MAPS Calorimetry for FCC?

Exploratory “Hobby Project” with Claude Code

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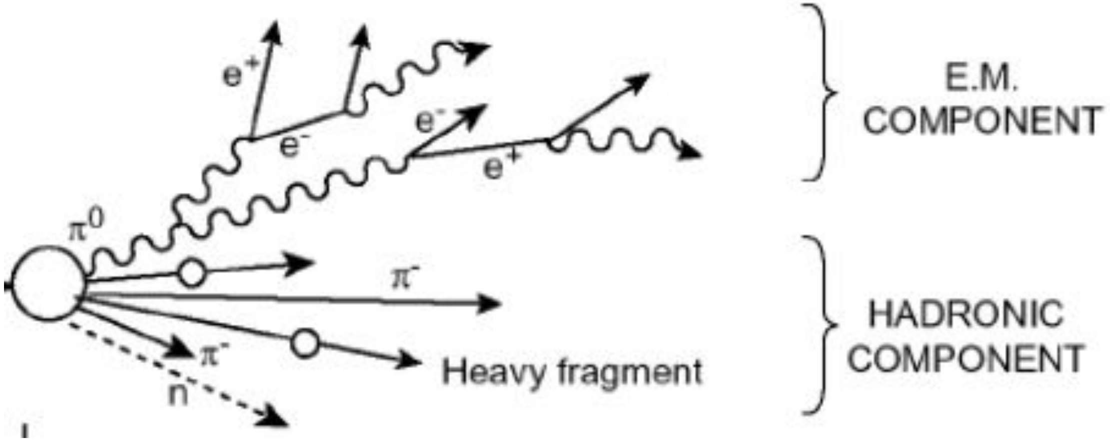
U.S. DEPARTMENT of ENERGY

FCC & Detector Motivation

- **Goal: measure Higgs couplings to per mille precision**
- **Detector requirement: unprecedented performance, often quoted as 3-4% on jet energy resolution**



- Ideas for FCC calorimetry
  - Dual readout crystal to measure scintillation & Chrenekov
  - Si/W sampling calorimeter designed for pflow

Principle of p-flow

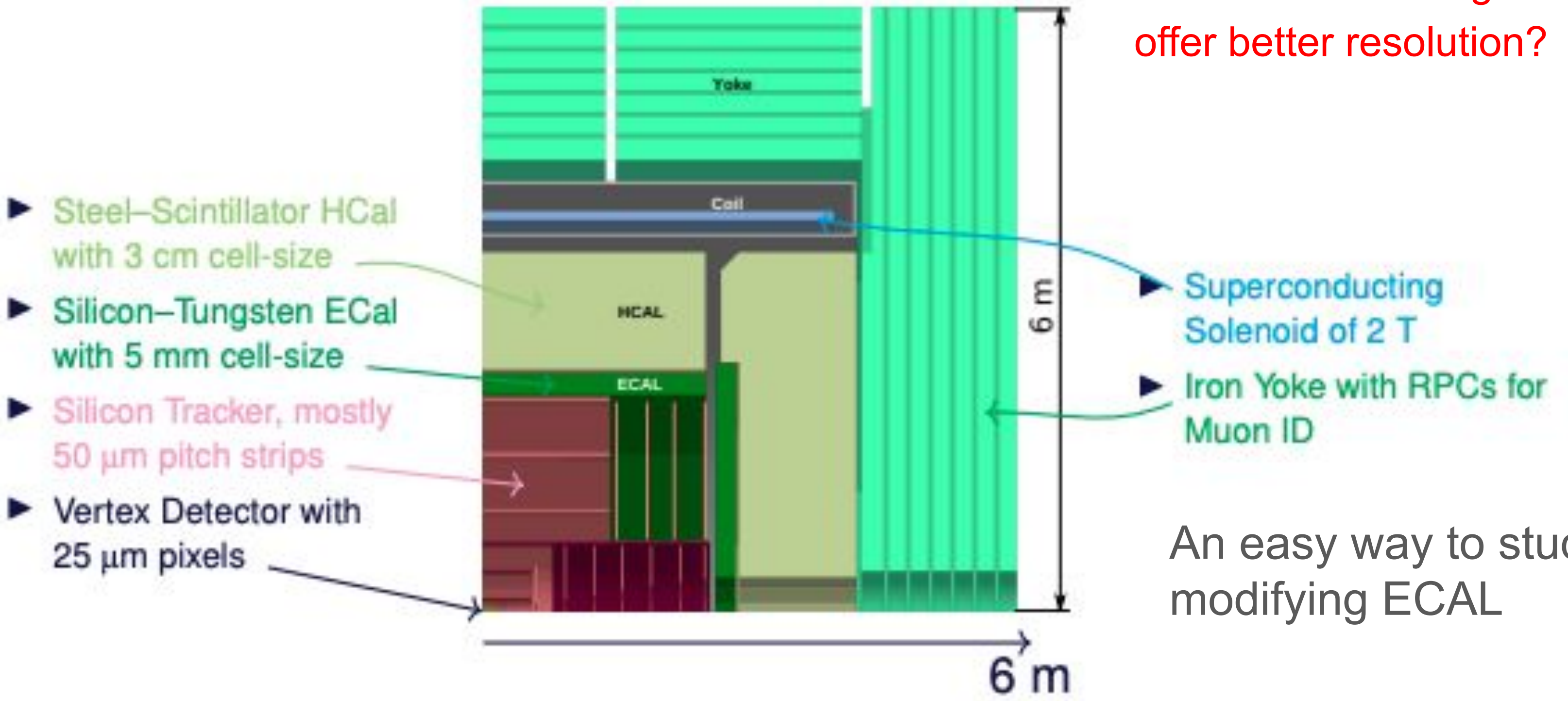
E_jet = Σ(p_charged) + Σ(E_photon) + Σ(E_neutral)

└─ Tracker ─┘ └─ ECAL ─┘ └─ HCAL ─┘

CLD

- CLD one of the detector concepts
- Designed for particle flow

Main question trying to understand through these studies does finer granularity offer better resolution?



An easy way to study this by modifying ECAL

MAPS for Calorimetry

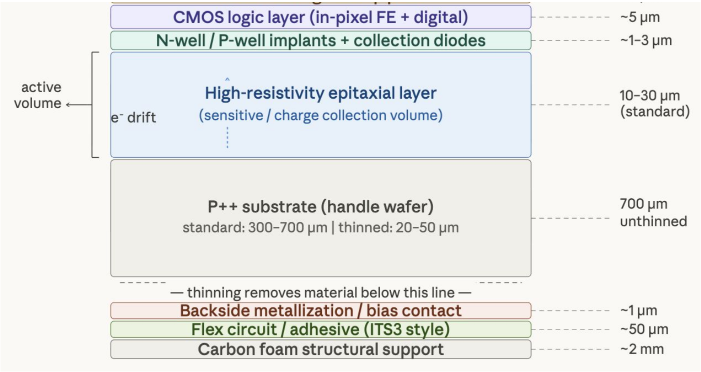
Explored in terms of electromagnetic calorimetry for SiD https://arxiv.org/abs/2110.09965v2

- Monolithic Active Pixel Sensors
- Both readout & sensitive region same layer
- Lower power consumption per channel than traditional sensors

Prototype studied: **NAPA-p1** (Habib et al., JINST 19, 2024)

Property	Value
Pixel pitch	**25 μm**
Pixels/cm^2	160,000
Epi-layer thickness	**12 μm**
ENC (noise)	13 e^- rms
Time jitter	$<$ 400 ps rms
Peak power	**115 mW/cm^2**
Avg. power ($<$ 1% duty)	1.15 mW/cm^2

Typical MAPS sensor layout



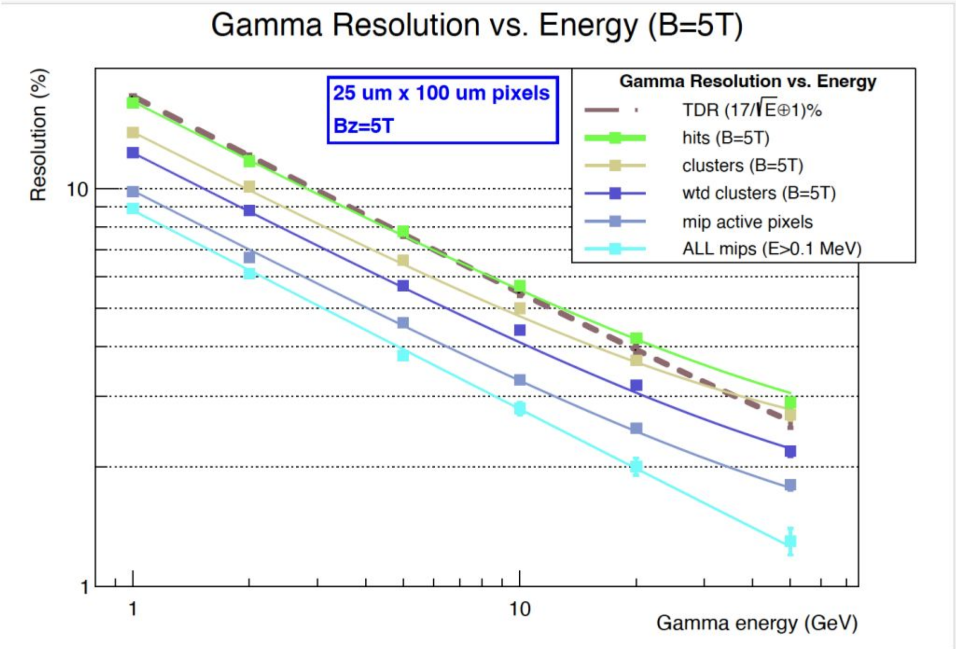
~50-100 um thickness if thin sensors

MAPS for Calorimetry

Explored in terms of electromagnetic calorimetry for SiD https://arxiv.org/abs/2110.09965v2

- Lower power consumption per channel than traditional sensors
- Possible for linear collider because of power pulsing, no active cooling required

Is this feasible for FCC? Does this bring any improvement?

