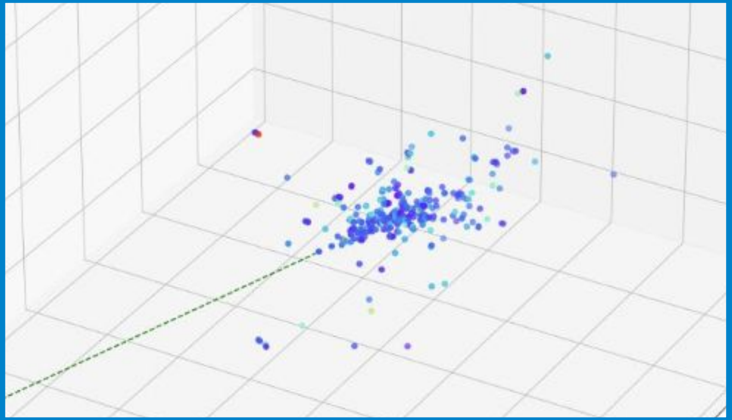
January 10, 2023

ePIC Collaboration Meeting

Imaging Barrel Electromagnetic Calorimeter



Maria ŻUREK, Argonne National Laboratory, zurek@anl.gov

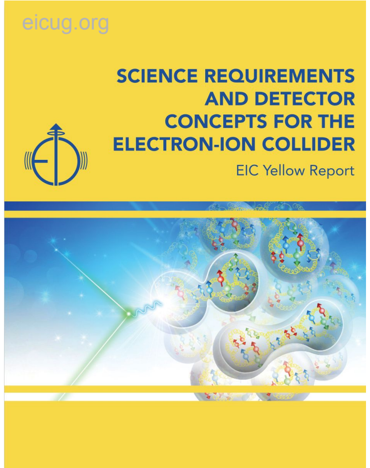
EIC Calorimetry Requirements

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 ɣ up to ~10 GeV**
- **Low energy photon** reconstruction ~100 MeV



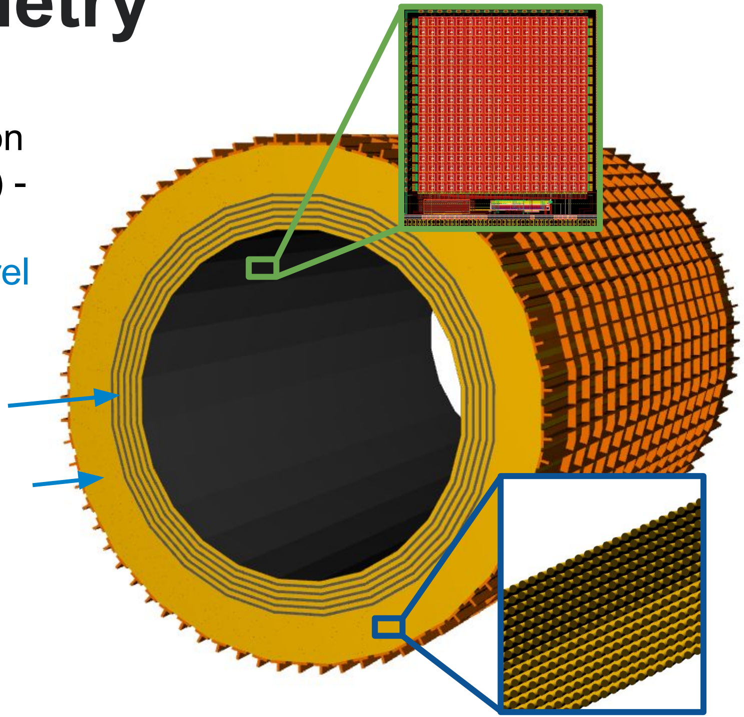
Challenges: e/π PID, ɣ/π^0 discrimination, dynamic range of sensors, available space

Imaging Barrel EM Calorimetry

- **Hybrid concept**
  - Imaging calorimetry based on monolithic silicon sensors AstroPix (NASA's AMEGO-X mission) - 500 μm x 500 μm pixels NIM, A 1019 (2021) 165795
  - Scintillating fibers in Pb (Similar to GlueX Barrel ECal, 2-side readout w/ SiPMs) NIM, A 896 (2018) 24-42

- **6 layers of imaging Si sensors** interleaved with **5 SciFi/Pb layers**
- Followed by a **large section of SciFi/Pb section** (can serve as inner HCAL)

- Total radiation thickness for EMCAL of ~21 X_0 (only ~38 cm! deep)



Energy resolution - SciFi/Pb Layers: 5.2% $/\sqrt{E} \oplus$ 1.0%
Position resolution - Imaging Layers (+ 2-side SciFi readout): with 1st layer hit information ~ pixel size

SciFi/Pb layers technology

SciFi/Pb layers follow the **GlueX Barrel Calorimeter**
Energy resolution: $\sigma = 5.2\% / \sqrt{E} \oplus 3.6\%$[1)]

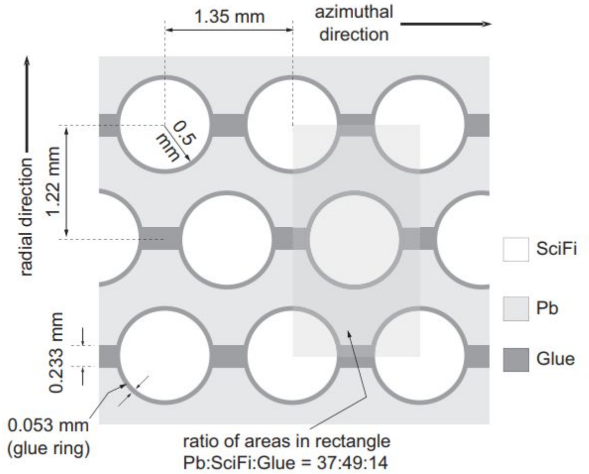
- 15.5 X_0, extracted for low energy photons < ~1 GeV

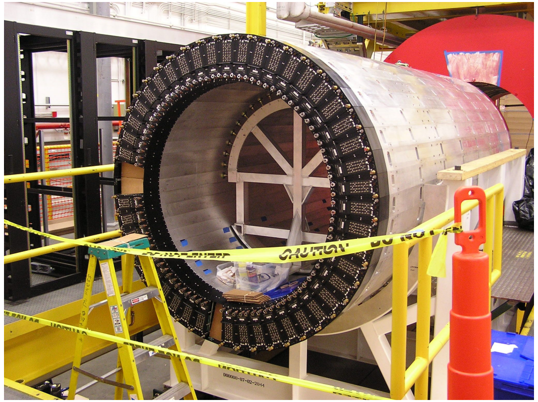
Position resolution in z: $1.1\text{cm}/\sqrt{E}$ [2)]

- 2-side SiPM readout, Δt measurement

Mature technology used in Barrel ECALs (GlueX, KLOE)

- Detailed studies on **calorimetry performance**, including the light collection uniformity in fibers, light collection efficiencies, etc.
- **Module construction** (lead handling, swaging, SciFi/Pb layers assembly, module machining) fully developed for GlueX
  Z. Papandreou, https://halldweb.jlab.org/DocDB/0031/003164/
  - Previously used equipment still available (swager machine, presses)
- Assembly and installation of self-supporting barrel based on GlueX experience





