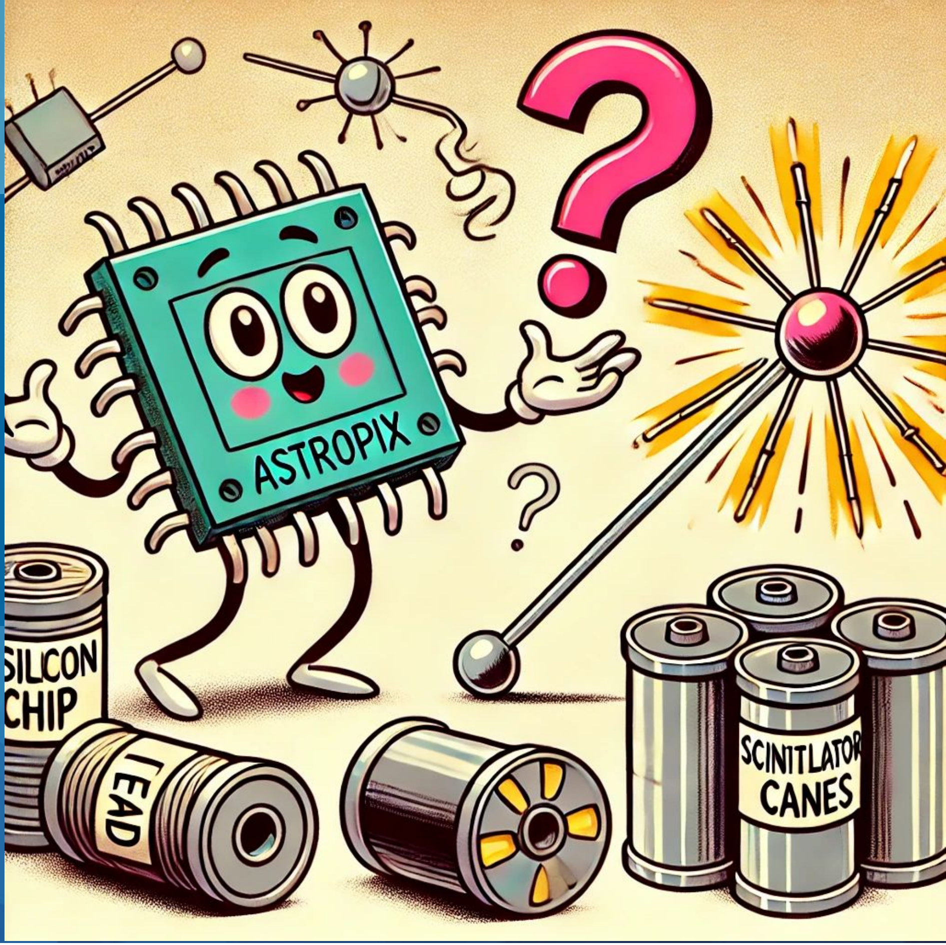
ePIC TIC Meeting, October 7, 2024

The ePIC Barrel Imaging Calorimeter

PDR 2 Summary

Sylvester Joosten
Argonne National Laboratory
on behalf of the BIC DSC



Purpose and Focus

Charge

The scope of this review includes all aspects of particle detection using the Barrel Imaging electromagnetic Calorimeter (BIC) of the ePIC detector at EIC, which combines two technologies, light-collecting calorimetry based on SciFi embedded in Pb and imaging calorimetry based on monolithic silicon sensors AstroPix. The review includes design and fabrication scenarios and their cost-effectiveness, optimization of physics performance, construction schedule, early considerations for safety and quality assurance, front-end electronics and interface to the data acquisition system, commissioning and calibration procedures, considerations for materials and labor, operational reliability and longevity, and any other considerations that may influence the construction and operation of the Calorimeter.

You are asked to address the following questions:

1. Are the technical performance requirements appropriately defined and complete for this stage of the project?
2. Are the plans for achieving detector performance and construction sufficiently developed and documented for the present phase of the project?
3. Are the current designs and plans for detector and electronics readout likely to achieve the performance requirements with a low risk of cost increases, schedule delays, and technical problems?
4. Are the calorimeter fabrication and assembly plans consistent with the overall project and detector schedule?
5. Are the plans for detector integration in the EIC detector appropriately developed for the present phase of the project?
6. Have ES&H and QA considerations been adequately incorporated into the designs at their present stage?

Purpose: Evaluate the status and readiness of the BIC design

Focus: Technical performance requirements, plans for achieving performance, detector and electronics readiness, assembly plans, integration, and ES&H considerations.

Schedule

09:30 → 09:50 **Welcome and Introduction**

Speakers: Dr E. C. Aschenauer (BNL), Rolf Ent (Jefferson Lab)

Barrel.ECal.FDR_v2....

10:00 → 10:30 **BIC Overview (includes eRD115 R&D progress)**

Speaker: Sylvester Joosten (Argonne National Laboratory)

2024-09-19_01. BIC ...

10:40 → 11:00 **Simulation framework (with focus on BIC) and BIC optimization**

Speaker: Maria Zurek (Argonne National Laboratory)

2024-09-19_02. Sim... 2024-09-19_02. Sim...

11:10 → 11:30 **Pb/SciFi progress to preliminary design**

Speaker: Zisis Papandreou (University of Regina)

2024-09-19_03. Pb_...

11:35 → 11:45 **Pb/ScFi FEE**

Speaker: Norbert Novitzky (ORNL)

20240914BICRevie...

13:00 → 13:15 **AstroPix Sensor**

Speaker: Regina Caputo (NASA GSFC)

2024-09-19_05. Astr...

13:20 → 13:40 **AstroPix Module and Readout**

Speaker: Manoj Bhanudas Jadhav (Argonne National Laboratory)

2024-09-19_06. Astr...

13:50 → 14:05 **Imaging Layer Production Strategy**

Speaker: Anthony Affolder (University of California Santa Cruz)

2024-09-19_07. FY2...

14:10 → 14:30 **Sector Mechanical Design and Assembly**

Speaker: Kevin Bailey (member@anl.gov)

2024-09-19_08. Me...

14:40 → 14:55 **BIC Integration and Installation**

Speaker: Roland Wimmer

2024-09-19_FinalDr...

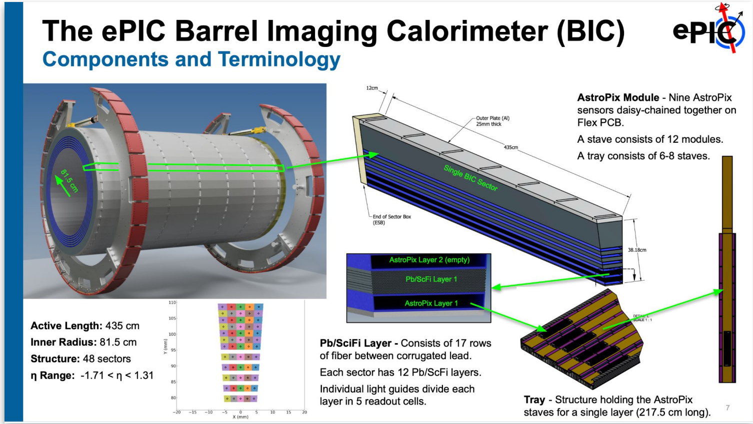
BIC Overview (includes eRD115 R&D progress)

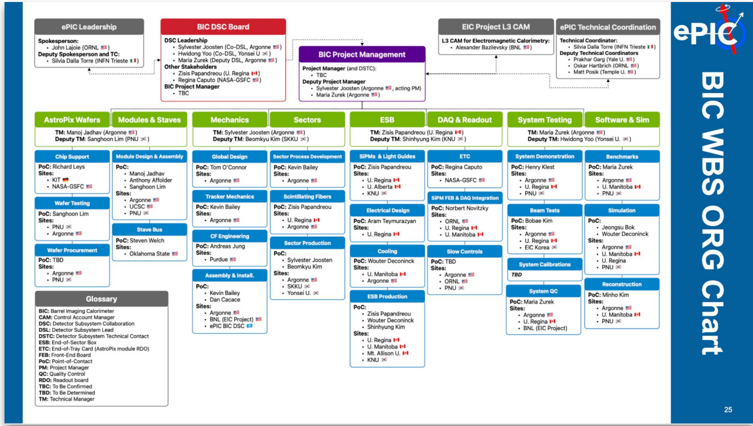
Sylvester Joosten (Argonne)