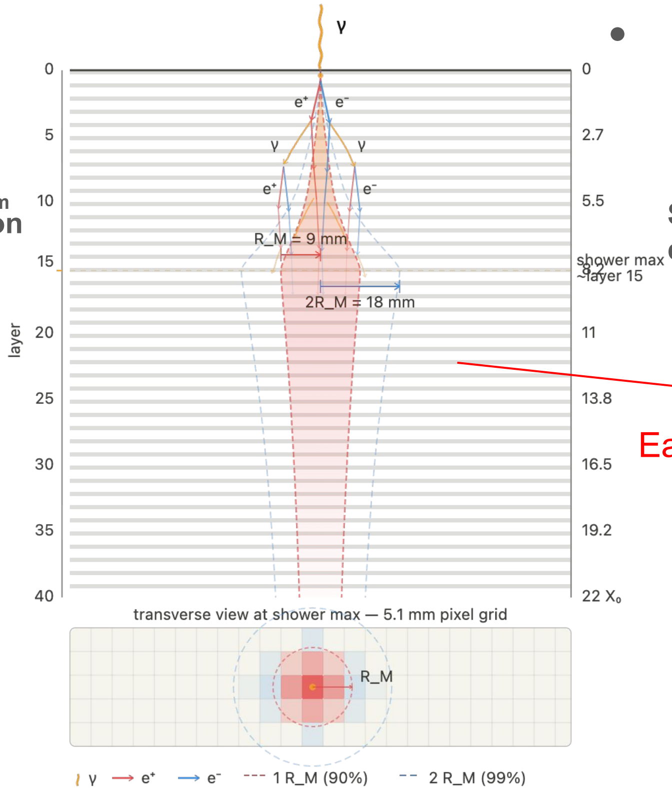


Baseline CLD Calorimetry

Sampling calorimeter with 5.1mmX5.1mm Si pixel, 40 layers total

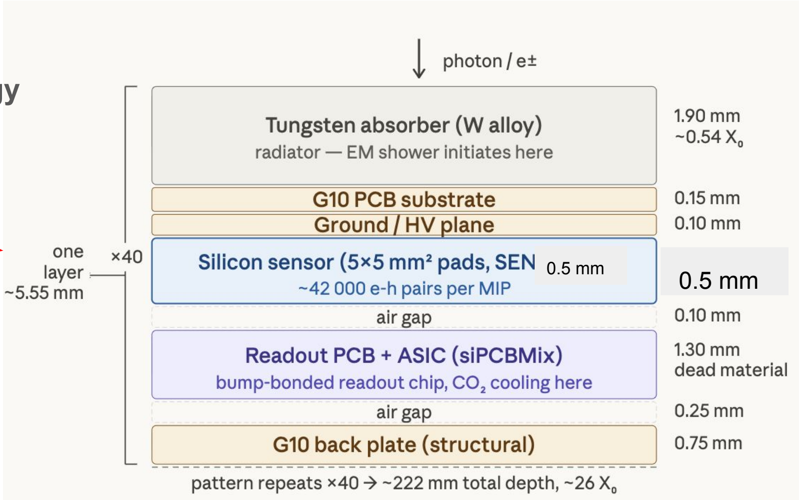
- Analog sensors collect all charges above some threshold
- Cooling assumed to be passive, no active cooling for sensors

Moliere radius R_m depend on material



Shower max depend on energy

Each layer



Why MAPS & What are Challenges of using for Calorimetry?

Why?

→ Low power consumption, for regular pixel higher granularity would require enormous power & cooling

Challenges?

→ Cooling, for linear collider MAPS in calorimeter feasible because of power pulsing (only operational 1% of the time)

→ Adding cooling material reduces calorimeter performance

Main Question: An optimal pixel size to balance granularity & cooling needs?

Roadmap of this study

Step 1 ✅

→ Understand current workflow/setup

→ key4hep software, DD4hep ddsim Geant4 full simulation

→ starting with FCC tutorial

→ CLD baseline config

CLD o2 v07 from k4geo, CalBarrel o2 v01 03.xml

✅ **shown in these slide**

Step 2

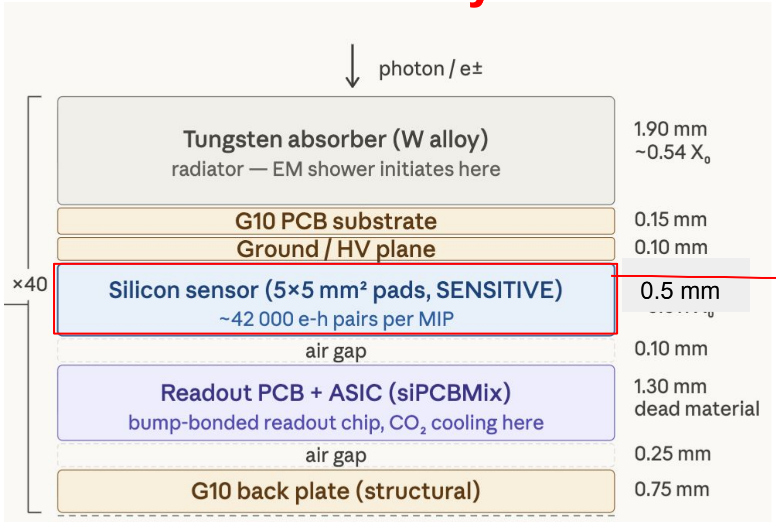
→ Change pixel size & study ECAL performance

→ Photon gun study; resolution?

→ pion gun study; are granular pixels better for photon from pi0 separation?

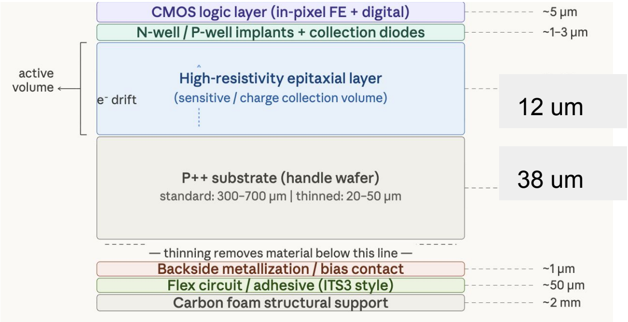
Changes in Simulation for this Study

Baseline CLD layer



Replaced by MAPS like sensor

Sensor for this study



Changes:

- **5 mm size to 500 um, 200 um, 100 um, 50 um & 25 um changed separately**
- **Thickness changed from 500 um to 12um sensitive + 38 um substrate**
- **Analog → digital readout, hit vs no hit**

- All additional layers like PCB/ASIC on the baseline kept as is, idea would be to replace this eventually by active cooling material

Photon Resolution

Step 1: Fire a single photon at different energies 1, 5, 15, 20, 50, 100, 200 GeV for ECAL with different pixel size [25um, 50um, 100um, 200um, 500um & baseline 5.1mm]

- This was done for two different angles eta = 0 & eta = 0.3

Photon Resolution

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- This was done for two different angles eta = 0 & eta = 0.3
- For each configuration 1000 events were generated

Step 2: Collect all hits (energies) in all layers of the ECAL for MAPS-digital (baseline-analog) above some threshold

