3D Clustering in the CMS High Granularity Calorimeter at the Level 1 Trigger

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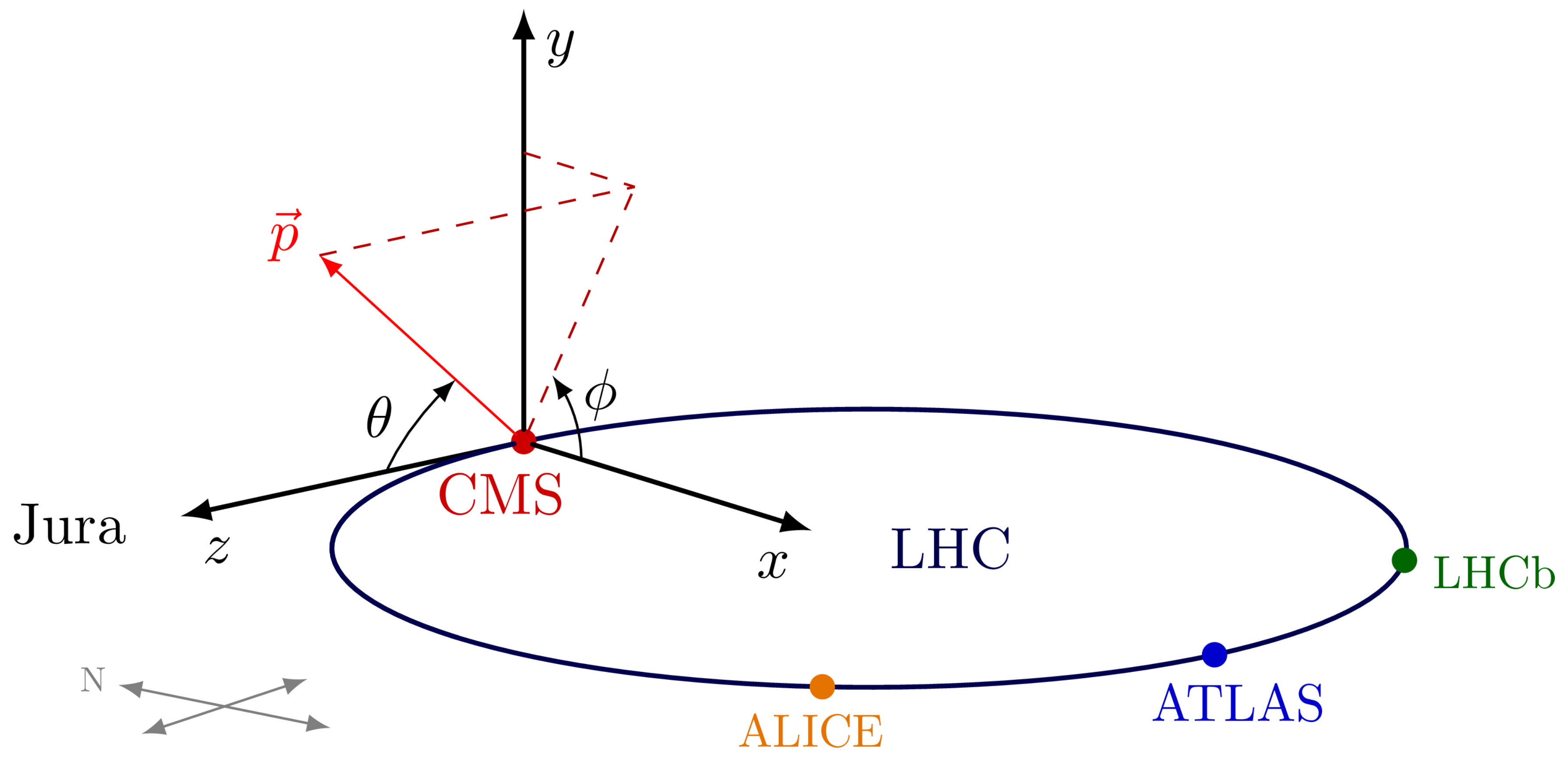
Outline

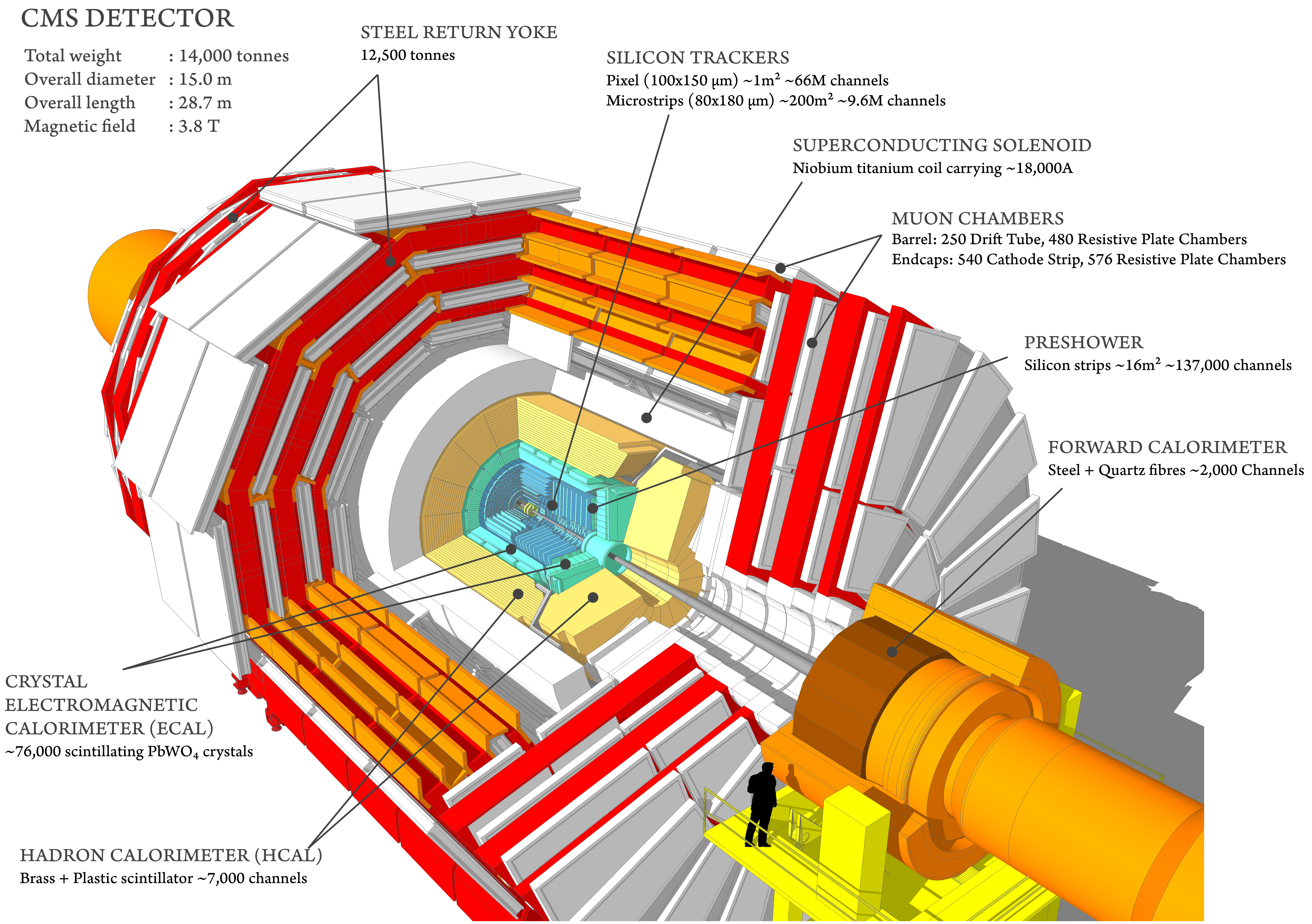
- Introduction
  - The CMS Experiment and Detector
  - The HL-LHC and the HGCAL
- The Trigger System
  - HGCROC
  - ECON-T
  - Trigger Primitive Generator
- 3D Clustering
  - Basic Idea
  - Weighting/Calibration
  - Results
- Conclusion and Outlook

The CMS Experiment and Detector

- Sub-detectors in cylindrical shells
- Combinations used for identification and kinematic properties
- Beamline of the LHC points along z-axis with collisions at the center of the detector



