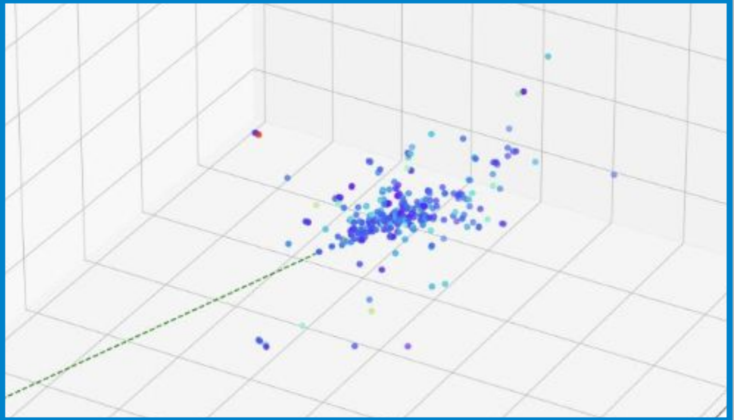
EPIC Barrel ECal Review, March 13-14, 2023

The Imaging Calorimeter for ePIC
Performance



Maria Żurek
PHY, Argonne National Laboratory

EIC Calorimetry Requirements

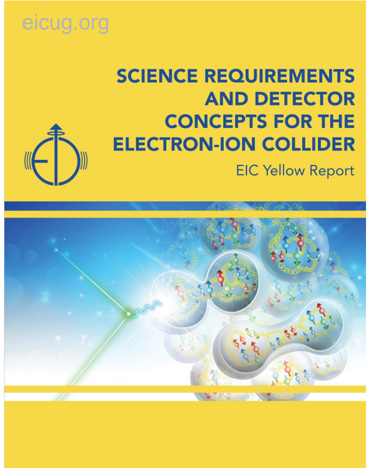
Barrel ECAL in EIC Yellow Report

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

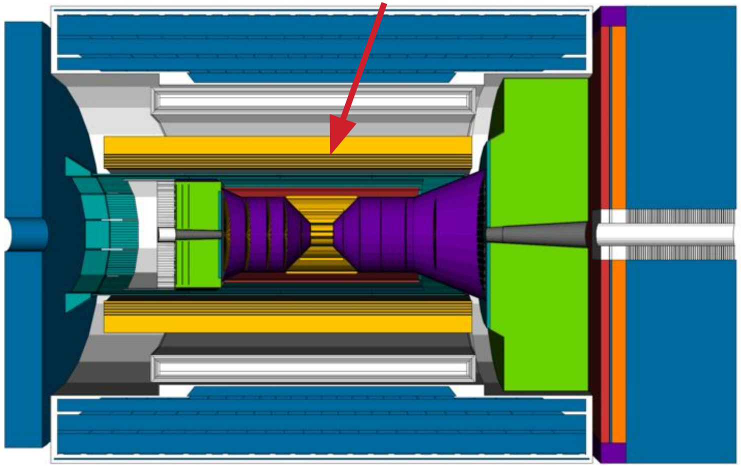


Simulations

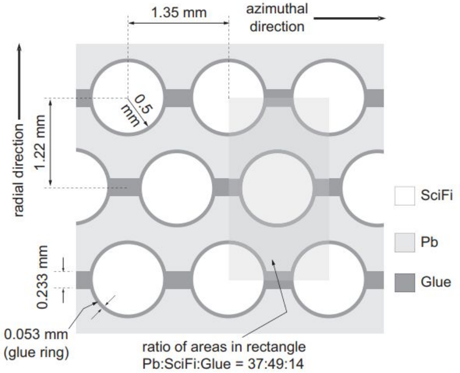
- Official ePIC geometry, simulation and reconstruction: epic_brycecanyon 23.03.0, EICrecon v0.6.2
- Official samples: S3/eictest/EPIC/RECO/23.03.0/epic_brycecanyon

- **Realistic implementation of Pb/ScFi matrix** with glue and cladding and AstroPiX layers
- Signal **digitization and reconstruction** implemented in EICrecon

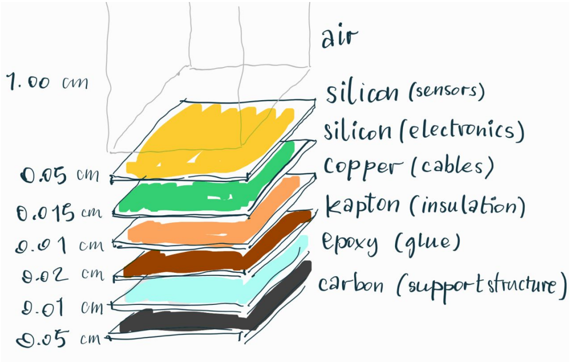
ePIC geometry implementation in simulation



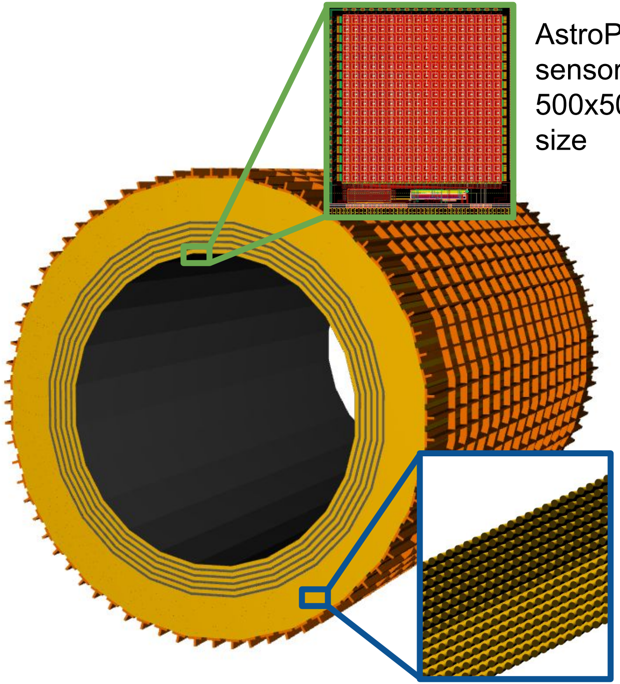
Pb/ScFi matrix materials



Imaging layer materials



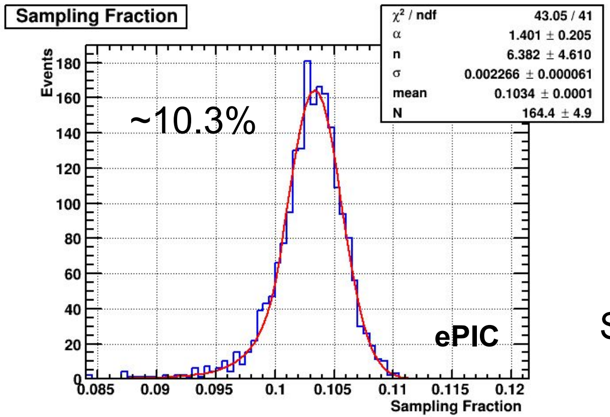
Geometry Reminder



AstroPix: silicon sensor with $500x500\mu m^2$ pixel size

ScFi Layers with two-sided SiPM readout

- **6 layers of imaging Si sensors** interleaved with **5 Pb/ScFi layers**
- Followed by a **large section of Pb/ScFi section**
- Total radiation thickness ~21 X_0
- Sampling fraction ~10%



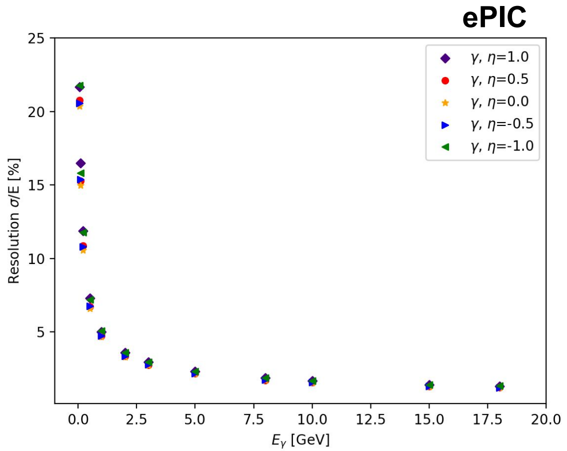
Simulations of **single photons** at η=0 (~21 X_0)

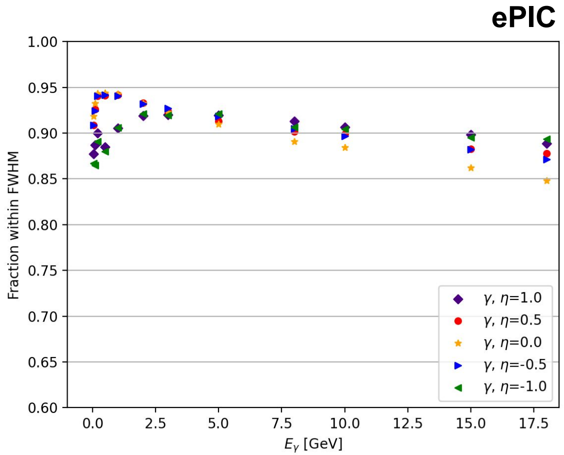
Sampling fraction = $\Sigma E_{fibers} / E_{thrown}$

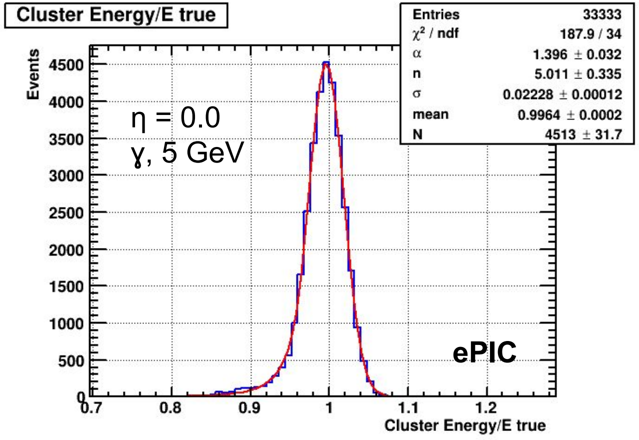
Energy resolution - Primarily from Pb/ScFi layers (+ Imaging pixels energy information)
Position resolution - Primarily from Imaging Layers (+ 2-side Pb/ScFi readout)

Energy and Position Resolution

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)

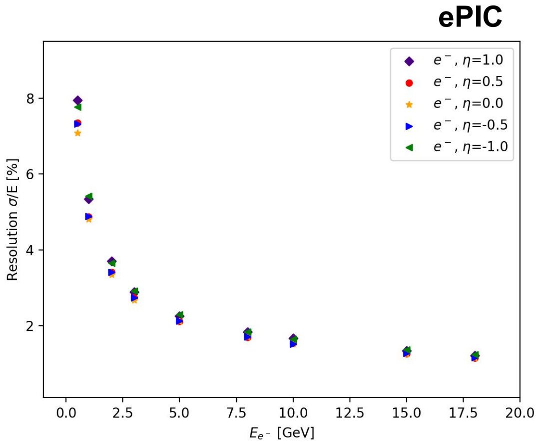
- Based of Pb/ScFi part of the calorimeter
- Resolution extracted from a Crystal Ball fit σ

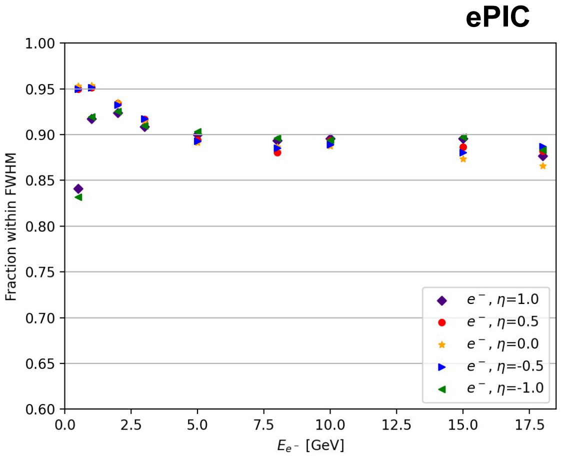
GlueX Pb/ScFi ECal: $\sigma = 5.2\% /\sqrt{E} \oplus 3.6\%$ NIM, A 896 (2018) 24-42

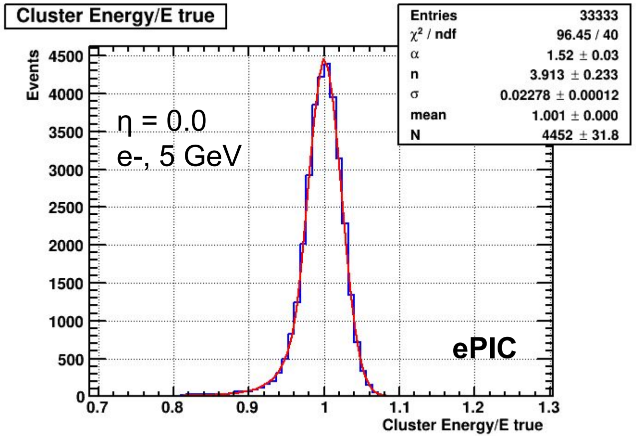
- 15.5 X_0, extracted for integrated range over the angular distributions for π^0 and η production at GlueX (E_γ = 0.5 - 2.5 GeV)
- Measured energies not able to fully constrain the constant term

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

Energy Resolution - Electrons







Fit parameters

η	a/√(E) [%]	b [%]
-1	5.22(0.02)	0(0.08)
-0.5	4.88(0.01)	0(0.04)
0	4.81(0.01)	0(0.08)
0.5	4.88(0.01)	0(0.04)
1	5.19(0.01)	0(0.06)

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)
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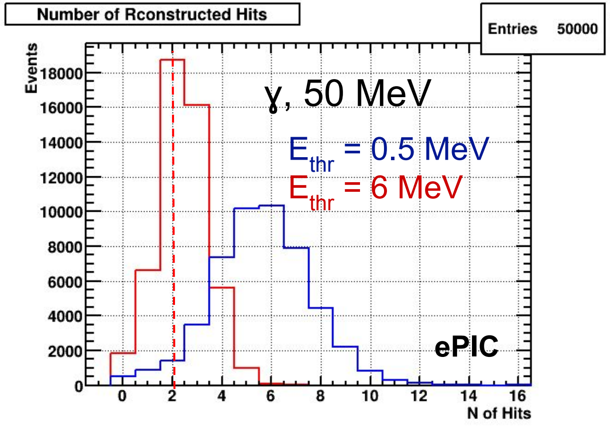
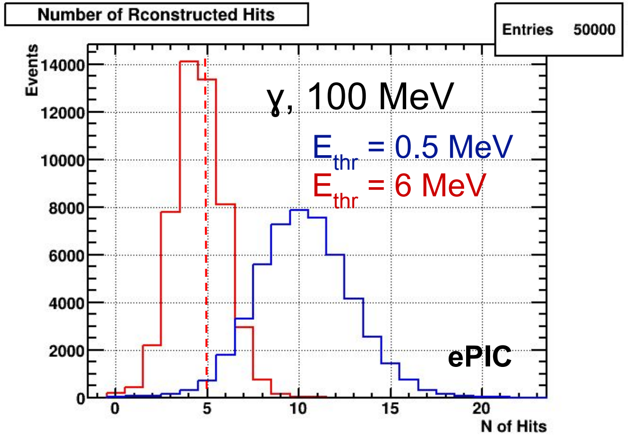
Low Energy Particles

