2024 EIC User Group Early Career Workshop

The Performance of the AstroPix Sensor for the Barrel Imaging Calorimeter in ePIC

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Argonne National Laboratory

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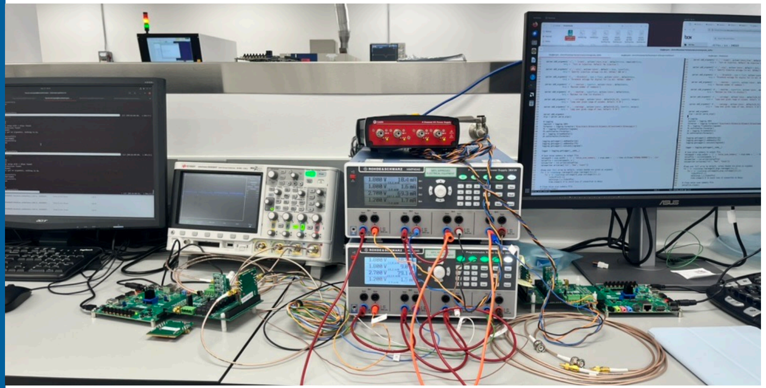
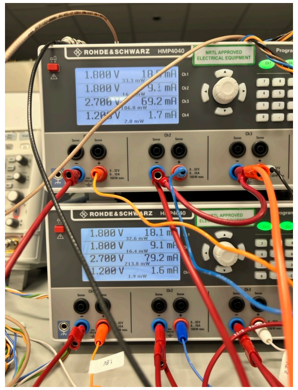
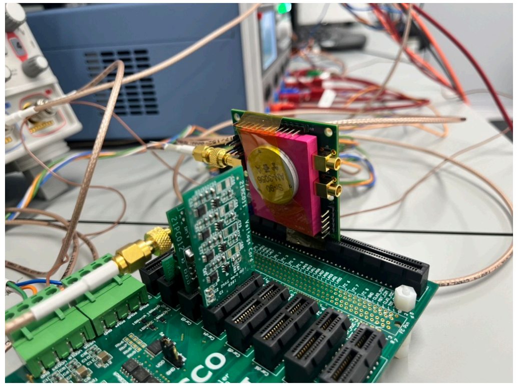
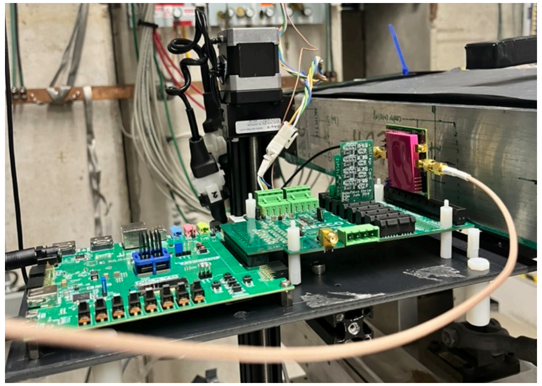
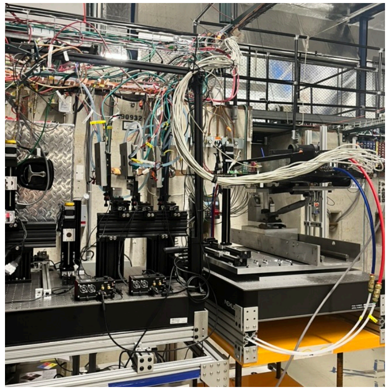
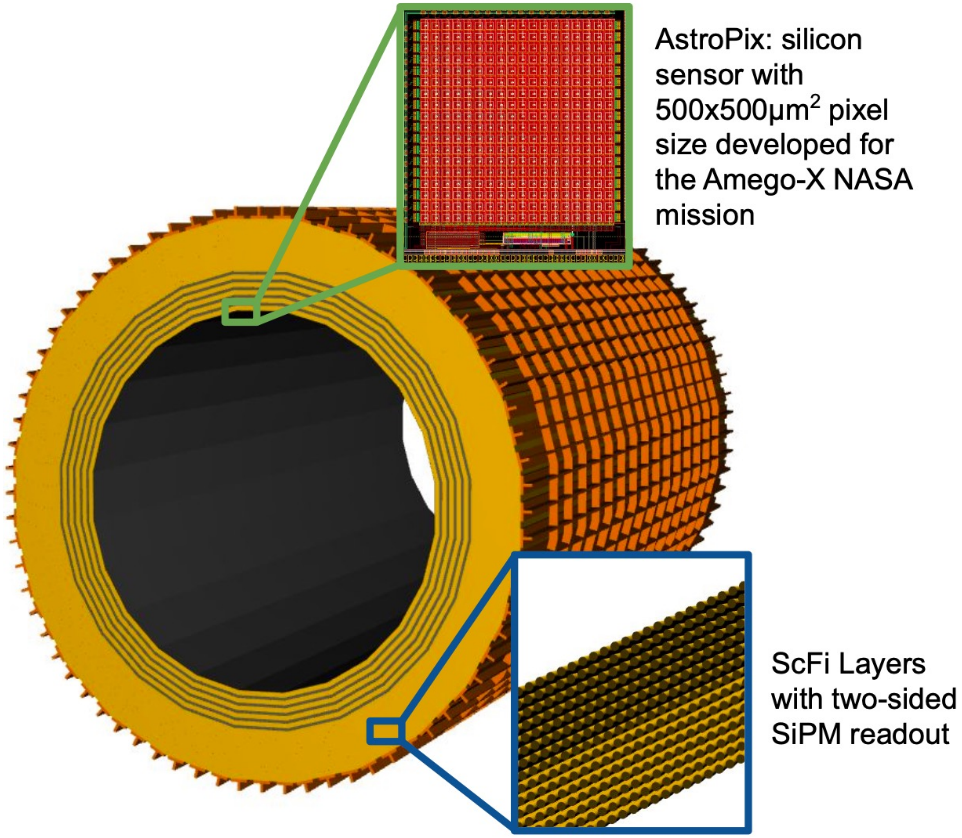






- Barrel Imaging Calorimeter in EIC detector
- Astropix Sensor: Imaging Part in Barrel Imaging Calorimeter
- Bench Test at ANL
    - Noise scan
    - Injection scan
    - Source test
- Beam Test at FANL: 120 GeV proton
    - Astropix v3 single chip
    - Astropix v3 single chip + Baby bcal
    - Double layer using Astropix v3 single chips
- Summary

Barrel Imaging Calorimeter in EIC detector



- The electromagnetic calorimeter is the main detector for electron-pion separation in the barrel region.
  - Detection of electrons/photons to measure energy and position
- Requirements for Barrel EM Calorimeter
  - 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
- 4(+2) layers of Astropix sensors interleaved with the first 5 Pb/SciFi layers
- Followed by a **large section of Pb/ScFi section**
- Total radiation thickness ~ 17.1 X_0 at $\eta=0$
- Sampling fraction ~ 10%

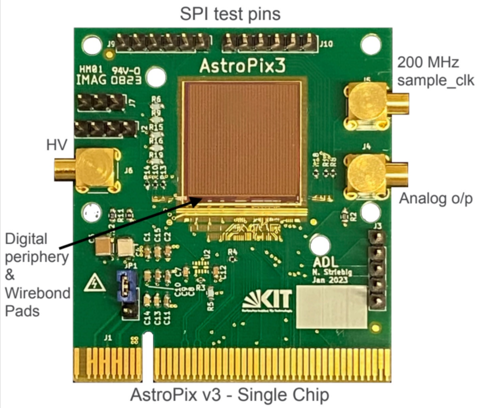
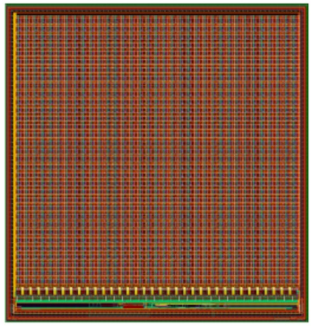
R&D goals for FY24

- Commissioning and characterizing a small Pb/SciFi calorimeter prototype, termed Baby BCAL, using mixed electron/pion and proton beams at the Fermilab Test Beam Facility (FTBF)
- Testing the first integration of the AstroPix v3 single chip with the Pb/SciFi system and the double layer using Astropix v3 single chips

Astropix sensor: Introduction

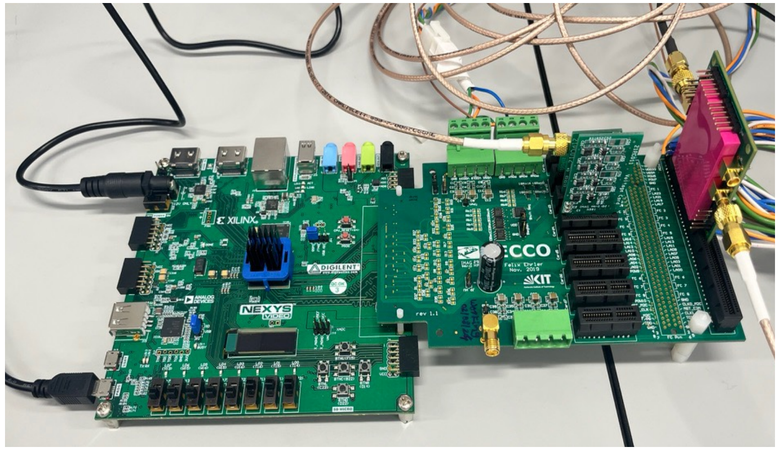
AstroPix R&D for BIC

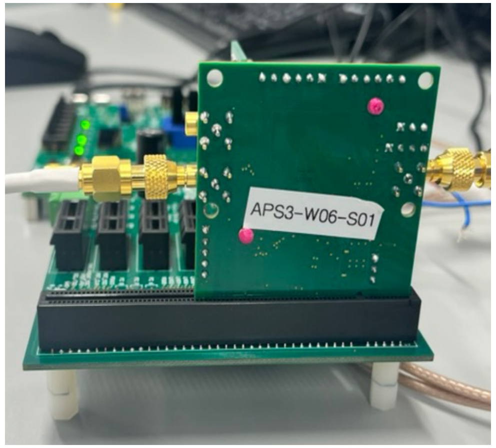
- v3: Application in larger NASA payloads
  - Not final version for BIC
  - Single chip and quad chip: under test at ANL
- v4: Currently under test in NASA
- v5: Just submitted engineering run in mid June
  - For use in BIC
  - Similar to AstroPix v3

v3	v4	v5
		
• Full size 2 x 2 cm^2 array • 500 x 500 µm^2 pixel pitch • 35 x 35 pixels	• 1 x 1 cm^2 array • 500 x 500 µm^2 pixel pitch • 16 x 13 pixels	• Full size 2 x 2 cm^2 array • 500 x 500 µm^2 pixel pitch • 35 x 33 pixels

AstroPix v3 single chip

- 2×2 cm^2 -size with 35 × 35 pixel matrix, 500 µm × 500 µm pixel pitch, 720 µm thickness
- Very low power dissipation < 1.5 mW/cm2
- The good energy resolution (<10% @ 60 keV)
- Timestamp clock: 2 MHz (500 ns), 8-bit (0-255)
- ToT (Time over Threshold) clock: 200 MHz (5 ns), 12-bit (0-4,096)
- 10-byte data frame per hit
  - Header including Layer ID
  - 5 Bytes of hit information from sensor (chip ID, pixel location, time stamp, Time over threshold)
  - 4 Bytes of FPGA timestamp



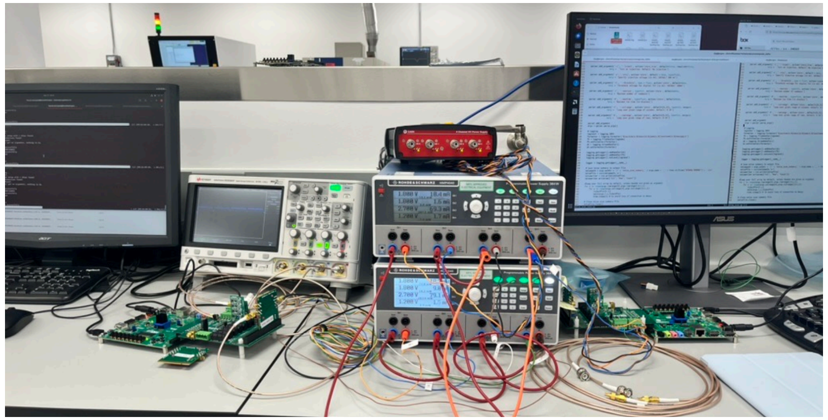


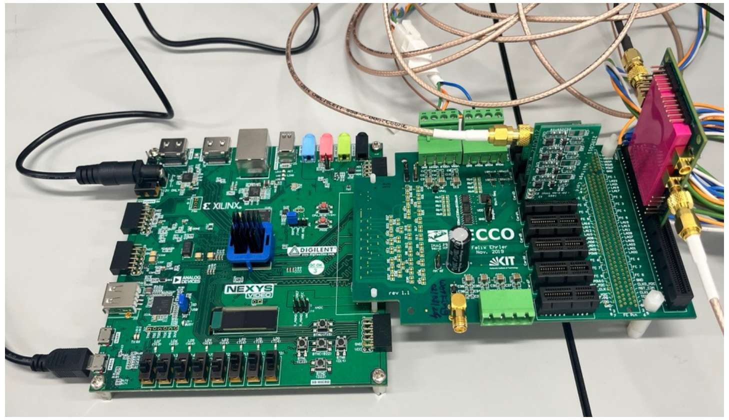
R&D Goal

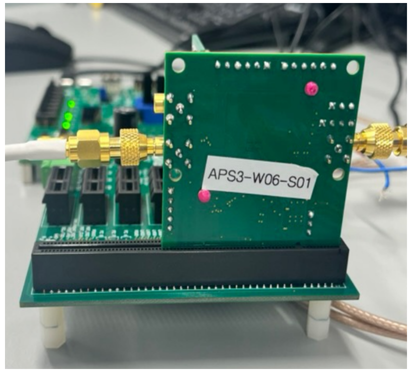
- M2: AstroPix chips prepared at the bench

1-1. Noise Scan
with respect to threshold

- Used Astropix v3 single chips: APS3w06s01
- Bias voltage: - 150 V
- LV supply
  - Digital and analog: 1.8 V
  - Gecco board: 2.7 V
  - Amplifier: 1.2 V
- Time windows: 5 secs
- Threshold: 100, 150, 175, 200, 250, and 300 mV

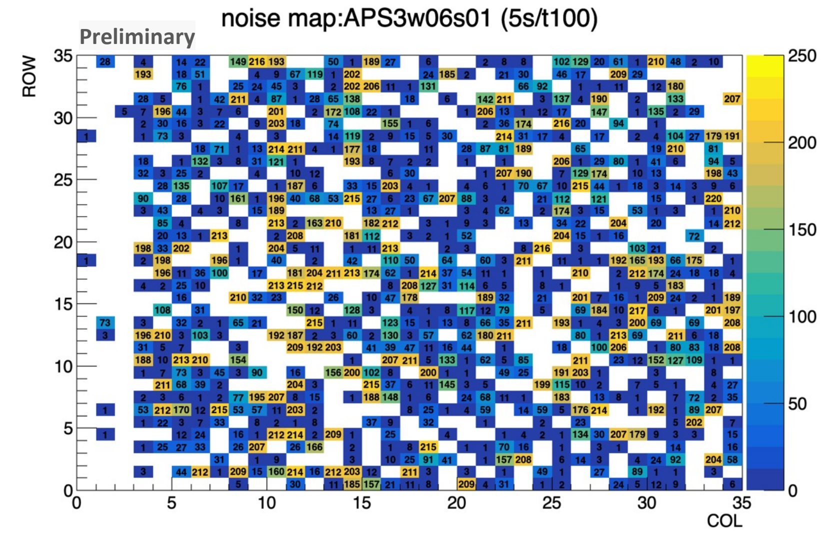




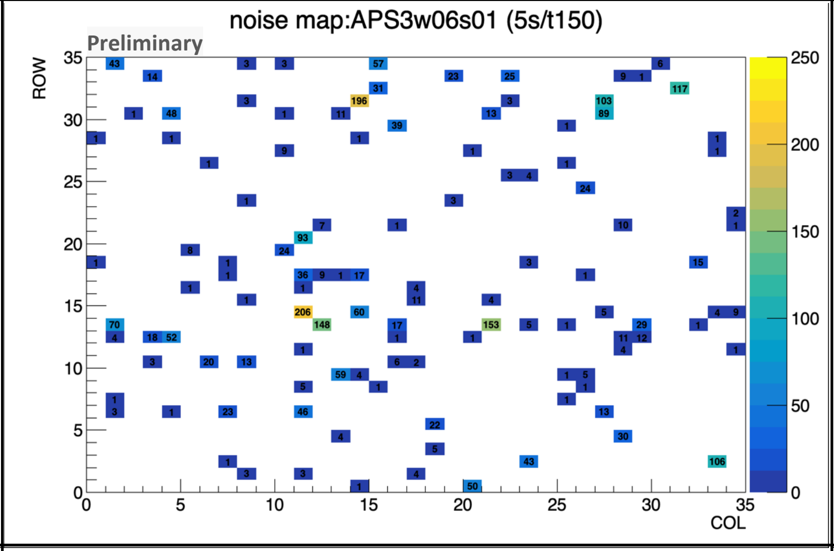


Noise Scan with respect to Threshold [100 mV – 300 mV]

