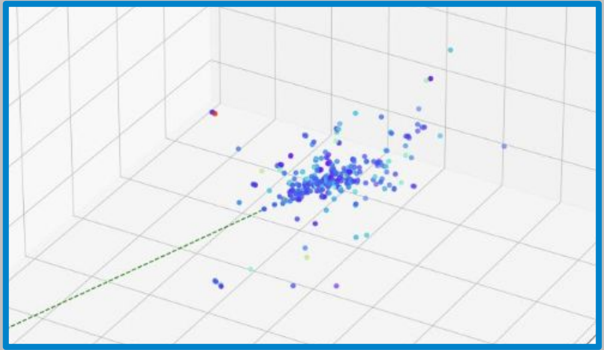
Barrel ECAL

Integration Meeting

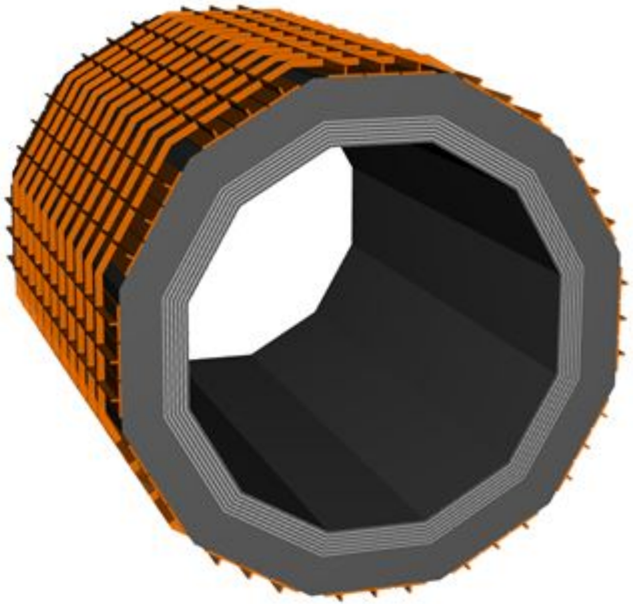


ANL EIC Calorimetry Team
W. Armstrong, M. Jadhav, S. Joosten, J. Kim, J. Metcalfe, Z.E. Meziani, C. Peng, M. Scott, M. Żurek

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

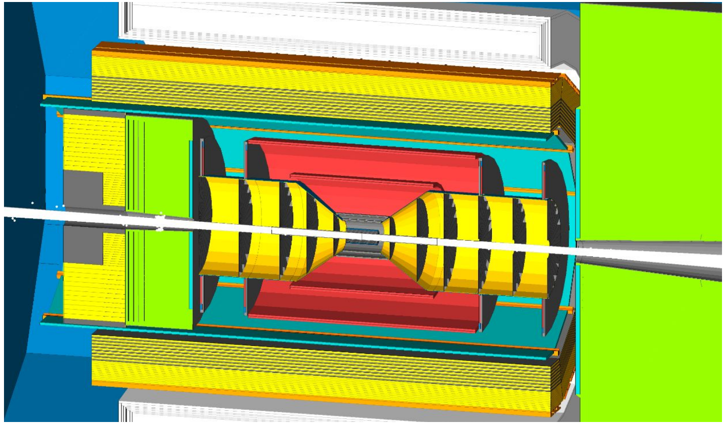
11/10/2021

ATEHNA Barrel ECal



- Layers with two types of sensors
  - AstroPix, Monolithic Silicon Sensors
  - Pb/ScFi

- Geometry
  - R_{min} = 1.03 m, L = 4.05 m, Thickness ~40 cm
  - AstroPix: 1.155 cm per layer (1 cm of air), 1.8% X_0
  - Pb/ScFi: 1.586 cm per layer, ~1.08X_0
  - Imaging layers interleaved with Pb/ScFi layers for the first several X_0



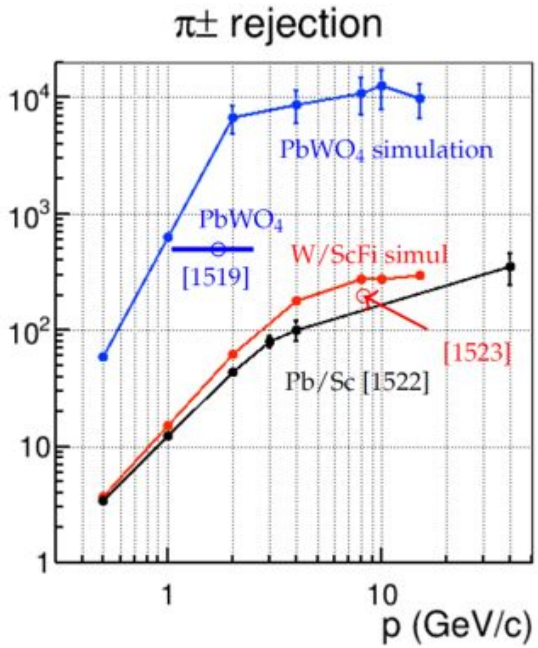
- Geometry
  - Followed by a large chunk of Pb/ScFi resulting in a total radiation thickness ~20X_0
  - Contains negative Endcap inside (partially serves as the Endcap detector)