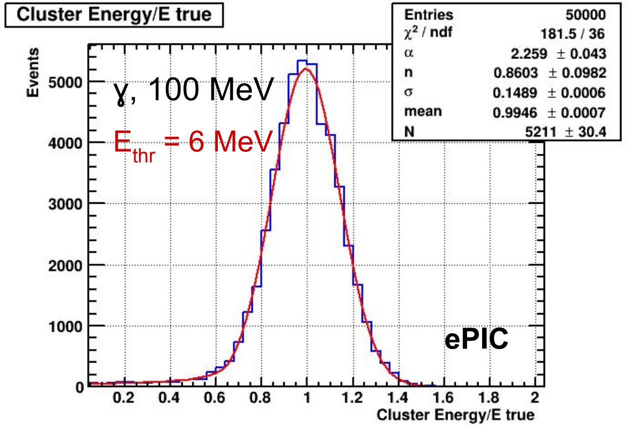
- For electrons: cut out because of the 1.7 T field to reach the calorimeter (p < ~408 MeV)
- For photons shown number of fired readout cells with different thresholds at η = 0



Thresholds corrected for f_{sam}



Blue threshold very low just to illustrate the distribution shape

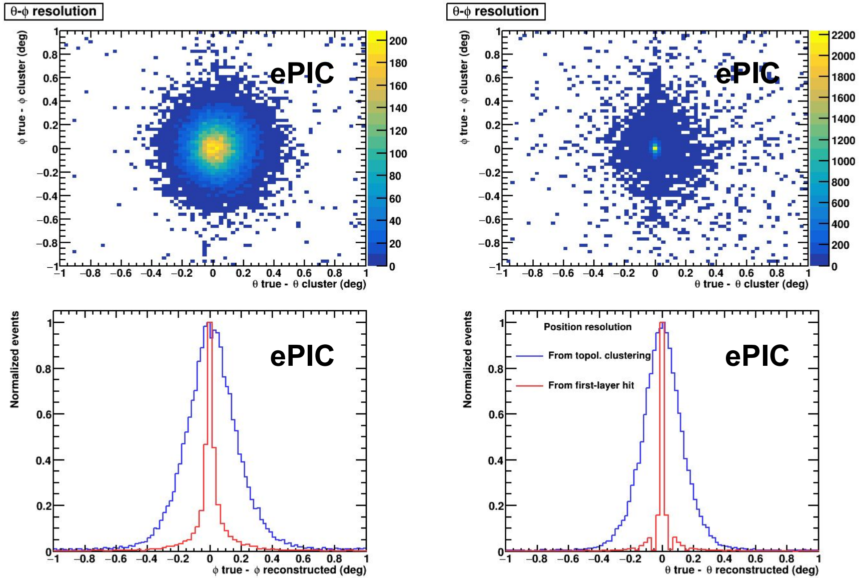


- **From GlueX** studies: cluster/shower threshold is 100 MeV nominal (down to 50 MeV for some analyses, with mostly two cells per event only). Low energy detection threshold studied also with Michel electrons. (NIM, A 896 (2018) 24-42)

Position Resolution

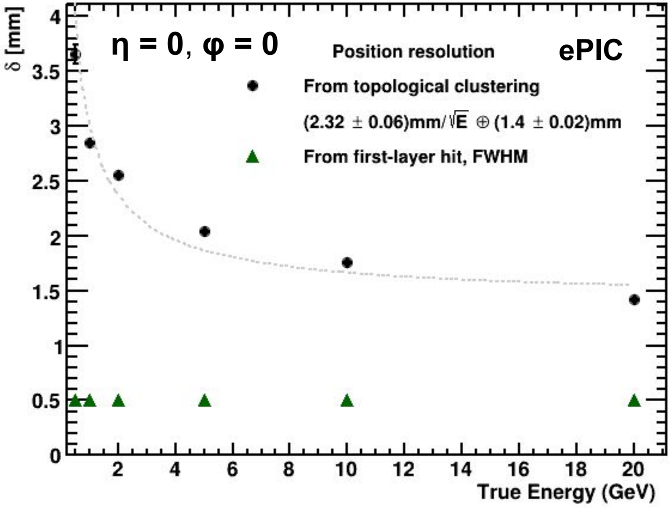
Example of θ - φ resolution for 5 GeV photons

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



Position resolution for photons

Particles thrown perpendicular to the calo surface

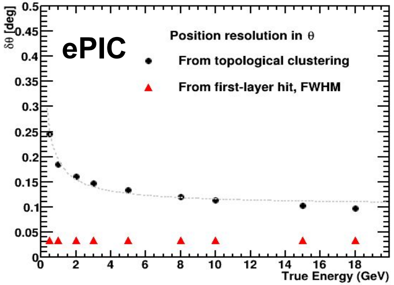


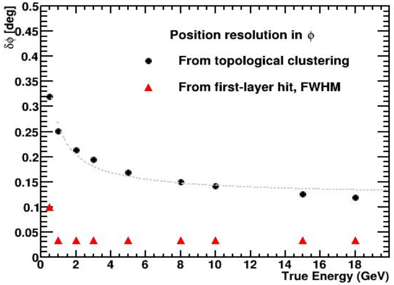
- Clusters from Imaging Si layers reconstructed with 3D topological algorithm
- Cluster level information: $\sigma_{position}$ = (2.32 ± 0.06) mm/√E ⊕ (1.4 ± 0.02) mm at η=0
- First-layer hit information added: $\sigma_{position}$= **~0.5 mm (pixel size)**

Position resolution studies

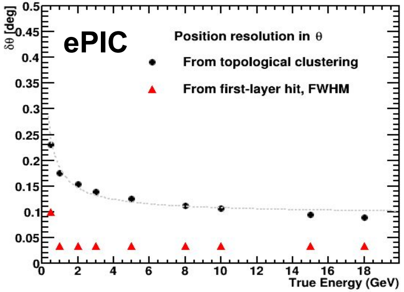
Angular resolution for different η

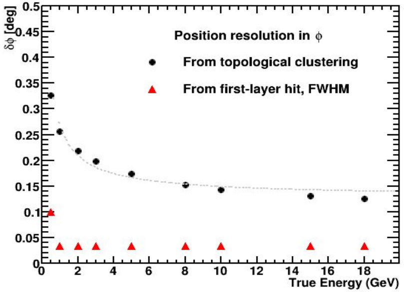
η = 0, φ = (0,2π)



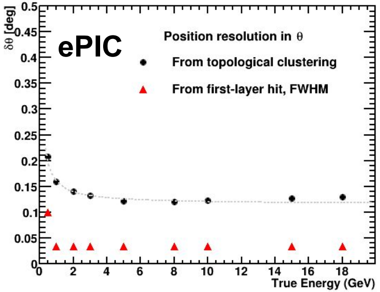


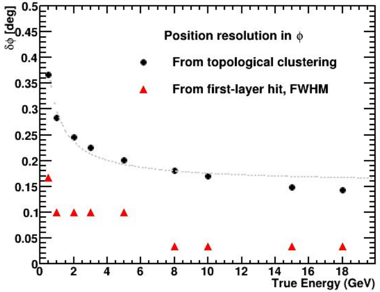
η = 0.5, φ = (0,2π)





η = 1, φ = (0,2π)

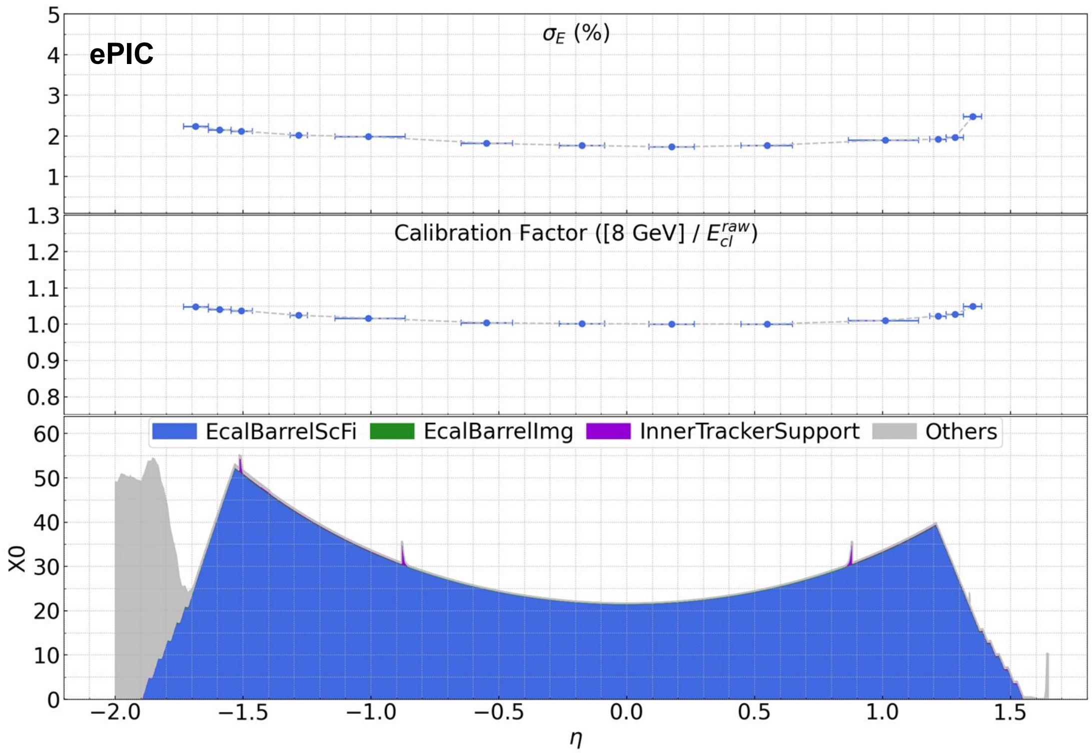




- Small dependence seen with changing η
- Angular resolution in all regions well below 0.1 deg (in majority regions on the level of single pixel resolution)
- Results well below any tower-like calorimetry

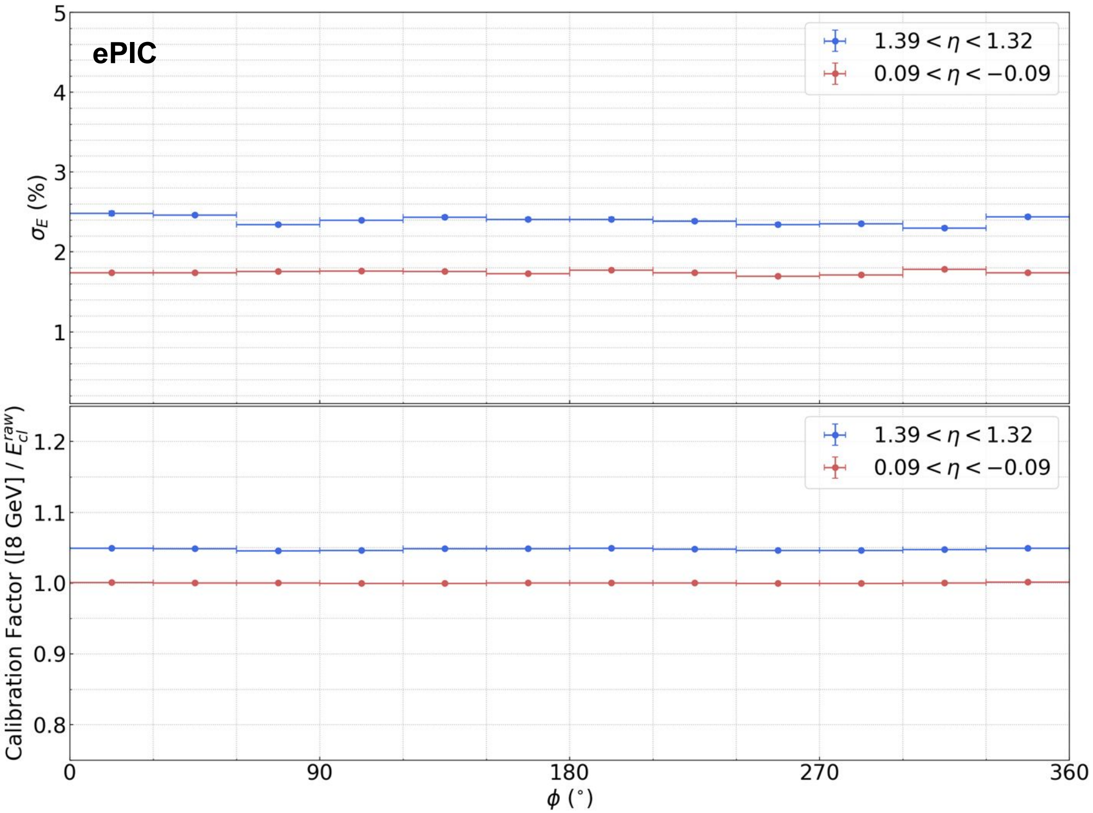
Clustering at 8 GeV/c

- Top: energy resolution (σ from Crystal Ball fit) and calibration curve
- Bottom: material scan up to R(x, y) = 120 cm
- Slight degradation of energy resolution with larger pseudorapidity value
  - Consistent with energy resolution study
- Calibration curve is flat within (-0.6, 0.6), < 2% within (-1.1, 1.1)
  - Energy leakage correction in future study for overlap regions with forward and backward calo



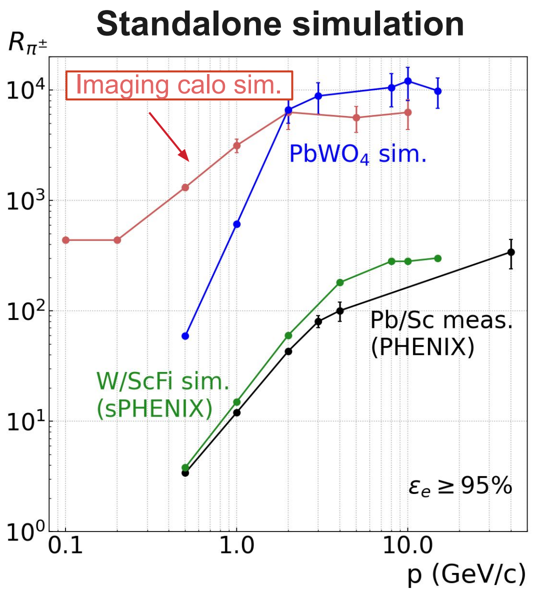
Clustering at 8 GeV/c - Symmetry over ϕ

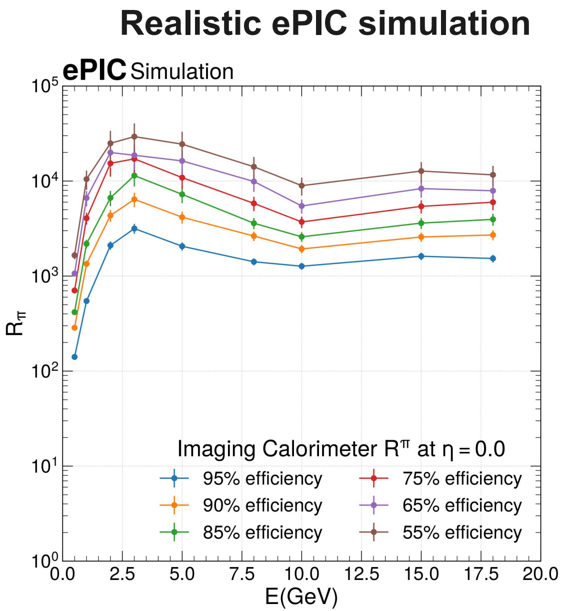
- Top: Non-linear calibration curve over phi
- Bottom: Energy resolution over phi
- Imaging BECal behaves very symmetric over phi in the simulation, as expected