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

SciFi/Pb calorimetry - R&D

SciFi/Pb tested extensively in for energies **E_γ < 2.5 GeV**

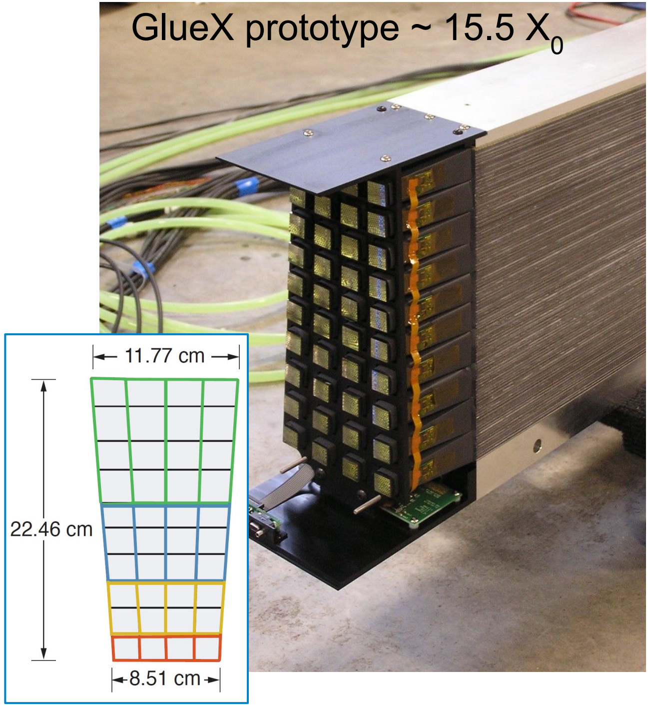
- At EIC energies up to ~10 GeV for photons and ~50 GeV for electrons
- **Higher-energy data** important to constrain the constant term of energy resolution

R&D goals with GlueX prototype

- Obtain **responses to electromagnetic and hadronic showers** to benchmark simulations and provide input to realistic **waveform analysis**
- This will be further used to optimize the detector design

Beam tests plans

- **Hall D, electrons** (energies up to ~6.2 GeV), FY23 (before 03/2023)
- Following tests in **FNAL with pion/electron beams** for hadronic response



- 60-cm long prototype
- 40 light guides on either side
- 40 SiPMs per side

Imaging layers technology

Imaging layers based on AstroPix sensors

- Developed for AMEGOX NASA mission
- CMOS sensor based on ATLASpix3
  arXiv:2109.13409 [astro-ph.IM]

Key features:

- Very low power dissipation
- Good energy resolution
- 500 μm pixel size

AstroPix chip R&D:

v1 (4.5×4.5 mm^2, 200 μm pixel)

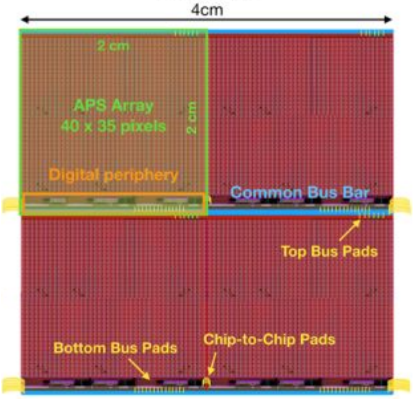
v2 (1×1 cm^2, 250 μm pixel)

- Both chips tested with γ,β sources and in 120 GeV proton beam
- See results in arXiv:2209.02631 [astro-ph.IM]

v3a (2×2 cm^2, 500 μm pixel, **quad chip**)

- Expected ready for tests in **January 2023**

Quad chip v3a



v2 carrier board

arXiv:2208.04990 **[astro-ph.IM]**

Targeted AstroPix performance goals

Pixel size	$500\,\mu m \times 500\,\mu m$
Power usage	< 1 mW/cm^2
Energy resolution	10% @ 60 keV (based on the noise floor of 5 keV)
Dynamic range	$\sim$ 700 keV
Passive material	$< 5\%$ on the active area of Si
Time resolution	25 ns
Si Thickness	$500\,\mu m$

Planned choice of the foundry TSI (v1-v3). With a large production order, AMS as a backup.

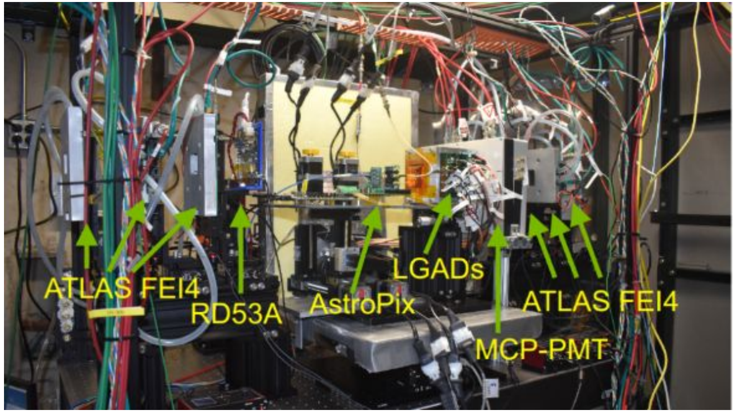
Imaging layers - R&D

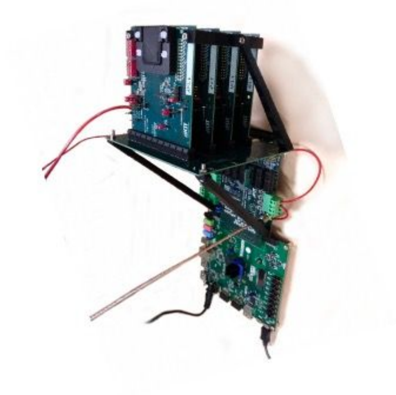
R&D program towards prototyping the generic imaging calorimetry for EIC in FY23

- Tests of **AstroPix v2/v3a sensor** in the EM calorimetry environment
  - **Multilayer chip tests** in FNAL with protons, pions and electrons, tests with tungsten radiator, readout aspects (ANL LDRD grant)
    - Beam tests in February and May 2023
  - **Irradiation test** in the FNAL ITA Facility (ANL LDRD grant)
  - Readout of multilayer chips with the **Felix board** (activities within the ANL HEP and NASA community)

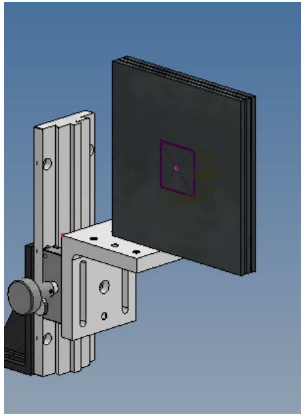
FY24 Plan

- Response to electromagnetic/hadronic shower with multilayer AstroPix v3b prototype