Photon Resolution

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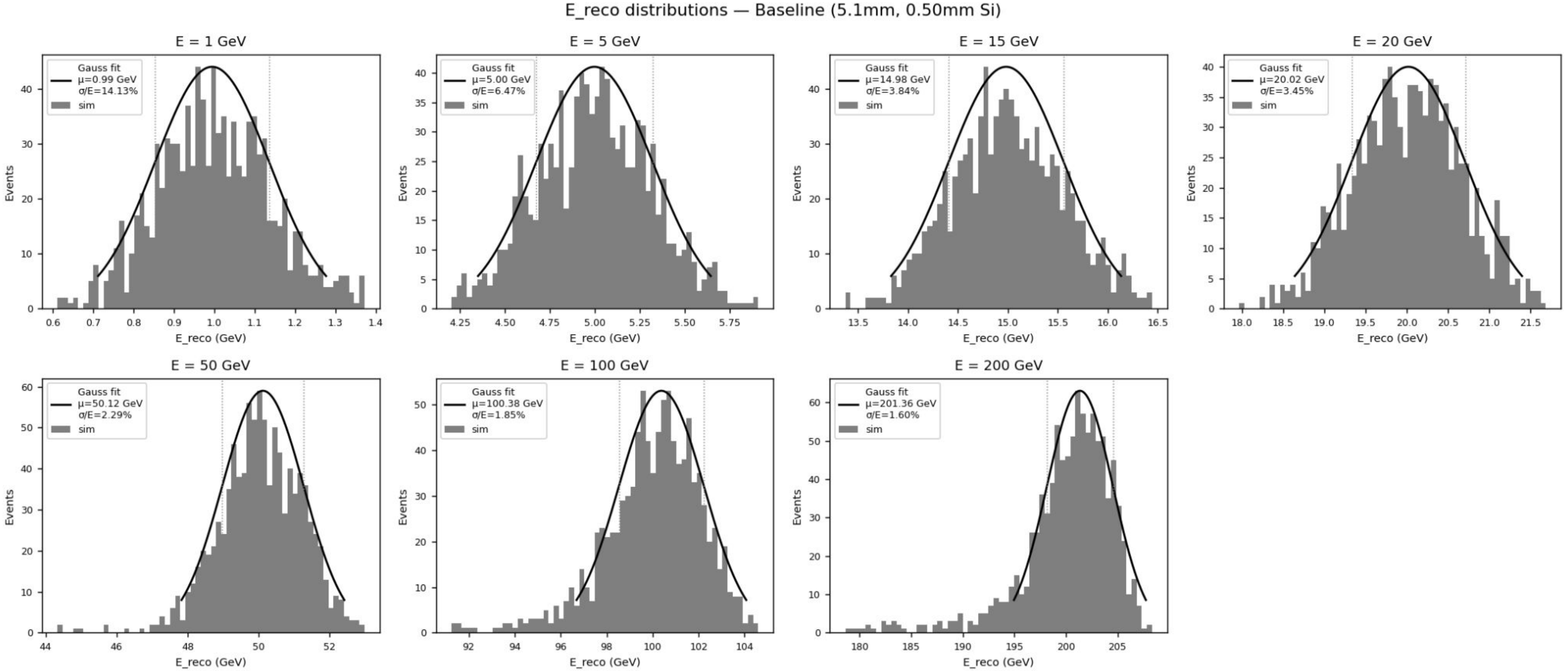
- This was done for two different angles eta = 0 & eta = 0.3
- For each configuration 1000 events were generated

Step 2: Collect all hits (energies) in all layers of the ECAL for MAPS-digital (baseline-analog) above some threshold

Step 3: Apply a calibration to these collected hits (energies) to estimate reconstructed energy of a photon; calibration necessary because most of shower happens in W

Photon Resolution

Step 4: From distribution of the reconstructed energy fit a Gaussian to extract the energy resolution at a given true energy



Photon Resolution

Step 4: Deduce calorimeter performance

Stochastic term

Noise term ignore for now

Constant term

$$\frac{\sigma(E)}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c$$

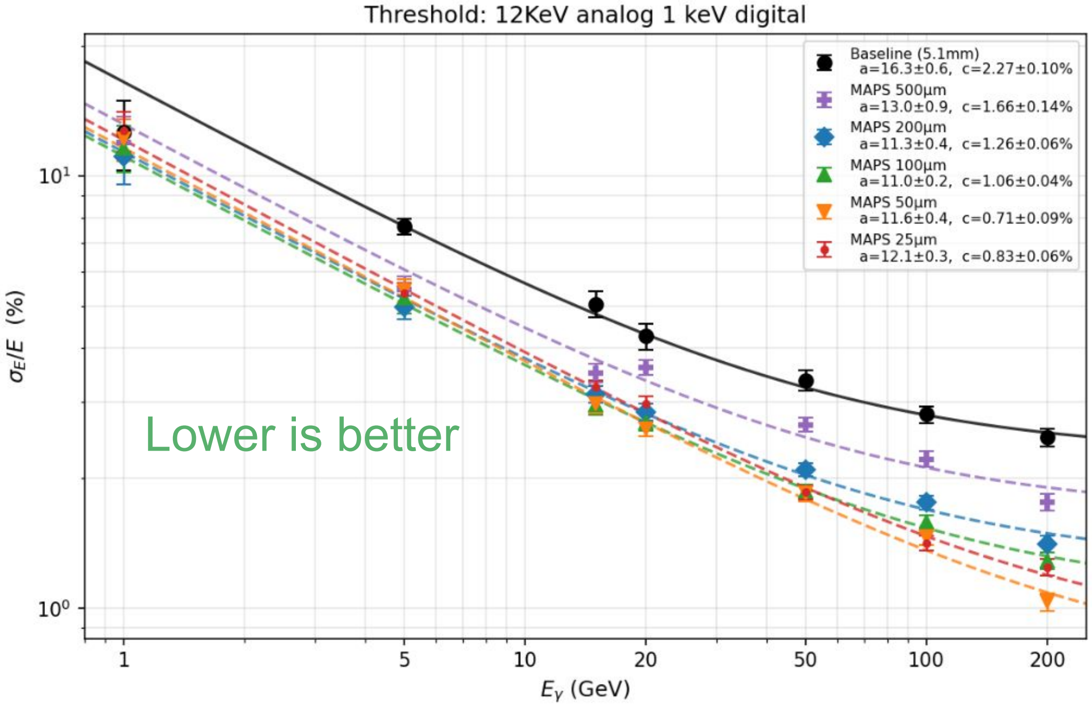
Dominates at low energy
From statistical fluctuation of number of particles sampled

More important at high energy
From systematic effects

Better calorimeter has smaller a & c terms; can extract from the resolutions

Calorimeter Performance

Photon Gun @ eta = 0.3

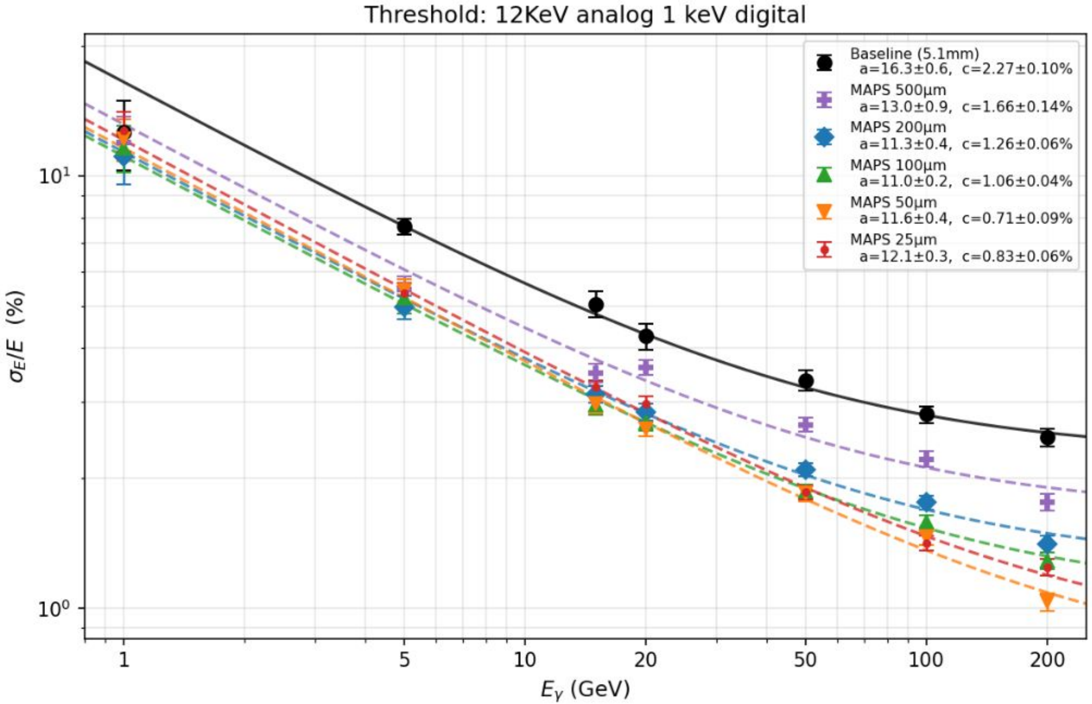


Lines fitted extracting a & c for resolution formula ignoring pileup & noise

- For each pixel size (each curve) general resolution trend looks as expected, decreases as function of energy

