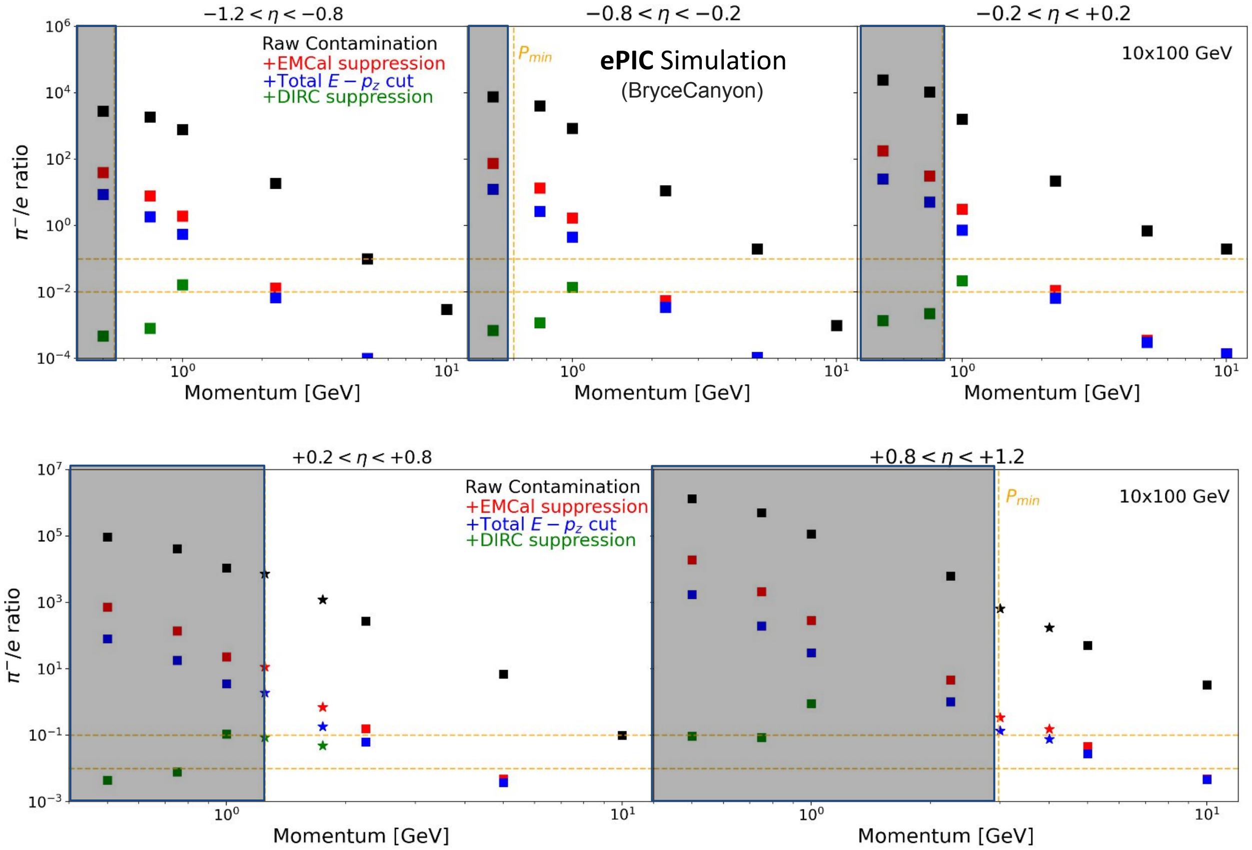




- **Goal:** Separation of electrons from background in Deep Inelastic Scattering (DIS) processes
- Method: **E/p cut (Pb/ScFi) + Neural Network** using 3D position and energy info from imaging layers

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

Example Barrel e/π Performance for 10 x 100 GeV



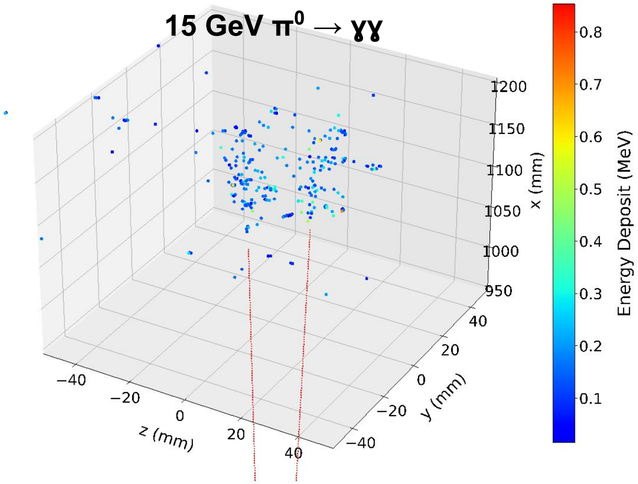
Challenging goal: Achieve 90% electron purity from the combined detector performance (ECAL + DIRC)

