Detector Advisory Meeting
28-29 August 2024

Barrel Imaging Calorimeter

eRD115

08/28/2024
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for the Barrel Imaging Calorimeter DSC
Argonne National Laboratory

R&D Motivation

EIC Calorimetry Requirements

Barrel ECAL in EIC Yellow Report

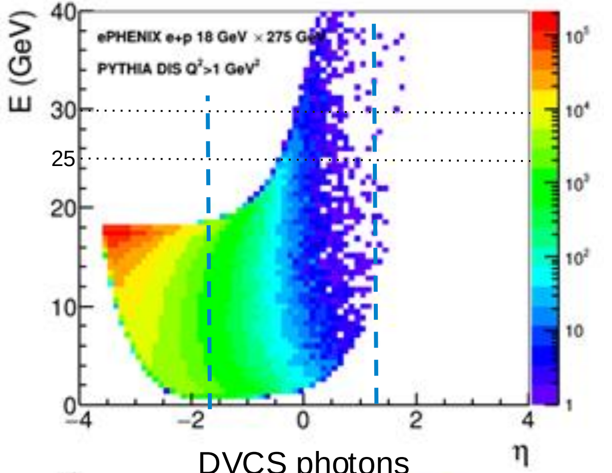
EIC Community outlined physics, detector requirements, and evolving detector concepts in the EIC Yellow Report.

EIC Yellow Report requirements for Barrel EM Calorimeter

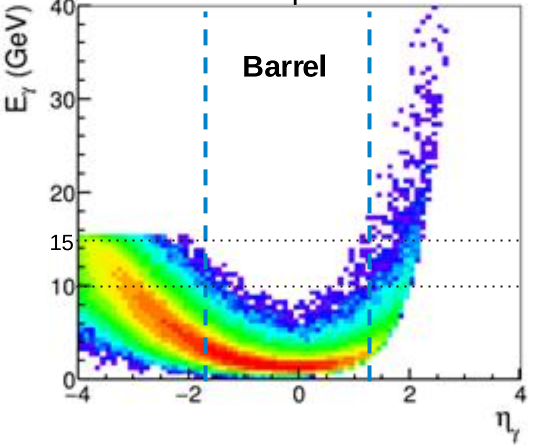
- Detection of electrons/photons to measure **energy and position**
- Require **moderate energy resolution** $(7-10)\%/\sqrt{E} \oplus (1-3)\%$
- Require **electron-pion separation up to 10^4** at low momenta in combination with other detectors
- Discriminate between **π^0 decays and single γ up to ~10 GeV**
- **Low energy photon** reconstruction ~100 MeV

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

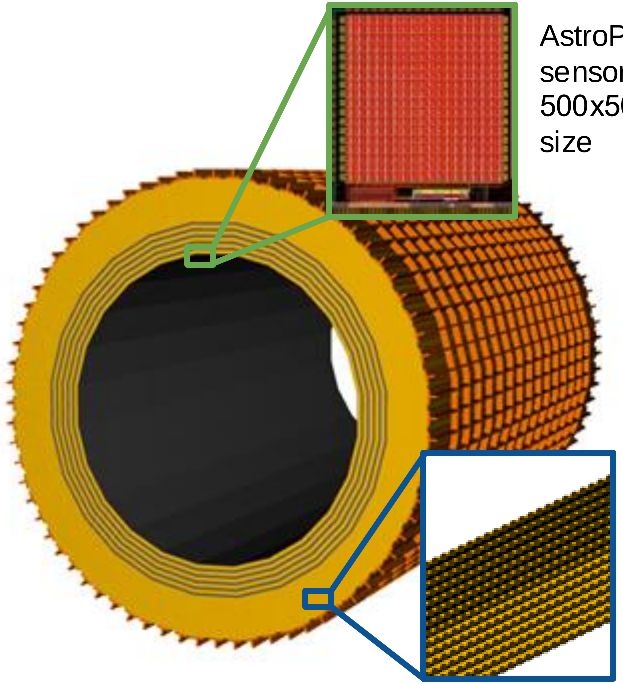
DIS electrons



DVCS photons



Barrel Imaging Calorimeter: General Overview

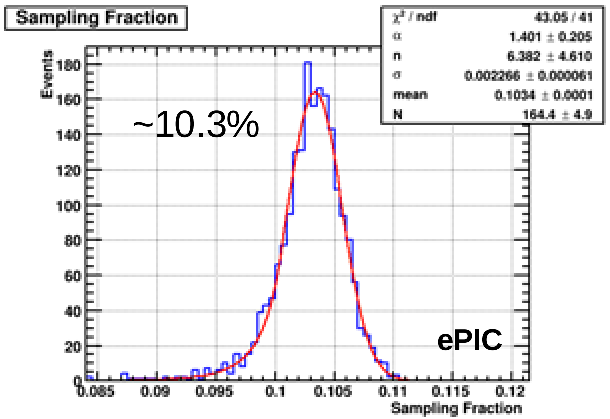


AstroPix: silicon sensor with 500x500μm^2 pixel size

ScFi Layers with two-sided SiPM readout

- **4(+2) layers of imaging Si sensors** interleaved with **5 Pb/ScFi layers**
- Followed by a **large section of Pb/ScFi section**

- Total radiation thickness ~17.1 X_0
- Sampling fraction ~10%



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

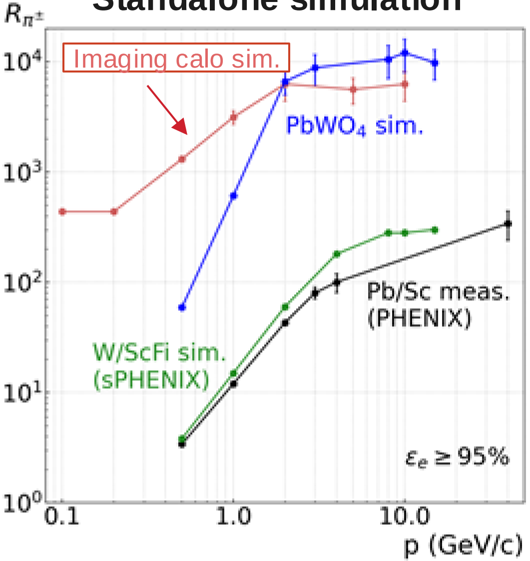
Sampling fraction = $\Sigma E_{fibers} / E_{thrown}$

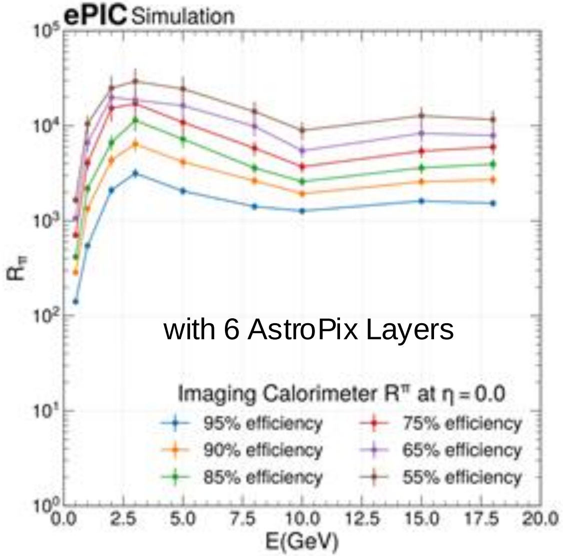
Energy resolution - Primarily from Pb/ScFi layers (+ Imaging pixels energy information)
Position resolution - Primarily from Imaging Layers (+ 2-side Pb/ScFi readout)

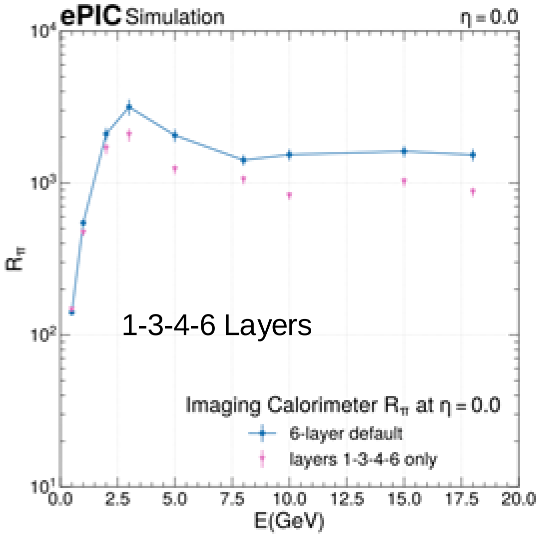
Barrel Imaging Calorimeter: Performance Example

Realistic ePIC simulation

Standalone 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!

R&D Directions

SciFi/Pb Barrel technology: 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)

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

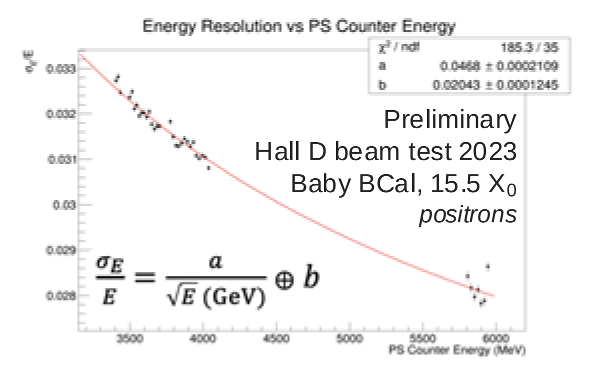
General BIC direction of R&D:
Demonstrate using SciFi/Pb and AstroPix in the environment of EIC:

- Benchmarking of high energy simulation performance (e.g., response to pions and electrons)
- Test of AstroPix in high rate/shower-like environment
- SciFi/Pb integrated with the AstroPix sensor layers

FY23 Snapshot:

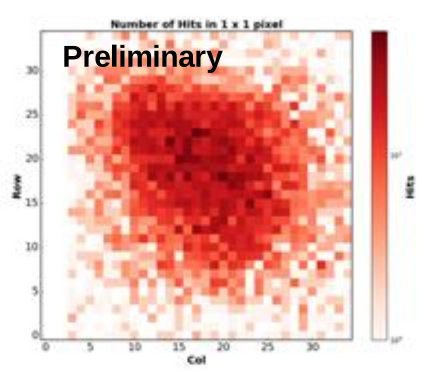
Response to positrons in **SciFi/Pb** measured in Hall D

