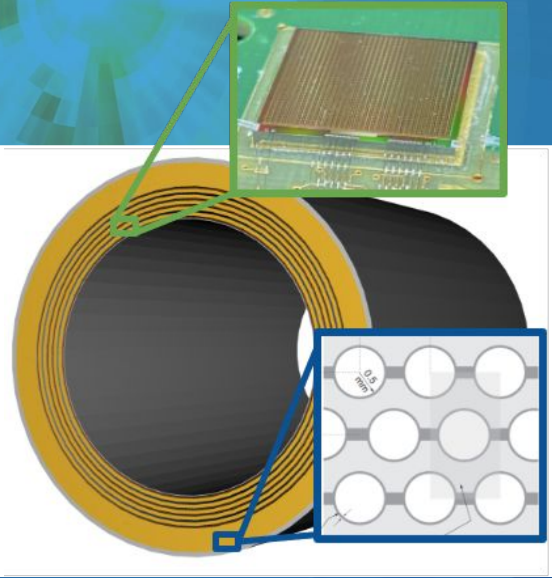
The ePIC Barrel Imaging Calorimeter

Barrel Imaging Calorimeter



Jessica Metcalfe
Argonne National Laboratory
on behalf of the BIC DSC

EIC DAC Review
June 13, 2025

Outline

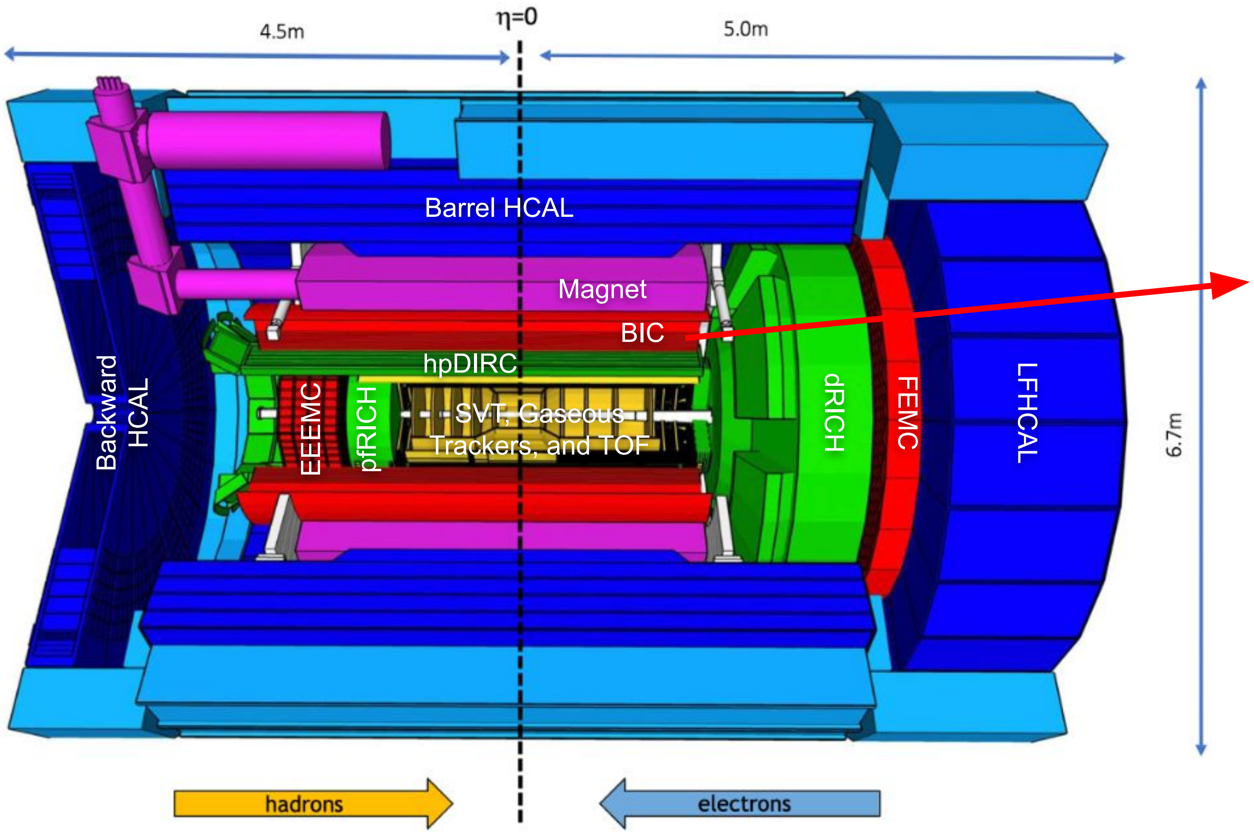
- BIC Overview
- Recent Progress & Plans

Charge:

- Is the design of the ePIC detector and its sub-systems appropriate and progressing well?
- Are the remaining work and technical, cost and schedule risks adequately understood? Are there opportunities?
- Will the detector be technically ready for baselining by late 2025?
- Are the detector integration and planning for installation and maintenance progressing well? Are there areas where further ideas should be pursued?
- Will the detector be ready for start of construction by late 2026?

Barrel Imaging Calorimeter (BIC)

–Barrel Electromagnetic Calorimeter for ePIC



BIC Detector Geometry:

Active Length: 435 cm

Inner Radius: 82 cm

Structure: 48 trapezoidal sectors

Weight: 42.5 US Tons

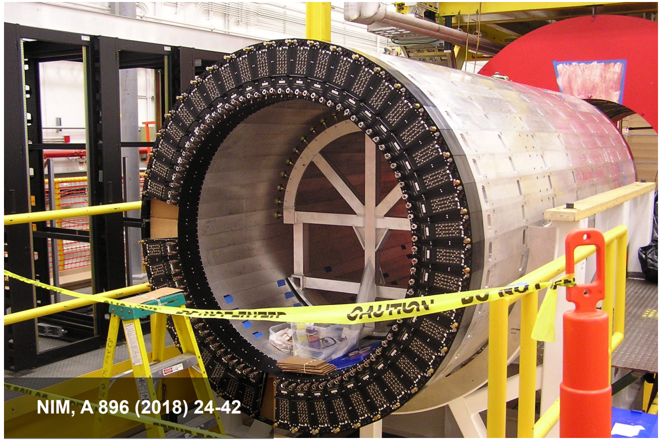
η Range: $-1.71 < \eta < 1.31$

Sector thickness: ~40cm

Total thickness > 17.1 X_0 (depending on η)

Concept: A Hybrid Imaging Calorimeter

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

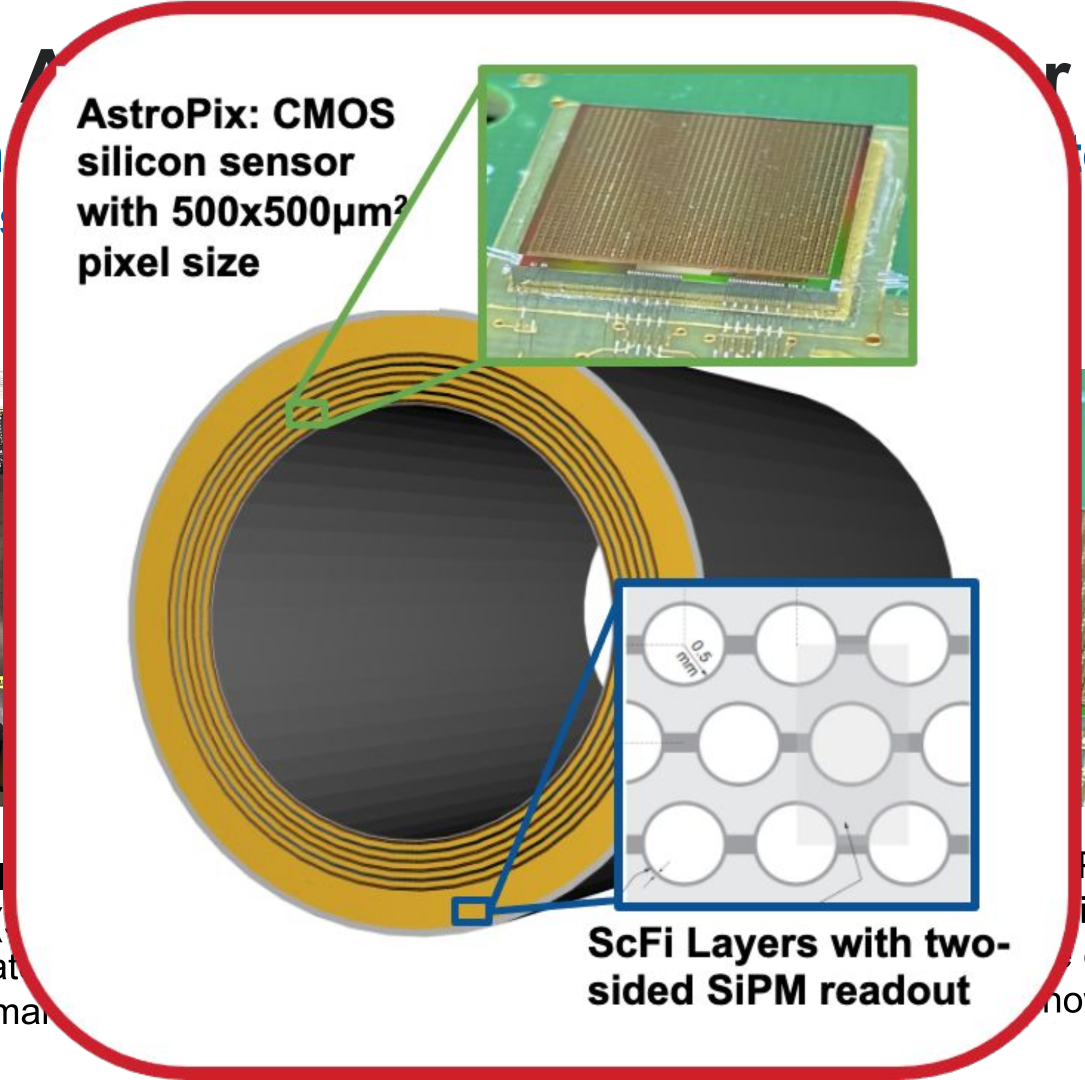


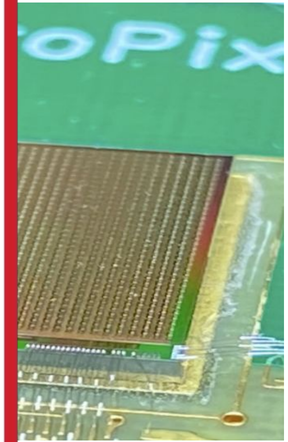
Start from mature layered Pb/ScFi technology with side-readout (same as the GlueX calorimeter) for state-of-the-art sampling calorimeter performance

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 3D image of the developing shower

Concept: A ... r

Combination ... ter with inexpensive ...





Start from mature ... with side-readout (... calorimeter) for stat... calorimeter performa...

...Pix sensors ...icon sensor developed ... calorimeter to capture a ...hower

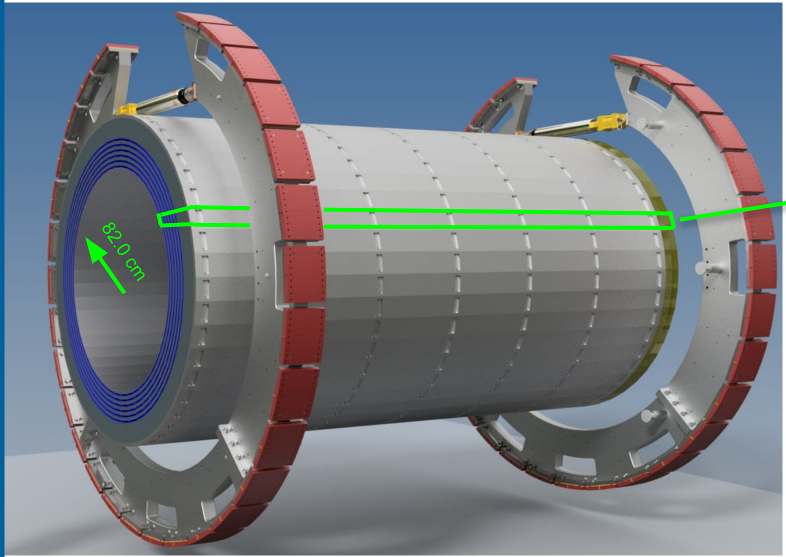
Barrel Imaging Calorimeter

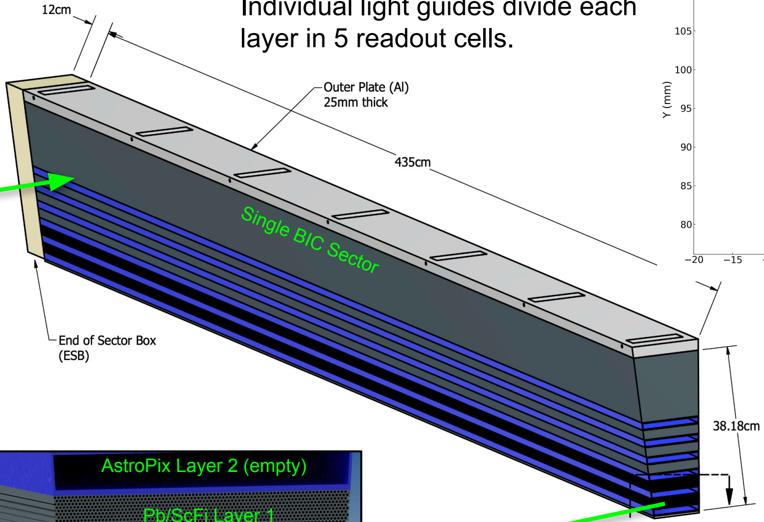
Sector Mechanics

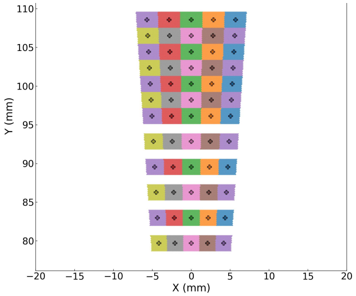
Pb/SciFi Layers - 17 rows of fiber between corrugated lead.