- Beam tests (FY23-24 Hall D & FTBF, and FY25 plans):
  - Measured Pb/ScFi high-energy response, studied SiPM waveforms, studied response to hadronic showers
  - AstroPix tests for calorimetry, irradiation tests, proof-of-concept integration testing with Pb/ScFi
  - Successful R&D program concluding by Spring 2025, with early beam tests showing promising results
- Other topics:
  - In-kind R&D and Design in Canada and South-Korea, Cooling Strategy, Performance and Calibration Strategy, Collaboration and Organization, Schedule, QC and ESH

Bottom-lines:

- Design evolving rapidly after receiving PED funding in the Summer of FY24, with rapid progress toward key milestones and on track for a May 2025 PDR
- Long-lead procurement items moving forward
- Major progress towards large in-kind contributions from our South-Korean and Canadian collaborators



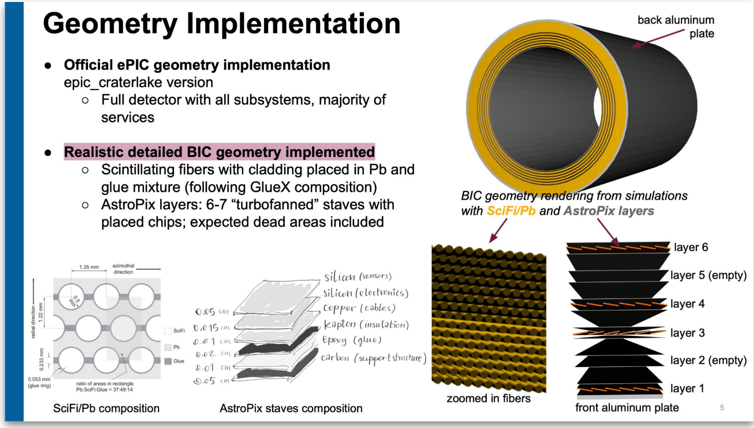


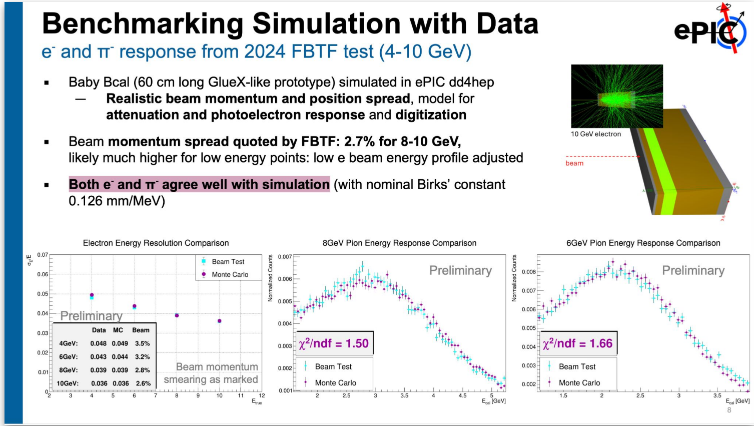
Simulation framework (with focus on BIC) and BIC optimization

Maria Żurek (Argonne)

- **Framework & Implementation:** Realistic BIC geometry in ePIC framework, including Pb/ScFi and AstroPix layers with detailed digitization
- **Validation:** Simulations benchmarked against test beam data from FTBF (FY24) & Hall D (FY23)
- **Performance Achievements:** Meet or exceed all performance requirements, showed details on energy resolution, effective MIP response, and energy tail
- **AstroPix Layer Optimization:** 4(+2) imaging layer configuration, demonstrated angular and position resolution
- **Particle ID**: CNN-based e/π separation with >10^3 rejection at 95% efficiency; initial γ/π^0 studies show 82% rejection
- **Next Steps:** Refine simulation with realistic electronics; further optimize configurations; fold in results from FY25 beam tests

Bottom Line: Simulations confirm the BIC meets key performance targets, supporting readiness for full-scale testing





Pb/SciFi progress to preliminary design

Zisis Papandreou (U. Regina)

- **Design & Concept:** Build on BCAL experience
- **LLP and Fiber Testing:** Long-lead procurement (LLP) for fibers underway, establishing test procedure for ScFi testing for LLP; SiPM requirements well-established
- **Light Guides (LGs):** Detailed simulations of light guide designs and light collection efficiency to optimize performance, improved design with 5cm LG, demonstrate need for optical cookies. Ready for test measurements.
- **ESB Development:** Progress on End-of-Sector Box (ESB) design for integrating readout and cooling; early prototype assembly
- **QC and Production:** Adapted BCAL QC methods for fibers, light guides, and electronics; prepared for large-scale production at Argonne

Bottom Line: Pb/ScFi design is advanced with strong QC processes, LLP progress, ESB development, and readiness for production, leveraging GlueX BCAL experience.

Photodiode Station

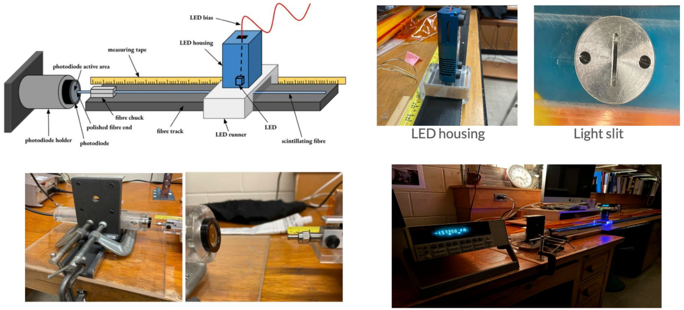


Fig. 5. Photodiode is levelled and secured to the table using clamps.

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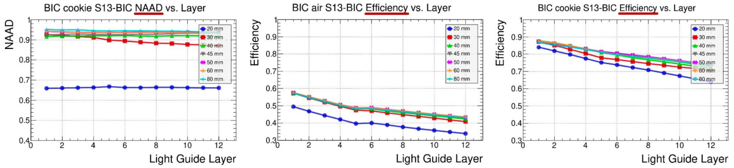
NAAD and Efficiencies vs. Layer



Conclusions

- 50 – 70% more efficient with 1 mm Si cookie than with 0.5 mm air gap
- Efficiency begins to drop off at 30 – 35 mm length
- Spatial correlations between input and detected photons are strong below 40 mm length
- 40 – 50 mm seems reasonable in terms of efficiency and light mixing
- Ongoing studies: alternate light guide shapes, smaller light guides with 6 mm x 6 mm SiPMs, alternate SiPM form factors, etc.

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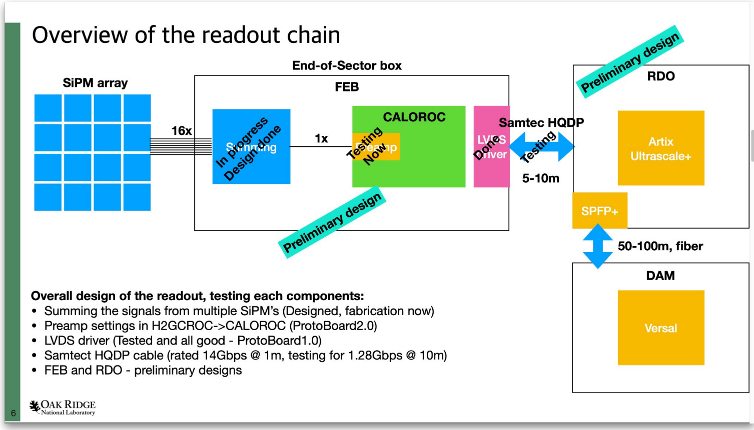
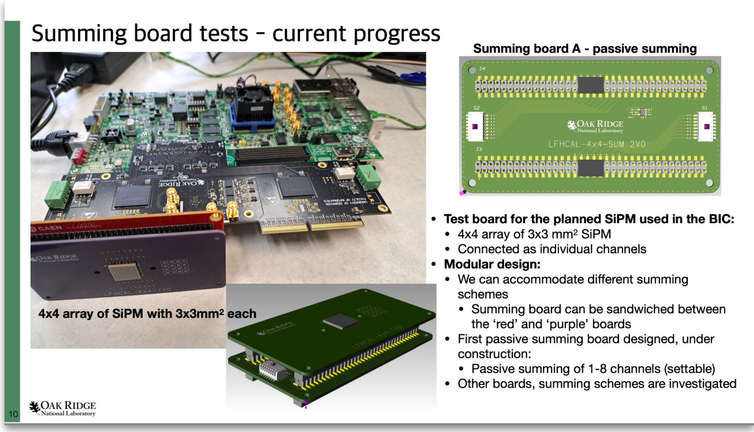
Pb/ScFi FEE