CMS Coordinate System

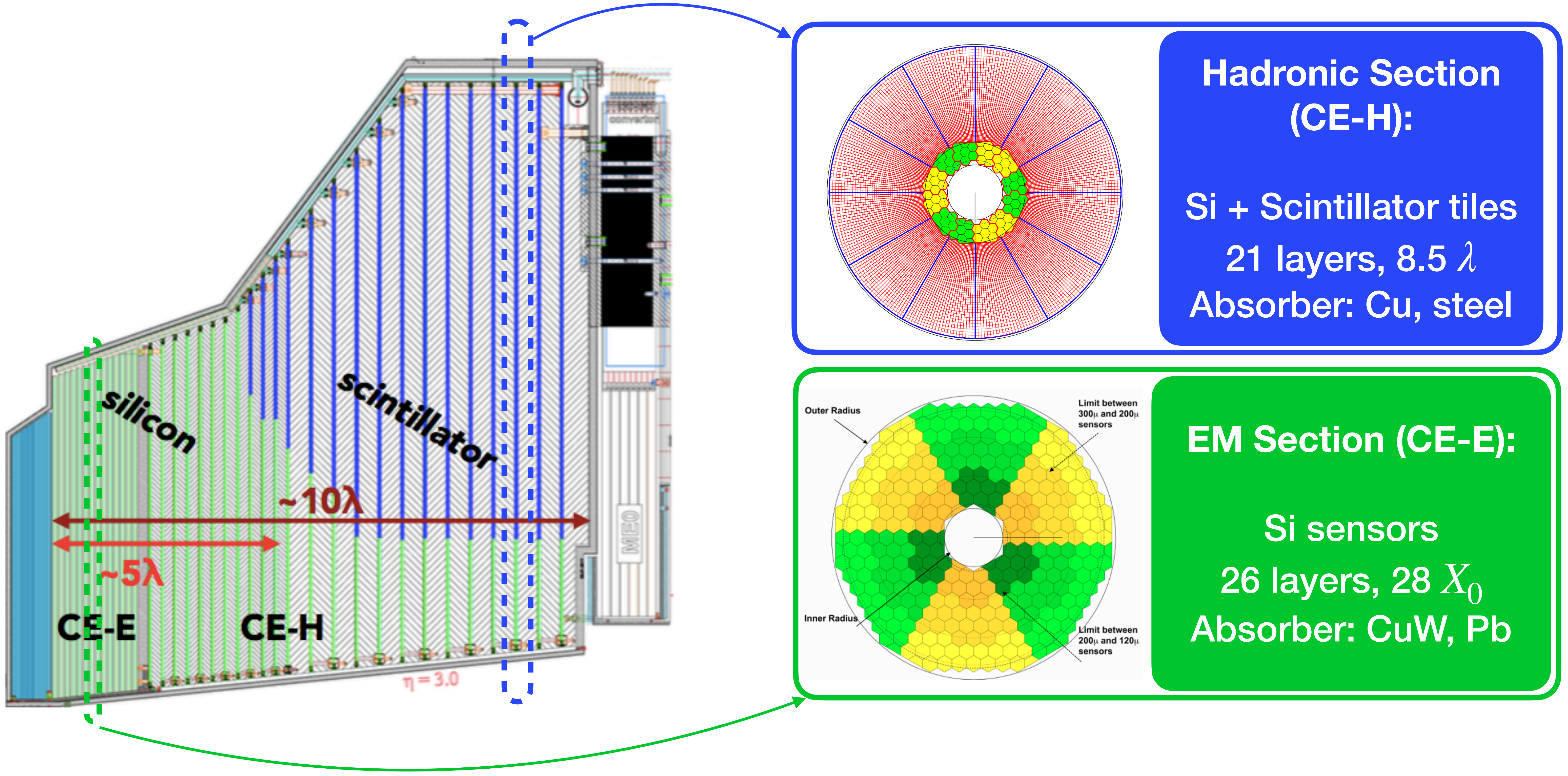


CMS Subdetectors

The HL-LHC and the HGCAL

The High Luminosity LHC (HL-LHC):

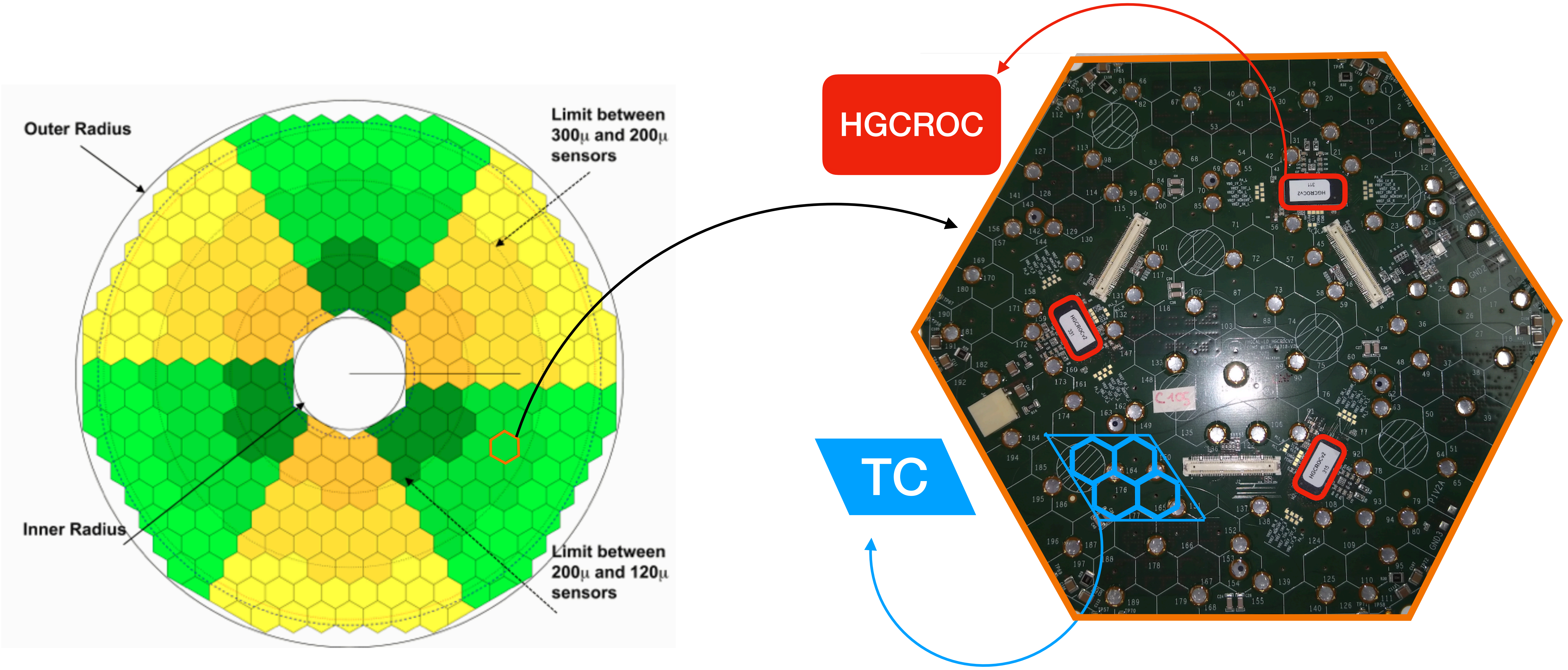
- Luminosity:
  $L = 10^{34}\ cm^{-2}s^{-1} \rightarrow 4 \times L_{LHC}$
- Integrated Luminosity:
  $L_{Int} \approx 3000\ fb^{-1}$ (nominal),
  $4000\ fb^{-1}$ (ultimate) $\rightarrow 10 \times L_{Int}^{LHC}$
- Pileup: ~ 140 (nominal) , ~ 200 (ultimate) $\rightarrow 3.5 \times PU_{LHC}$



HGCAL Cross Section and Layers

The Trigger System: HGCROC

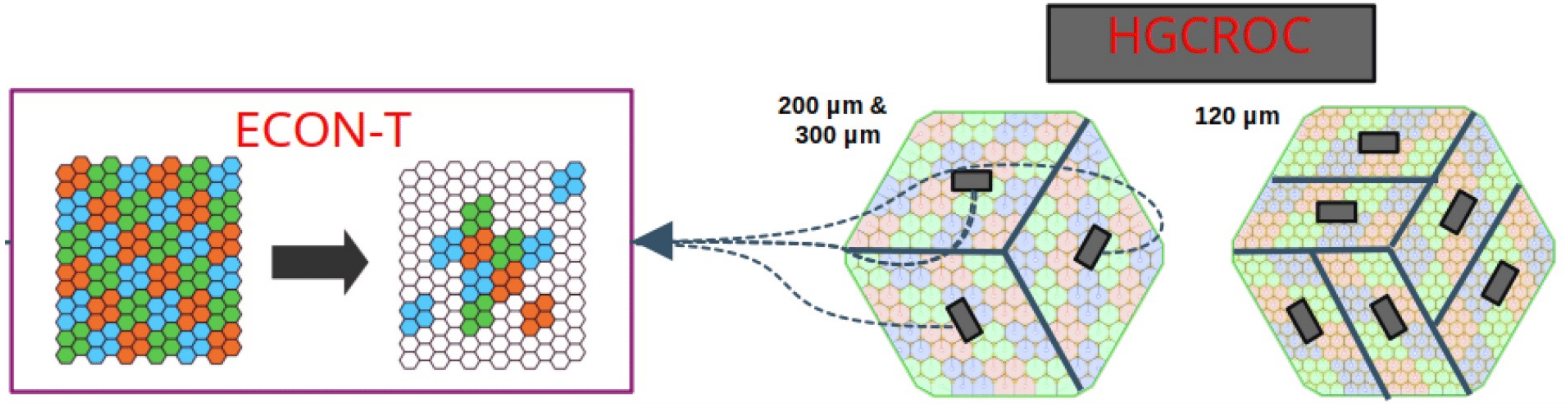
- **Measures individual cell charges at** $40\ MHz$
- **Groups individual sensors into Trigger Cells (TCs).**
  - **3x3 in high-density regions**
  - **2x2 in low-density regions**
- **Compresses resulting sums into 7-bit floating point**