v2 multilayer chip boards



W radiator holder

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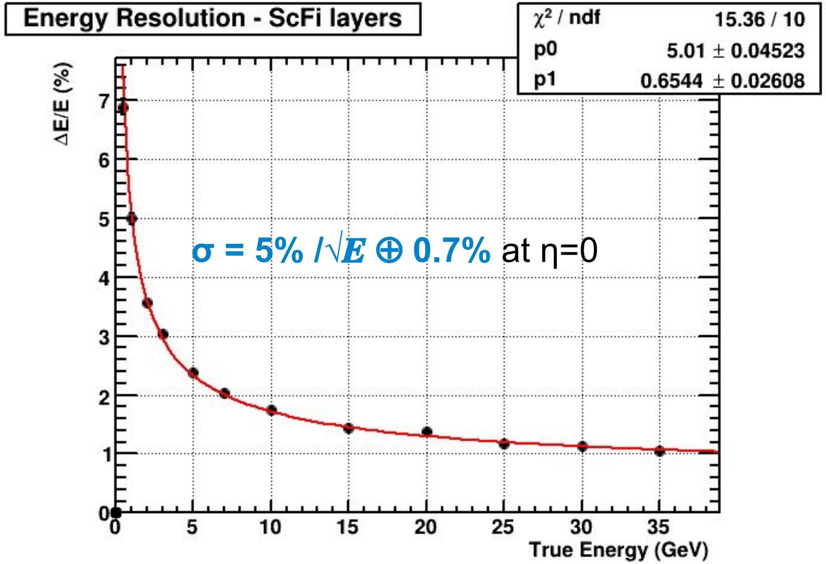
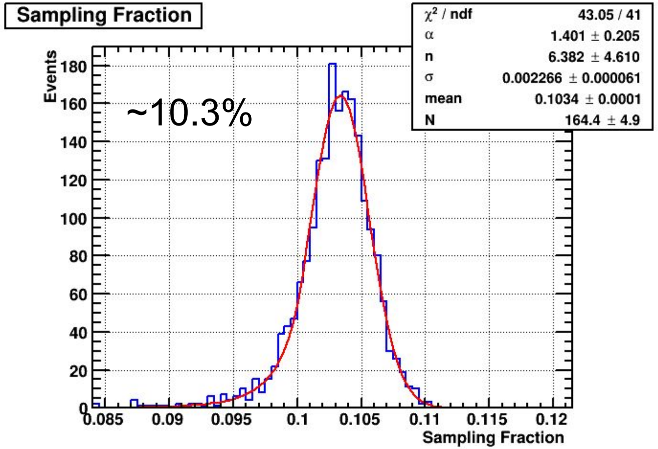
Performance Study

Energy resolution from SciFi/Pb layers



Simulations of **single photons** at η=0 (~21 X_0)

- **Realistic implementation of SciFi/Pb matrix** with glue and cladding
- Energy resolution takes into account **realistic signal digitization and reconstruction**



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

GlueX SciFi/Pb ECal

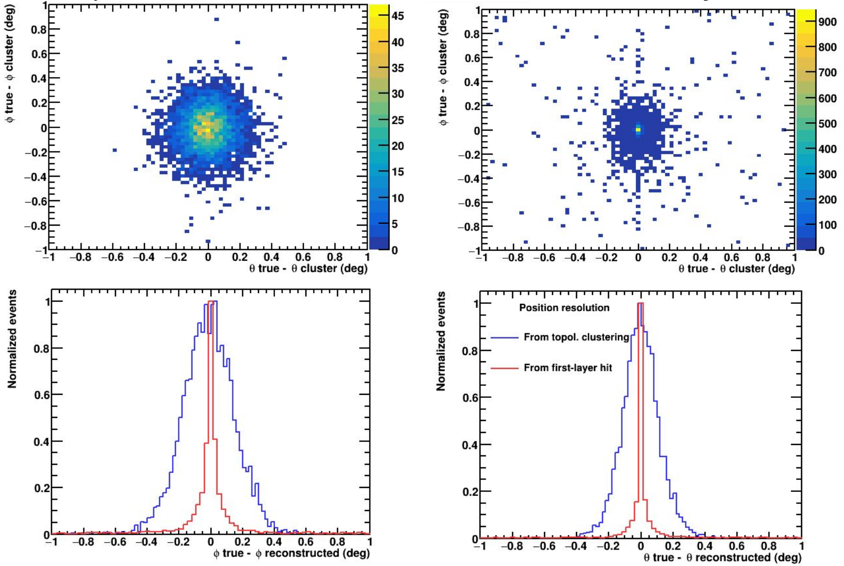
$\sigma = 5.2\% / \sqrt{E} \oplus 3.6\%$ (NIM, A 896 (2018) 24-42)

- 15.5 X_0, extracted for low energy photons < ~1 GeV
- Measured energies not able to fully constrain the constant term

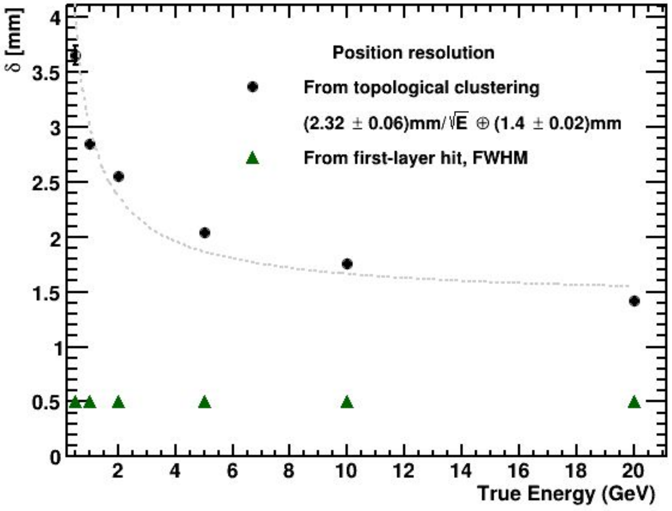
Performance Study
Position resolution from imaging layers

Example of θ - φ resolution for 5 GeV photons

Only information from **clusters** | **Clusters + first-layer hit**



Position resolution for photons



- Clusters from Imaging Si layers reconstructed with 3D topological algorithm
- Cluster level information: $\sigma_{position}$ = (2.32 ± 0.06) mm/√E ⊕ (1.4 ± 0.02) mm at η=0
- First-layer hit information added: $\sigma_{position}$ = **~0.5 mm (pixel size)**

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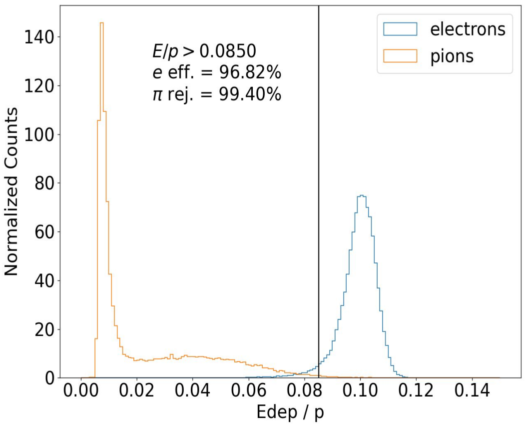
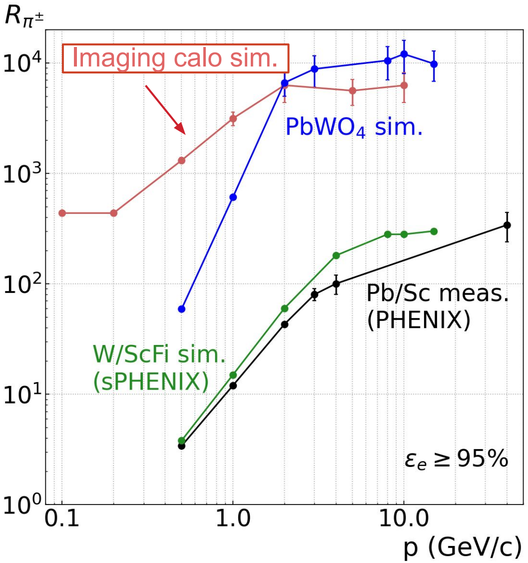
Performance Study
Electron Identification