Each sector has 12 Pb/ScFi layers.

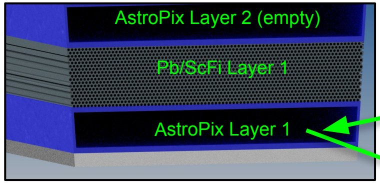
Individual light guides divide each layer in 5 readout cells.

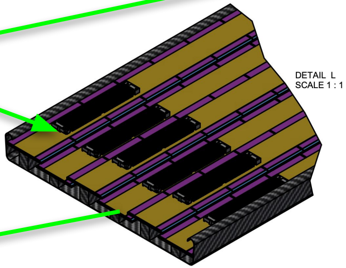






SiPMs - 5 per layer x 12 layers = 60 (Hamamatsu S14161-3050)



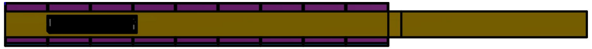


Tray - Structure holding the AstroPix staves for a single layer (217.5 cm long).

AstroPix Module - Nine AstroPix sensors daisy-chained together on Flex PCB.

A stave consists of 12 modules.

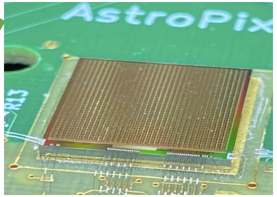
A tray contains of 6-8 staves.

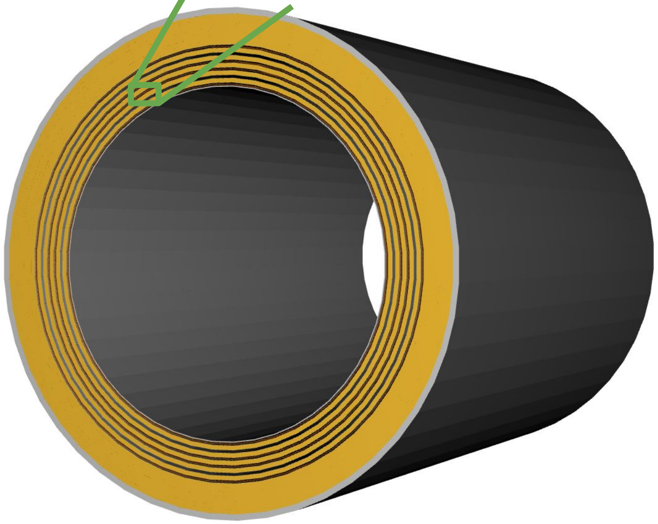


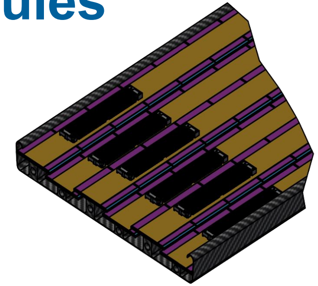
Barrel Imaging Calorimeter

AstroPix Wafers & Modules

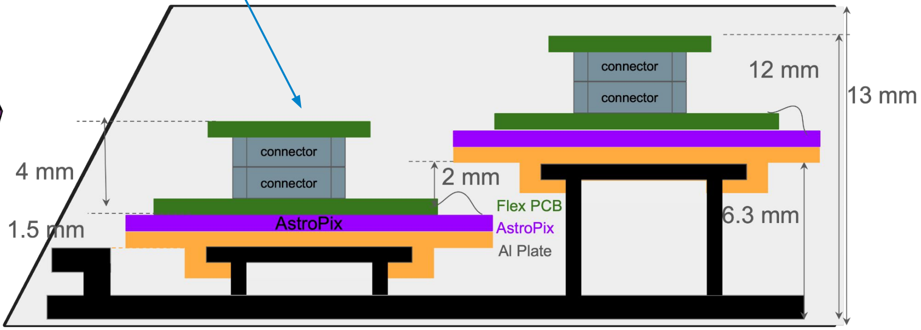
AstroPix: silicon sensor with $500x500\mu m^2$ pixel size



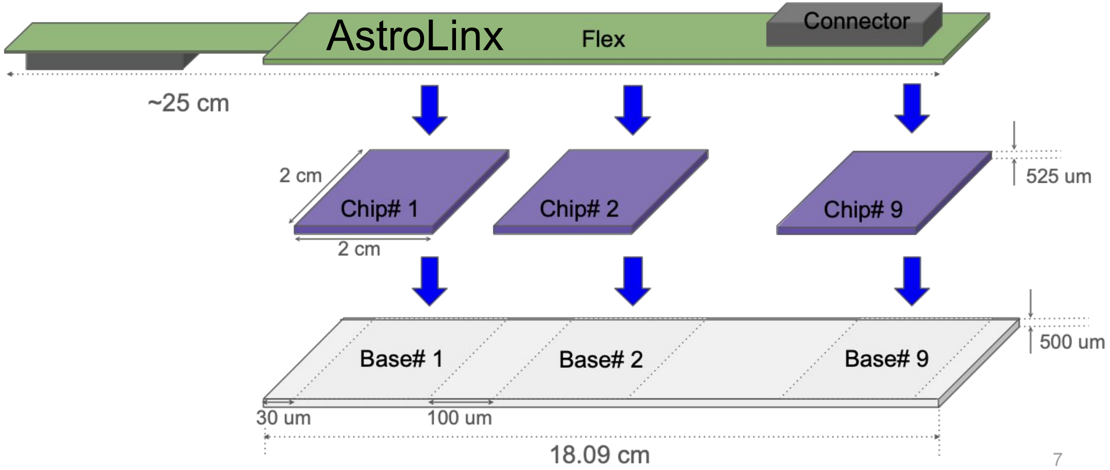




Stave (12 modules)

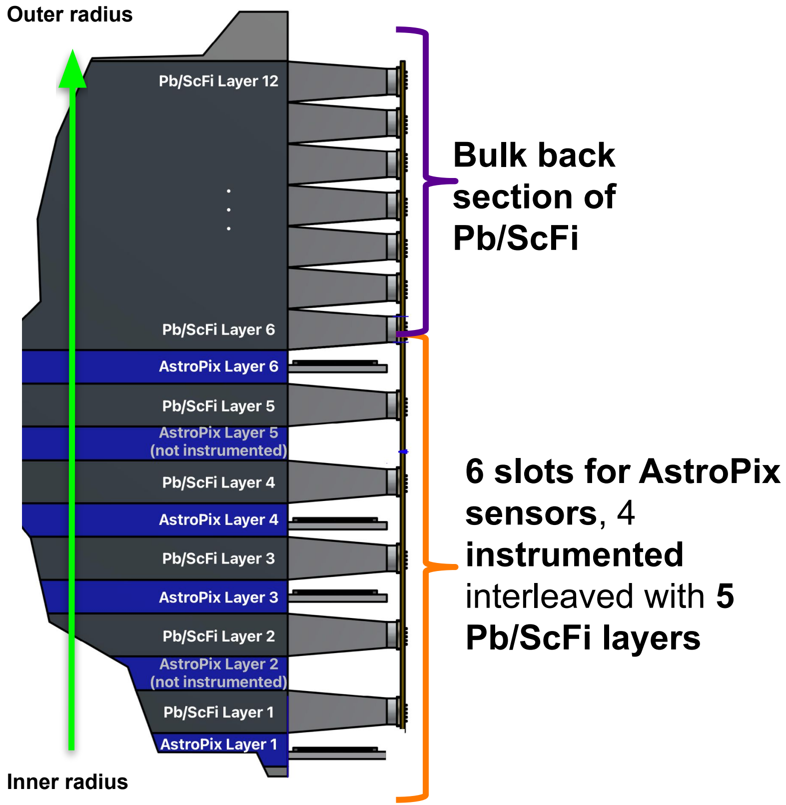


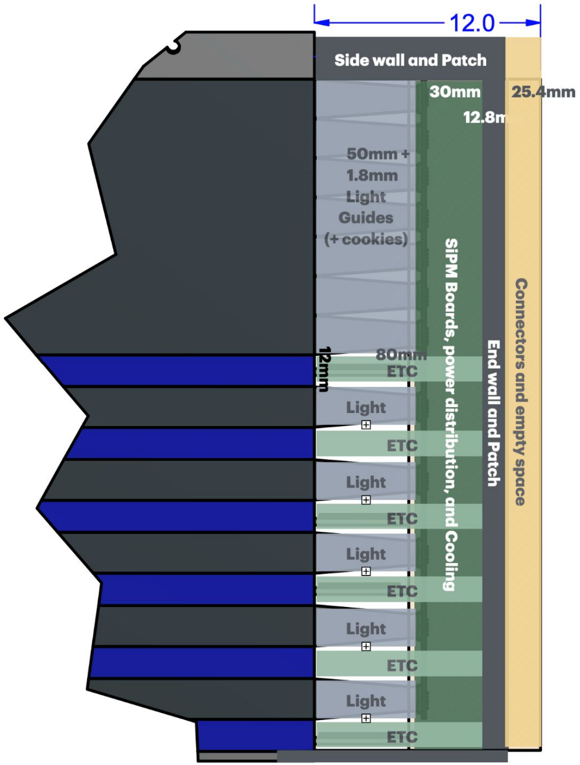
Module:



Barrel Imaging Calorimeter

End-of-Sector Boxes (ESB) & DAQ





Pb/SciFi:

- light guides
- cookies
- SiPMs
- CALOROC
- cooling

Tracker:

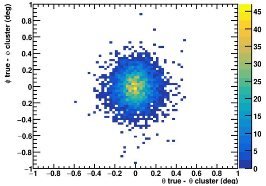
- ETC: End of Tray Card for AstroPix readout

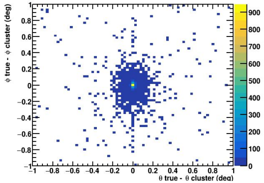
BIC Performance

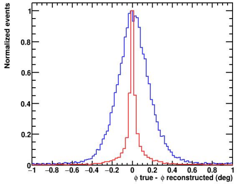
Simulations

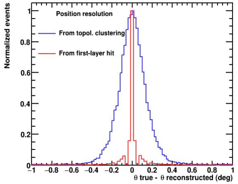
- ✓ Deep calorimeter (η = 0 ~17.1 X_0) while compact at ~ 40 cm
- ✓ Excellent energy resolution (5.2% $/\sqrt{E} \oplus$ 1.0%)
- ✓ Unrivaled low-energy electron-pion separation by combining the energy measurement with shower imaging
- ✓ Unrivaled position resolution due to the silicon layers
- ✓ Deep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