Constant term integrated over probed impact z position and angle: ~2%



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

Performs well in much harsher conditions than EIC



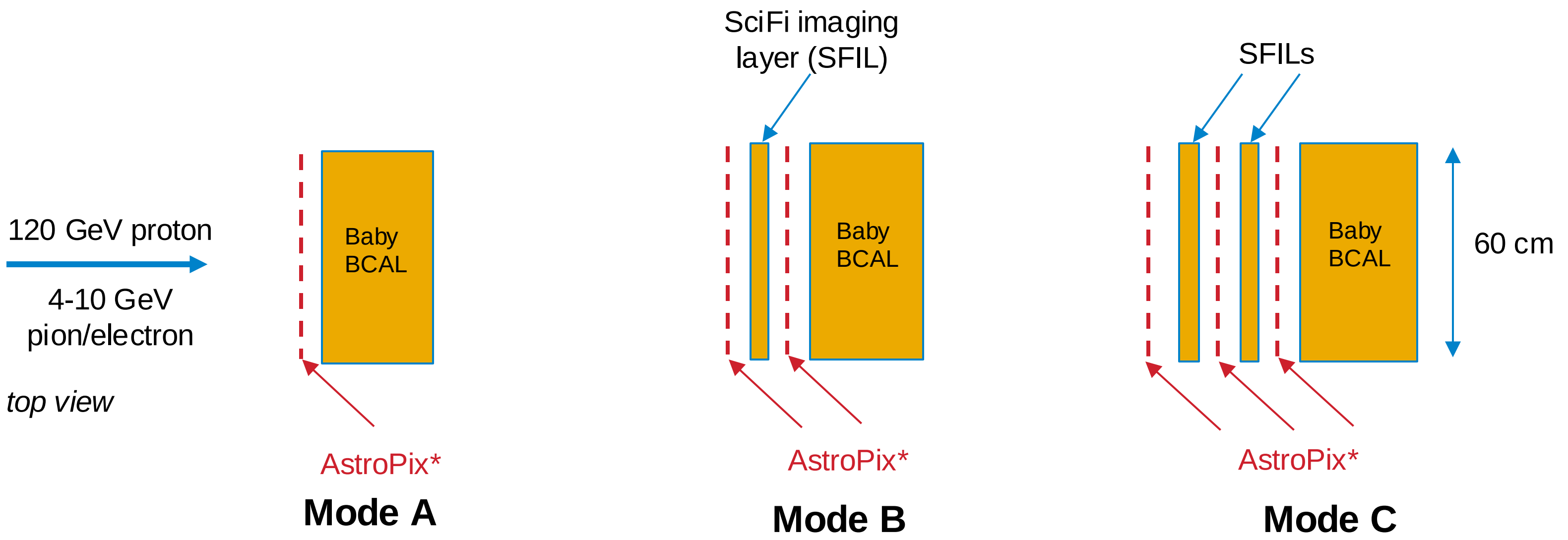
FY24 Goals

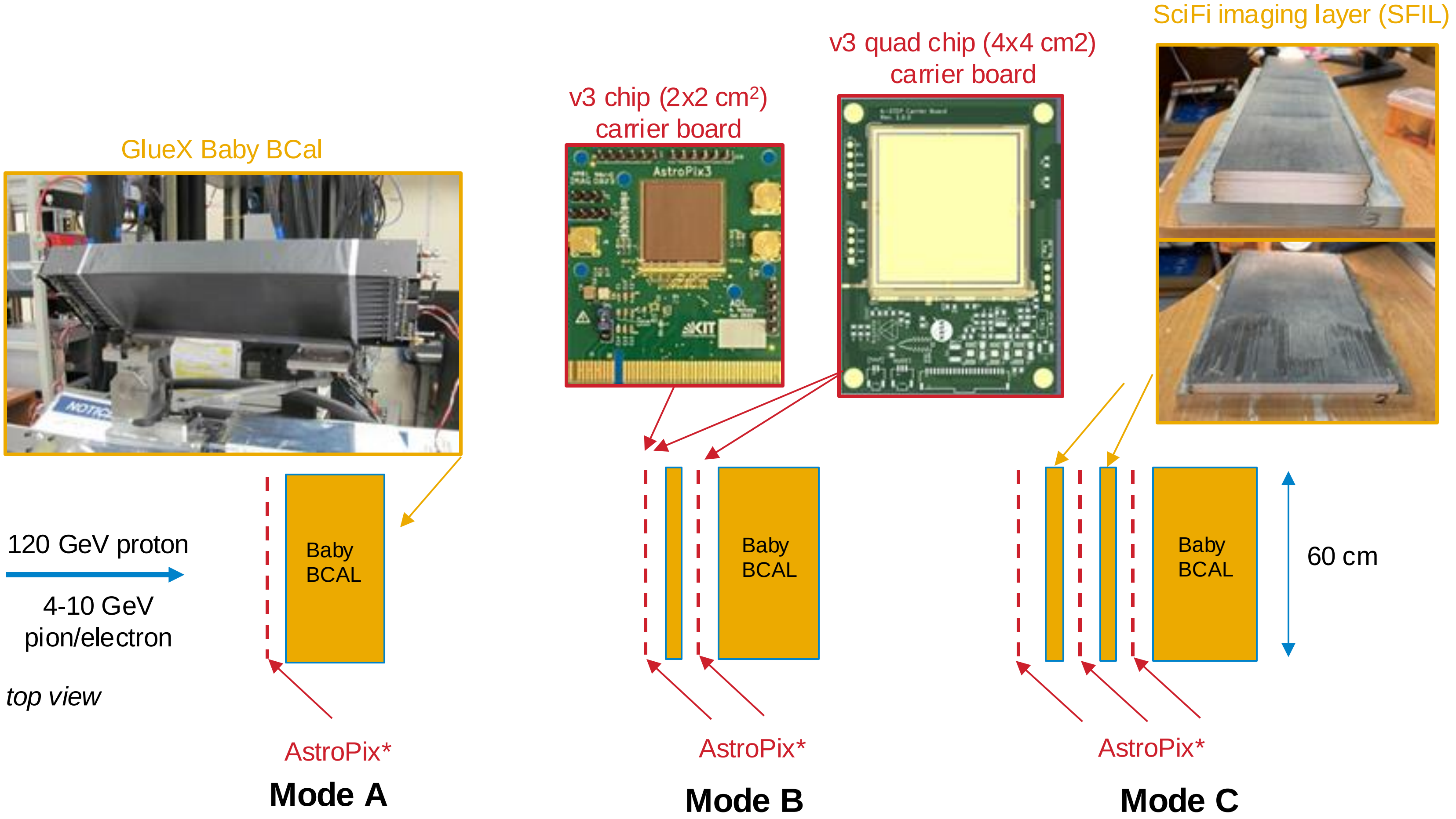
FY24 R&D Goals

Goal: Characterize the integrated AstroPix and SciFi/Pb system with a mixed e/π beam and MIPs, benchmarking the response to charged pions, benchmarking the electron-pion separation capability, and testing the new generation SiPMs.

Possible modes of system integration:

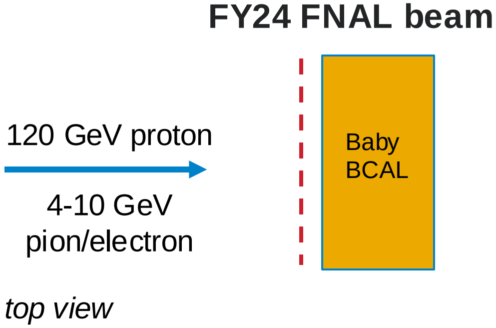
* System flexible for testing single AstroPix chip, quad chip, any any further module test design

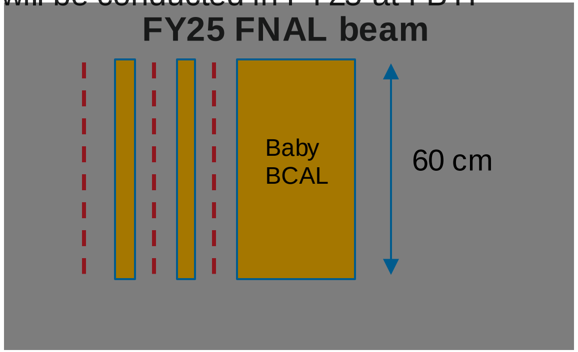



GlueX Baby BCal
v3 chip (2x2 cm²) carrier board
v3 quad chip (4x4 cm2) carrier board
SciFi imaging layer (SFIL)
120 GeV proton
4-10 GeV pion/electron
top view
Baby BCAL
Baby BCAL
Baby BCAL
60 cm
AstroPix*
AstroPix*
AstroPix*
Mode A
Mode B
Mode C

FY24 Beam Availability Summary

- Delays in the start of the beam at the Fermilab Test Beam Facility in FY24 caused by ESH paperwork: our team received only **one week** (6 days, 76 hours) of beam test **out of the planned 4-6 weeks + funds to ANL available end of March 2024 only**
- Due to a heat wave in the Chicago area we were provided only **30.5 hours** of beam (**~ 30% of the nominal 1-week allocation**)
- Given these severe reductions we decided to **focus on setting up our DAQ system** for the Baby BCAL aiming **to collect initial analysis-quality data with the π/e** beam while **simultaneously working on the integration of AstroPix layers and Baby BCAL**
- Further integration with SFILs and additional AstroPix layers will be conducted in FY25 at FBTF





FY24 Deliverables and Results

R&D Phase I - Preparations

Baby BCal moved to Argonne

AstroPix set up at Argonne

- Shipment of Baby BCAL, SiPM wedges, voltage distribution system, and cables ✅
- Final design of the system fixture ✅
- AstroPix telescope and Baby BCAL assembly and tests with cosmics ✅

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

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

Deliverable (M1-M4): Integrated system with DAQ tested with cosmics/sources

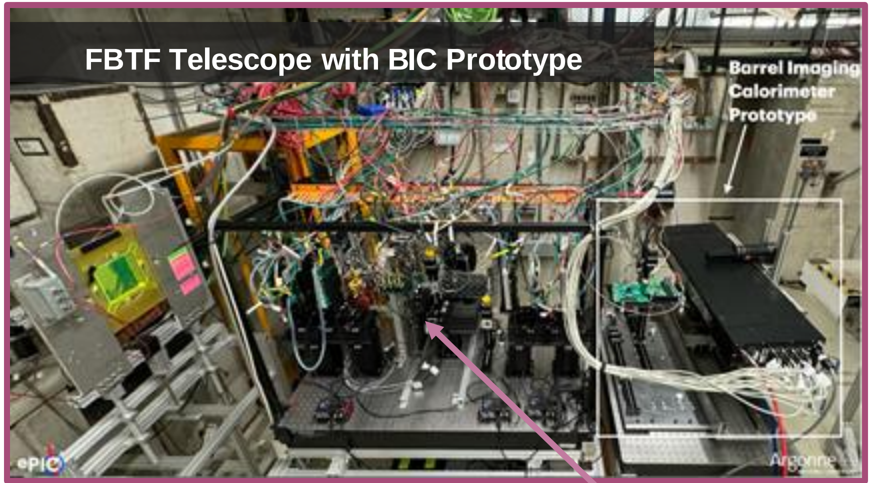
See backup slides 30-35 for more preparation summary

R&D Phase II - Beam Test

June beam test at Fermilab Test Beam Facility

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 with successful daisy chain readout of v3



Beam Test goal:

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

Deliverable (M6): Prototype commissioned in beam and data collected

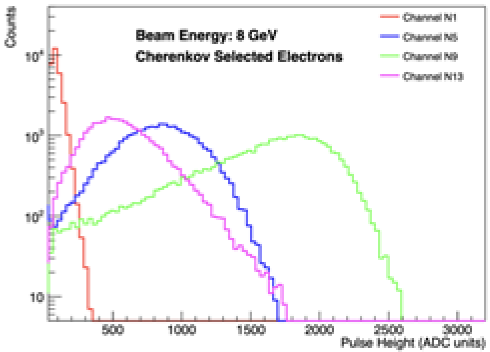
See backup slides 36 - 46 for more details

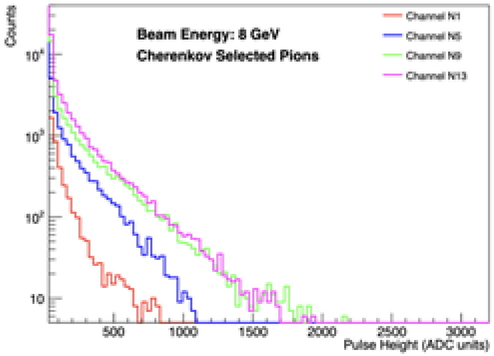
R&D Phase II - Beam Test

June beam test at Fermilab Test Beam Facility

Despite extremely challenging conditions:

- 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
  - After initial assessment data seems analysis-quality

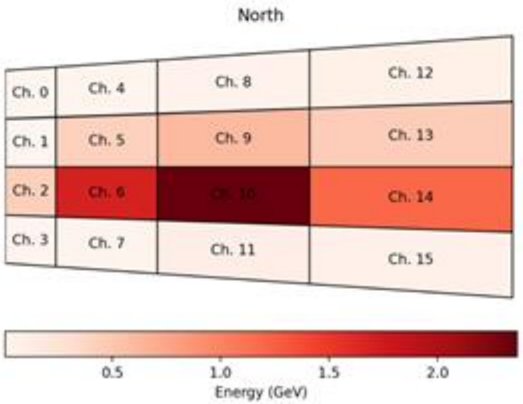




Collected **energy response** in selected Baby BCAL channels at different depths in the calorimeter prototype for a sample of pions (right) and electrons (left) identified with the Cherenkov counters.

e/π beam

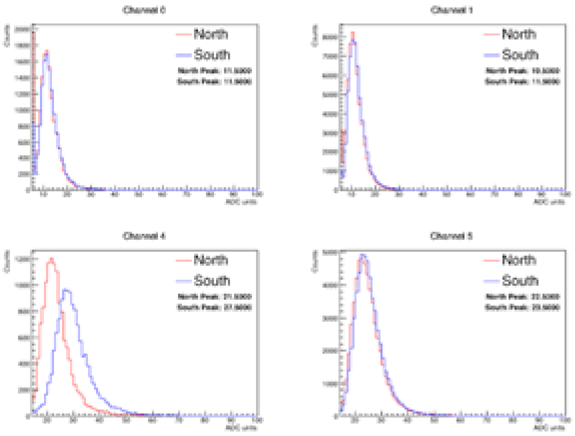
Example electron event energy deposit in Baby BCAL