Calorimeter Performance

Photon Gun @ eta = 0.3

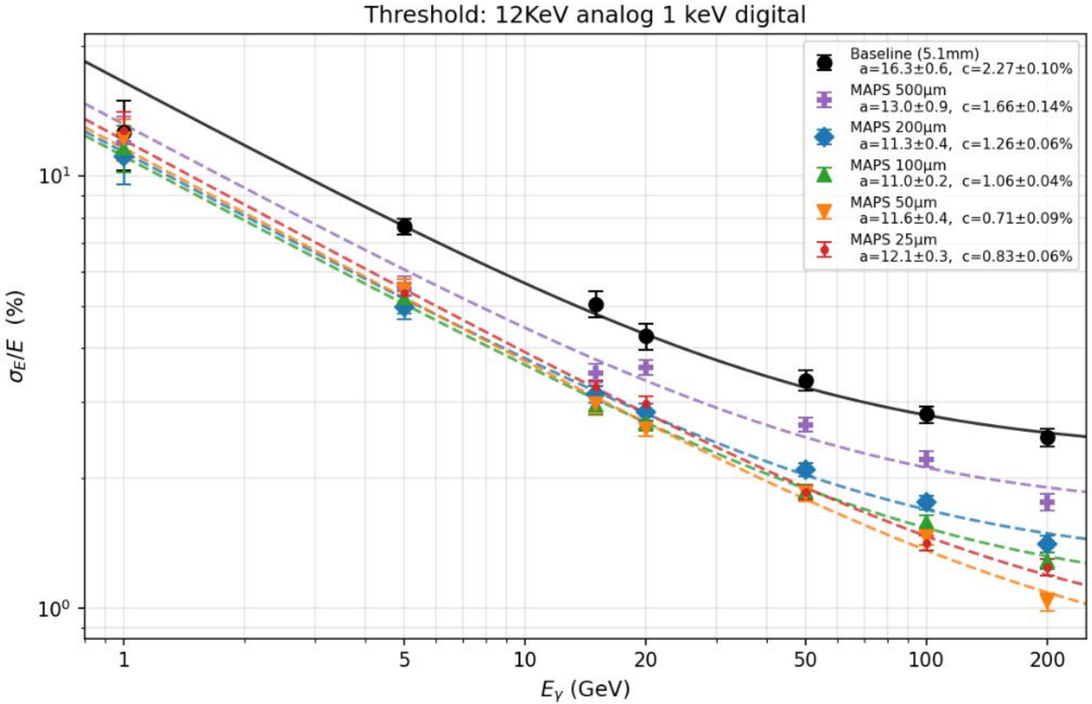


Lines fitted extracting a & c for resolution formula ignoring pileup & noise

- For each pixel size (each curve) general resolution trend looks as expected, decreases as function of energy
- **Threshold values**
  → 12 KeV analog threshold ~1/10th of MIP energy for baseline CLD config
  → 1 KeV digital threshold ~1/5th of MIP for MAPs sensor with active thickness of ~12um
  → also changed threshold to 4KeV for digital

Calorimeter Performance

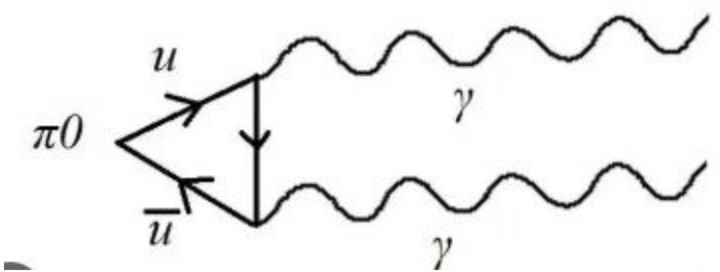
Photon Gun @ eta = 0.3



Based on hits counting, 100 um seems to be the sweet spot! Same conclusion for eta=0 photon gun

- For each pixel size (each curve) general resolution trend looks as expected, decreases as function of energy
- **Threshold values**
  → 12 KeV analog threshold ~1/10th of MIP energy for baseline CLD config
  → 1 KeV digital threshold ~1/4th of MIP for MAPs sensor with active thickness of ~12um
  → also changed threshold to 4KeV for digital
- **Pixel Size Comparison**
  → Smaller pixel size better resolution going from 5 mm to 100 um
  → 50 um & 25 um worse resolution at low photon energy, highly granular not enough particles above threshold per pixel size
  → 25 um worse than 50 um at high photon energy, caused by charge sharing [same particle passing through multiple pixels]

Pion Gun:



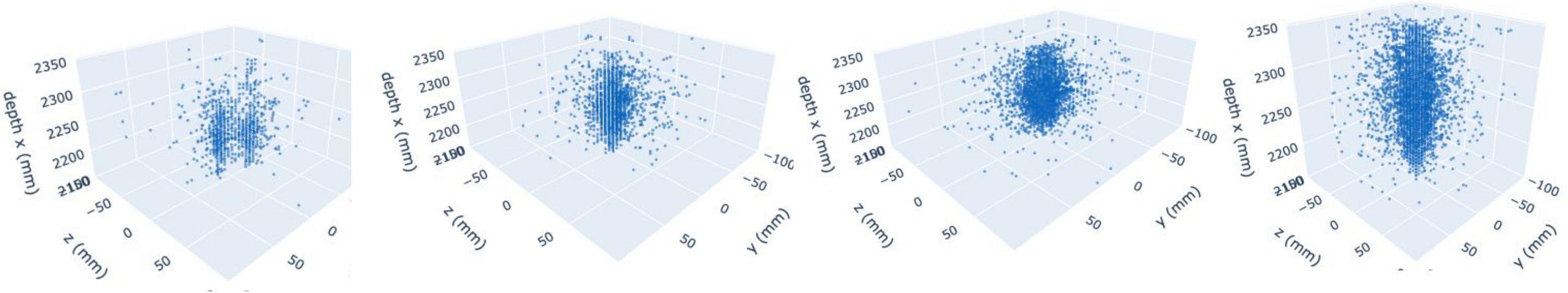
- Similar to photon gun study simulated a pi0
- For baseline, 200 um, 100 um pixel sizes 500 events generated
- Tried to understand if granularity helps here

Pion Gun at various energies: Baseline

For each energy/pixel size 500 events generated

Similar study but for a pi0 gun to understand if smaller pixel size brings better separation

Pi0 20 GeV **Pi0 50 GeV** **Pi0 100 GeV** **Pi0 200 GeV**



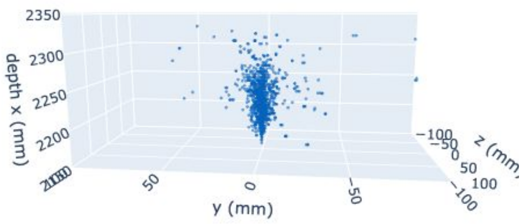
- This is an event picked randomly for visualization purposes
- Link to interactive baseline pi0 plot

Pion Gun at various energies: 200um

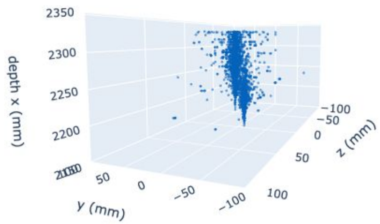
For each energy/pixel size 500 events generated

Similar study but for a pion gun to understand if smaller pixel size brings better separation

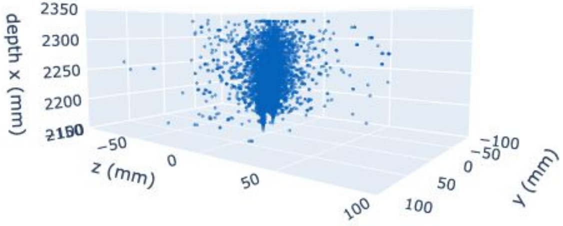
Pi0 20 GeV



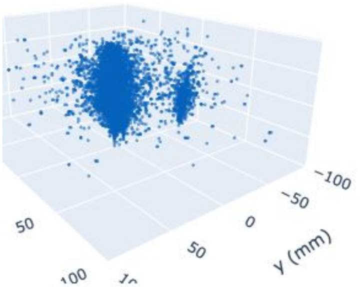
Pi0 50 GeV



Pi0 100 GeV



Pi0 200 GeV



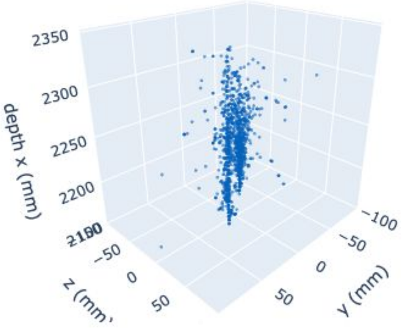
- This is an event picked randomly for visualization purposes
- Link to 200um interactive pi0 plot

Pion Gun at various energies: 100um

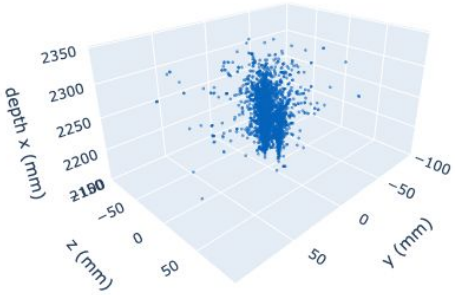
For each energy/pixel size 500 events generated

Pixel size: 100um

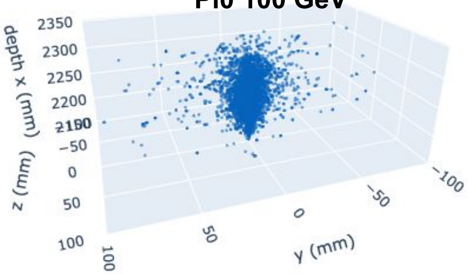
Pi0 20 GeV



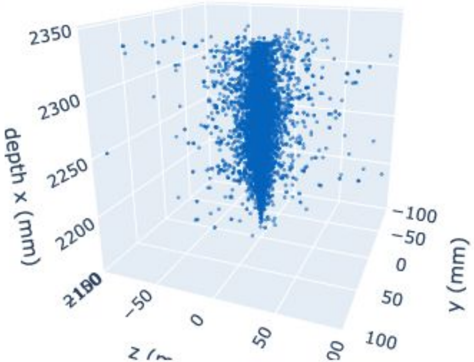
Pi0 50 GeV



Pi0 100 GeV



Pi0 200 GeV



- Event picked randomly for visualization purposes
- Link to interactive 100um plot

Can we go beyond visualization?