Particle Identification

Electron Identification





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

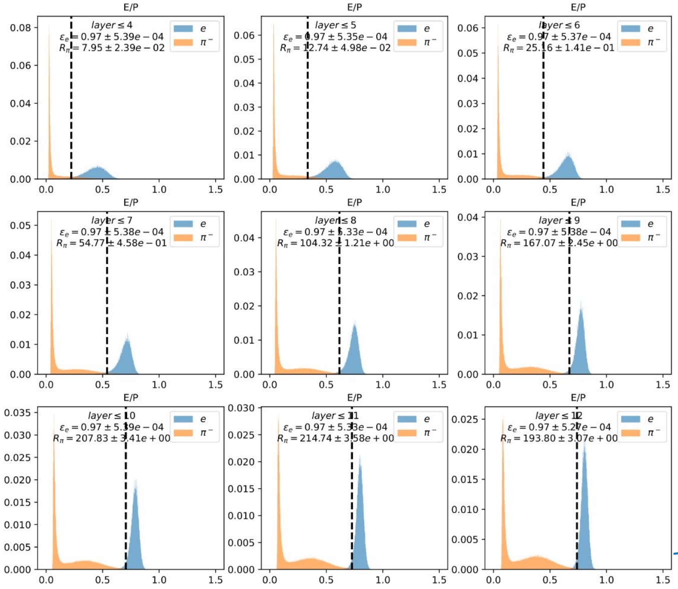
- e-π separation exceeds **10^3** in pion suppression at **95% efficiency** above 1 GeV in realistic conditions!

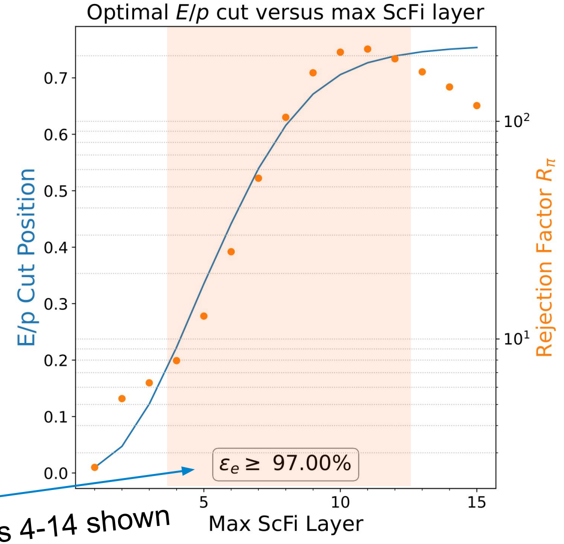
e/π Separation - Method

Steps:

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

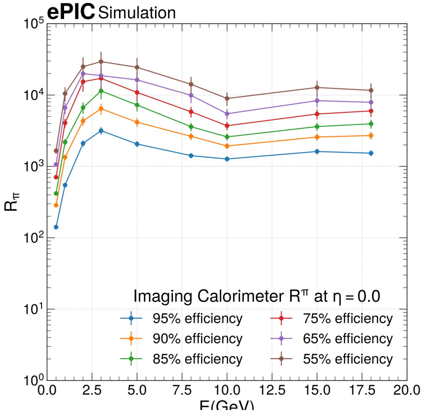
Example for 2 GeV e/π





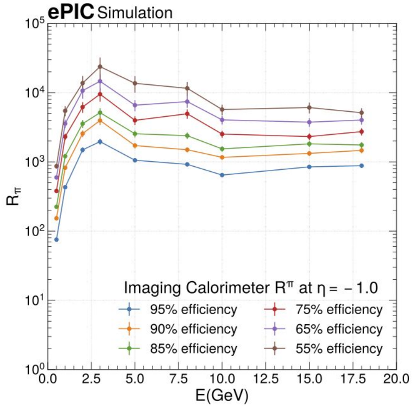
ScFi layers 4-14 shown

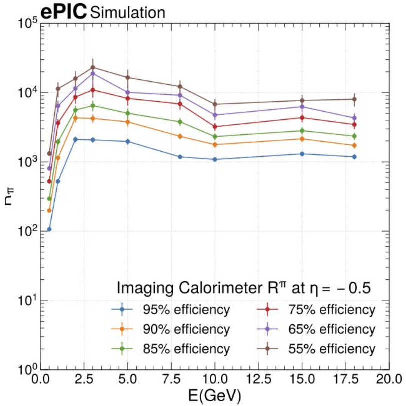
e/π Separation - Results

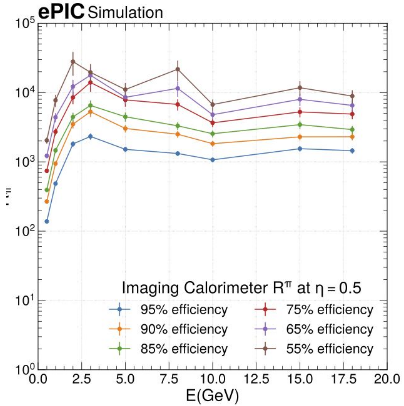


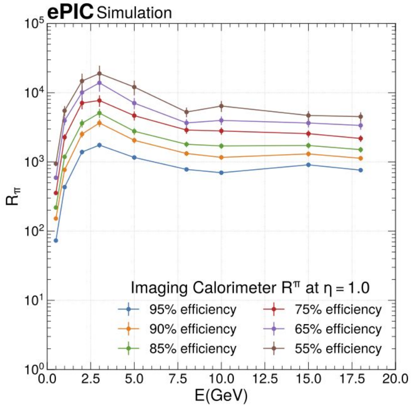
e/π separation - η, energy and efficiency dependence

- Results depend strongly on electron efficiency
- **For desired 95% efficiency for all η regions we are ≥ 10^3 above ~ 1.5 GeV**
- Responses at different energies and η have been folded into the purity studies

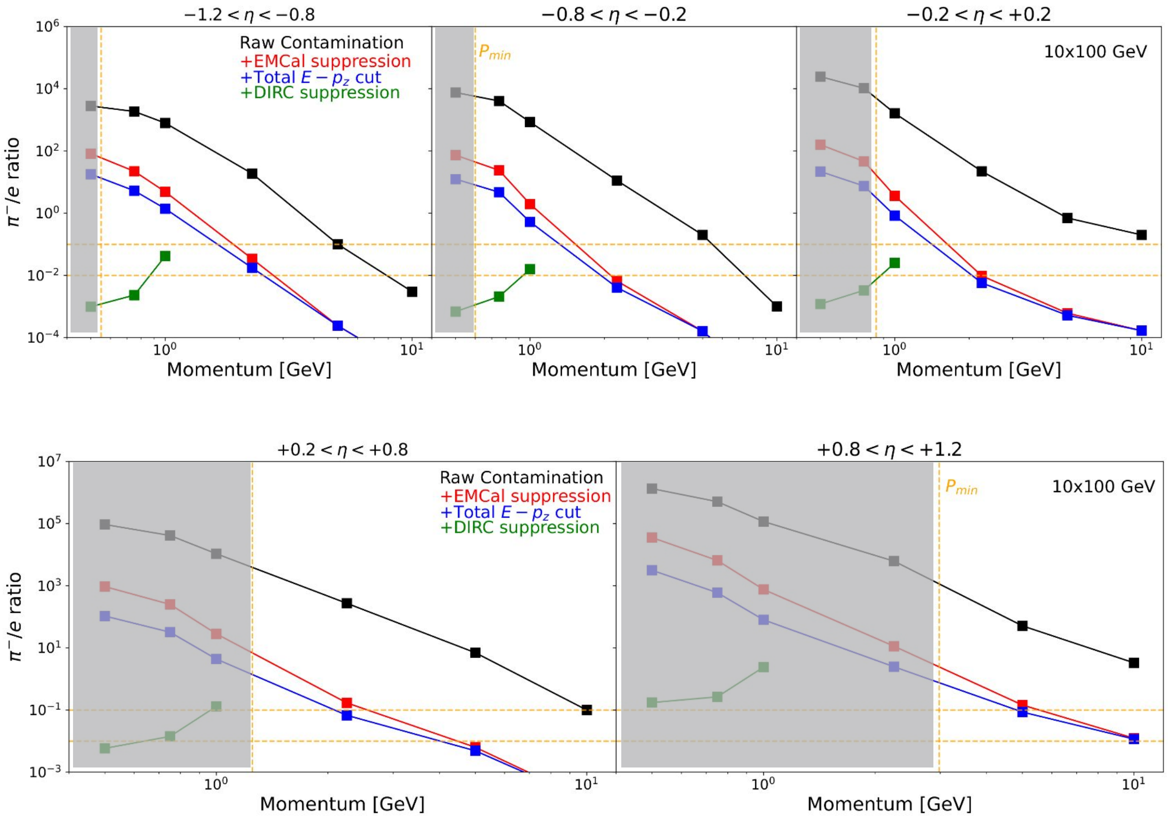








e/π Separation - Results



Studies on π contamination performed by B. Schmookler (UCR)

- See ePIC Collaboration Meeting contribution (link)

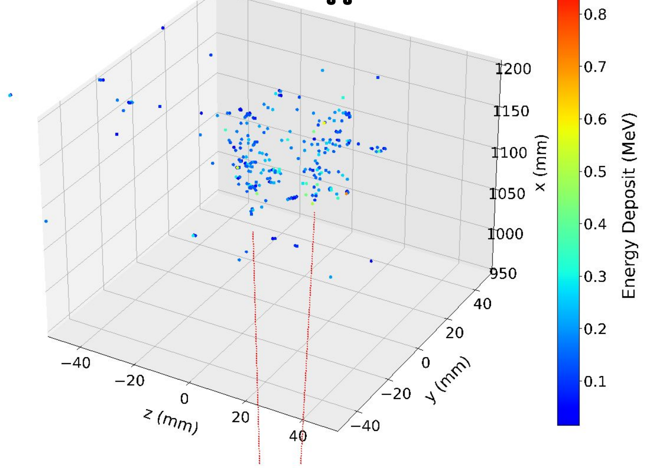
Challenging goal: Achieve 90% electron purity from the combined detector performance (ECAL + DIRC)

- To keep pion contamination systematic uncertainty to required 1% level

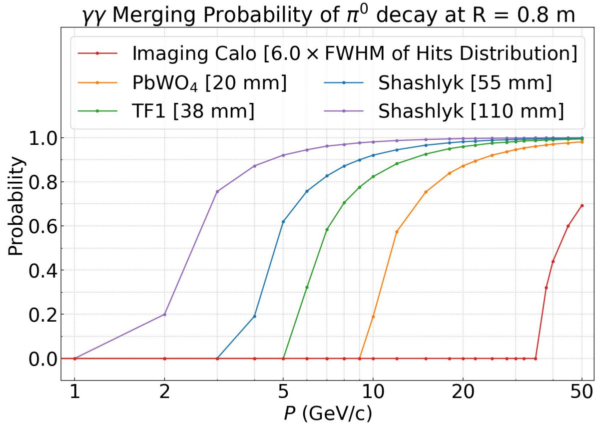
Imaging calorimeter fulfills the requirement in all η ranges

Neutral Pion Identification

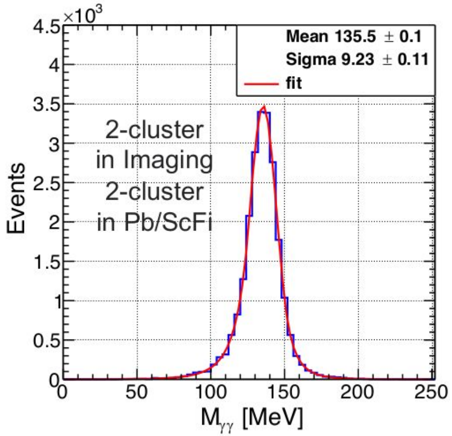
15 GeV $\pi^0 \rightarrow \gamma\gamma$



Separation of γ/π^0 (upper limit)



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 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

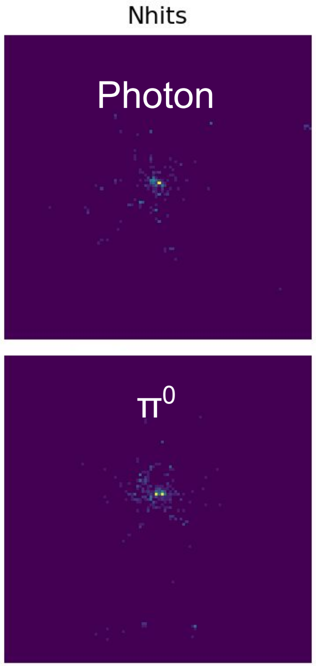
No proper **topological clustering algorithm** in the ePIC reconstruction yet

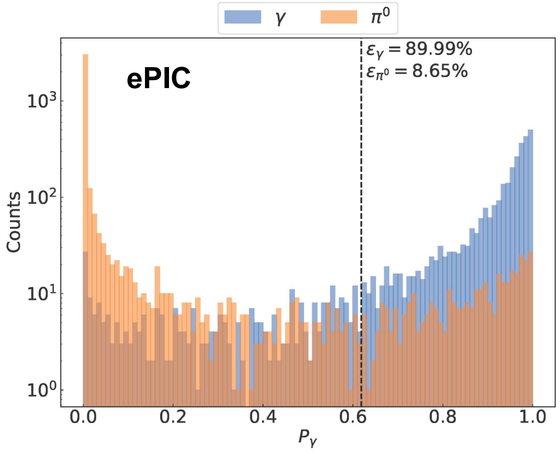
With a quick study we easily achieved

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

Full study is ongoing:

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





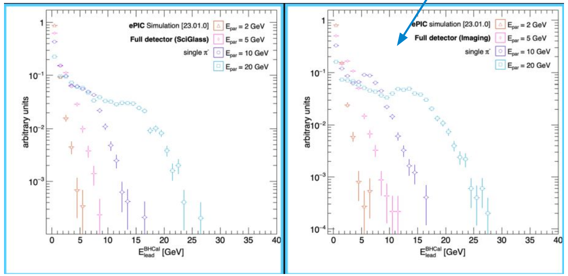
Hadronic Response

Preliminary studies on **single pion** simulations at η = (-1,1) on how the imaging barrel ECAL affects the energy resolution of hadrons (imaging ECal as an “inner” HCal) - D. Anderson (ISU)