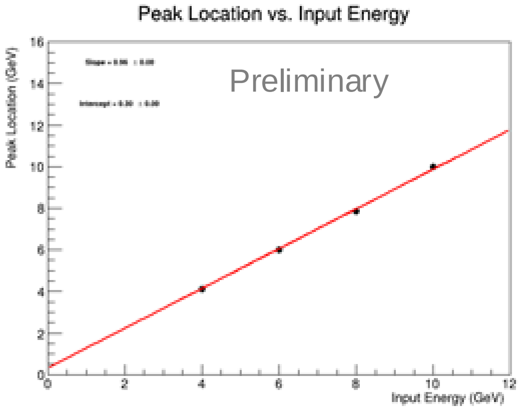
R&D Phase III - Data Calibration and Selection

- Baby BCal data **calibrated** initially with **muons** and iterated with **electron-based** calibration
  - Response to muons simulated for every Baby BCal cell for absolute 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

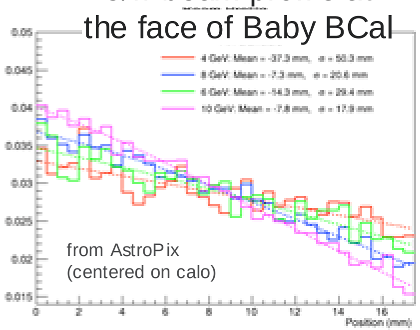
Example response to muons from Baby BCal channels

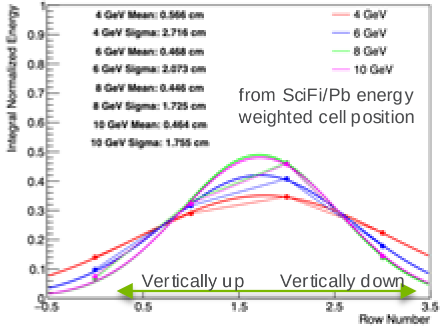


Calibrated electron energy vs beam energy



e/π beam profile at the face of Baby BCal

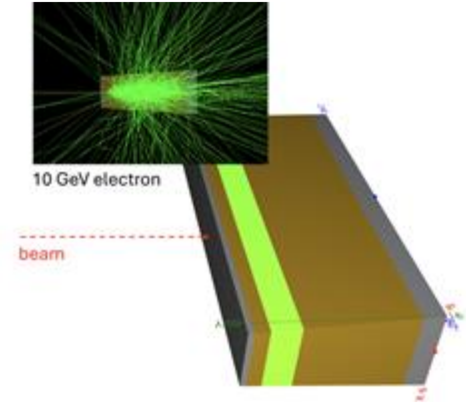


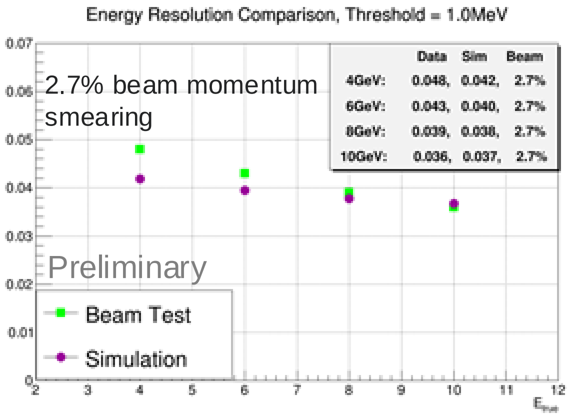


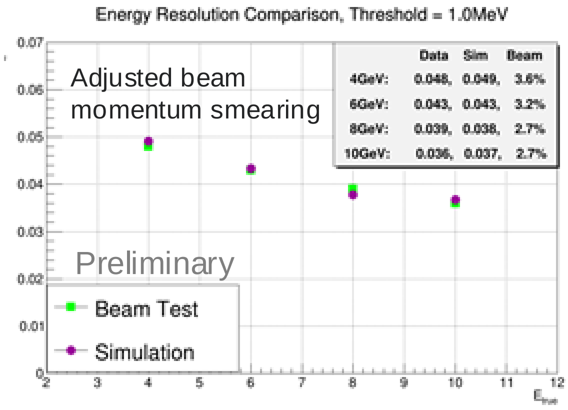
R&D Phase III - electron energy response

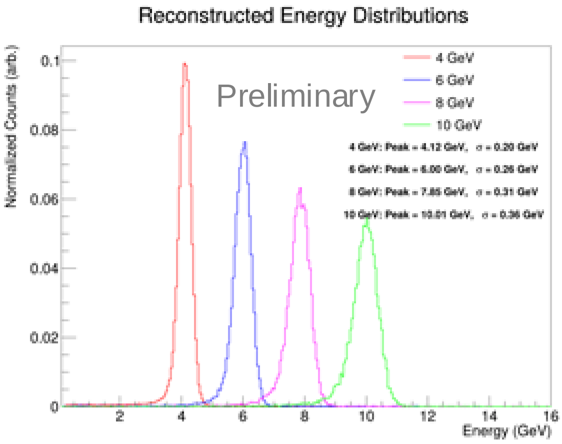
Benchmark simulations and beam energy spread using electron response

- 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**
- Beam **momentum spread quoted by FBTF: 2.7%, very likely higher for lower energies (see backup)**







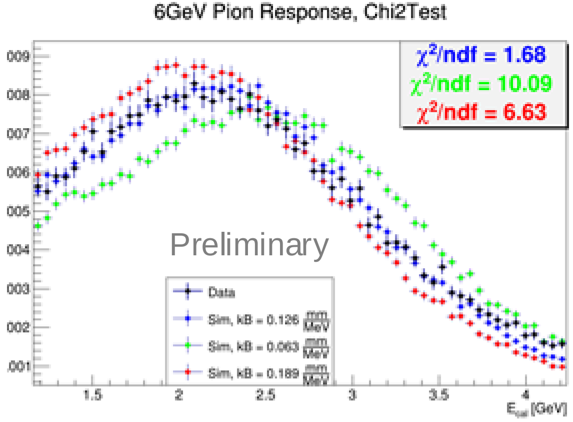


R&D Phase III - pion response

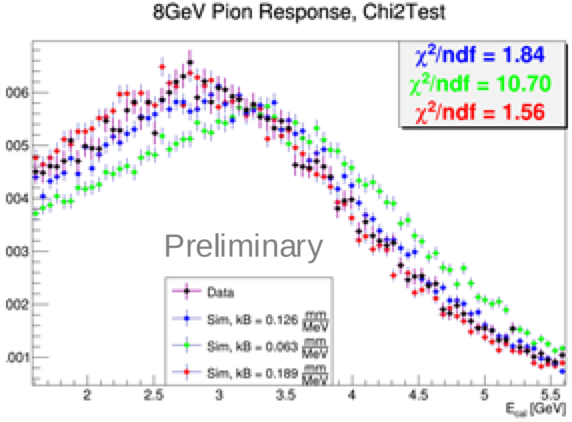
Benchmark pion response in simulations

- Pions elected in data by requiring **no hits in the Cherenkovs** exhibit a **MIP peak** and a **shower peak**
- Compare data and simu **shower peak with different Birks constants to tune it in simulations**
- **Lower limit on e/π separation for Baby BCAL extracted** from data (**E/p highly affected by FTBF beam Δp spread**; contribution to MIP peak from muons determined from simulations)
  - Benchmarking in simulations in progress

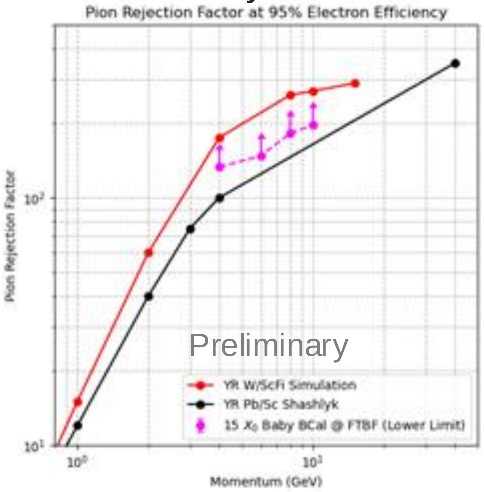
Response to 6 GeV π^-



Response to 8 GeV π^-

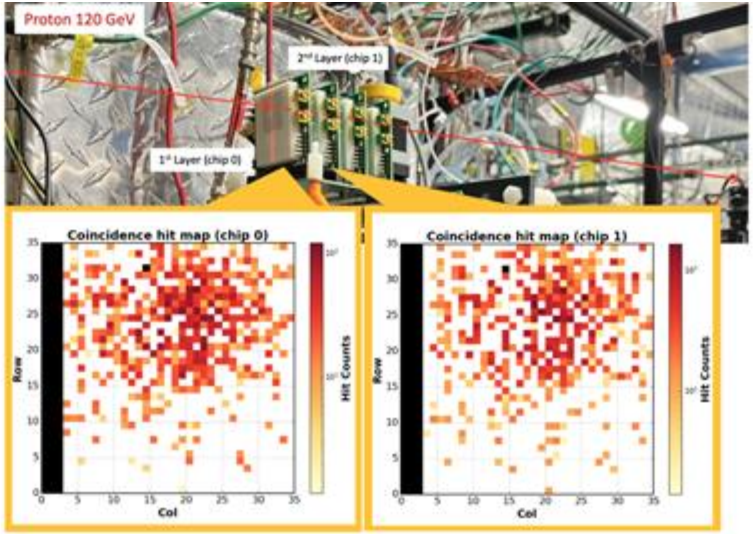


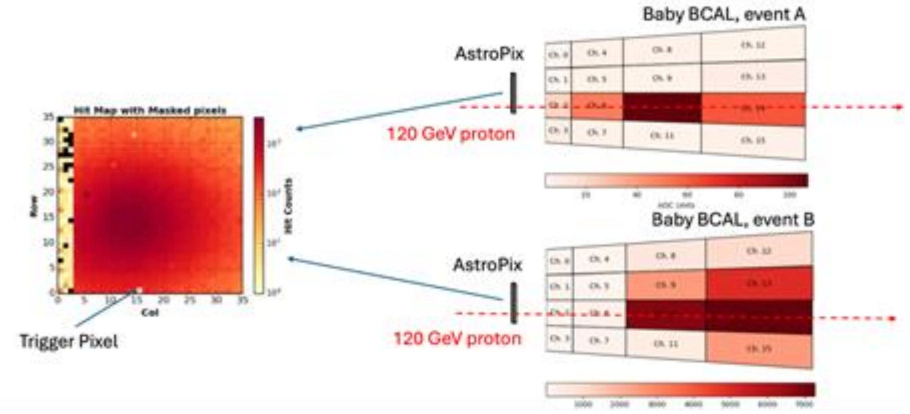
Lower limit on e/π separation in Baby BCal



R&D Phase II & III - AstroPix 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.