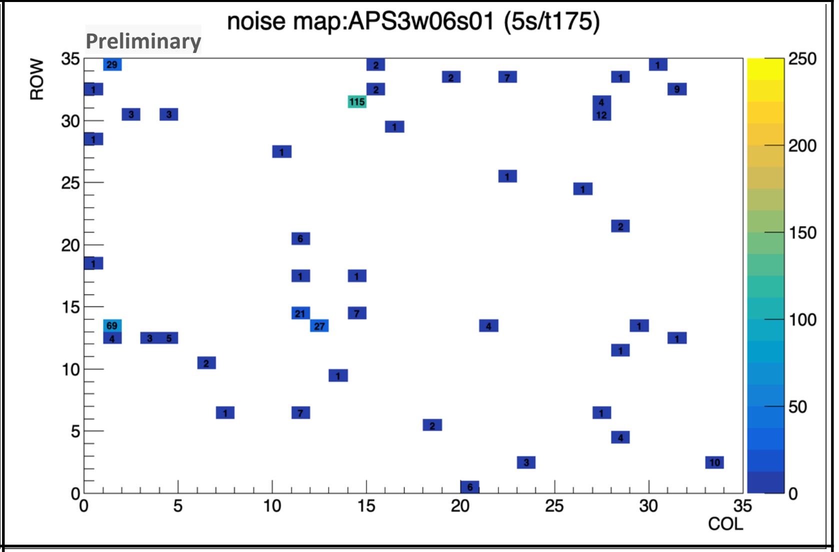
100 mV



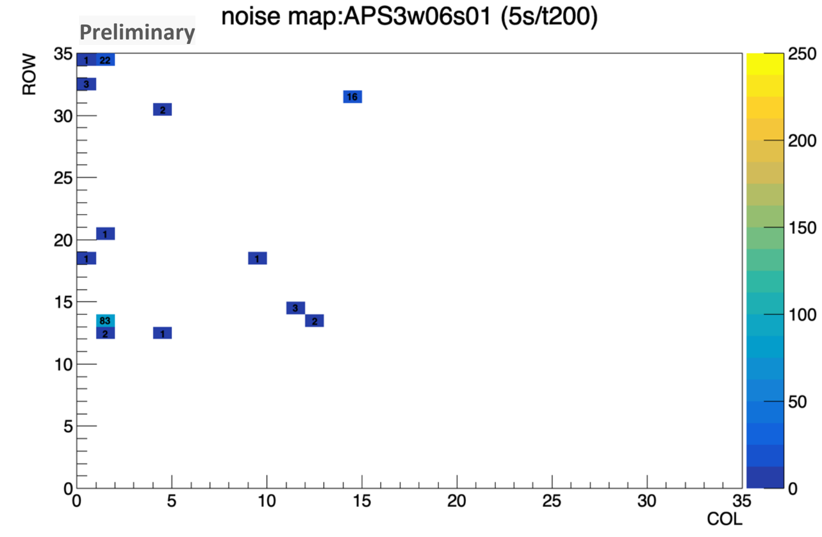
150 mV



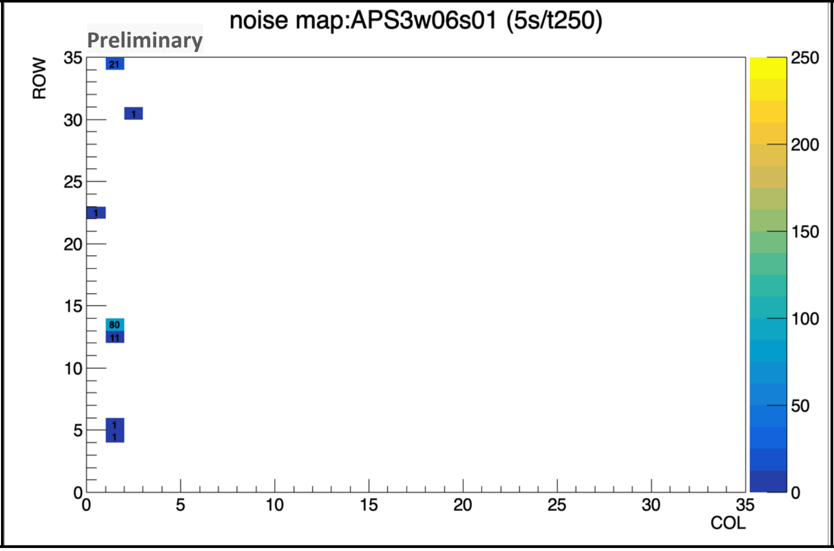
175 mV



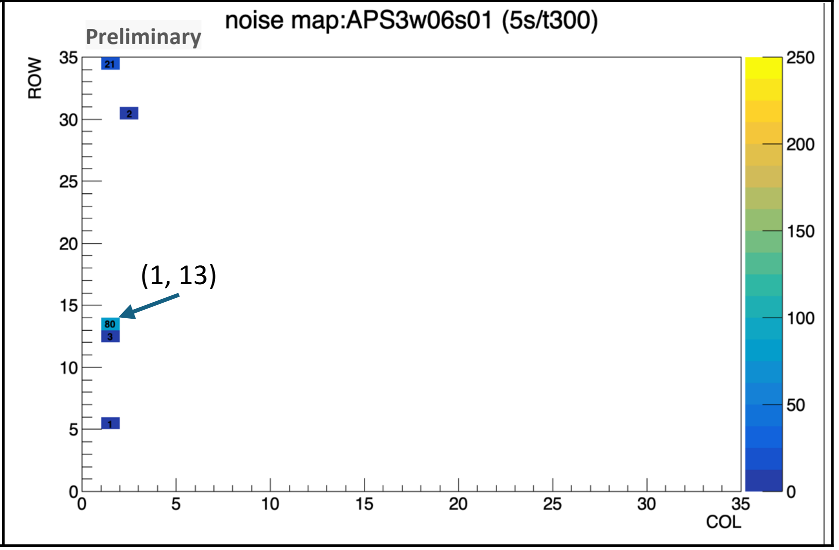
200 mV



250 mV



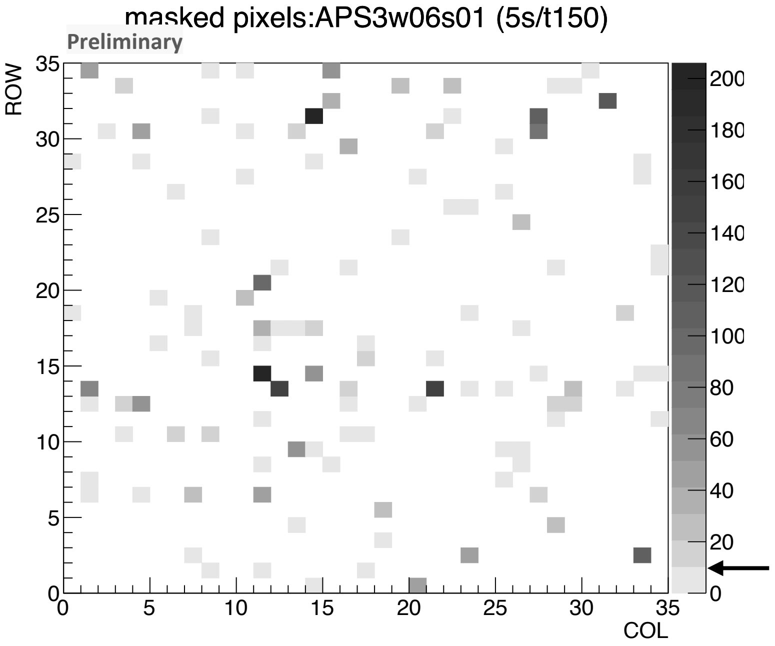
300 mV



Noise Scan: Masked Pixels

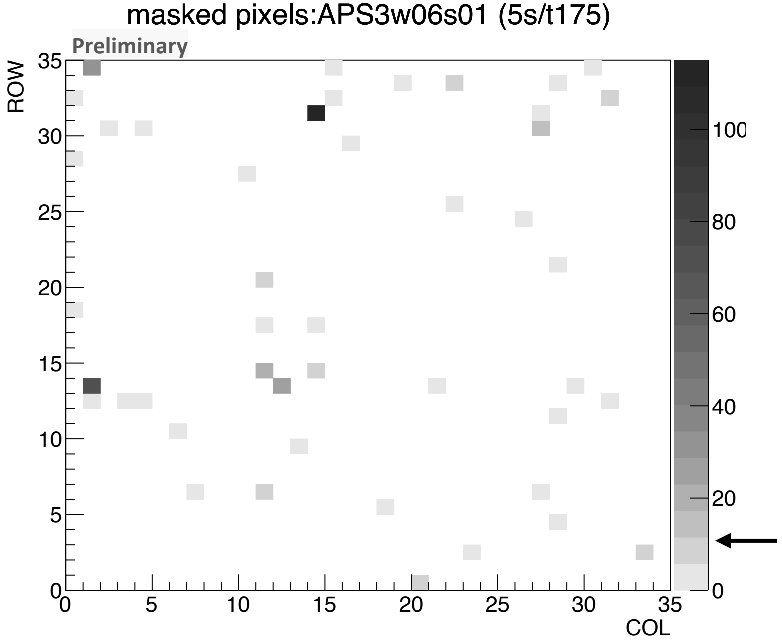
- Disable pixel : Noise > 10
- Used 200 mV threshold for source test and beam test

V_{th}= 150 mV



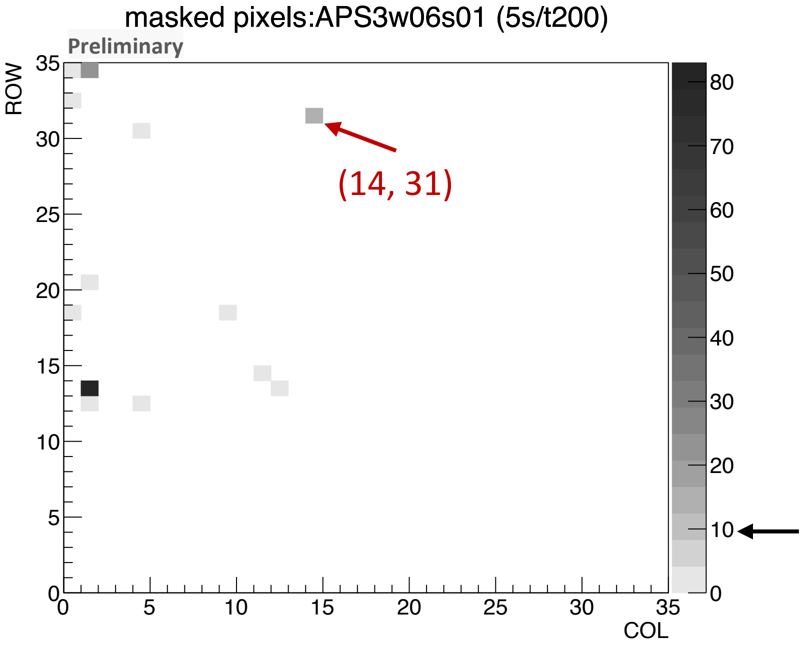
- Active pixels: ~ 96.5%
- 43/1225 pixels are disable.

V_{th}= 175 mV



- Active pixels: ~ 99.5%
- 6/1225 pixels are disable.

V_{th}= 200 mV



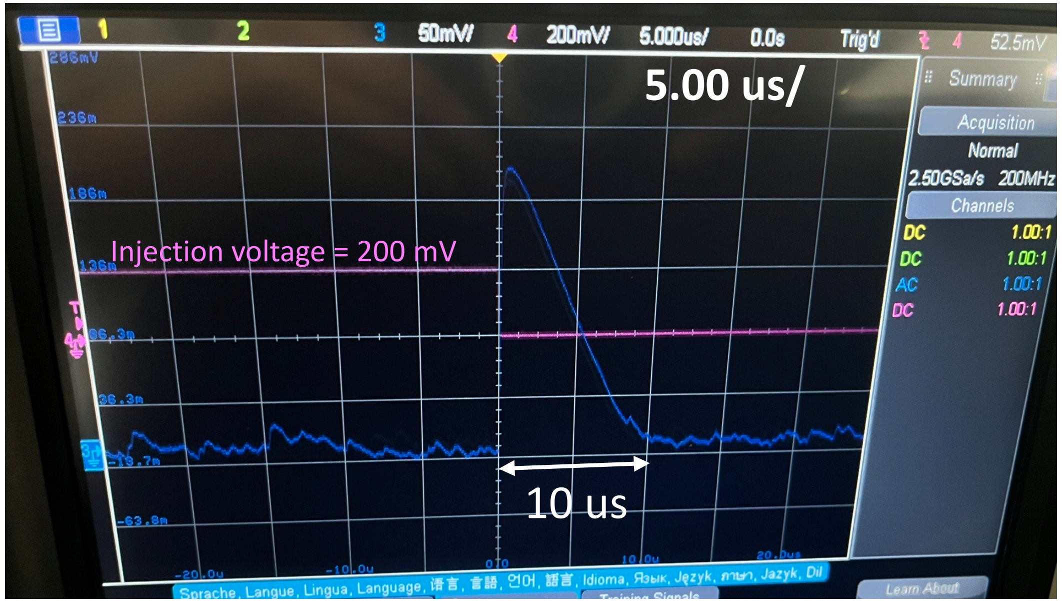
- Active pixels: ~ 99.8%
- 3/1225 pixels are disable.

→ Masked noisy pixel (14, 31)

R&D Goal

- M2: AstroPix chips prepared at the bench

1-2. Injection Scan

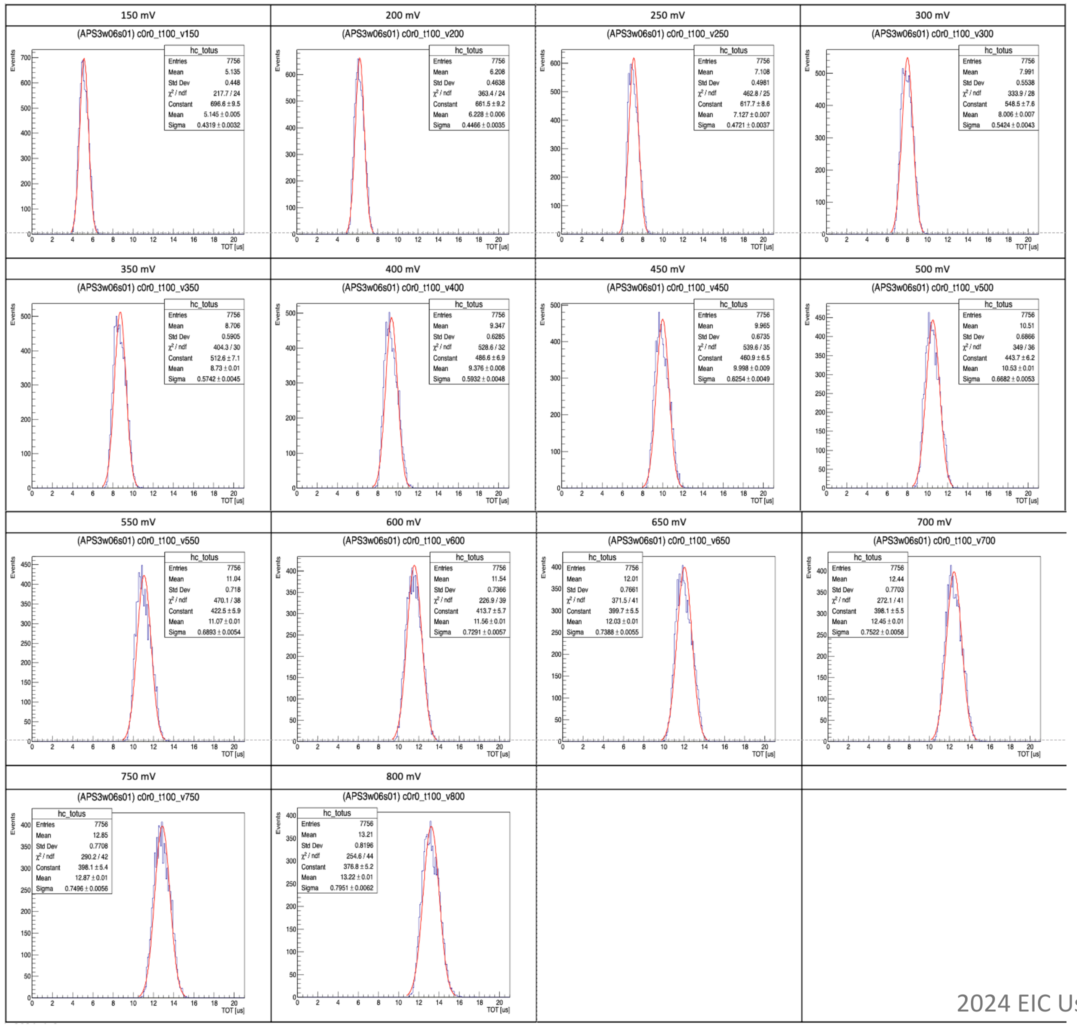


- Used Astropix v3 single chips: APS3w06s01
- Bias voltage: - 150 V
- LV supply
  - Digital and analog: 1.8 V
  - Gecco board: 2.7 V
  - Amplifier: 1.2 V
- Threshold: 100 mV
- With respect to injection voltages at (COL #, ROW #)
  - Column (0, 1, 2, 3, 4, 5, 6) & Row 0
  - 150 mV – 800 mV in steps of 50 mV
  - Time windows: ~ 90 secs for 1k events