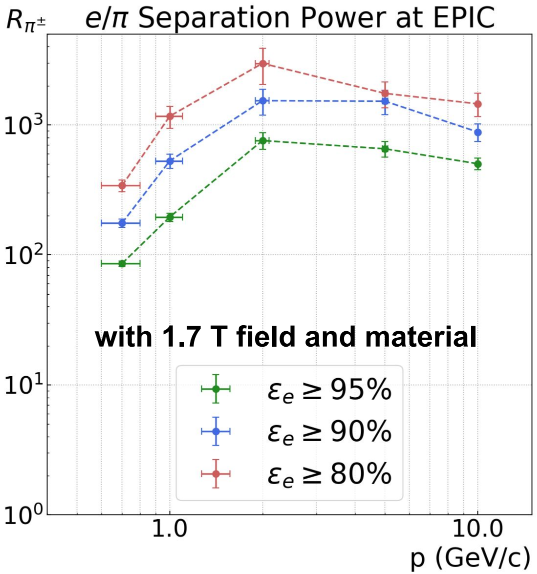


Initial cut on E/p from SciFi/Pb layers for e-π separation

Standalone simulation



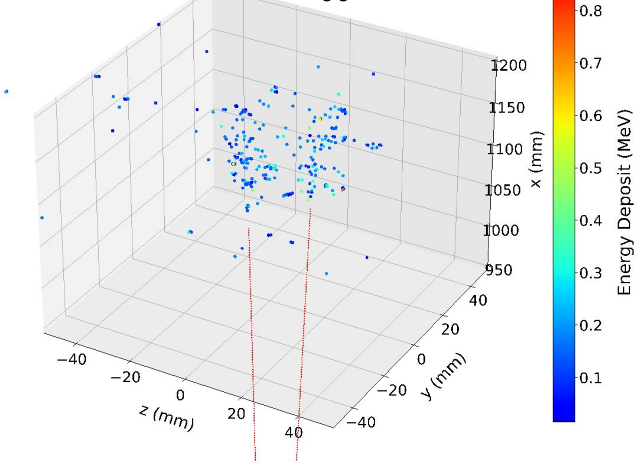
Realistic ePIC simulation



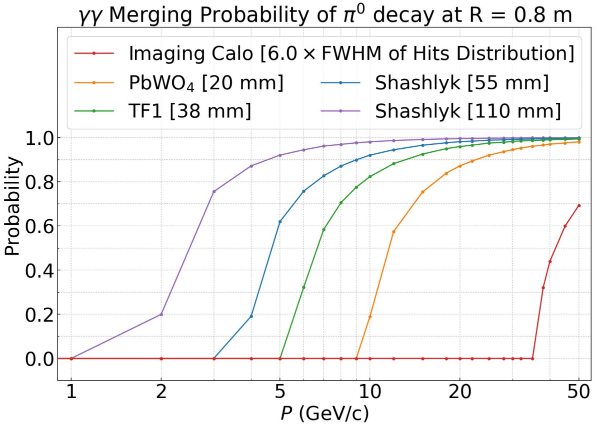
- **Goal:** Separation of electrons from background in Deep Inelastic Scattering (DIS) processes
- Method: **E/p cut (SciFi) + Neural Network** using 3D position and energy info from imaging layers
- Simulations beyond stand-alone with magnetic field and material and optimized EPIC geometry
- e-π separation up to **10^3** in pion suppression at **95% efficiency**

Performance Study
Neutral pion identification

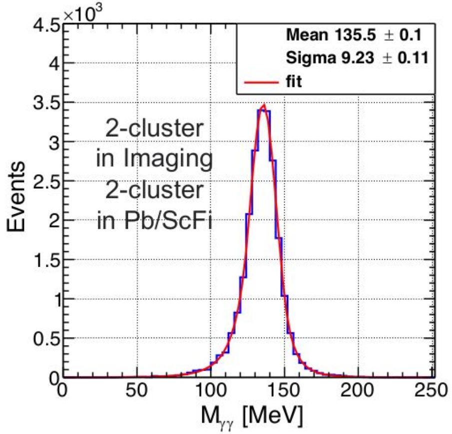
15 GeV $\pi^0 \rightarrow \gamma\gamma$



Separation of γ/π^0



M_{inv} reconstruction 2 GeV π^0



- **Goal:** Discriminate between π^0 decays and single γ from DVCS, neutral pion identification
- Precise position resolution allow for excellent separation of γ/π^0 **based on the 3D shower profile**
- Reconstruction of 2 GeV π^0 invariant mass as a testing ground for cluster energy splitting

Separation of two gammas from neutral pion well above 10 GeV

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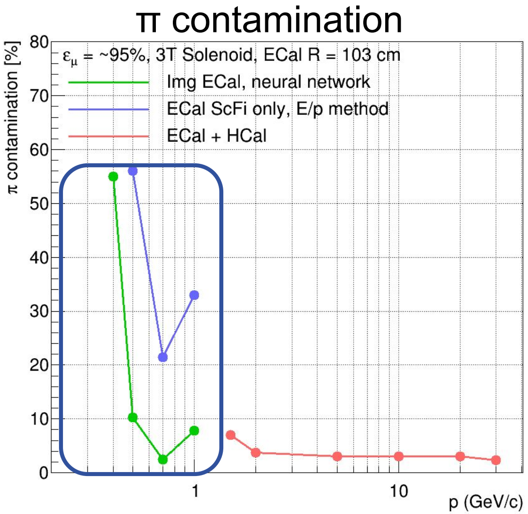
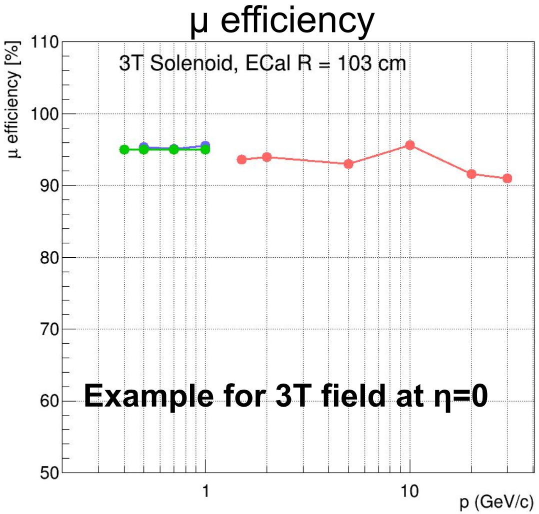
Performance Study

Muon identification

Muon-pion separation in **central region** uses information from the **electromagnetic (ECal) and hadronic (HCal) calorimeters**





Low energy muons curl inside the barrel EM calorimeter

- **< ~1.5 GeV/c with 3T** field (shown in the plots)
- **< ~0.9 GeV/c for 1.7T** field **for EPIC geometry**

The discontinuity in reaching HCal is rapidity dependent

- Incorporating imaging layer information into Neural Network studies **significantly improved the μ-π separation at low energies** wrt E/p studies from ECal only
- Pion contamination for particles that reach HCal - ECal+HCal studies: below 5%
- Plots above for 3T Solenoid, ECal radius = 1.03 cm and "tailcatcher" HCAL. Similar low energy muon performance expected for EPIC geometry with 1.7 T field for muons momenta < 1 GeV/c at η = 0

Integration

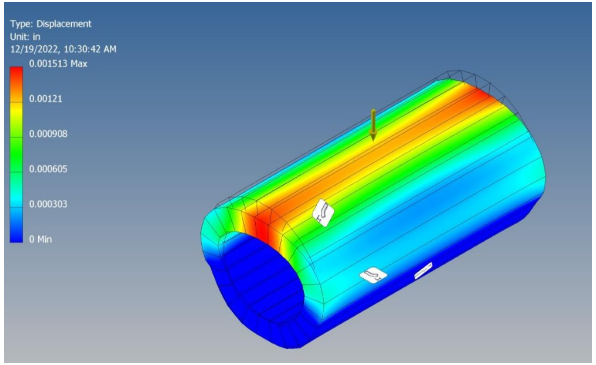
Following GlueX Barrel design

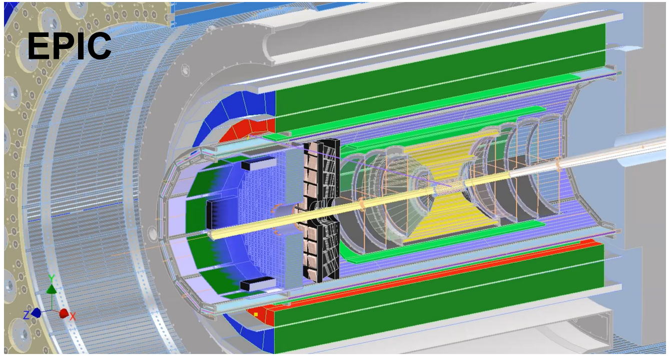
- Self-supporting structure
- Each sector attached to its neighbour
- Entire ECAL has to be slided into the detector
- **2-side SiPM readout** (leverage for support structure)
    - Radial size ~38 cm for 21 X_0

