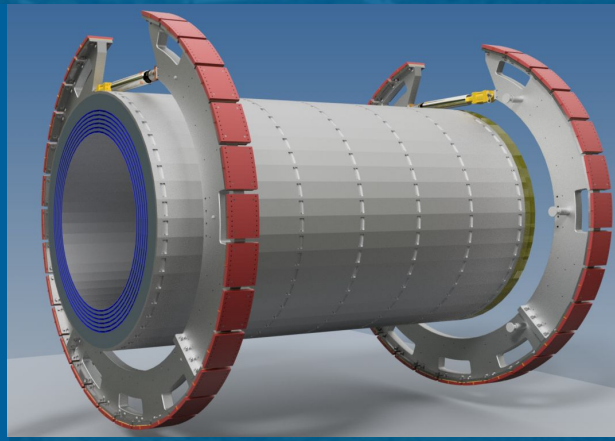
2026 CAP Congress

University of Ottawa and Carleton University, Ottawa, ON

The Barrel Imaging Calorimeter for the future EIC facility



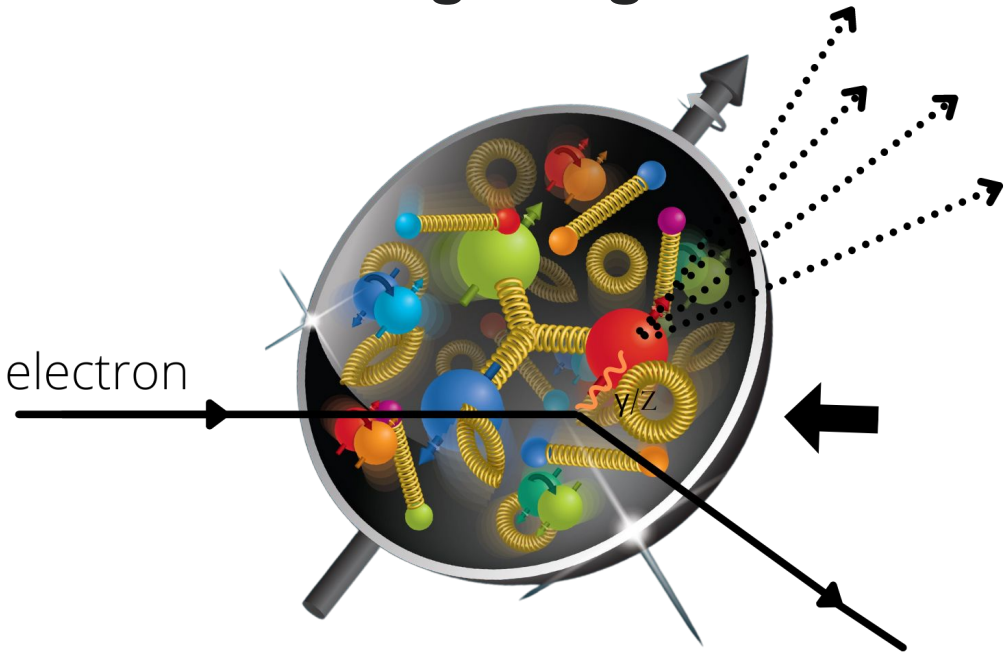
Maria Żurek, zurek@anl.gov

Argonne National Laboratory
for the ePIC BIC Detector Subsystem Collaboration

ePIC

Argonne NATIONAL LABORATORY

Towards understanding the glue that binds us all



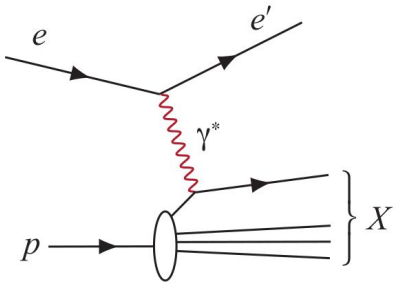
The EIC will uniquely address three profound questions about nucleons and how they are assembled to form the nuclei of atoms:

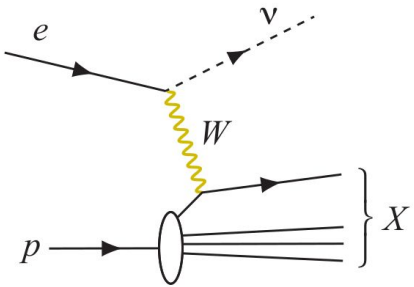
- How does the mass of the nucleon arise?
- How does the spin of the nucleon arise?
- What are the emergent properties of dense systems of gluons?

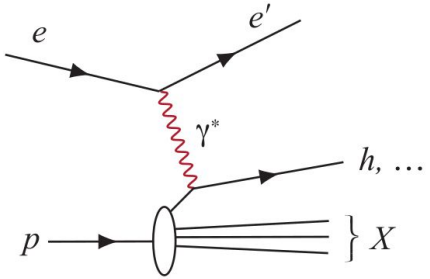
EIC Physics Case

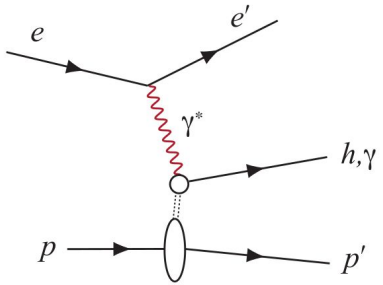
Calorimetry Role

DIS event kinematics - scattered electron or final state particles









Neutral Current DIS

- Detection of scattered electron with high precision - event kinematics
- Excellent e/h separation needed

Charged Current DIS

- Event kinematics from the final state particles
- Jet measurement capabilities

Semi-Inclusive DIS

- Precise detection of scattered electron in coincidence with at least 1 hadron
- Measurement of SIDIS π^0, decay electrons