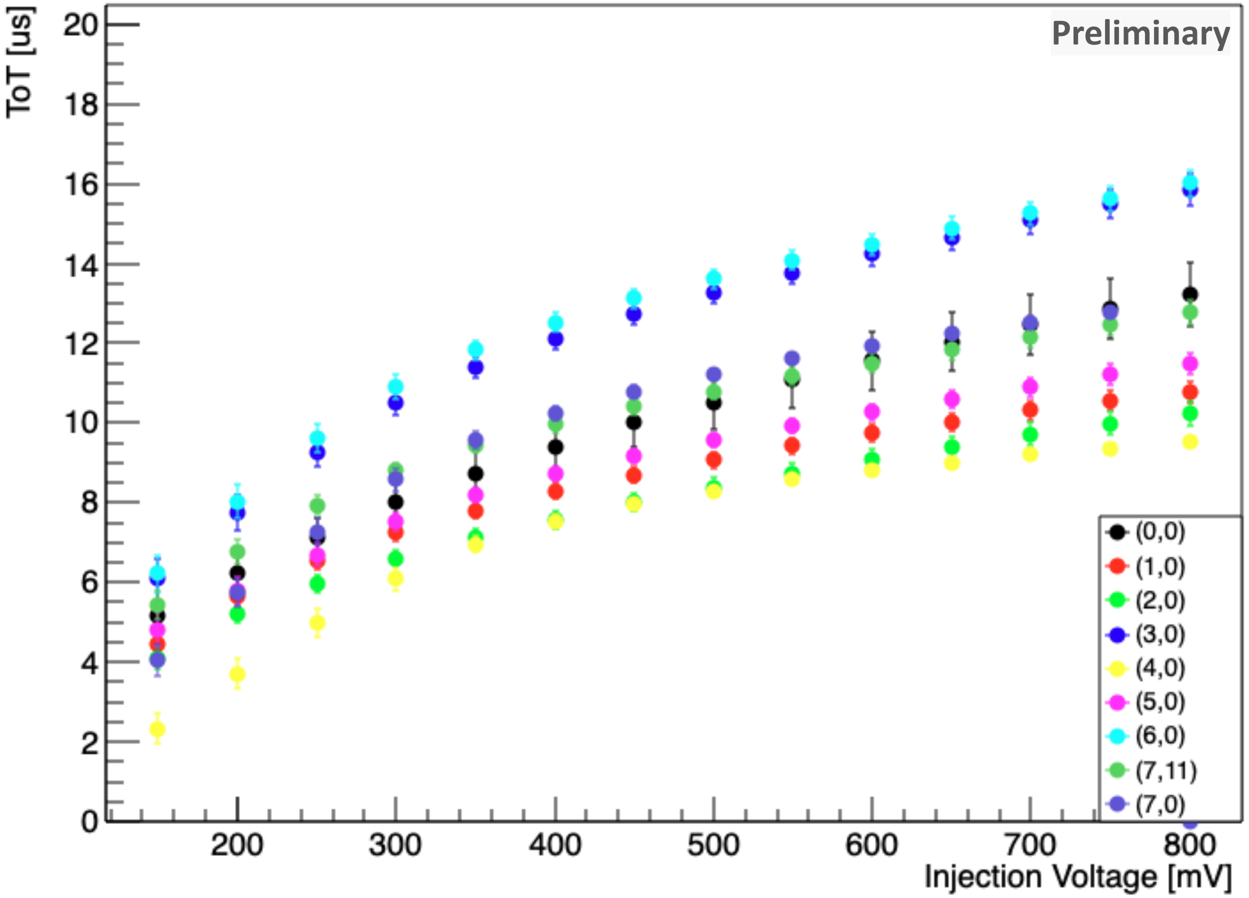
Injection Scan: Injection Voltage vs ToT [us]

- Column (0, 1, 2, 3, 4, 5, 6, 7) & Row 0 and [7, 11]
- ToT [us] as a function of injection voltages from 150 mV to 800 mV in steps of 50 mV.
- Fitting using gaussian function then mean and sigma values from fitting results are plotted.

- ToT spectra w.r.t various injection voltages at pixel (0, 0)



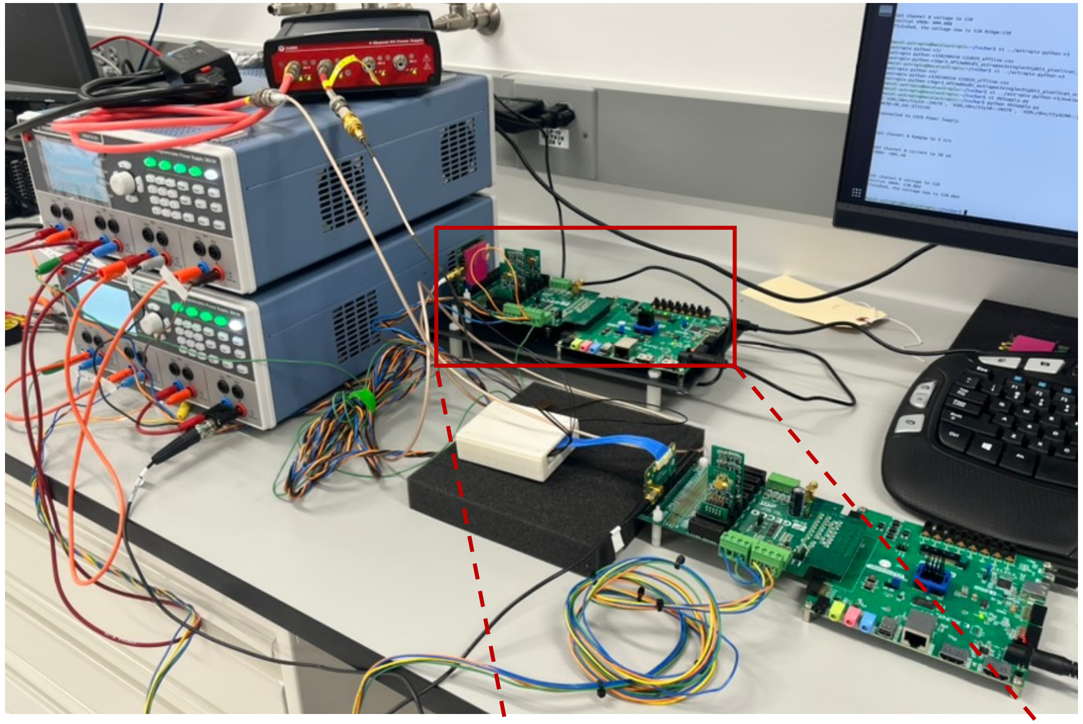
- ToT mean values as a function of various injection voltages

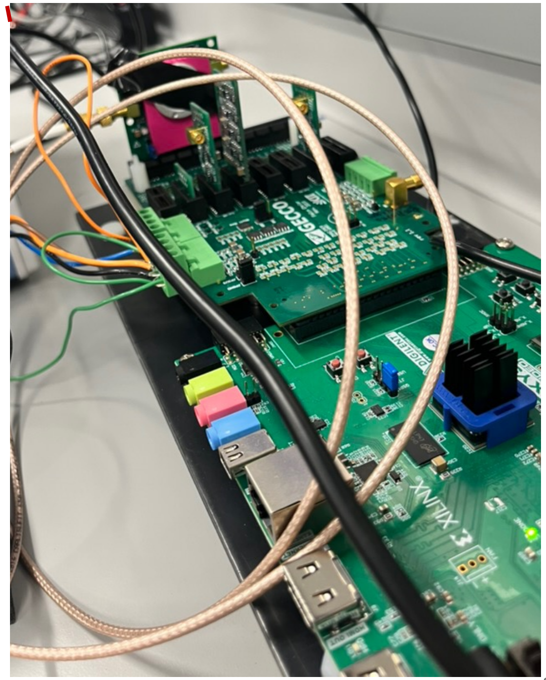


R&D Goal

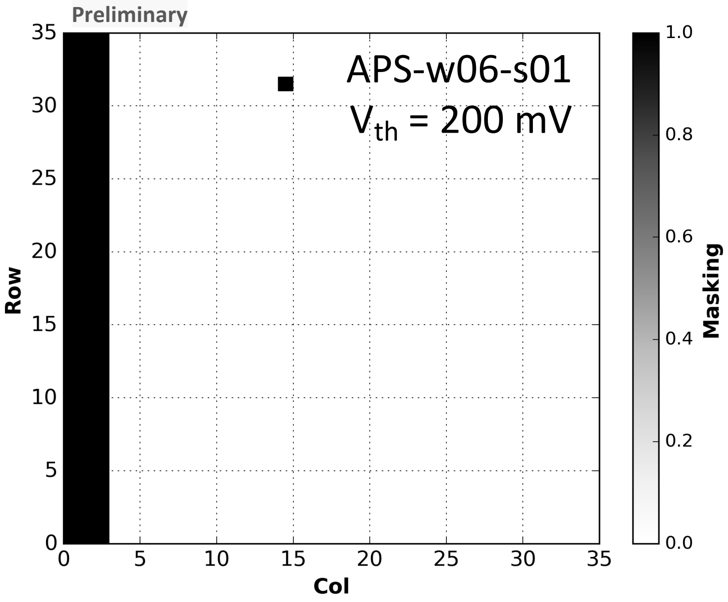
- M2: AstroPix chips prepared at the bench

1-3. Source Test using Am-241

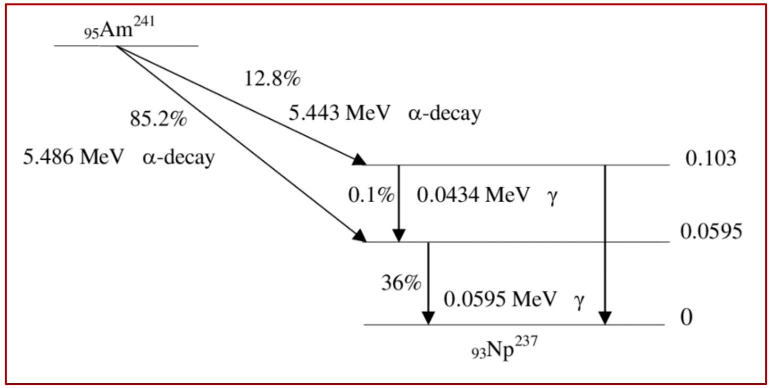




- Used Astropix v3 single chips: APS3w06s01
- Bias voltage: - 150 V
- LV supply
  - Digital and analog: 1.8 V
  - Gecco board: 2.7 V
  - Amplifier: 1.2 V
- Used threshold = 200 mV
- Masked first three column pixels



Am-241 Result: 32 × 35 pixels

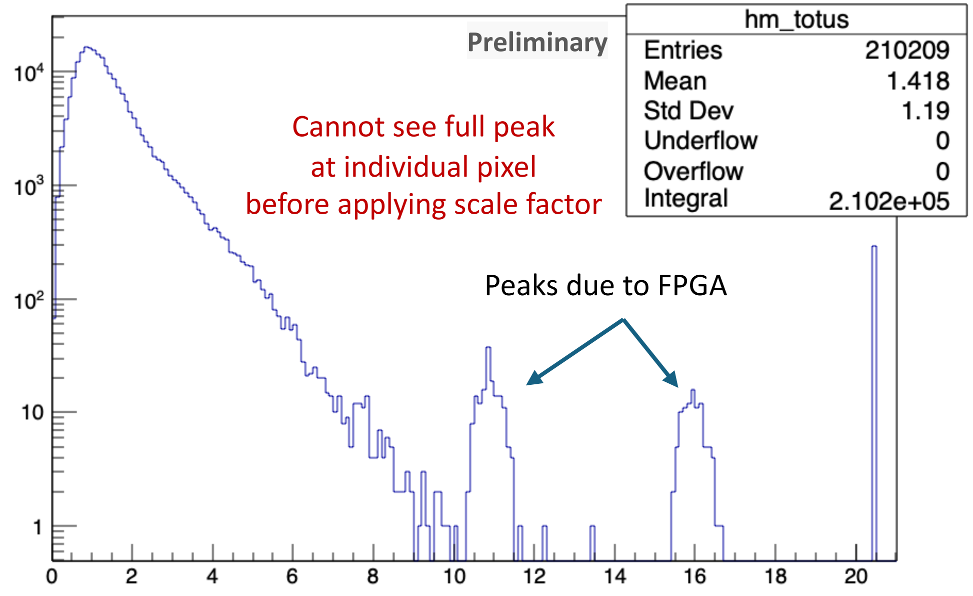


- Data-taking for 12 hours with 32 × 35 pixels (1,120 pixels)
- ToT distribution for all pixels after applying to scale factor (from proton result)
- Full peak, fitted with gaussian function

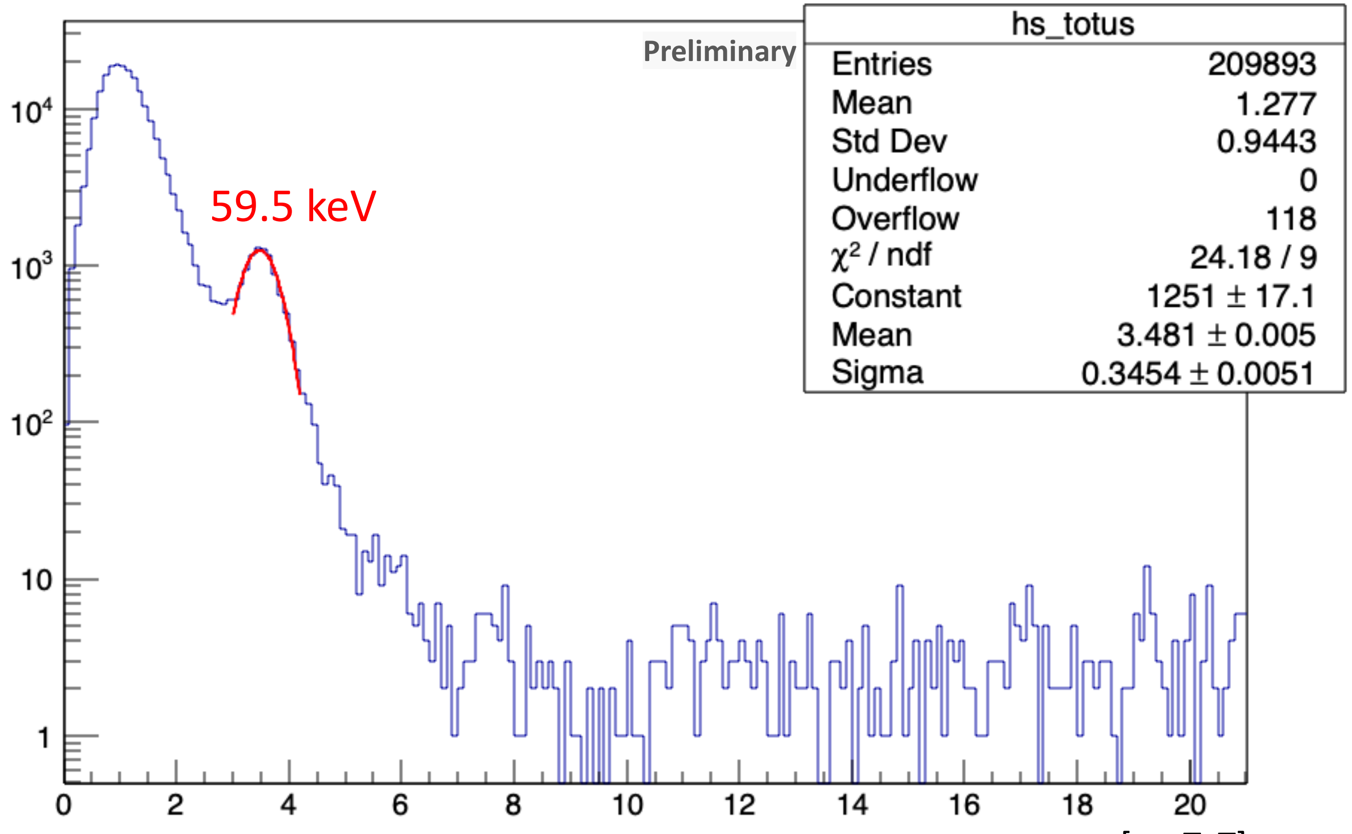
- A **calibration constant** is calculated:
  59.5 [keV] /3.481 [us, TOT]= 17.09 [keV]/[us, ToT]

- $\mathbf{E_{res}}$ **(FWHM)** $= 2.35\times\frac{Sigma}{Mean}$ = 23.3 % @ 59.5 keV

ToT distribution of all pixels **before** applying scale factor

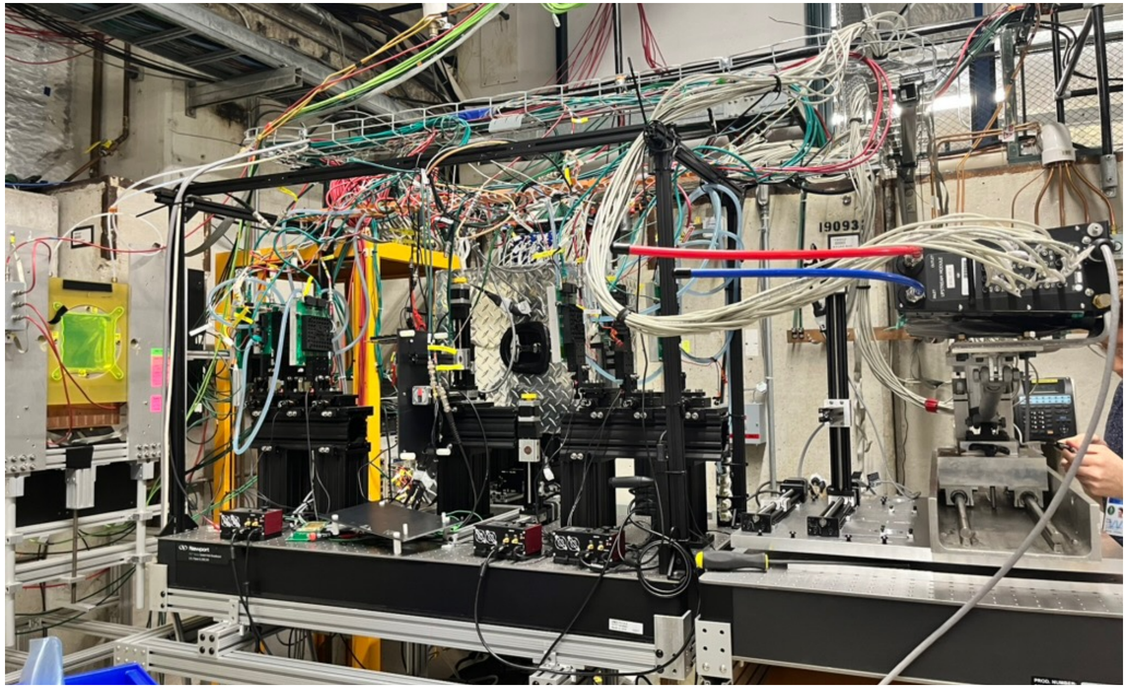


ToT distribution of all pixels after applying scale factor



Beam Test R&D Goal

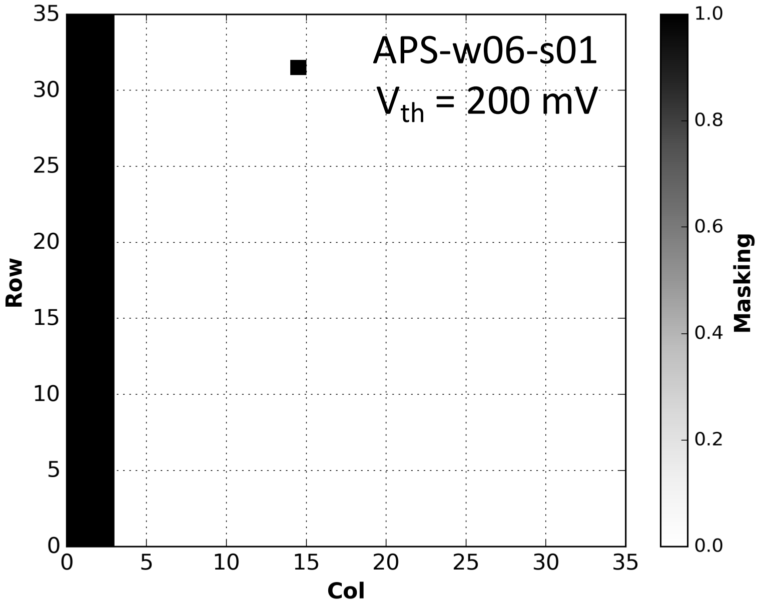
- M6: Integrated system commissioned with proton beam
  - AstroPix v3 single chip with Baby BCAL
  - Double layer with two AstroPix v3 single chips