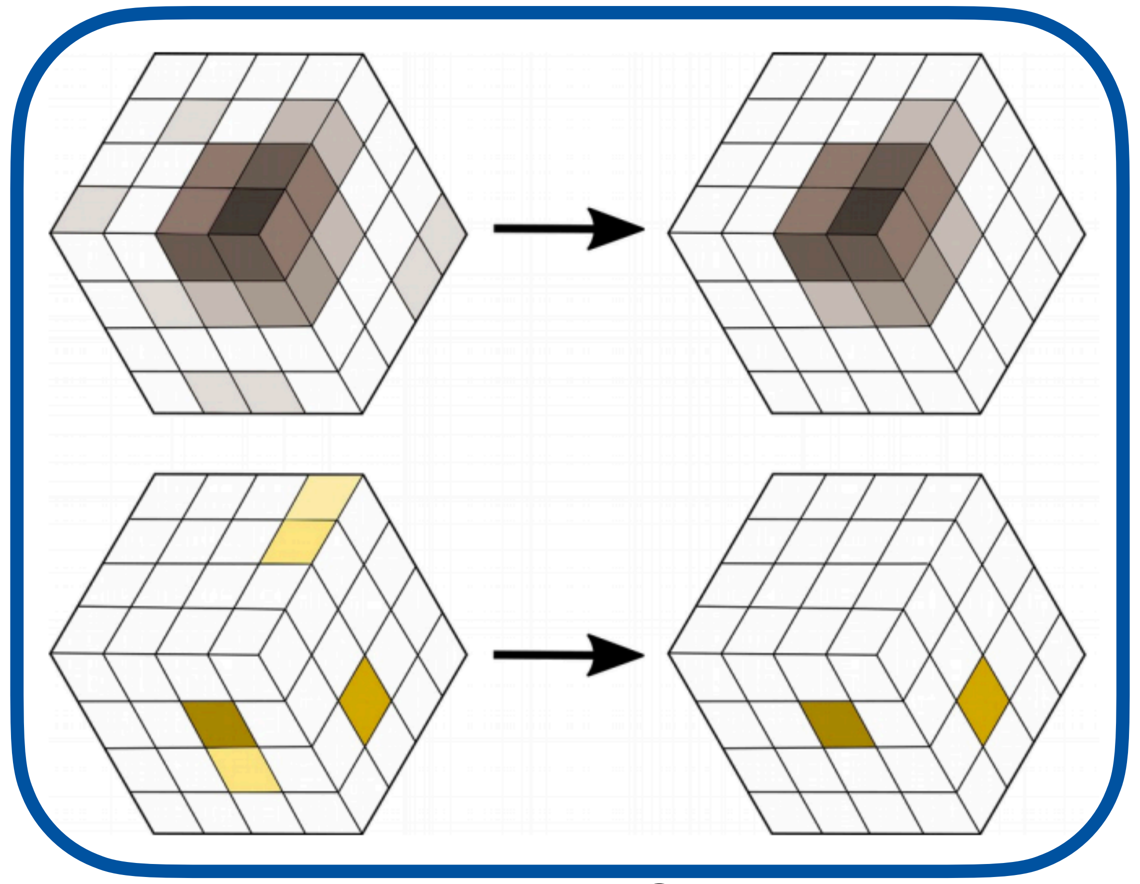
HGCAL Module

The Trigger System: ECON-T

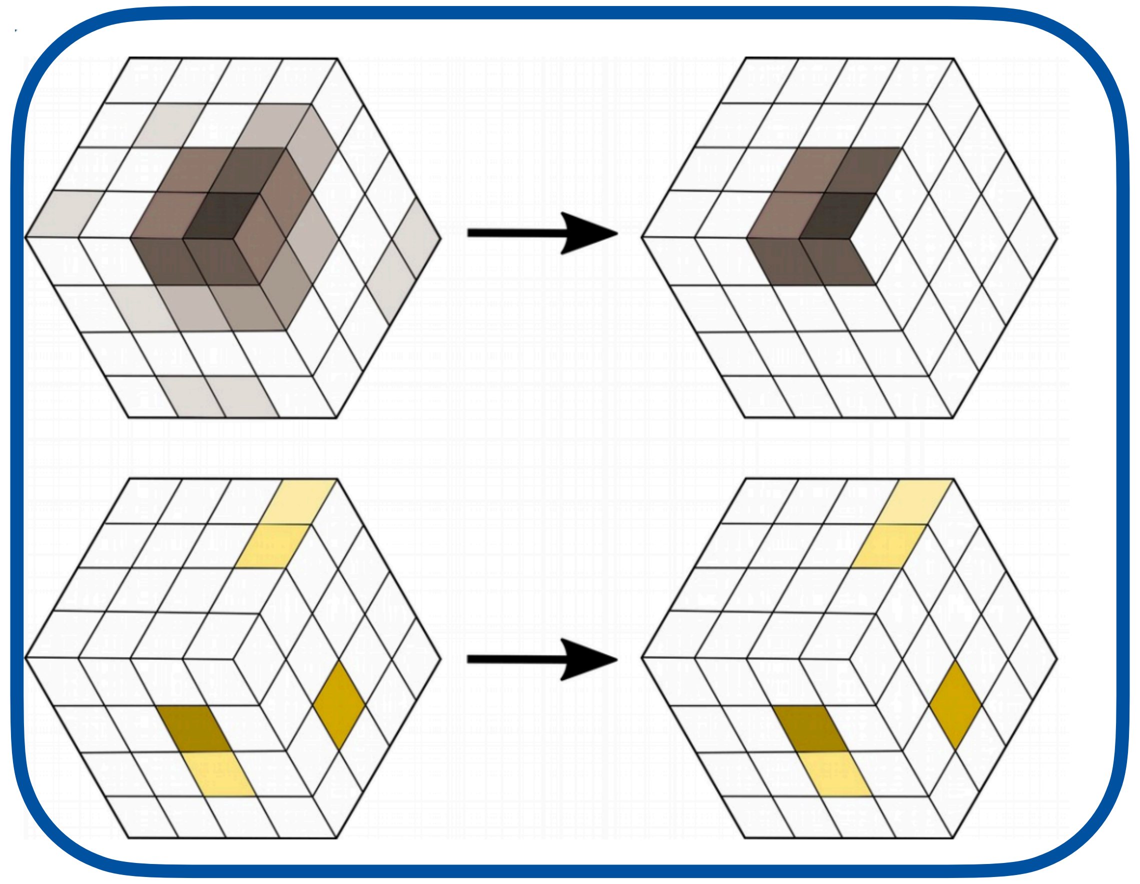
- Receives TC data from HGCROC and reduces the data stream via:
  - Energy thresholds or
  - N most energetic TCs (best choice) or
  - TC aggregation into super trigger cells (STCs)
- Performs energy sums of the whole module without applying any threshold



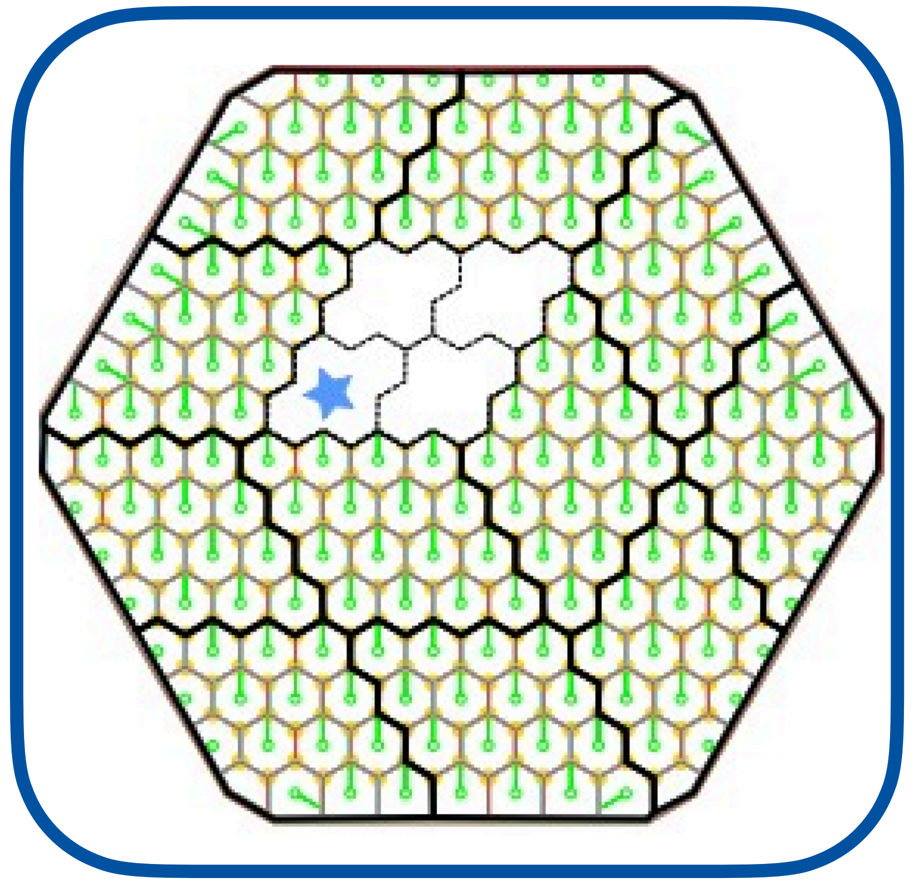
Threshold



Best Choice



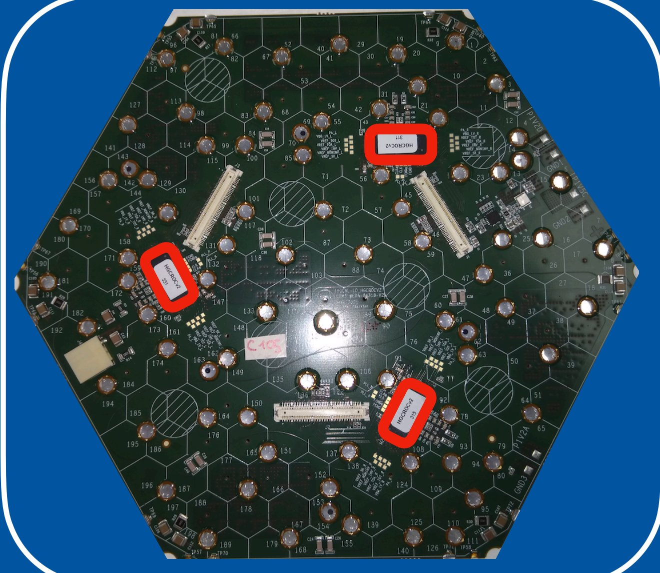
STCs



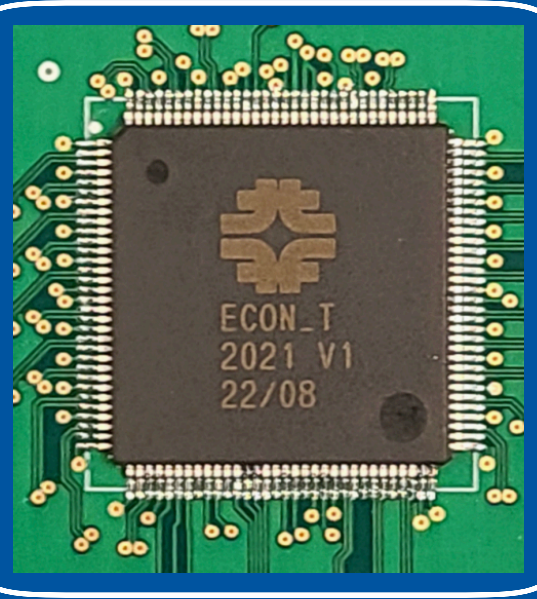
Trigger Primitive Generator: TCs → 3D Clusters