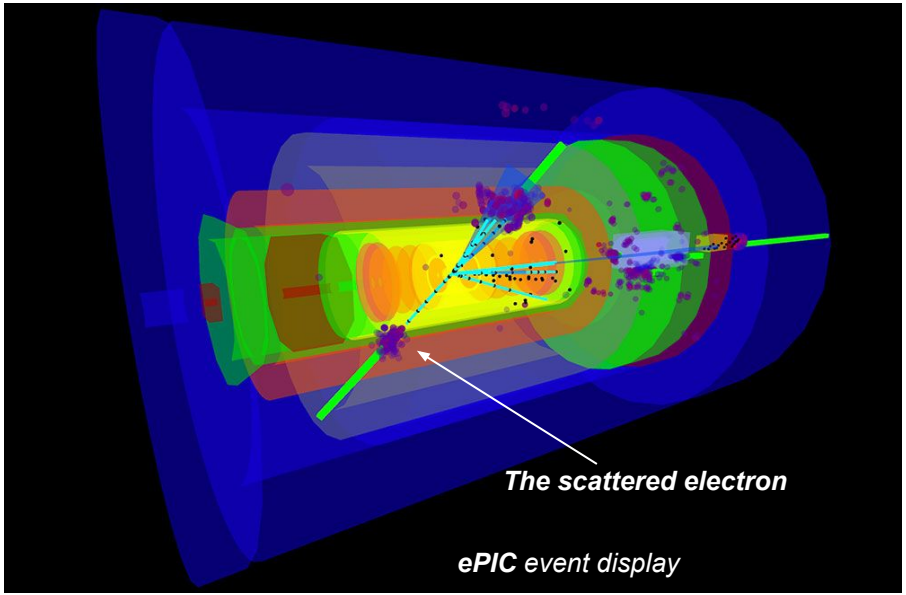
Deep Exclusive Processes

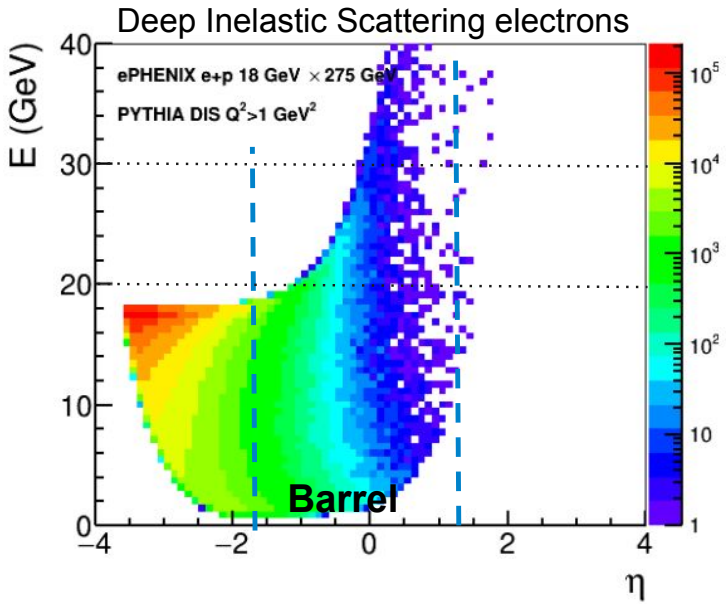
- Detection of all particles in event
- Detection of DVCS γ, exclusive π^0, decay electrons (e.g. VM)
- Separation of γ/π^0 for DVCS

Electromagnetic Calorimetry at the EIC

Key challenges for Barrel EM Calorimeter

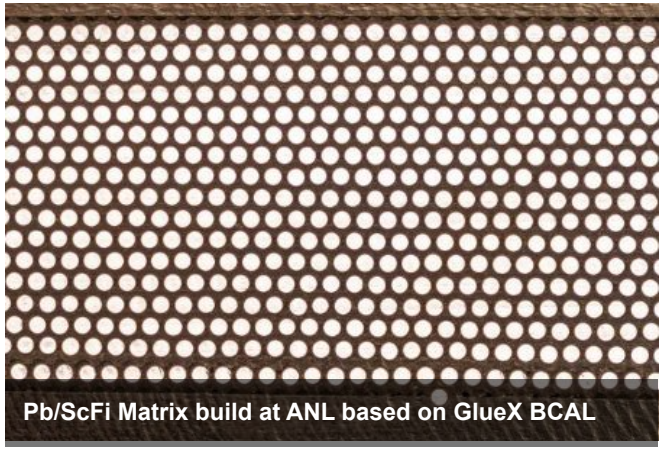
- Electron scattering machine: inclusive physics program requires high power for e/π separation down to 1 GeV/c: Suppression **up to 10^4 combined with other subsystems in the barrel region**
- The exclusive program requires **good energy resolution** (< 10%/√(E) + (2-3)%) for ɣ up to 10 GeV, and **fine granularity** for good π^0/ɣ separation up to 10 GeV.
- The system is very **space-constrained** inside the solenoid



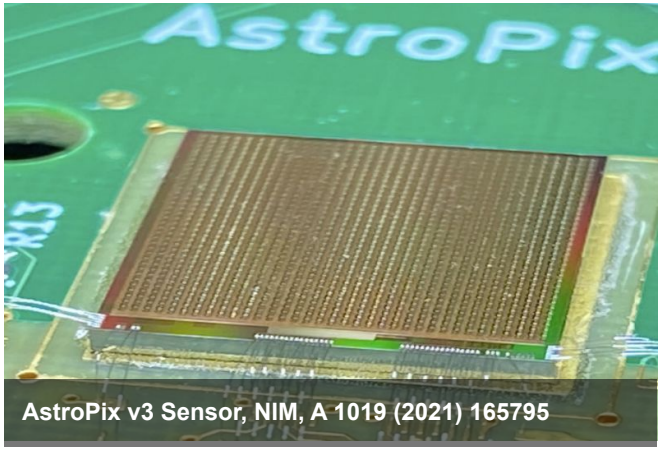


A Hybrid Imaging Calorimeter

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



Pb/ScFi Matrix build at ANL based on GlueX BCAL



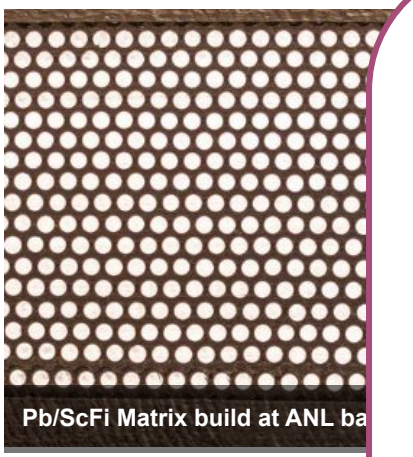
AstroPix v3 Sensor, NIM, A 1019 (2021) 165795

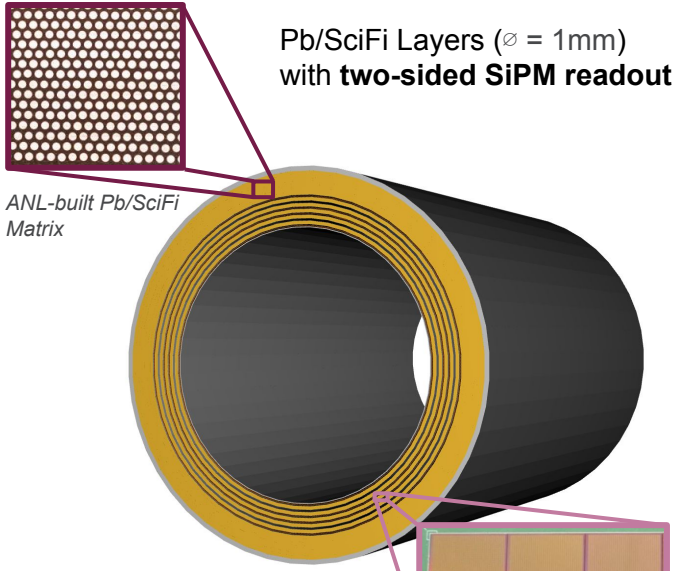
Start from mature layered Pb/ScFi technology with side-readout (same as the GlueX calorimeter) for state-of-the-art sampling calorimeter performance

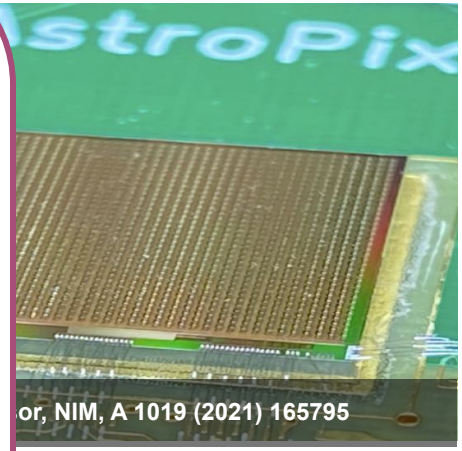
Insert layers of monolithic AstroPix sensors (ultra-low-power silicon sensor developed for NASA) in the first half of the calorimeter to capture a 3D image of the developing shower

Barrel Imaging Calorimeter (BIC)