Benchmarks and performance tests

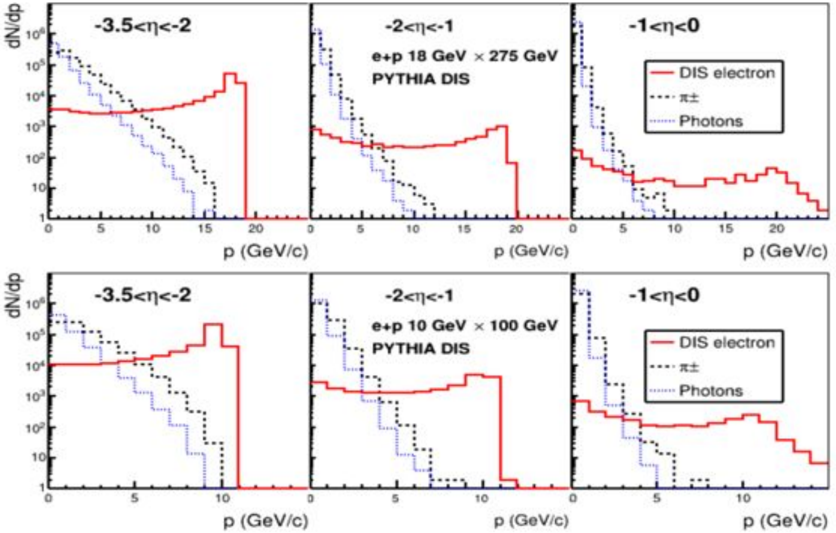
- e/π particle identification
  - Best performance at $p < 2$ GeV/c
  - High pion suppression for inclusive DIS physics

- Spatial separation of $\pi^0 \rightarrow \gamma\gamma$
  - High granularity of pixels to separate two gamma clusters
  - No merging for $p < 30$ GeV/c at 1.03 m (barrel region)

Pion Contamination in Inclusive DIS Physics



pion:electron > 10^3:1 for p < 2 GeV/c in barrel
No existing calorimetry fully satisfy the requirement



18x275 GeV

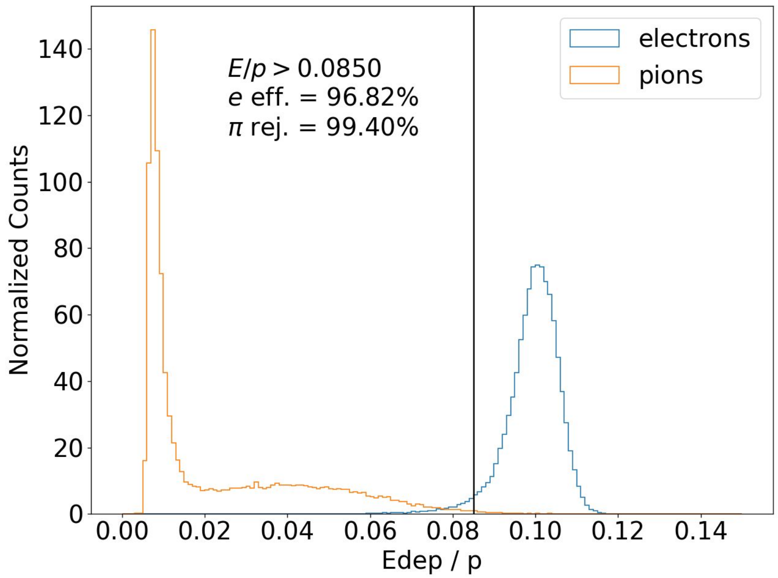
10x100 GeV

https://indico.bnl.gov/event/8231/contributions/37820/attachments/28257/43445/EIC_EMCal_Pavia_21may20_v2.pdf

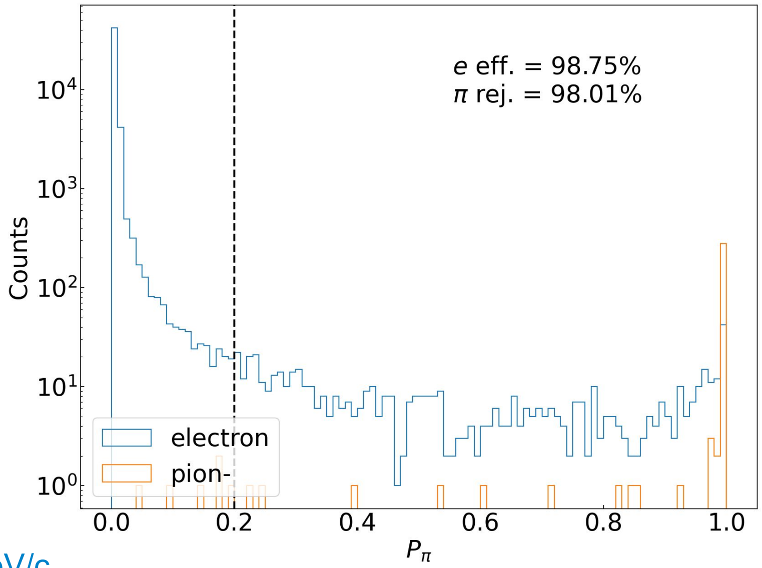
Two-steps Pion Rejection with ATHENA BECal