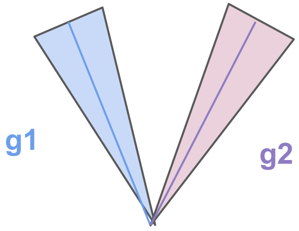
$$\theta_{min} = \frac{2m_{\pi^0}}{E_{\pi^0}}; \;\; if \; E_{\pi^0} >> m_{\pi 0}$$

- If ECAL is L=2150 mm for CLD

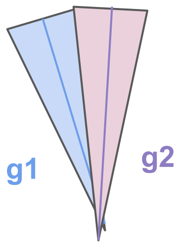
$$\Delta x = L \cdot \theta_{\gamma\gamma}^{min} = \frac{L \cdot 2m_{\pi^0}}{E_{\pi^0}}$$

- Only photons that have Δx > 2 times Moliere radius can be separate :(
    - Moliere radius for tungsten ~9.4 mm

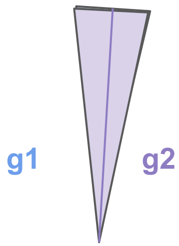
Case 1: Δx > 2Rm



Case 2: Rm< Δx < 2Rm



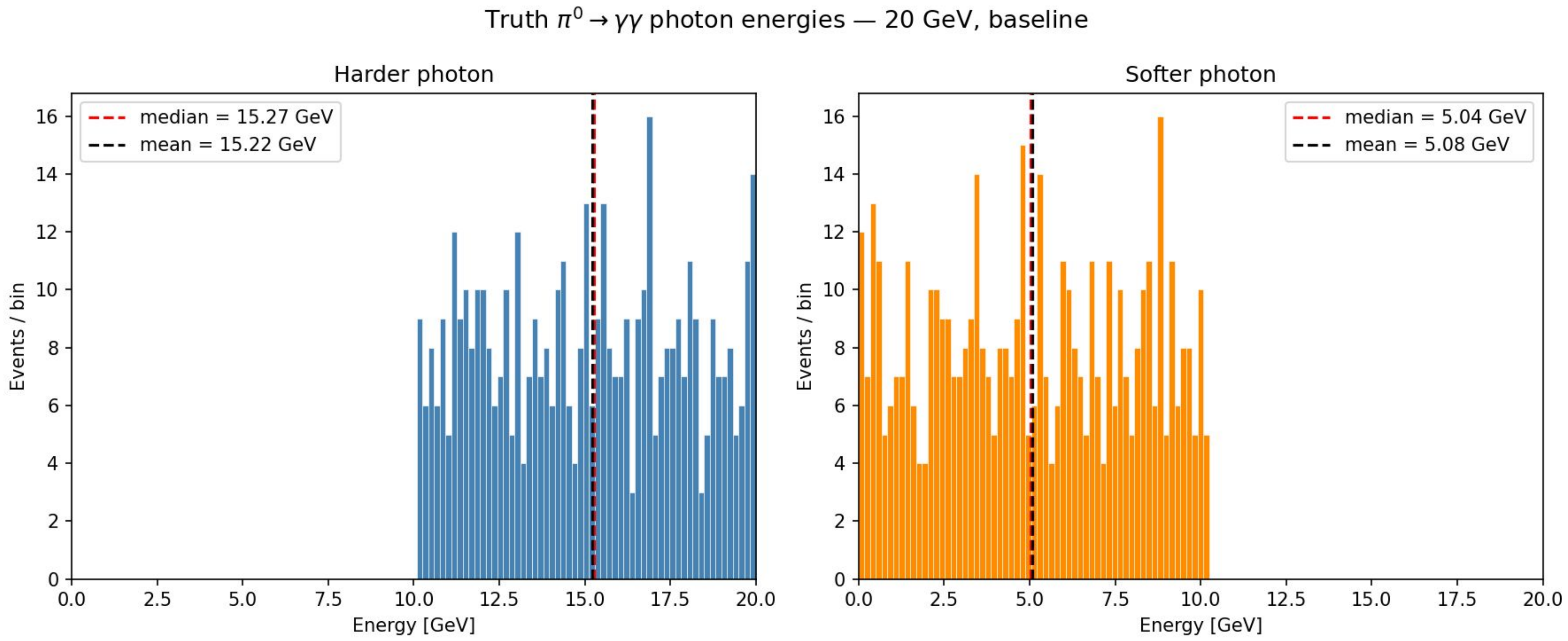
Case 3: Δx < Rm



This is assuming that two photons have same energies, often one photon is more energetic in lab frame, so we could figure out distance from MC & look at showers to understand thresholds

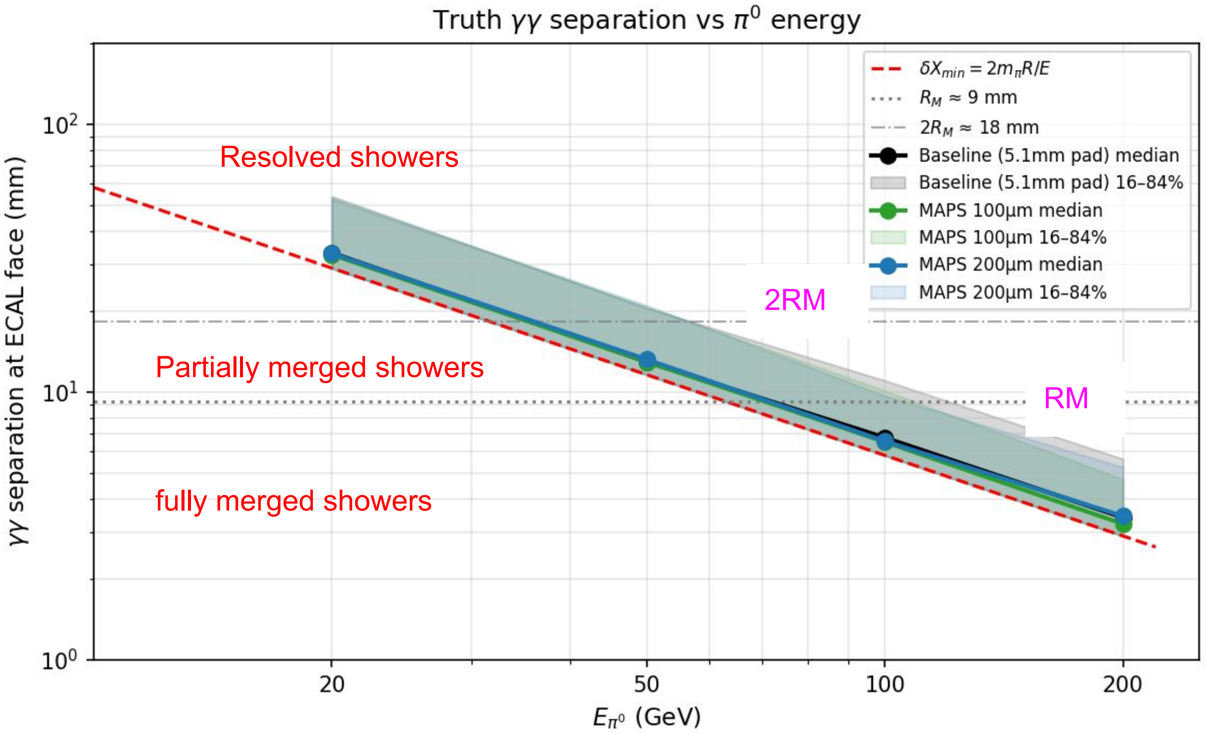
Truth pion and photon studies

Shown truth photon energy distribution for 20GeV baseline, in most cases 1 harder photon