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

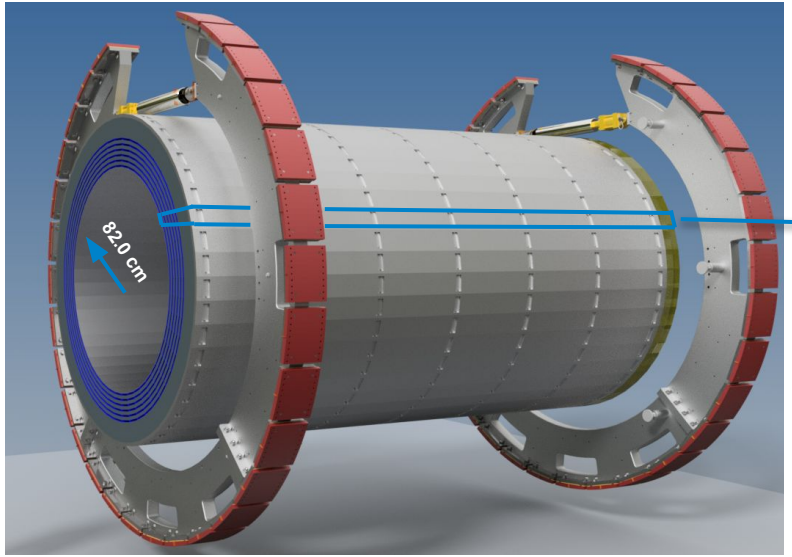




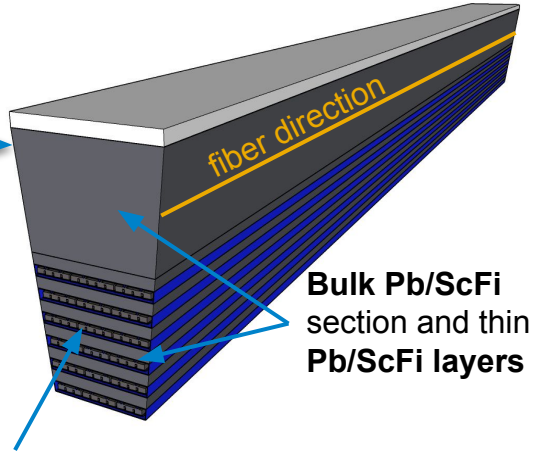


Start from mature layere
with side-readout (same
calorimeter) for state-of-
calorimeter performance

lithic AstroPix sensors
on sensor developed for NASA) in
lorimeter to capture a 3D image of
ver



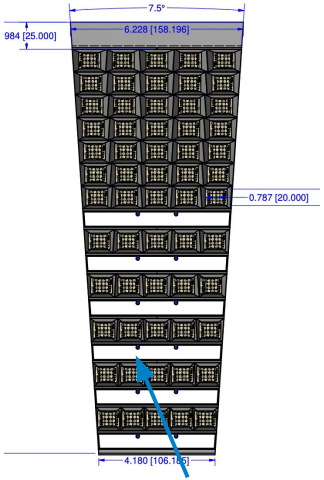
Sector



Bulk Pb/ScFi section and thin **Pb/ScFi layers**

6 slots for AstroPix trays

Sector End View



Pb/SciFi Layer ($1.4X_0$)

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

Length: ~435 cm

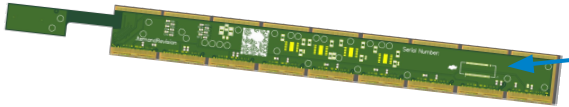
Radius: ~ 82 cm

η Coverage: -1.71 < η < 1.31

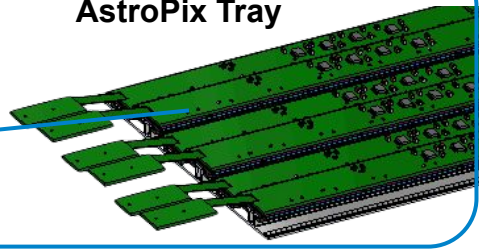
Depth: $17.1X_0$ at η = 0

Sampling fraction ~ 10%

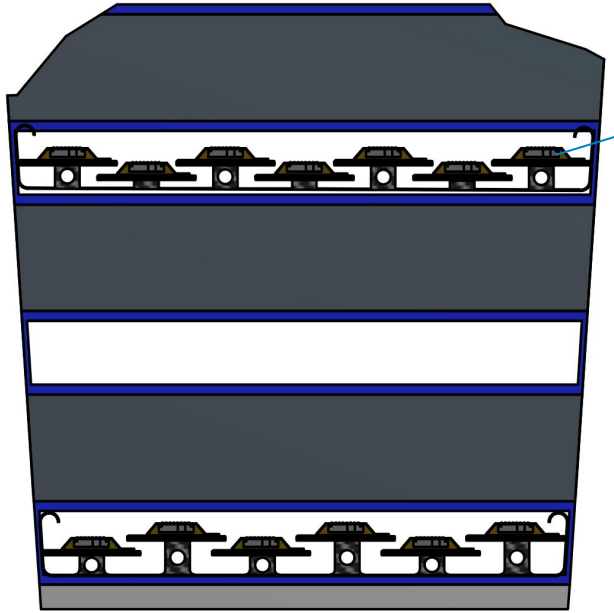
AstroPix Module - 9 AstroPix chips daisy chained together



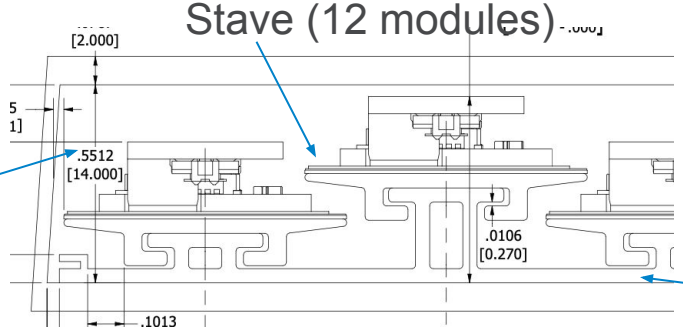
AstroPix Tray



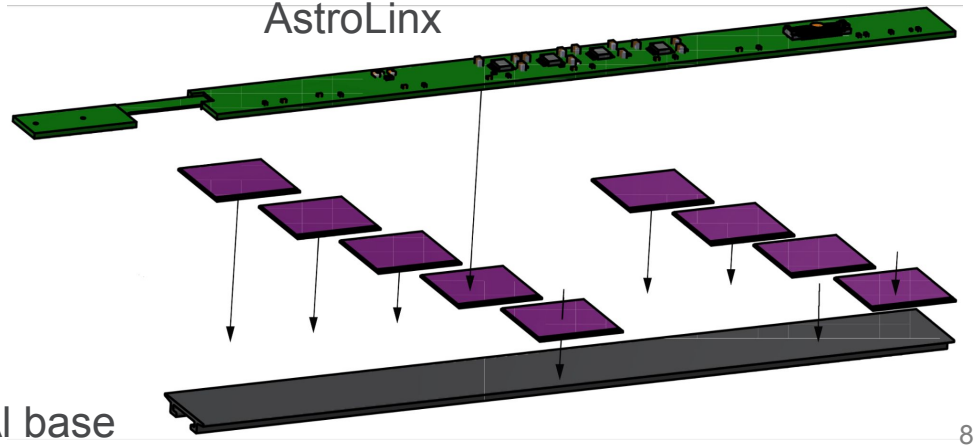
Tracker Mechanics



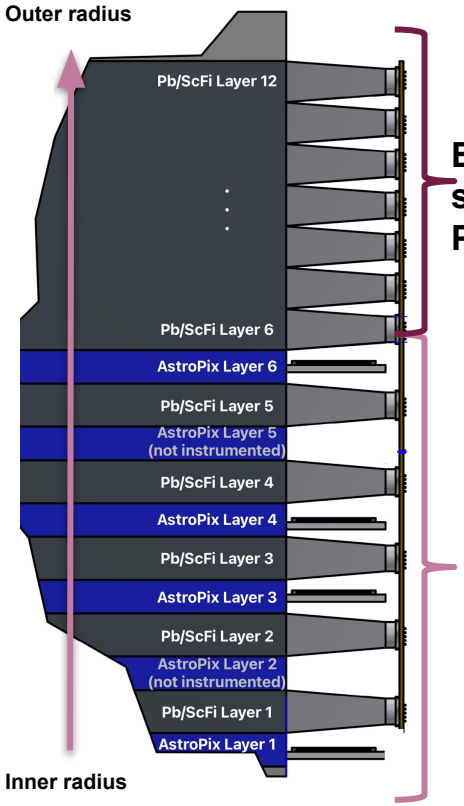
Single BIC Sector



Module (9 chips):