2. Beam Test at FNAL

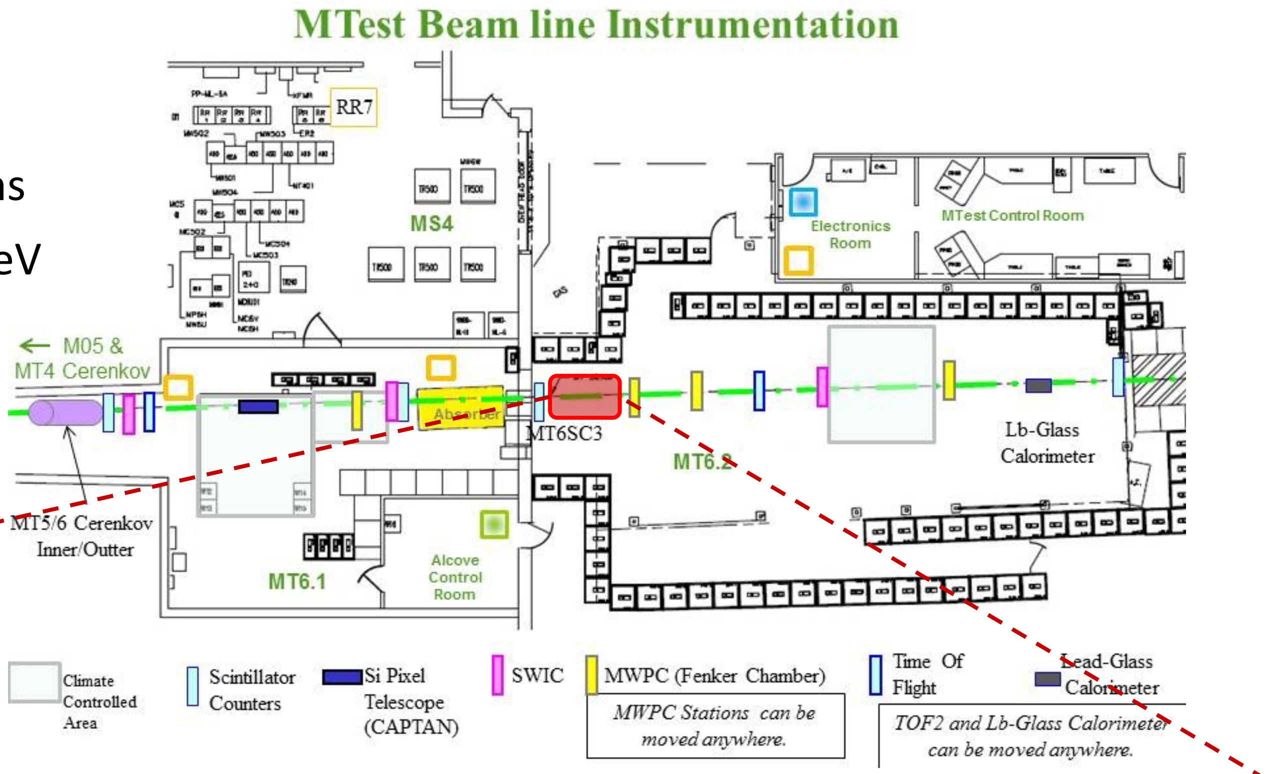
On June 13-18

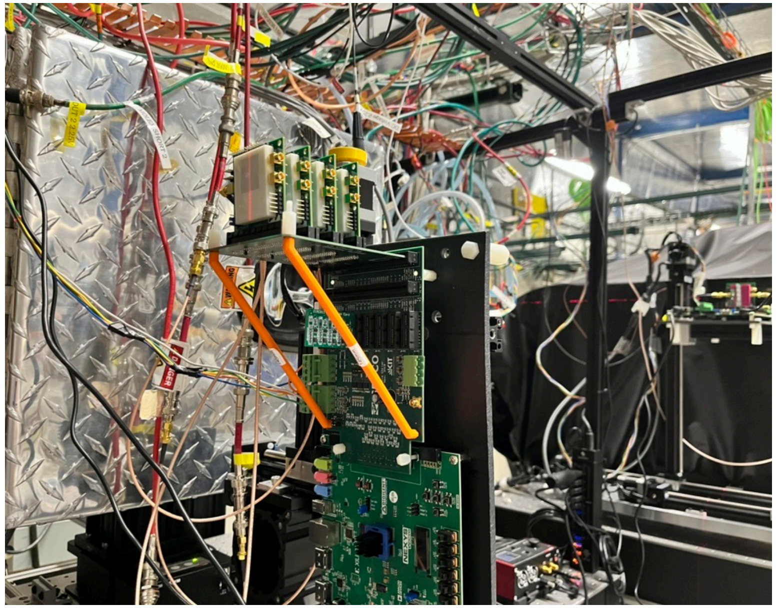
1. Single layer in front of Baby Bcal
   1. MIP response
   2. Astropix+Baby Bcal: coincident event
2. Double layer using two v3 single chips
   1. Coincident hits

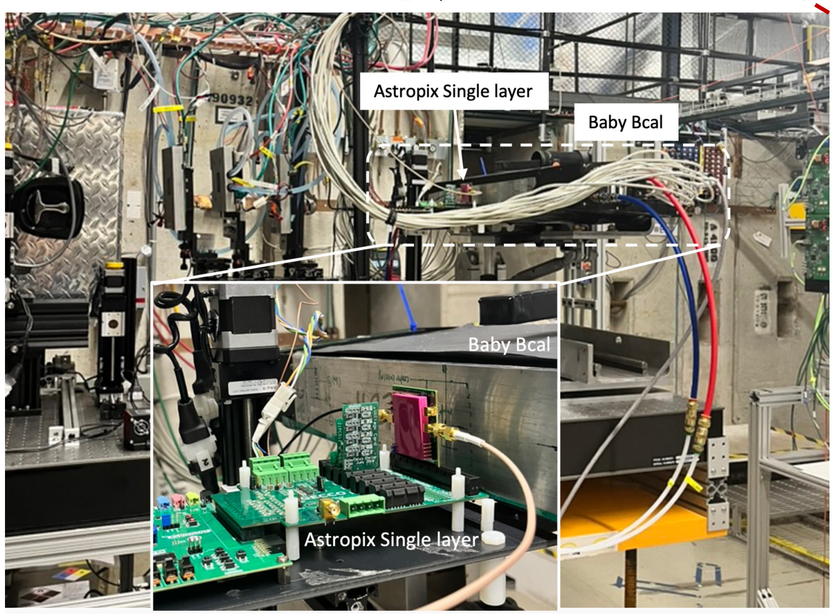


Beam Test Setup @FNAL

- ‘Mtest’ Beam line provides particles from 120 GeV protons to secondaries (electrons, muons, and pions) of ~ 200 MeV
    - Single 4.2 s long spill per every 60 seconds
- FNAL instrumentation system
    - Segmented Wire Ionization Chambers (SWICs); 2 mm wire spacing for tracking
    - Scintillator counter for triggering
    - Two Cherenkov detectors for PID

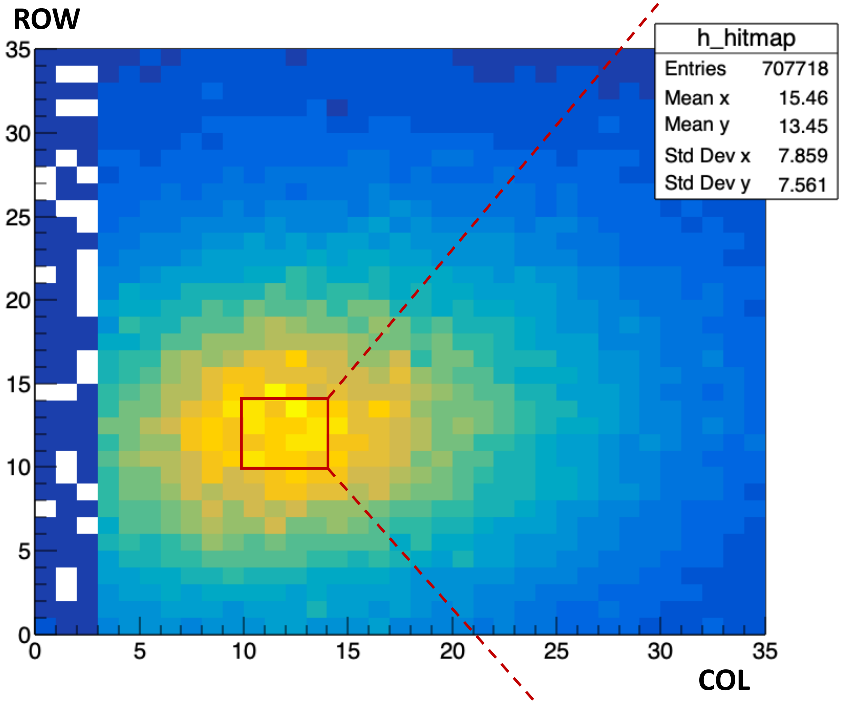


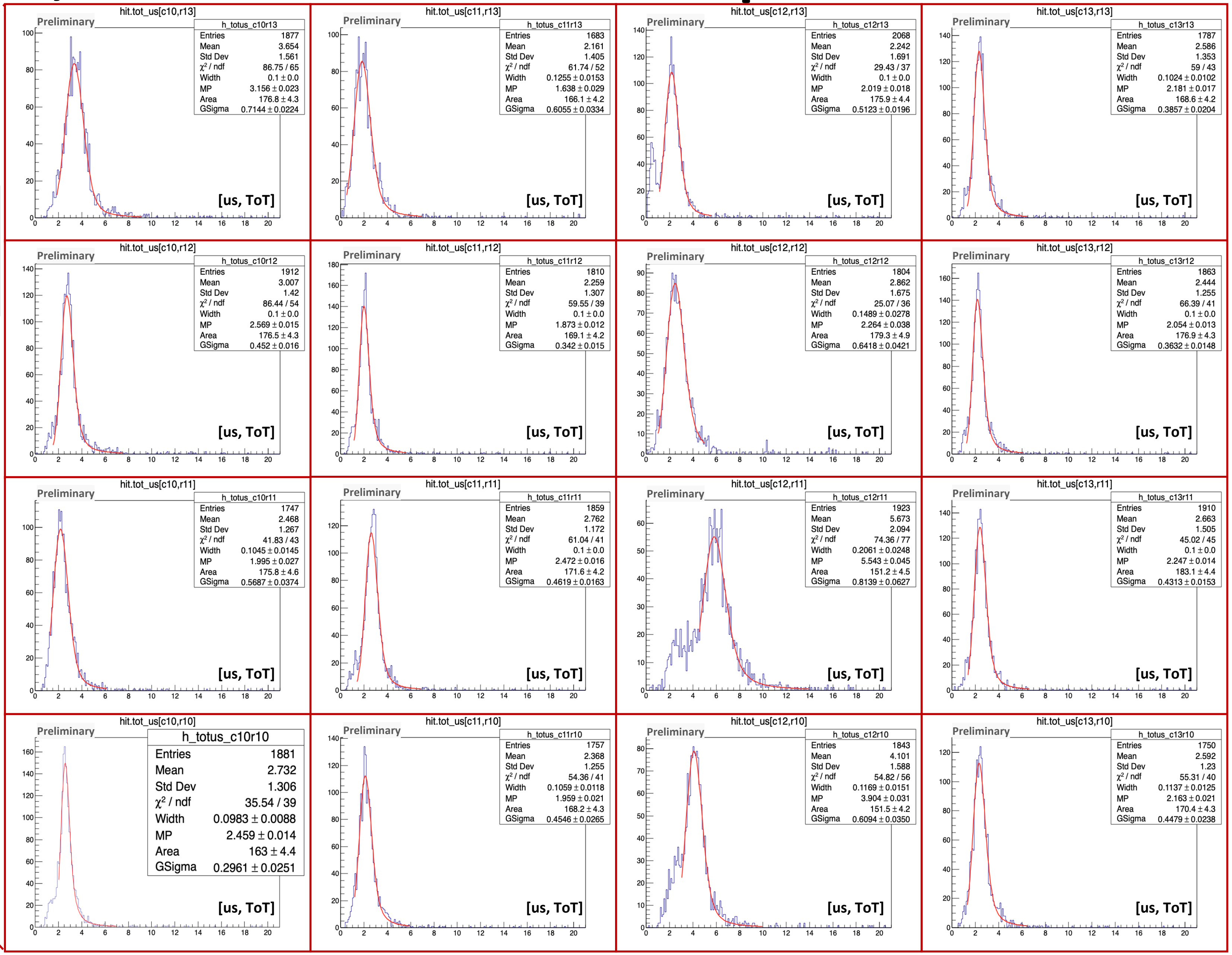




120 GeV Proton: Astropix, ToT Distributions of 4×4 pixels

- 4×4
  - Col 10−13
  - Row 10−13



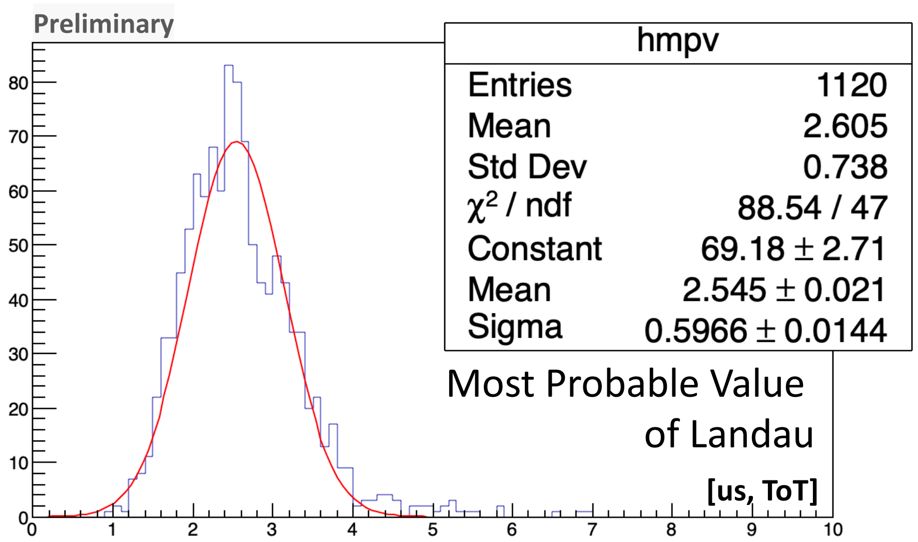


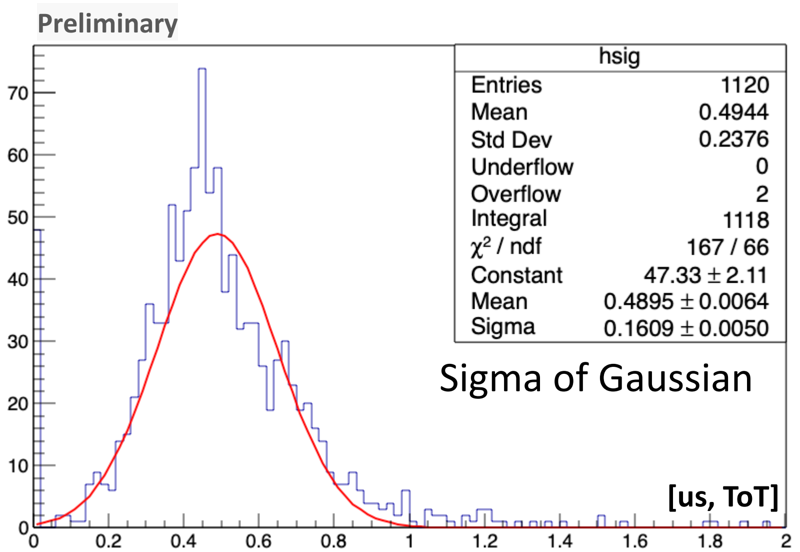
- Fit with landau convoluted with gaussian function on ToT distribution