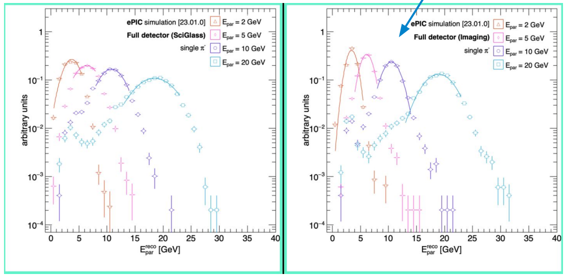
Calibrated BHCal energies

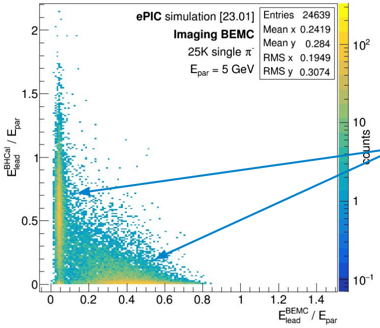
- TMVA regression analysis with particle energy as target
- Energy from ECal and HCal used
- Not yet information from different depth of SciFi/Pb and AstroPix layers used

Energy in HCal **before calibration**



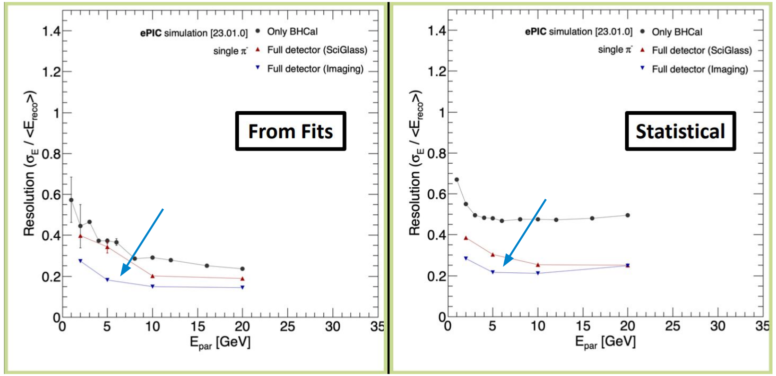
After calibration





Ongoing effort on looking into particles starting showering at different depth in Barrel E+HCal

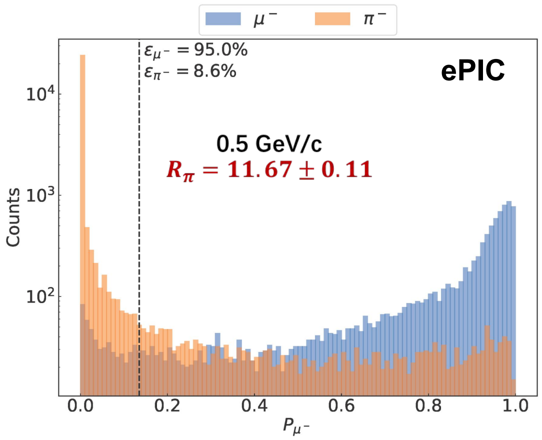
Energy resolution



Muon Identification

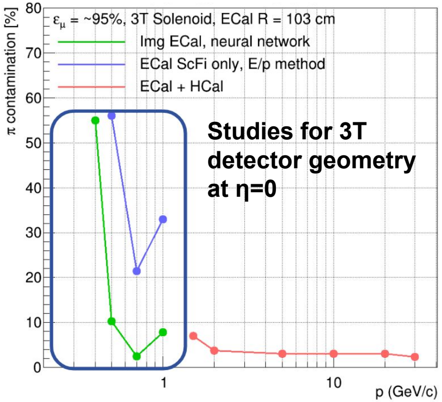
- Muon-pion separation in **central region** uses information from the **electromagnetic (ECal) and hadronic (HCal) calorimeters**
- **Low energy muons** curl inside the barrel EM calorimeter (do not reach HCAL) < ~**0.9 GeV/c for 1.7T at η = 0** field **for ePIC geometry.** The discontinuity in reaching HCal is rapidity dependent.
- Incorporating imaging layer information into Neural Network studies **significantly improves the μ-π separation at low energies** wrt E/p studies from ECal only - studies for 3T detector geometry on that.
- ePIC barrel HCAL reconstruction in progress. **A preliminary study focused on μ^-/π^- separation in Barrel ECAL.**

This muons curl inside BCAL

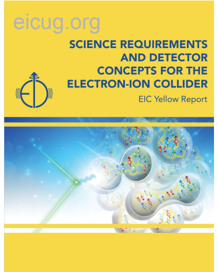


Preliminary studies show already **> 90% π suppression** at 95% muon efficiency

Studies in 3T detector geometry (not ePIC) with same imaging layer structure



Summary



EIC Yellow Report requirements for Barrel EM Calorimeter

- Detection of electrons/photons to measure **energy and position -** ✅
- Require **moderate energy resolution** $(7-10)\%/\sqrt{E} \oplus (1-3)\%$ **-** ✅
  Energy resolutions of the order of $5.2\%/\sqrt{E} \oplus (1-3)\%$
- Require **electron-pion separation up to 10^4** at low momenta in combination with other detectors **-** ✅
  Challenging requirement of 90% electron purity achieved thanks to precise 3D shower imaging
- Discriminate between **π^0 decays and single ɣ up to ~10 GeV -** ✅
  Precise shower profile determination and position resolution allows for π^0/ɣ way above the requirement
- **Low energy photon** reconstruction ~100 MeV **-** ✅

Beyond Yellow report: hadronic response improvement (“inner HCAL”), low energy muon detection, precise position and pointing resolution

Backup Slides

3. Performance:

a. Key plots to be shown

i. Energy resolution σ/E as a function of E (0-18 GeV) at η=0, 0.5, 1 **(slides 5-7)**

1. For each point, please extract FWHM and percentage of electrons within a cut window of |E/p-1| < 1x FWHM. Please provide the E/p lineshape in the backup material.

ii. Angular resolution (φ, η) as a function of E (0-18 GeV) at η=0, 0.5, 1 **(slides 8-9)**

iii. Pion rejection as a function of truth momentum p (0-18 GeV/c) at 95% e efficiency at |η| = 0, 0.5, 1 **(slides 12-14)**

iv. Pion rejection versus e efficiency at truth momentum p = 1, 5, 10 GeV/c at |η| = 0, 0.5, 1 **(slides 12-14)**

v. Separation of gamma from π^0 decay: Separation probability as a function of p at η = 0, 0.5, 1 **(slides 16-17)**

vi. Reconstructed cluster energy response to E= 8 GeV single electron vs η & φ in the full acceptance
Please use vertex = (0,0,0), and make two 2D plots of E vs η and E vs φ **(slides 10-11)**

b. Comparison of the present assessment of the detector performance compared with the YR requirements? **(slide 19 for summary)**

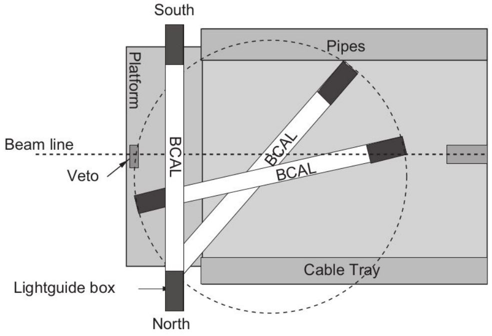
c. Pion contamination to the electron sample as a function of pseudorapidity **(slide 15)**

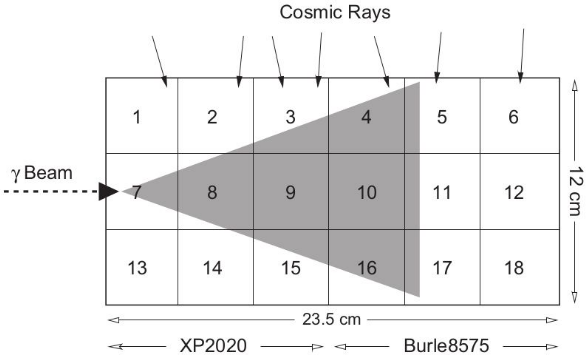
d. Performance perspectives beyond the YR requirements, if any ?

- Hadronic response **(slide 18)**
- Muon detection **(slide 24)**

Comparison with GlueX prototype data

Test at JLab Hall B with **full size one stave prototype**, secondary **photon beam**, **~0.15-0.6 GeV**, **90º angle**
NIM, 596 (2008) 327–337, Performance of the prototype module of the GlueX electromagnetic barrel calorimeter





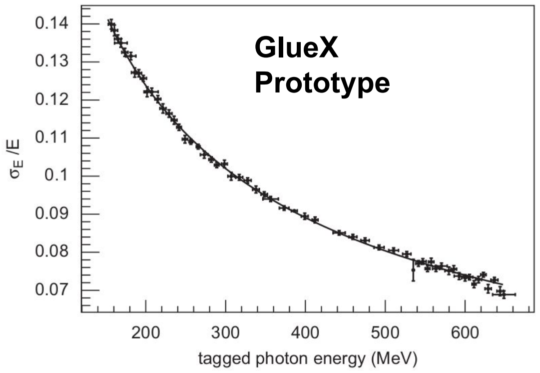


Fig. 11. Energy resolution vs. E_{BEAM} for photons for $\theta = 90^{\circ}$ and $z = 0$ cm. The fit gives $\sigma_{\mathrm{E}}/E = 5.4\%/\sqrt{E(\mathrm{GeV})} \oplus 2.3\%$. The fit of Fig. 10 corresponds to the 40th datum from the right (19th from the left) in this figure.

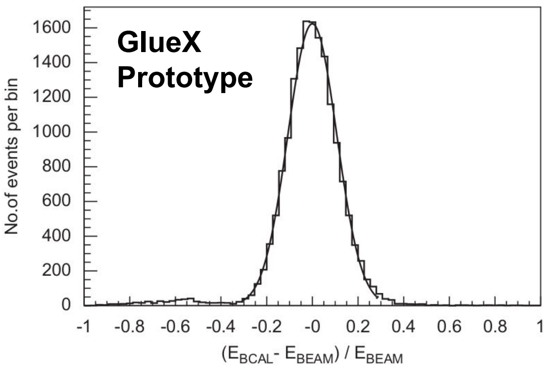
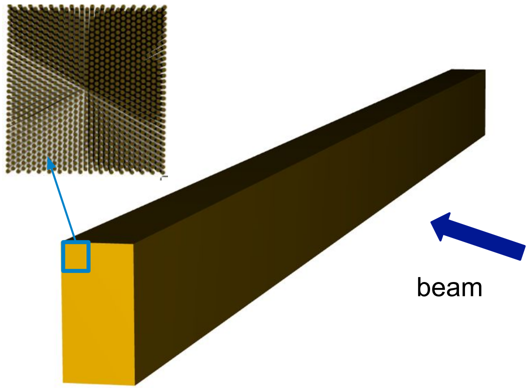
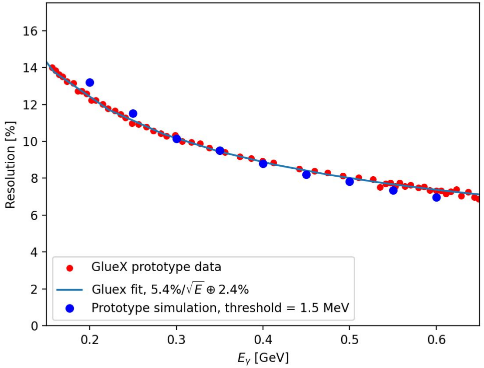


Fig. 10. The calibrated spectrum for D is shown for timing counter 40, corresponding to a beam energy of 273 MeV. The solid line is a Gaussian fit to the data.

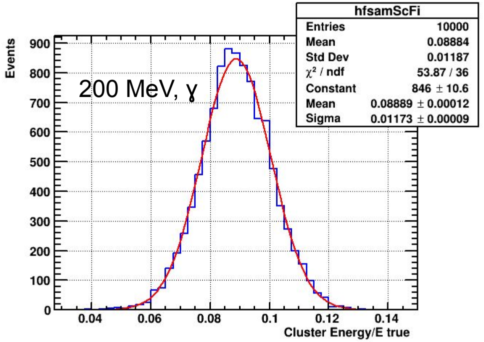
Comparison with GlueX prototype data

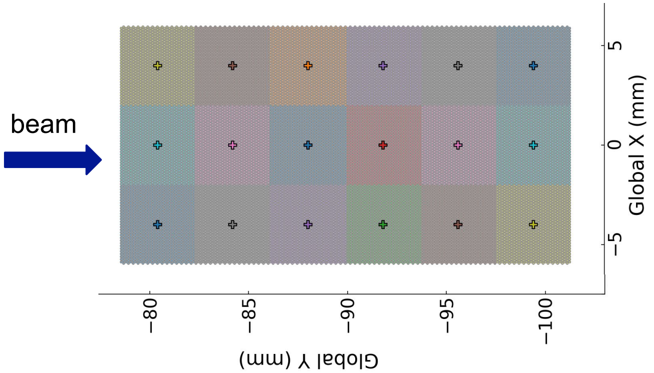
Simulation of GlueX prototype and readout scheme in **ePIC simulation environment**





Reconstructed Energy/True energy

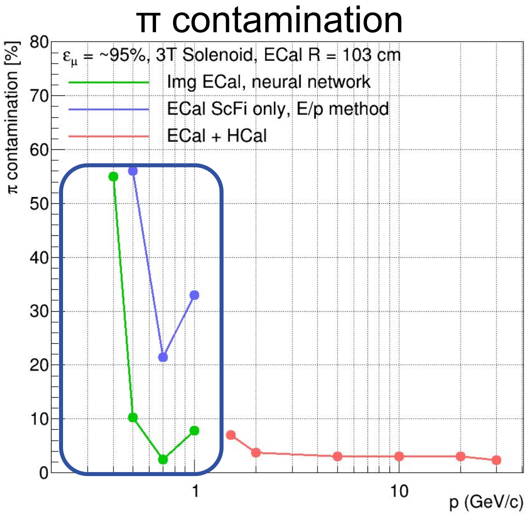


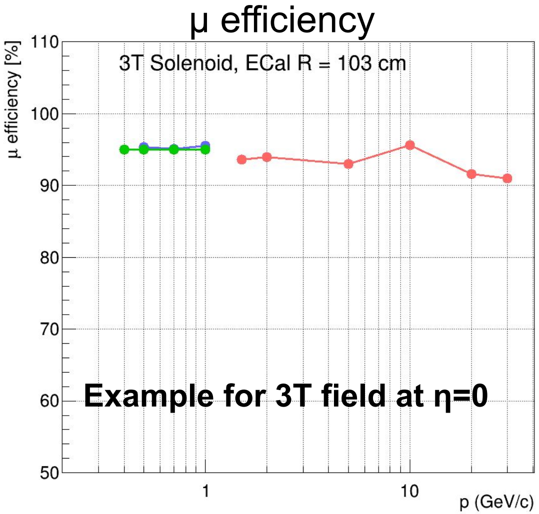


- Realistic geometry implementation and simulation of the prototype and readout
- Low energy data described quite well by the simulation
- Energies up to ~6 GeV tested in the ongoing test at Hall D