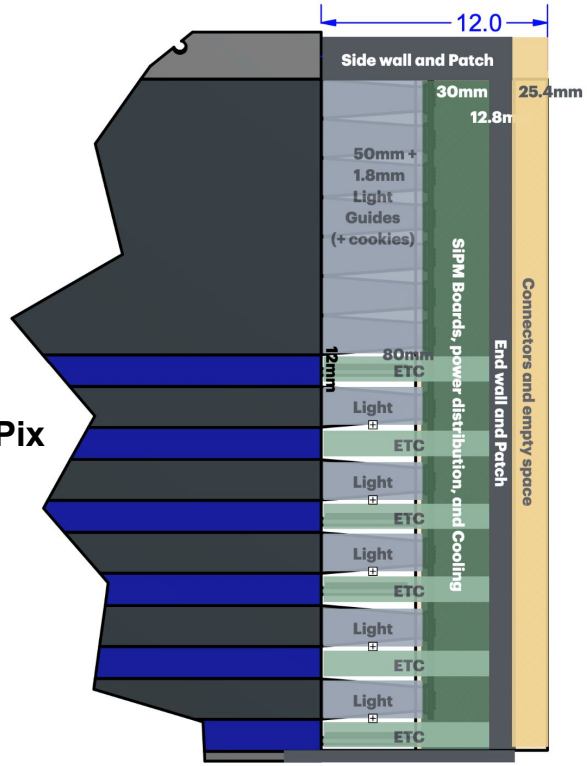


End-of-Sector Boxes (ESB)



Bulk back section of Pb/ScFi

6 slots for AstroPix sensors, 4 **instrumented** interleaved with **5 Pb/ScFi layers**



Pb/SciFi:

- light guides
- cookies
- SiPMs
- SiPM amp/sum boards (UofR)
- CALOROC
- LMS system (KNU)

Tracker:

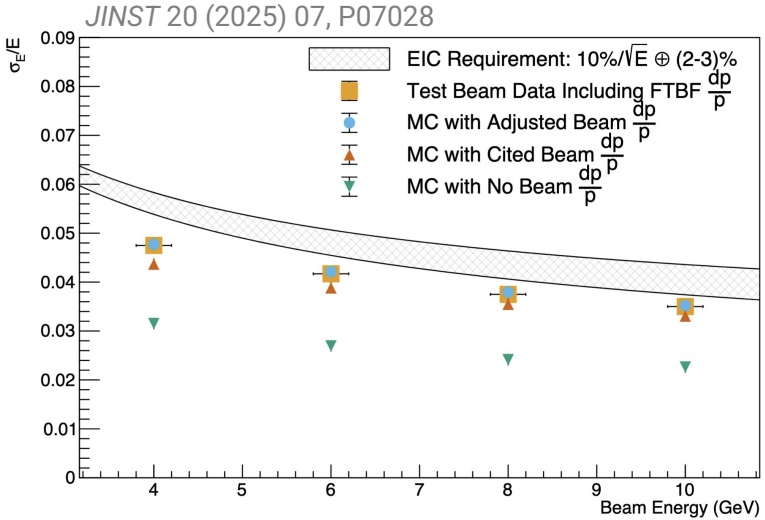
- ETC: End of Tray Card for AstroPix readout

Cooling

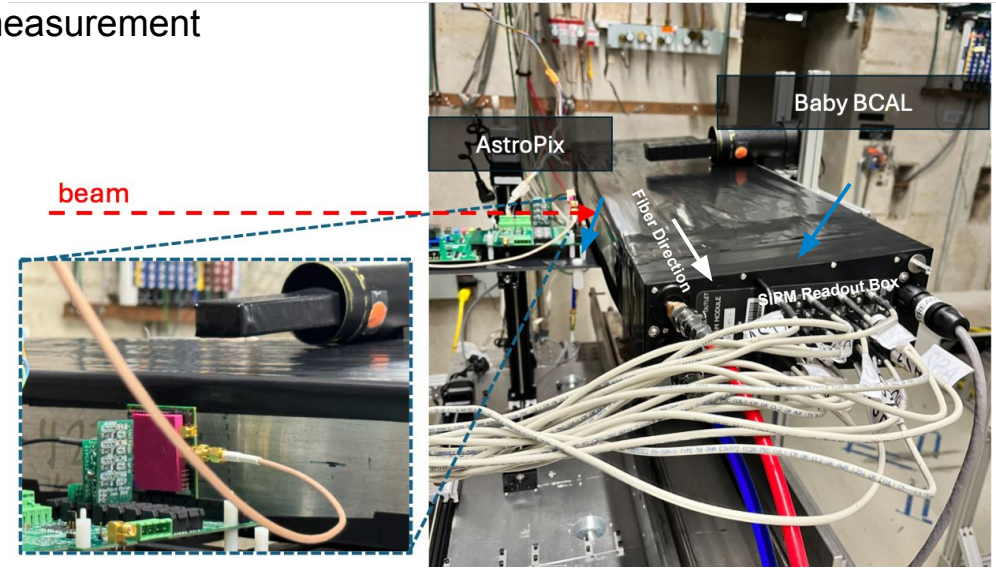
Pb/ScFi Layers Technology

Mature technology: SciFi/Pb layers follow the GlueX Barrel Calorimeter

- **Energy resolution:**
  - σ = 5.2% /√E ⊕ 3.6% from GlueX extracted for low energy γ < ~2.5 GeV
  - **Constant term** for energy up to 10 GeV constrained at FNAL and Hall D: ~1.5%
- **Position resolution in z:**
  - 1.1cm/√E 2-side SiPM readout, Δt measurement



Electromagnetic Energy Resolution measured at Fermilab Beam Test



Experimental Setup at the Fermilab Beam Test

Imaging Layers Technology

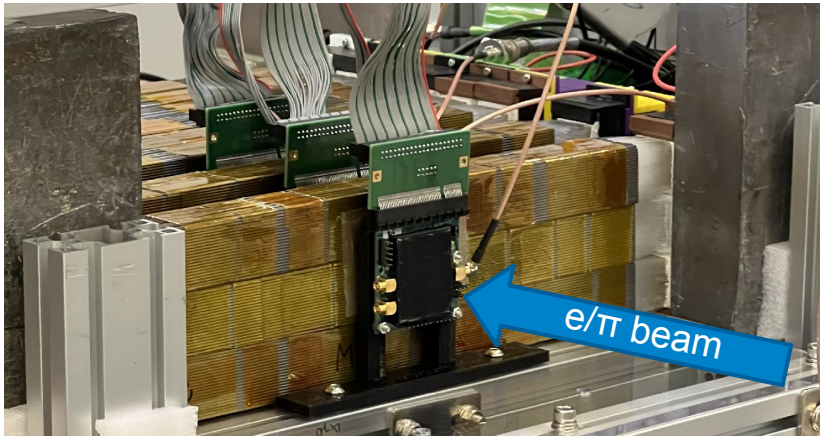
AstroPix sensors

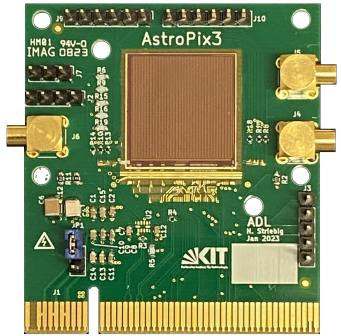
- HV-CMOS MAPS
- designed for the AMEGO-X NASA mission

Key features:

- Very low power dissipation (< 1.5 mW/cm^2)
- Good energy resolution (10% at 60 keV)
- 500 x 500 µm pixel size
- 525 um Si thickness
- **Perfect for calorimetry!**

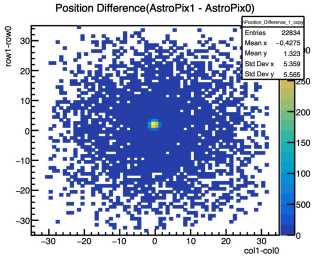
J. Bok, AstroPix-SciFi/Pb Beam Test in KEK



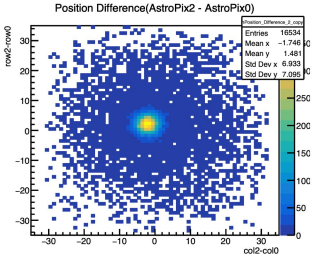


e-Print: 2605.07681

Pions

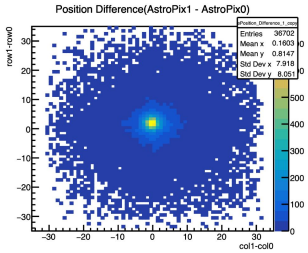


Position difference between 1st-2nd layer

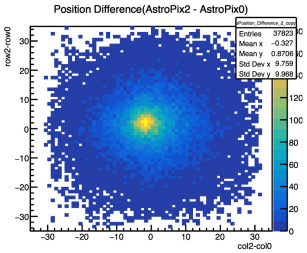


Position difference between 1st-3rd layer

Electrons



Position difference between 1st-2nd layer



Position difference between 1st-3rd layer

AstroPix Timeline

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

Test Readiness Review (TRR)
Critical Design Review (CDR)
Program Implementation Review (PIR)

We are here

FY9 FY20 FY21 FY22 FY23 FY24 FY25 FY26 FY27 FY28 FY29 FY30
Q3 Q4 Q1 Q2 Q3 Q4 Q1 Q2 Q3 Q4 Q1 Q2 Q3 Q4 Q1 Q2 Q3 Q4 Q1 Q2 Q3 Q4 Q1 Q2 Q3 Q4 Q1 Q2 Q3 Q4 Q1 Q2 Q3 Q4 Q1 Q2 Q3 Q4 Q1 Q2 Q3 Q4 Q1 Q2 Q3 Q4

- AstroPix v1: Design & Fabr. | Test
- AstroPix v2: Design & Fabr. | Test
- AstroPix v3: Design & Fabr. | Test | Test
- AstroPix v4: Design & Fabr. | Test
- AstroPix v5: Design & Fabr. | Test | PreProduction - Fab and QC
- AstroPix v6: Design & Fabr. | Test | Production - Fabrication and QC

v3 has comprehensive test program: benchtop and testbeam, irradiation, quad-chip readout for NASA payload mission (A-STEP), integration with Pb/ScFi for ePIC (R&D studies and test article production)

first v5 wafers used for preproduction

Start of production driven by project fund availability (estimated ~ 1 year after CD2/3)

EIC Project Milestone
New AstroPix version

ePIC BIC Timeline

- Design and generic R&D
- Final design and EIC R&D
- BIC Preproduction
- AstroPix v6 (production)
- BIC Production

CD0 CD1 CD3a CD3b CD2/3c CD3

*Dec 2031 - ready for 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

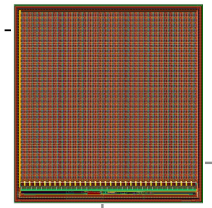
1 x 1 cm^2 chip, 250 µm pixel pitch
35 x 35 pixel matrix
Row/column readout
Power dissipation 3.4 mW/cm^2

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



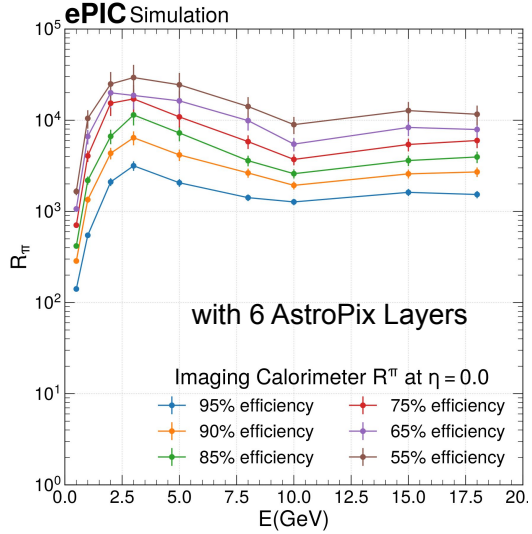
AstroPix v5
pre-production chip
1.87 x 1.9575 cm^2 chip, 500 µm pixel pitch
Design identical to v4 (with bug fixes and modification for **AMS foundry**)

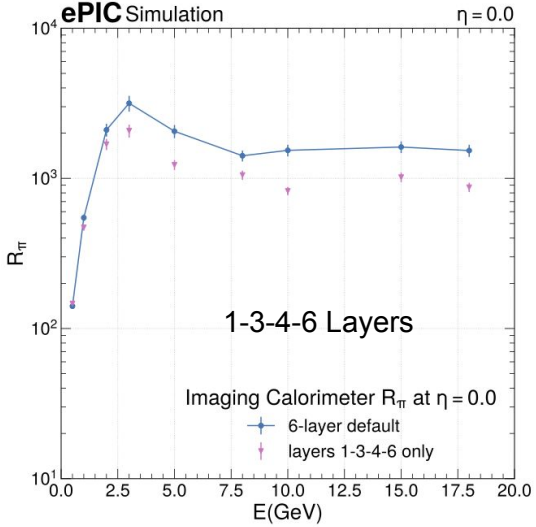
TSI AMS

AstroPix v6
production chip
2 x 2 cm^2 chip, 500 µm pixel pitch
Design identical to v5 (with bug fixes)

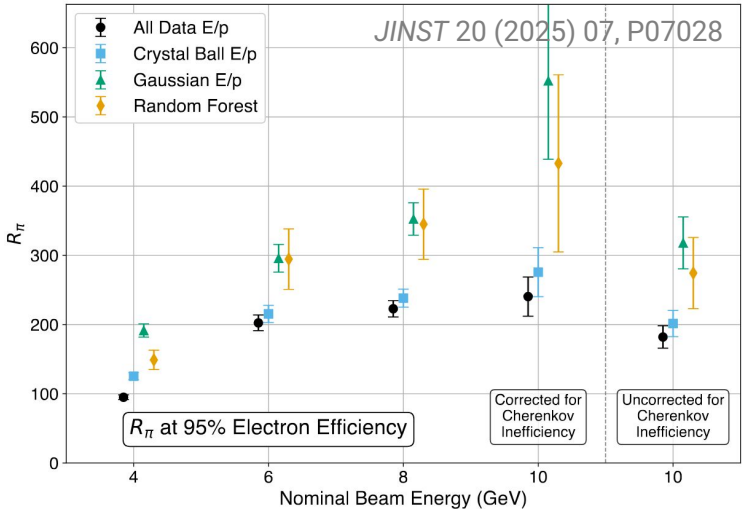
Detector Performance Example: e/π Identification