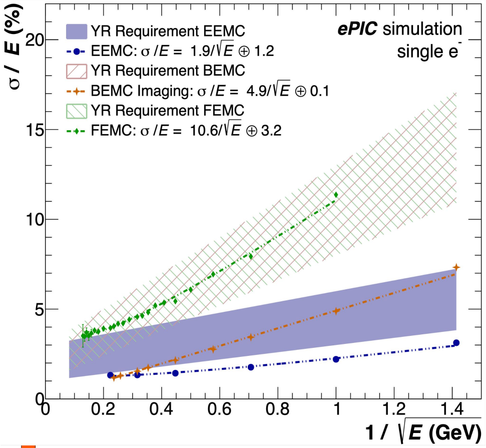
See prebrief materials for more detail

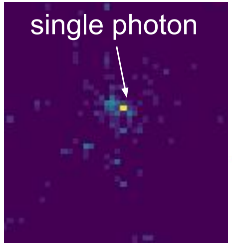


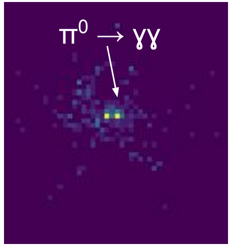


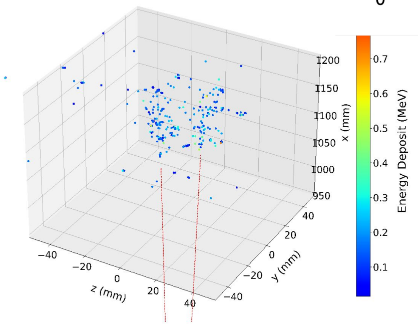


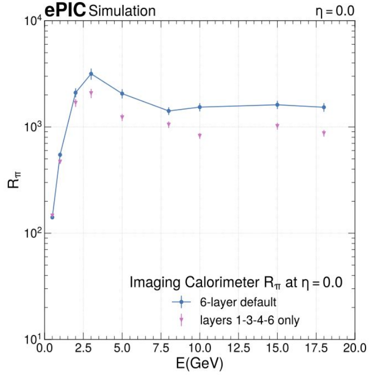












BIC Recent Progress & Plans

Summary of Design and Test Articles Status

BIC Design Completion		Concept	Preliminary Design (60%)	First Test Article	Final Design (90%)
Sector Mechanics	Scintillating Fibers (CD3a/b)	✓	✓	✓	✓
	Pb/SciFi Matrix Construction	✓	✓	✓ Short matrix	Oct 2025
	Carbon Fiber Frames	✓	✓	Short Frame Jul 2025	Nov 2025
	Sector Construction	✓	✓	Short Multi-layer Aug 2025	Nov 2025
	Tracker Tray	✓	Aug 2025	Sep 2025	Oct 2025
	Tracker Module Base	✓	✓	Jun 2025	
Tracker: AstroPix Modules	AstroPix	✓	✓	✓ (v3)	✓ (v5)
	Wafer/chip probing	✓	✓	Aug 2025	Nov 2025
	AstroLinx	✓	✓	Jul 2025	Apr 2026
	AstroPix Module	✓	✓	Sep 2025	May 2026
	Stave/SuperStave	✓	✓	Nov 2025	May 2026
End-of-Sector Box (ESB) & DAQ	Lightguides	✓	✓	Jun 2025	Jun 2025
	SiPM's	✓	✓	✓	✓
	CALOROC readout	✓	✓	✓ (H2GCROC)	✓ (H2GCROC)
	End-of-Tray Card	✓	Contract delay		
	Electrical Services	✓	75%	July 2025	Sep 2025
	Cooling	✓	40%	July 2025	Sep 2025
	ESB Test Article	✓	✓	July 2025	Sep 2025
System Test	Integrated System Tests	✓	✓	✓ (BabyBCal + SFILs + Chip/Module)	Aug 2026

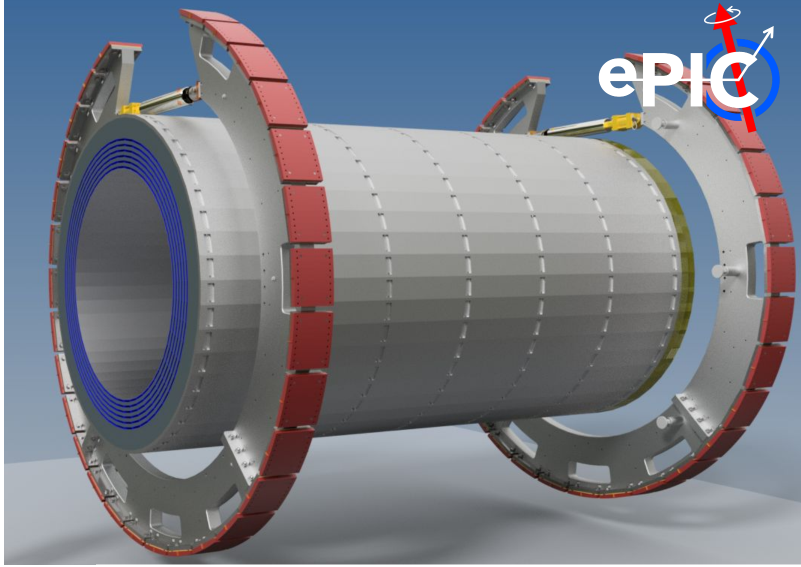
Sector Mechanics

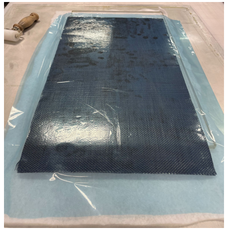
Design Progress

- Interfaces to the rest of ePIC well-defined and mostly frozen
- BIC engineers in close contact with the Project engineers
- Geometries & envelopes documented and versioned

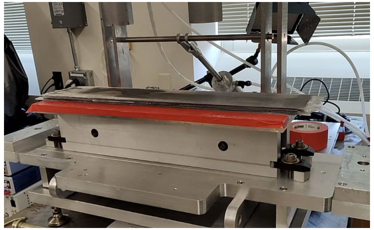
Technical challenges:

- Demonstrate self-supporting design and integration with ePIC
  - Detailed FEA needs delamination measurements for CF-Pb interface, and for the Pb/SciFi matrix itself.
  - We are building test articles for Mode I & II Interlaminar Fracture Toughness measurements (ongoing, due late June 2025)
- CF frame integration and matrix construction tolerances
- Subcontract with Purdue Composites to design/build CF components and for FEA



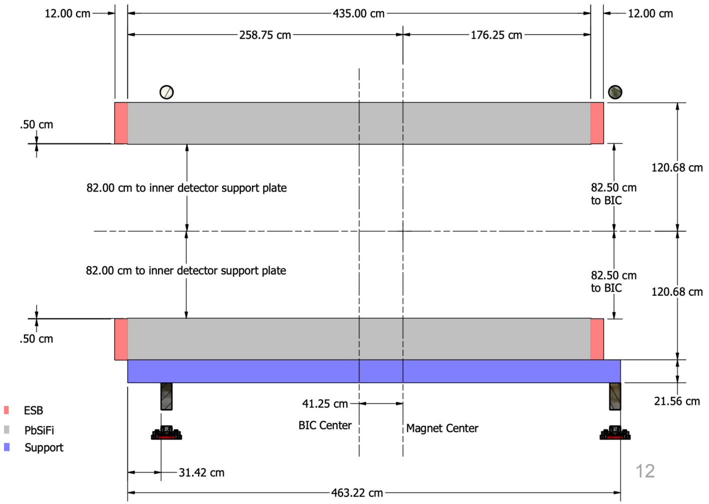


First CF layup for delamination test articles *(May 28, 2025)*



Short Pb/ScFi test article on the press bed, in preparation for the delamination test articles *(May 23, 2025)*

Exploded view of the CF fiber frame components, with filler material on the sides (to be machined away after pressing)



Sector Mechanics

Planned Test Articles

Goals and Test Articles:

Preliminary Design

Demonstrate we can reproduce the GlueX matrix production for short sizes (0.5m) - *almost done*

- short test article with inert optical fibers, short SFIL with GlueX fibers, short Bulk sector with GlueX fibers

Demonstrate we can integrate CF frames with the required tolerances - *Summer 2025*

- Short multilayer test articles with integrated CF frames (inert fibers)

Final Design

Demonstrate we can reproduce the GlueX matrix quality for longer sizes (3m) - *Fall 2025*

- Long SFIL with GlueX fibers

Demonstrate we can integrate CF frames at these longer sizes - *Winter 2025*

- Long multilayer test article with GlueX fibers

Preproduction

Demonstrate we can build a full-scale 4.35m long BIC sector - *2026*

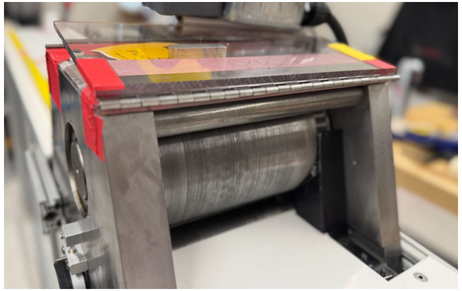
- Preproduction test article using the BIC fibers

All critical equipment commissioned and operational to produce test articles on schedule!

Equipment Status

Newly built press for short test articles, and for evaluating press piston quality (pistons inherited from U. Regina)

Swager inherited from U. Regina, upgraded with new table and guarding and fully operational



Full-size press inherited from U. Regina, being modified for BIC to accommodate longer sectors and taller stack height

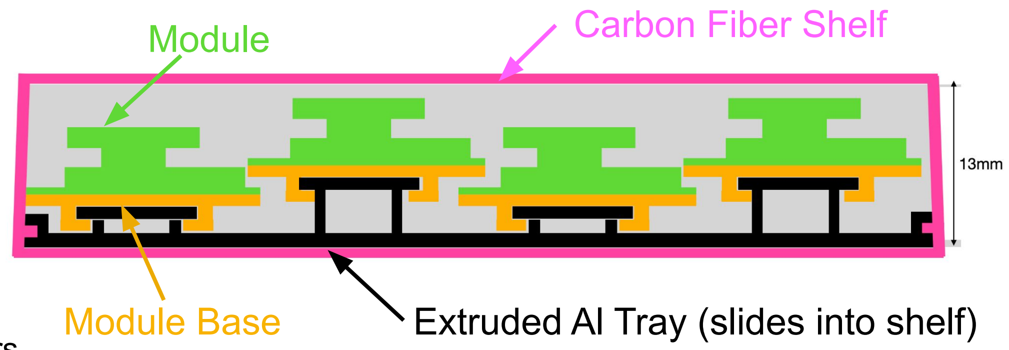
Assembled press @ University of Regina for GlueX BCAL fabrication

Press frame @ Argonne in our new sector production space (5500 sq ft)

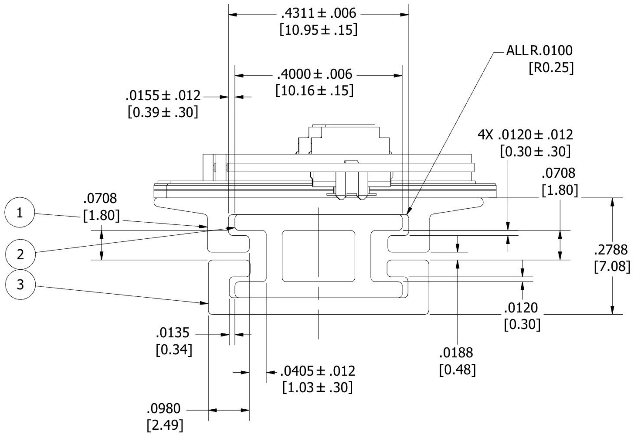
Tray, Stave, & Module Mechanics

Design & Test Article Progress

- Design: staves integrated into tray
  - slide modules directly onto tray
  - tray slides into sector drawer/slot
  - minimize height and simplify installation
  - reduce number of components to produce
  - Trays positioned at outer radius has sensors pointing inwards
  - locked in place: leverages trapezoidal design
- First fabrication of mechanical test article based on earlier design concept
  - Components made out of extruded aluminum to minimize cost
  - Validate fabrication tolerances with extruded aluminum
  - Validate mechanical stability
  - Delivery expected in June



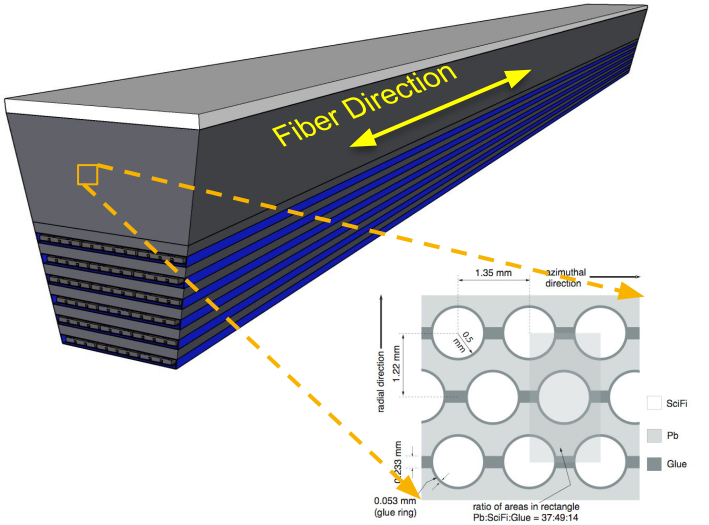
Initial stave concept being produced:

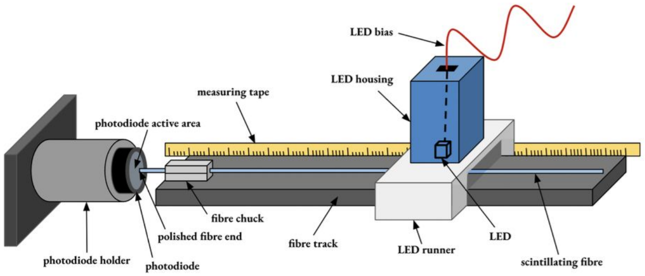


Fibers

CD3a

- Attenuated signal from showers reaches both sides of the calorimeter
    - **Read out from two sides with light-guides and SiPMs** enclosed in end-of-sector box (**ESB**)
    - Pb/SciFi layers **probe shower radially**
    - Shower position extracted from both ends' TOA (in addition to AstroPix position information)
- Production test stands completed
- Bidding process for production fibers is wrapping up
    - Testing of two vendor options completed
    - **Contract being awarded, expect in mid-June**