- To keep pion contamination systematic uncertainty to required 1% level
- Impact of total E-pz cut, DIRC suppression and EMCal suppression studies

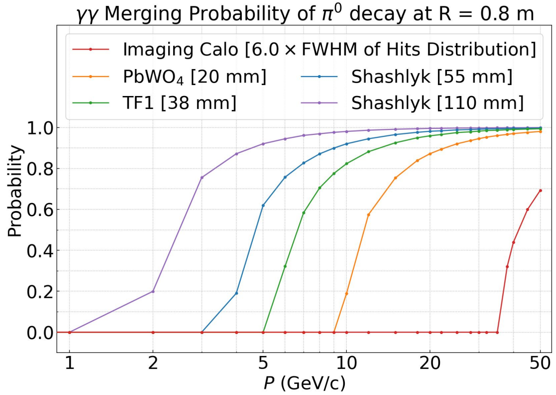
Requirement fulfilled in all η ranges

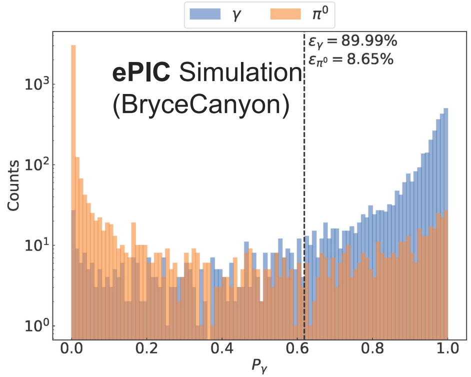
Detector Performance: π^0 identification

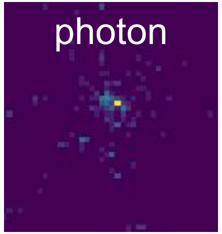
15 GeV $\pi^0 \rightarrow \gamma\gamma$

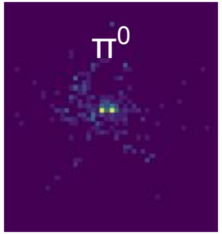


Separation of γ/π^0 (upper limit)







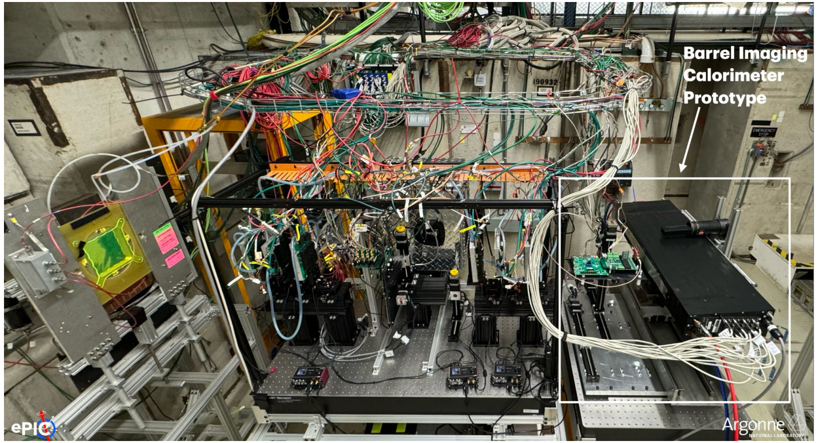


- **Goal:** Discriminate between π^0 decays and single γ from DVCS, neutral pion identification
- Precise position resolution allow for excellent separation of γ/π^0 **based on the 3D shower profile**
- Initial evaluations based on convolutional NN show 91.4% rejection of π^0 at 90% efficiency of γ at 10 GeV/c

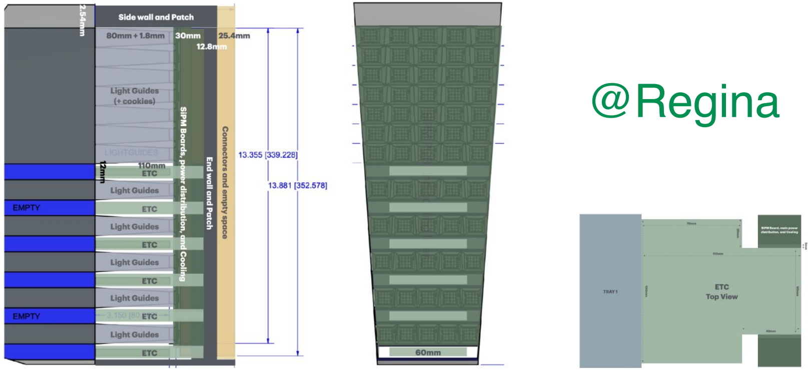
Separation of two gammas from neutral pion well above required 10 GeV