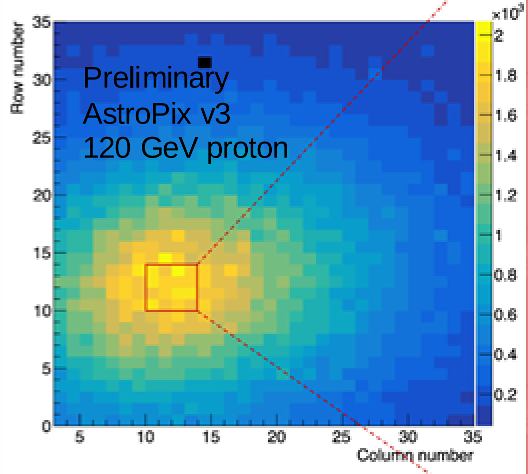


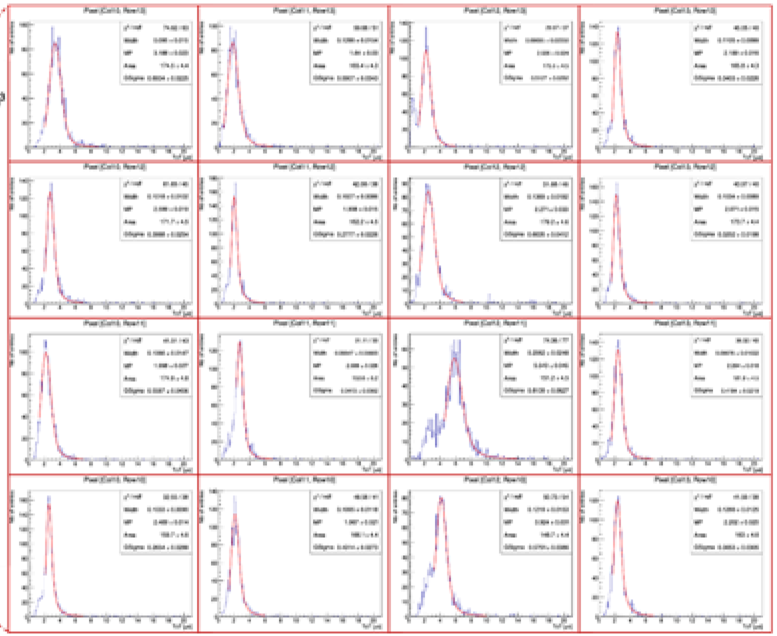


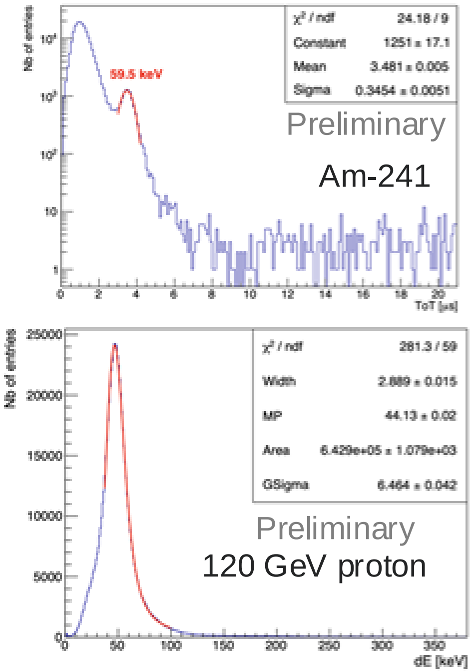
The multilayer AstroPix v3 setup which we tested at FTBF, and an example of the recorded **120 GeV proton beam events from the first two layers, read in coincidence**

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

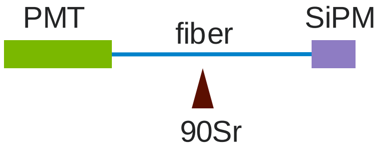
Calibrated response to 120 GeV protons and Am-241 calibration response

FY24 R&D - Outlook on SFILs @URegina

Phase II/III - beam and bench tests with SFILs (SciFi/Pb Imaging Layers)

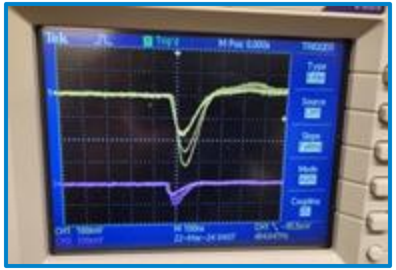
First prototype of custom SiPM readout board

- SensL/onsemi 3x3mm2 SiPM (26V)
- Two-stage amplification
- Initial tests with 90Sr source and scintillating fiber
- Next step: tests with S13360 & S14160 SiPMs with modified board



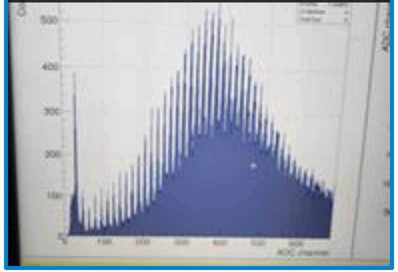
Aiming for 2 SFILs with 2 lightguides and SiPMs per side for Fall 2025 FTBF tests. Available for bench testing in September 2025.

Prototype readout board tests with 90Sr

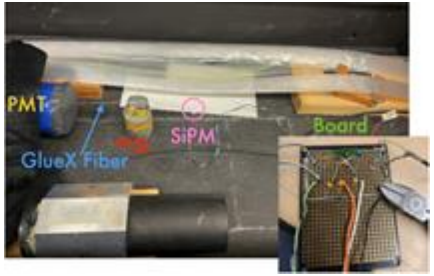


SciFi/Pb Imaging Layer

Digitized signal form SiPM



Test setup for the board



Deliverables:

Commissioned system with SFILs DAQ (with cosmics FY24)
Comparison of light output with GlueX and new generation SiPMs

Milestones Summary

FY24 R&D Milestones

Milestone	Original Timeline*	Status
M1: Integrated setup with Baby BCal and AstroPix chip designed and built at Argonne	t0 + 3 months Q1 FY24*	Done ✅
M2: AstroPix chips prepared at the bench for integrated tests with Baby BCal	t0 + 3 months Q1 FY24*	Done ✅
M3: Data Acquisition (DAQ) for the integrated system of Baby BCal and AstroPix chip designed and tested	t0 + 5 months Q1-Q2 FY24*	Done ✅ • Proof-of-concept tested in the beam
M4: Integrated prototype system tested at the bench with cosmics and/or source	t0 + 6 months Q2 FY24*	Done ✅ • Proof-of-concept tested in the beam
M5: SciFi Imaging Layer (SFIL) delivered by the University of Regina, integrated, and tested at the bench	t0 + 7 months Q2-Q3 FY 24*	In progress 🚧
M6: Integrated system commissioned at the beam test facility with protons	t0 + 9 months Q3 FY24*	Done ✅ • Single AstroPix v3 chip with Baby BCal • Two AstroPix v3 chips daisy-chained
M7: Response to pions tested in the beam environment and e/pi separation benchmarked in the simulations	t0 + 12 months Q3-Q4 FY24*	Done ✅ /In progress 🚧

***Assuming Start of Funds in Q1 FY24 (funds available from March 2024)**

Budget and Project R&D Completion

Budget FY24

Argonne: Cost Subcategory	Amount (including overhead)
Personnel FTEs - Postdoctoral Researcher	$45,000
M&S	$15,900
Sum:	**$60,900**

Postdoc FTEs for design and integration of DAQ, AstroPix tests, and beamtest

Materials to instrument, mount and readout SFILs

- FTE funds spent till end of FY24, M&S $7.3K spent in FY24
- M&S $8.6K: request for NCE to support the beam test with SFILs in FBTF Fall/Winter 25

URegina: Cost Subcategory	Amount (including overhead)
Personnel FTEs - Postdoctoral Researcher	$20,000
Travel to ANL/FNAL	$7,500
M&S	$5,000
Sum:	**$32,500**

Postdoc FTEs for the installation and commissioning of the Baby BCAL and SFILs at FNAL, related bench tests, simulation and data analysis, travel for beamtests at FNAL

Design and fabrication of SiPM boards for SFILs

Expenses as of today:
- PDF $12,318
- M&S $1,718
- Travel $0

Subtotal $14,036

Balance:
- PDF: $3,682
- M&S: $2,282
- Travel: $6,000

Subtotal $11,964

- URegina spending deadline in SoW with JLab (12/2024)
- Remaining funds to support beam test with SFILs

Projection of completion of the final project detector R&D milestones

- From December 2022 Calorimetry Review: Move towards tests of prototypes or more detailed engineering test articles as soon as possible. Since single-component tests were done, interpreted as: “The performance, including response to pions, needs to be benchmarked in a prototype of the hybrid integrated system.” [Summer 2025] – on schedule to complete, but dependent on FBTF beam availability.

- The project is progressing well towards completion, with majority of milestones achieved. We have made significant progress, despite the fact that funds became available only at the end of January 2024 for the University of Regina and in March 2024 for Argonne and in spite of FTBF issues reducing our beam time to 30.5 hours out of a planned 4-6 weeks (~10% of expected beam).

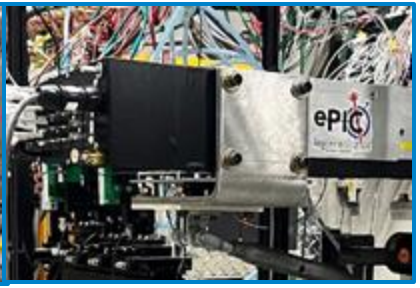
- We **have either met or are on schedule to meet all milestones before the end of FY24** for the **integrated setup with a single AstroPix layer with Baby BCAL**, achieving proof-of-concept DAQ integration between the two setups. Due to the severely limited beam time, the extended setup with SFILs and subsequent steps of the DAQ integration are planned for the beginning of the next fiscal year, without the need for additional R&D funds.

Summary

Successful R&D program in FY24:

- **Baby BCal commissioned** with proton, pion, and electron beams during the June 2024 FBTF test
- Data allows **benchmarking the response to pions and electrons** in simulations
- Proof-of-concept **synchronization of AstroPix and Baby BCAL** was achieved triggering on the analog AstroPix signal in the beam environment
- Building on the extensive AstroPix tests previously conducted at FTBF, we continued to collect **high-quality data with the v3 chip**






Thank you

Backup

EiC Calo Review Recommendations

December 6-7, 2022, Close-Out Report:

Recommendations

✅ ***R5*** *Do full physics simulation as soon as possible and demonstrate the added value of the imaging stage.*

- The system has been extensively simulated in preparation to the Barrel ECal review and following the design optimisation. See, e.g., review performance talk.
  - Based on the simulations it has been demonstrated that integration of imaging layers with SciFi/Pb is crucial in achieving the required e/π separation

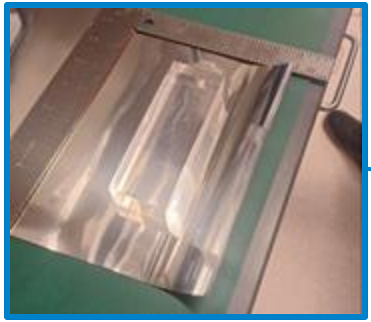
🚧 ***R6*** *Move towards tests of prototypes or more detailed engineering test articles as soon as possible.*

- Single-technology prototype tests have been performed (SciFi/Pb with e+, AstroPix with p) in FY23, See, e.g. Hall D Baby BCAL Tests, AstroPix FNAL FTBT Tests and Irradiations
- The performance, including response to pions, needs to be benchmarked in a prototype of the **hybrid integrated system**.