120 GeV Proton: Astropix, 32×35 pixels

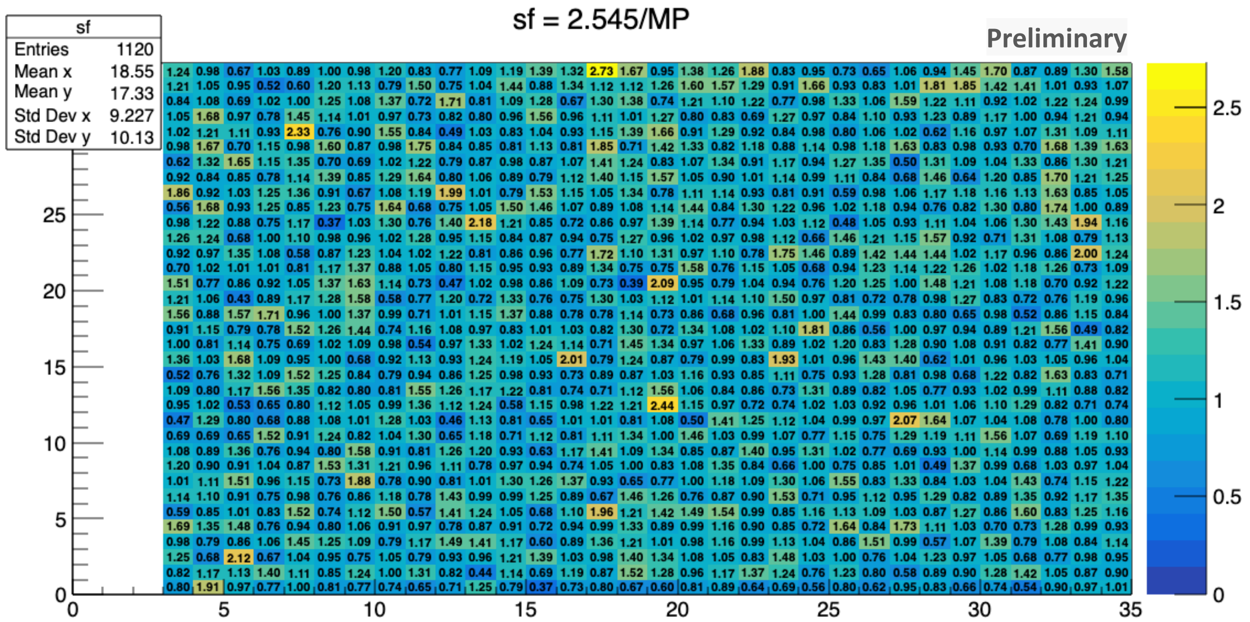
- 32×35 (1,120 pixels)
  - Col 3–24
  - Row 0–35

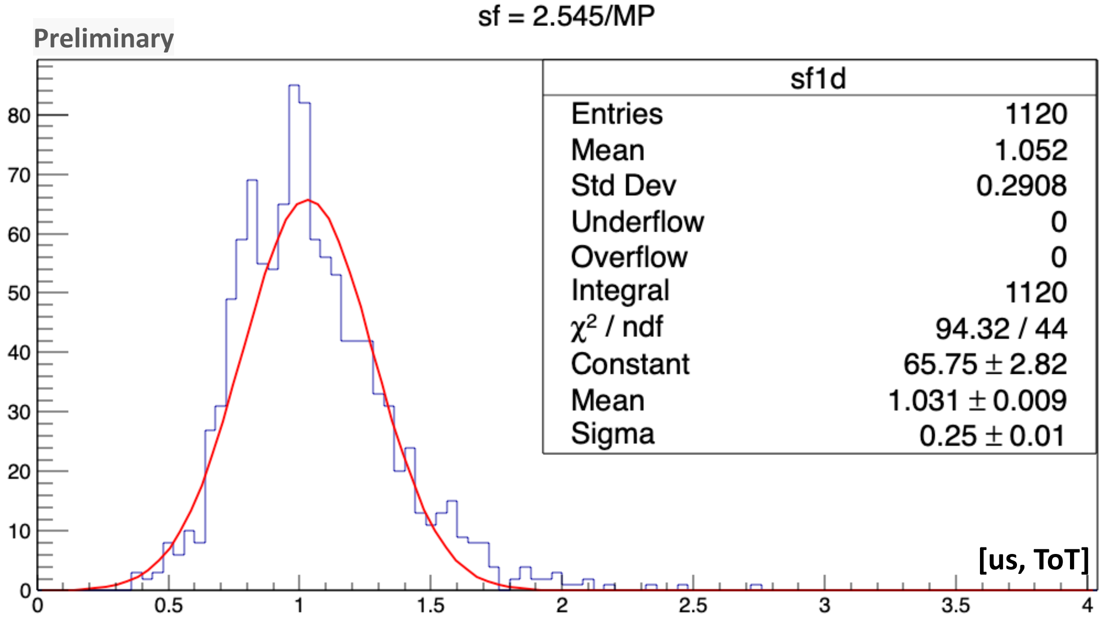
- Fit with landau convoluted with gaussian function on ToT distribution for all pixels





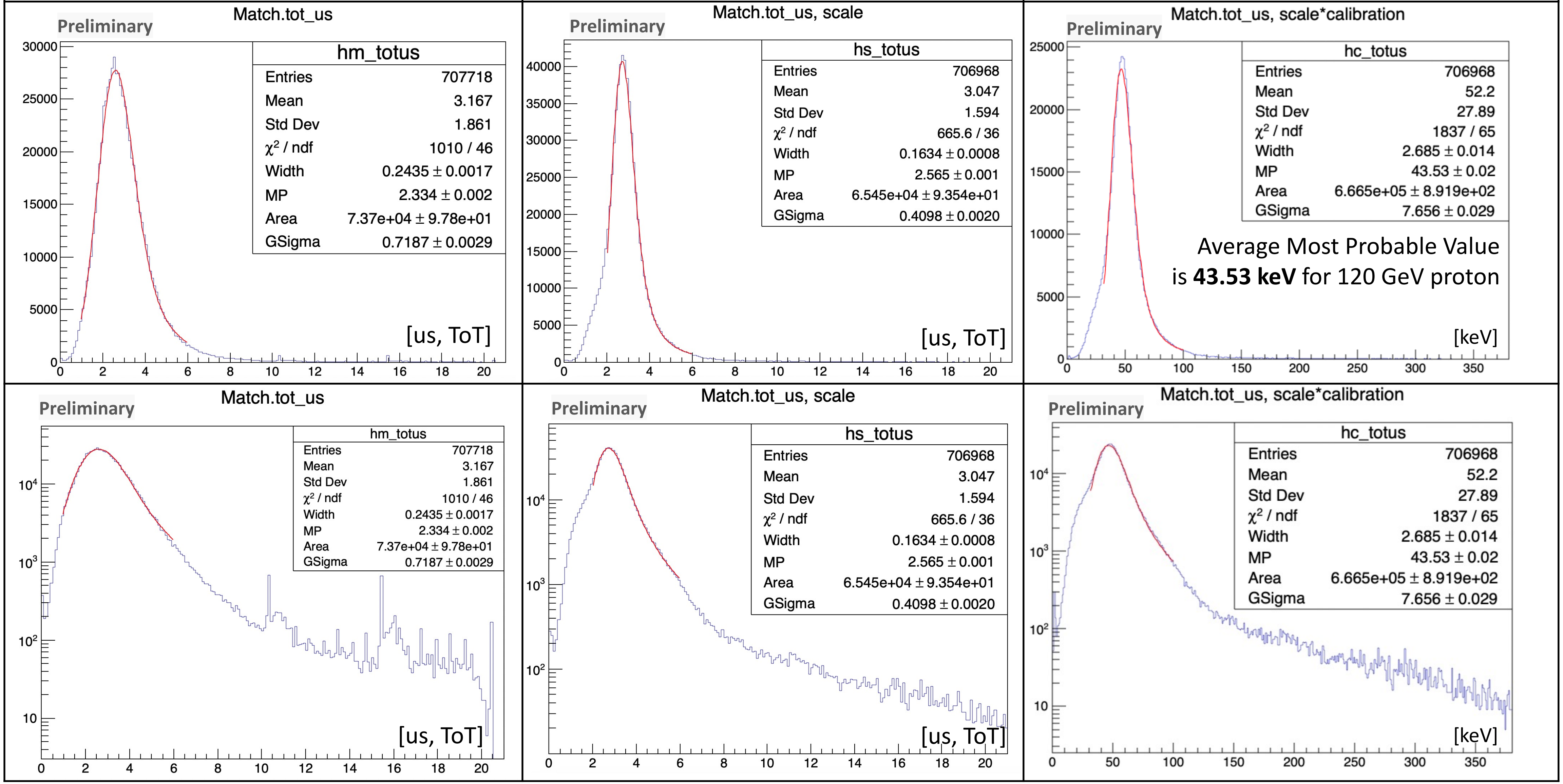
- Scale factor (sf), defined as mean of Most probable value for all pixels/Most probable value of each pixel





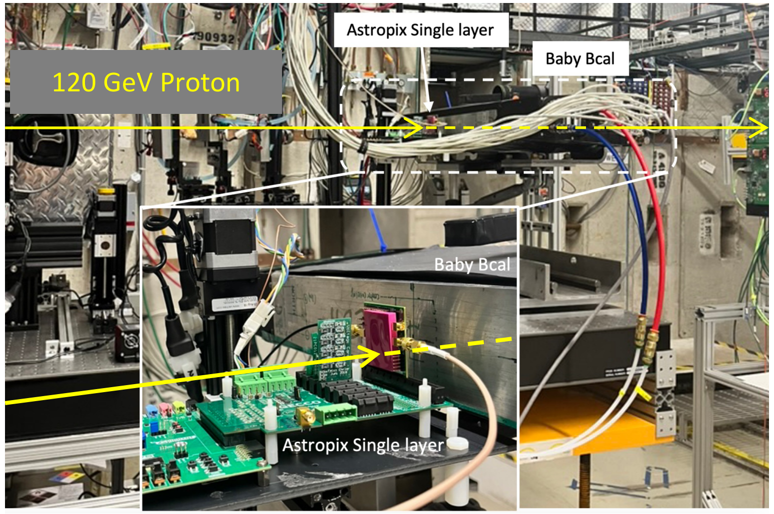
120 GeV Proton: Astropix, Energy Distribution of 32×35 pixels

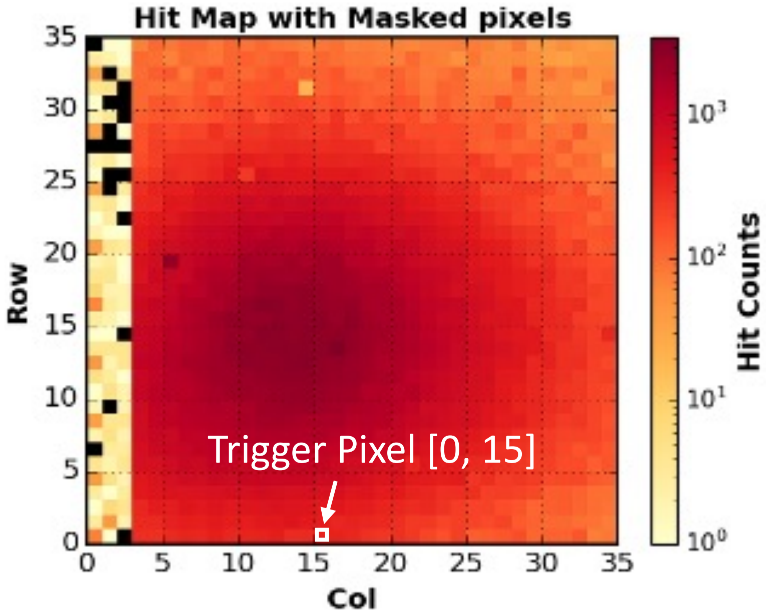
Before applying scale factor	After applying scale factor	After applying scale factor and calibration constant



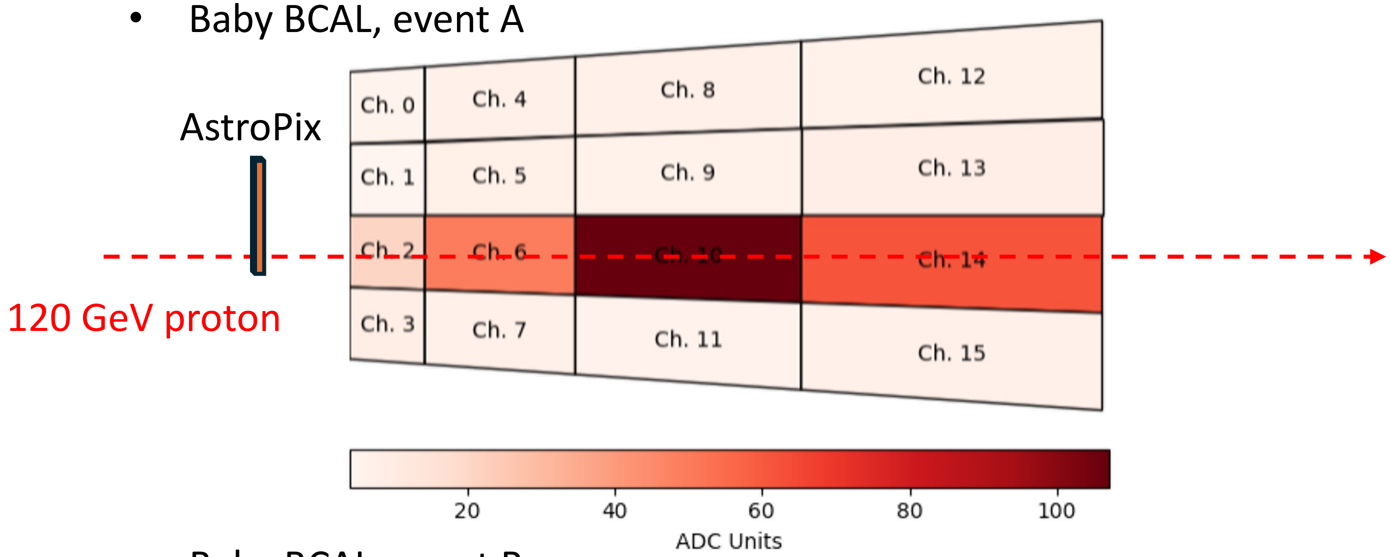
120 GeV Proton: Coincident Event Display of AstroPix and Baby BCAL