Imaging layer support structure and cooling under development

- “Si tracker layer” structure
- First imaging layer - outer tracker for DIRC

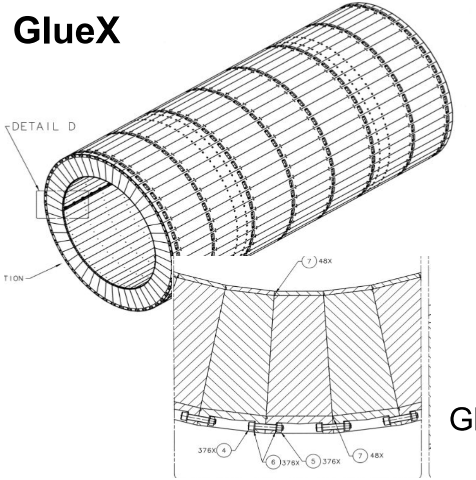
First studies on EIC barrel displacement

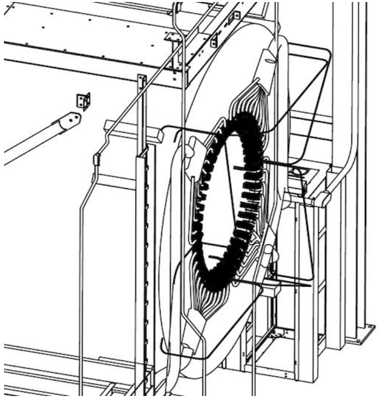




Status of CAD/Engineering Efforts on BEMC, R. Wimmer, EPIC GD/I WG Meeting, Sep 12, 2022

GlueX



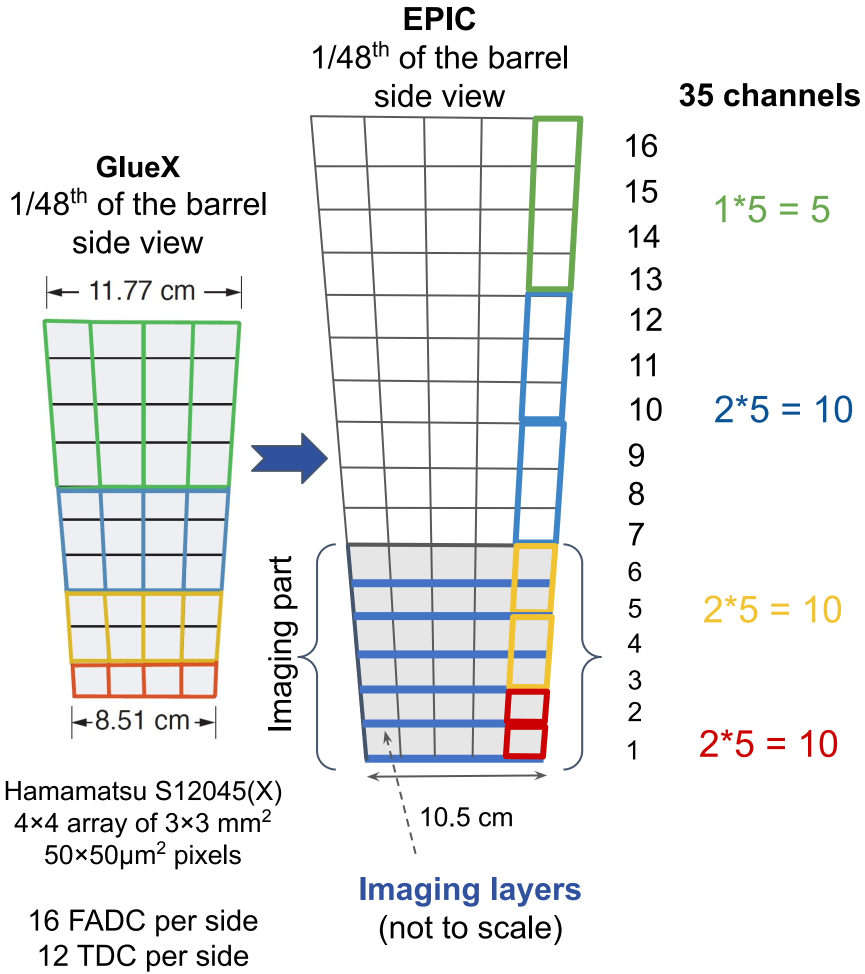


GlueX self-supporting structure

Readout SciFi/Pb

Similar readout scheme as GlueX

- **2-side SiPM readout**
- **Lightguides** attached to the stave sides
  - inner surface ~2×2 cm^2
  - output face 1.3×1.3 cm^2
- SiPM candidate: S13360-6050PE (6×6 mm^2, 50×50μm^2 pixels) - 4 per lightguide
- **Summing scheme**
  - Following the preamp stage, outputs summed by columns (see picture)
  - Optimization of the scheme based on simulations in progress
  - **35 channels per side** (3360 in total)
- To be implemented in the common readout strategy



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Readout AstroPix

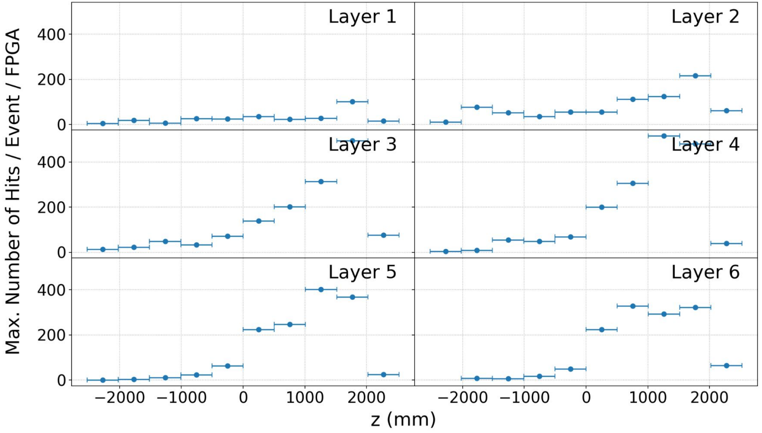
General outline of the scheme

- **Single readout unit:** 2×2 cm^2 quad-chip 500×500 μm^2
- Signals from each pixel **digitized** and **passed through daisy chain**
- Zero-suppression **energy threshold** applied to the pixels: **4σ = 4×5 keV**

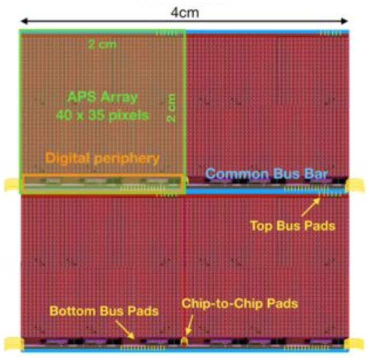
- The hit packet from each pixel: **5 bytes**
  - chip ID, pixel location, timing information, and two bytes for the ToT