Front-end: On Detector

HGCROC



ECON-T



Back-end: Off Detector

Stage 1

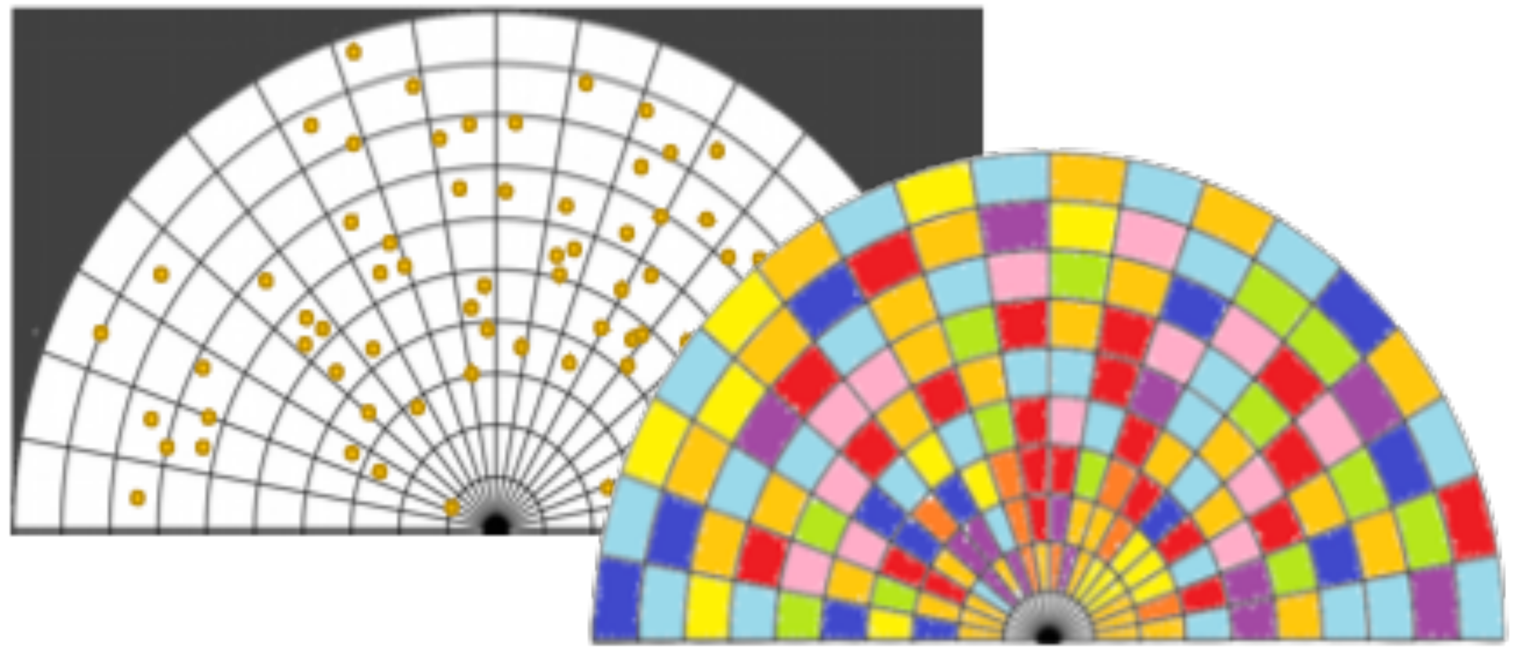
- Groups data sent from ECON-T per bunch crossing
- Groups module sums into partial Trigger Towers (pTTs)
- Sorts TCs in 1D ϕ bins
- Creates data-stream and time-multiplex

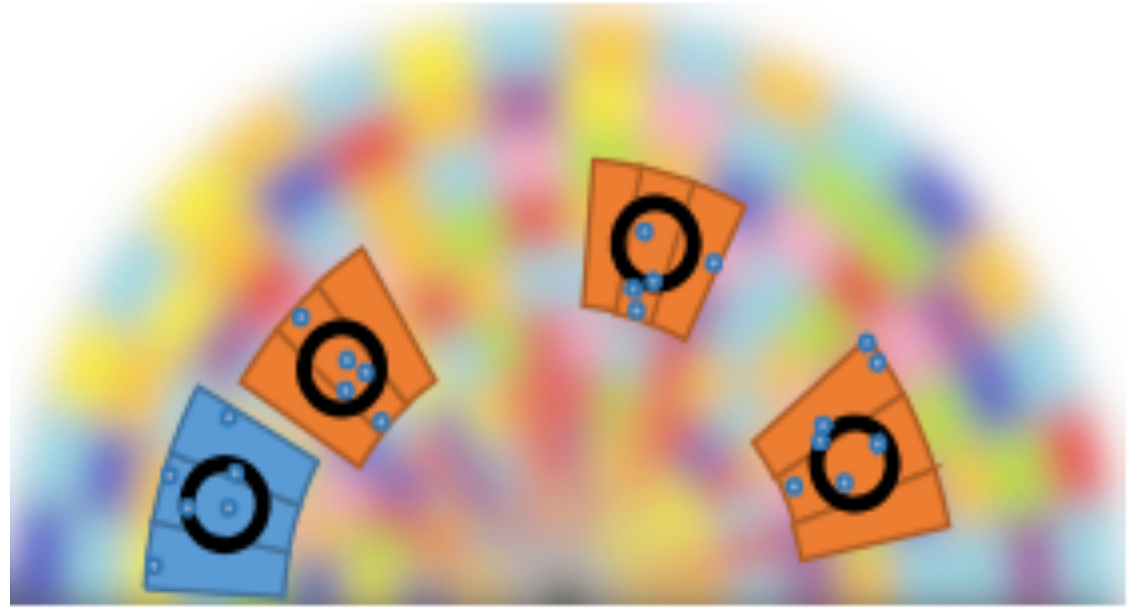
Stage 2

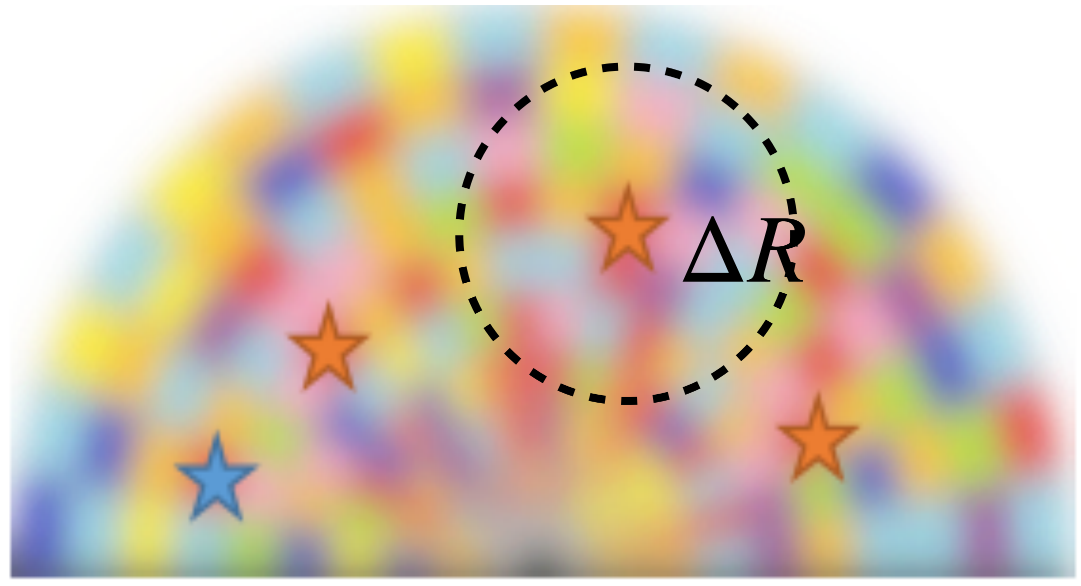
- Unpacks Stage 1 Data
- Groups pTTs into (η, ϕ) Trigger Towers (TTs)
- Builds 3D Clusters of TCs