Current Focus: Towards CD-2/3 and TDR

- Final design optimizations driven by realistic simulations, R&D, and engineering design
    - Ongoing R&D activities at Fermilab Beam Test Facility focused on **system integration** and **benchmarking response to pions.**
    - Ongoing design activities within the Project Engineering Design funds with **recently frozen detector interfaces**
- Establishing construction and testing strategies with international partners



Fermilab Beam Test Facility Setup



@Regina

Example of mechanical envelopes of End-of-Sector Box

Open R&D Questions

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

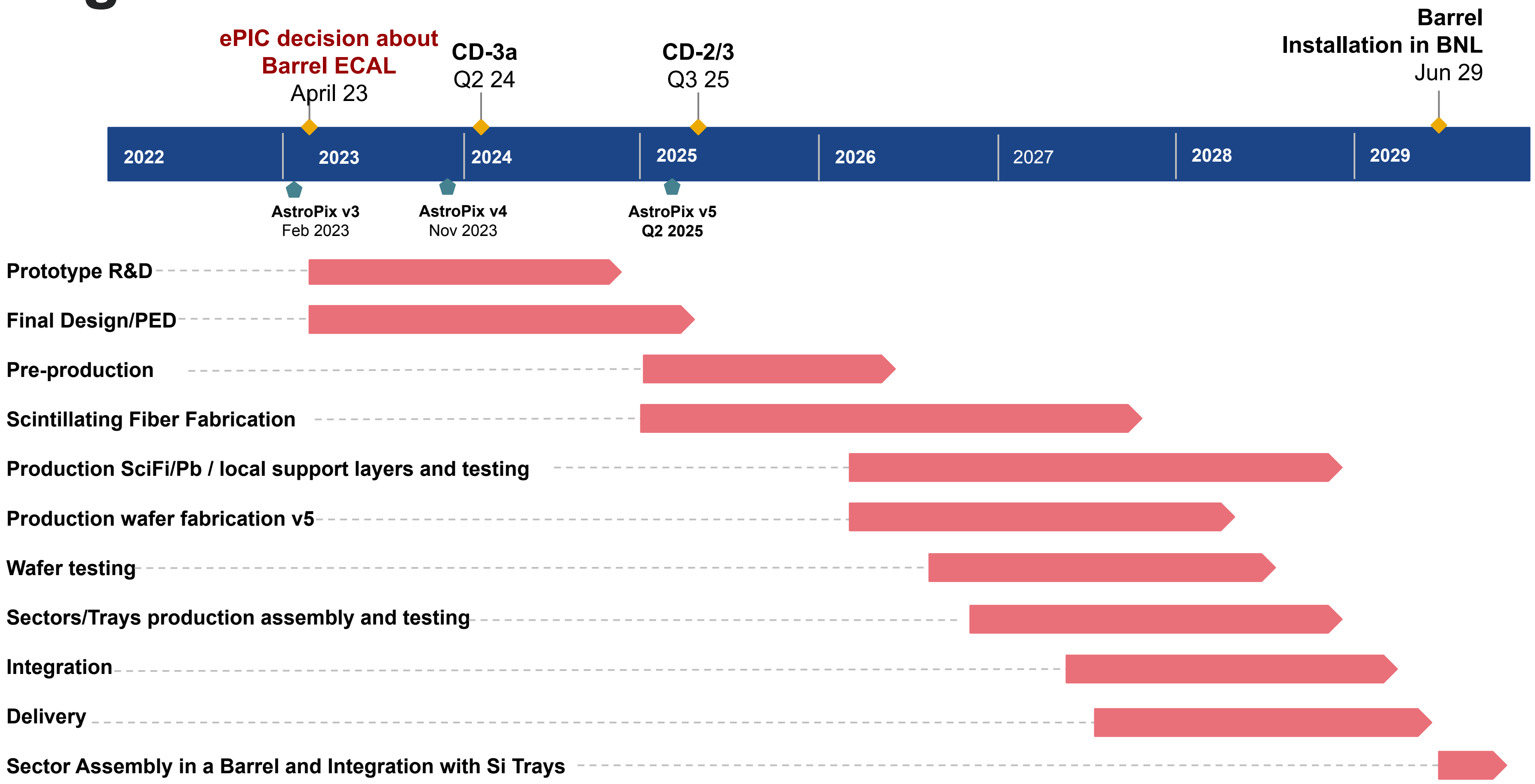
How detector performance obtained from detailed simulations compare with the measurements in the integrated SciFi/Pb and AstroPix prototype system?