Boosting e/pi separation on top of E/p cut with 3D-imaging of particle showers

1: Edep/p cut



2: NN Classification + Likelihood cut



2 GeV/c

Classification Neural Network

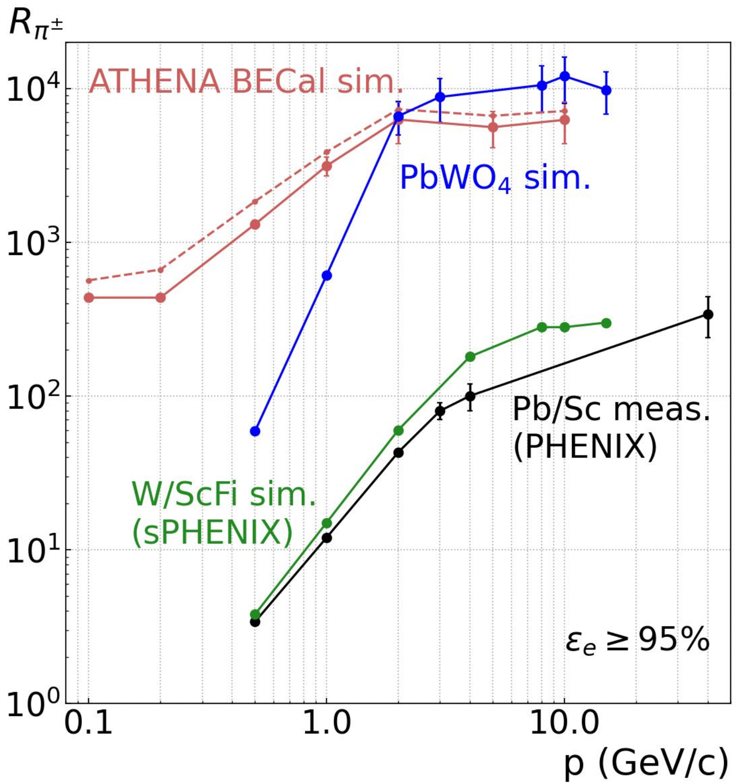
- 3 Layers Convolutional Neural Network + 3 Layers Perceptron Network
  - Combined data from AstroPix and Pb/ScFi
  - 3 inserted dropout layers to control overfitting
  - Data formatted to N_events x N_layers x N_hits x N_features
  - 4 features (Edep, Rc, eta, phi), energy and spatial information for shower
  - 125k trainable parameters

- Supervised training
  - 100k events (electrons and pions), 80% training, 20% validating
  - 100k electrons and 100k pions benchmarking
  - 20 epochs
  - Statistical uncertainty (binomial dist.) of benchmarking samples is shown

Pion Rejection Power

Solid line: 6 AstroPix Layers
Dashed line: 9 AstroPix Layers

- Best e/pi separation for p < 2 GeV/c
- Comparable to crystal calorimeter at higher momentum
- A factor of 30~100 boost on top of E/p cut for p > 1 GeV/c
- 500:1 rejection at lower momentum from when E/p does not work well