3D Clustering: Basic Idea

$$\Delta R \equiv \sqrt{\Delta(x/z)^2 + \Delta(y/z)^2}$$







Histogram TCs in $(r/z, \phi)$ bins and smooth across $(r/z, \phi)$

→ Seeds defined as local E_{max}

→ 3D Clusters built from TCs around seed with $\Delta R(seed, TC) \leq r^{Cl}$

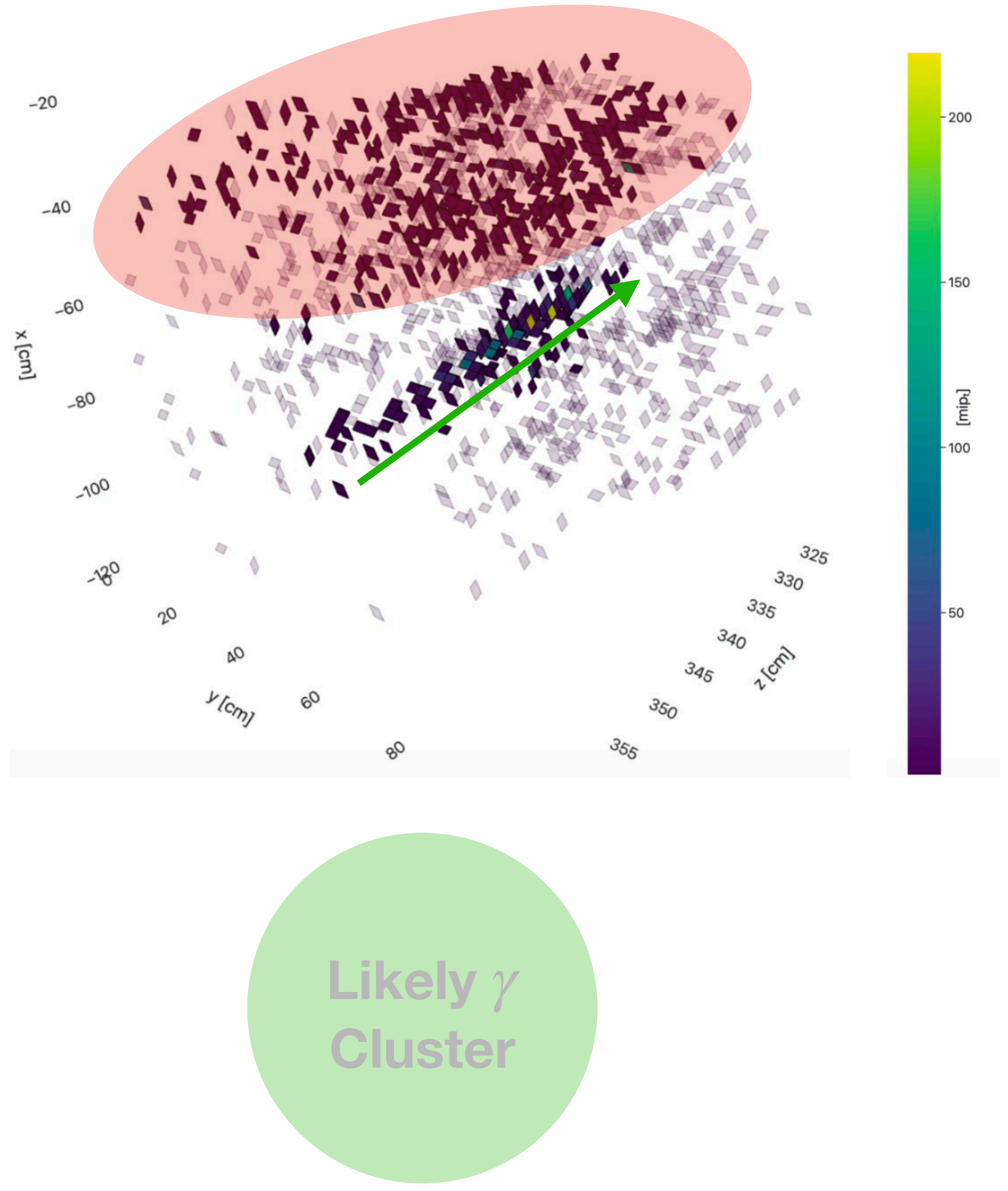
→ L1 Trigger

3D Clustering: Basic Idea

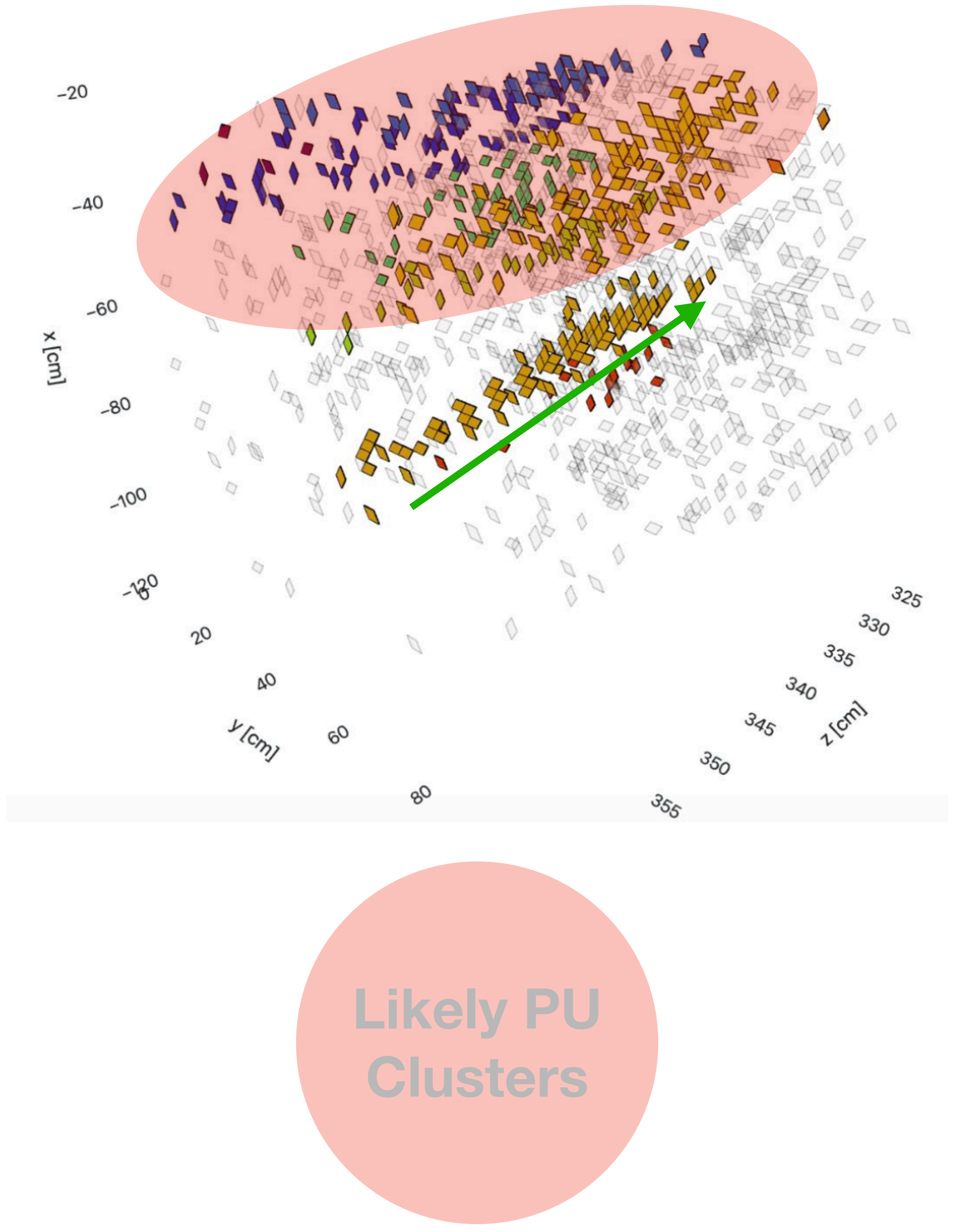
200 PU Photon Event

- TCs with $E \geq E_{thresh}$ and $\Delta R(TC, seed) \leq r^{Cl}$ assigned to cluster
- Large pileup events contain clusters not originating from incident particle