Norbert Novitzky (ORNL)

- **ASIC Choice:** Using modified H2GCROC chip for initial tests; developing CALOROC ASIC with streaming readout and self-triggering for final design
- **Readout Architecture:** Data path includes 2x1.28 Gbps links with zero suppression; adaptable design using FPGA-based RDO
- **Early Testing:** Prototype boards tested for ADC performance and summing circuits; early results from cosmic tests with H2GCROC
- **Beam Test Plans:** FEE will be integrated into upcoming beam tests for BIC prototypes to validate readout performance in realistic conditions.
- **Development Timeline:** CALOROC planned to be ready for production by end of 2024, with first full-scale readout tests expected in 2025

Bottom Line: Strong progress on FEE design with scalable readout strategy and early test results guiding final design and integration



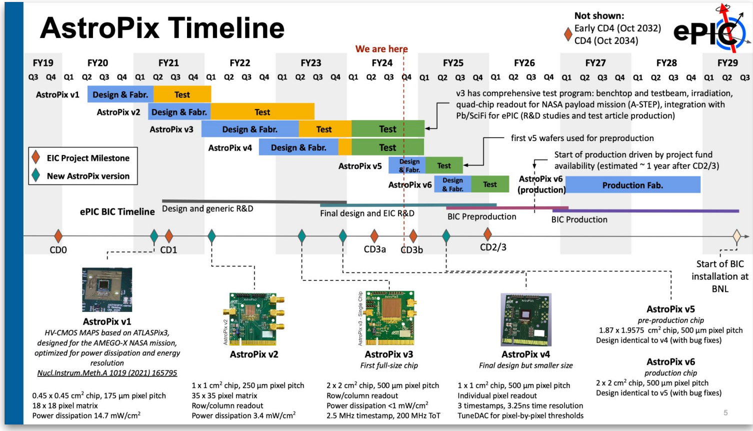


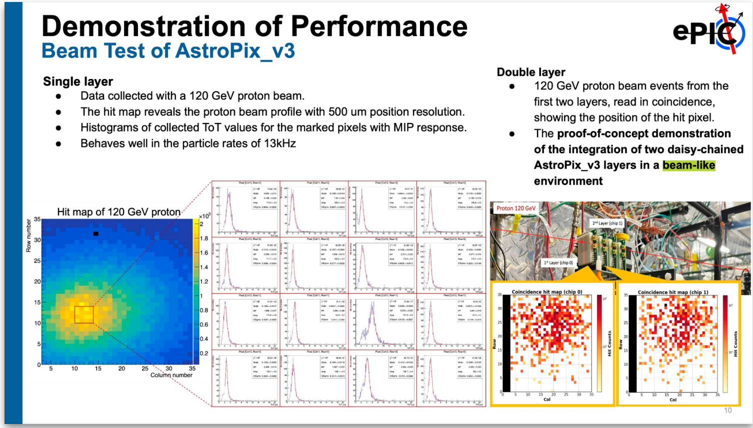
AstroPix Sensor

Regina Caputo (NASA GSFC)

- **Overview:** AstroPix sensors are monolithic silicon CMOS sensors initially developed for NASA's AMEGO-X mission, adapted for the BIC
- **Key Specs:** 500 μm pixel pitch, 25-700 keV dynamic range, <1.5 mW/cm² power consumption, and 3.125 ns time resolution in AstroPix_v5
- **Performance Tests:** Bench tests with v3 promising; radiation tests validate stability under irradiation
- **Beam Test Results:** 120 GeV proton beam tests demonstrate effective position resolution and MIP response
- **Foundry Transition:** Moved production from TSI to AMS; AstroPix_v5 is set for fabrication at AMS in early 2025

Bottom Line: AstroPix development is on track with promising performance and flexibility, ensuring adaptability to the BIC needs through a focused development program



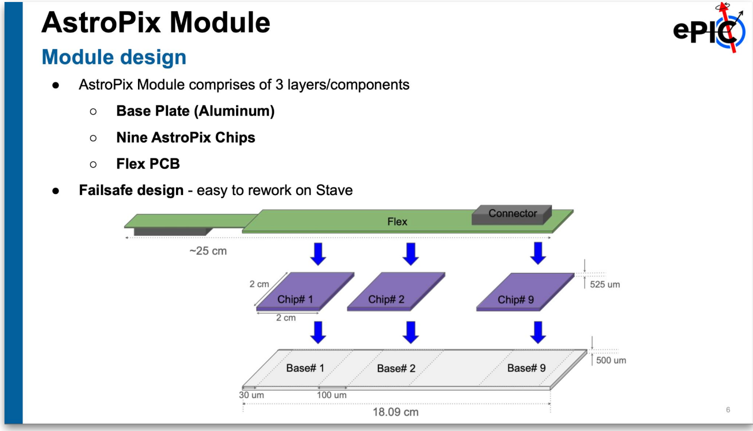


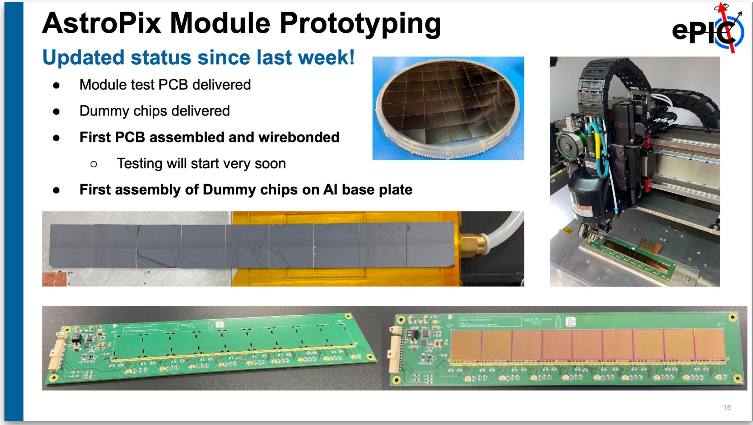
AstroPix Module and End-of-Tray Card (ETC)

Manoj Jadhav (Argonne)

- **AstroPix Module Design:** Detailed conceptual design with three main components: aluminum base plate, nine AstroPix chips, and Flex PCB
- **Scalability:** Single-flavor module design simplifies production (~31,000 modules) and assembly processes
- **Electrical Integration:** Modules daisy-chained into staves; controlled via ETC using SPI protocol for communication
- **Test Articles:** Test PCB delivered; initial assembly with dummy chips underway; integration testing with ETC planned
- **Mechanical Loading:** Automated pick-and-place for precise chip alignment; ongoing discussions on locking mechanisms

Bottom Line: Progressing toward scalable and integrated module design, with a focus on reliability and ease of assembly. Upcoming tests will validate electrical performance and assembly procedures



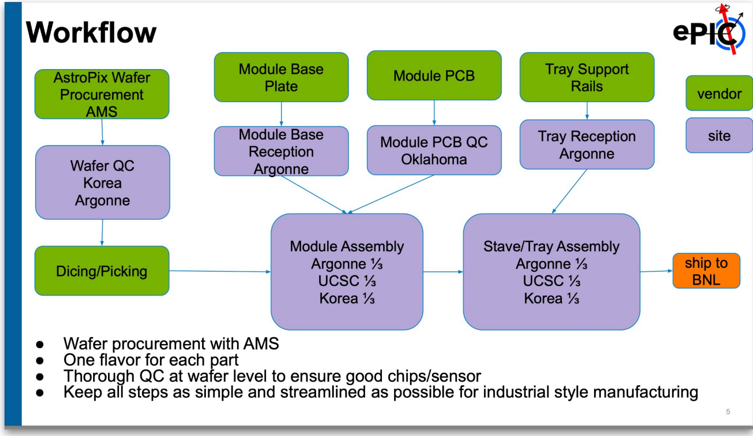


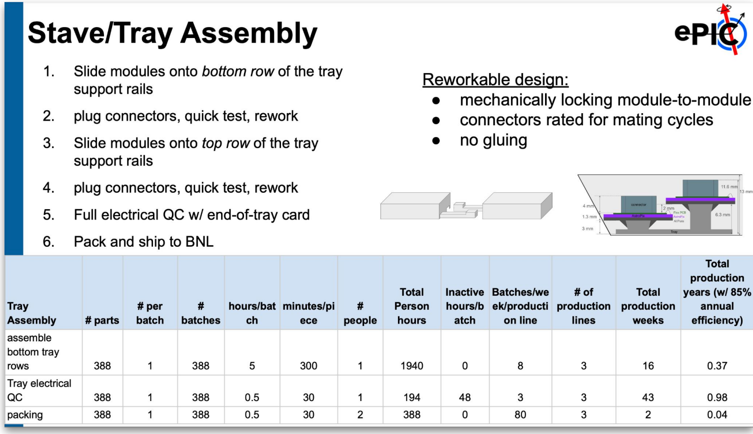
Imaging Layer Production Strategy

Anthony Affolder (UCSC)