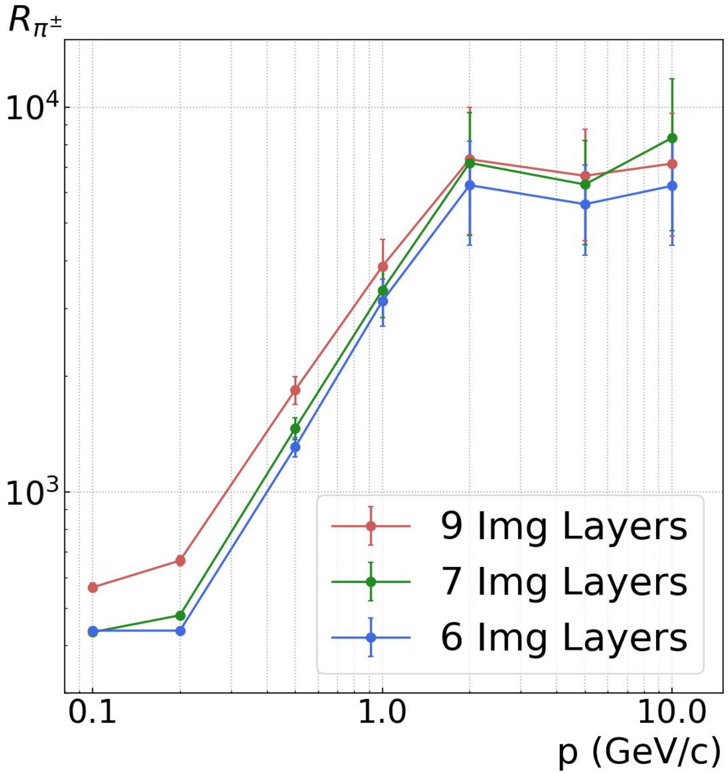


Pion Rejection Power - Different Layers

9 layers → 6 layers
about a factor of 1.5 in pion rejection power

9 layers → 7 layers
similar performance at higher momentum

6 layers → 7 layers
small improvement at lower momentum as compared to



Detection of $\pi_0 \to \gamma\gamma$

EIC Yellow Report

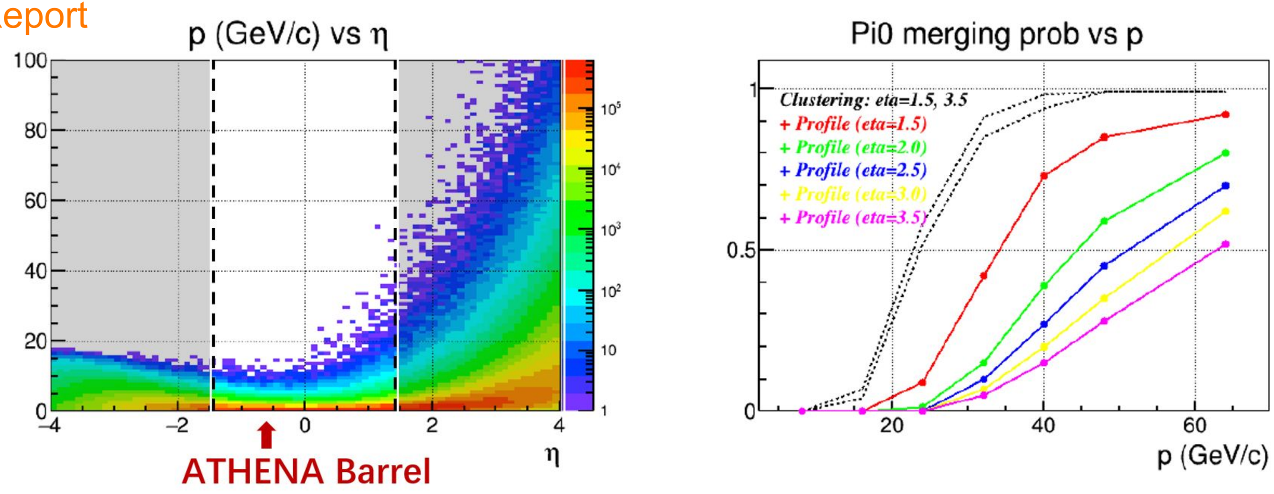
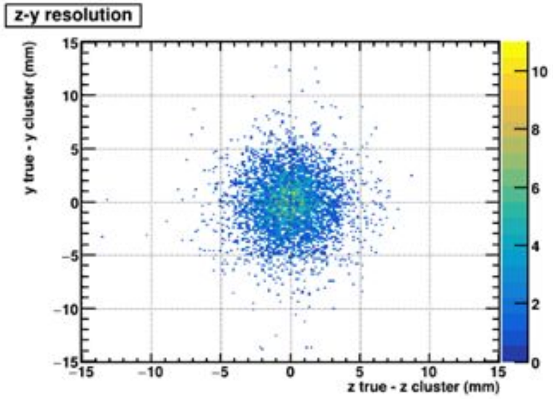
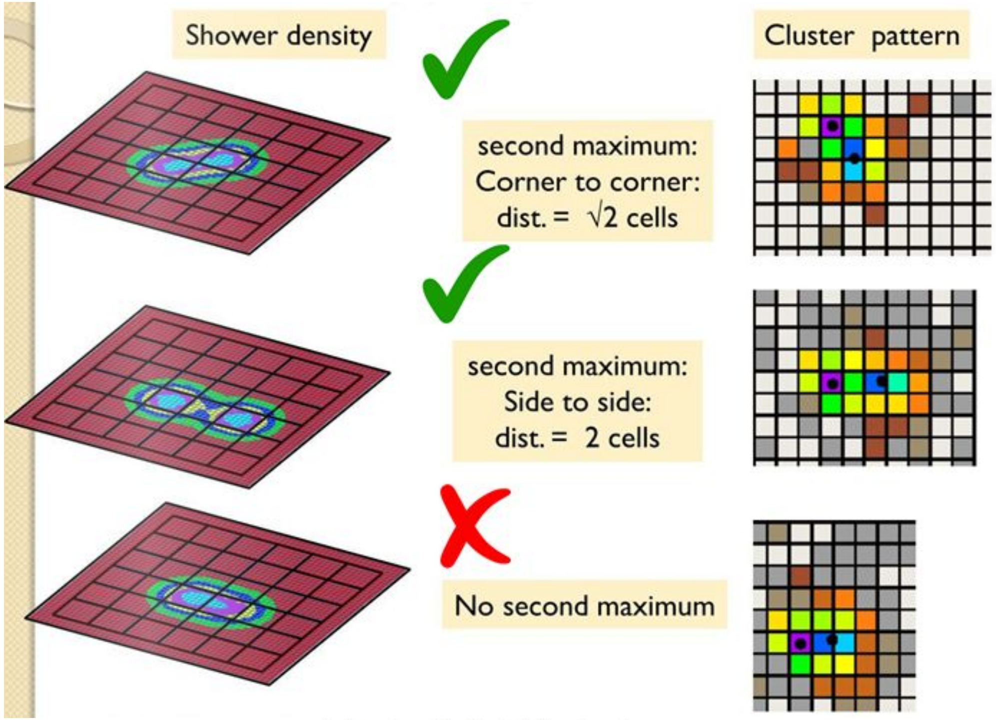