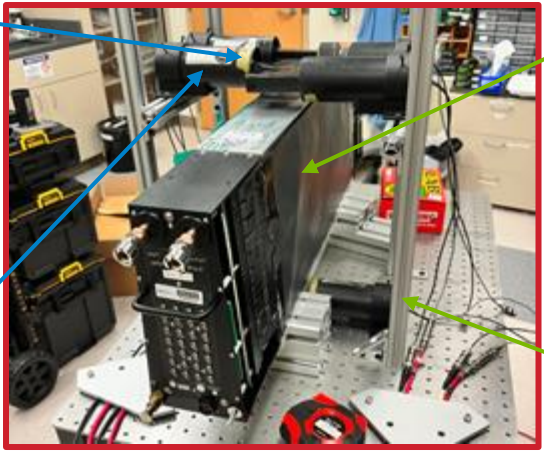
This R&D program is about addressing the R6 Recommendation

Phase I - Preparations

FY24 R&D Phase I - Cosmic Setup



Baby BCal Setup for Cosmics at Argonne



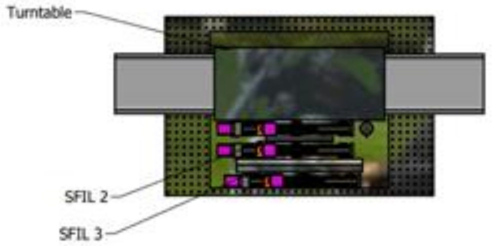
Baby BCal arrives from JLab

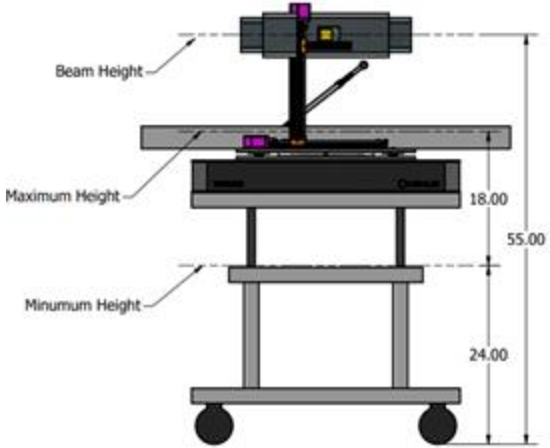
Preparation and testing of trigger paddles

Shipment and assembly of the setup

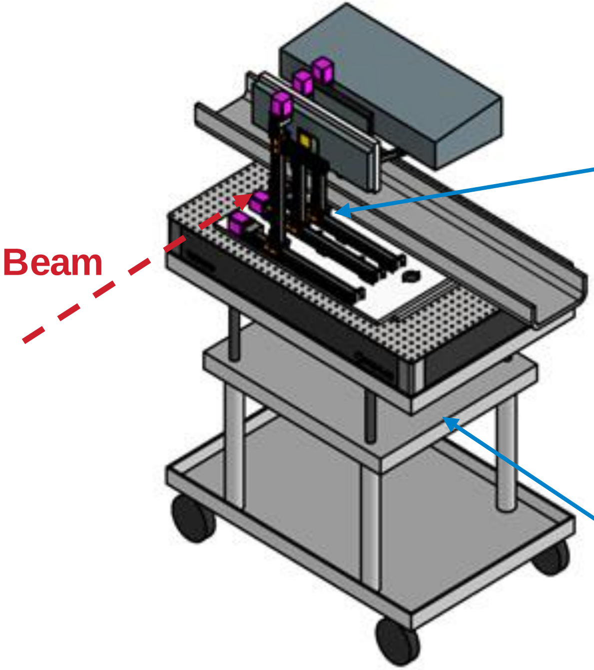
FY24 R&D Phase I - Beam Test Setup

top view





side view




Integrated setup fixture


Baby BCal on a lift table

FY24 R&D Phase I - Baby BCal Cosmic Tests

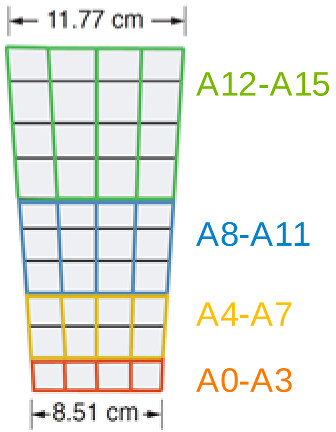
All channels tested on oscilloscope: Upstream (U) and Downstream (D) channels in coincidence

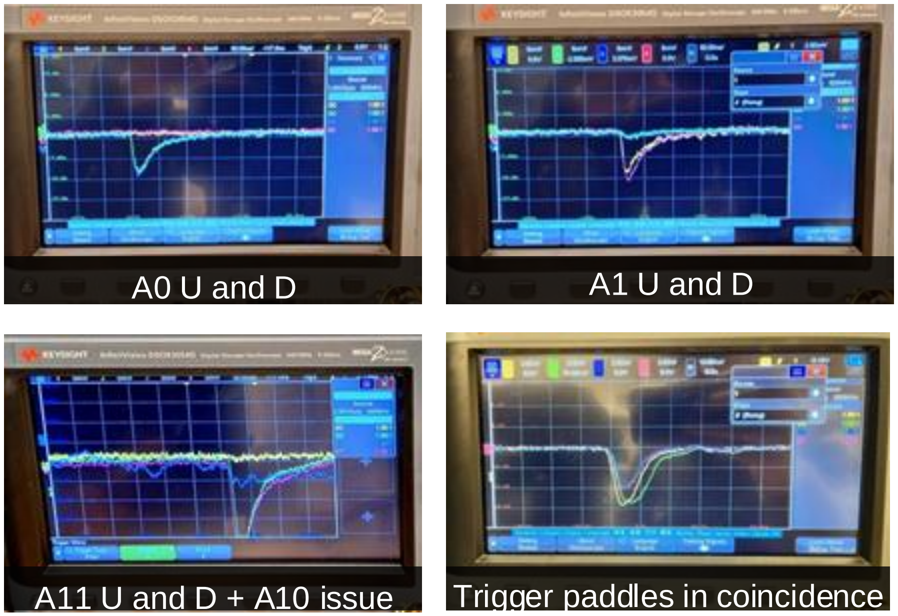
- S12045(X) SiPMs signal summed as shown below
- Only S10 channel has output (known) issue

Baby BCal testing and data analysis: Henry Klest, Jonathan Zarling

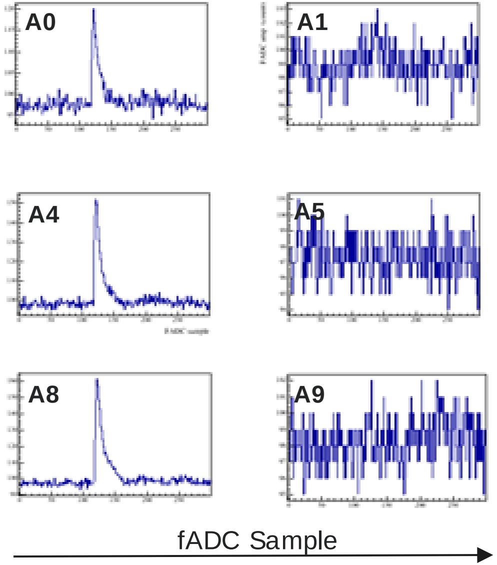
Work in progress on integration within JLab DAQ with fADC

Channel numbering





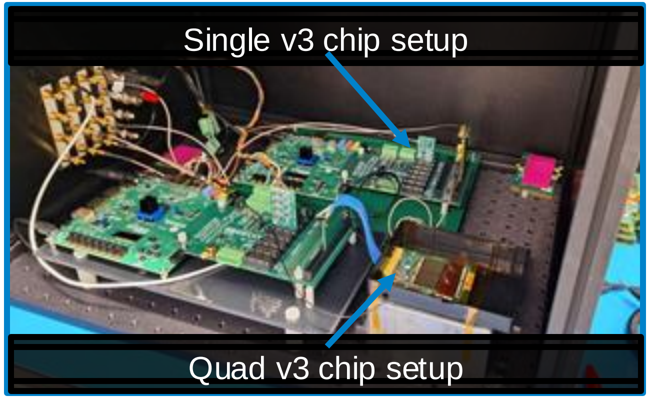
Example fADC amplitudes from a cosmic in Baby BCal



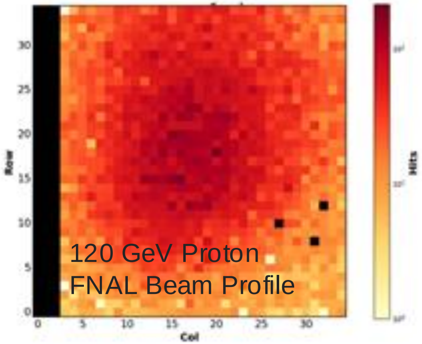
FY24 R&D Phase I - AstroPix Preparations

- AstroPix v3 chips preparation: masking maps and optimal threshold studies
- Calibration with sources in progress and initial tests for the quad chip

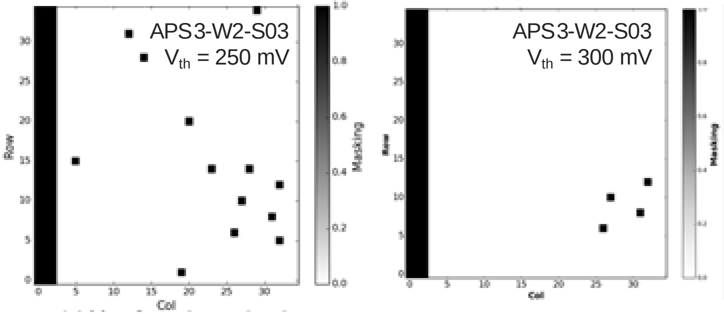
Beam Test FY23 Results: Jihee Kim
Bench Tests FY24: Bobae Kim



Example Beam Profile
FY23 Beam Test



Example Noise Scans



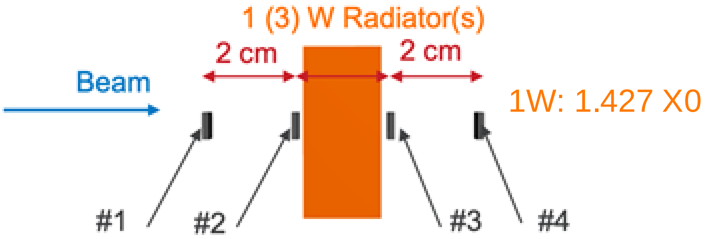
Analog Signal with Injection

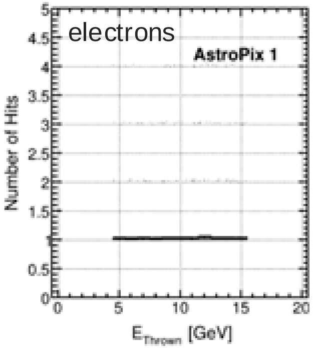
FY24 R&D Phase I - Simulations

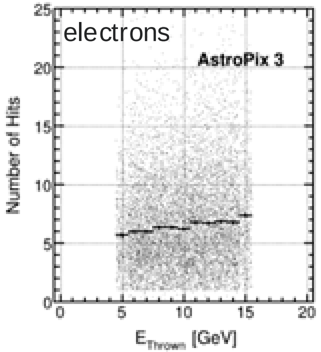
AstroPix Simulations: Jihee Kim
Baby BCal Simulations: Jared Richards

- **Full simulation of AstroPix and SciFi/Pb** matrix implemented for **ePIC**
- Simulation of effective response **including light attenuation and SiPMs responses** implemented
    - Based on measured phe statistics from FY23 Baby BCal beamtest in Hall D
- Current effort on implementing the **Baby BCal and AstroPix Prototype geometry**

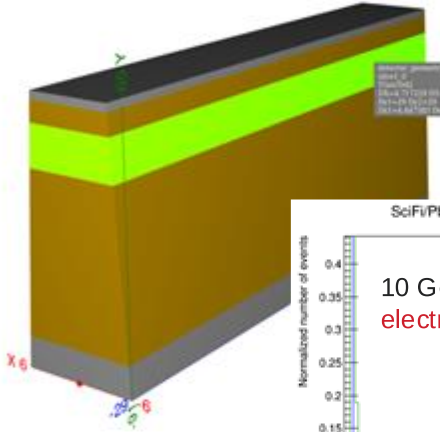
AstroPix telescope simulations w/ and w/o radiator