Energy Display



Cluster ID Display

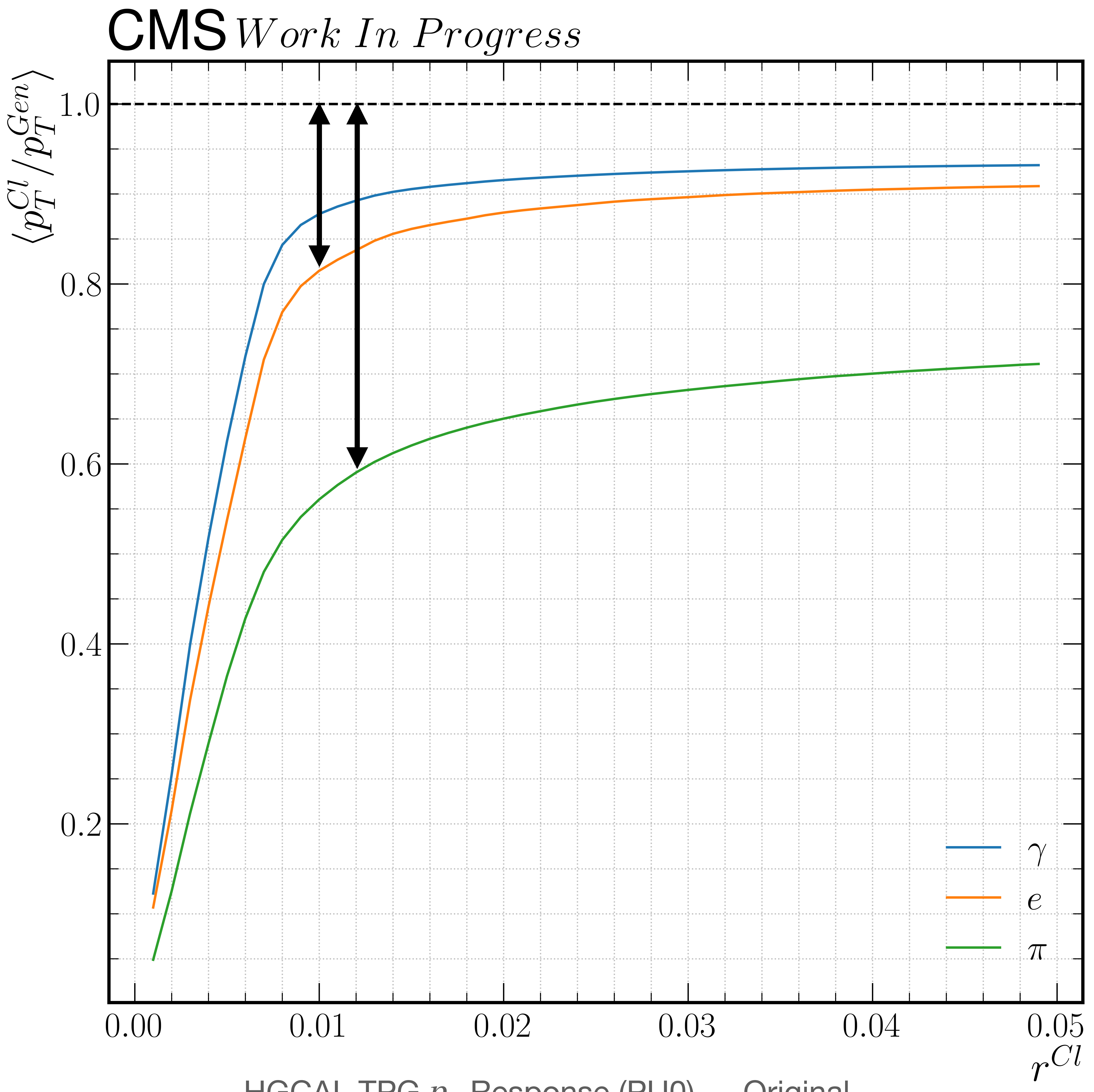


3D Clustering

- $Response_{\gamma/\pi} \equiv \langle p_T^{Cl} / p_T^{Gen} \rangle$
- $Response_e \equiv mode(p_T^{Cl} / p_T^{Gen})$

The bare response plateaus with $\langle p_T^{Cl} \rangle < \langle p_T^{Gen} \rangle$ due to:

- Thresholds
- TC selection
- Out-of-cluster energy
- Invisible energy (hadronic showers)



HGCAL TPG p_T Response (PU0) — Original

3D Clustering: Weighting and Calibration

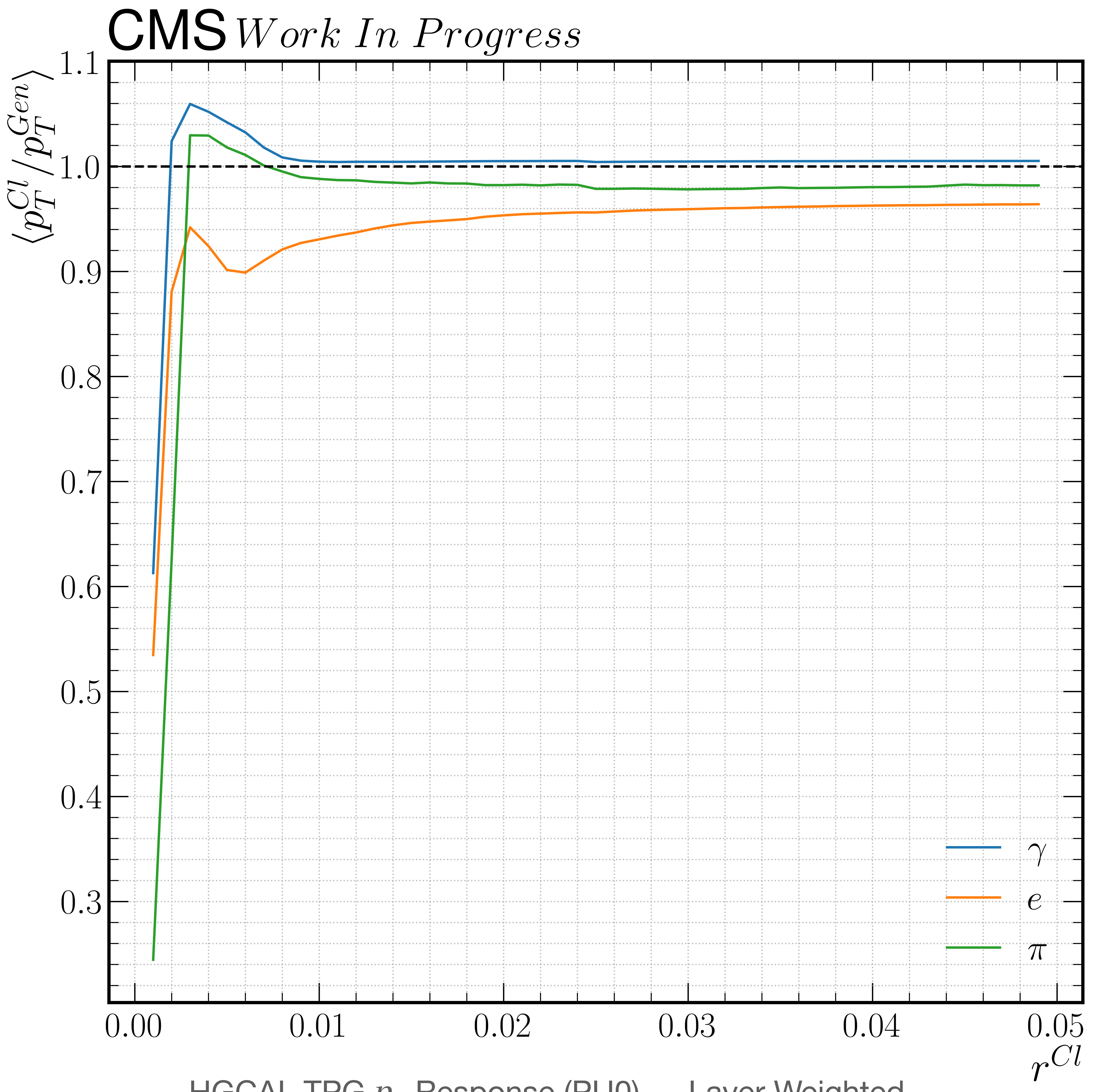
Layer Correction on 0 PU

Weights $\overrightarrow{w}$ are calculated for each layer of the HGCAL to account for energy losses. For N layers and M events, we minimize

$$\frac{||L\overrightarrow{w} - \overrightarrow{p_T^{Gen}}||^2}{2}$$

with

$$L = \begin{pmatrix} p_T^{l_0,e_0} & \dots & p_T^{l_N,e_0} \\ \vdots & \ddots & \vdots \\ p_T^{l_0,e_M} & \dots & p_T^{l_N,e_M} \end{pmatrix}$$



HGCAL TPG p_T Response (PU0) — Layer Weighted

3D Clustering: Weighting and Calibration

Layer Correction on 0 PU

Weights $\overrightarrow{w}$ are calculated for each layer of the HGCAL to account for leakage and energy losses in the absorbers. For N layers and M events, we minimize

$$\frac{||L\overrightarrow{w} - \overrightarrow{p_T^{Gen}}||^2}{2}$$

with

$$L = \begin{pmatrix} p_T^{l_0,e_0} & \cdots & p_T^{l_N,e_0} \\ \vdots & \ddots & \vdots \\ p_T^{l_0,e_M} & \cdots & p_T^{l_N,e_M} \end{pmatrix}$$

Energy Correction on 0 PU

Hadronic showers have a non-linear dependence with energy that requires an extra calibration

$$p_T = p_T^0 \times f^{-1}(E),$$

where $f(E)$ is the best fit function to p_T^{Cl}/p_T^{Gen}.