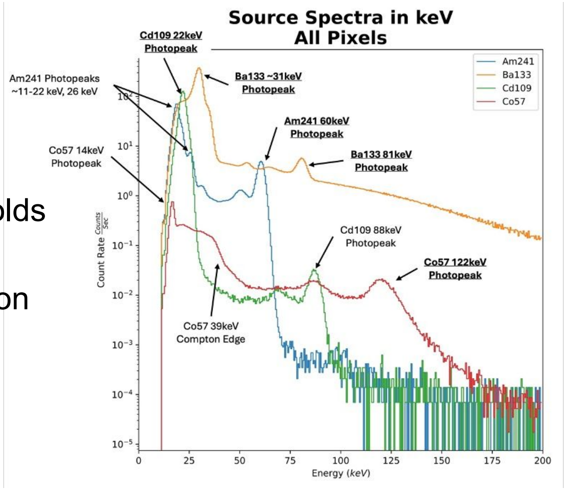




Fiber test stand with photodiode + LED

AstroPix

PED: Preliminary/Final Designs



AstroPix v3

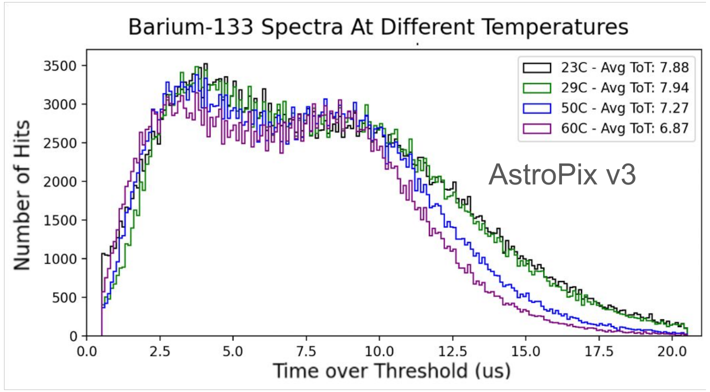
- First full size design: 1.87 cm × 1.96 cm
- Row/Column readout
- Pixel pitch: 500 μm
- Pixel matrix: 35 × 35
- 0.88 mW/cm^2 analog, 12 mW digital
- 2.5 MHz timestamp, 200 MHz ToT

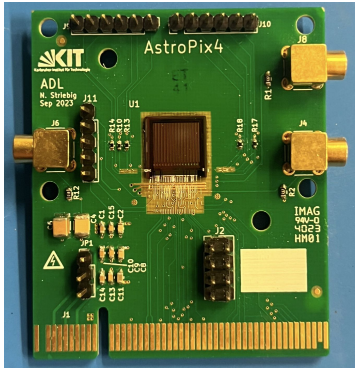
→ **Large size chip for mechanical testing, early performance criteria, daisy chaining**

AstroPix v4

- MPW run, small size: 1 cm × 1 cm
- Individual pixel readout
- TuneDAC for pixel-by-pixel thresholds
- 0.96 mW/cm^2 analog, 3 mW digital
- 3 timestamps, 3.25ns time resolution
  - bug: flash TDC reset
- Pixel pitch: 500 μm
- Pixel matrix: 13 × 16

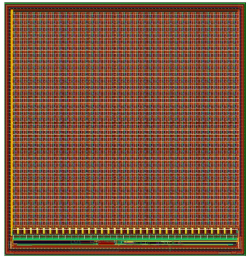
→**Excellent tuning, energy resolution**





AstroPix

BIC PRE-Production:

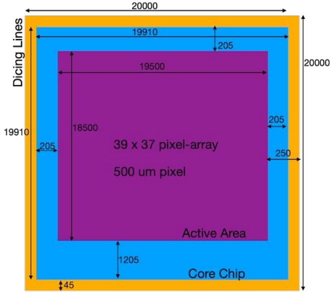


AstroPix v5

- Large size: 1.87 cm × 1.96 cm
- Pixel pitch: 500 µm
- Pixel matrix: 36 × 34
- 0.96 mW/cm^2 analog, 3 mW digital
- 3 timestamps, 3.25ns time resolution (bug-fix)
- **Change of design to new vendor (AMS)**
  - **Switch to deep p-well (from n-well)**
  - **No in-pixel CMOS comparators → implemented some columns with different NMOS comparators in order to optimize power/performance**
  - **Two columns with full dynamic range**

→Being submitted for fabrication now (experienced delays with contract)

BIC Final Chip Design:



AstroPix v6

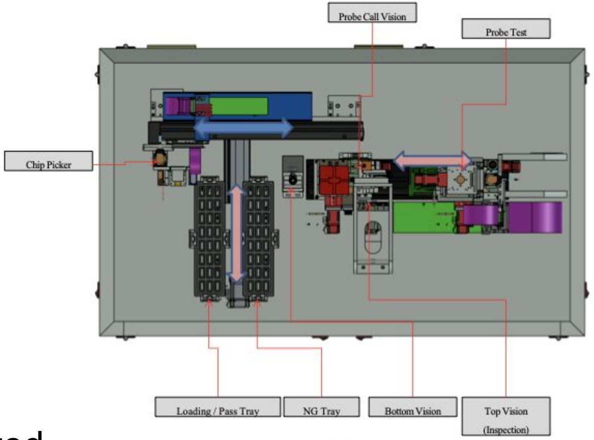
- Final Full Size: 2 cm × 2 cm
- Pixel pitch: ~500 µm
- Pixel matrix: 39 × 37
- 2 mW/cm^2
- **Expected**
  - **Minor updates to size**
  - **Select comparator design (from v5 columns)**
  - **Bug fixes (if any)**

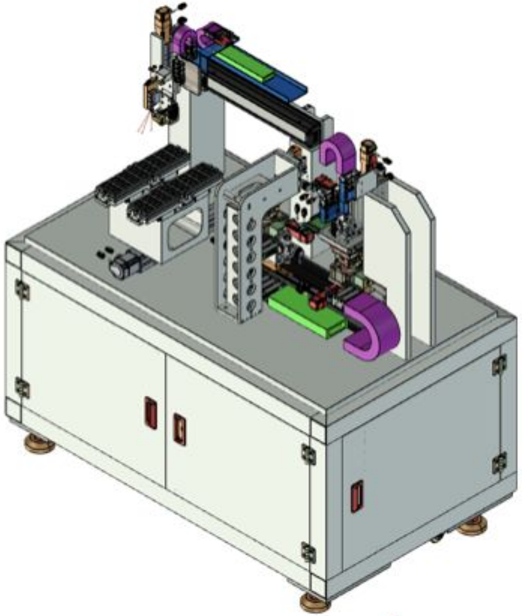
→Expect to submit the Final production design in an engineering run in 2026

- paid for by EIC Project
  - timescale does not match NASA funding, would have to wait until December 2028 for the next full size run (as decided in NASA AstroPix proposal in January 2025)
- verify the design before production fabrication can start

Wafer/Chip Probing

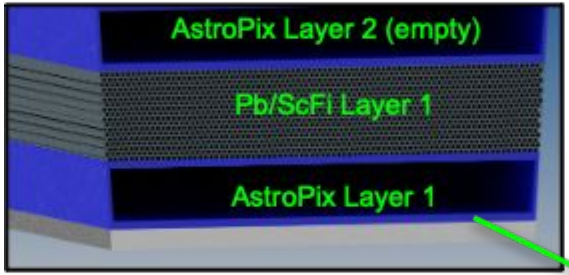
- Wafer/chip level testing prior to module assembly
- Quality Control Testing
  - Sensor bias with HV, analog and digital performance check, threshold tuning calibration checks
- Chip probe card design for v3 is complete and expected delivery in June
  - Allow us to validate the chip QC testing on ~80 v3 chips this summer
  - Opportunity to switch from wafer to chip probing
    - leverage experience and equipment from Koreans on ALICE
    - dicing happens before chip probing–next step is module assembly
    - need to confirm testing rates fit in schedule
- V5 design update will be ready in the fall

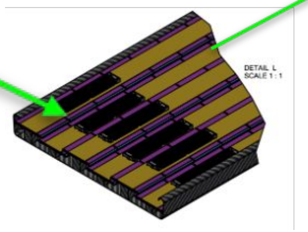




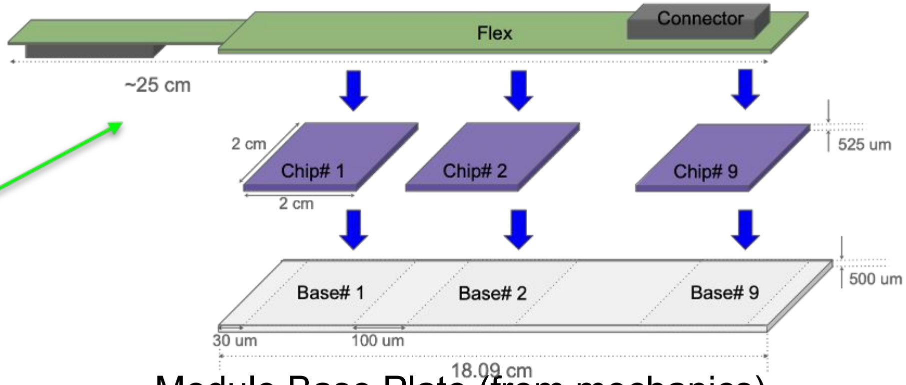
Modules

9-chips, 1 flavor



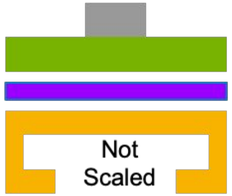


AstroLinx: Module PCB

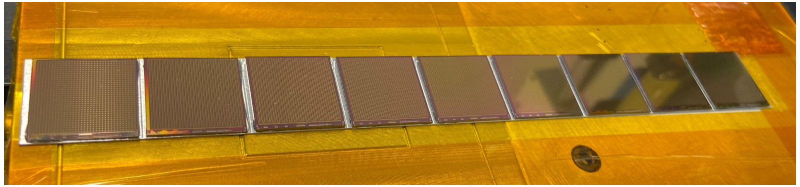


Module Base Plate (from mechanics)

Module Stackup:



1.7 mm - Connector
1.7 mm - AstroLinx
0.1 mm - Glue
0.525 mm - AstroPix
0.1 mm - Glue
1 mm - Module Baseplate



Iterated stackup with AstroLinx design and mechanics module baseplate/stave/tray design to fit within envelope

9 AstroPix chips on Al sheet (first mechanical prototype)

- Assembly/handling procedures and tools started development

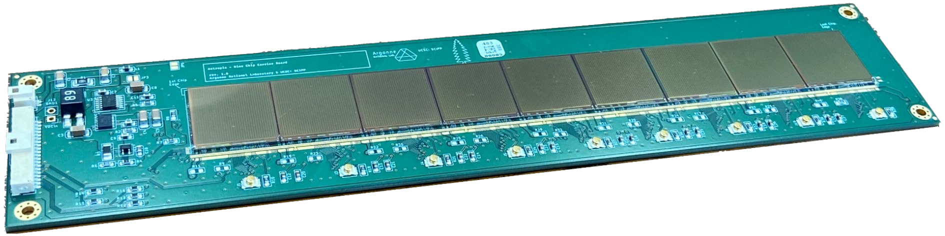
Modules

9-chip PCB prototype

- Mockup the AstroLinx electronics
- Power distribution stability
- Daisy chain read-out
- Testing DAQ development

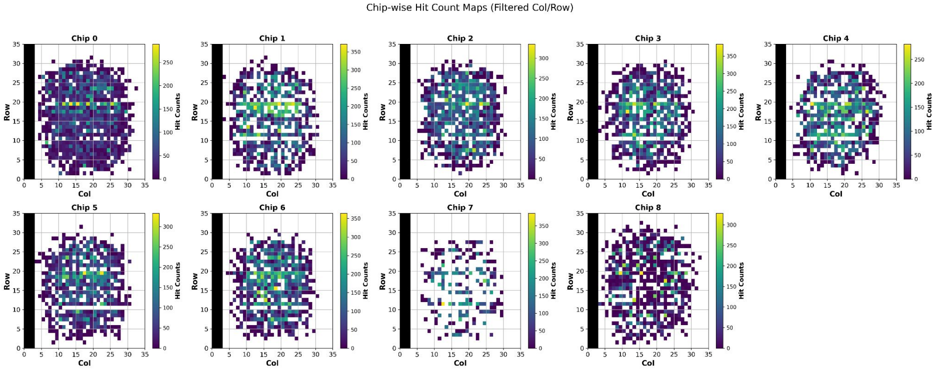
AstroLinx

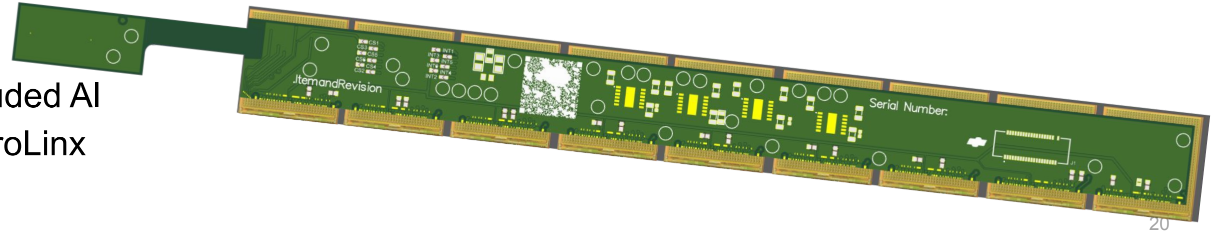
- Optimized for module performance
- Meets all required operation specifications
- Bulkier design than expected in order to keep a single flavor for all modules
- First design completed and under review
- First fabricated parts are expected this summer
- Another iteration is anticipated for final design
- First Module Prototypes
- Plan to build ~6 modules with extruded Al module base, AstroPix v3, and AstroLinx this summer/fall