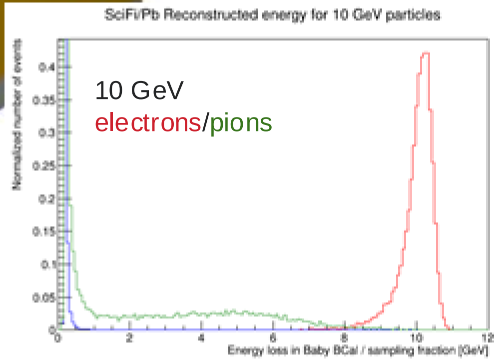






Baby BCal geometry implementation



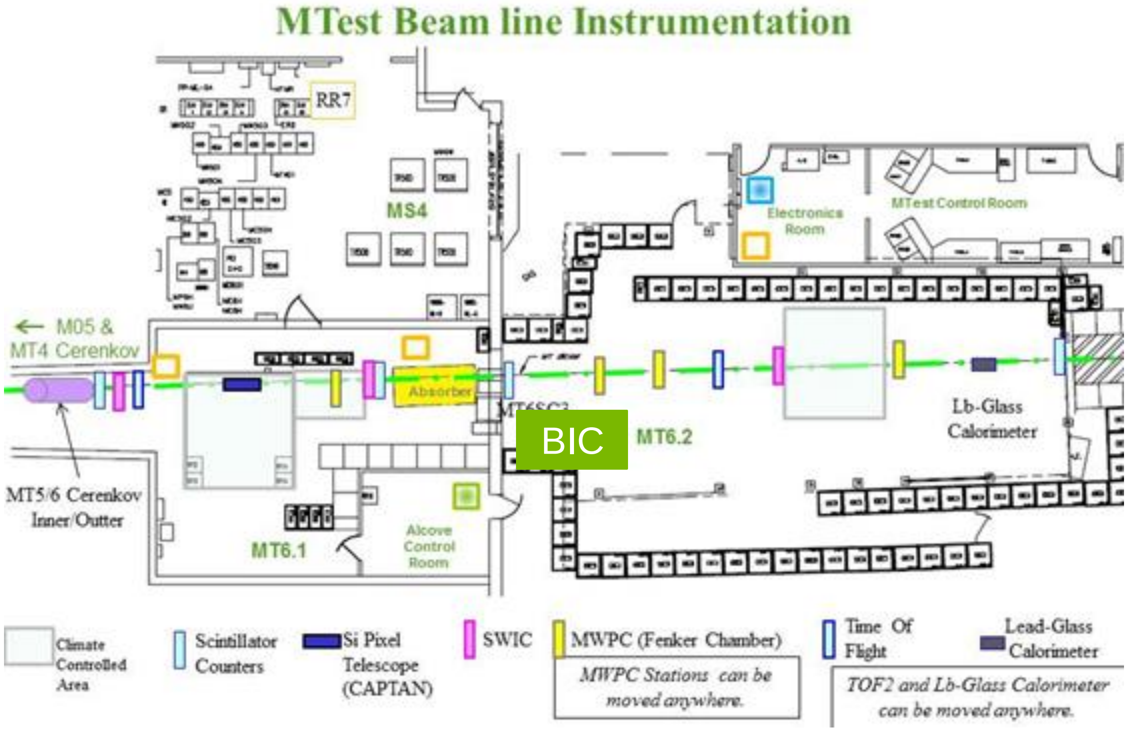


Phase II and III - Beam Test and Data Analysis

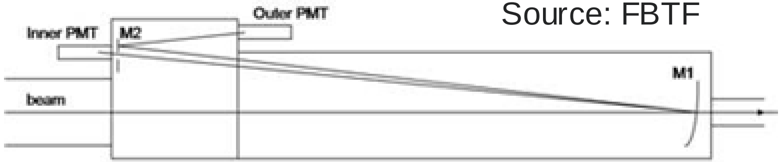
Fermilab Beam Test Facility

- Nominal beam is 120 GeV protons from main injector
- Secondary hadron/electron beam from sending 120 GeV protons on a 30 cm thick aluminum target
- Scintillators provided by FTBF along beamline for trigger
- Two Cherenkovs for PID

Source: FBTF

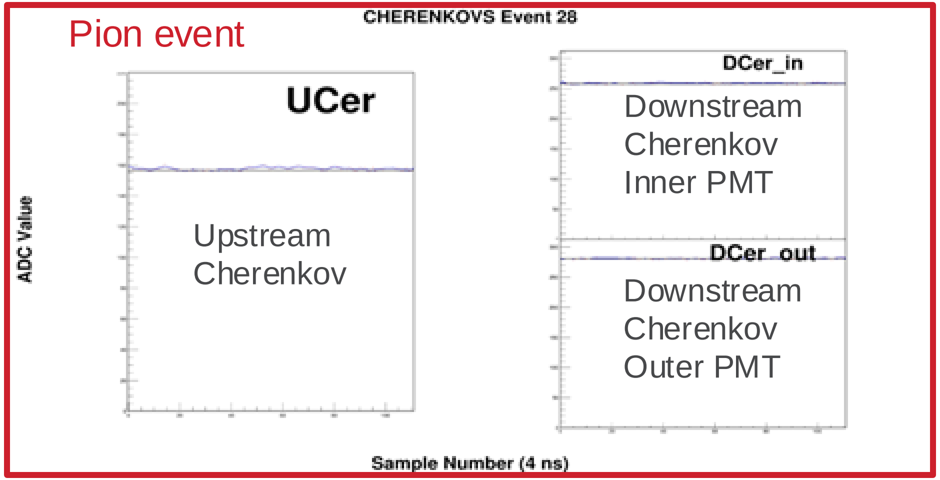


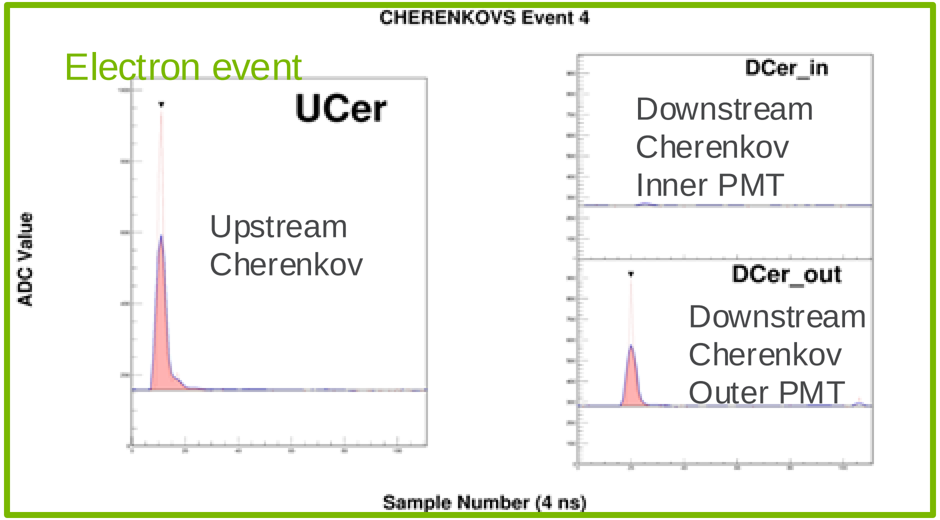
Cherenkov Detectors



Source: FBTF

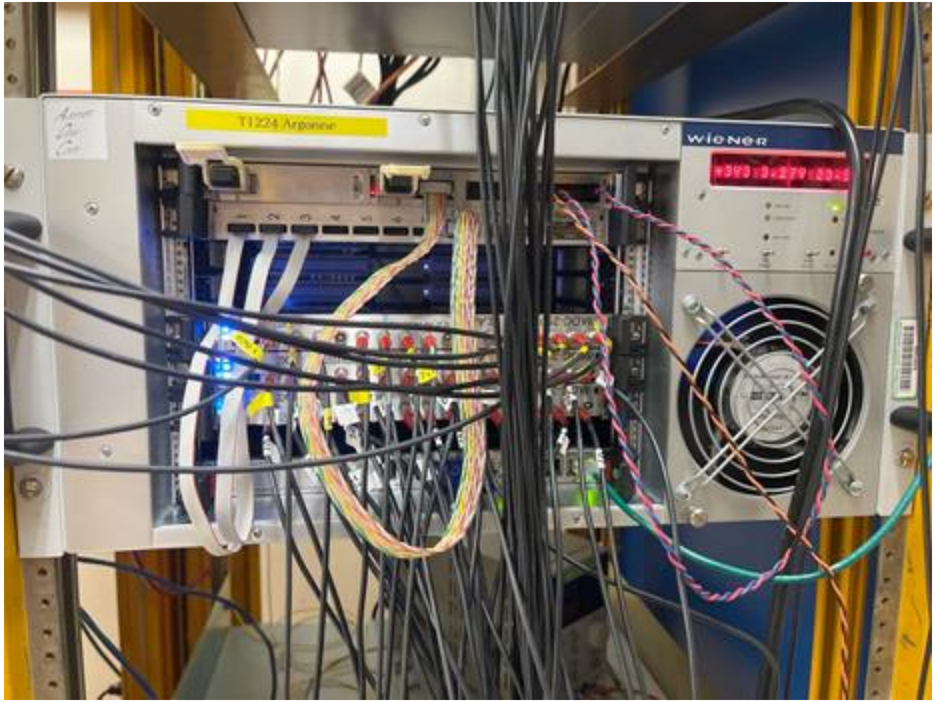
Downstream Cherenkov





DAQ

- Used 3 x 16 channel JLab 250 MHz fADCs in full waveform readout mode
- Sent analog signals from the North and South sets of 16 baby BCal channels into two blades of fADC
- Remaining blade used for FTBF detectors, cosmic ray paddles, AstroPix analog signal



Datasets

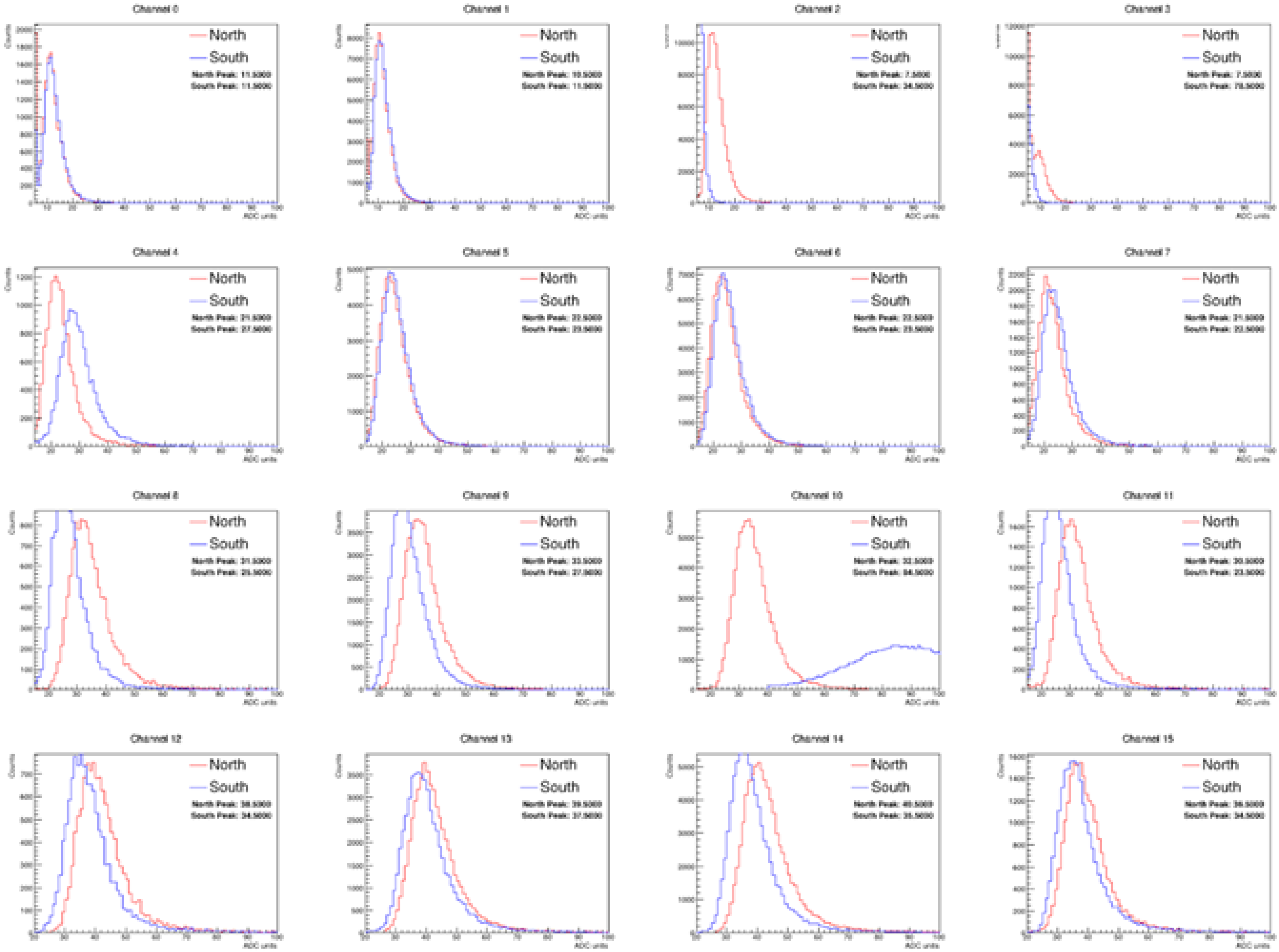
- Due to heat issues at FNAL, only ran for ~30% of our allotted week
- DAQ limited to ~7 kHz due to full waveform readout
- **120 GeV protons**
  - Mostly parasitic overnight
  - Large dataset, few million events
- **10 GeV e/pi**
  - Also large dataset, but mostly taken with FADC jumpers set in the wrong positions, so gain is 2x higher than it should be
  - After the jumper repositioning, took an hour and a half of e/pi at 10 GeV (540K)
- **10 GeV mu/pi**
  - Taken with a lead sheet in the beam to absorb electrons
  - Provides a large MIP calibration dataset
- **Energy scan e/pi**
  - 4 GeV (1.4M), 6 GeV (440K), and 8 GeV (320K)
  - Took a larger 4 GeV because pions are rarer at low energies