$|\eta|$ Calibration on 200 PU

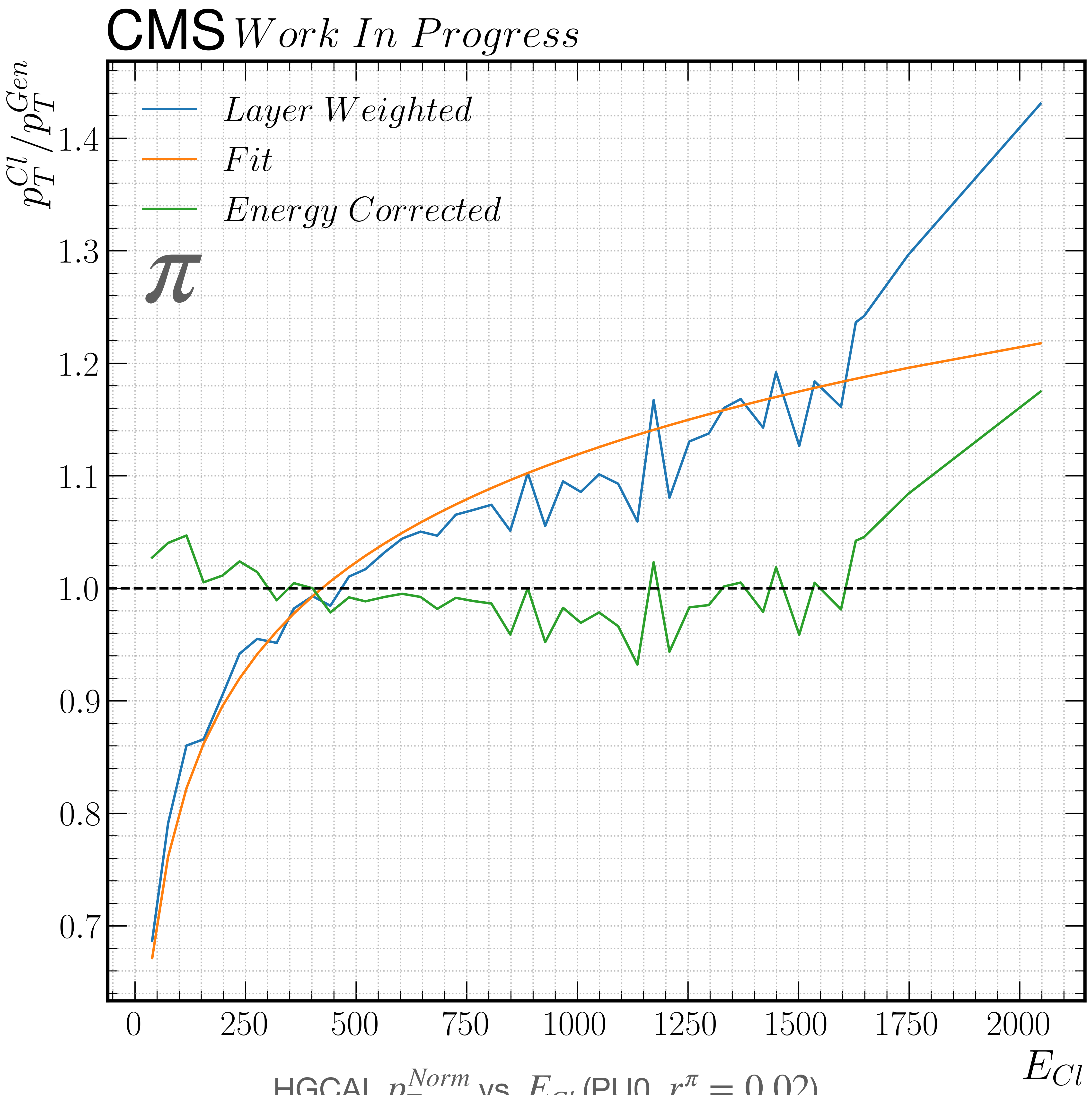
The amount of excess energy due to pileup contamination grows quasi-linearly with the absolute pseudo-rapidity.

$$p_T = \sum_i^N w_i p_T^{l_i} - (a|\eta| + b)$$

3D Clustering: Weighting and Calibration

Energy Correction on 0 PU

A pré(~~fou~~)liminary correction appears to work well across the majority of the cluster energy range.

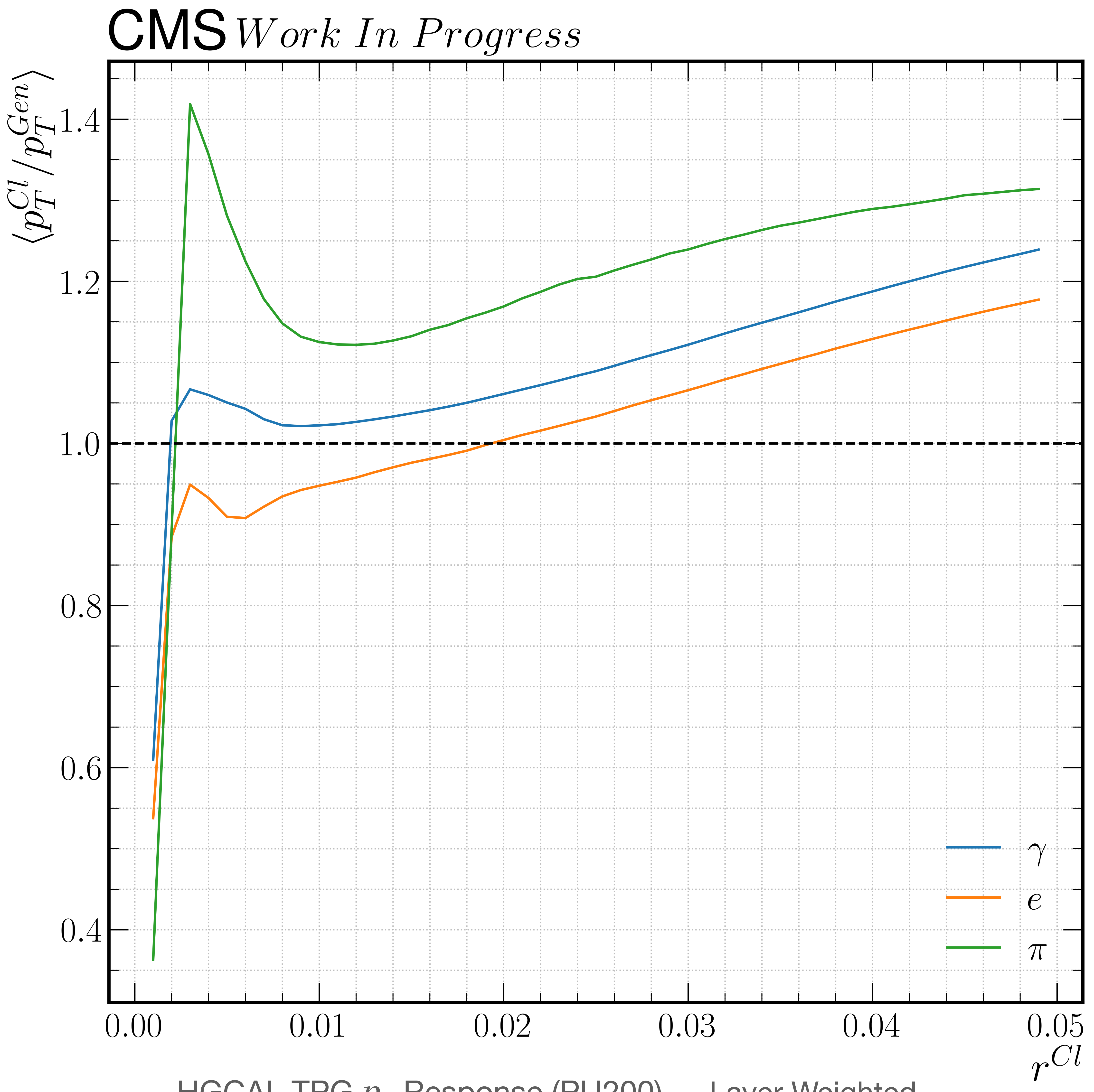


HGCAL p_T^{Norm} vs. E_{Cl} (PU0, $r^{\pi} = 0.02$)

3D Clustering: Weighting and Calibration

Layer Correction on 200 PU

- Weights $\vec{w}$ applied to 200 PU samples
- Larger r^{Cl} $\rightarrow$ larger effect from PU contamination



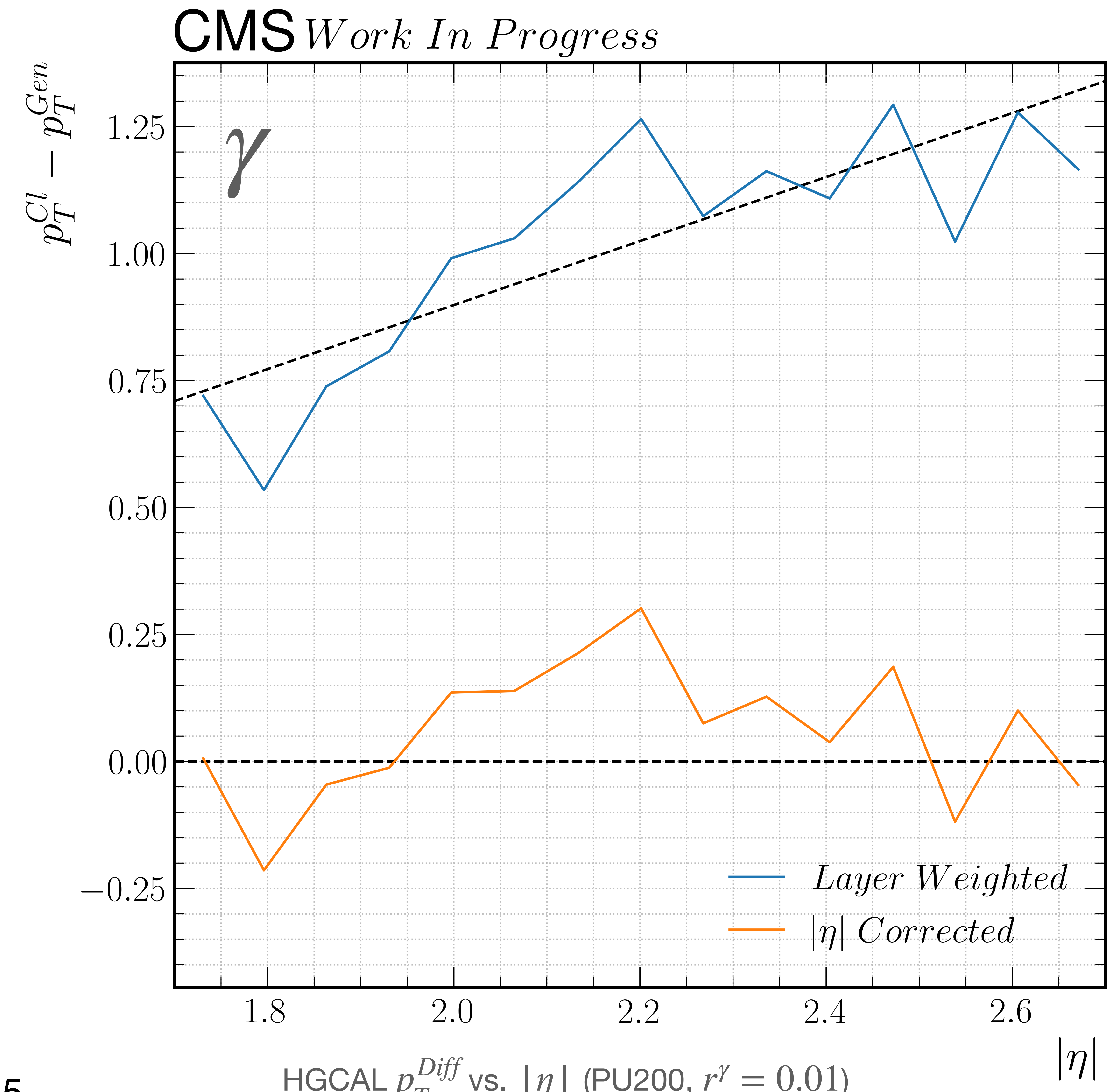
HGCAL TPG p_T Response (PU200) — Layer Weighted

3D Clustering: Weighting and Calibration

$|\eta|$ Calibration on 200 PU

The amount of excess energy due to pileup contamination grows quasi-linearly with the absolute pseudo-rapidity.