- Baby BCAL triggered by analog signal from [0, 15] pixel of Astropix

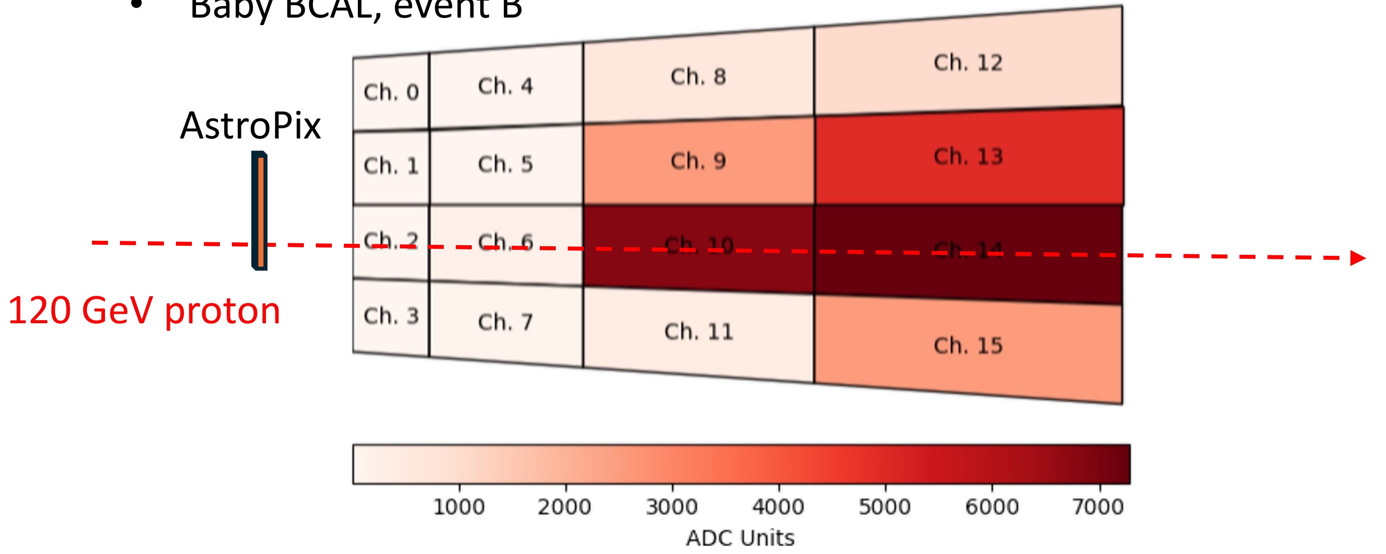




- Baby BCAL, event A

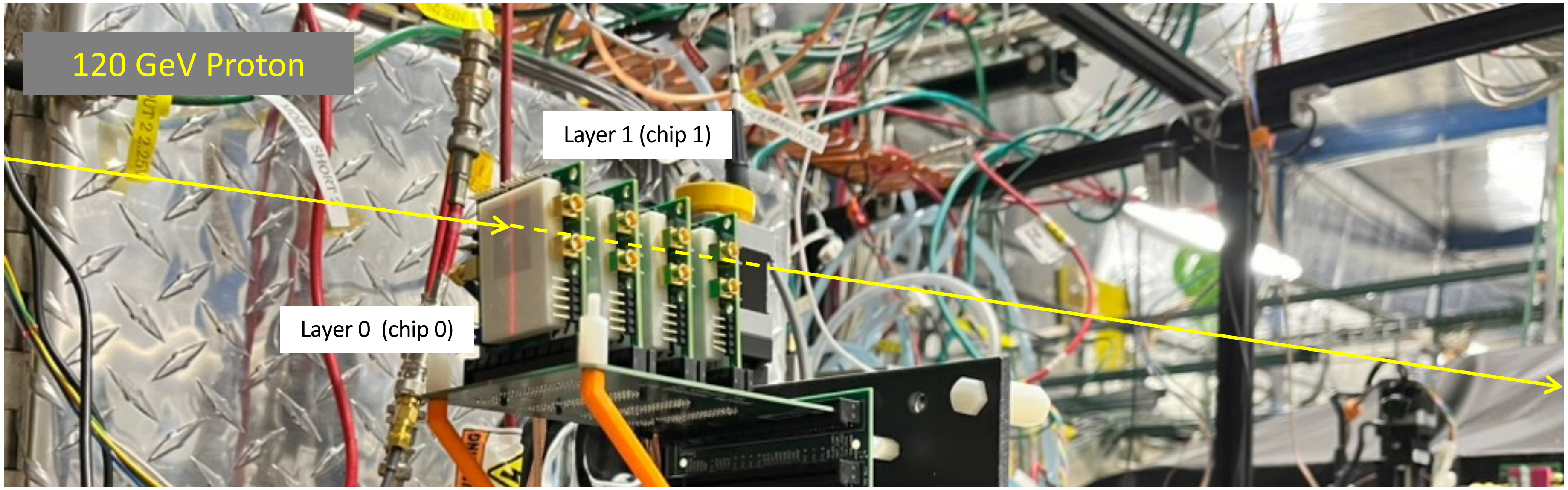


- Baby BCAL, event B

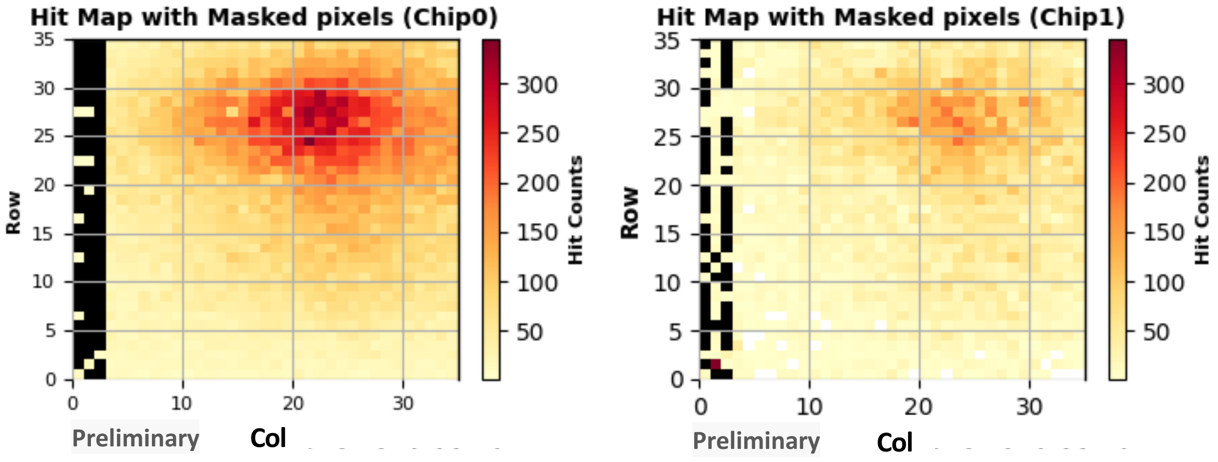


*Example plot of 120 GeV proton event display from an integrated system of Baby BCAL and a single-layer AstroPix v3 chip by Henry Klest

120 GeV Proton: Double Layer, Hit Map of Coincident Hit

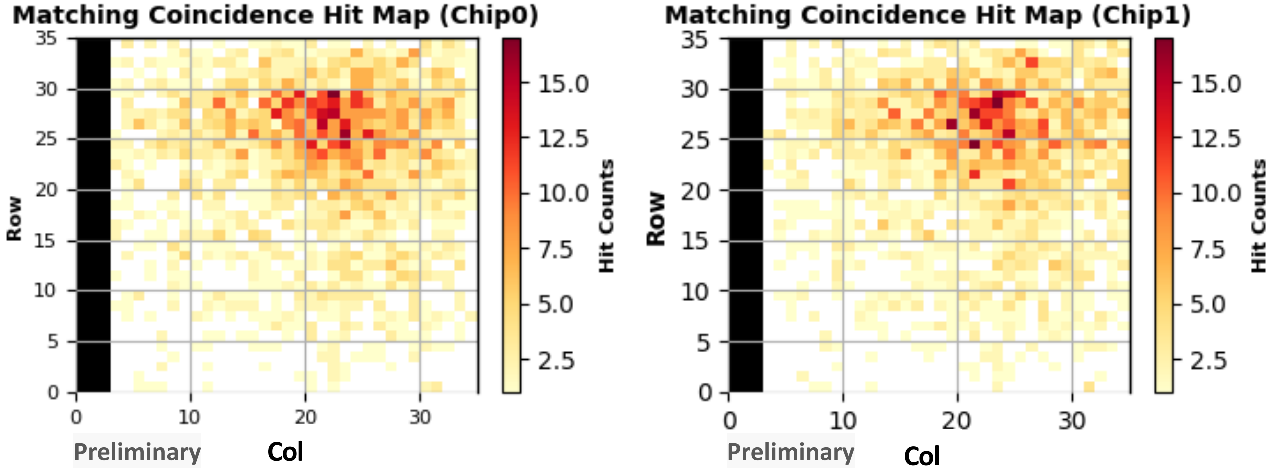


- Matching hit using col&row information on same chip



- Matching hits with time stamp <2 and ToT error < 10%

- Matching coincident hit between chip0 and chip1



- Matching hits with location difference < 3 and time stamp difference < 5

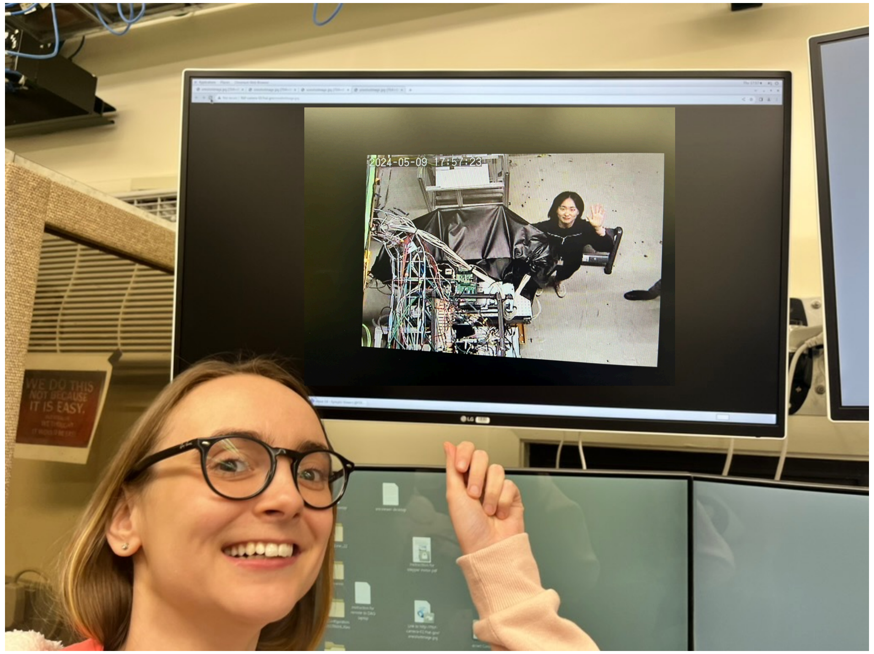
Summary

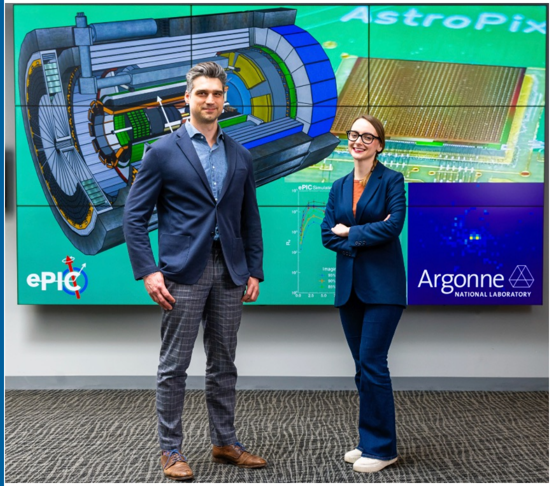
- The performance of Astropix v3 single chip is measured at ANL:
  - Noise scan: measured noisy pixels
  - Injection scan: measured a relation between injection voltage and individual pixel output
  - Source test: measured a calibration constant of 17.09 [keV]/[us, ToT]
- Using 120 GeV proton beam at FNAL
  - Astropix v3 single chip,
    - Measured beam position by hit map and average MIP deposited energy of 43.53 keV

    → Extract MIP response
  - Astropix and Baby BCAL,
    - Measured coincident hits between Astropix and Baby BCAL

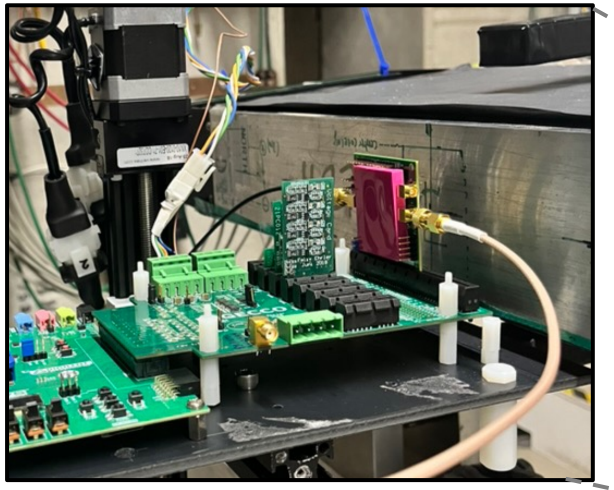
    → Proof-of-concept tested in the beam
  - Double layer of two Astropix v3 single chips
    - Measured coincident hits between double layer
- Collaboration paper is in progress during this summer.

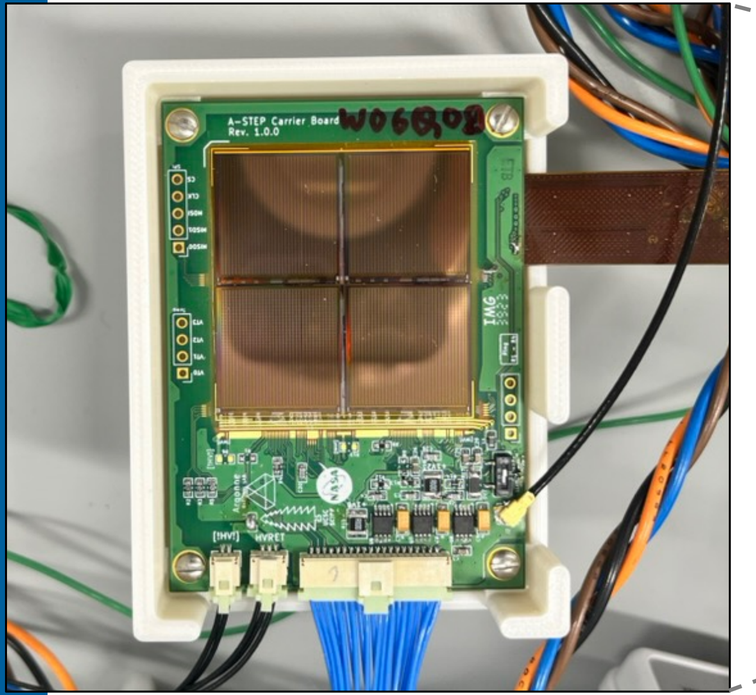
Thank you

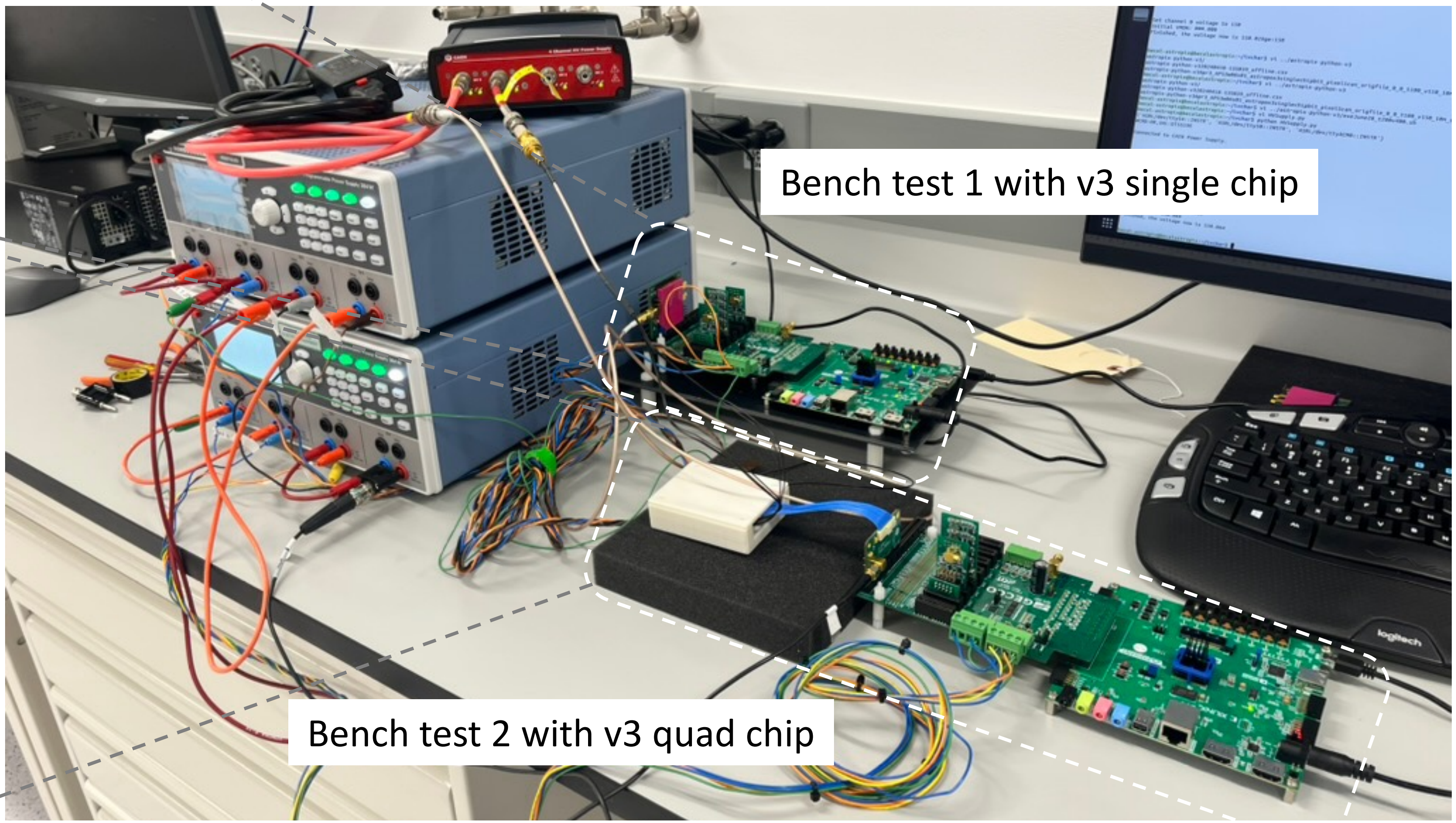




Bench setup **at ANL** with AstroPix







ePIC / EIC Project Detector R&D Day, **by Maria Zurek**
https://indico.bnl.gov/event/22388/contributions/87696/attachments/53512/91595/eRD115_ImagingCal_Zurek.pdf

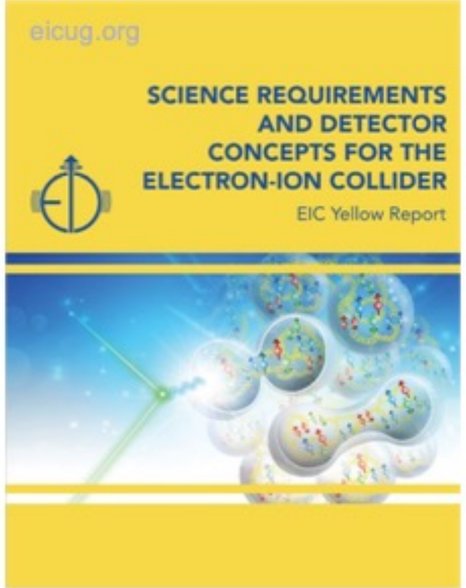
EIC Calorimetry Requirements

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



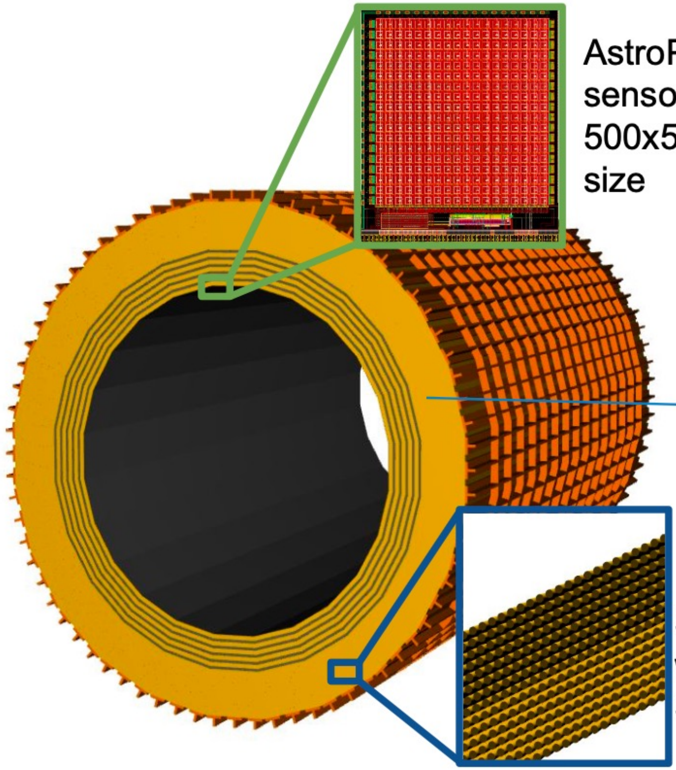
Challenges: e/π PID, γ/π^0 discrimination, available space

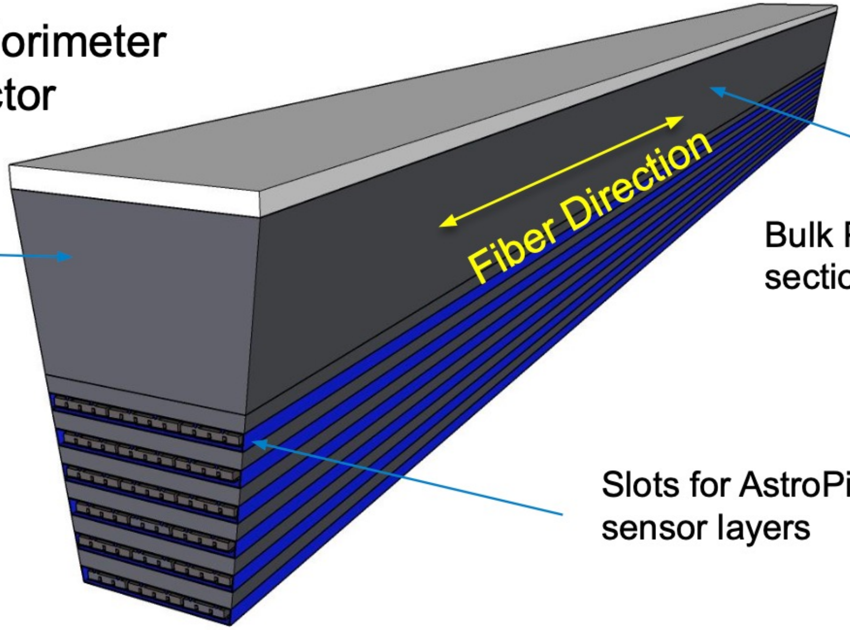
DSC-barrel Ecal by Maria Zurek@Electron-Ion Collider User Group Meeting 2023
https://indico.cern.ch/event/1238718/contributions/5431950/attachments/2691871/4671467/ePIC-July-WAW-%20Zurek.pdf

Geometry

ePIC

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





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

U.S. DEPARTMENT OF ENERGY Argonne National Laboratory is a U.S. Department of Energy laboratory managed by UChicago Argonne, LLC.