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**

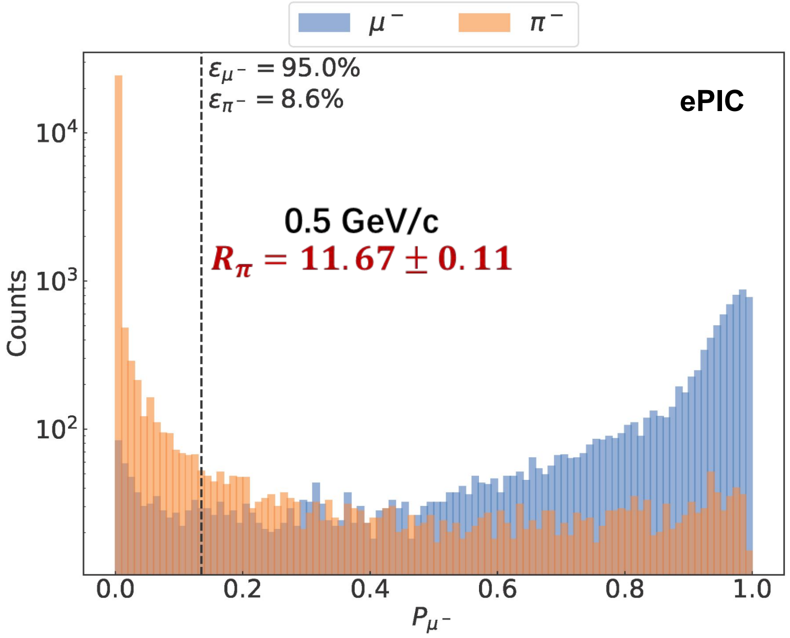
The discontinuity in reaching HCal is rapidity dependent

- 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

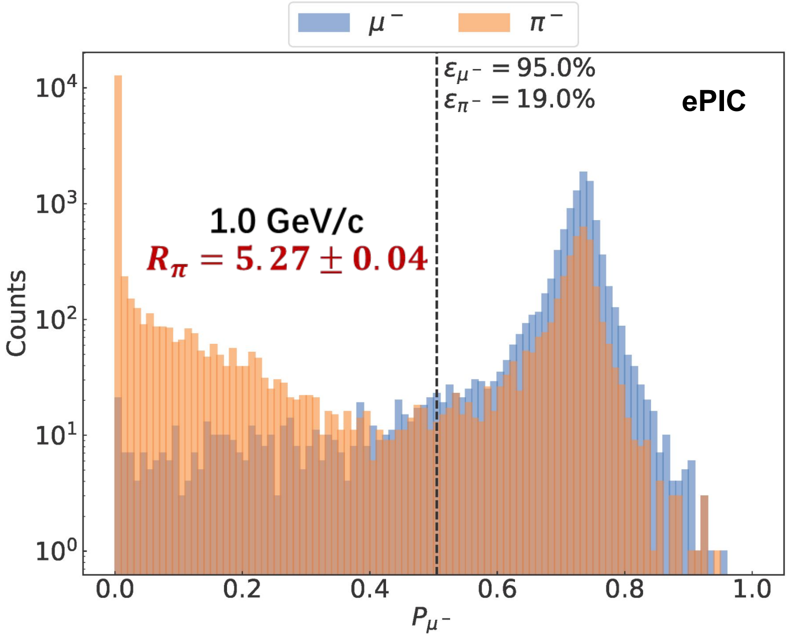
μ^-/π^- Separation

- A preliminary study focused on μ^-/π^- separation
  - Similar to ML e^-/π^- separation, without the E/p cut

This muons curl inside BCAL



This μ^-/π^- partially punch through BCAL



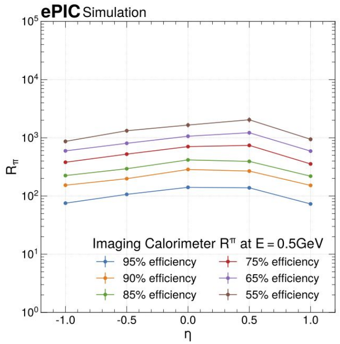
Classification Neural Network

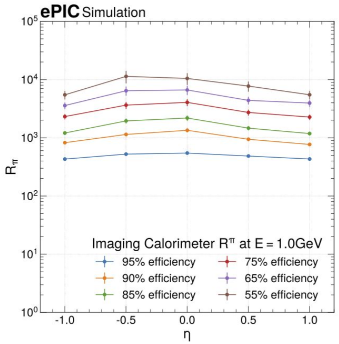
- 10-layer VGG-style **convolutional neural network** (CNN)
  - Combined data from AstroPix and Pb/ScFi
  - 5+2 convolutional and pooling layers, and 3 dense layers
  - Data formatted for each event to N_layers x N_hits x N_features
  - 4 features (Edep, Rc, eta, phi), energy and spatial information for shower

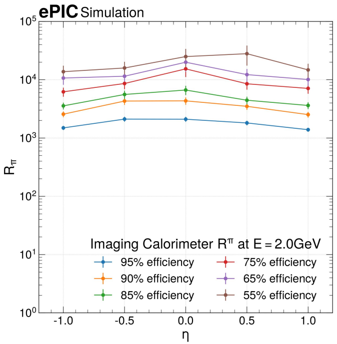
- **Supervised training**
  - Used all official singles productions with 10:1 pion to electron samples (to ensure enough remaining pions after E/P cut. Typically 100-200k events in the AI training sample. Processed over 2TB of simulation results.
  - 20 epochs per training cycle, data split 70-10-20 for training, validation, and testing
  - All uncertainties are based on binomial statistics

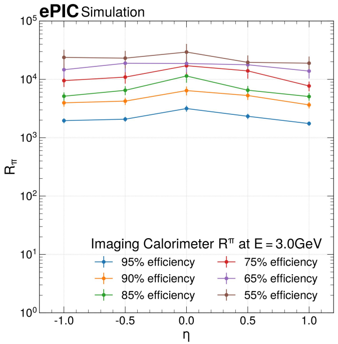
e/π Separation

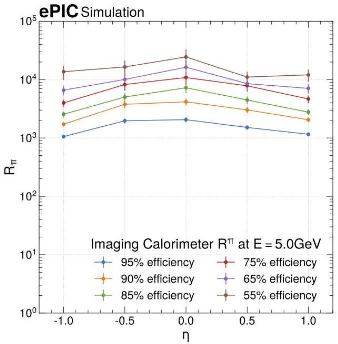
η, energy and efficiency dependence

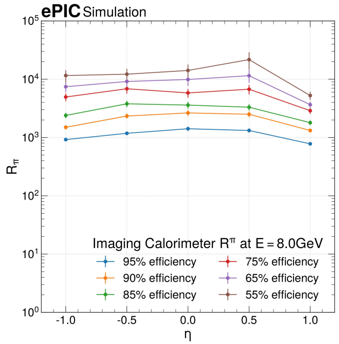


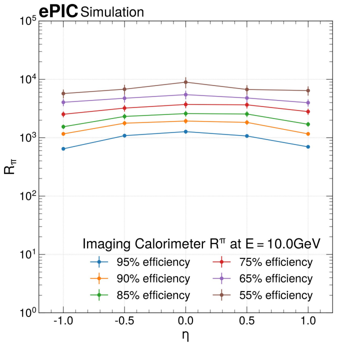


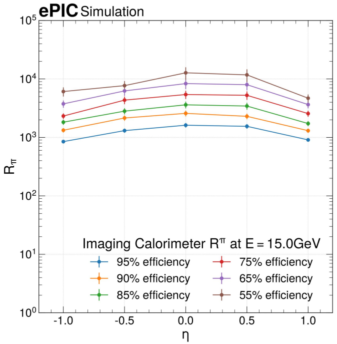


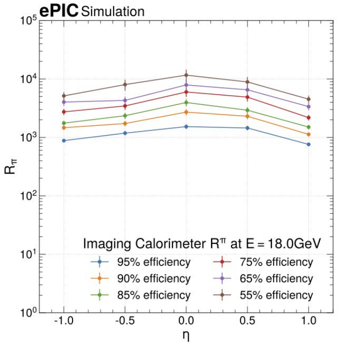












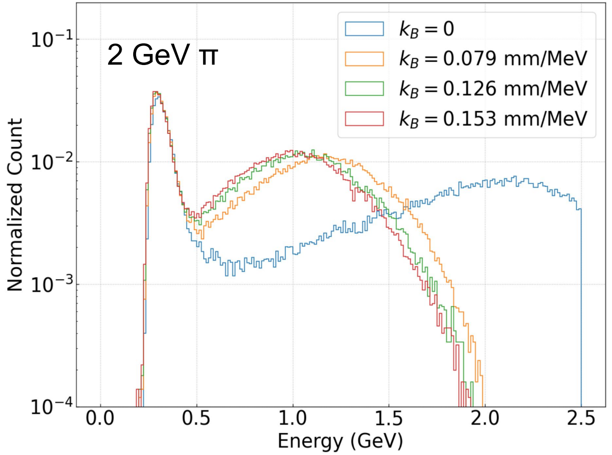
Pb/ScFi

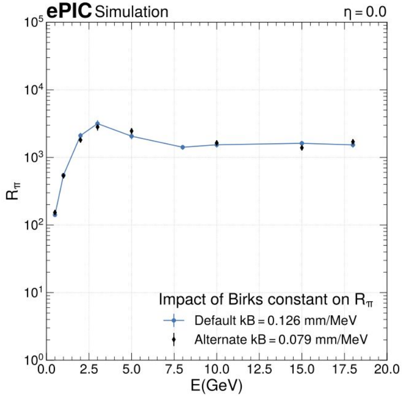
Confidence in the hadron rejection simulation

Birk's constant

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

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





γ/π^0 Separation - NN Model Training

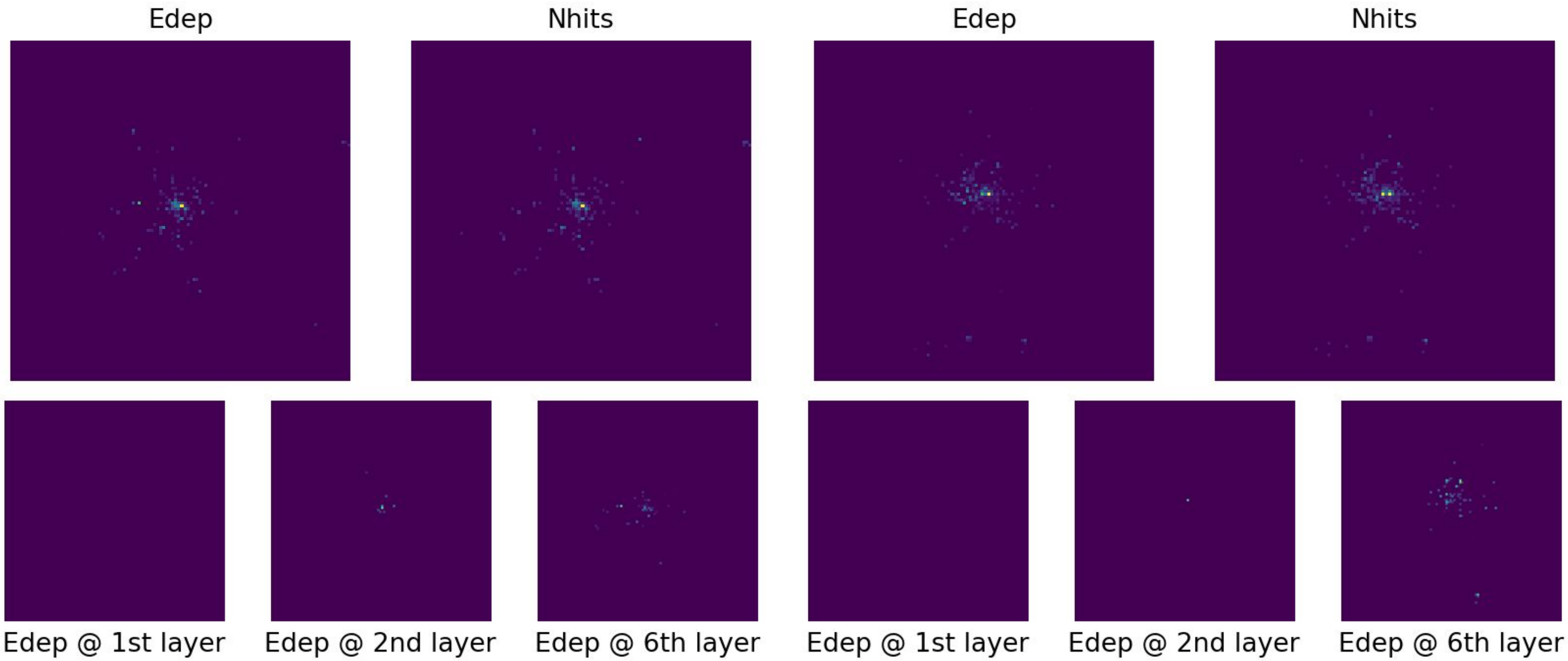
I. **Data preprocess**
   A. AtroPix data only, each event -> a 112 x 112 image on (η,ϕ) with bin size (0.001, 0.001 mrad)
   B. Image centered at the gravity center of all hits
   C. Each pixel has 5 channels: E_{dep} and N_{hits} from all layers, E_{dep} from 1st, 2nd, and 6th layers
   D. Sum of E_{dep} for multiple hits in the same pixel

II. **Classification with NN**
   A. VGG-like model with a simplified structure
   B. Optimized for sparse pixels (fired hits), since they would not go deep in the NN

III. **Ongoing study**
   A. More channels that characterize each hit
   B. More sophisticated NN model
   C. More data to train the model

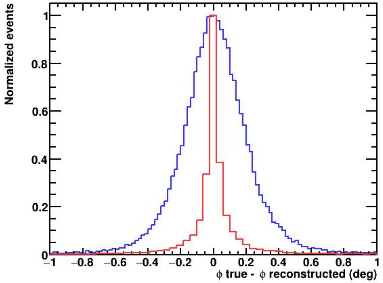
γ/π^0 Separation - ML Training Samples

Samples of the 112 x 112 x 5 images

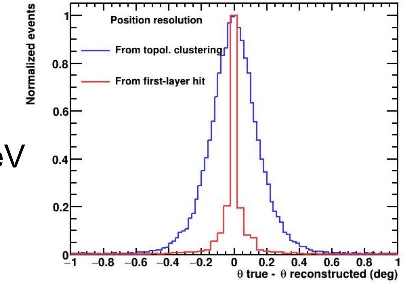


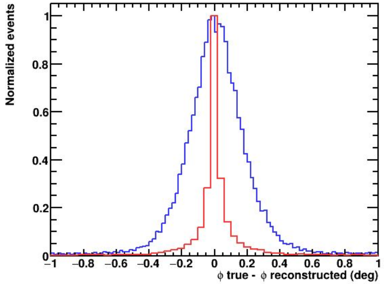
a 10 GeV/c photon **a 10 GeV/c pion-0**

Position resolution - Photons (η = 0)