- **Production Scale:** Over 30,000 modules and ~6000 wafers needed for BIC; industrial-scale production approach
- **Streamlined Processes:** Single flavor of module, 2 tray flavors (mirror images); automated wafer QC, dicing, and module assembly
- **Three Production Sites:** Argonne, UCSC, and PNU (Korea) for module and tray assembly, ensuring redundancy and consistent quality
- **Reworkable Design:** Mechanically locking modules enable easy maintenance and upgrades
- **QC and ES&H:** Comprehensive QC steps at each stage, with strict safety protocols for handling, testing, and assembly
- **Production Timeline:** Estimated 2 years for full production once parts are in hand, leveraging automation for efficiency

Bottom Line: Focused on scalability and simplicity, the strategy ensures reliable production with automated processes, reworkability, and multi-site manufacturing





Stave/Tray Assembly

1. Slide modules onto *bottom row* of the tray support rails
2. plug connectors, quick test, rework
3. Slide modules onto *top row* of the tray support rails
4. plug connectors, quick test, rework
5. Full electrical QC w/ end-of-tray card
6. Pack and ship to BNL

Reworkable design:

- mechanically locking module-to-module
- connectors rated for mating cycles
- no gluing

Tray Assembly	# parts	# per batch	# batches	hours/batch	minutes/piece	# people	Total Person hours	Inactive hours/batch	Batches/week/production line	# of production lines	Total production weeks	Total production years (w/ 85% annual efficiency)
assemble bottom tray rows	388	1	388	5	300	1	1940	0	8	3	16	0.37
Tray electrical QC	388	1	388	0.5	30	1	194	48	3	3	43	0.98
packing	388	1	388	0.5	30	2	388	0	80	3	2	0.04

Sector Mechanical Design and Assembly

Kevin Bailey (Argonne)

Design Progress:

- Defined global and internal engineering envelopes for the BIC
- Progress on AstroPix tray design, carbon fiber frame integration, and ESB development
- Close collaboration with EIC engineers for global FEA and integration

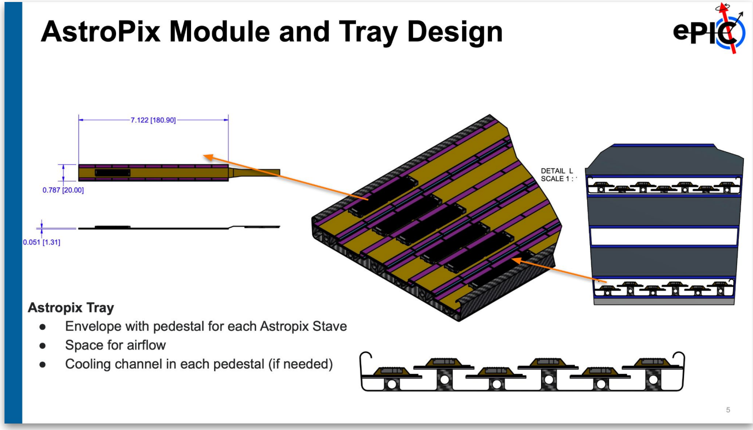
Sector Production Setup:

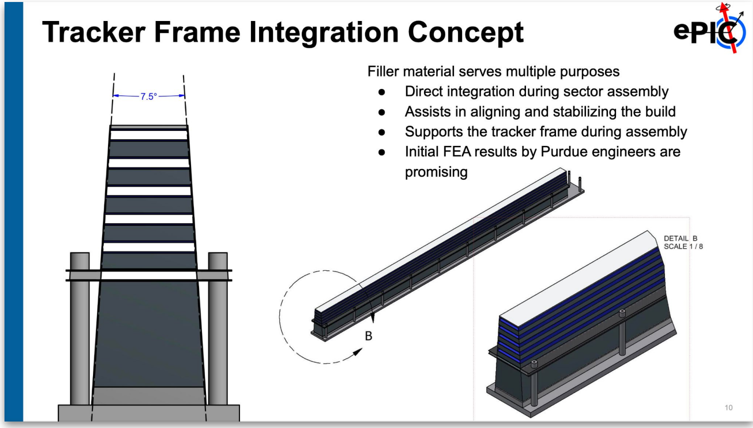
- Ongoing assembly of production tools for PED program
- Production and QC modeled on the proven GlueX approach

Environment, Health, & Safety (EH&S):

- Comprehensive EH&S plan with targeted safety training and task-specific controls
- Current focus on safe handling of lead, epoxy, and press operations, meeting Argonne and EIC safety standards

Bottom Line: Design and production development on schedule, integrating safety from the beginning. On-track for a May 2025 PDR.





Closeout: Committee Response to Charge (prelim.)

1. Are the technical performance requirements appropriately defined and complete for this stage of the project?

- **Response:** SCIFI: Project design is considered very advanced, and technical specifications have been met in several parts. There are some relevant items (e.g. noise pedestal position with respect to MIP, that is a critical scope for the calibration of the calorimeter) that have to be confirmed by a full prototype test with final electronics and cabling. The group can rely heavily on the past experience with GLUEX.
- Imaging Layers: the AstroPix chip (designed for space applications) was chosen to equip these layers. The chip design is well advanced, and a production size prototype is ready for the characterization. The performance figures of the present version of the chip are already very close to the specifications for the BIC imaging layers, even though a further optimization of the timing performance is needed.

<My Summary>:

- **ScFi:** Design advanced; specs met; critical MIP calibration needs full prototype confirmation
- **Imaging Layers:** AstroPix very close to required performance; further timing optimization needed

Closeout: Committee Response to Charge (prelim.)

2. Are the plans for achieving detector performance and construction sufficiently developed and documented for the present phase of the project?

Response:

- SCIFI: The review showed a quite complete level of documentation about tests and performance achieved, in small scale prototypes and in test beams, and in overall project schedule management.
- Imaging Layers: The design of modules, staves and trays is ongoing. The review showed a reasonable level of development of the detection system for the present phase of the project; better understanding of the different elements is expected by the beginning of 2025, when first prototypes will be available.

<My Summary>:

- **ScFi:** Good documentation on tests and performance, in small scale prototypes and test beams, and project schedule management
- **Imaging Layers:** Design of modules, staves, trays ongoing; reasonable level of development for current phase of the project; better understanding expected with test articles in FY25

Closeout: Committee Response to Charge (prelim.)

3. Are the current designs and plans for detector and electronics readout likely to achieve the performance requirements with a low risk of cost increases, schedule delays, and technical problems?

Response:

- SCIFI: Testing the final assembly layout of signal processing is considered mandatory to obtain real figures for overall performance and to reduce to a minimum the risks of problems (delays, non-conformity, etc…). This activity, if not yet present, should be adequately integrated in the current schedule, with adequate timing allocated.
- Imaging Layers: similar considerations apply to Imaging layers. In addition, redundancy of readout and power interconnections should be carefully addressed.

<My Summary>:

- **ScFi:** Testing of final assembly layout needed to reduce risk of delays
- **Imaging Layers:** Same, also address redundancy of readout and power interconnections

Closeout: Committee Response to Charge (prelim.)

4. Are the calorimeter fabrication and assembly plans consistent with the overall project and detector schedule?

Response:

- SCIFI: A detailed schedule of calorimeter fabrication has been presented, and it is consistent with the rest of the project. QA/QC procedures for fiber quality and construction dimensional checks are relevant and should be reinforced to maintain excellent performance of the modules throughout the construction.
- Imaging Layers: the review showed that the collaboration has a detailed plan for the construction, including person power and timeline figures. Detailed QA procedures for the selection of production grade detection elements should be envisaged and quality levels determined once prototypes of each element are available

<My Summary>:

- **ScFi:** Detailed schedule aligns with project; reinforce QA/QC during production
- **Imaging Layers:** Comprehensive construction plans; QA for production elements to be defined with test articles.

Closeout: Committee Response to Charge (prelim.)

5. Are the plans for detector integration in the EIC detector appropriately developed for the present phase of the project?