AstroPix v3 9-chip board

Daisy chain readout through 9 chips

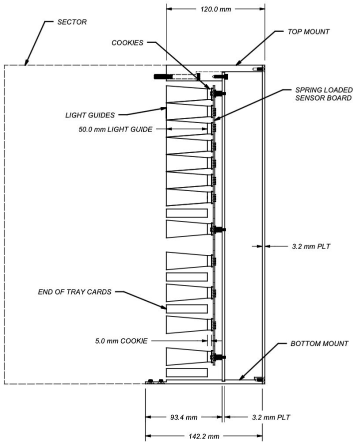


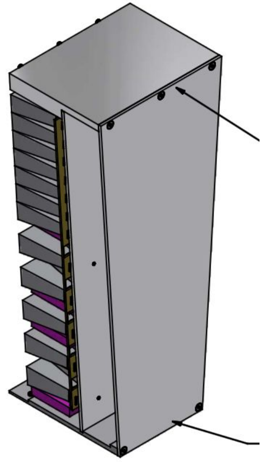


End-of-Sector Boxes

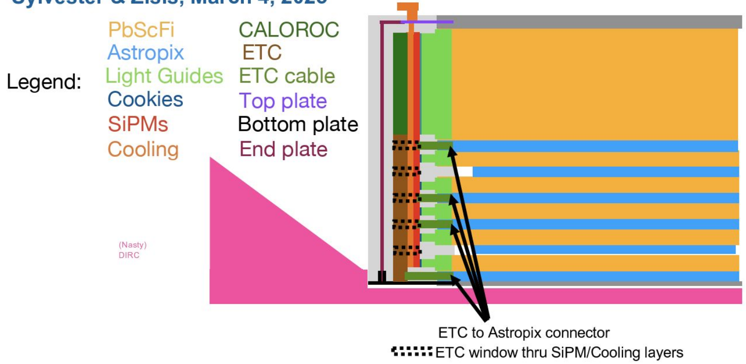
Lightguides, cookies, SiPMs, CALOROC, ETC

- Manages all powering and data collection on-detector
- Interfaces for envelope, services and cooling with ePIC
  - envelope & integration procedure nearly final
  - provide electrical cabling service requirements, cooling, and other DAQ needs to ePIC
- CALOROC for SiPM readout, then common RDO to FELIX
  - Lightguide options under test, comparing to SFILs
  - CALOROC design being submitted now, evolution of H2GCROC used by CMS, ALICE
- End of Tray Card (ETC) to readout AstroPix to FELIX
  - ETC to be designed by NASA Goddard Space Flight Center (GSFC), but ***work has not started due to extensive delays in processing the contract***. GSFC has designed similar FPGA boards for AstroPix, so they will be able to start from existing designs





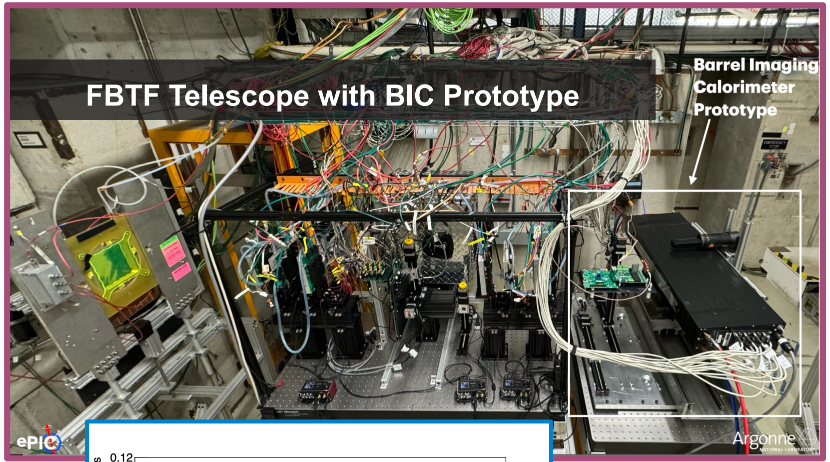
Sylvester & Zisis, March 4, 2025

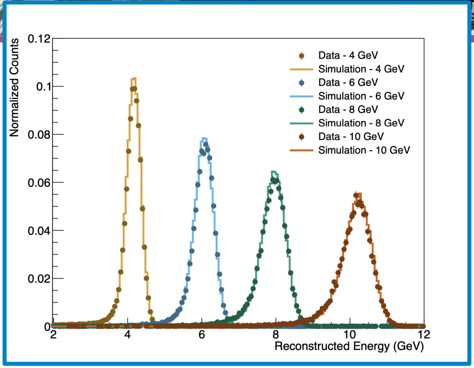


System Testing

Project R&D Phase Completed: See 2025 [R&D Day Presentation]

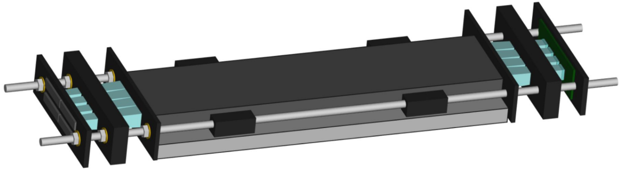
- GlueX Baby BCal tested at FTBF in FY24 with mixed e/π beams & MIPs, despite limited beam time.
- Data **analyzed for e and π response** and separation in SciFi/Pb section. Simulations benchmarked. https://arxiv.org/abs/2504.03079
- AstroPix v3 performance validated against design requirements.
- **Proof-of-principle AstroPix integration demonstrated** in beam and on bench.
- **Thin ScFi/Pb layers** with new SiPMs and optical cookies **commissioned** on bench.
- Large-scale readout integration now pursued under PED program.





Comparison of reconstructed e⁻ energy in Baby BCAL for data and simulation measured at FBTF.

Thin ScFi/Pb layer



BIC-Korea: Beam test campaigns (CERN, KEK) focused on building capabilities and team expertise in testing readout and system integration.

BIC Project Phases

PED: Preliminary Design → PED: Final Design → Preproduction → Production

Preliminary Design Review
Summer 2025

Final Design Review
Spring/Summer 2026

Need CD3 approval to start production articles
~early 2027
Production Readiness Review

Deliver BIC to BNL
~Dec 2031

- 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

Summary

- Technical progress is rapidly progressing
  - 60% design complete at PDR, summer 2025
- Interfaces to ePIC and between BIC sub-systems are complete and documented
  - geometry/envelope, integration into ePIC, electrical services, cooling
  - expect there could still be some minor adjustments
- Fiber type selected
- AstroPix v6 final design will be ready for submission in 2026
- First designs of almost all components complete now
  - End-of-Tray Card delayed, but intermediate DAQ available
- Expect demonstration of individual test articles ready by the end of 2025
  - Pb/SciFi sections, Lightguide/SiPm’s, Wafer probing, Module (v3), Carbon Fiber sections, Short Sector

Backup

BIC Organization Chart

ePIC Leadership
Spokesperson:
- John Lajoie (ORNL)

Deputy Spokesperson and TC:
- Silvia Dalla Torre (INFN Trieste)

BIC DSC Board
DSC Leadership (DSL)
- Sylvester Joosten (Argonne)
- Hwidong Yoo (Yonsei U)
- Maria Żurek (Argonne)

Other Stakeholders
- Zisis Papandreou (U. Regina)
- Regina Caputo (NASA-GSFC)

BIC Project Manager
- Jessica Metcalfe (Argonne)

EIC Project L3 CAM
L3 CAM for Electromagnetic Calorimetry:
- Alexander Bazilevsky (BNL)

ePIC Technical Coordination
Technical Coordinator:
- Silvia Dalla Torre (INFN Trieste)

Deputy Technical Coordinators
- Prakhar Garg (Yale U.)
- Oskar Hartbrich (ORNL)
- Matt Posik (Temple U.)

BIC Project Management
Project Manager (and DSTC):
- Jessica Metcalfe (Argonne)

Deputy Project Manager
- Sylvester Joosten (Argonne)
- Maria Żurek (Argonne)

AstroPix Wafers / Modules & Staves
TM: Manoj Jadhav (Argonne)
Deputy TM: Sanghoon Lim (PNU)

Chip Support
PoC: Richard Leys
Sites:
- KIT
- NASA-GSFC

Wafer Testing
PoC: Sanghoon Lim
Sites:
- PNU
- Argonne

Wafer Procurement
PoC: Jessica Metcalfe
Sites:
- Argonne
- PNU

Module Design & Assembly
PoC:
- Manoj Jadhav
- Anthony Affolder
- Sanghoon Lim

Sites:
- Argonne
- UCSC
- PNU

Stave Bus
PoC: Steven Welch
Sites:
- Oklahoma State

Mechanics / Sectors
TM: Sylvester Joosten (Argonne)
Deputy TM: Beomkyu Kim (SKKU)

Global Design
PoC: Tom O'Connor
Sites:
- Argonne

Tracker Mechanics
PoC: Vic Guarino
Sites:
- Argonne

CF Engineering
PoC: Andreas Jung
Sites:
- Purdue

Assembly & Install.
PoC:
- Kevin Bailey
- Dan Cacace

Sites:
- Argonne
- BNL (EIC Project)
- ePIC BIC DSC

Sector Production
PoC:
- Kevin Bailey

Sites:
- Argonne
- SKKU
- Yonsei U.

Scintillating Fibers
PoC: Zisis Papandreou
Sites:
- U. Regina
- Argonne

ESB / DAQ & Readout
TM: Zisis Papandreou (U. Regina)
Deputy TM: Shinhyung Kim (KNU)

SiPMs & Light Guides
PoC: Zisis Papandreou
Sites:
- U. Regina
- KNU

Electrical Design
PoC: Aram Teymurazyan
Sites:
- U. Regina

Cooling
PoC: Wouter Deconinck
Sites:
- U. Manitoba
- Argonne

ESB Production
PoC:
- Zisis Papandreou
- Wouter Deconinck
- Shinhyung Kim

Sites:
- U. Regina
- U. Manitoba
- Mt. Allison U.
- KNU

ETC
PoC: Regina Caputo
Sites:
- NASA-GSFC

SiPM FEB & DAQ Integration
PoC: Norbert Novitzky
Sites:
- ORNL
- U. Regina
- U. Manitoba

Slow Controls
PoC: TBD
Sites:
- Argonne
- ORNL
- PNU

System Testing / Software & Sim
TM: Maria Żurek (Argonne)
Deputy TM: Hwidong Yoo (Yonsei U.)

System Demonstration
PoC: Henry Klest
Sites:
- Argonne
- U. Regina
- PNU

Beam Tests
PoC: Bobae Kim
Sites:
- Argonne
- U. Regina
- EIC Korea

System Calibrations
TBD

System QC
PoC: Maria Żurek
Sites:
- Argonne
- U. Regina
- BNL (EIC Project)

Rapid Response
PoC: Maria Żurek
Sites:
- Argonne
- U. Manitoba
- PNU

Development
PoC: Chao Peng
Sites:
- Argonne
- U. Manitoba
- U. Regina
- PNU

Benchmarks
PoC: TBD
Sites:
- Argonne
- U. Manitoba
- PNU

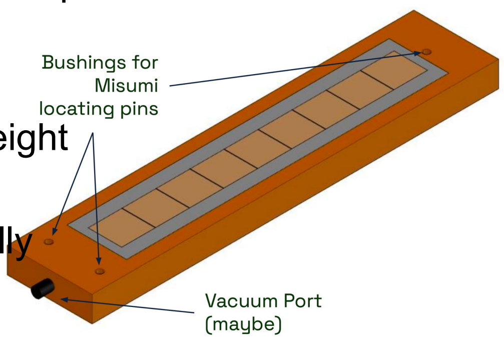
Glossary
BIC: Barrel Imaging Calorimeter
CAM: Control Account Manager
DSC: Detector Subsystem Collaboration
DSL: Detector Subsystem Lead
DSTC: Detector Subsystem Technical Contact
ESB: End-of-Sector Box
ETC: End-of-Tray Card (AstroPix module RDO)
FEB: Front-End Board
PoC: Point-of-Contact
PM: Project Manager
QC: Quality Control
RDO: Readout board
TBC: To Be Confirmed
TBD: To Be Determined
TM: Technical Manager

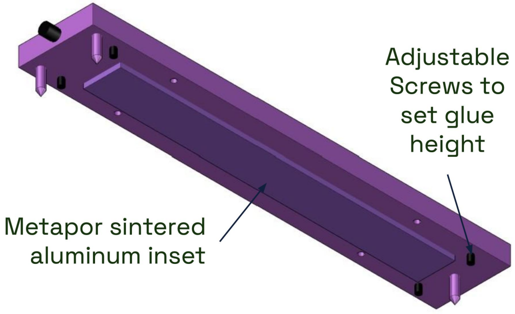
BIC ORG Chart v1.0

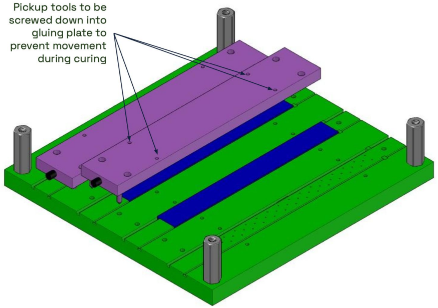
Note: *The BIC internal work packages (AstroPix Wafers, Modules & Staves, Mechanics, Sectors, ESB, DAQ & Readout, and System Testing) are integrated under the EIC Project P6 Work Packages*