ePIC simulation: BIC AstroPix and ScFi - Full Geometry





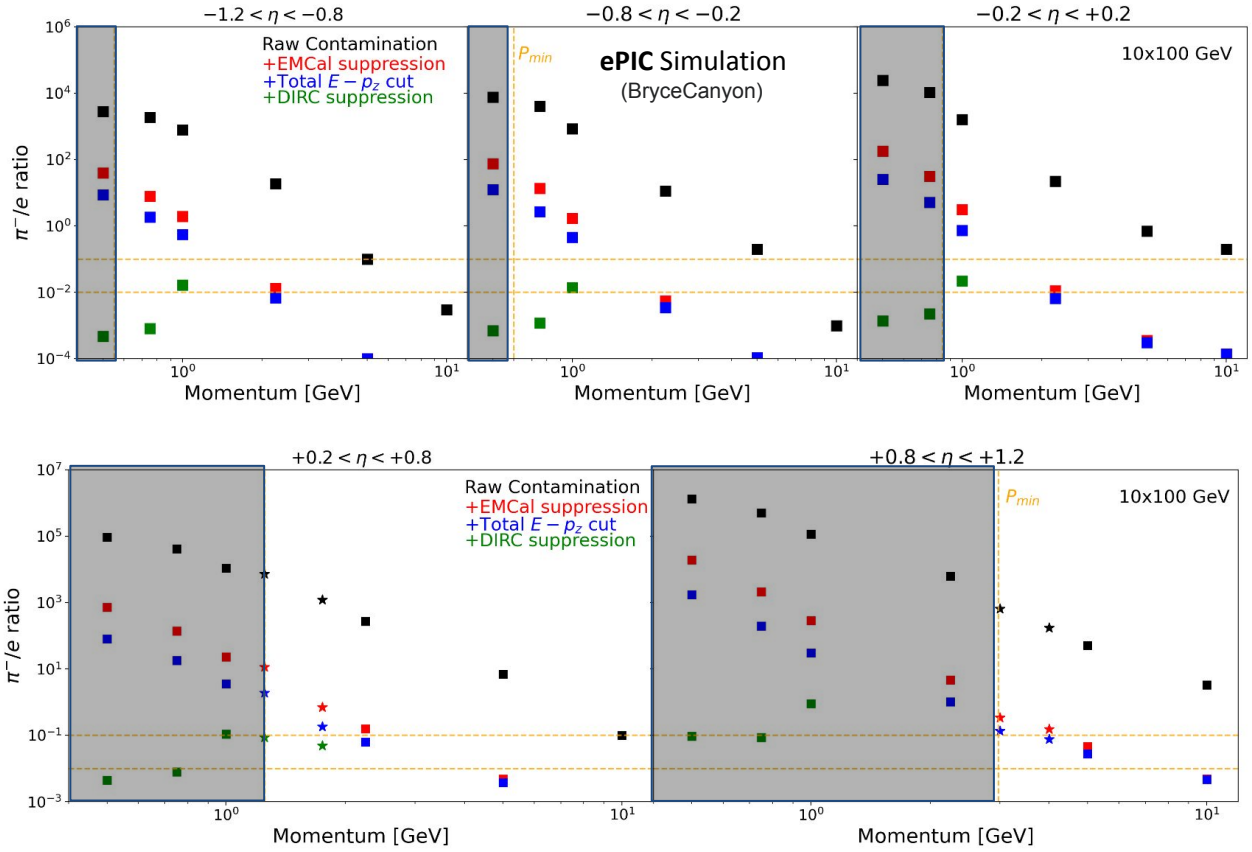
Baby BCal Fermilab Beam Test
Compact ScFi Only (no AstroPix)



- **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

BIC: e-π separation exceeds 10^3 in pion suppression at 95% efficiency above 1 GeV
Response to pions and electrons benchmarked in Beam Test for the SciFi/Pb technology only.

Example Barrel e/π Performance for 10 x 100 GeV

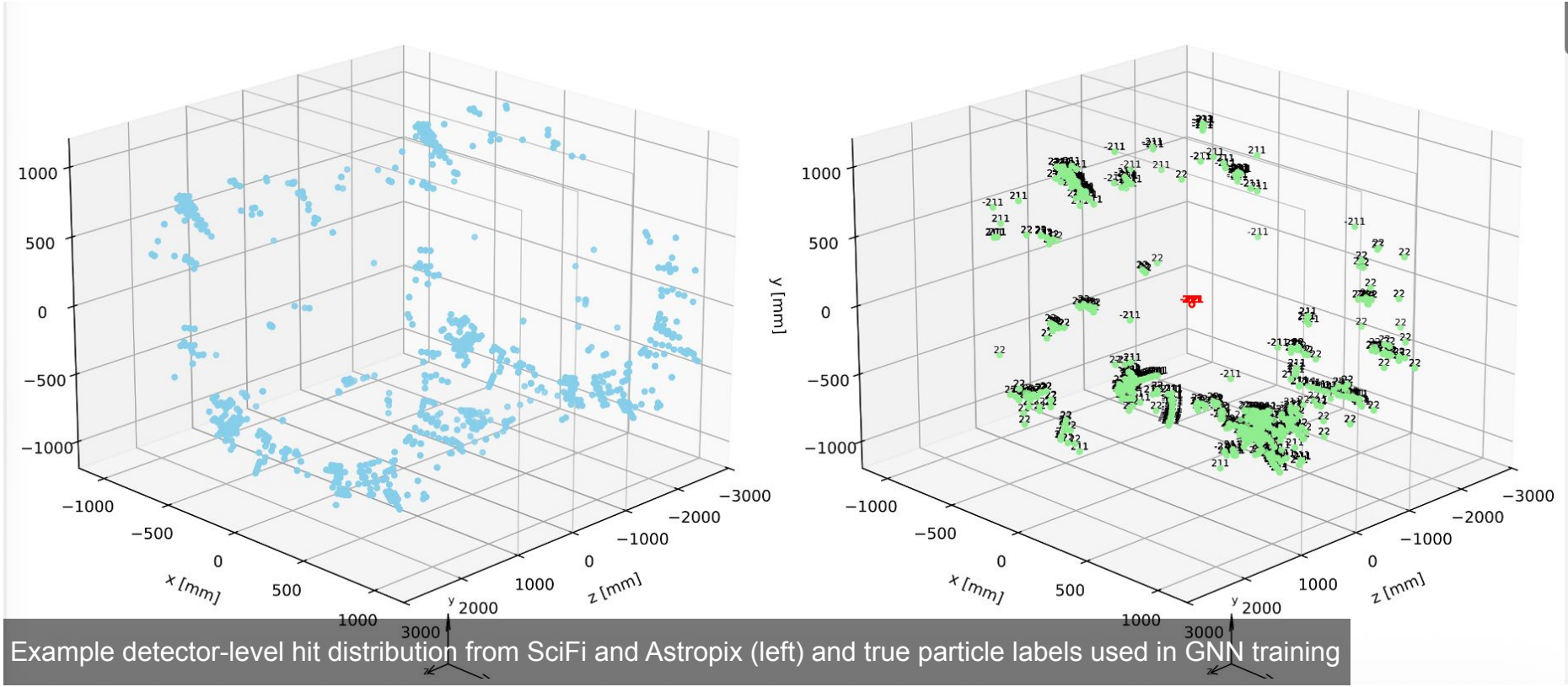


Challenging goal: Achieve 90% electron purity from the combined detector performance (ECAL + DIRC)