Response:

- SCIFI: Mechanical and electronic integration schemes have been presented. Final assembly procedures, including cabling and cooling should be tested on mockups to guarantee a reliable construction. Here again the group can profit of GLUEX and BNL expertise.
- Imaging Layers: The integration at the two front faces of the calorimeter is in the phase of the conceptual design. The front face PCB of the SciFi part foresees slots for the insertion of the AstroPix trays. The conceptual design is appropriate at the current level. The realization requires close collaboration between the teams that work on the subsystems within BIC.

<My Summary>:

- **ScFi:** Mechanical and electronic integration schemes presented; mockup testing for cabling and cooling recommended
- **Imaging Layers:** Conceptual design suitable for current phase; close collaboration needed between subsystem teams for successful implementation

Closeout: Committee Response to Charge (prelim.)

ePIC

6. Have ES&H and QA considerations been adequately incorporated into the designs at their present stage?

Response:

- SCIFI: ES&H and QA have been fully addressed throughout the entire review and are considered fully compliant to standards.
- Imaging Layers: Plans for the QA chain have been presented. They look well-conceived and feasible. A minor risk is t (yet) uncertain participation of the Korean groups. ES&H aspects have been fully addressed and comply with standa

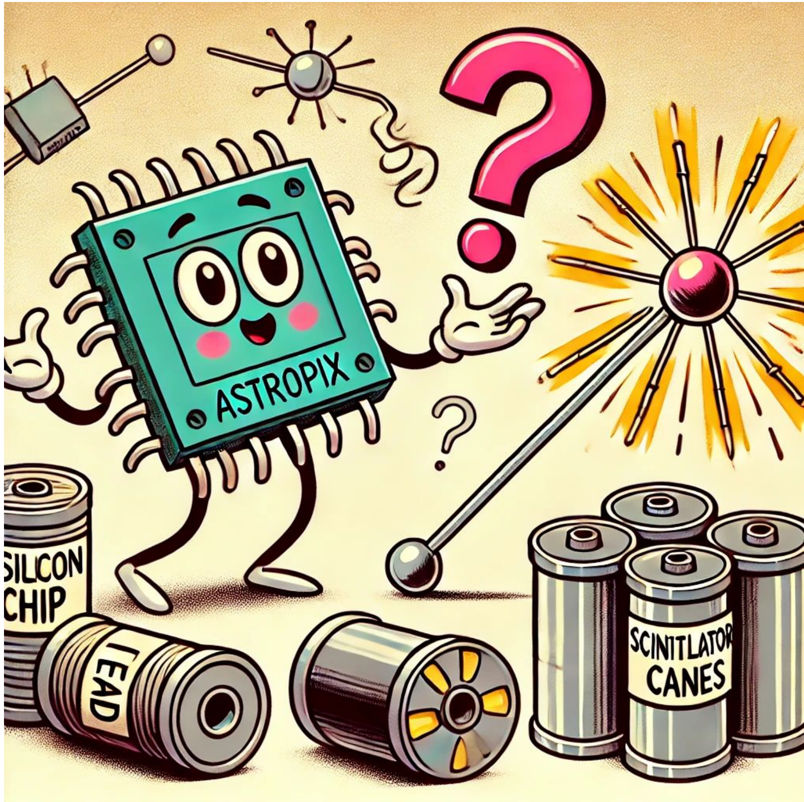
<My Summary>:

- **ScFi:** ES&H and QA fully addressed, compliant with standard
- **Imaging Layers:** QA plans well-designed; minor risk due to uncertain participation of Korean groups. ES&H fully compliant.

  Note: the remark on the Korean groups is a misunderstanding: Korean participation is certain, only Korean in-kind funding is still uncertain (but evolving rapidly!)

Final thoughts on the BIC PDR2

- The BIC design is maturing rapidly
- The reviewer comments did not include any surprises, boiling down to encouraging us to execute our PED program as planned
    - Looking forward to the final Findings and Recommendations - *Just got notification this morning that the final report is ready!*
- I am proud of the performance of our team preparing for the review!



Layer Placement

AstroPix Layer Placement

Layer Placement (1-3-4-6): General Motivation

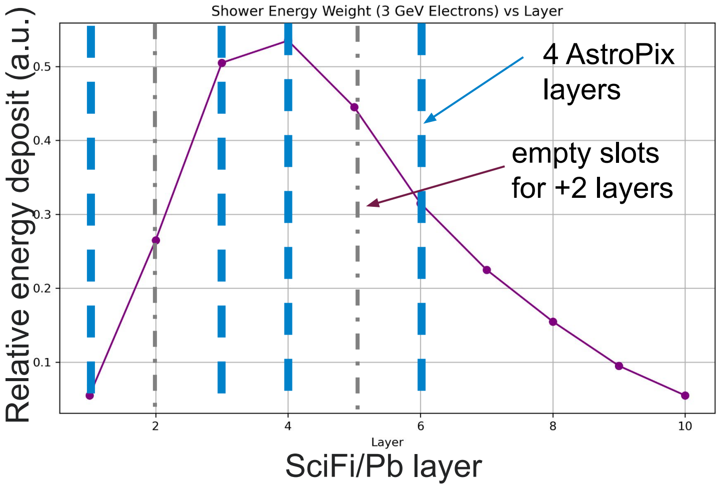
6 imaging layers separated by 1.45X_0 at η = 0 of Pb/ScFi

All layers important for the e/π separation for mid energy particles <5 GeV and overall sampling of shower energy for SciFi/Pb close shower energy splitting

Front layers important for γ/π^0 separation and position resolution

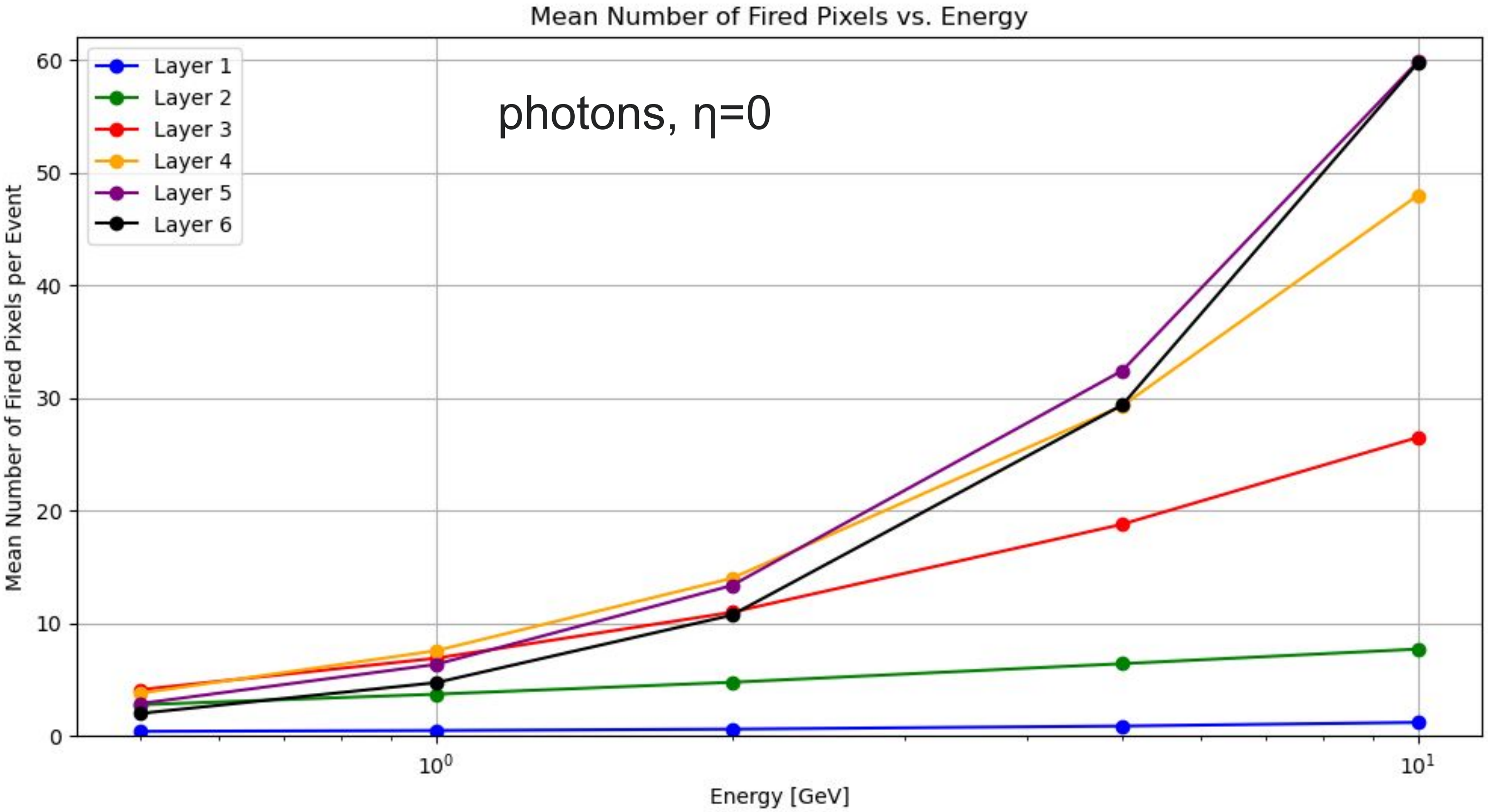
- 1st layer in front of the calorimeter: effectively a tracking layer for charged particles to support DIRC PID - very little “calorimetric” performance
- 1 pre-shower slot empty (impact on γ/π^0 separation and position resolution)
- 2 layers around shower max (sample much total of shower for energy reconstruction and shower separation and e/π separation)
- 1 post-shower slot empty (important sampling overall shower energy, e/π)
- 1 layer in tail (deeper in the tail for larger η to catch e/π separation and still sample important part of shower energy)