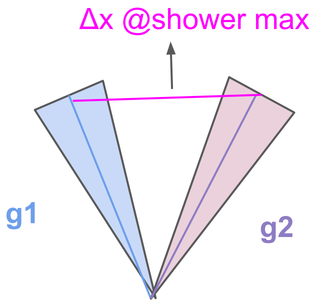


Baseline vs 100 vs 200 um MAPS: Truth Study

Expecting merged photons from pi0 decay at shower depth

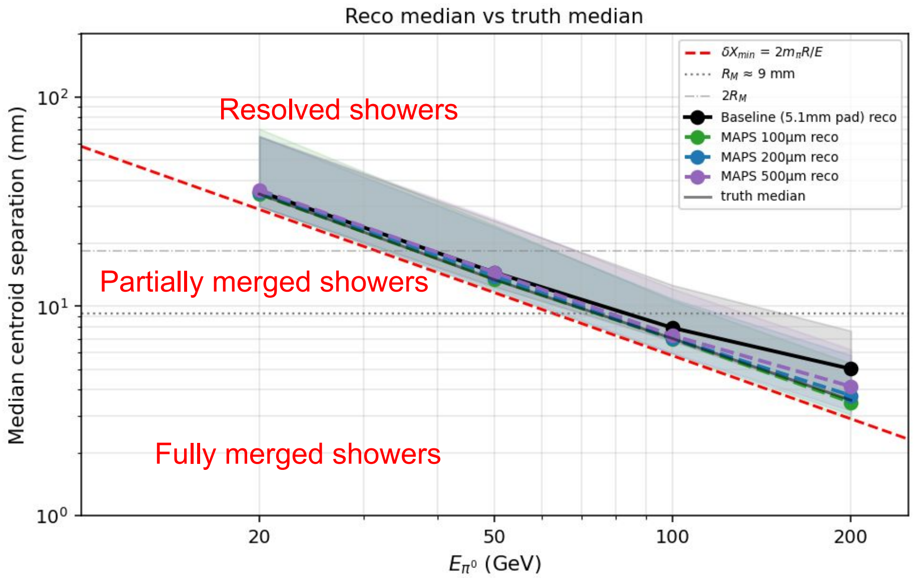


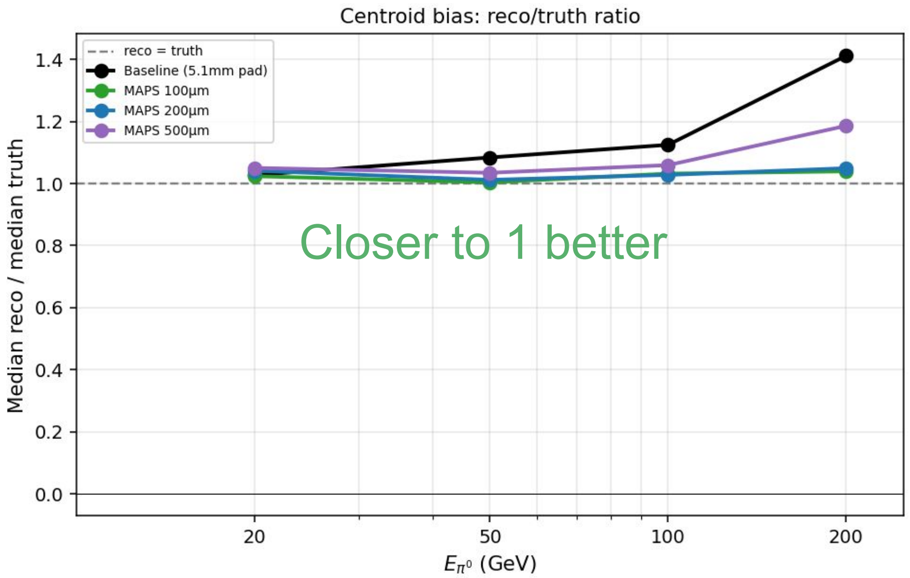
- From MC truth
- Photons start to merge ~30GeV pion energy



Baseline vs 100 vs 200 um MAPS: Reco Separation

Now looking at truth-matched reco photons, best case scenario for a clustering algorithm

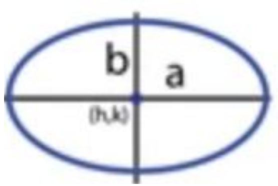




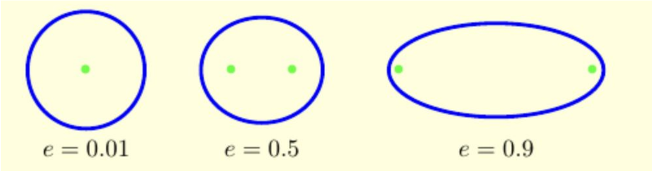
- First find energy weighted centroid of each photon and get the separation of two shower centroids, this uses truth matching for clustering
- This is very interesting, "reconstructed" photons for overlapping hits are pulled towards higher energy photon by construction [thus shifting the tail of the distribution]

Ellipse of Merged Pi0 Showers

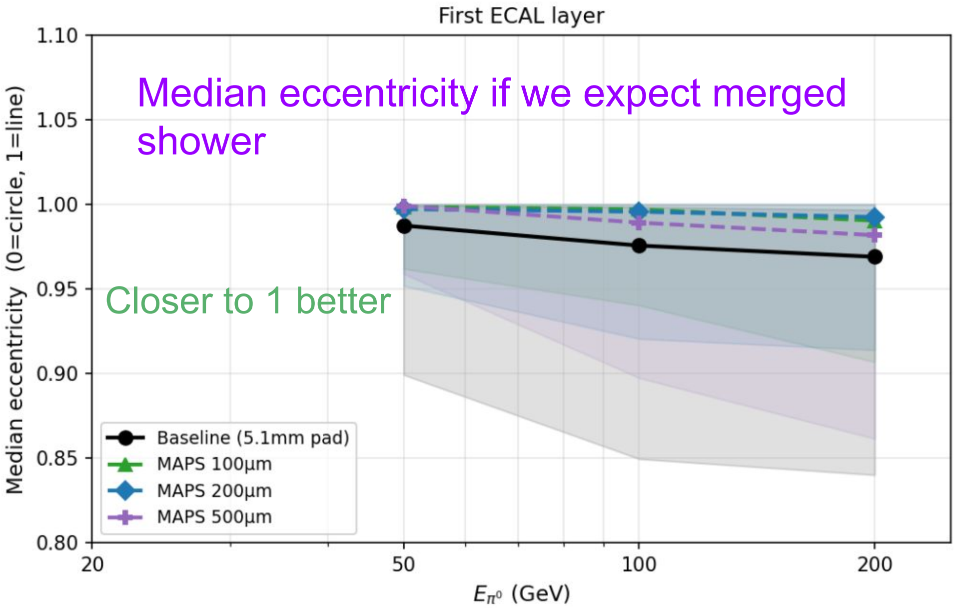
- At a given layer, merged photon shower more elliptical (single shower more round)
- Extract eccentricity (e) for cases where we expect merged shower with different configurations at different energy



$$= \frac{\sqrt{(a^2 - b^2)}}{a}$$



Higher value of e more elliptical!



Granular ECAL even with simple algorithms seem to help with pi0/photon separation

Summary

- First set of checks look mostly reasonable?

Step 1 ✅

→ Understand current workflow/setup

→ key4hep software, DD4hep ddsim Geant4 full simulation

→ starting with FCC tutorial

→ CLD baseline config

CLD o2 v07 from k4geo, CalBarrel o2 v01 03.xml

✅ shown in these slide

Step 2

→ Change pixel size & study ECAL performance

→ Photon gun study; resolution?

→ pion gun study; are granular pixels better for photon from pi0 separation?

only planning for 1 pixel size

Next Steps

→ start adding cooling material & study performance degradation

→ beyond single particle gun: clustering/granular pflow?

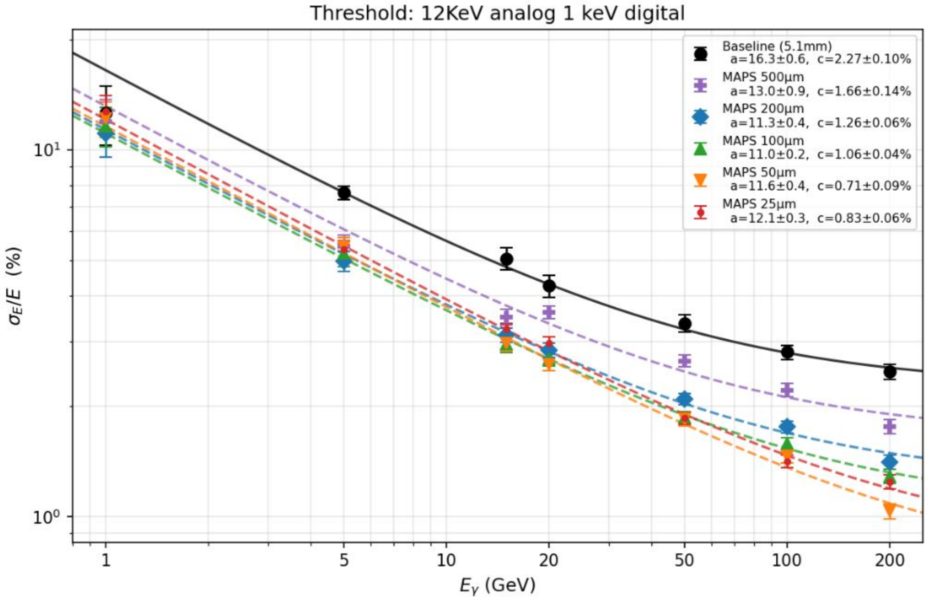
→ eventually study impact on jet energy resolution