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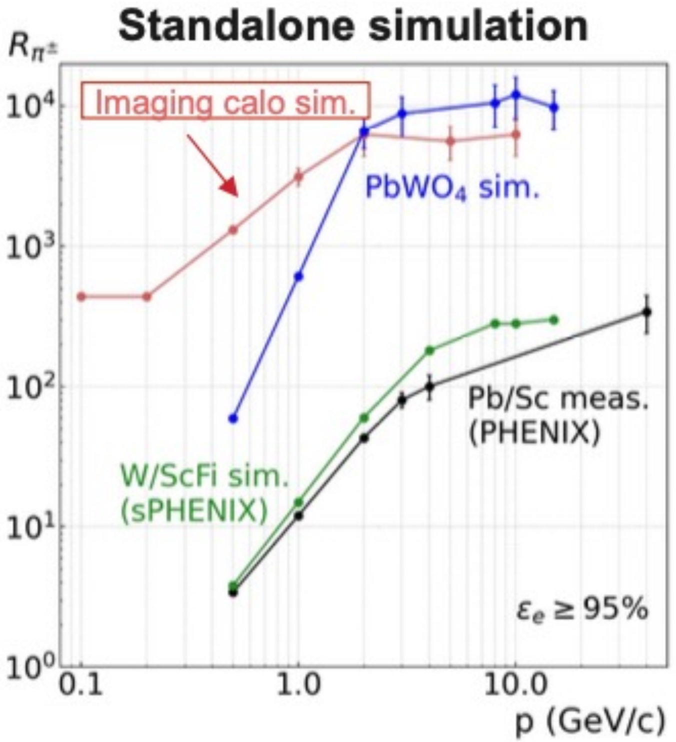
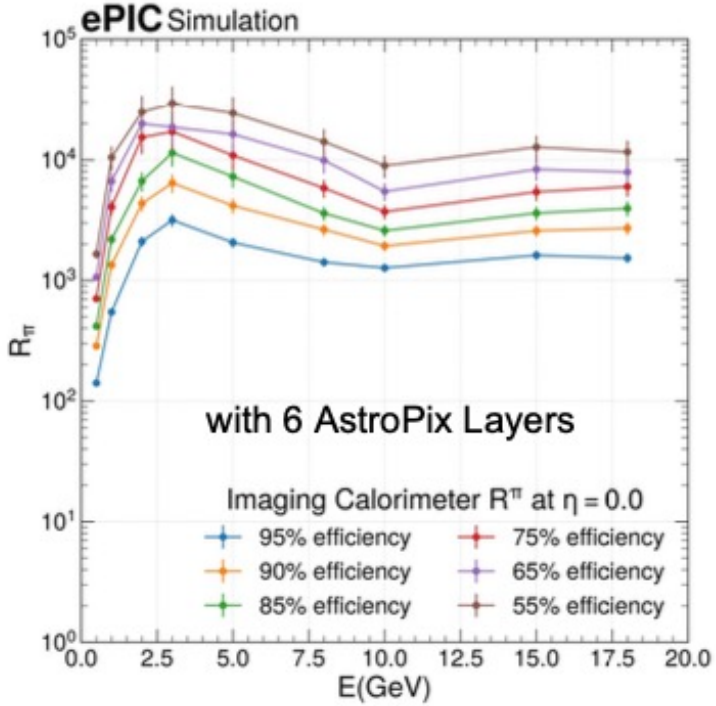
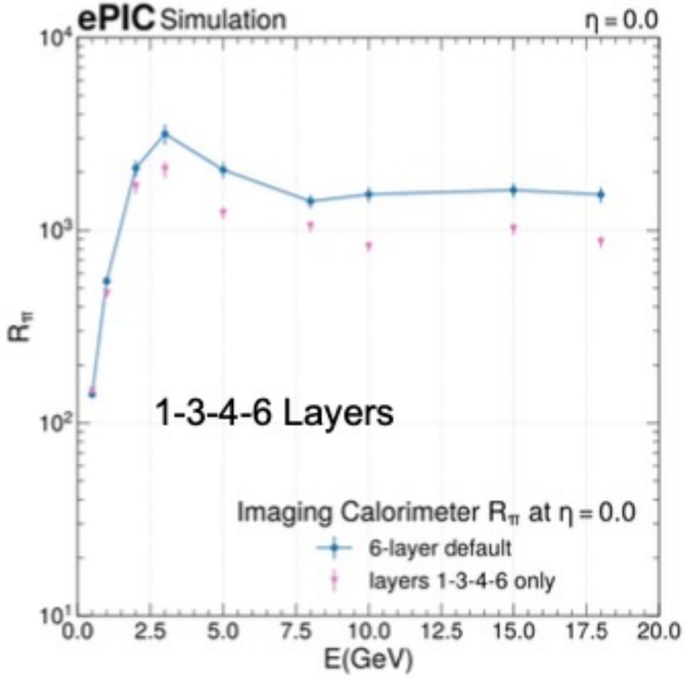
Barrel Imaging Calorimeter: Performance Example



Realistic ePIC simulation





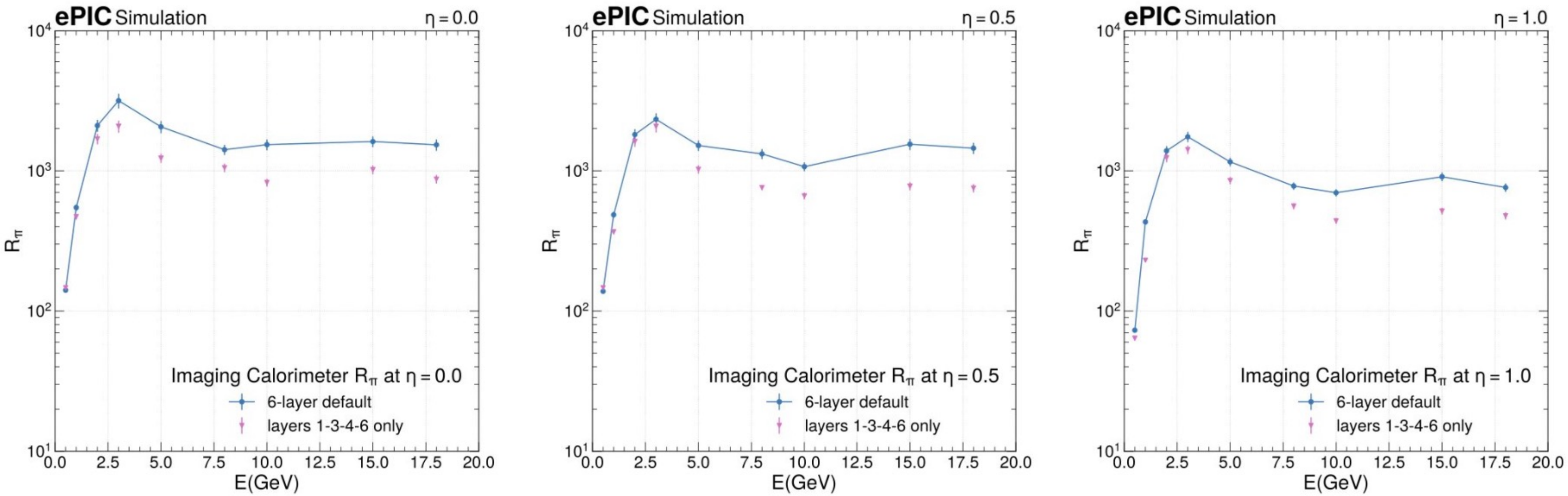
- **Goal:** Separation of electrons from background in Deep Inelastic Scattering (DIS) processes
- Method: **E/p cut (Pb/ScFi) + Neural Network** using 3D position and energy info from imaging layers

- e-π separation exceeds **10³** in pion suppression at **95% efficiency** above 1 GeV in realistic conditions!

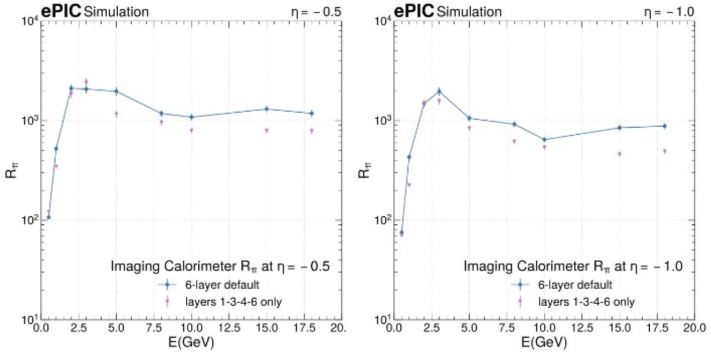
DSC-barrel Ecal by Maria Zurek@Electron-Ion Collider User Group Meeting 2023
https://indico.cern.ch/event/1238718/contributions/5431950/attachments/2691871/4671467/ePIC-July-WAW-%20Zurek.pdf

Performance with reduced number of layers

e/π separation at 95% efficiency



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



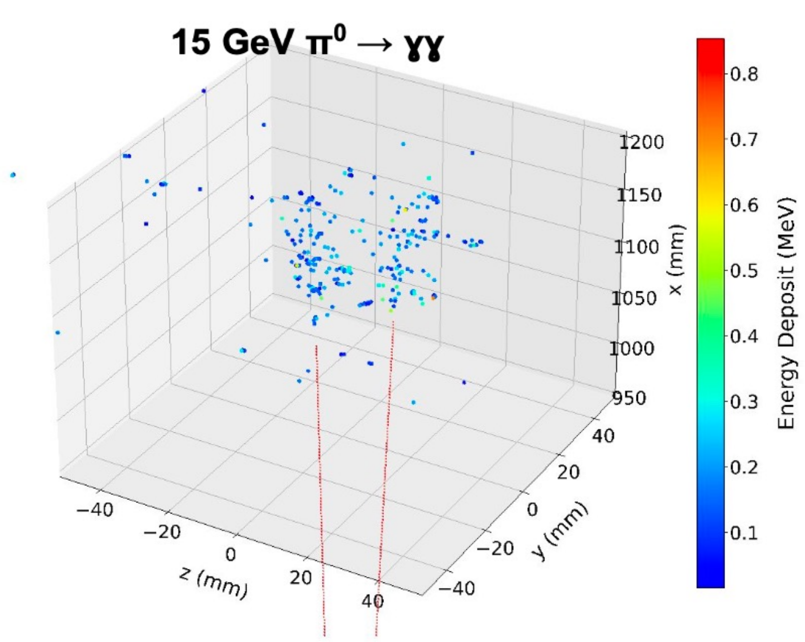
Default configuration exceeds 10^3 pion rejection almost everywhere

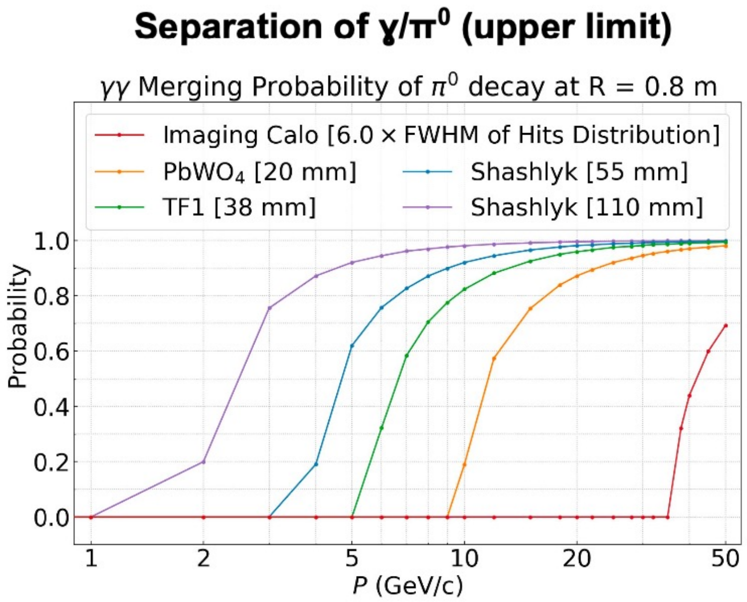
4-layer alternate still performs relatively well at lower energies (where most rejection is needed), larger degradation at higher energies

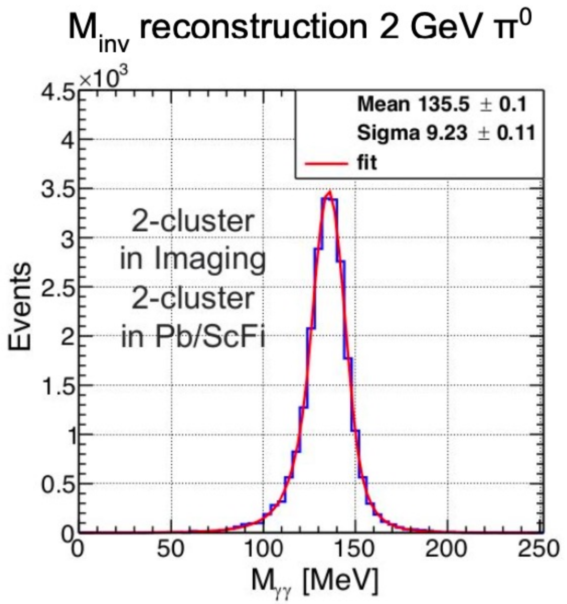
4-layer alternate seems workable compromise.