Energy Calibration

- Plot pulse heights in ADC units for events which left energy only in a line through the calorimeter

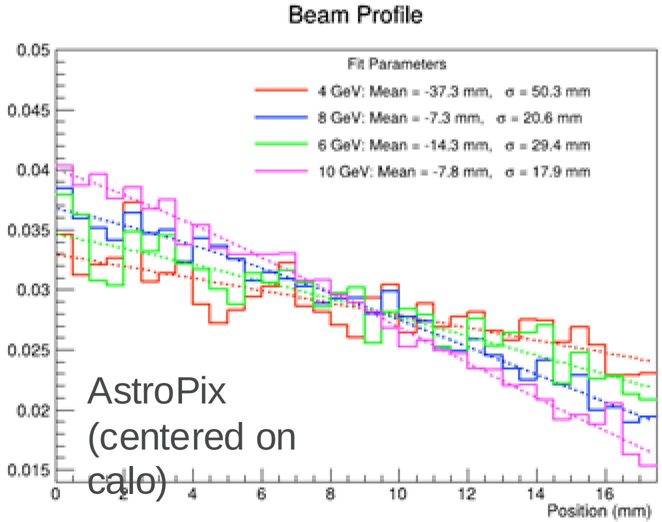
- Use muon/pion run to get clean MIP sample

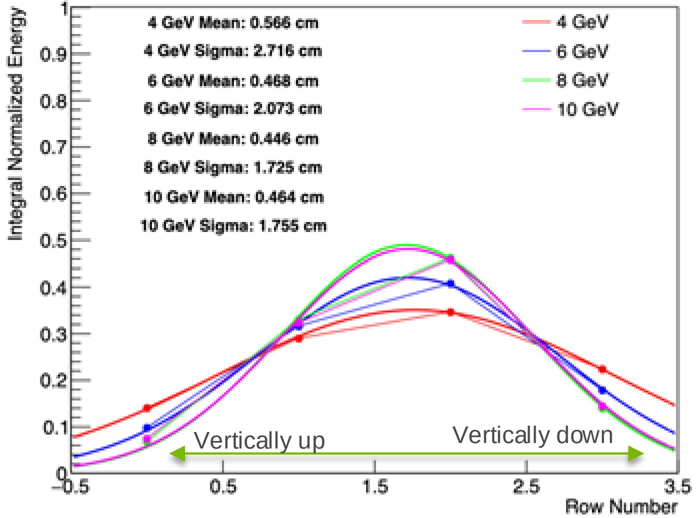
- Nice MIP peak visible in all channels except for South 2&3



Beam Profile

- For Baby BCal analysis: important to know the **profile of the beam in the vertical direction**
  - Determines amount of leakage
- Not much info from FTBF detectors
  - MWPCs were out of gas
  - SWICs showed poor performance for secondary beams
- Used **AstroPix & Baby BCal information**
- Both agree beam widens at lower energy, both agree the beam center is vertically below the center of the calorimeter





Beam Δp

- An important factor in understanding the energy response is the beam momentum spread
- This term enters as a constant term on the energy resolution
- Quoted beam spread is 2.7% at low energies, improving to 2% at 120 GeV
  - However, statement from Joe at FTBF is that: ”every calo group is telling me it looks like the momentum spread is higher than the website indicates it should be.”

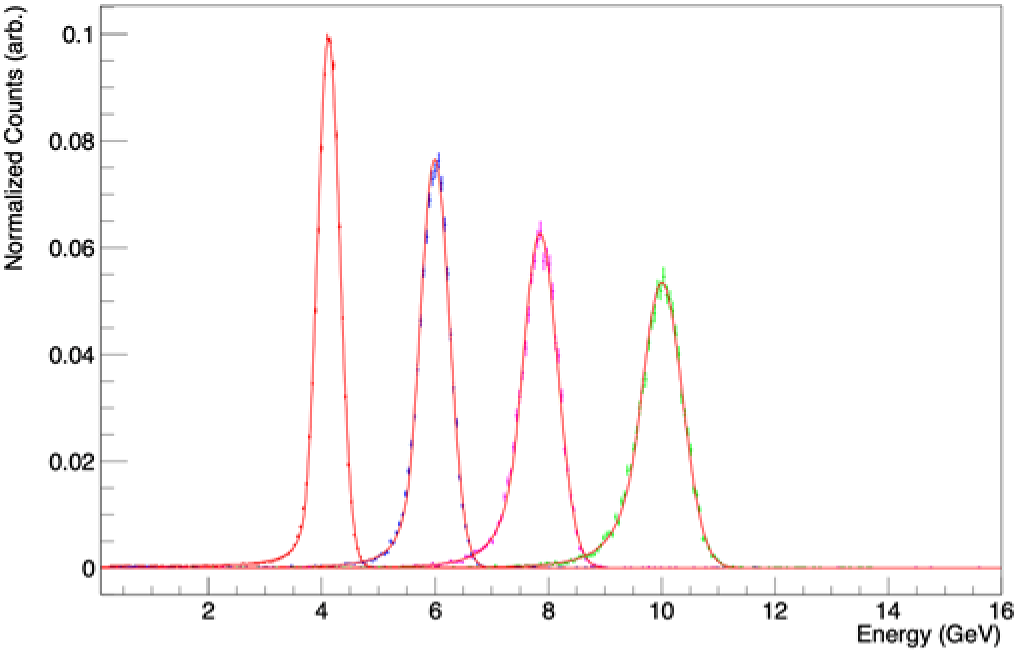
- This number depends on beam tune, which can vary from run to run
- We see the 4 GeV beam is physically wider, which suggests it also has a larger momentum spread

Source: FBTF

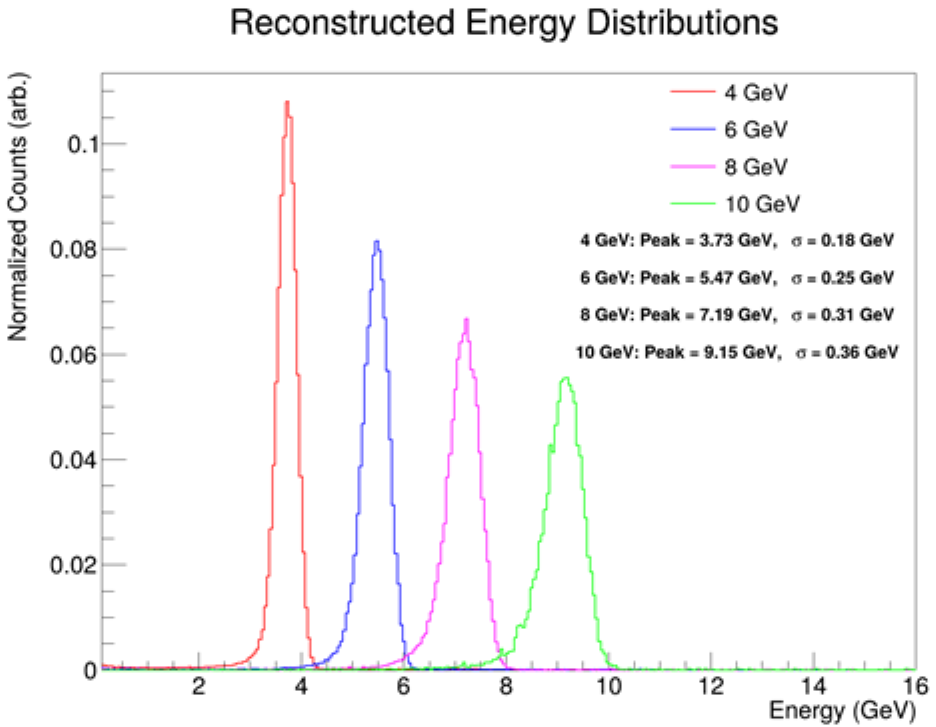
Energy	Mode[1]	Protons	Pions[2]	Highest Intensity[3]	Muons	Kaons	electrons	Spot Size[4]	Δp
10 GeV	LEπ +/-								
8 GeV	LEπ +/-		55%	750,000	98%			12mm	2.3%
6 GeV	LEπ +								
4 GeV	LEπ +/-		31%	400,000	74%			13mm	2.7%
3 GeV	LEπ +/-								2.7%
2 GeV	LEπ +/-		<30%	450,000				13mm	2.7%
1 GeV	LEπ +/-		<30%	69,000					2.7%

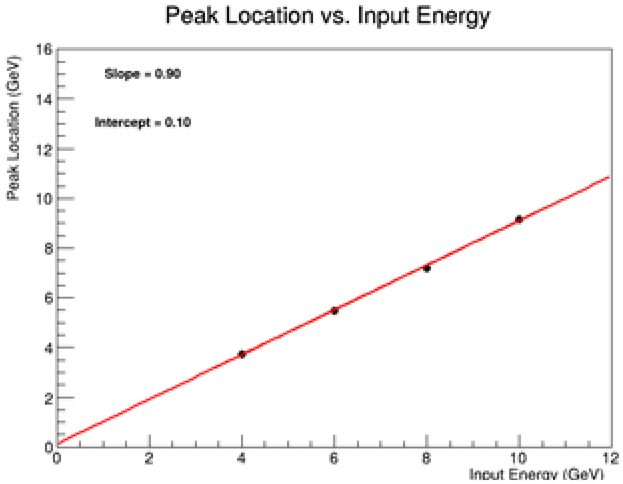
Energy Resolution

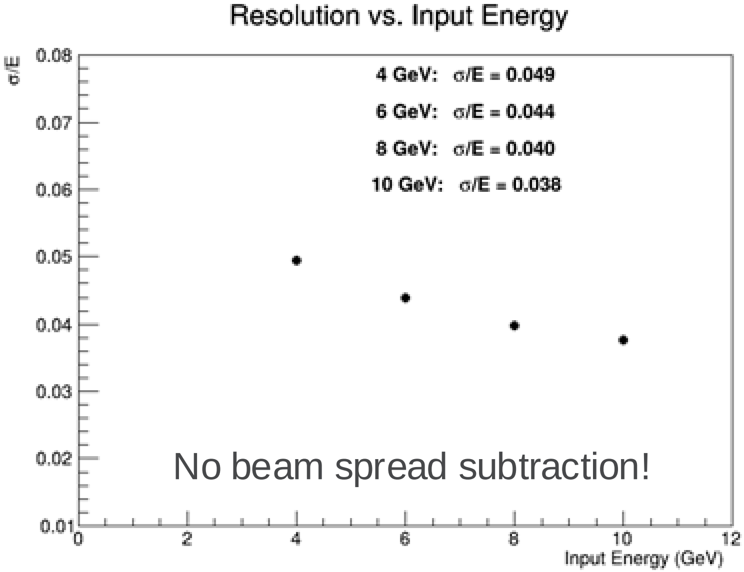
- Now that MIPs provided ADC units to energy conversion factors, can determine EM energy resolution
- Select electrons by selecting events where upstream Cherenkov & downstream Cherenkov outer PMT fired
- Some refinement cuts necessary
  - In particular, cuts to remove spurious signals and to improve containment of showers
- Total energy from geometric sum of N & S reconstructed energies



- Using only MIP calibration
- Containment & data quality cuts applied
- Achieves a reasonable resolution, but reconstructs the peaks about 10% lower than the beam energy we requested