3 GeV electron shower profile at η = 0



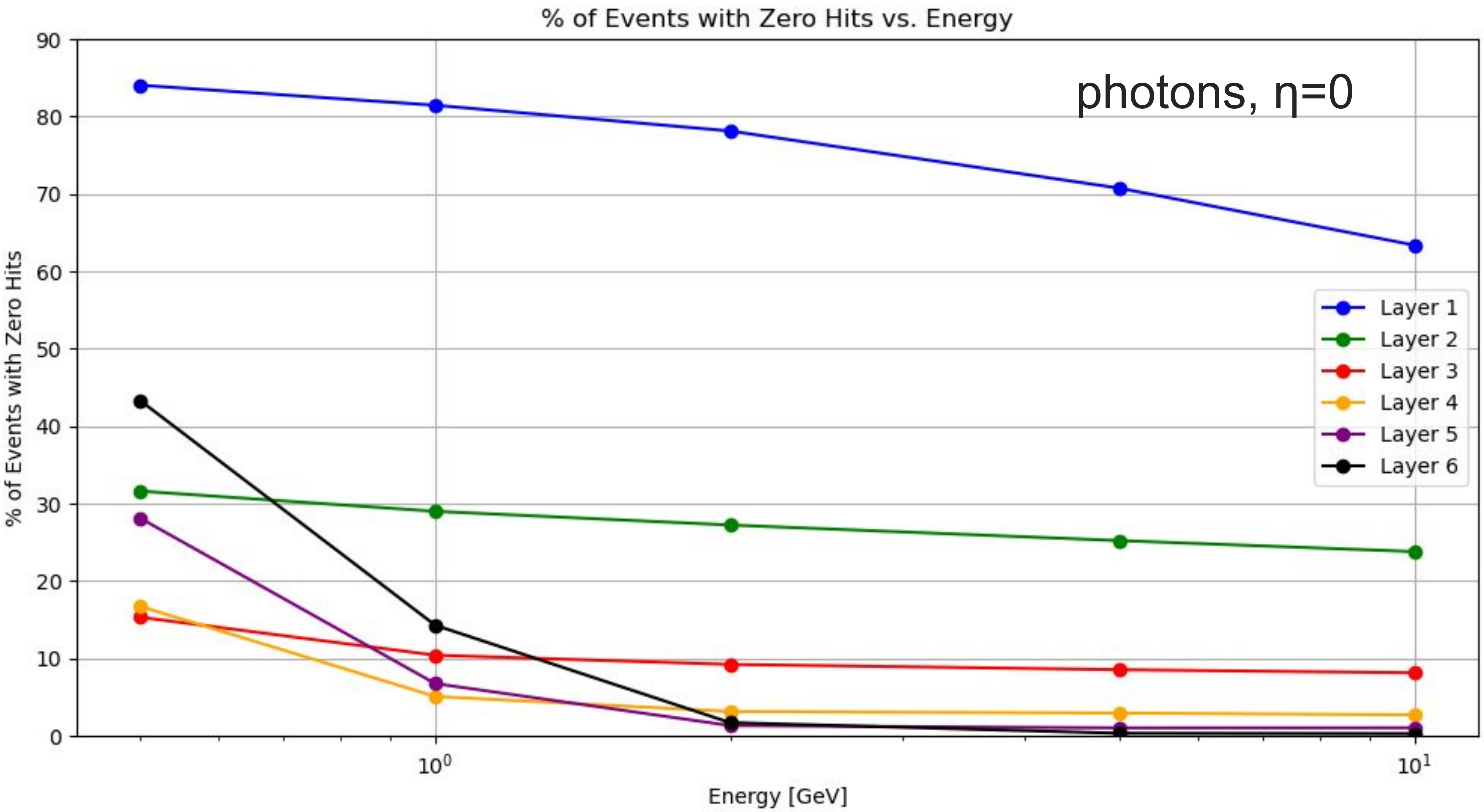
Optimized for preserving e/π separation for mid energy particles and max shower sampling for effective 3 calorimetric layers only

Mean hit multiplicity per AstroPix Layer vs Energy



Note that mean includes the cases when there is no hits at all

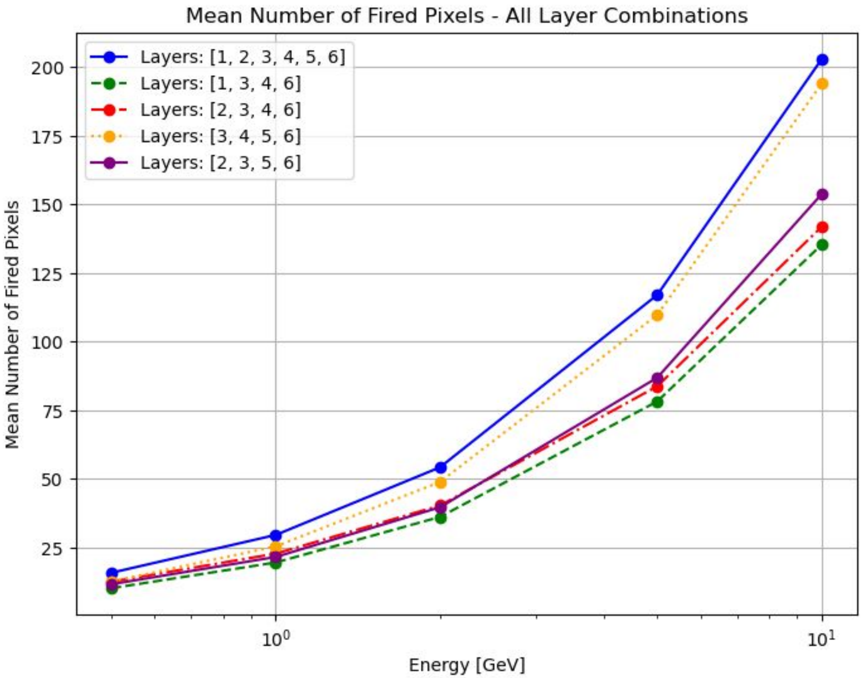
% of events with zero hits in the layers