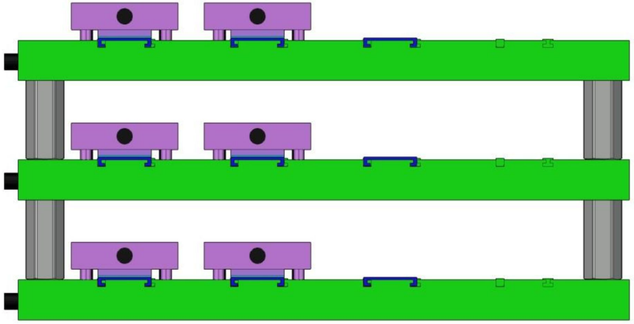
Modules toolings

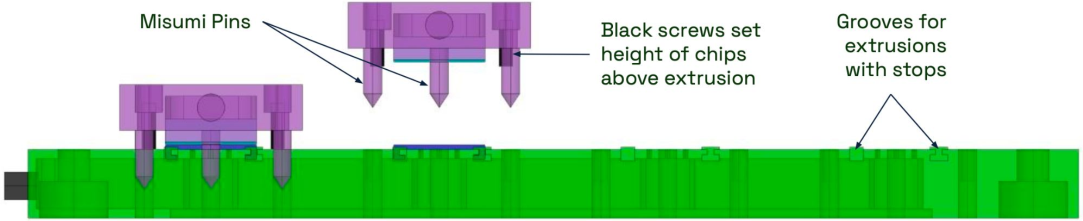
- **Toolings for assembly during PED phase**
- Align the chips on Al base plate with chip-to-chip gap of 100 um
- aligns AstroLinx with chips
- allow glue amount control and fixes glue height during cure time
- multiple modules can be assembled parallelly









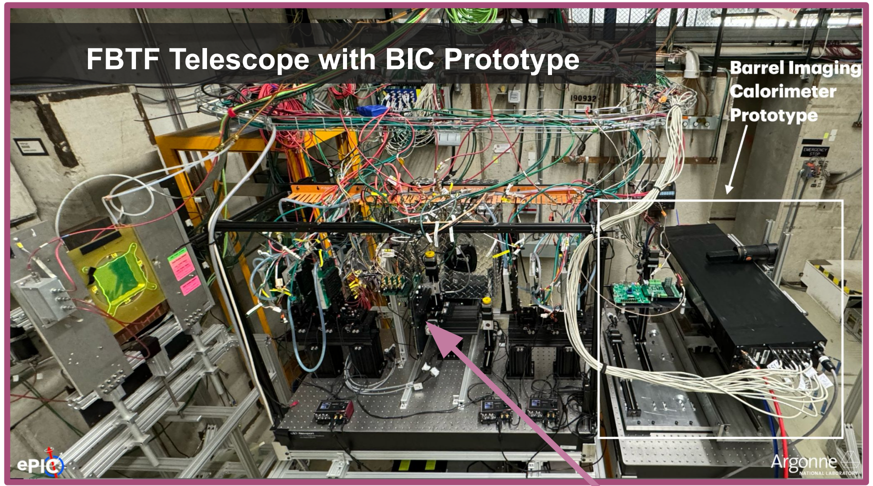


System Testing - FTBF Beam Test

June 2024 beam test
Extremely challenging conditions: only 30% of the 1-week test beam

Prototypes and test articles:

- **Setup 1:** Baby BCal (ScFi/Pb prototype) shipped from JLab to Argonne/FBTF integrated with single AstroPix v3 chip
- **Setup 2:** AstroPix multi-channel board and quad chip with successful daisy chain readout of v3



Beam Test goals:

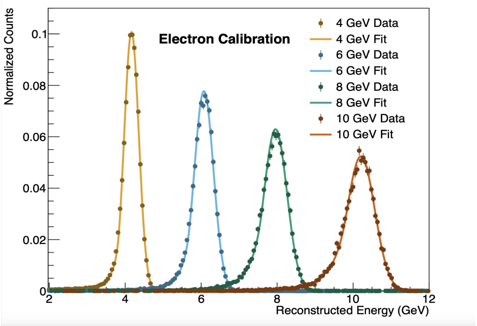
- **Commission** both setups in the beam including the first test of the integration between AstroPix and Pb/SciFi
- Benchmark **response to electrons and pions**

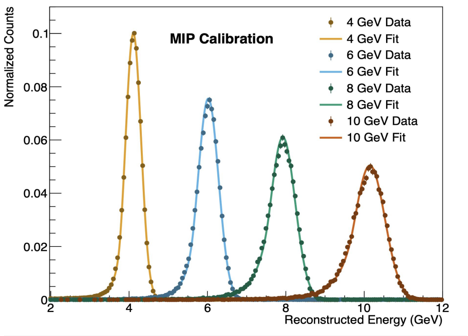
SciFi/Pb results from June 2024 summarized in https://arxiv.org/abs/2504.03079

FTBF Beam Test - Overview

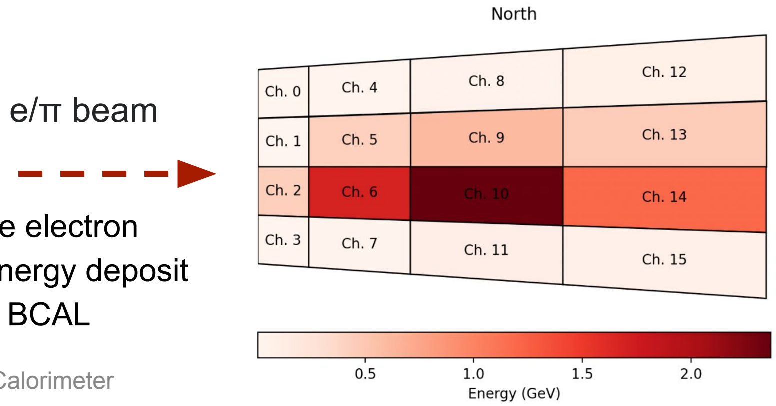
Despite extremely challenging FTBF conditions (30% of the 1 week beam test):

- Successfully **commissioned the DAQ** system for the Baby BCAL
- Tuned and included **Cherenkov counter information** for electron/pion particle identification in our data stream
- Performed a **proof-of-concept integration between the AstroPix** layer and Baby BCAL using the AstroPix analog signal
- Collected sets of **electron/pion data at 4, 6, 8, and 10 GeV**, as well as sets of muon/pion and proton data for calibration purposes





Calibrated **energy response** with two different calibration methods



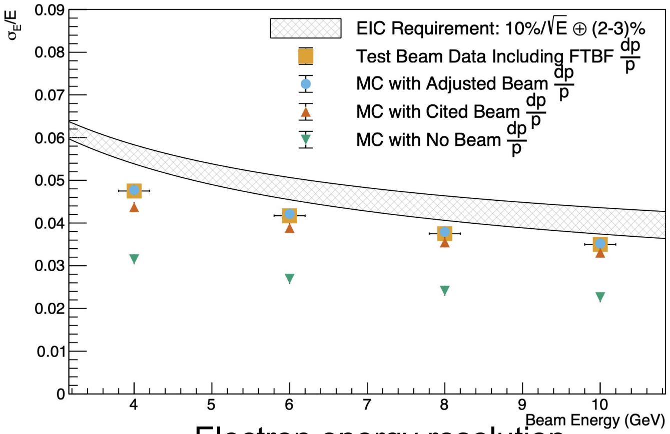
Example electron event energy deposit in Baby BCAL

FTBF Beam Test - Electron Energy Response

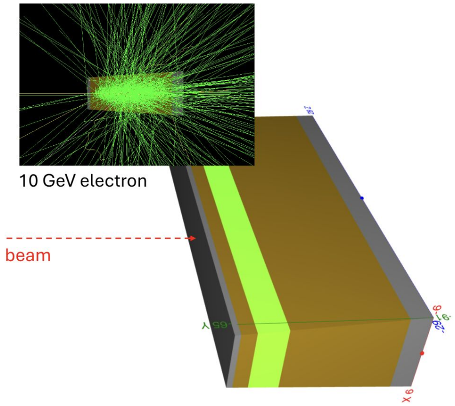
Benchmark simulations and beam energy spread using electron response

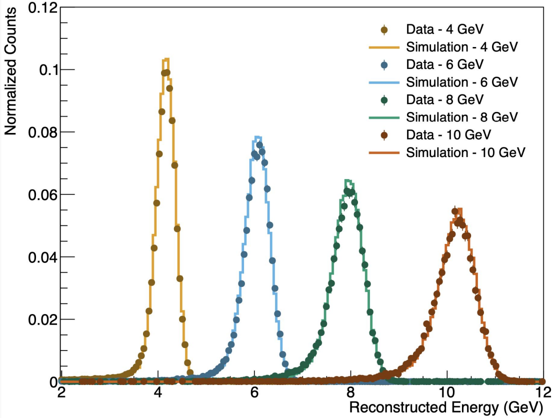
- Baby Bcal implemented in dd4hep: Response simulated including **realistic beam momentum and position spread**, realistic model for **attenuation and photoelectron response** based on measured phe/GeV and fiber attenuation and **digitization**

- Energy resolution extracted (measurement limitation: 2-3% dp/p at FTBF)
- Good constrain power over the constant term ~1.5 ± 0.4%
- Simulations describe the electron data well



Electron energy resolution

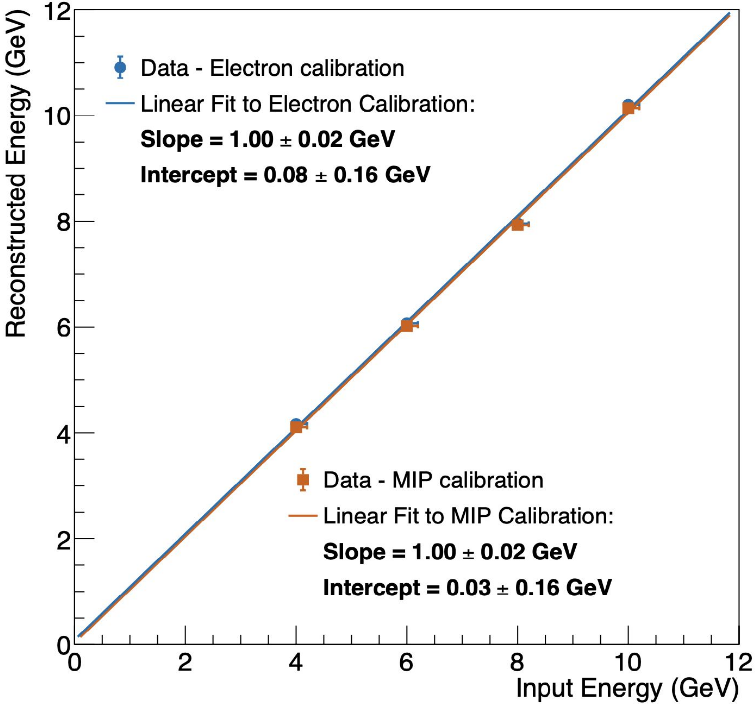




Comparison between e^- data and simulation

FTBF Beam Test - Data Analysis

- Baby BCal data **calibrated** with **muons** and **electron-based** calibration
- **Electrons selected** by events where upstream Cherenkov & downstream Cherenkov outer PMT fired
- **Refinement cuts** to remove spurious signals and to improve containment of showers
- Total energy from **geometric sum of North & South** (2 sides of Baby BCAL) reconstructed energies
- **Beam profile** from AstroPix (wide, especially for 4 GeV π/e)
- Non-negligible and not precisely known beam **Δp/p (~3%)** affecting constant term

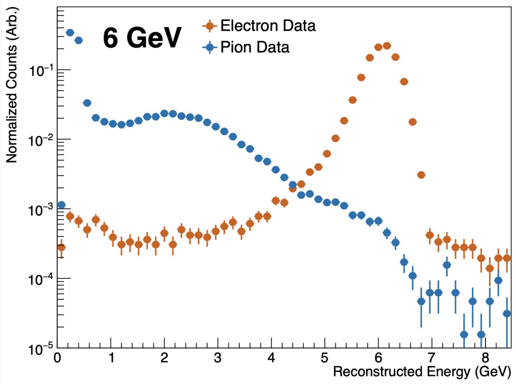


Linearity of the calorimeter response

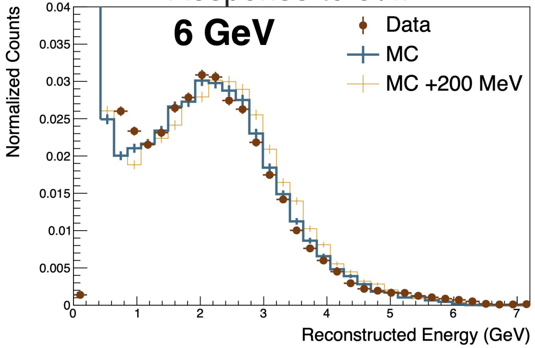
FTBF Beam Test - Pion Response

- Pions selected with **no hits in the Cherenkovs** exhibit a **MIP peak** and a **shower peak**
- **Electrons and pions well separated**, but both have tails: Electron tail – showers upstream, horizontal leakage, Pion tail – electron misID, pileup.
- **Data/simulation agreement reasonable**, agrees well in 6 GeV, slightly overshoots at 4 GeV, and undershoots at 8 GeV (A possible contributor: mean beam momentum and its spread)
- **e/pion separation extracted for the Baby BCAL** in the test beam environment (also affected by the beam spread): shows the impact of longitudinal segmentation