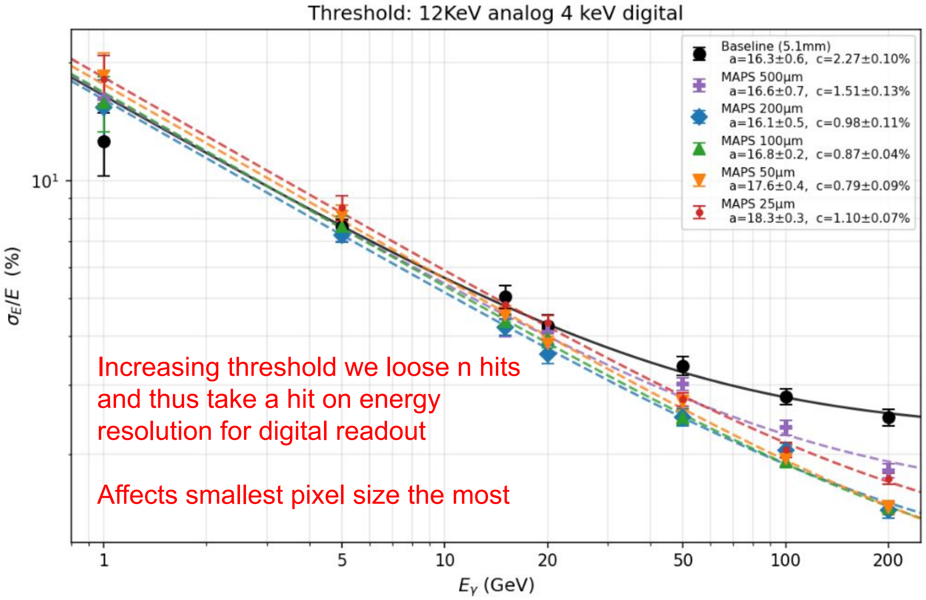
Backup

Threshold effect

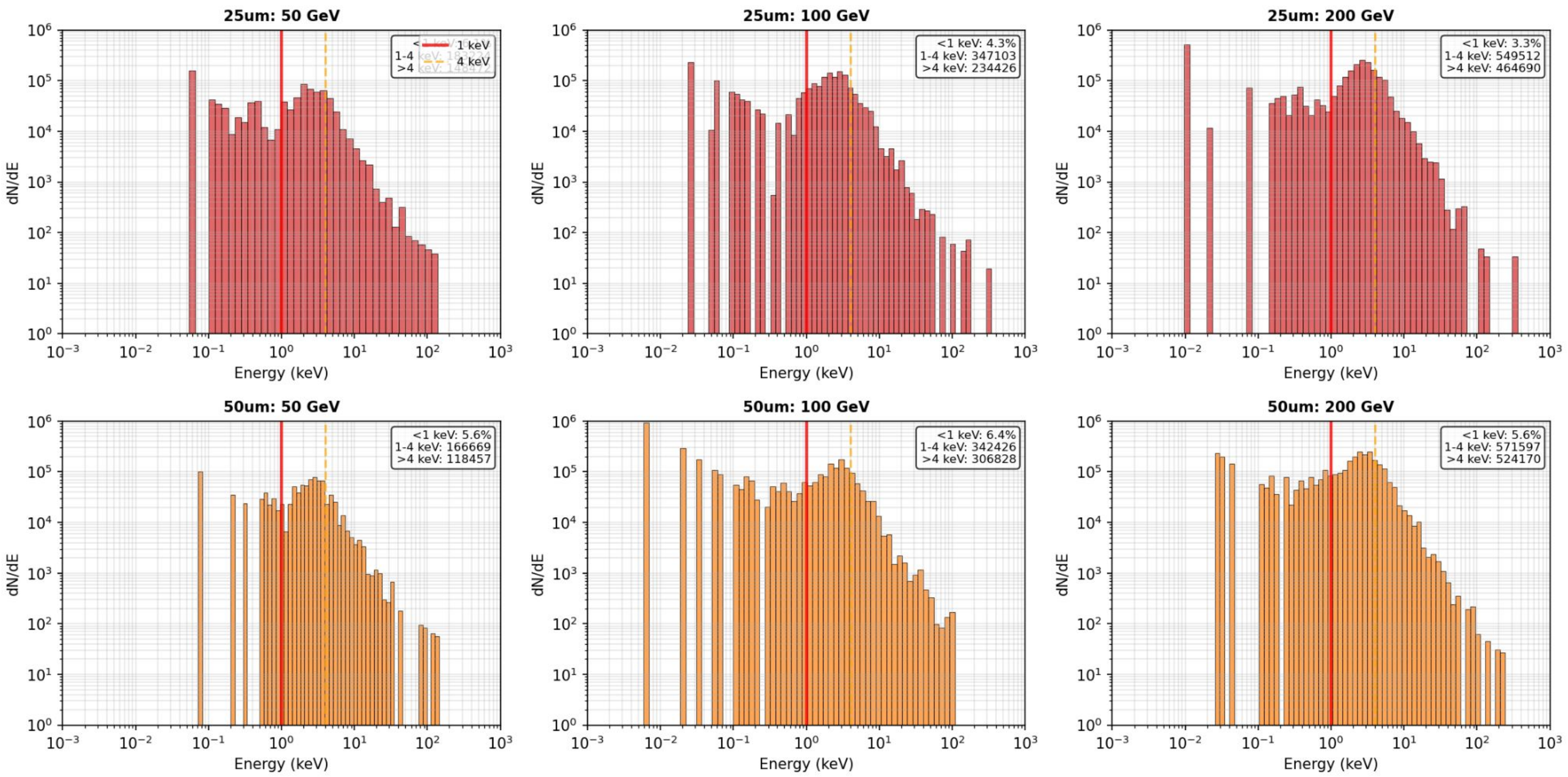
Jim pointed out 1KeV threshold too low

- ~3.4 KeV/um MIP for Si
- For 12um thick active layer ~4KeV ; 1KeV is still not too small for noise free simulation
- baseline of ~500um thick layer ~1700, [taking 12 KeV ~1/10th of MIP]



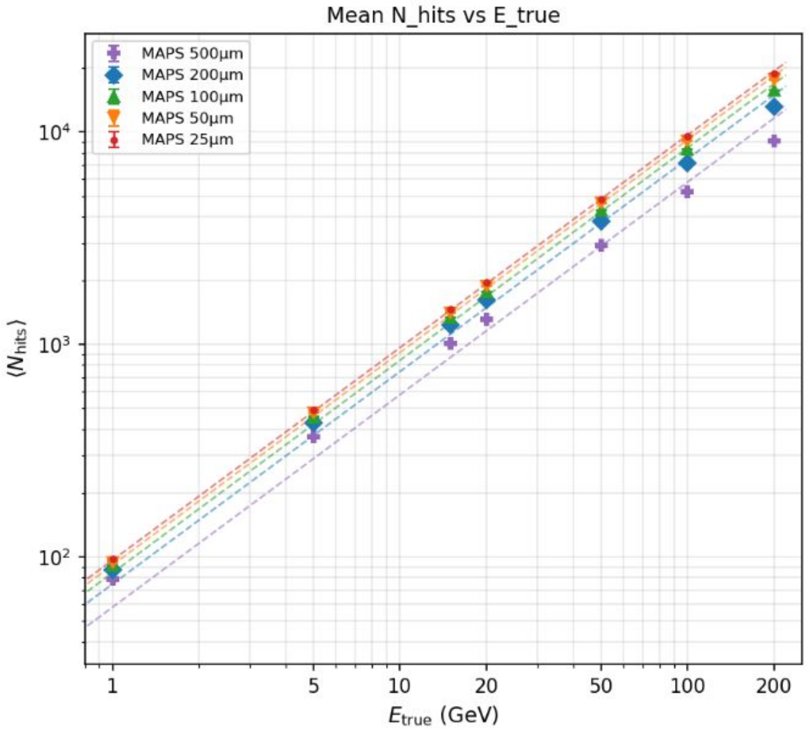


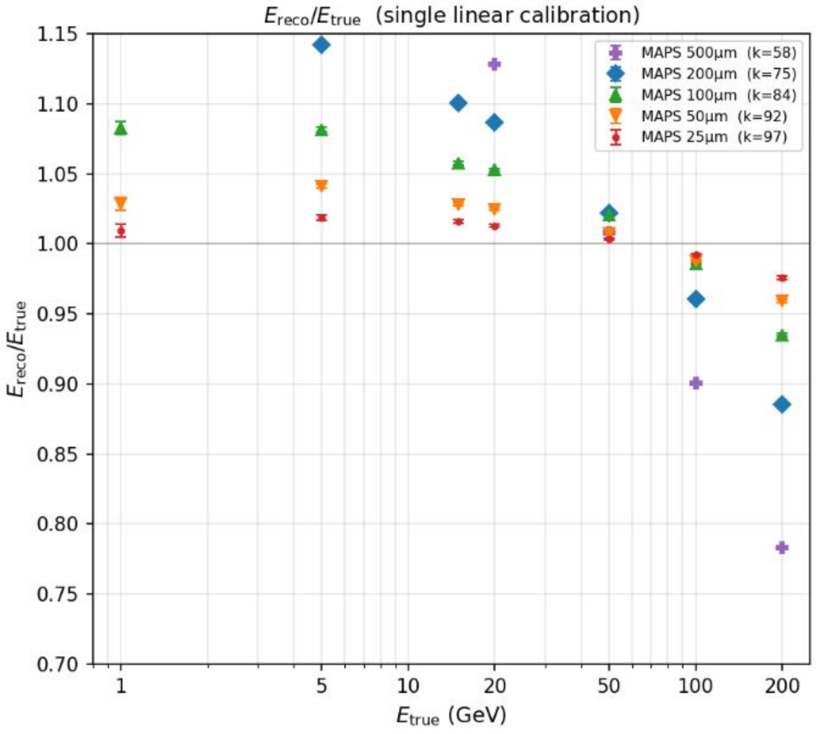
Too many sub particles?



This shows that for smaller pixel size more lower energy deposits

What about the trend at 25um?