Figure 11.46: Left: The calculated π^0 momentum spectrum for SiDIS at $e + p$ 18 × 275 GeV collisions, using PYTHIA [1371]. **Right**: The probability of two photons to merge, calculated [1517] using GEANT4 [1412] for the cell size of 25 × 25 mm^2 located at 3 m from the interaction point, for the non-projective geometry. For the projective geometry the results for $\eta > 3.5$ would be close to the non-projective curve at for η=3.5.

Hard Limit for Cluster Merging

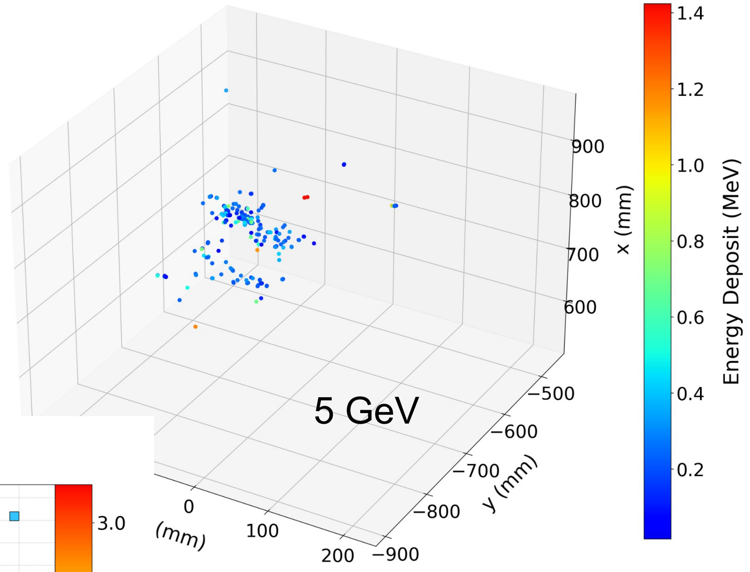
- For modular calorimeters, cell size is the limit
  - No reliable splitting for hits in neighboring cells or the same cell
- For pixel sensors, cluster profile is used ($3\sigma + 3\sigma$ spatial resolution)
  - Single pixel Edep (MIP) cannot locate the center