- 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

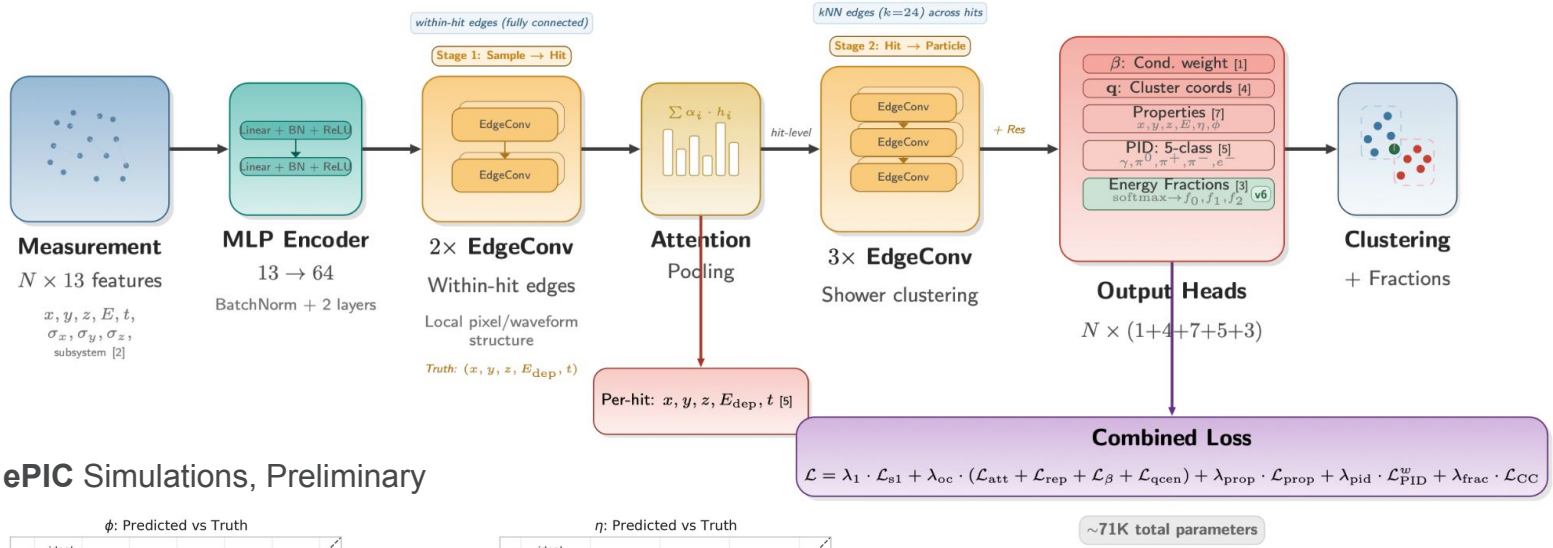
Towards AI-based Detector Reconstruction



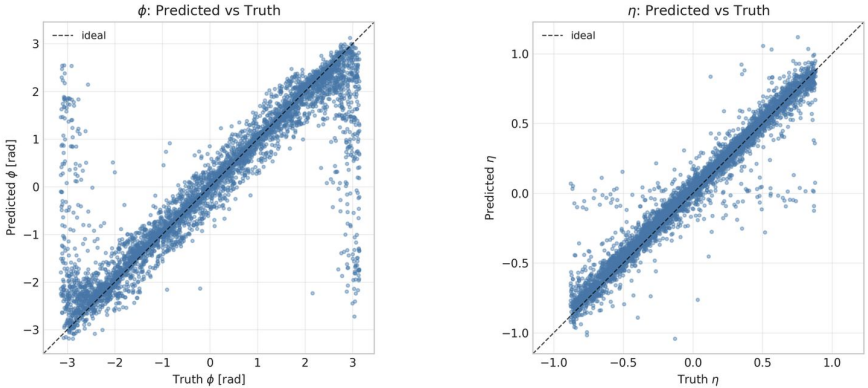
Example detector-level hit distribution from SciFi and Astropix (left) and true particle labels used in GNN training

Design Principles for AI-Ready QCD Data with a Barrel Imaging Calorimeter Application, e-Print: 2606.07667

Towards AI-based Detector Reconstruction



ePIC Simulations, Preliminary



First look into single particle training (5 species) and extracted angular position reconstruction

Advancing Through Design and Testing

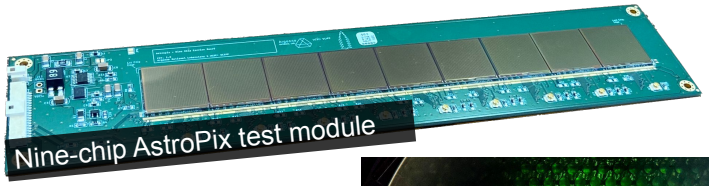
Successfully completed **Preliminary Design and Safety Review**, demonstrating readiness to exceed **60% design maturity by CD-2**.

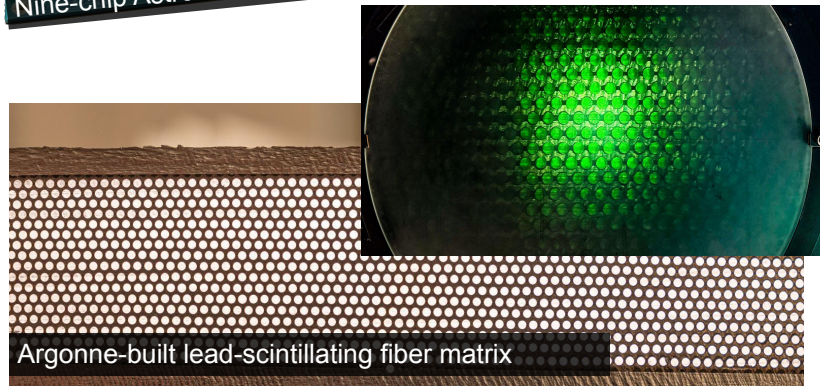
- Focused on a **“learning by building”** approach to converge on the **final design (CD-3)**.

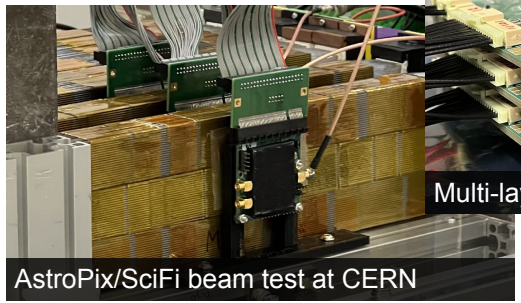
Built and tested key test-articles:

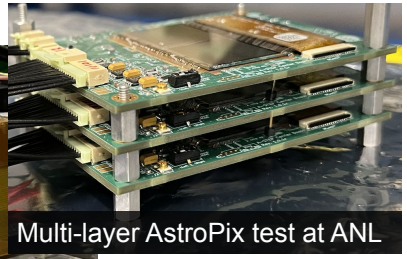
- **Pb/ScFi calorimeter layers** at Argonne for production development and tolerance optimization.
- **First nine-chip AstroPix modules**, meeting performance and integration requirements.

Executed FY25 test beam campaigns at KEK and CERN and advanced **ongoing campaigns at Hall D, CERN, and KEK**, providing critical validation of technology selections and supporting progression to final design.