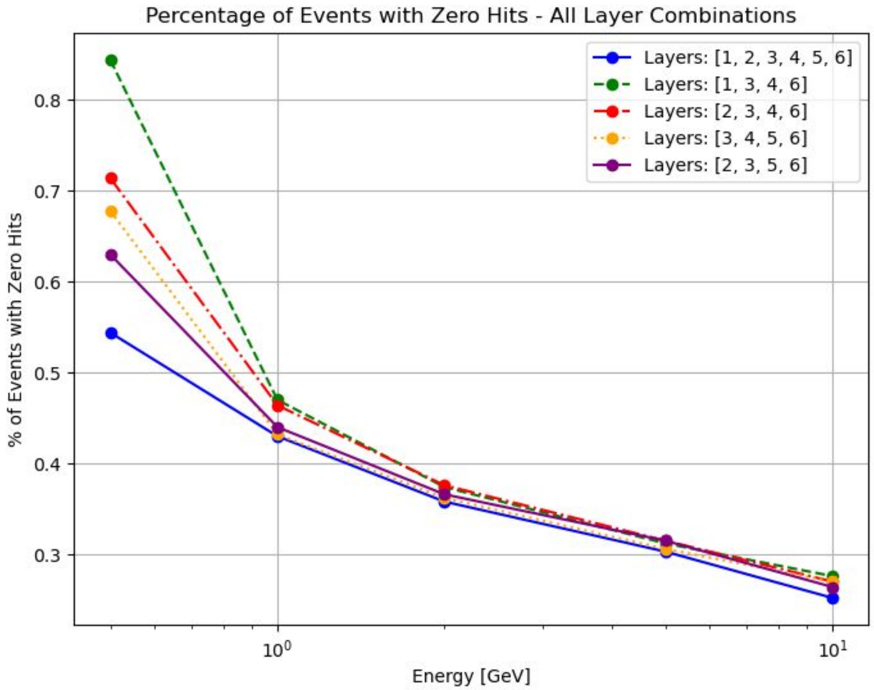


See backup for example distributions of nb of hits per layer

Mean hit multiplicity and % of zero hits in all AstroPix layers

Different layer configurations





Note that this is for photons at η=0, different η will differ

Thoughts on Layer Placement Optimization

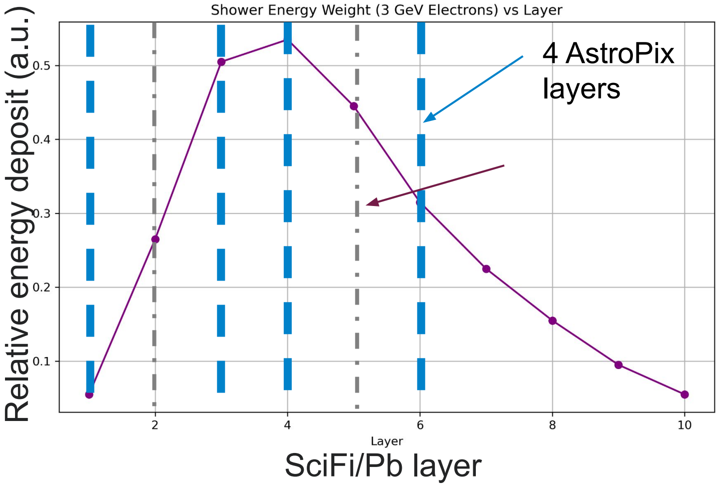
The baseline configuration (1-3-4-6) is a compromise:

- Layer 1 is purely there to support the DIRC, negligible impact on calorimeter performance
- Other layers placed to maximize electron-pion separation: sample shower maximum and shower tail
- Not instrumenting layer 2 misses the shower onset for most electromagnetic showers:
  - Large impact on neutral particle reconstruction and π^0-photon separation (strongly degrades neutral particle performance)
  - Moderate impact on precision of energy separation of overlapping showers in ScFi

If Layer 1 is not needed for the DIRC:

- Can move to 2-3-4-6 or 2-3-5-6 configuration
- Alternate 4-layer configurations will boost all performance metrics
- Greatly reduce risk of underperformance in neutral particle reconstruction

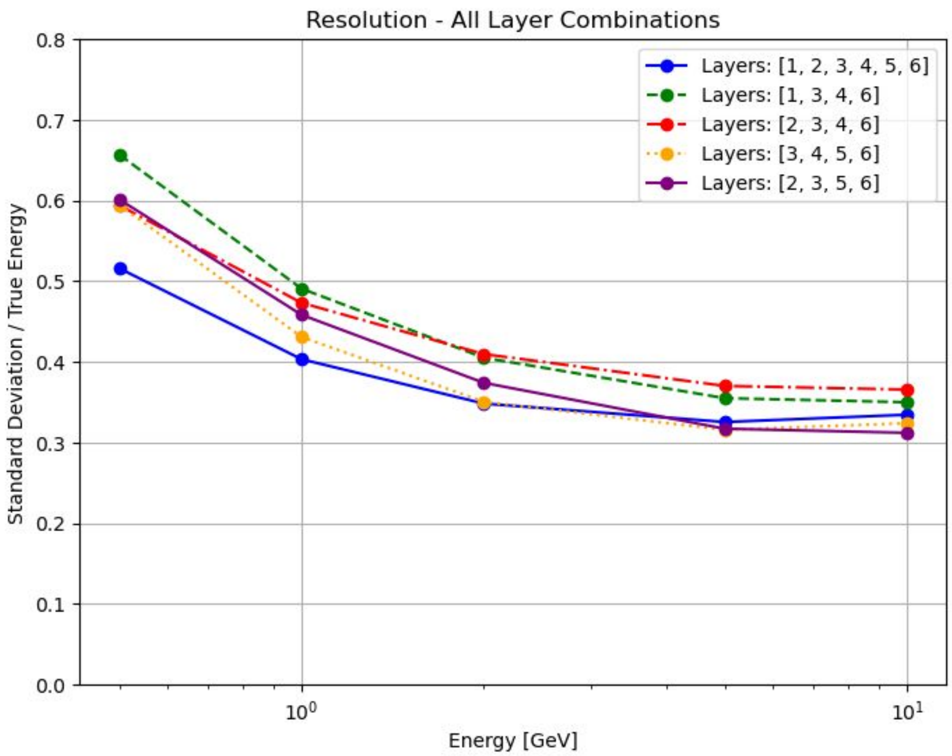
3 GeV electron shower profile at η = 0



Studies to prepare detailed impact metrics ongoing

Backup/Extra Info

Energy Resolution
Different layer configurations



Plot show Standard Deviation of energy deposit in AstroPix layers

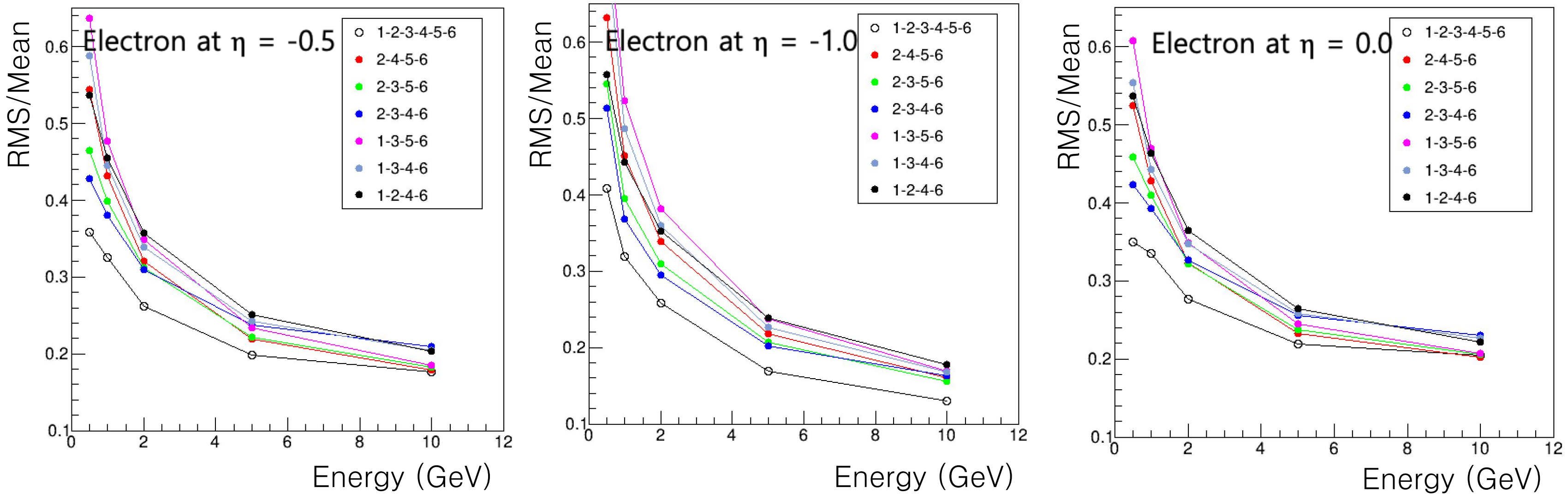
Photons, η=0: for low energy response at this rapidity, 3-4-5-6, 2-3-5-6, 2-3-4-6 look preferable

For high energy, overall energy reconstruction affected by longitudinal shower (and it's shower max) fluctuations.