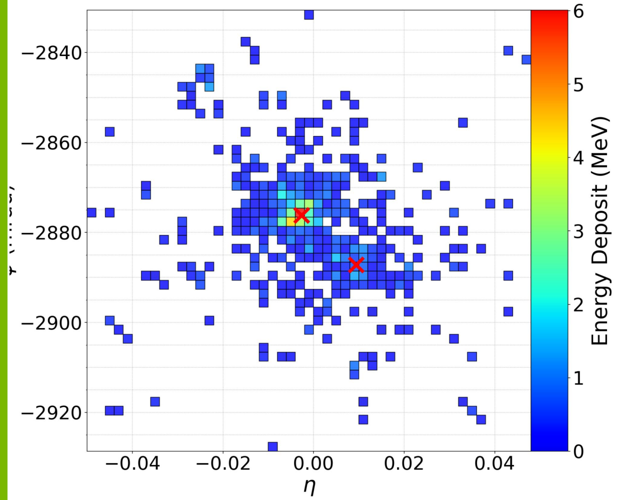
I. Larin, HyCal Clustering

Cluster Merging

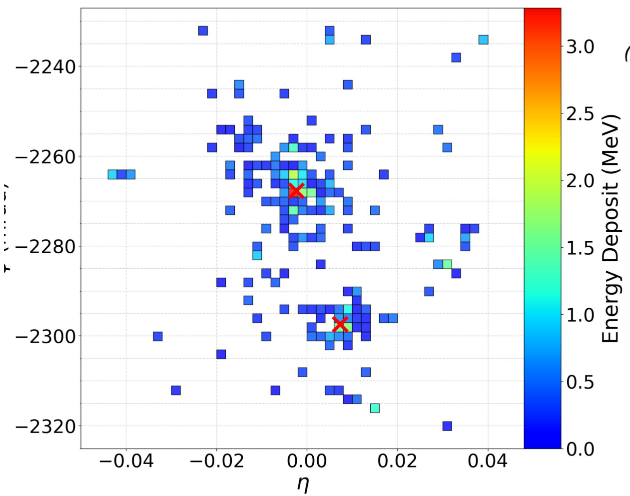


5 GeV

20 GeV



10 GeV



Merging Probability of $\pi_0 \rightarrow \gamma\gamma$

Fast simulation of π^0 decays in barrel region

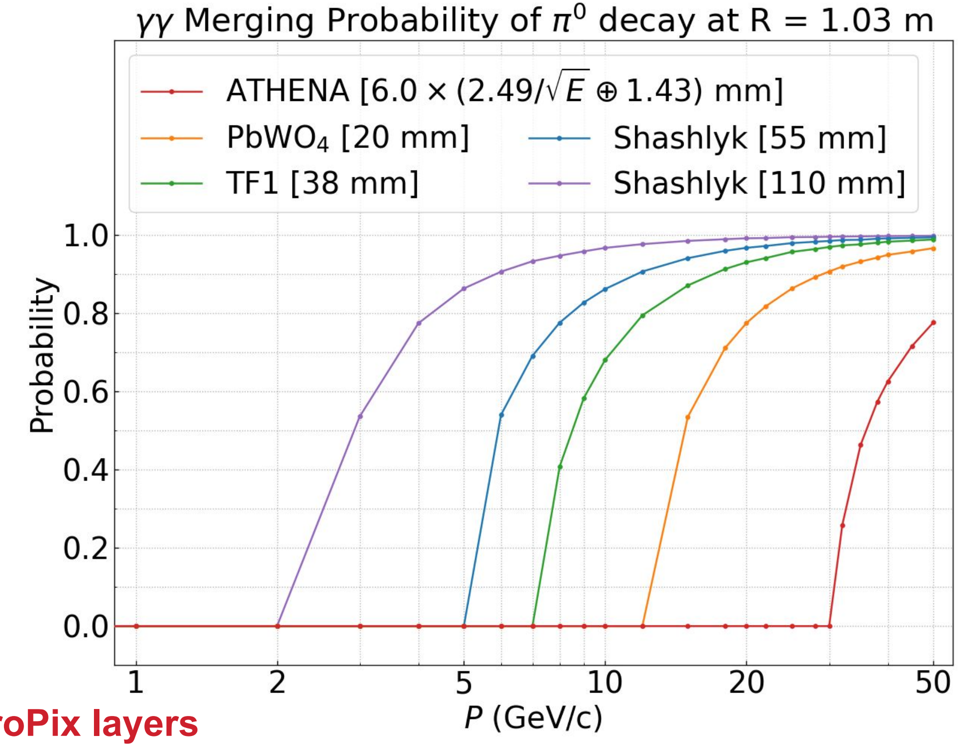
Detection of photons at R = 1.03 m

Cut out-of-acceptance events

Cut very low energy events (photon energy > 100 MeV)

Hard limit of merging

- Cell size for modular calo
- 6 sigma for AstroPix



Cluster position resolution from 6 AstroPix layers

Budget

Budget

Nb of layers	Direct Materials Total	Total Labor cost	Total Cost to project	Total in-kind Cost	Total
9	$10,426,509	$8,133,552	$16,740,826	$1,819,235	$18,560,061
7	$8,355,911	$7,293,906	$13,984,133	$1,665,684	$15,649,817
6	$7,417,311	$7,040,636	$12,863,723	$1,594,224	$14,457,947

Difference between 9 and 6 layers: $4.23M
Difference between 9 and 7 layers: $3.04M
Difference between 7 and 6 layers: $1.2M

Main Impact on Price

Main contributions that **do not scale** with nb of layers

Task	Cost	Comment
Mechanical design	$1,621,360	Estimated top-down from ATLASPix
Electrical design	$1,735,126	Estimated top-down from ATLASPix
Assembly in BNL	$631,776	Assumed 1 year ($440K in-kind)
Wafer prober	$1.5M	Assumed 1 prober (will need eventually 2)

Main impact on price

Main contributions that **do scale** with nb of layers

Task	6 layers	9 layers
Testing	$760K	$950K
In-house assembly	$1.86M	$2.86M
Wafers	$5.44M	$8.34M

Summary

- Early simulations demonstrated that 9 tracking layers would meet the π/e separation goal.
- Continued effort on more realistic shower energy deposition demonstrates that
  - 7 layers will definitely achieve these goals
  - 6 layers may be sufficient with slight degradation in performance, less redundancy, and *less room for MC vs reality differences*.
  - Optimization of layer spacing is continuing and performance with 6 (or 7) layers may increase.
- Each layer costs approx. $1.3 M

Based on cost and performance, the Argonne BECal group recommends that we use 7 tracking layers, but also considers 6 layers as acceptable in terms of performance, with caveats.