- Each stave layer: **8 first-level aggregators** (~0.1 m^2)
  - Collect the signals from the covered area and send to the 2nd-level aggregators
- 2nd-level aggregator: inject the AstroPix data into the main data stream

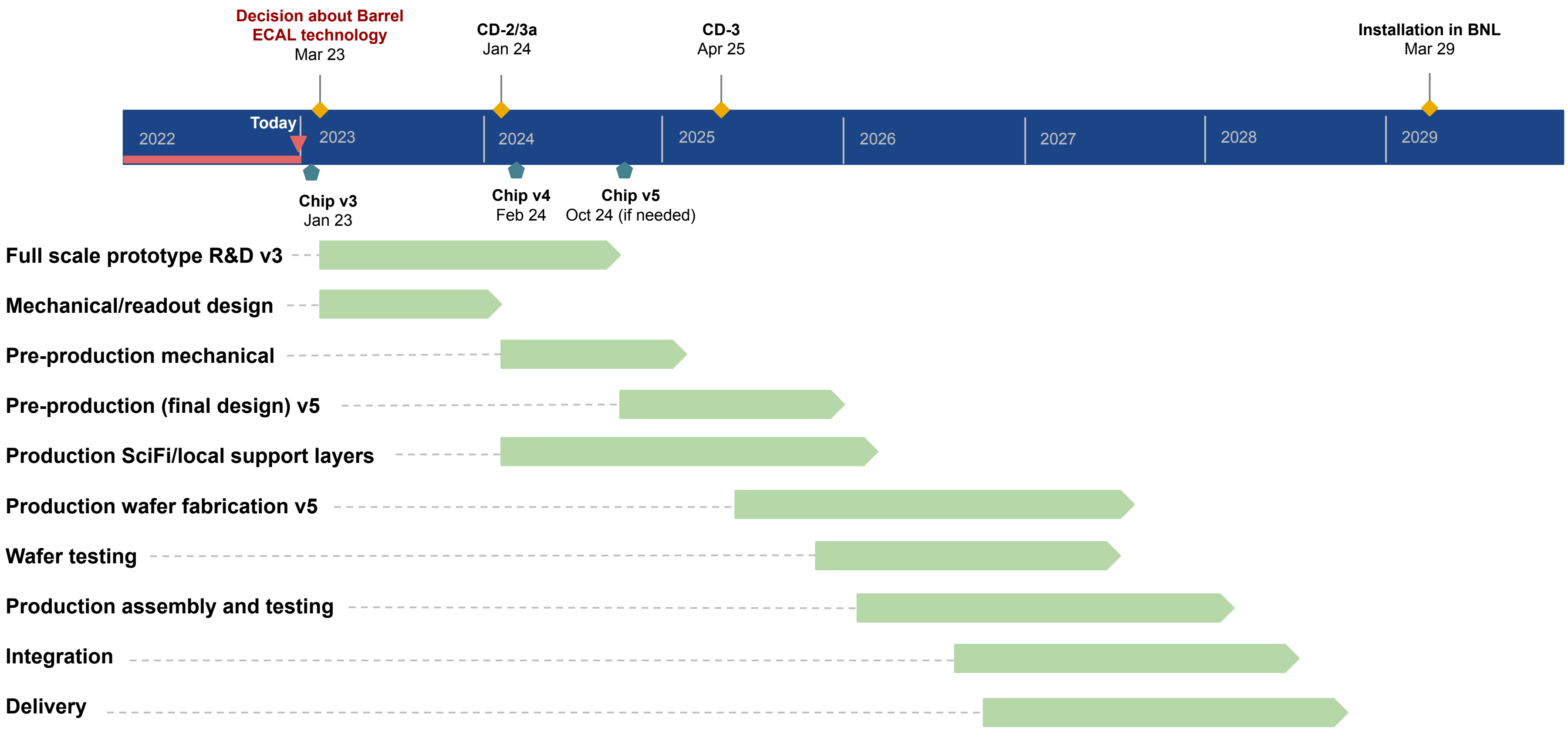
Total expected data rate < 20 Gb/s



Example max occupancy for NC DIS for 18×275 GeV beam energies and minimal Q^2 = 1000 GeV^2



Timeline


Decision about Barrel ECAL technology
Mar 23
CD-2/3a
Jan 24
CD-3
Apr 25
Installation in BNL
Mar 29
2022
Today
2023
2024
2025
2026
2027
2028
2029
Chip v3
Jan 23
Chip v4
Feb 24
Chip v5
Oct 24 (if needed)
Full scale prototype R&D v3
Mechanical/readout design
Pre-production mechanical
Pre-production (final design) v5
Production SciFi/local support layers
Production wafer fabrication v5
Wafer testing
Production assembly and testing
Integration
Delivery

Imaging Layers in Barrel ECAL: Summary

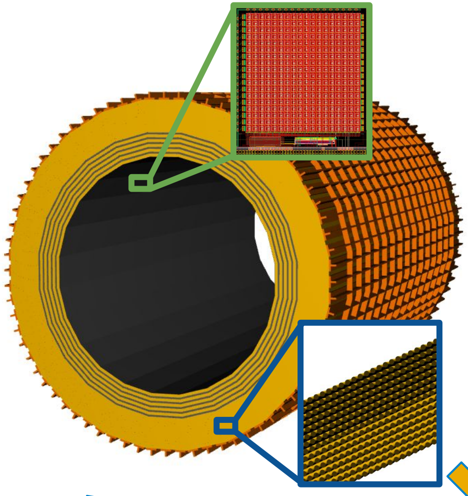
Excellent position resolution allowing precise 3D shower imaging

Significantly improved **electron/pion separation** with respect to E/p method

- Impact on DIS cross section and asymmetries

Separation of ɣs from π^0 decays at high momenta well above 10 GeV. Precise position reconstruction of **ɣs** (below 1 mm at 5 GeV).

- Impact on DVCS and photon physics



Precise measurement of **photon coordinates** and the **angle between electron and photon**

- Tagging **final state radiative photons** from nuclear/nucleon elastic scattering at low x to **benchmark QED internal corrections**

Allowing PID of **low energy muons** that curl inside the barrel ECal

- < ~1.5 GeV/c with 3T field
- < ~0.9 GeV/c for 1.7T field

- Impact on J/psi reconstruction, TCS

Advantages in detector system integration

- Outer tracker layer for the PID detector (DIRC)
- Small radial size with shower confinement
- Inner hadronic calorimeter

Summary and Outlook

Hybrid Imaging calorimeter - combination of Pb/SciFi calorimeter with a silicon tracker to precisely measure the energy profile and exact position of each particle inside electromagnetic showers - 3D shower imaging

- **SciFi/Pb:** mature technology, design and assembly procedures based on GlueX ECAL
- **Imaging layers:** based on MAPS AstroPix sensors, developed for NASA, planned to be used off-the-shelf

Dedicated tests of both technologies in the EIC-like conditions in FY23+

- Multilayer AstroPix chip tests with p/e/π beam with W radiator at FNAL
- SciFi/Pb prototype test with electromagnetic (JLab) and hadronic (FNAL) showers

Mechanical structure and readout design under development based on experience from GlueX and AMEGO-X mission designs

Realistic simulations show that design meets the EIC Yellow Report requirements and offers new opportunities:

- Design provides considerably more information compared to traditional 2D calorimeters which synergizes particularly well with event reconstruction approaches based on ML/AI

Collaborators

Argonne National Lab (SciFi/Pb and AstoPix R&D, simulations)
Manoj Jadhav, Sylvester Joosten, Jihee Kim, Jessica Metcalfe, Zein-Eddine Meziani, Tom O'Connor, Chao Peng, Paul E. Reimer, Marshall Scott, Junqi Xie, Maria Żurek