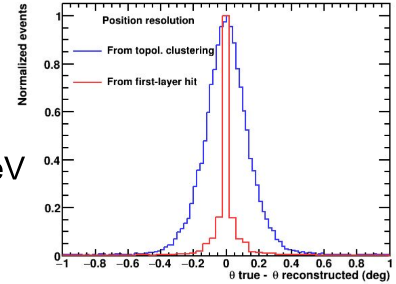


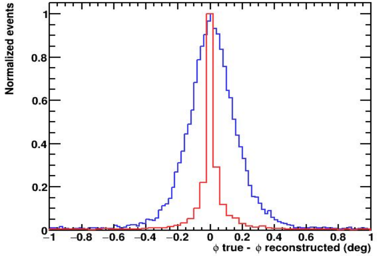
3 GeV



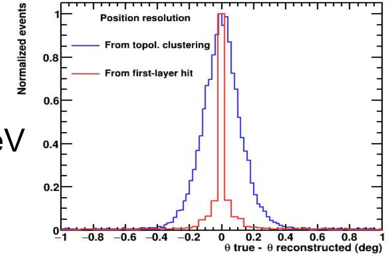


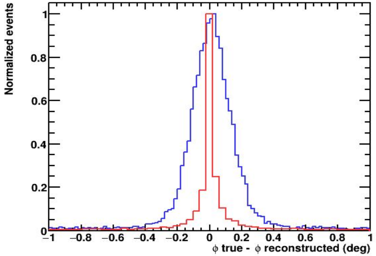
5 GeV



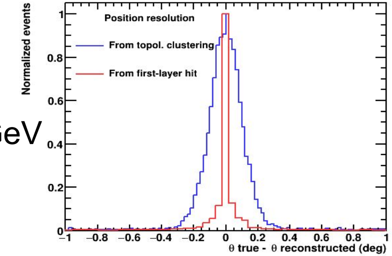


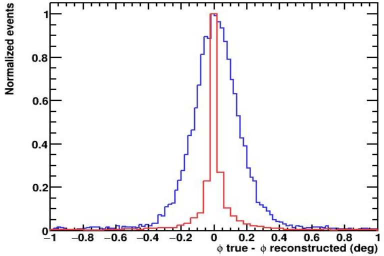
8 GeV



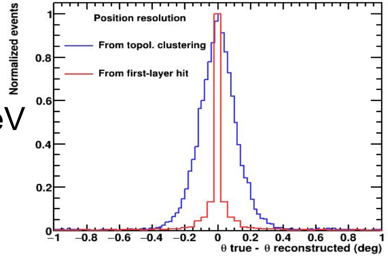


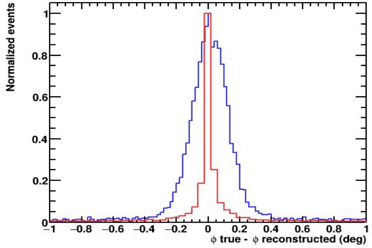
10 GeV



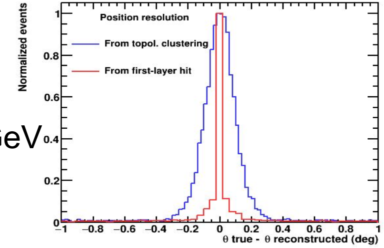


15 GeV

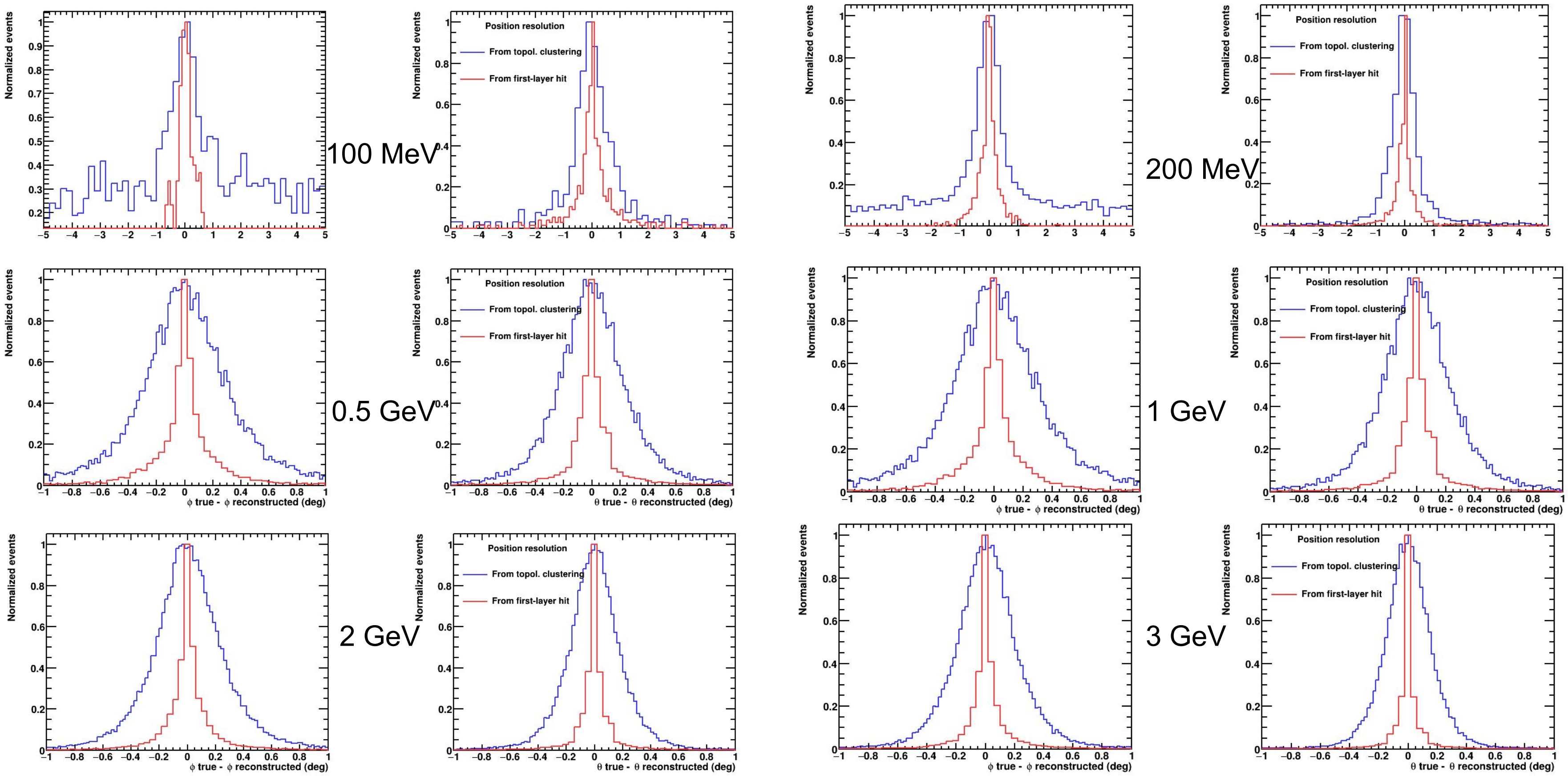




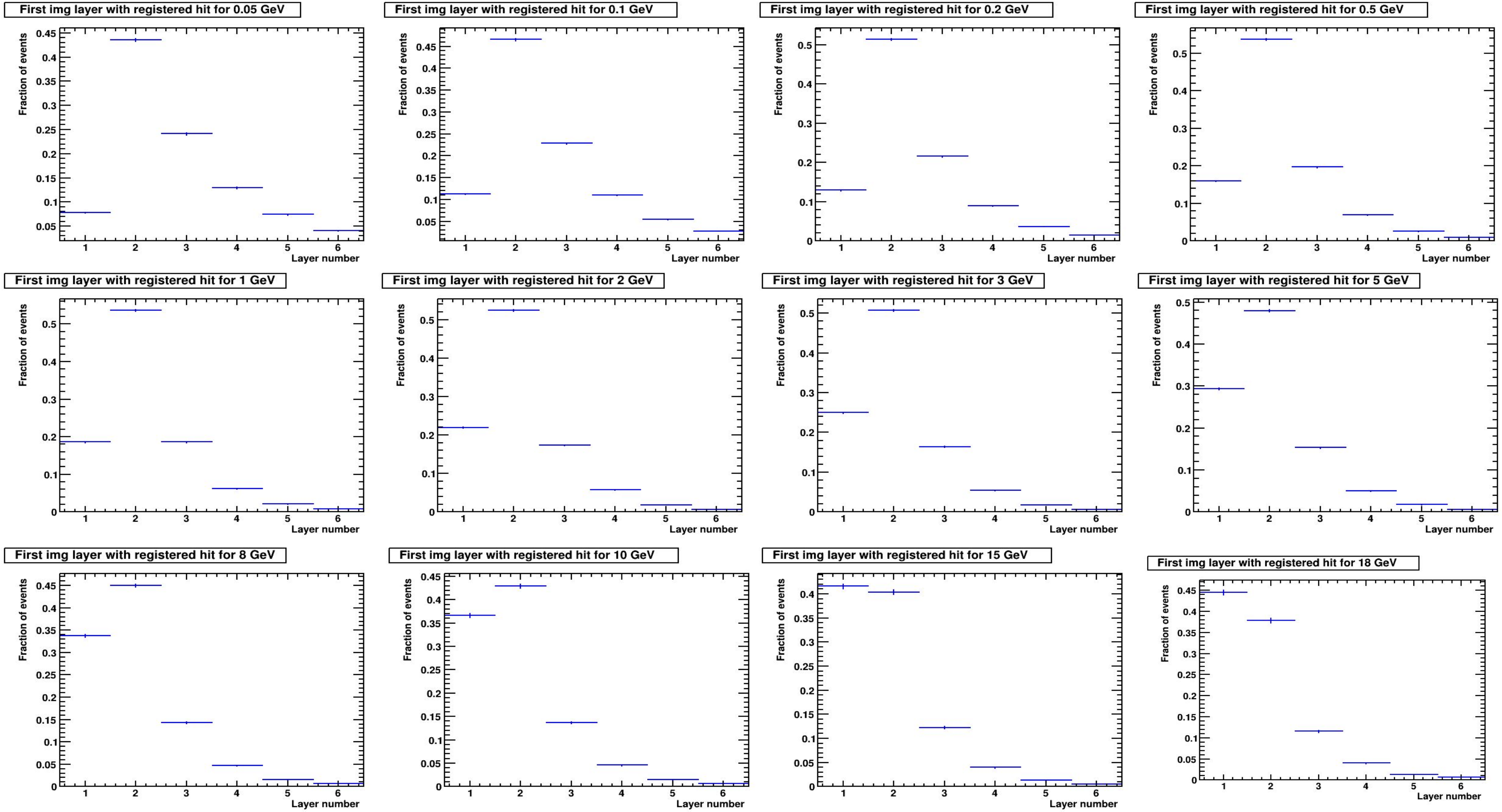
18 GeV



Very low energies < 0.5 GeV impacted by clustering reconstruction - a separate algorithm would need to be developed

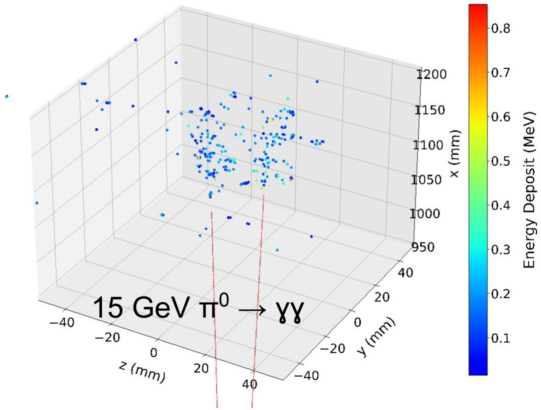


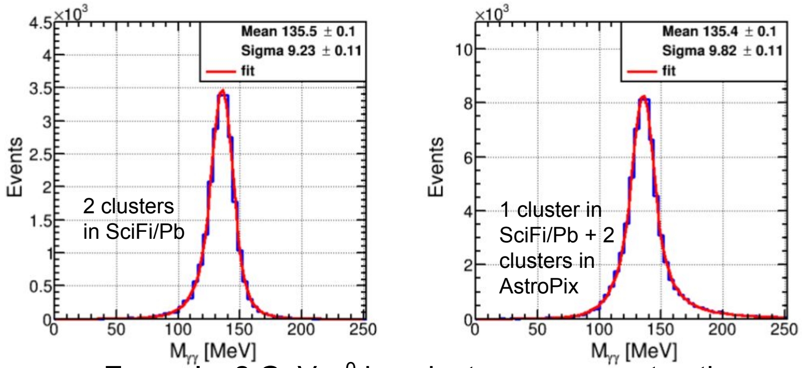
First imaging layer ɣ leave a hit



ScFi/Pb - Shower energy separation

- Currently considered granularity with r = 80 cm and lightguide width of 2 cm: **one sector covers Δφ = ~1.5 deg**





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%

ScFi/Pb - Shower energy separation

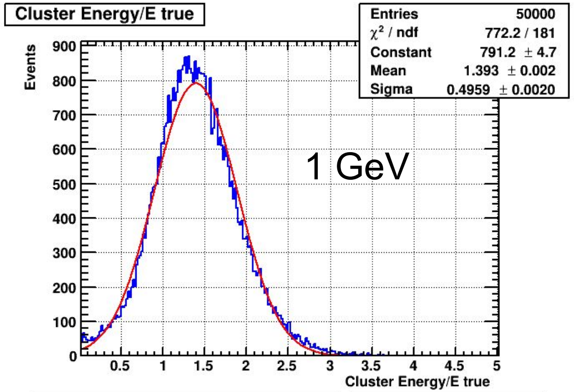
- **Probability of 2 particles hit exactly the same Δφ = 1.5 deg sector quite low.** For example:
  - 3% of all gamma pairs from SIDIS π^0 decays
  - For jets (anti-kT, R=1.0) 60% has more than 1 gamma, out of them ~ 17% fall within **3 sectors Δφ = 4.5 deg**

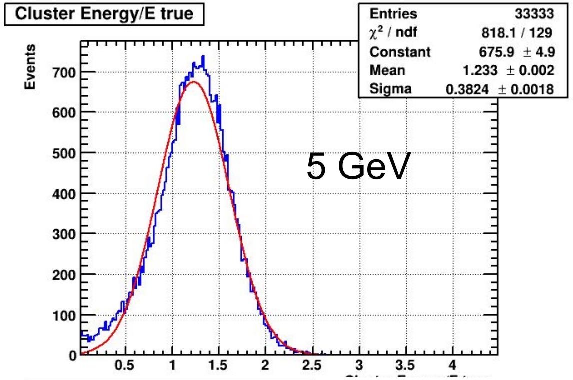
- For the small fraction of events that end up in the same (or close) Δφ = 1.5 deg sector, the rough separation based on the example waveforms seems to allow for separation ~50 cm