Barrel Imaging Calorimeter 23 Argonne NATIONAL LABORATORY

Neutral Pion Identification







- **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 required 10 GeV

γ/π^0 Separation - Exploratory Studies

Convolutional neural network utilizing energy and spatial information from AstroPix layers

- Started from **10 GeV/c at η = 0** - the upper limit for γ/π^0 from YR

No proper **topological clustering algorithm** in the ePIC reconstruction yet

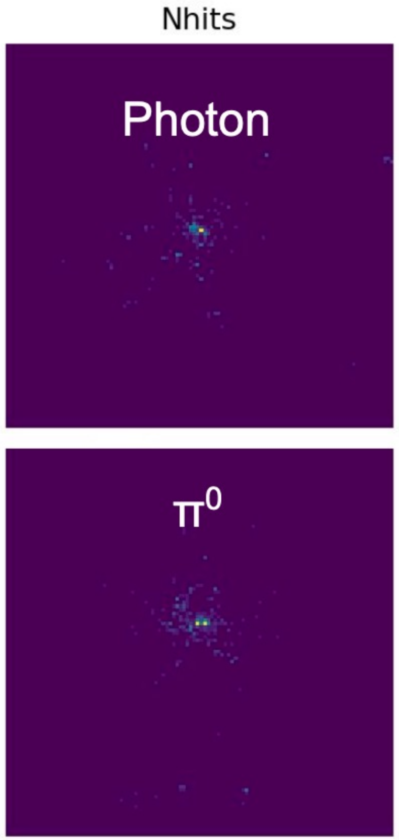
With a quick study we easily achieved

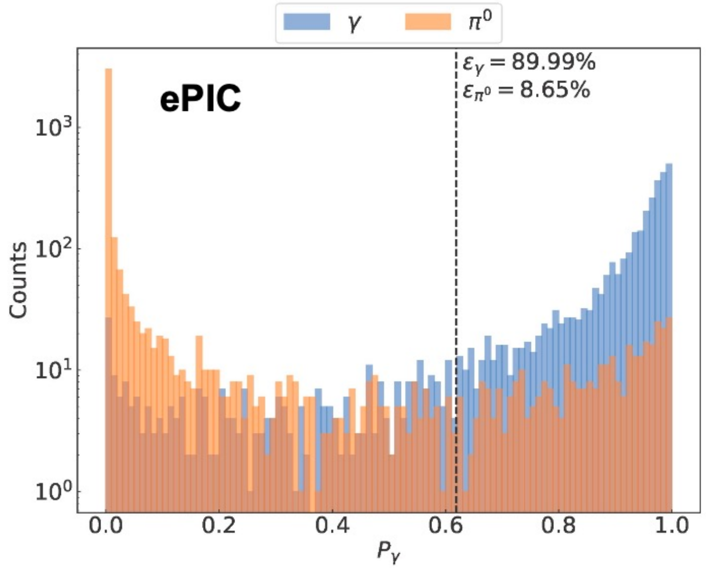
10 GeV/c particles - **91.4%** rejection of π^0 at **90%** efficiency of γ (better than $PbWO_4$ crystal with 20mm block size)

4-layer alternate is workable (still better than theoretical limit on a crystal calorimeter!), but reduced π^0

Full study is ongoing:

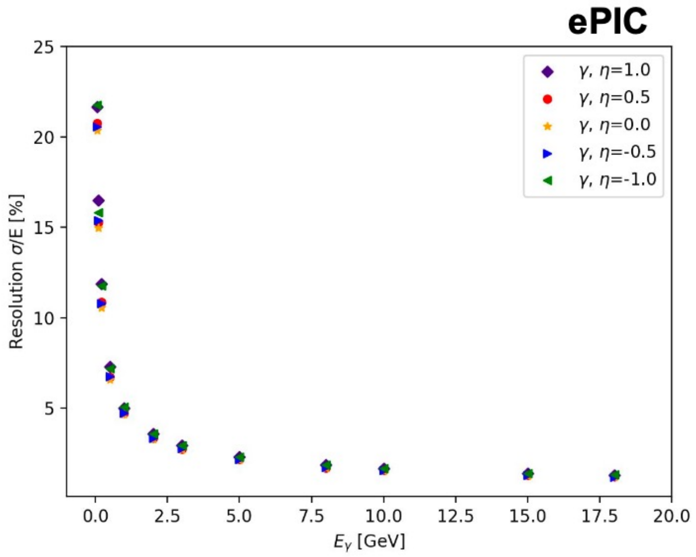
- Implementing optimized topological clustering for AstroPix layers
- Significant improvements expected

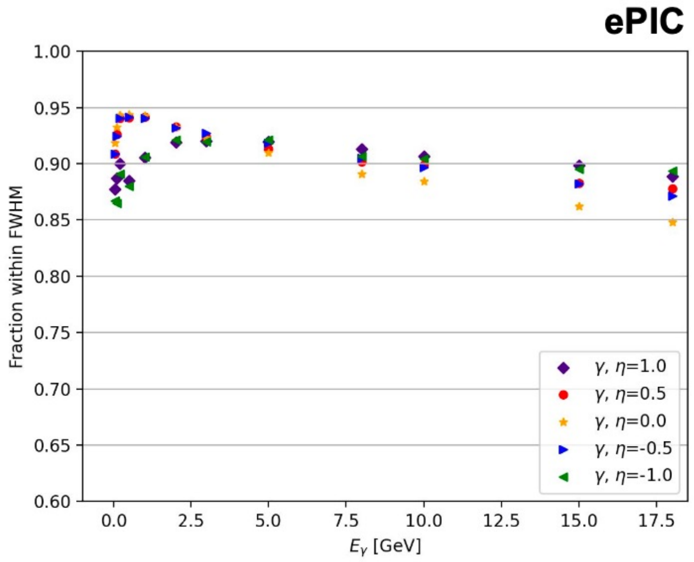


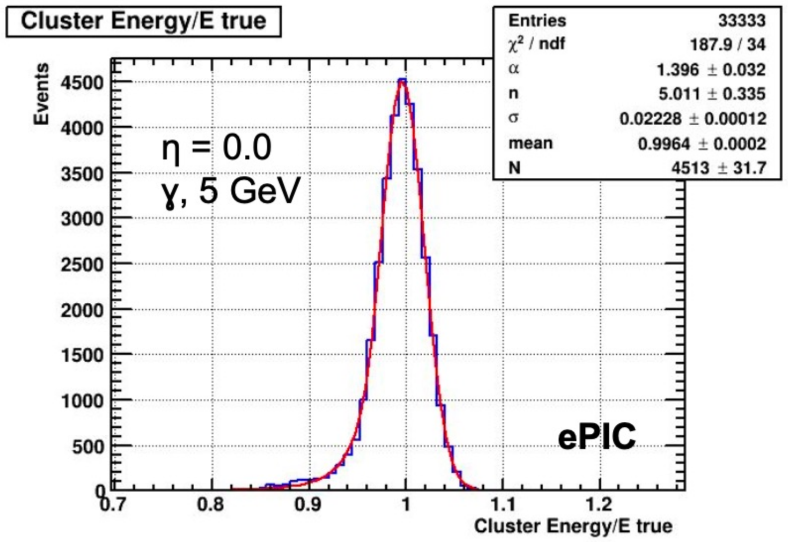


Configuration	γ efficiency	π^0 rejection at 10 GeV/c
6-layer default	90%	11.5
4-layer alternate	90%	5.4

Energy Resolution - Photons







Fit parameters

η	a/√(E) [%]	b [%]
-1	5.1(0.01)	0.47(0.03)
-0.5	4.77(0.01)	0.38(0.02)
0	4.67(0.01)	0.40(0.02)
0.5	4.75(0.01)	0.39(0.02)
1	5.1(0.01)	0.41(0.02)

- Based of Pb/ScFi part of the calorimeter
- Resolution extracted from a Crystal Ball fit σ

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

- 15.5 X_0, extracted for integrated range over the angular distributions for π^0 and η production at GlueX (E_γ = 0.5 - 2.5 GeV)
- Measured energies not able to fully constrain the constant term

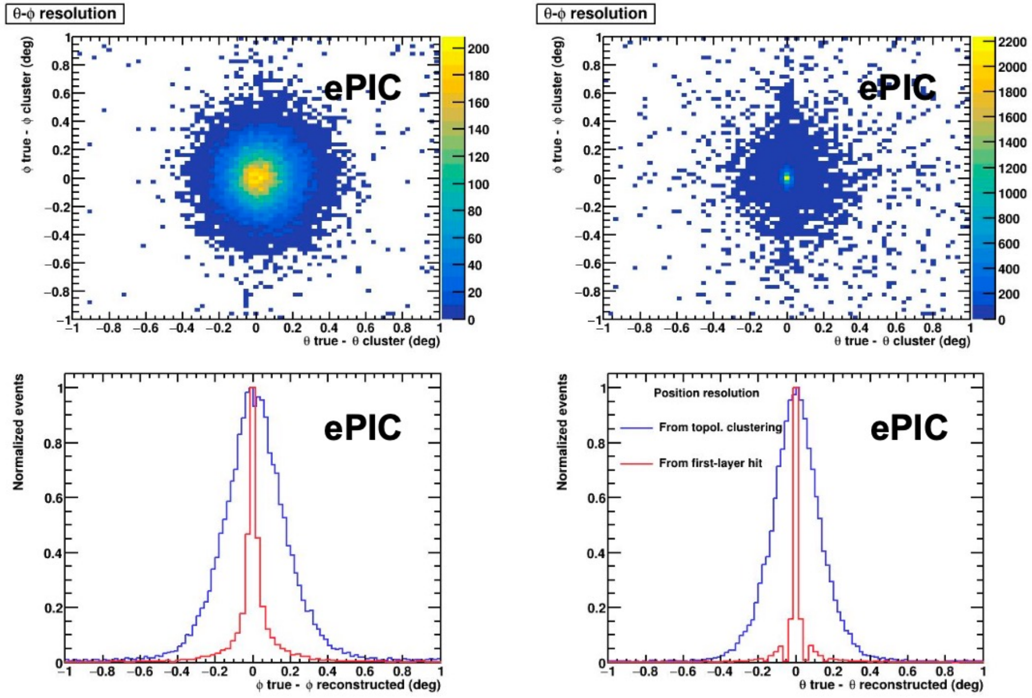
Simulations of **GlueX prototype** in ePIC environment agree with data at E_γ < 0.5 NIM, 596 (2008) 327−337

Position Resolution

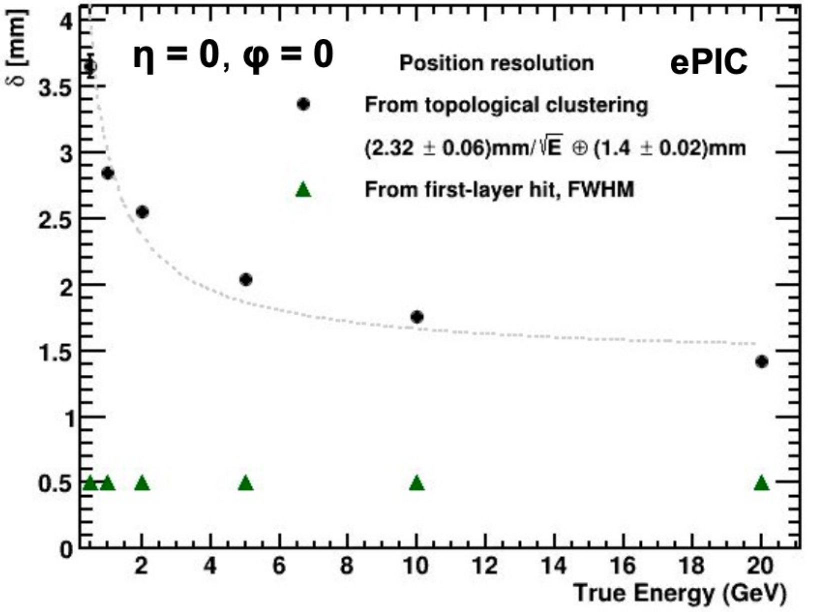
with 6 AstroPix Layers

Example of θ - φ resolution for 5 GeV photons

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



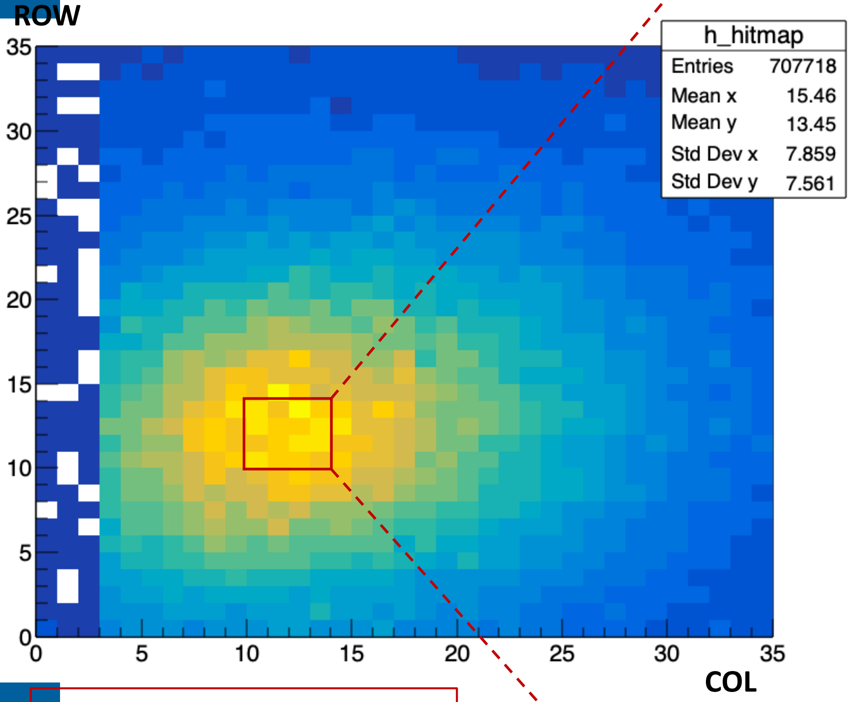
Position resolution for photons
Particles thrown perpendicular to the calo surface

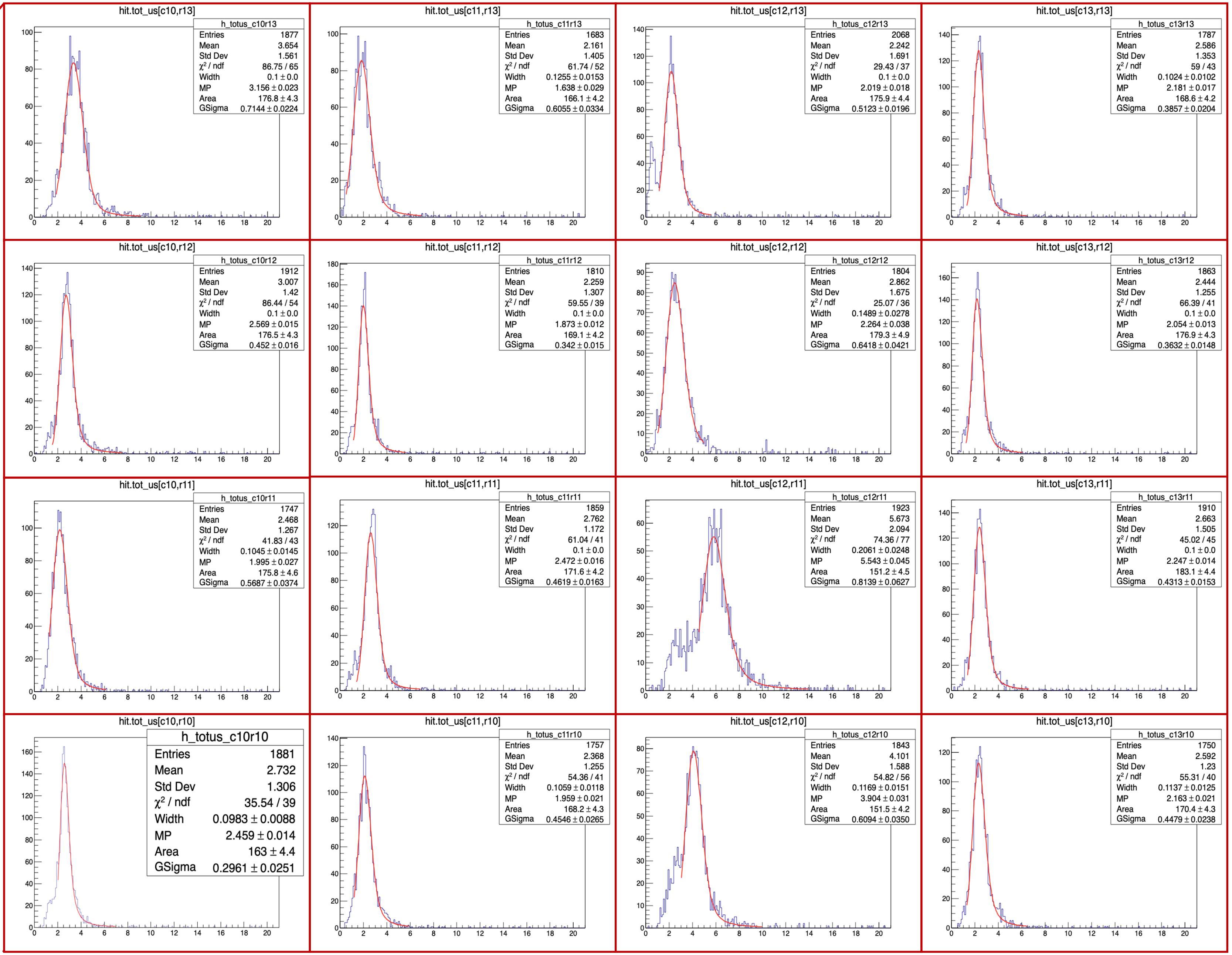


- Clusters from Imaging Si layers reconstructed with 3D topological algorithm
- Cluster level information: $\sigma_{position}$ = (2.32 ± 0.06) mm/√E ⊕ (1.4 ± 0.02) mm at η=0
- First-layer hit information added: $\sigma_{position}$ = **~0.5 mm (pixel size)**

120 GeV Proton: ToT distributions (June14)

- Fit with landau convoluted with gaussian function on ToT distribution

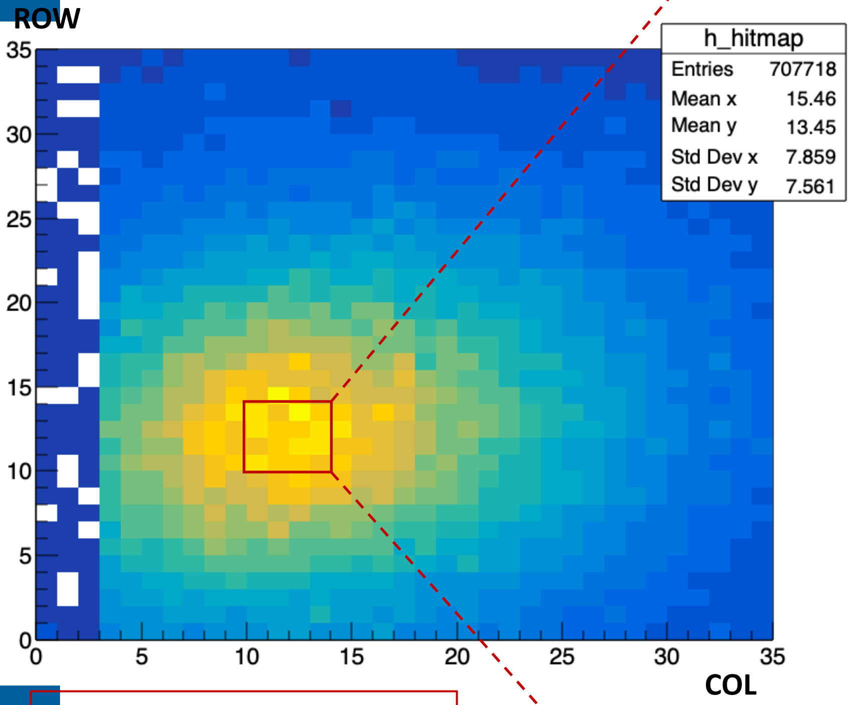




- 4 x 4
  - Col 10 – 13
  - Row 10 - 13

120 GeV Proton: ToT distributions (June14), **scaled**

- Fit with landau convoluted with gaussian function on ToT distribution



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  - Col 10 – 13
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