Backup Slides

Two-steps Pion Rejection - 9 Layers

9 layers

p (GeV)	Edep/p cut			ML			Combined	
	Cut	e Eff.	pion Rej.	e:pion Weighting	e Eff.	pion Rej.	e Eff.	pion Rej.
0.1	> 0.055 @ $9X_0$	99.83%	1.15	1:10	95.20%	490.39	95.03%	565
0.2	> 0.070 @ $9X_0$	99.49%	1.33	1:15	95.68%	499.23	95.19%	663
0.5	> 0.085 @ $9X_0$	97.26%	18.99	1:20	98.09%	96.96	95.40%	1841
1	> 0.085 @ $9X_0$	97.70%	44.28	1:40	97.27%	87.15	95.04%	3859
2	> 0.085 @ $9X_0$	96.82%	166.63	1:40	98.75%	43.93	95.62%	7320
5	> 0.095 @ $20X_0$	99.06%	184.44	1:40	96.84%	35.95	95.92%	6631
10	> 0.095 @ $20X_0$	98.61%	236.68	1:40	96.73%	30.14	95.39%	7134

Two-steps Pion Rejection - 7 Layers

7 layers

p (GeV)	Edep/p cut			ML			Combined	
	Cut	e Eff.	pion Rej.	e:pion Weighting	e Eff.	pion Rej.	e Eff.	pion Rej.
0.1	> 0.055 @ $9X_0$	99.83%	1.15	1:10	95.18%	375.25	95.02%	432
0.2	> 0.070 @ $9X_0$	99.49%	1.33	1:15	95.87%	360.02	95.39%	478
0.5	> 0.085 @ $9X_0$	97.26%	18.99	1:20	98.86%	77.00	96.15%	1462
1	> 0.085 @ $9X_0$	97.70%	44.28	1:40	97.45%	75.53	95.21%	3345
2	> 0.085 @ $9X_0$	96.82%	166.63	1:40	98.30%	43.00	95.18%	7165
5	> 0.095 @ $20X_0$	99.06%	184.44	1:40	96.13%	34.13	95.22%	6294
10	> 0.095 @ $20X_0$	98.61%	236.68	1:40	97.44%	35.17	96.08%	8323

Two-steps Pion Rejection - 6 Layers

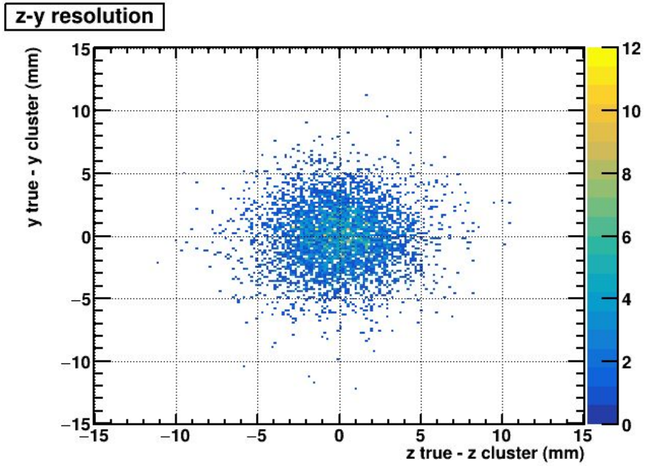
6 layers

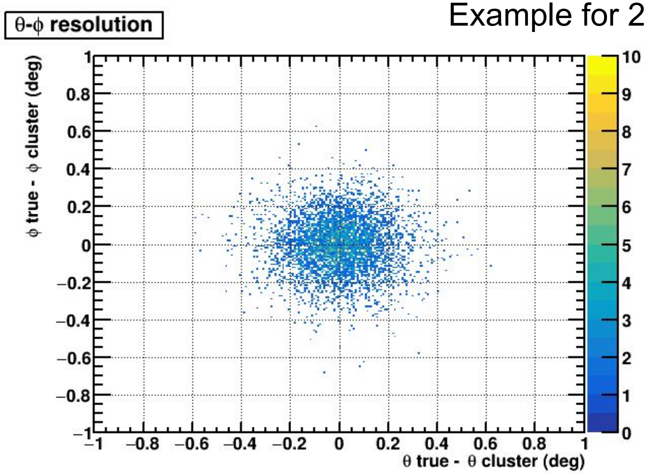
p (GeV)	Edep/p cut			ML			Combined	
	Cut	e Eff.	pion Rej.	e:pion Weighting	e Eff.	pion Rej.	e Eff.	pion Rej.
0.1	> 0.055 @ $9X_0$	99.83%	1.15	1:10	95.17%	378.54	95.01%	436
0.2	> 0.070 @ $9X_0$	99.49%	1.33	1:15	95.63%	328.44	95.14%	436
0.5	> 0.085 @ $9X_0$	97.26%	18.99	1:20	97.98%	68.89	95.29%	1308
1	> 0.085 @ $9X_0$	97.70%	44.28	1:40	97.43%	70.81	95.19%	3136
2	> 0.085 @ $9X_0$	96.82%	166.63	1:40	98.26%	37.63	95.14%	6269
5	> 0.095 @ $20X_0$	99.06%	184.44	1:40	96.58%	30.33	95.67%	5595
10	> 0.095 @ $20X_0$	98.61%	236.68	1:40	97.04%	26.38	95.69%	6243