- Physics benchmark of energy response to electrons ✅
- Physics benchmark of energy response to pions and e/π separation: In progress 🚧
- Technical benchmark of streaming readout of both technologies: In progress 🚧

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 final design: usage of optical cookies, shape of lightguides, etc.

High-Level Schedule



USA

- Argonne National Laboratory
- NASA Goddard Space Flight Center
- Oklahoma 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

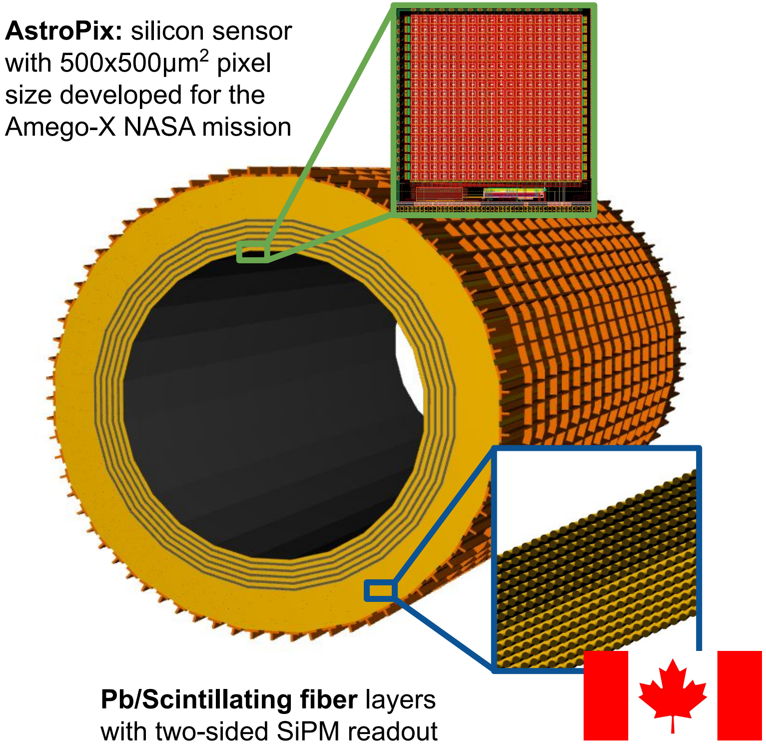
- Kyungpook National University
- Yonsei University
- University of Seoul
- Pusan National University
- Korea University
- Sungkyunkwan University
- Hanyang University
- Gangneung-Wonju National University

Germany

- Karlsruhe Institute of Technology
- University of Giessen

* Application in current round

Canadian Contributions to BIC



+ TRIUMF: SRF Accelerator technology

Current extensive involvement in Pb/ScFi layers

- R&D Tests at Hall D of Jefferson Lab and FNAL
- Scintillating fiber testing in preparation to CD-3a
- Detector Simulations

CFI IF: Combined ask from **UManitoba and URegina** envelopes

- TRIUMF involvement
- Visibility of key contribution to large international collaboration

Canadian scope for production and installation:

Lead/fiber sector construction

- Pressed assemblies of swaged Pb sheets, optical fibers, epoxy

End-of-sector readout boxes

- Lightguides, SiPMs, gain stabilization, signal digitization

Summary

Barrel Imaging Calorimeter for ePIC at EIC

- Excellent energy and spatial resolution
- Unrivaled low-energy electron-pion separation by combining the energy measurement with shower imaging
- Unrivaled position resolution due to the silicon layers

Current focus - Towards CD-2/3

- Final design optimizations driven by realistic simulations, R&D, and engineering design
- Establishing construction and testing strategies with international partners

Thank you

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Backup

Benefits to Canada

A Canadian flag on the flagship EIC detector for the next decades

- Canadian **international scientific competitiveness** depends on significant and visible participation in international collaborative science efforts.
  - **CFI** has already been delegating Mark Lagacé, Directory of Programs, to the twice-yearly EIC Resource Review Board meetings
- Silicon photo-multiplier sensors (**SiPMs**) and silicon pixel detectors are **key nuclear imaging methodologies**, with medical and industrial applications.
  - E.g. Dr. Teymurazyan's work using **nuclear imaging** to study nutrient uptake and water use of commercial crops in the Canadian Prairies.
- Participation in data-rich high-granularity detectors gives Canadian researchers opportunities to develop **novel data science techniques**.
  - The EIC is the first particle collider co-designed with artificial intelligence/**machine learning**: detector placements and parameters to optimize physics objectives

Example Barrel e/π Performance for 10 x 100 GeV