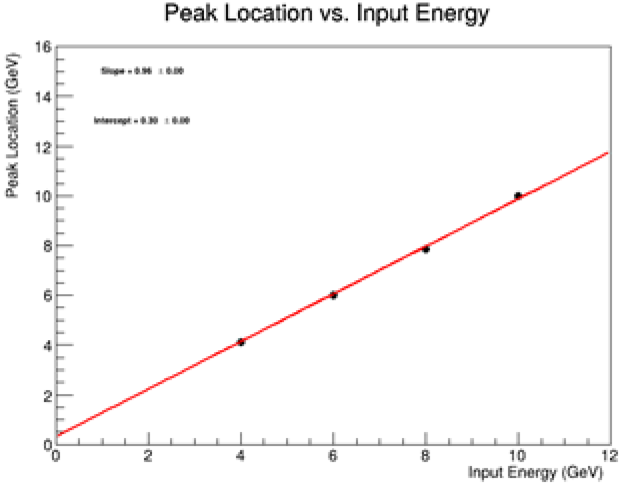


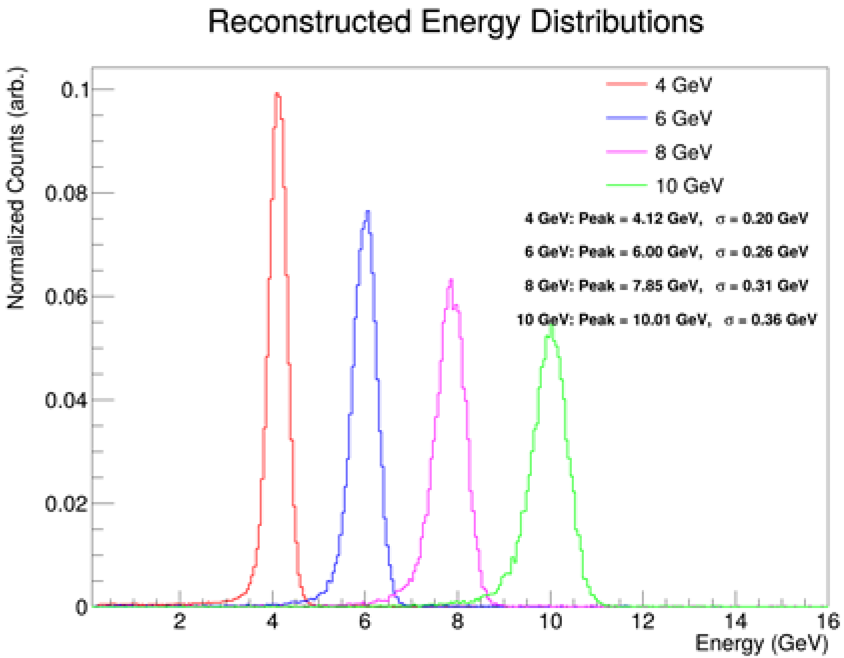


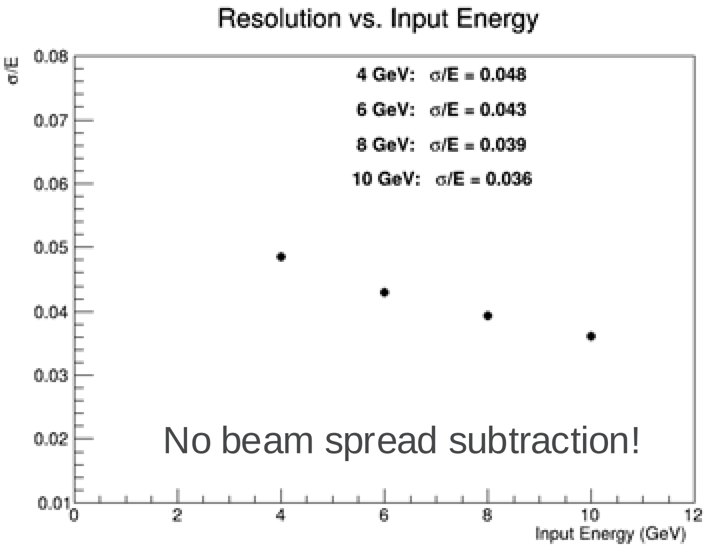


- Now using the MIP calibration as a starting point, use known electron beam energy to calibrate the sum of channels on each side to the “correct” energy
  - Similar to the GlueX technique

- This gets the peak locations ~correct (by construction)







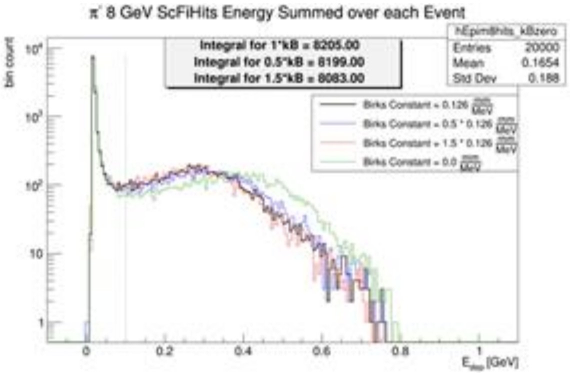
Other

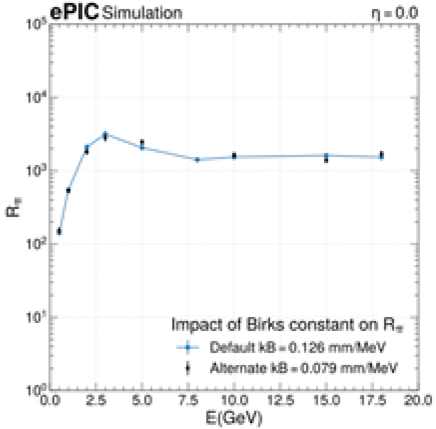
Pb/ScFi

Confidence in the hadron rejection simulation

Birk's constant

- FTFP_BERT physics list and 0.126 mm/MeV Birks constant
- **The response to pions** in Barrel ECal changes slightly while changing the Birks constant ~38%
- The larger the Birks constant the better E/p separation (pion responses are more "squished", see the plot)
- We have shown that **the e/π response leans heavily on imaging layers** (tested with kB = 0.079 mm/MeV with current geometry and stand alone simulations with extreme kB = 0)





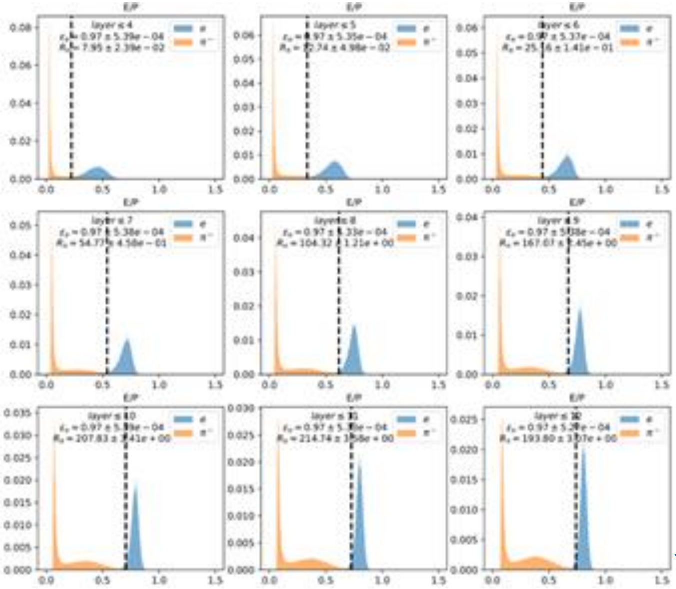
Material	kB [mm/MeV]	Source link
SCSF-78	0.132 ± 0.004	arXiv:2007.08366
BC-408	0.155 ± 0.005	arXiv:2007.08366
Polystyrene fiber, Kuraray SCSF– 81SJ	0.126	arXiv:1106.5649
SCSN-38	0.079	DOI: 10.1109/23.159657

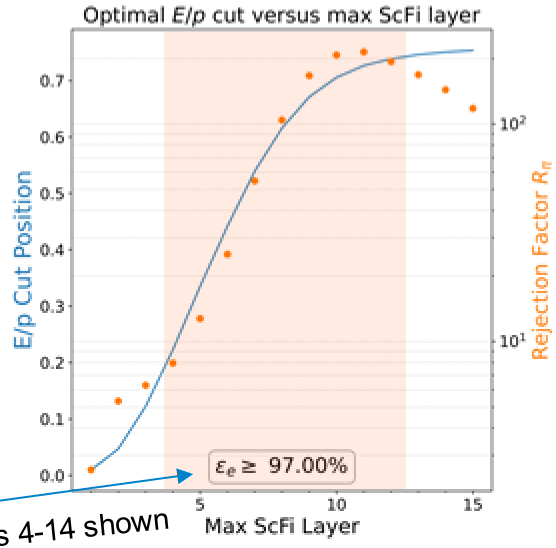
e/π Separation in Barrel ECal - Method

Steps:

1. **Optimized cut on E/p** from different depth of Pb/ScFi layers at very high electron efficiency
2. **Convolutional neural network** utilizing energy and spatial information for shower (see backup slides for details)

Example for 2 GeV e/π



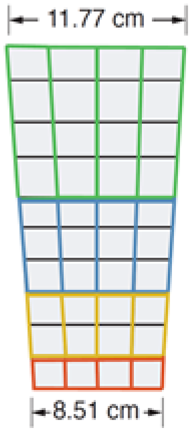


ScFi layers 4-14 shown

SiPM Readout

- **2-side SiPM readout**
- **Lightguides** attached to the sector sides
  - inner surface ~2×2 cm^2
  - output face 1.3×1.3 cm^2
- SiPMs: S14161-6050-04 array (4x4 array of 3×3 mm^2, 50×50μm^2 pixels)
- 12 layers x 5 cells x 2 sides x 48 sectors = 5760 channels

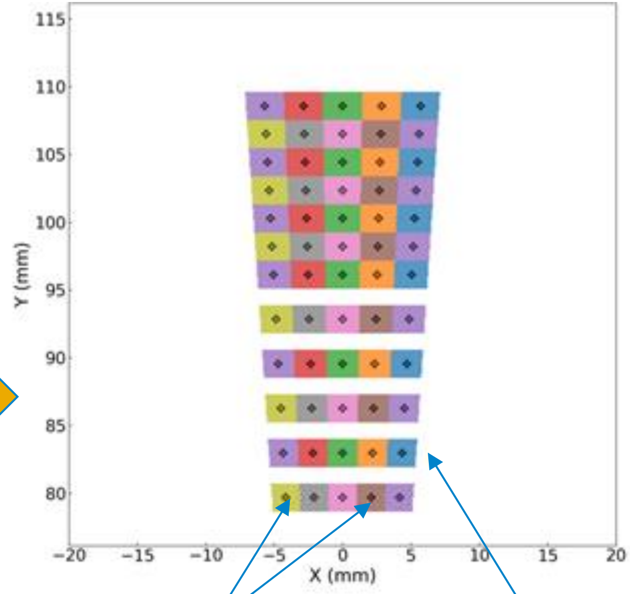
GlueX
1/48th of the barrel
end view



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

16 FADC per side
12 TDC per side

ePIC Sector End View
(x-y plane view)



Readout **Cell**
Layer = 5 cells

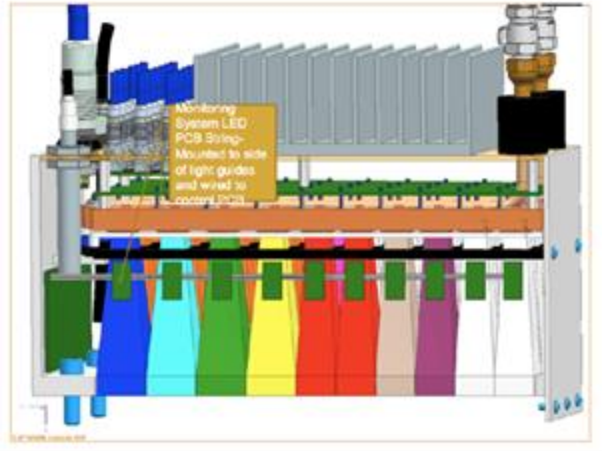
The area 1 light guide is attached

Pb/Sci **Layer**

1 sector = 12 layers
1 layer = 17 rows of fiber

GlueX BCAL Readout Design

- Pb/ScFi readout based on the GlueX BCAL readout
- Footprint excluding external connectors of GlueX BCAL readout box about 14cm
  - Dominated by light guides (~ 8 cm)
- We will likely be able to shrink this somewhat to < 12 cm
  - Space pressure in the forward direction, where space is limited.



CAD drawing of GlueX readout box

Baby BCAL prototype readout box