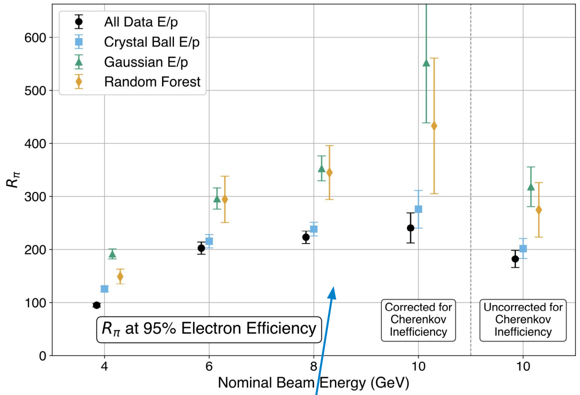
Data: Response to e^-/π^-



Data and Simulation: Response to e^-/π^-



Data: Separation e^-/π^-



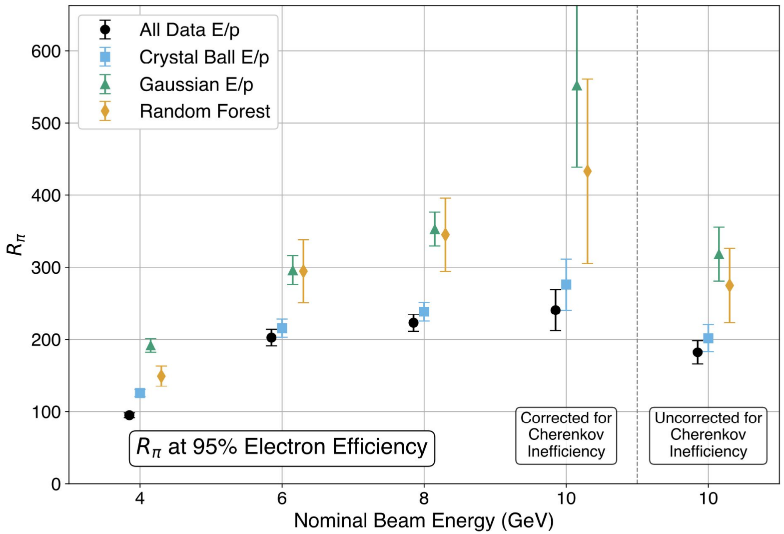
Presented methods in various degree incorporate artifacts of the test beam setup: beam momentum smearing, effects of upstream material, possible pileup, and beam profile variations

FTBF Beam Test Summary

SciFi/Pb results from June 2024 summarized in

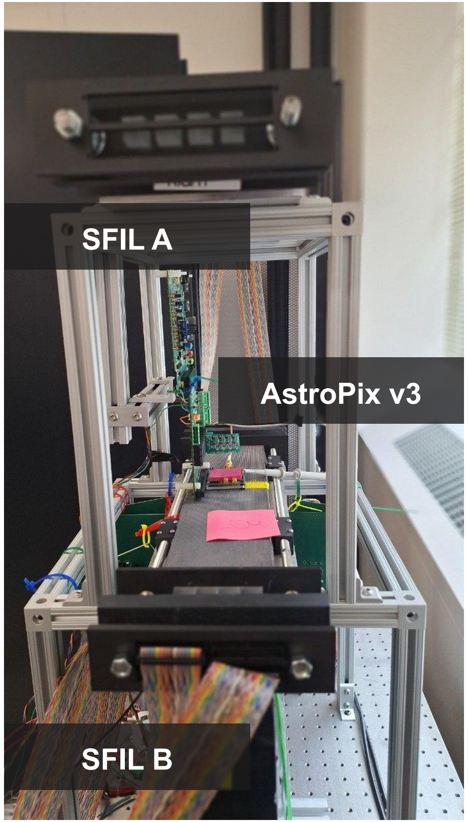
https://arxiv.org/abs/2504.03079

- Electron and pion response measured
- Energy resolution extracted (measurement limitation: 2-3% dp/p at FTBF)
- Good constrain power over the constant term ~1.5 ± 0.4%
- Simulations describe the electron and pion data well
- e/pion separation extracted within the full system in the test beam environment
  - affected by FTBF beam conditions including Δp spread

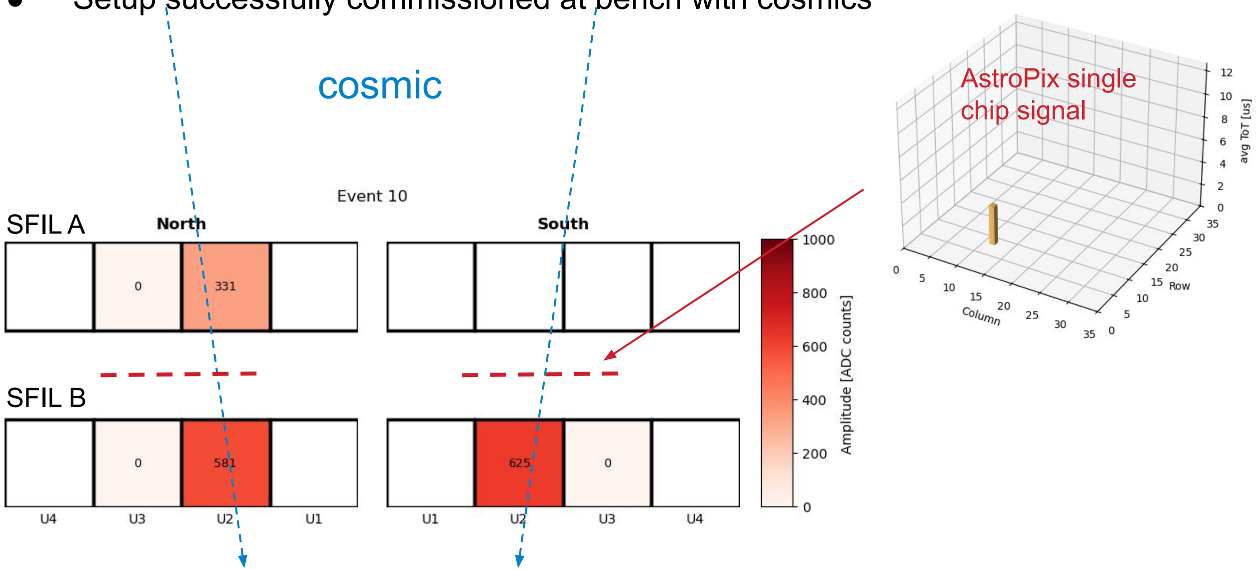


Presented methods in various degree incorporate artifacts of the test beam setup: beam momentum smearing, effects of upstream material, possible pileup, and beam profile variations

System Testing - AstroPix/SFILs Integrations

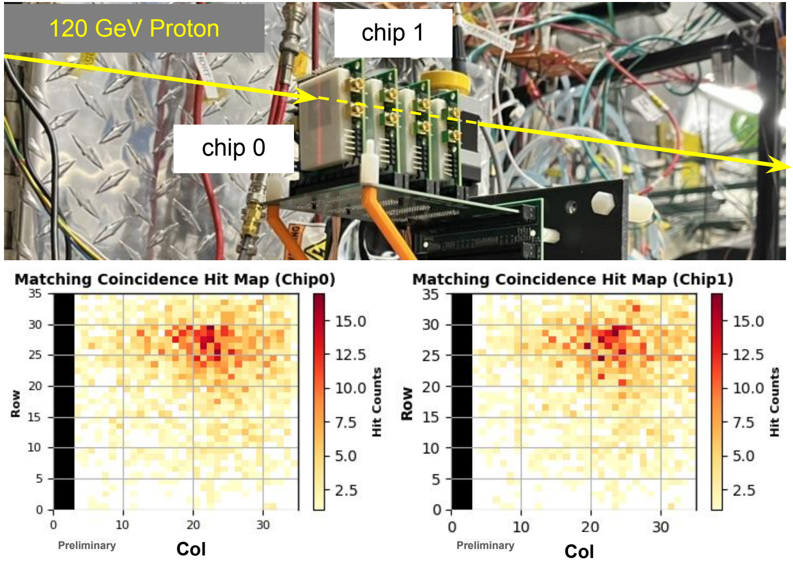


- Synchronization (AstroPix-SFILs): LVDS MISO0/1 signals that generated from Astropix used as trigger IN for Baby BCAL
- SFILs: new S14 SiPM arrays, optical cookies, 8 cm machined light-guides
  - Test station for optical coupling and improvements
- Setup successfully commissioned at bench with cosmics

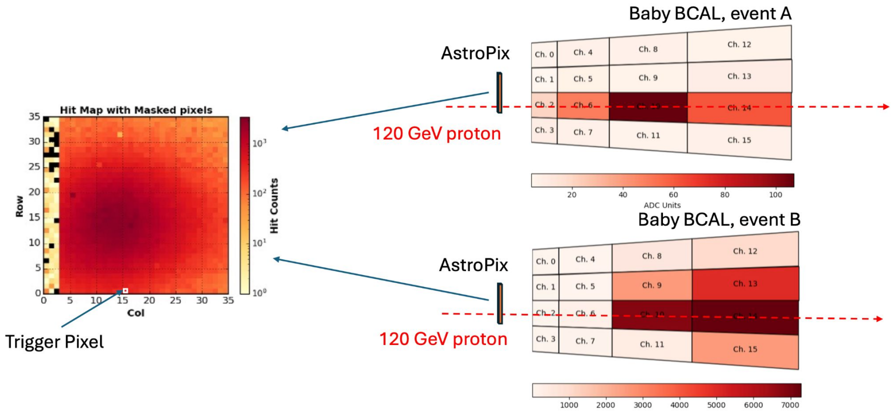


System Testing - AstroPix/BCAL Integrations

AstroPix v3 integration tests: first proof-of-concept demonstration of the integration of two daisy-chained AstroPix layers and Baby BCal and AstroPix in a beam-like environment.

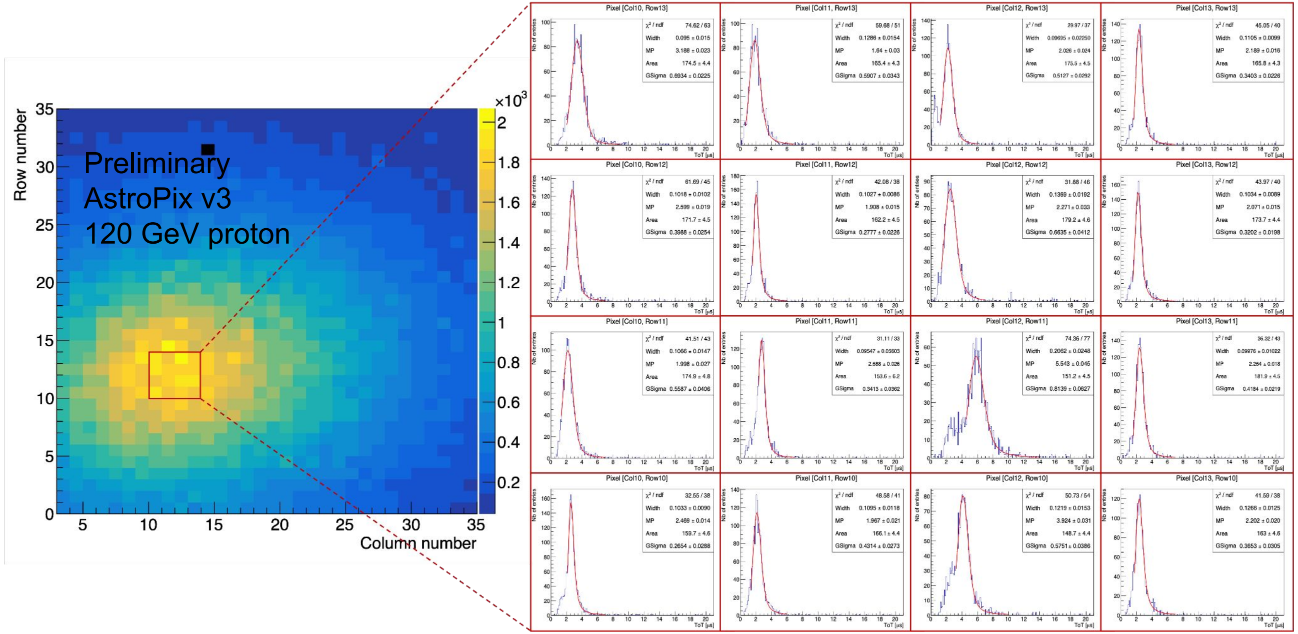


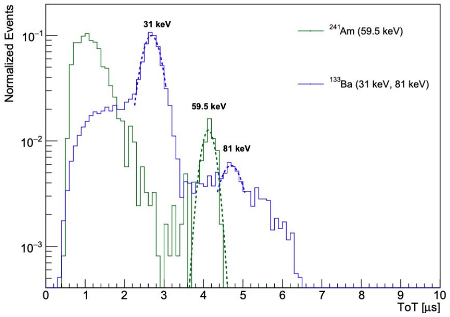
The multilayer AstroPix v3 setup which we tested at FTBF, and an example of the recorded **120 GeV proton beam events from the first two layers, read in coincidence**

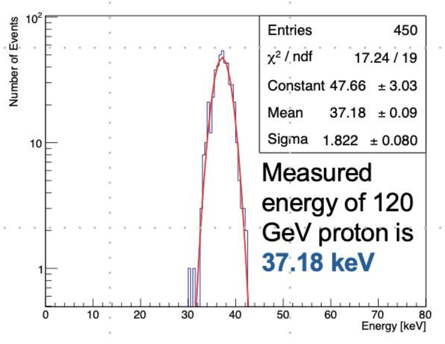


Baby BCal event triggered on AstroPix signal from 120 GeV proton. Event A shows MIP-like behavior, event B shows hadronic shower behavior.