EIC Canada: University of Regina and University of Manitoba (SciFi/Pb R&D)
Wouter Deconinck, Garth Huber, Stjepan Orešić, Zisis Papandreou, Love Preet, Jonathan Zarling

University of California, Santa Cruz (AstroPix)
Tony Affolder, Vitaliy Fadeyev

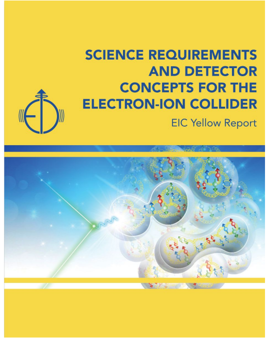
EIC Korea, new collaborators on the imaging barrel ECAL (after AP CTP Meeting, 3-5 Nov, 2022)

Kyungpook National U.: (dual readout/HCAL expertise, interest in all aspect of imaging calo)
Sehwook Lee (Professor), Hyon-Suk Jo (Professor), Min-Sang Ryu (Research Professor)
+ 5 graduate students and 1-2 postdocs

Pusan National U.: (Si sensors expertise, interest in all aspect of imaging calo)
Sanghoon Lim (Professor), In-kwon Yoo (Professor), Jeongsu Bok (Research Professor)
+ 5 graduate students and 1-2 postdocs

Backup Slides

EIC Calorimetry Requirements



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

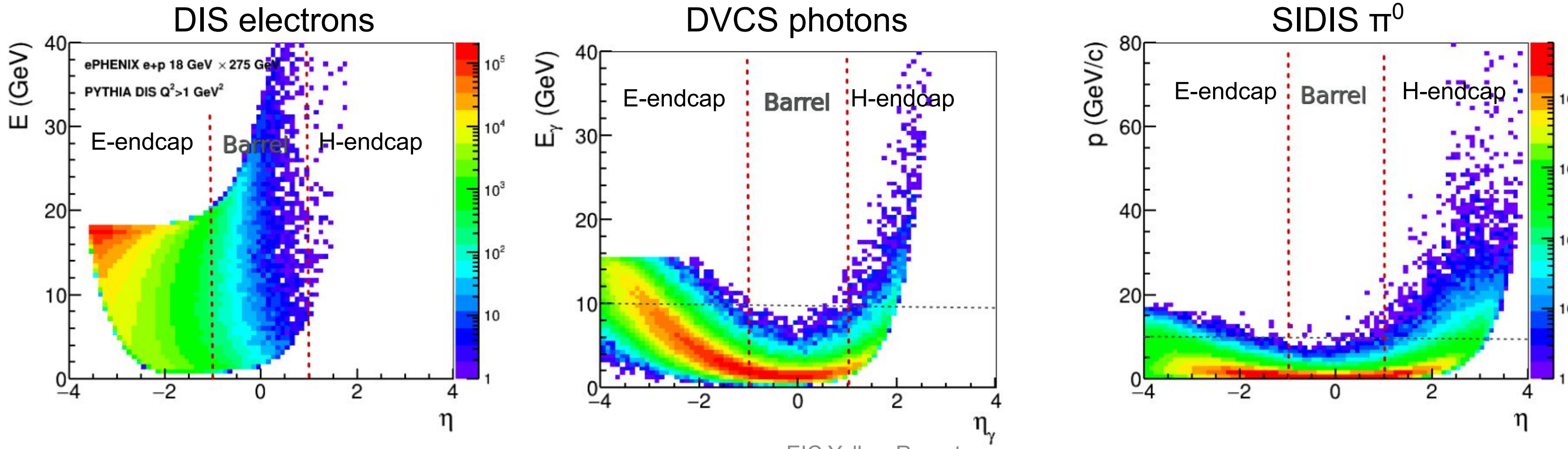
Main tasks of the ECAL

- Detect the scattered **e and separate them from π.**
- Improve the electron **momentum resolution at backward rapidities**.
- **Detect neutral particles (photons, π^0)**, and measure the energy and the coordinates of the impact.
- Separate **secondary electrons and positrons from charged hadrons**.
- Provide **spatial resolution of two photons sufficient to identify decays π^0 → γγ** at high energies.

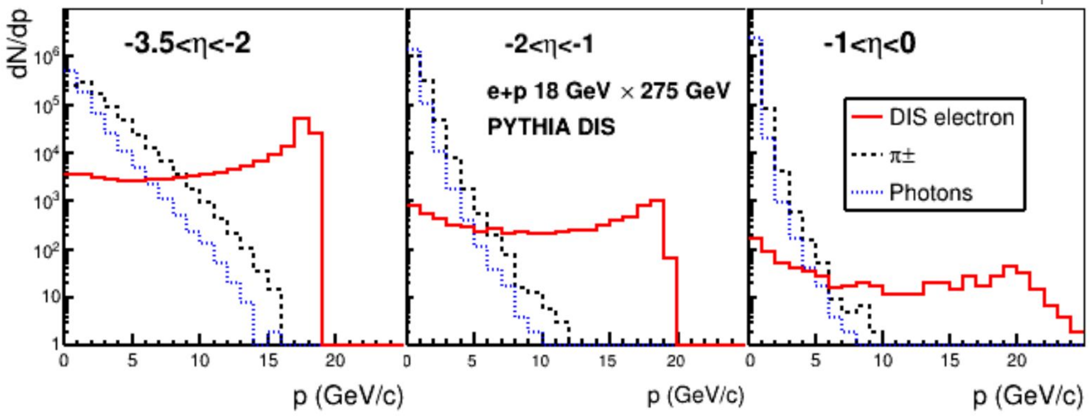
	-4 < η < -2	**-2 < η < -1**	**|η| < 1**	**1 < η < 4**
E resolution	$2\%/\sqrt{E} \oplus (1-3)\%$	$7\%/\sqrt{E} \oplus (1-3)\%$	$(10-2)\ \%/\sqrt{E} \oplus (1-3)\%$	$(10\text{-}12)\ \%/\sqrt{E} \oplus (1-3)\%$
e/π separation	up to 10^{-4}	up to 10^{-4}	up to 10^{-4}	3σ e/π
Min E [GeV]	0.1	0.1	0.1	0.1

EIC Calorimetry Requirements

EIC Yellow Report



EIC Yellow Report



e/π separation:

- Depends on momentum and η
- Tightest constrain from parity violating asymmetries 10^{-4}
- ΔG requires ~ 10^{-3}

AstroPix Sensor Layer Size

For **6 layers** of imaging layers that cover **$-1.5 < |\eta| < 1.2$** the AstroPix sensors area is about **140 m^2**
24 staves: ~2.5×10^3 sensors per stave, ~3.7×10^6 pixels per stave, ~4.6×10^5 pixels per aggregator area

Large Si detector arrays in advanced stage (large scale prototypes)

- ATLAS Inner Tracker - silicon strips[1] (ITk pixel) 160 m^2 (50 million channels)
- CMS high granularity calorimeter [2] ~ 600 m^2 (6.5 million channels)

- AstroPix sensors (derived from ATLASpix) will be used in the **AMEGO-X NASA mission**, which is a 40 m^2 experiment sent into space. We expect AstroPix-v3 to be ready in Jan 2023.
- We plan to use chips off-the-shelf, **meaning with no design modifications**.