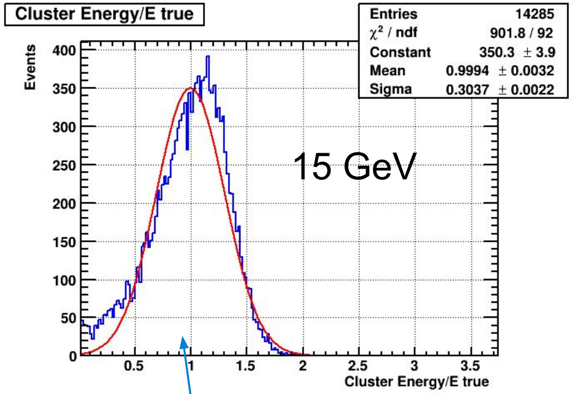
- Detailed analysis of specific physics aspects requires stimulation with realistic waveform analysis (obtained in ongoing prototype test)

Energy resolution of AstroPix Layers

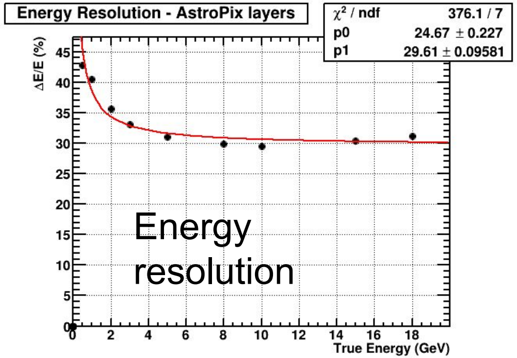
- **Sampling fraction < 0.5 %**
- Example Energy Lineshapes for photons at η = 0

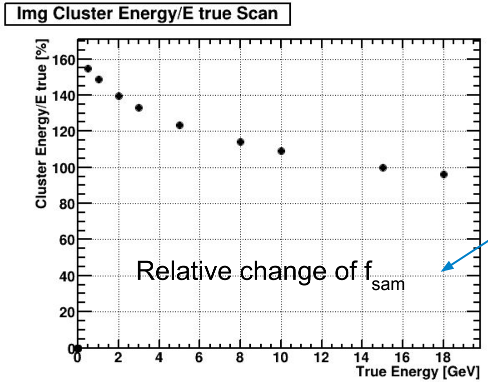






non-gaussian





strong dependence in this geometry

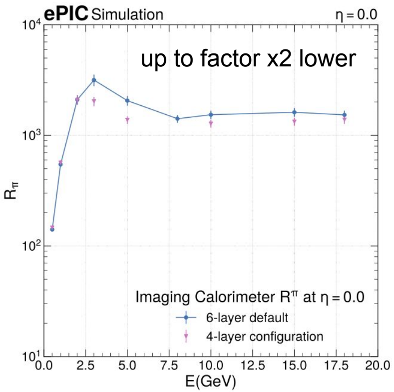
The case for 6 imaging layers

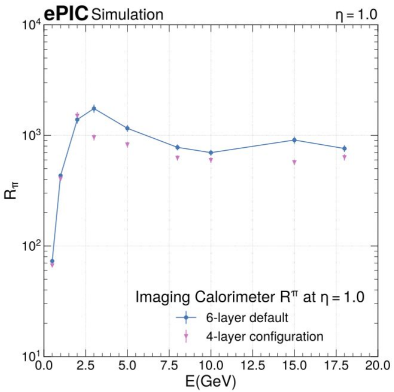
Default 6-layer configuration vs an equidistant 4-layer configuration

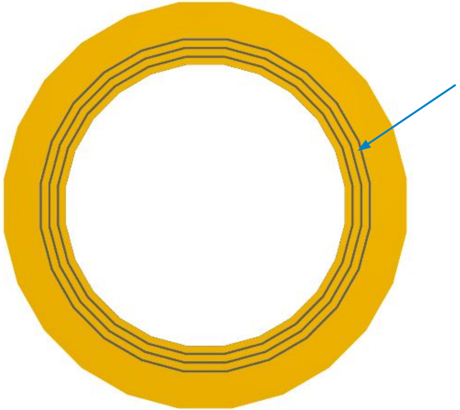
- Most pion rejection performance loss in **middle energy range**, where the barrel **ECal is the most crucial**
- **Exaggerated reduction at larger *η*** due to inflated radiation length between layers. Lose much of the shower imaging capabilities, impacting also photon-pion separation
- **Impacts Pb/ScFi 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 for relatively small cost savings
- A staged approach to installing the imaging layers could be a possible risk mitigation strategy



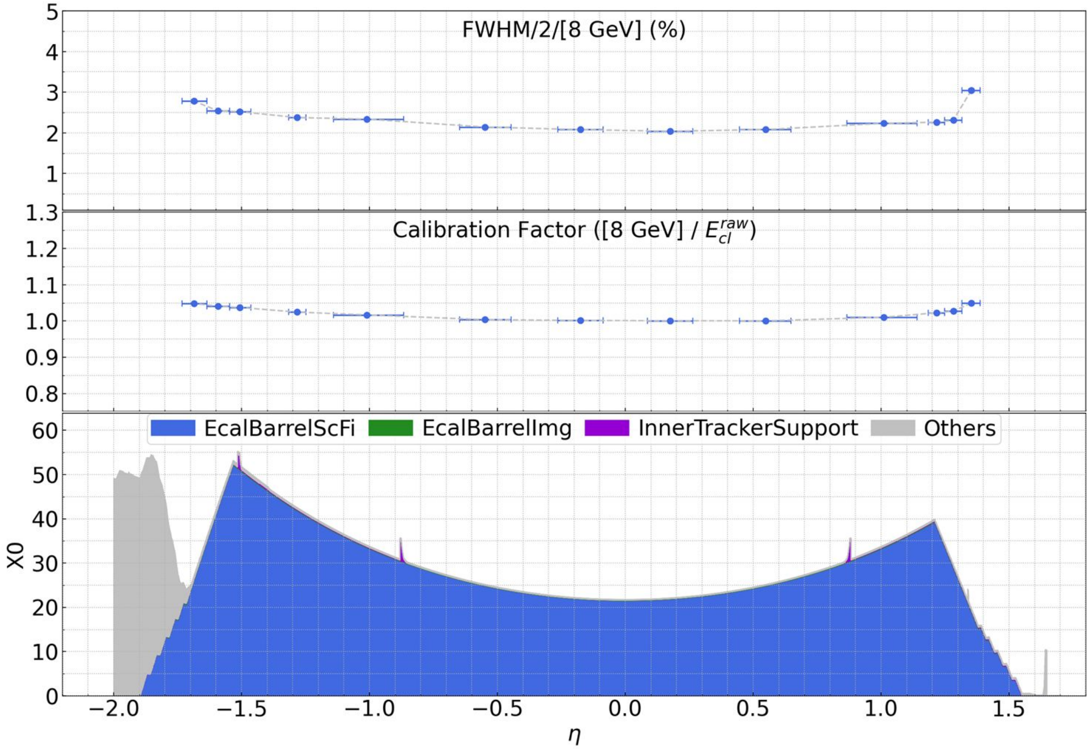




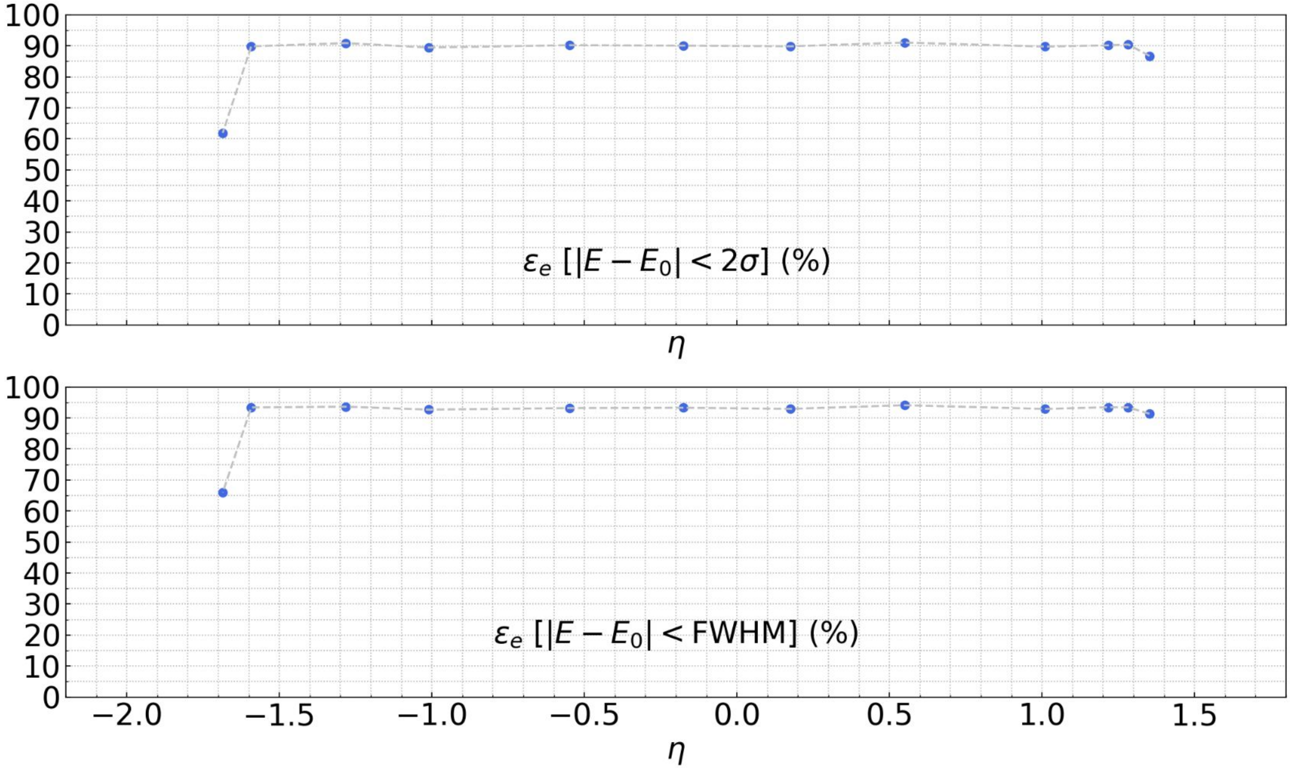
2.52 X_0 separation between imaging layers at η = 0 (1.45 X_0 separation in default geometry)

Clustering at 8 GeV/c - Resolution (FWHM/2)

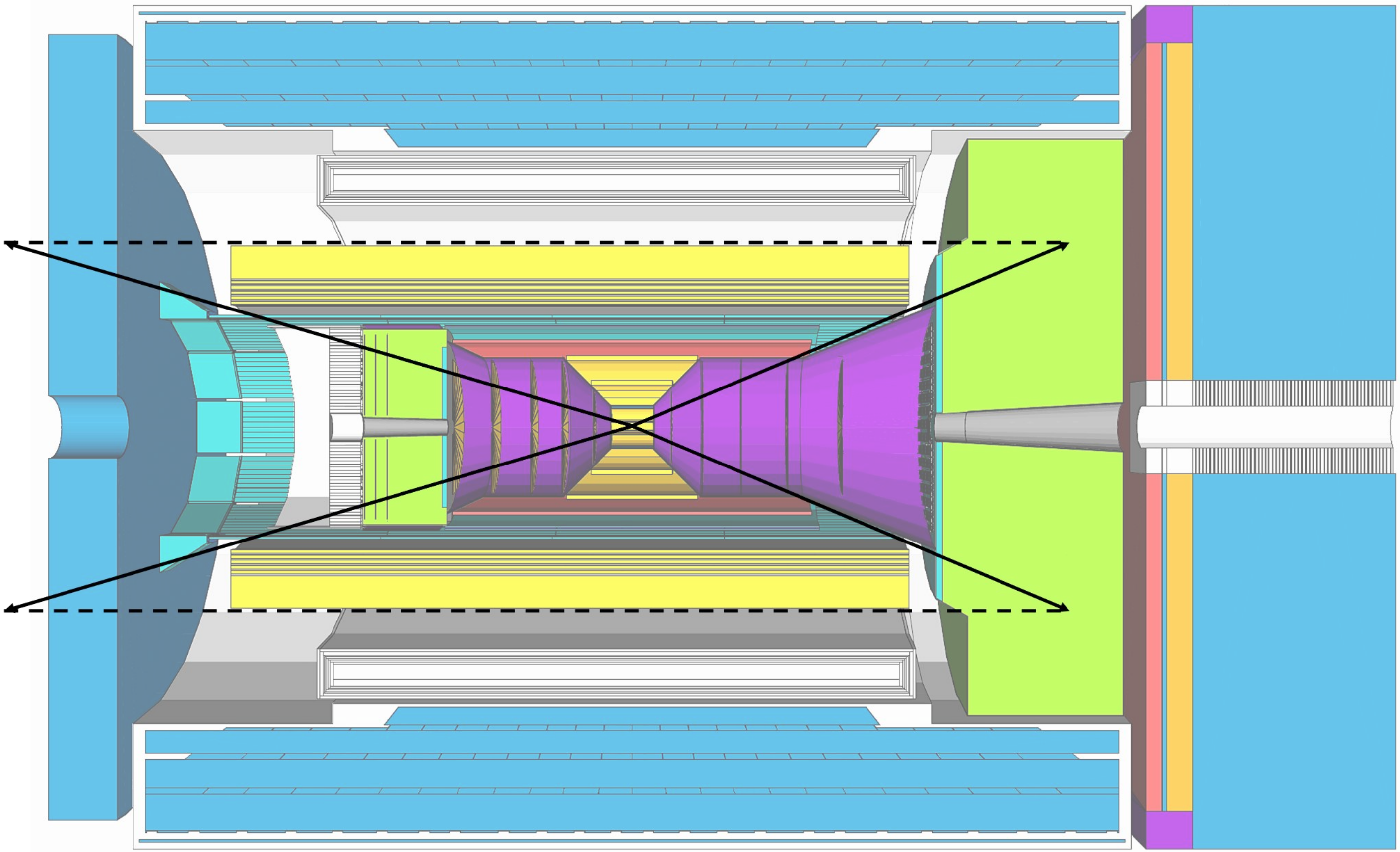
- Island clustering in official software (EICRecon)
- Top: energy resolution (FWHM from Crystal Ball fit) and calibration curve
- Bottom: material scan up to R(x, y) = 120 cm
- Slight degradation of energy resolution with larger pseudorapidity value
  - Consistent with energy resolution study
- Calibration curve is flat within (-0.6, 0.6), < 2% within (-1.1, 1.1)
  - Energy leakage correction in future study