R&D Phase III - AstroPix Beam Data Analysis







Example AstroPix data collected with a 120 GeV proton beam. The hit map reveals the proton beam profile. The collected ToT values for the marked pixels are presented in the matrix of plots on the right

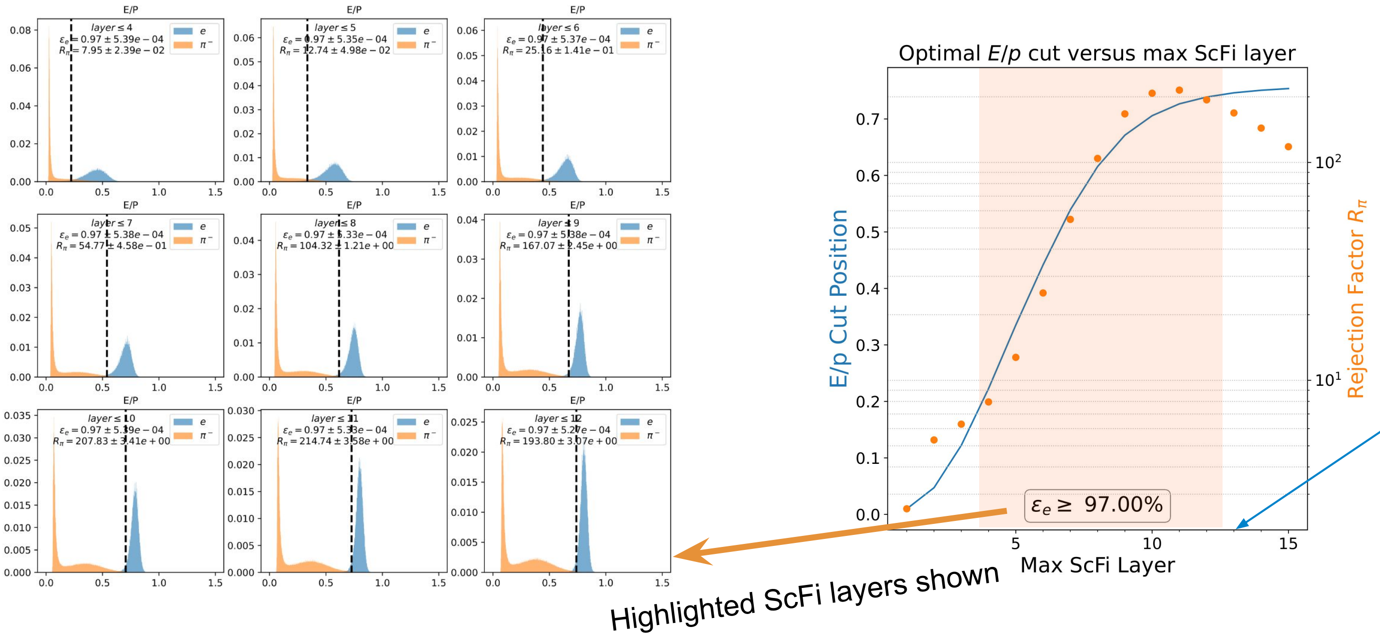
Calibrated response to 120 GeV protons and Am-241 and Ba-133 calibration response

Particle Identification

electron-pion: method

1. **Optimized cut on E/p** from different depth of Pb/ScFi layers at very high electron efficiency
   a. Finding optimal number of SciFi/Pb layers to optimize calorimeter depth
2. **Convolutional neural network** utilizing energy and spatial information for shower (details: backup)

Example for 2 GeV e/π

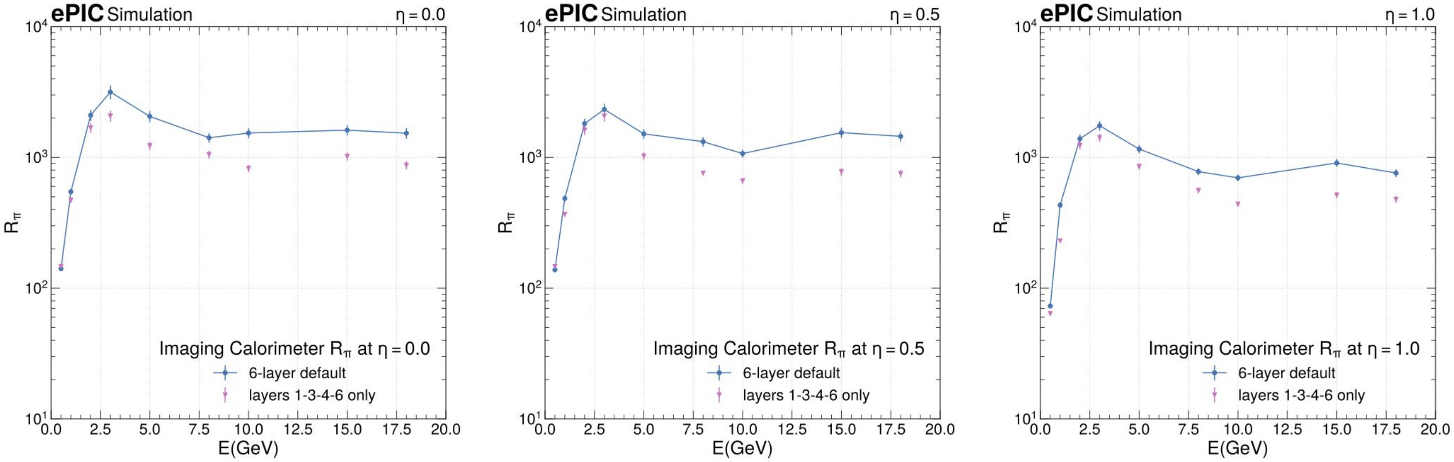


Scan through different number of SciFi/Pb layers to find the optimal maximal depth

Peak ~ layer 10-11

Particle Identification

electron-pion: nominal performance - 4 AstroPix layers



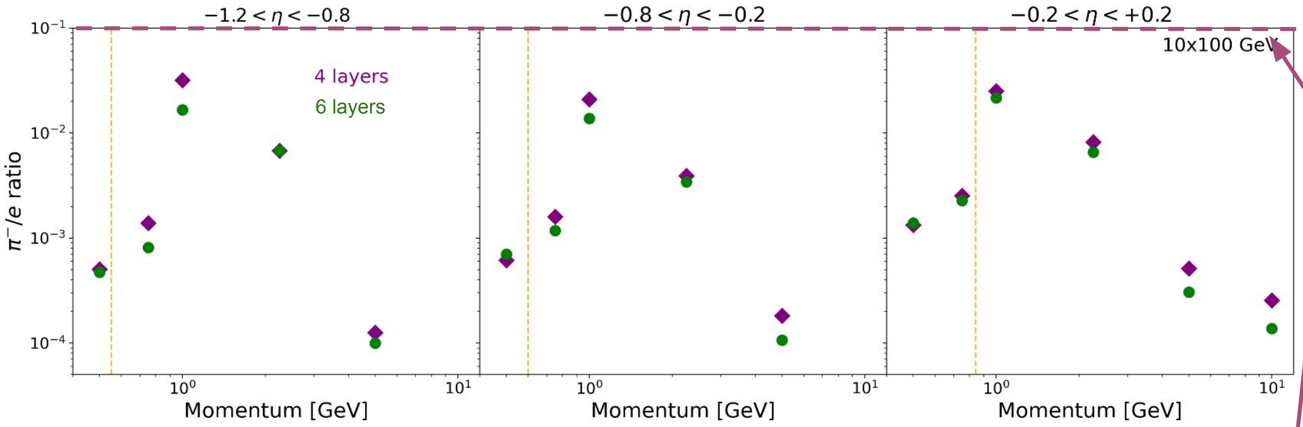
4-layer configuration: layers 1-3-4-6

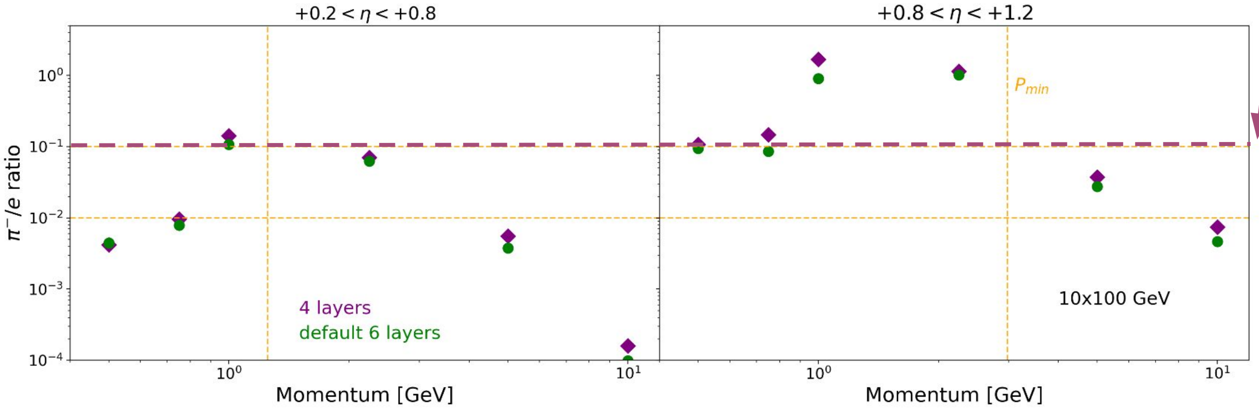
4-layer configuration: Exceeds 10^3 pion rejection performance loss at the low to mid energies where rejection is most needed

6-layer configuration Exceeds 10^3 pion rejection almost everywhere, including mid to high energies: future upgrade for future high-luminosity runs where more high-energy particles available

Particle Identification

Pion contamination in DIS 10 x 100 GeV - 4 AstroPix layers





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

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

BIC fulfills the requirement in all η ranges

Fiber Specs

3.1 Technical/Performance Characteristics

A. Light yield: the average response to a Sr-90 source shall be greater than 3.5 photoelectrons measured using a bialkali photomultiplier tube 200 cm from the source, and the opposite end blackened (assessed via methods mutually acceptable to the BSA and Contractor).

B. Diameter mean value and variation shall be 1.00 +/- 0.01 mm, RMS ≤0.02 mm.

C. Attenuation length for blue light > 4m.

D. Batch to batch or lot to lot variation of light yield <15%.

E. Batch to batch or lot to lot variation of attenuation length <10%.

F. Emission spectrum in blue-green light

G. Scintillation decay time <3ns

H. Total length 4900 km

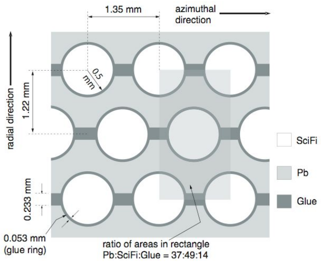
I. Delivery method in canes. Length of fibers 4.55 meters +/- 0.01m.

Sector Mechanics

Fabrication and Test Articles

- Swager was commissioned in test lab
- Fabricating short sections for first test articles
- First articles are almost within final specifications
- Expect to have demonstrated fabrication process this summer
- Production fabrication area is ready to move in

Pb/SciFi Matrix:



Production fabrication steps:

- **Fiber reception** + QC
  - Baseline: fibers come in canes (pre-cut, in contract!)
  - *Mitigation: fibers in spools: cutting + additional QC + relaxation*
- **Lead reception** (rolls to size) + swaging
- **CF frame** component reception, produced as subcontract
- **Manufacture matrix** (lead-epoxy-fiber), mayan pyramid
  - ~ 0.5-1 layer / press / day, continuous QC
  - Integrate CF frames in production process (monolith)
- **Machine sectors** at external machine shop; QC
- **Polish** ScFi + final QC
- **Ship** to BNL