Advantages of AstroPix with respect to pixels used in e.g. ATLAS

- AstroPix has very low power consumption (used in space) - 1000 times smaller power consumption per cm^2 than ITk pixel
- AstroPix is a monolithic sensor - less complicated structure
- No bump bonding - less risk of damaging sensors

[1] arXiv:2105.10367, ATLAS ITk Pixel Detector Overview
[2] arXiv:1802.05987, The CMS High-Granularity Calorimeter for Operation at the High-Luminosity LHC2

AstroPix Sensor Timeline

AstroPix: a monolithic CMOS sensor and ASIC

- Developed by NASA Goddard, Argonne, and Karlsruhe after the ATLASPix chip designed at Karlsruhe. Large pixel size, low power sensor.

R&D: ~2017-2020 (ATLASPix, MuPix, etc.)
Conceptual design: 2019-2020
First engineering run: v1 submitted in March 2020
Second version: v2 submitted June 2021, characterization and testing, heavy-ion irradiation studies
Flight prototype: v3 submitted in June 2022, fully functional chip
Integration with detector: start 2023 w/ v3, tracking implementation, test beams, irradiation studies
Integration with detector: v4 expected Feb 2024 (pixel), Sounding Rocket Payload (late 2024)
Version v4 available for production in 2024

SciFi/Pb Performance

Light collection uniformity in the scintillation fiber layers

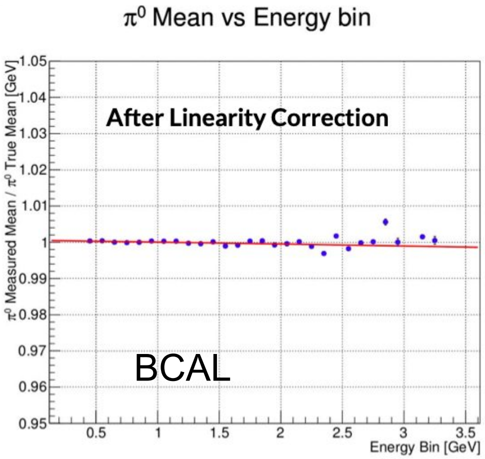
Experience from GlueX: detailed studies performed

- Naked fibres tested (random 0.5-1% from each fiber shipment); **agreed** with Kuraray checks:
- **Attenuation length** average **385 cm** (RMS = 7%)
  - **Npe** average **7.5** (RMS 8-10%) per fiber using ^{90}Sr source
- Cosmics in Pb/SciFi prototype w/ viewing 2x2cm^2 window (Winston Cone, calibrated PMT):
  - **Attenuation length 320 cm** for PMTs, **436 cm** for SiPMs, **Npe** consistent with naked fiber

- Up to 40% light loss due to the 0.5 mm air gap (versus silicon cookies or optical grease); tapered square profile light guides

- Bootstrap π^0 gain calibration: **E non-linearity correction works well**, position dependence **~few % non-uniform** due to bkdg under π^0

- But! GlueX experience shows that nonuniformities are calibrated out - **the system is forgiving**.



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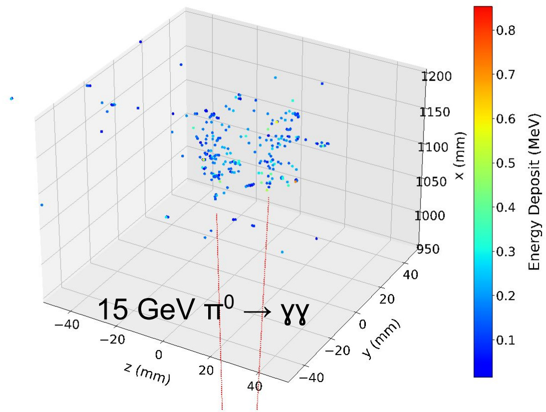
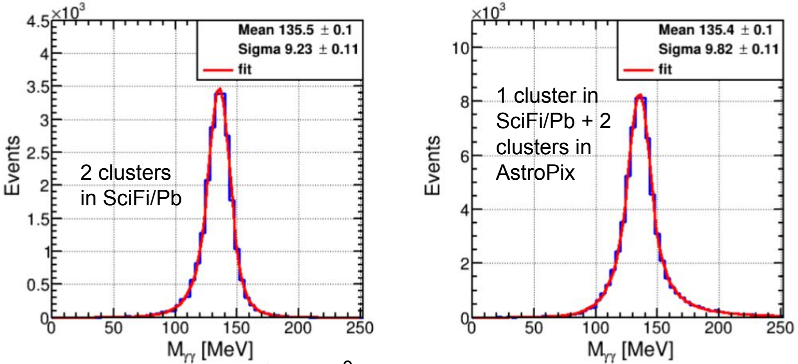
SciFi/Pb Performance

Shower separation

Currently considered readout granularity for SciFi/Pb: **Δφ = ~1.5 deg,** for pixels 0.5x0.5 mm^2



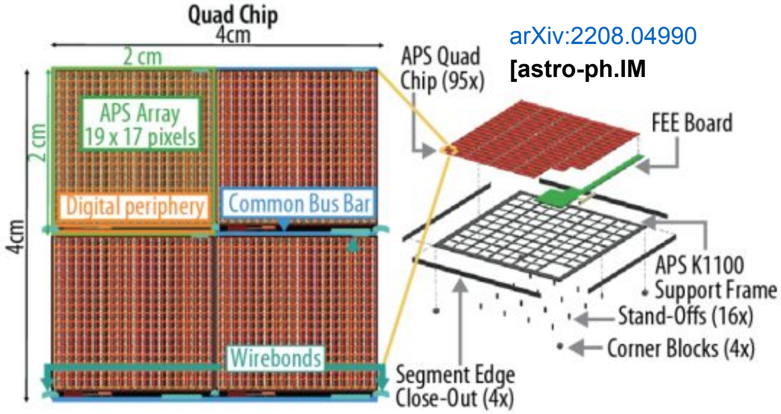


Example: 2 GeV π^0 invariant mass reconstruction

- **Position separation from AstroPix Layers** (~0.5 mm of impact point, precise shower profile imaging) and **SciFi timing information** (~1cm/√E) even if 2 particles hit exactly the same Δφ = 1.5 deg sector.
- **Energy separation** can be made to some extend with AstroPix layers (they are NOT digital, we have energy losses of every pixel). Energy resolution ~30%
- **Probability of 2 particles hit exactly the same Δφ = 1.5 deg sector low.** For example:
  - 3% of all gamma pairs from SIDIS π^0 decays
  - For jets (anti-kT, R=1.0) >60% has more than 1 gamma, out of them ~ 17% fall within **3 sectors Δφ = 4.5 deg**
- For the small fraction of events that end up in the same (or close) Δφ = 1.5 deg sector, the rough separation based on the example waveforms seems to allow for separation ~50 cm
- Detailed analysis of specific physics aspects requires stimulation with realistic waveform analysis

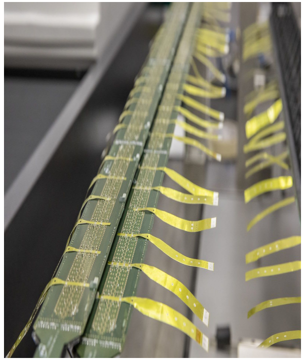
Imaging Layer Design

Tracker segment design for AMEGO-X

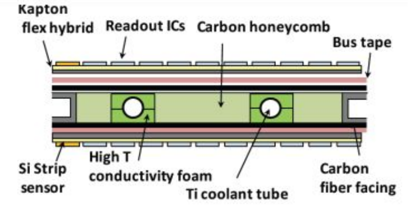


arXiv:2208.04990
[astro-ph.IM

ALICE Inner Tracker



ATLAS ITk



Tracker-like design, ALICE, ATLAS (pixels)

Tracker-like design, ATLAS strips

Design and integration under development

- Based on typical Si tracker layer design
- Overlapping staves of sensors mounted on the by the carbon fiber structure