Cluster φ and θ resolution

- Resolution from **3D topological cell clustering** using imaging layers
- Simulation for photons generated **at normal angle** to a calorimeter stave (θ = 90, φ = 0)
- Difference between true (generated) and reconstructed cluster angles checked
- If more than one cluster reconstructed - highest energy cluster taken

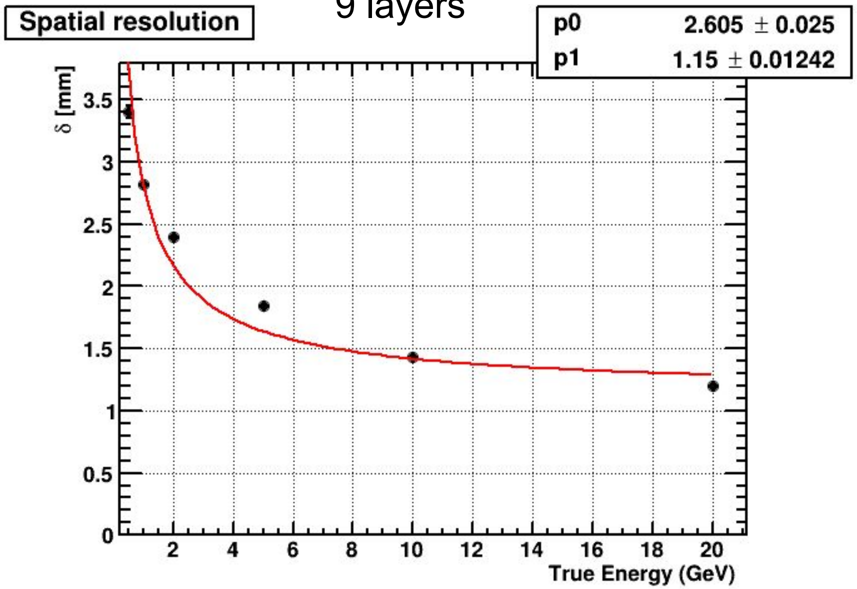
Example for 2 GeV photons



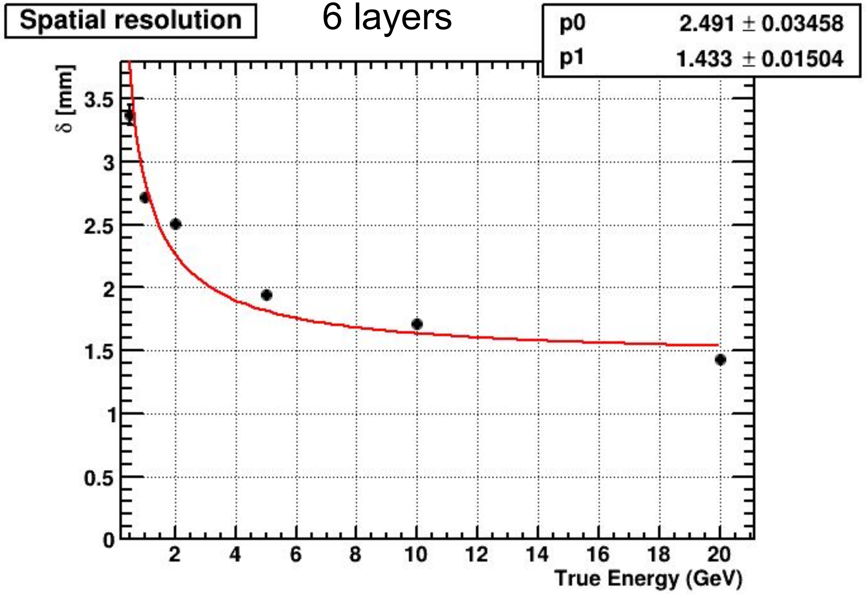


Cluster φ and θ resolution

9 layers



6 layers



- Comparable resolution, $\delta = p1 \oplus p0/\sqrt{E}$
- Further improvements for the position resolution from single hit position in first layers

Cell Sizes Listed in YR

EIC Yellow Report

Type	R_M, mm	cell size, mm	σ_E/E at 1 GeV	δ mm	ϵ, mm GeV$^{0.5}$	Ref
$PbWO_4$	20	20	2.9%	0.4	2.6	[1513]
$PbWO_4$	20	22	3.9%	0.3	2.6	[1514]
TF1	37	38	5.7%	0.5	6.0	[1515]
Shashlyk	41	55	8.4%	1.6	5.7	[1499]
Shashlyk	59	110	4.7%	3.3	15.4	[1516]

Table 11.28: The coordinate resolutions observed with several detectors for the normal incident angle θ_I. The resolution is parametrized using Equation 11.7. The stochastic factor ϵ appears to be approximately proportional to the cell size.