Extreme example for η=0, at larger η, more confinement

Energy Resolution - rapidity dependence

Different layer configurations

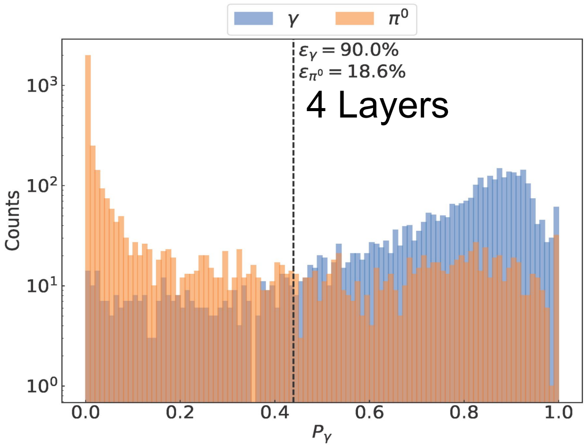


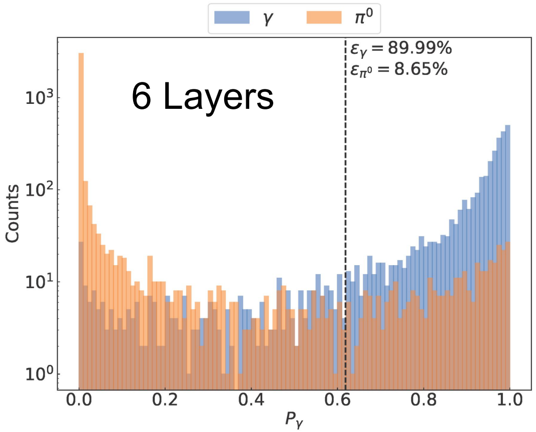
- The layer configurations starting with 2-3- (red and green) show better performances at low energy.
- The layer configuration ending with -5-6 (red, green, and purple) show better performances at high energy.
- At η = -0.5, the RMS/Mean decreases at higher energy compared to η = 0.0, but the trend stays the same
- At η = -1.0, the RMS/Mean gets worse at 0.5 GeV because of the experimental structure.
- At η = -1.0, the RMS/Mean decreases at higher energy compared to η = -0.5 and the trends from η = 0.0 begin to disappear as the electrons experience more X0.

Particle Identification

ɣ-π⁰: 4-6 layers

Momentum	Configuration	γ efficiency	π^0 rejection
10 GeV/c	6-layer	90%	11.5
10 GeV/c	4-layer	90%	5.4





Improvement in π^0 rejection at 10 GeV/c at η = 0 (high-energy where π^0 rejection is the hardest)

6-layer configuration, sees a factor of 2 of performance improvement (~9% π^0 contamination at 10 GeV)

The 4-layer configuration optimized for e/π separation with 3 "calorimetric" Si layers only with still decent ɣ-π^0 performance

- lack of layer "2" has notable impact on this metric
- performance can be improved through upgradable design

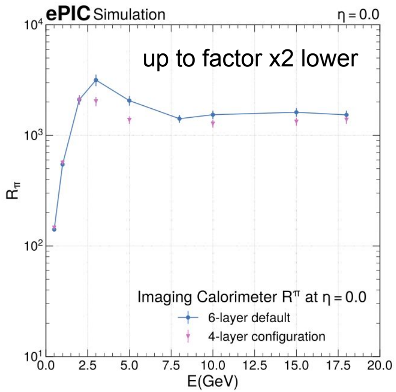
Layer Number Optimization

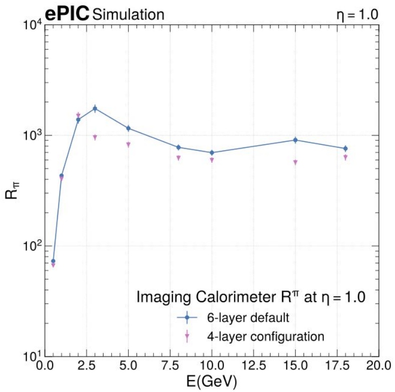
Default 6-layer configuration vs an equidistant 4-layer configuration

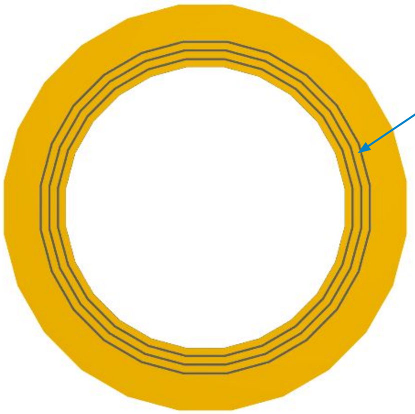
- Most pion rejection performance loss in **middle energy range**, where the barrel **ECal is the most crucial**
- **Exaggerated reduction at larger *η*** due to inflated radiation length between layers. Lose much of the shower imaging capabilities, impacting also photon-pion separation
- **Impacts Pb/ScFi energy splitting**, which relies on the cluster topology and energy resolution for nearby clusters in the same azimuthal region
- **Impacts the energy resolution** of the imaging part of the calorimeter, and **position resolution of gammas**

Bottom-line:

- Removing 2 layers reduces performance and redundancy
- A staged approach to installing the imaging layers could be a possible risk mitigation strategy

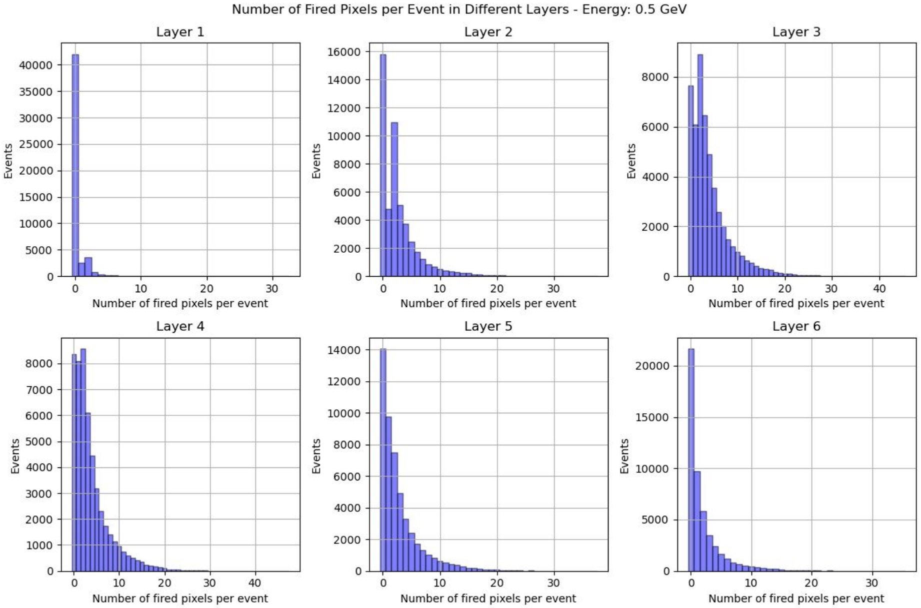




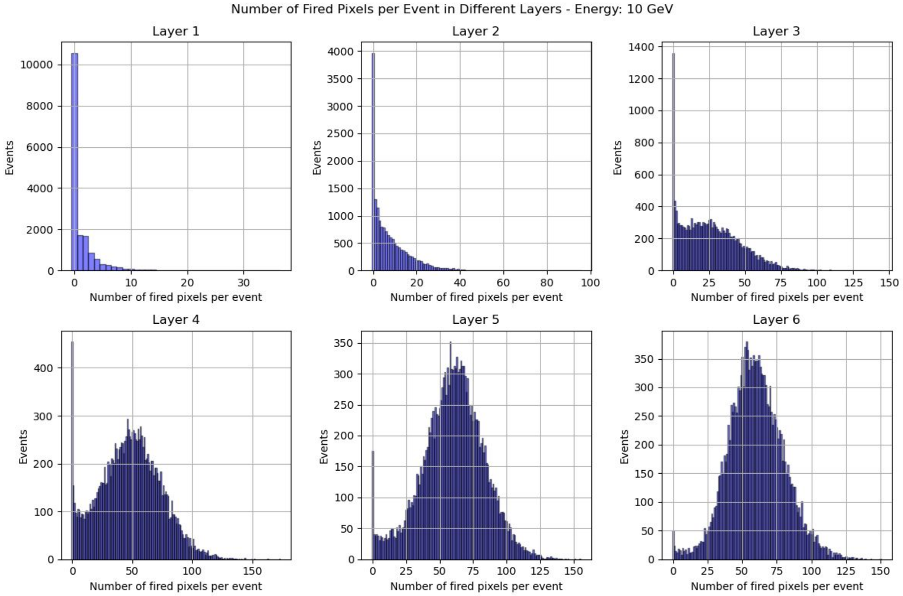


2.52 X_0 separation between imaging layers at η = 0 (1.45 X_0 separation in default geometry)

Hit multiplicity per AstroPix Layer: photons, η=0



0.5 GeV



10 GeV