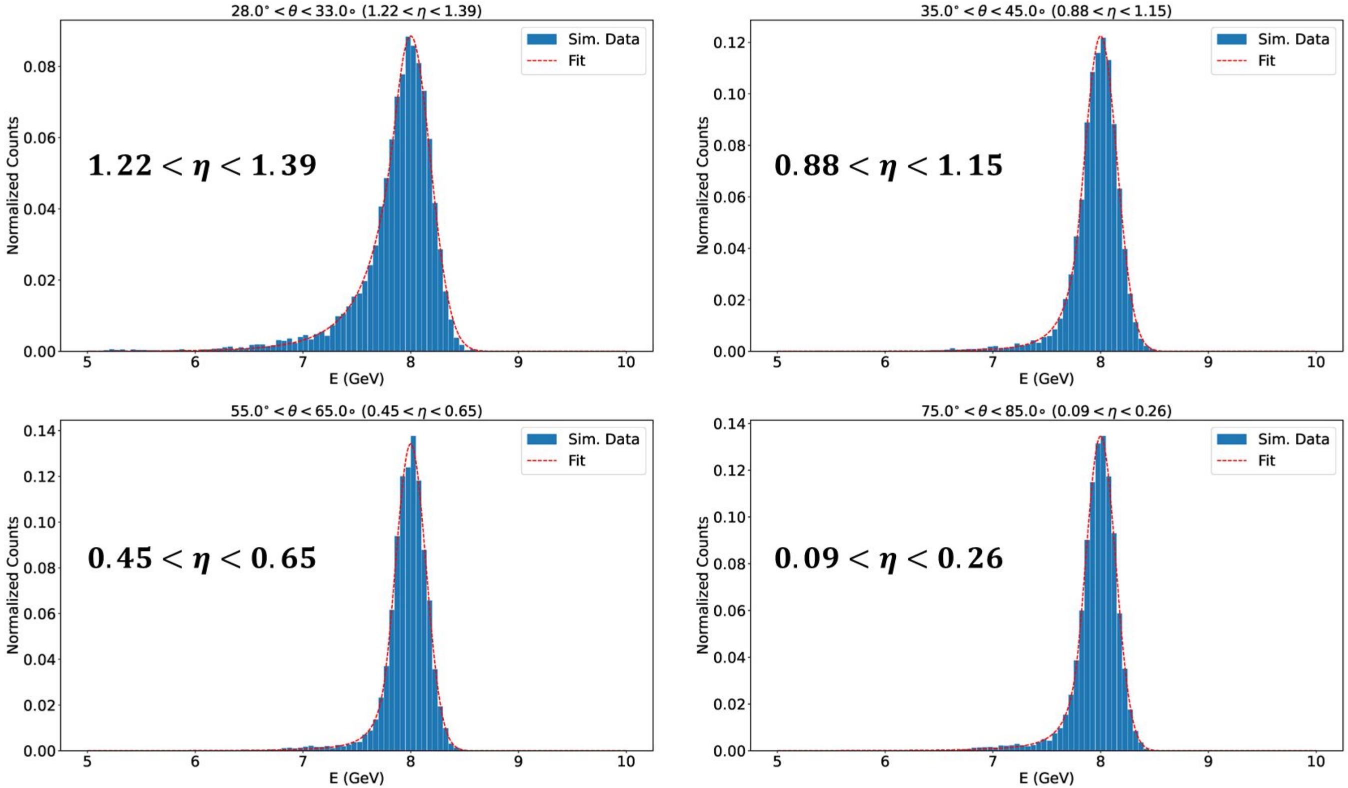
Clustering at 8 GeV/c - Efficiency



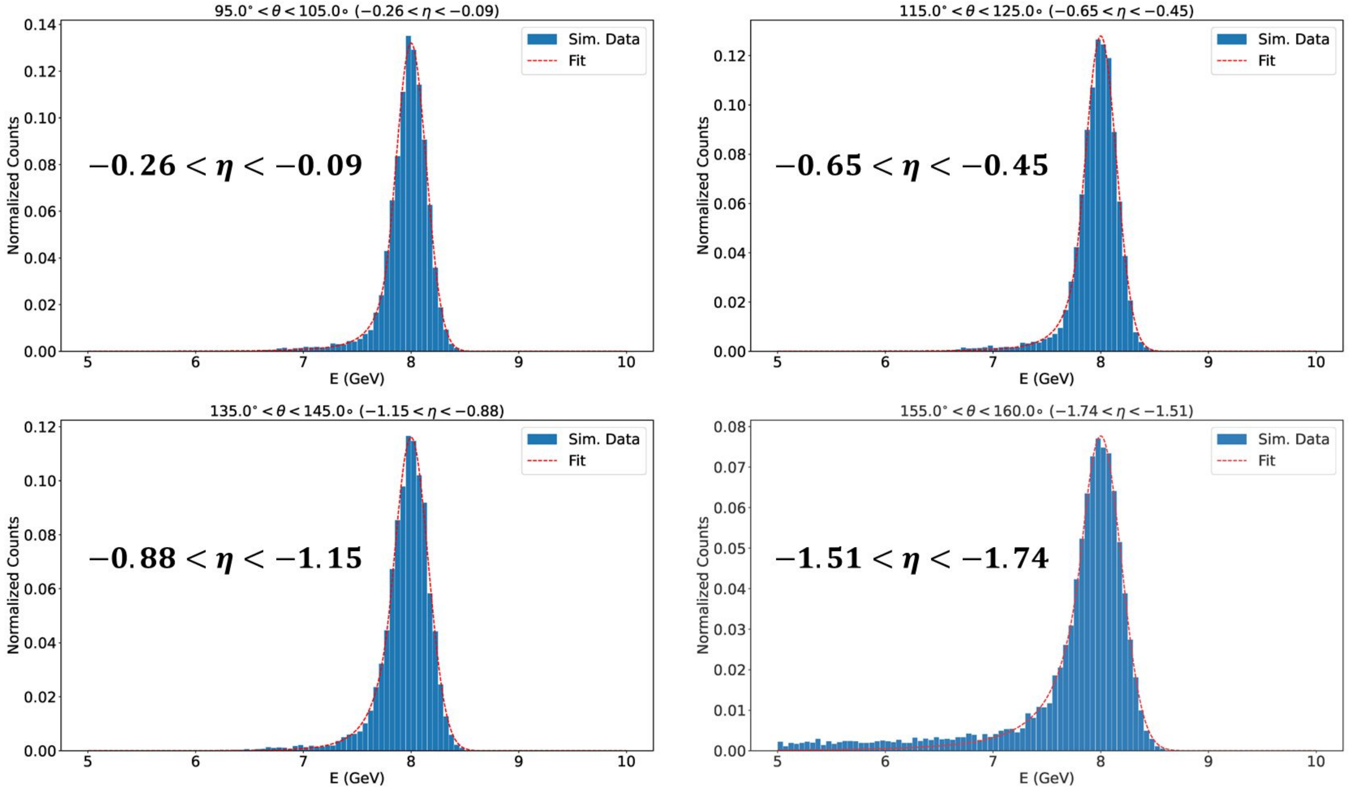
Material Scan Range



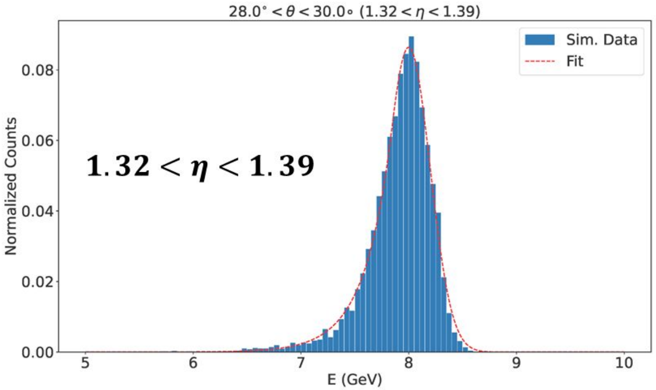
Crystal Ball Fits for 8 GeV/c Electrons

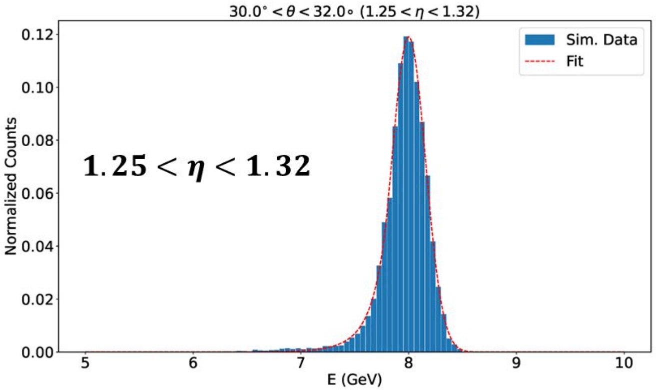


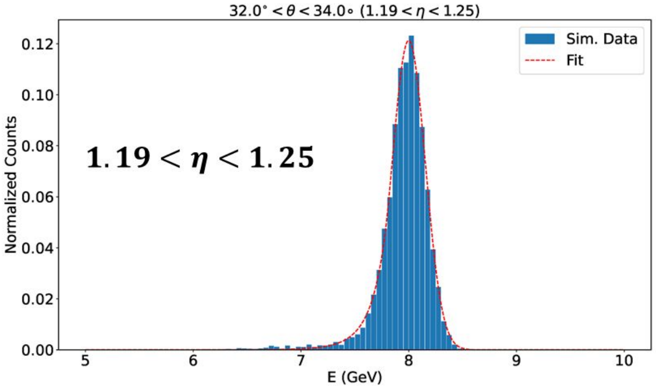
Crystal Ball Fits for 8 GeV/c Electrons



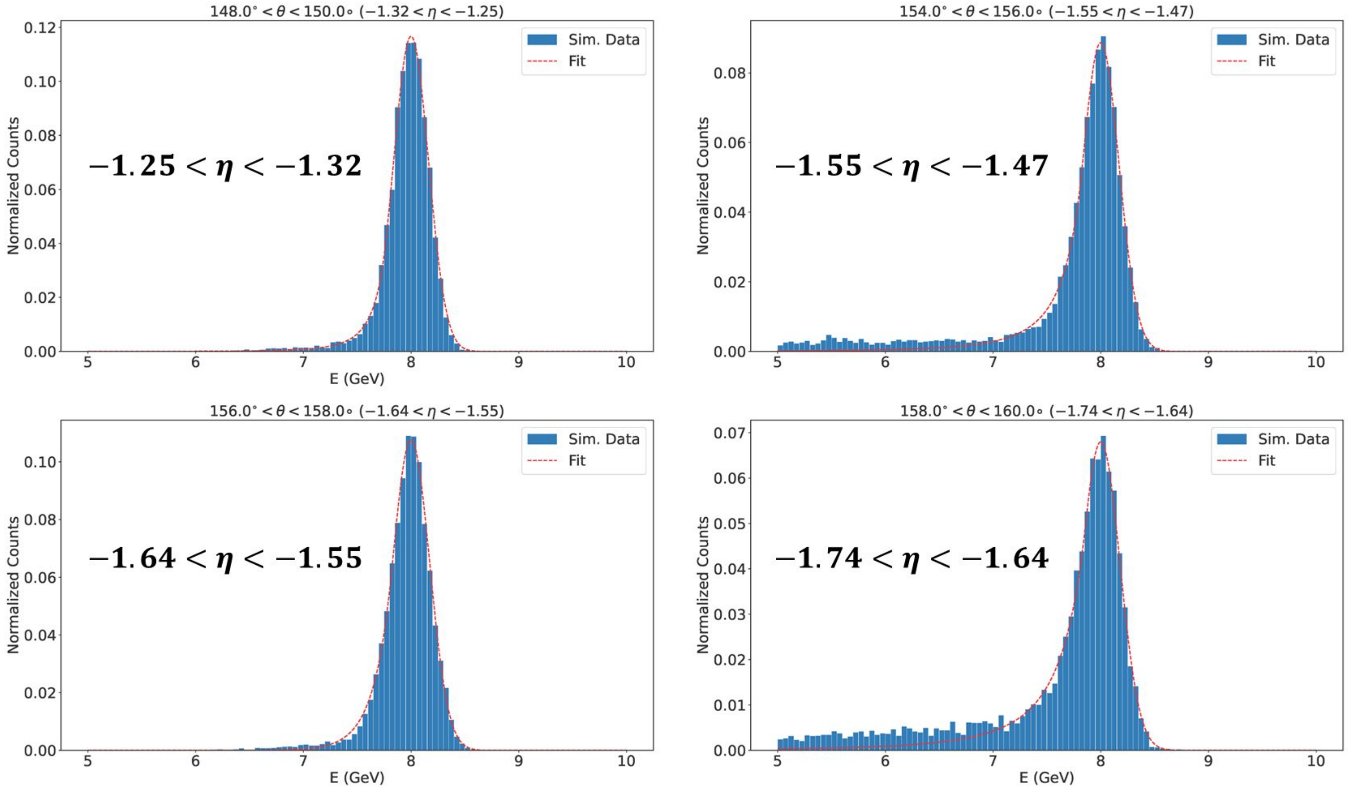
Crystal Ball Fits for 8 GeV/c Electrons





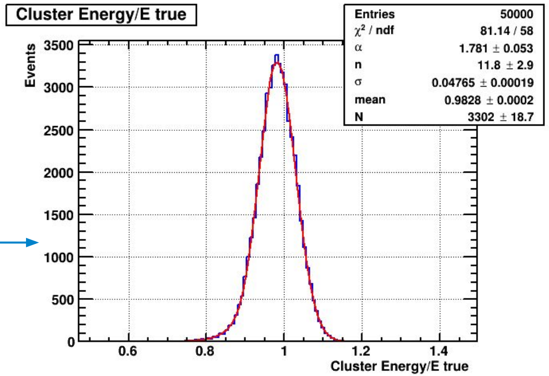


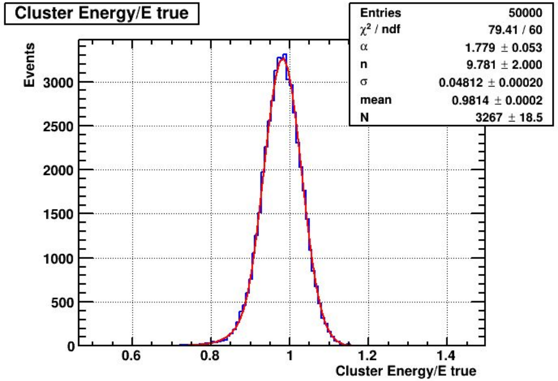
Crystal Ball Fits for 8 GeV/c Electrons

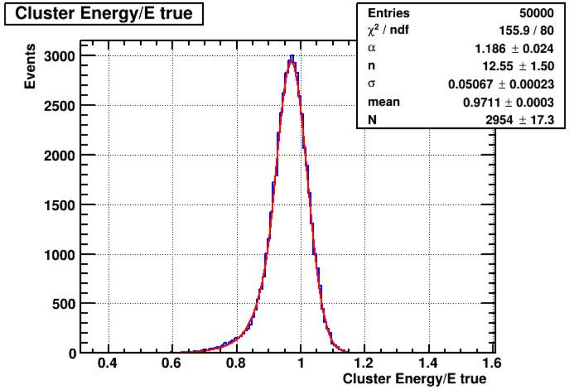


Example Energy Lineshapes for Photons

1 GeV







η = 0

η = 0.5

η = 1

10 GeV