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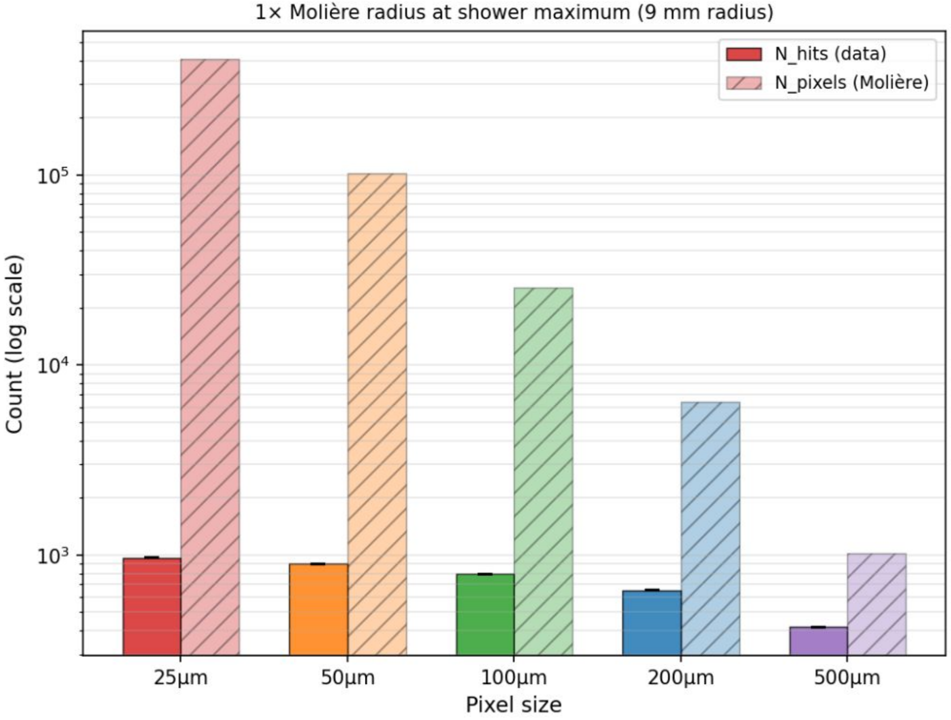
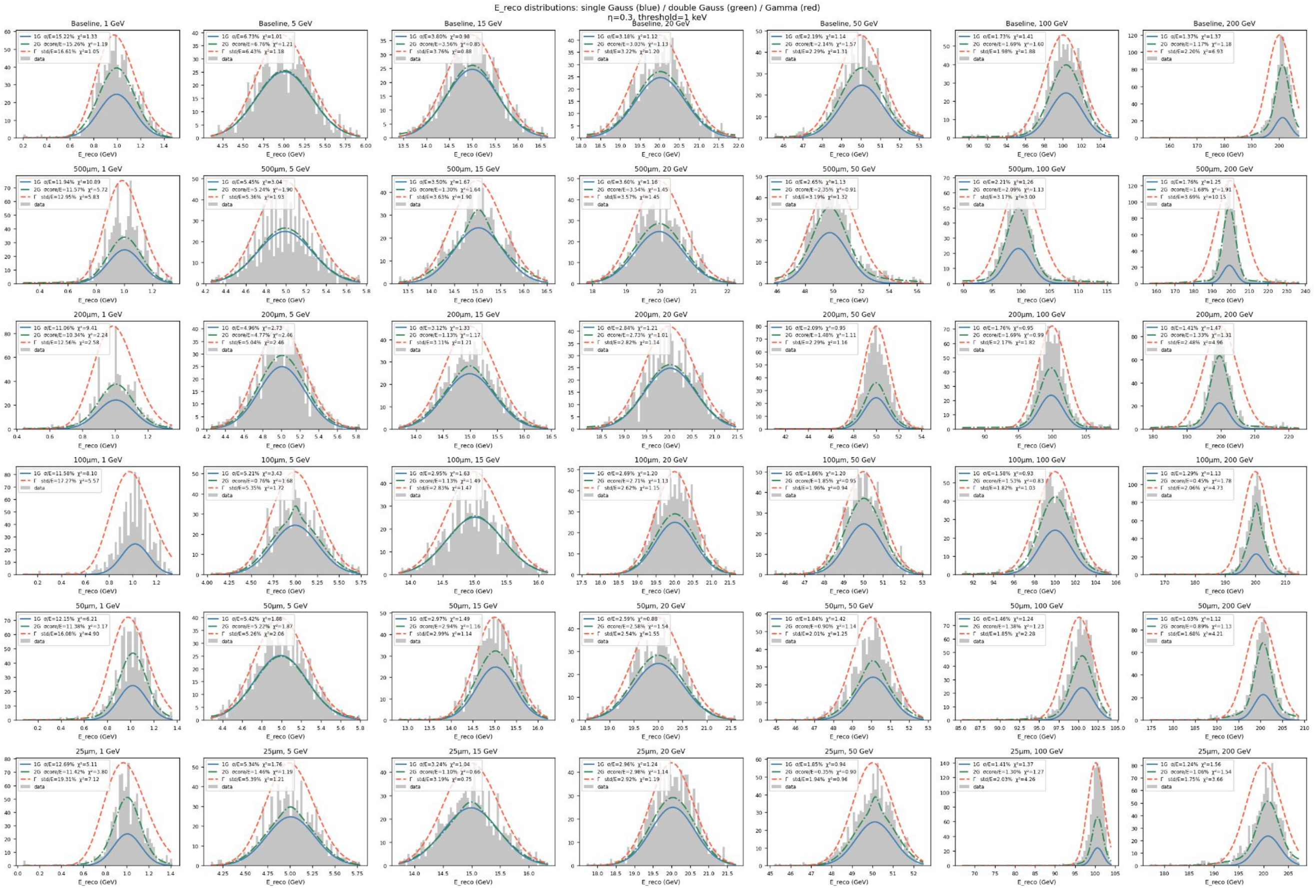


More pixels than n hits even at shower maximum core within 1 moliere radius, Charlie was right no saturation effect

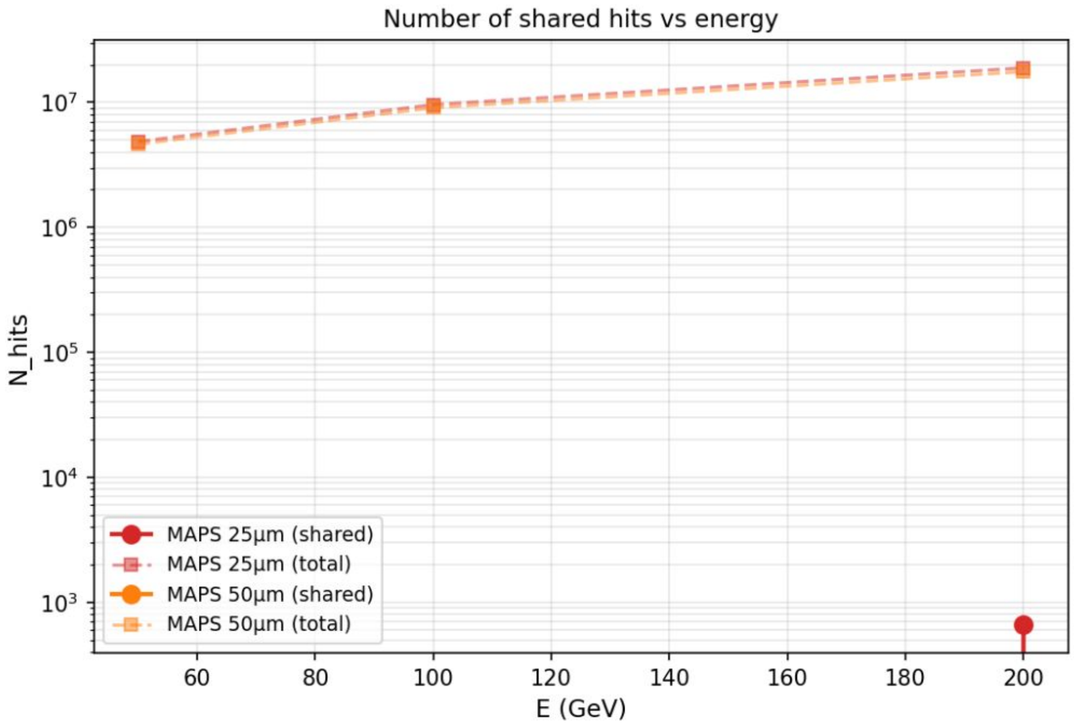
Gamma fit check from paper



Fit function to extract resolution looks similar to other pixel sizes

Charge Sharing:

How often do multiple particles hit same pixel?



- Number of hits for both pixel sizes are similar
- Number of multiple particles hitting the same pixel only appears at 25um 200 GeV energy limit

Goals of Pi0 Gun Study

Similar study but for a pi0 gun to understand if smaller pixel size brings better separation

Little math from Claude, used L = 2100 mm

E_{π^0}	Δx	**resolvable? ($2R_M \approx 18$ mm)**
1 GeV	567 mm	easily
5 GeV	113 mm	easily
10 GeV	57 mm	yes
20 GeV	28 mm	marginal
30 GeV	19 mm	borderline
50 GeV	11 mm	merged
100 GeV	5.7 mm	fully merged

This is assuming that two photons have same energies, often one photon is more energetic in lab frame, so we could figure out distance from MC & look at showers to understand thresholds