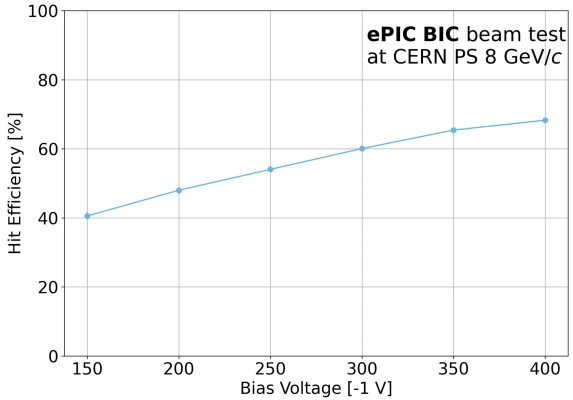

Nine-chip AstroPix test module


Argonne-built lead-scintillating fiber matrix

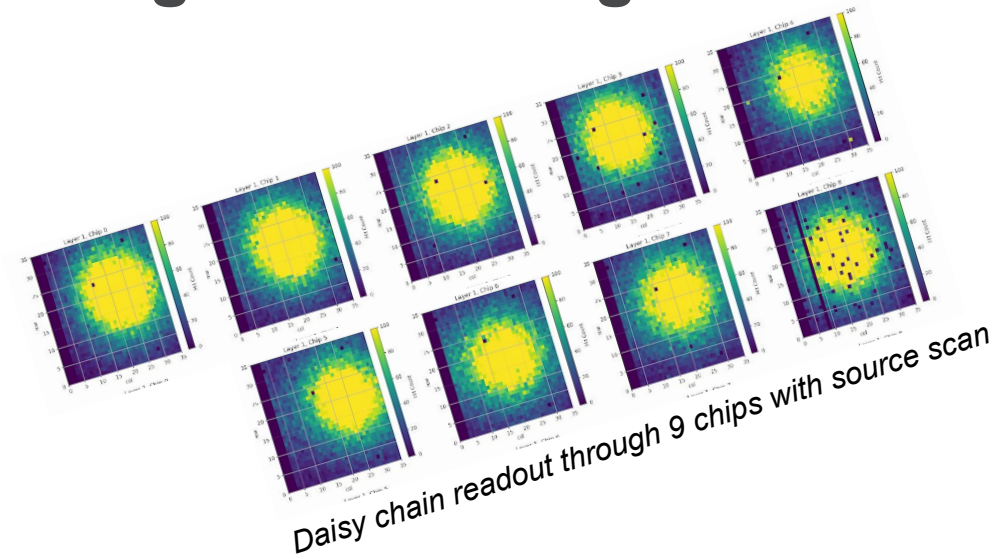

AstroPix/SciFi beam test at CERN


Multi-layer AstroPix test at ANL

Advancing Through Design and Testing

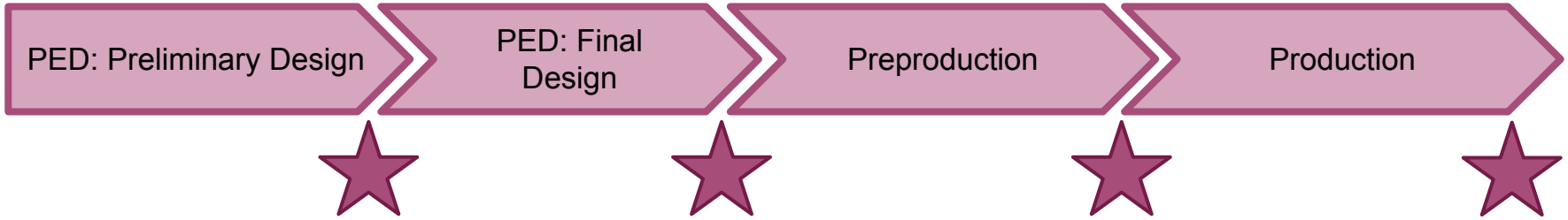


AstroPix v3 efficiency studies



1. Test-Beam Performance of the AstroPix Silicon Sensor for Imaging Calorimetry, e-Print: 2605.07681
2. Beam Test Performance of AstroPix sensor with 120 GeV protons, e-Print: 2512.23465
3. Performance of the AstroPix Prototype Module for the Barrel Imaging Calorimeter at the ePIC Detector and in Space-Based Payloads *PoS* VERTEX2025 (2025) 031, e-Print: 2511.05639
4. Beam test of a Pb/SciFi prototype for the Barrel Imaging Calorimeter at the Electron-Ion Collider, e-Print: 2604.22647
5. Evaluation of the response to electrons and pions in the scintillating fiber and lead calorimeter for the future electron-ion collider, *JINST* 20 (2025) 07, P07028, e-Print: 2504.03079

BIC Project Phases



- Preliminary Design Review, 60% design completion
- AstroPix v3 (and v4)
- BabyBCal & Lanky BCal
- Individual components
- First (second) test articles

- AstroPix v5
- One full sector
- Final designs (90%)
- Production style procedures
- AstroPix v6 validation tests

- AstroPix v6
- 48 sectors

USA

Argonne National Laboratory

NASA Goddard Space Flight Center

Oklahoma State University

University of Connecticut

University of California Santa Cruz

Oak Ridge National Laboratory

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

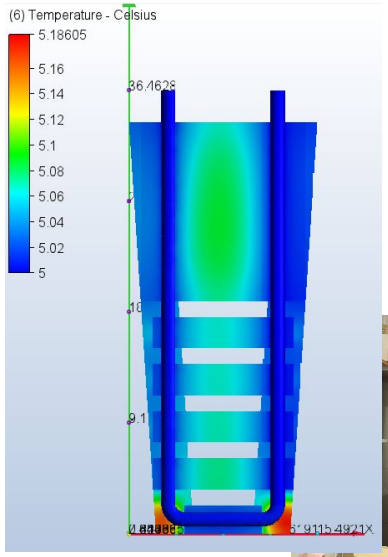
University of Giessen

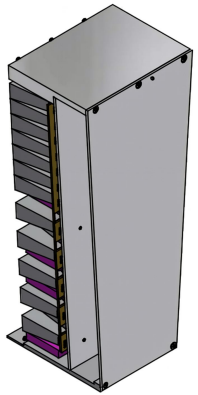
Canadian Contributions to BIC

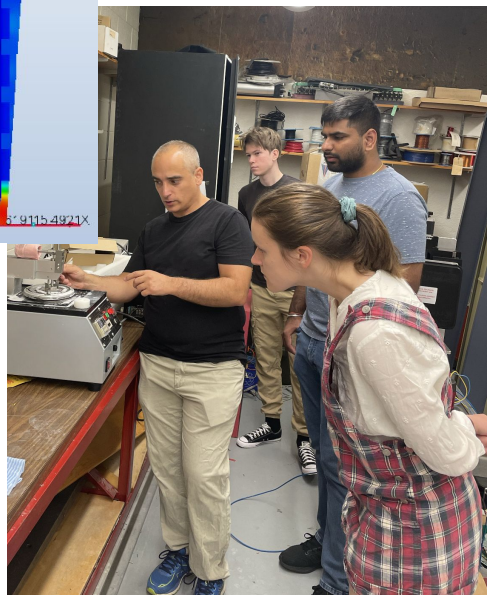
Part of the CFI IF ***Enabling High Intensity Collisions and High Granularity Detectors for the Electron-Ion Collider***

BIC End-of-sector boxes:

- **U. Regina**: technical lead for BIC, design (and construction, CFI IF) of ESBs, fibers testing for CD-3A/B long lead procurement
- **Mt. Allison**: HQP on dispatch to U. Regina for fiber and SiPM testing
- **U. Manitoba**: SiPM testing; ScFi layers: conductive cooling of AstroPIX sensors, ESB: convective water cooling for SiPM thermal stabilization, CFD studies of ESB cooling designs







See presentations by Akshaya Vijay (U. Manitoba) and Wouter Deconinck (U. Manitoba)

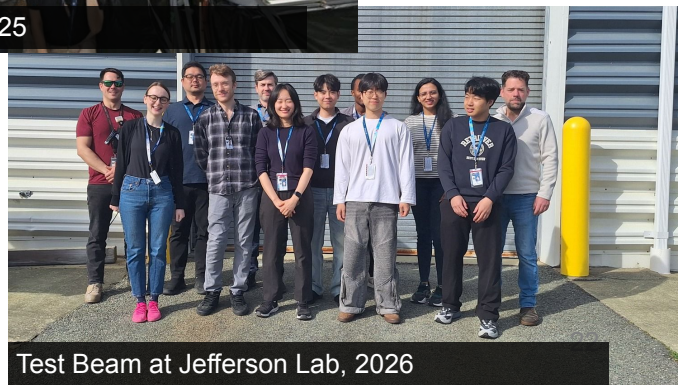
Summary

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!

This material is based upon work partially supported by Laboratory Directed Research and Development (LDRD) funding from Argonne National Laboratory, provided by the Director, Office of Science, of the U.S. Department of Energy under Contract No. DE-AC02-06CH11357