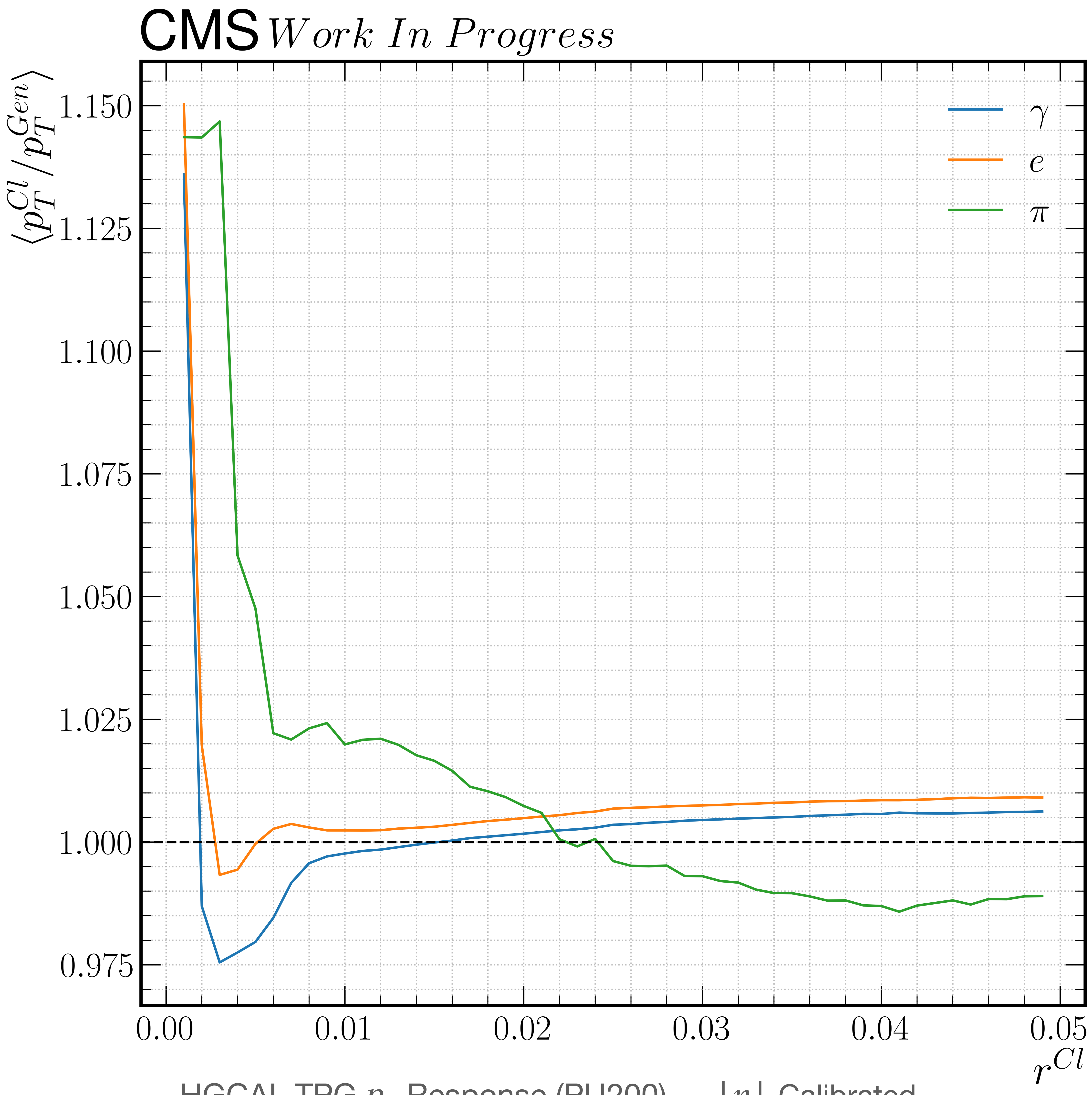
$$p_T = \sum_{i}^{N} w_i p_T^{l_i} - (a\,|\eta| + b)$$



HGCAL p_T^{Diff} vs. $|\eta|$ (PU200, $r^\gamma = 0.01$)

Results: Response

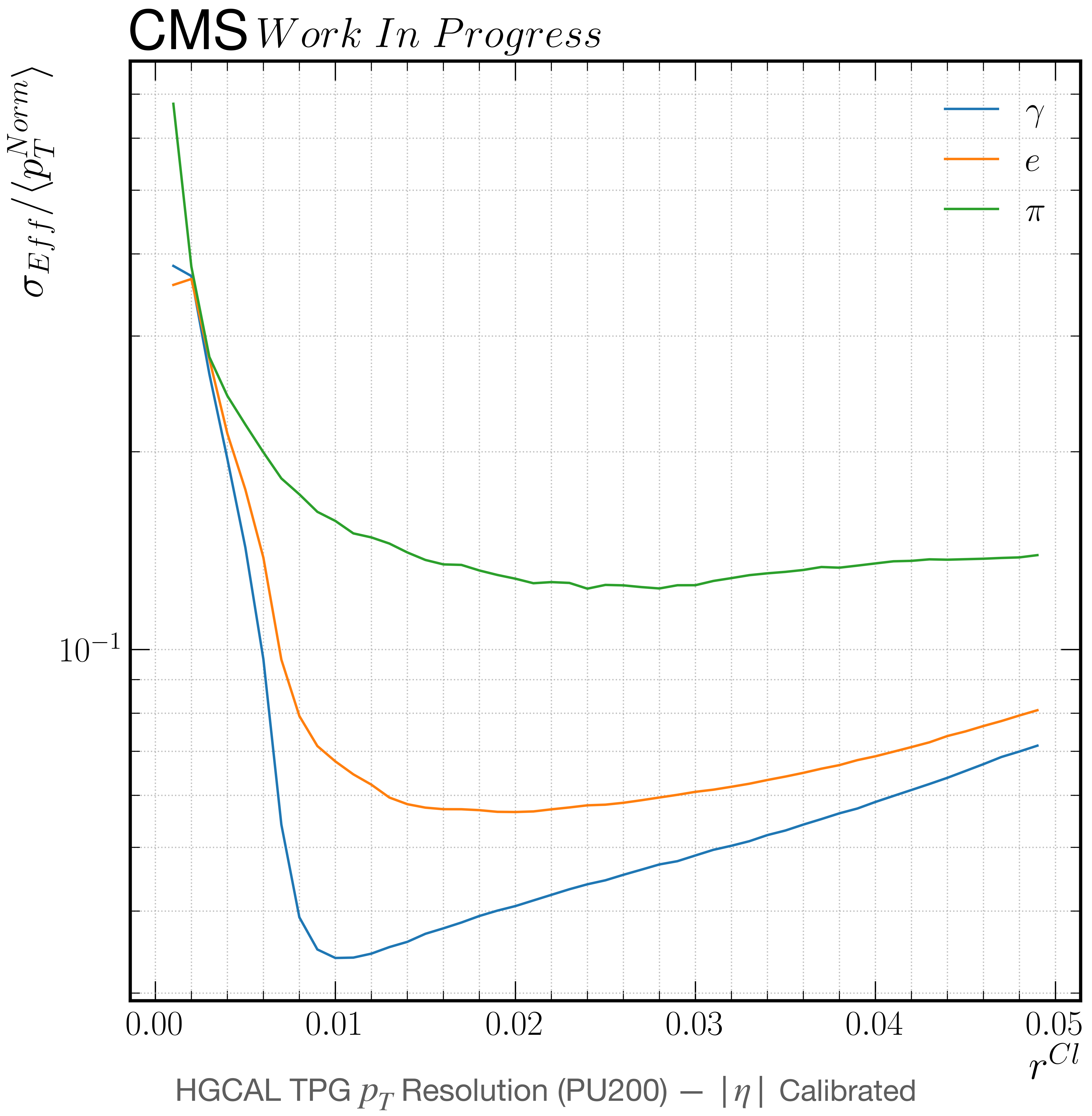
After all calibrations, response is ~ 1 for EM initiated showers and $\sim 1 \pm 0.02$ for hadronic showers.



HGCAL TPG p_T Response (PU200) — $|\eta|$ Calibrated

Results: Resolution

- $Resolution \equiv \sigma_{Eff}(p_T^{Norm}) / \langle p_T^{Norm} \rangle$
- $p_T^{Norm} = p_T^{Cl} / p_T^{Gen}$
- σ_{Eff} : smallest interval containing 68 % of events
- Optimal Radii:
  - $r_{EM}^{Cl} \sim 0.01$
  - $r_{Had}^{Cl} \sim 0.02$



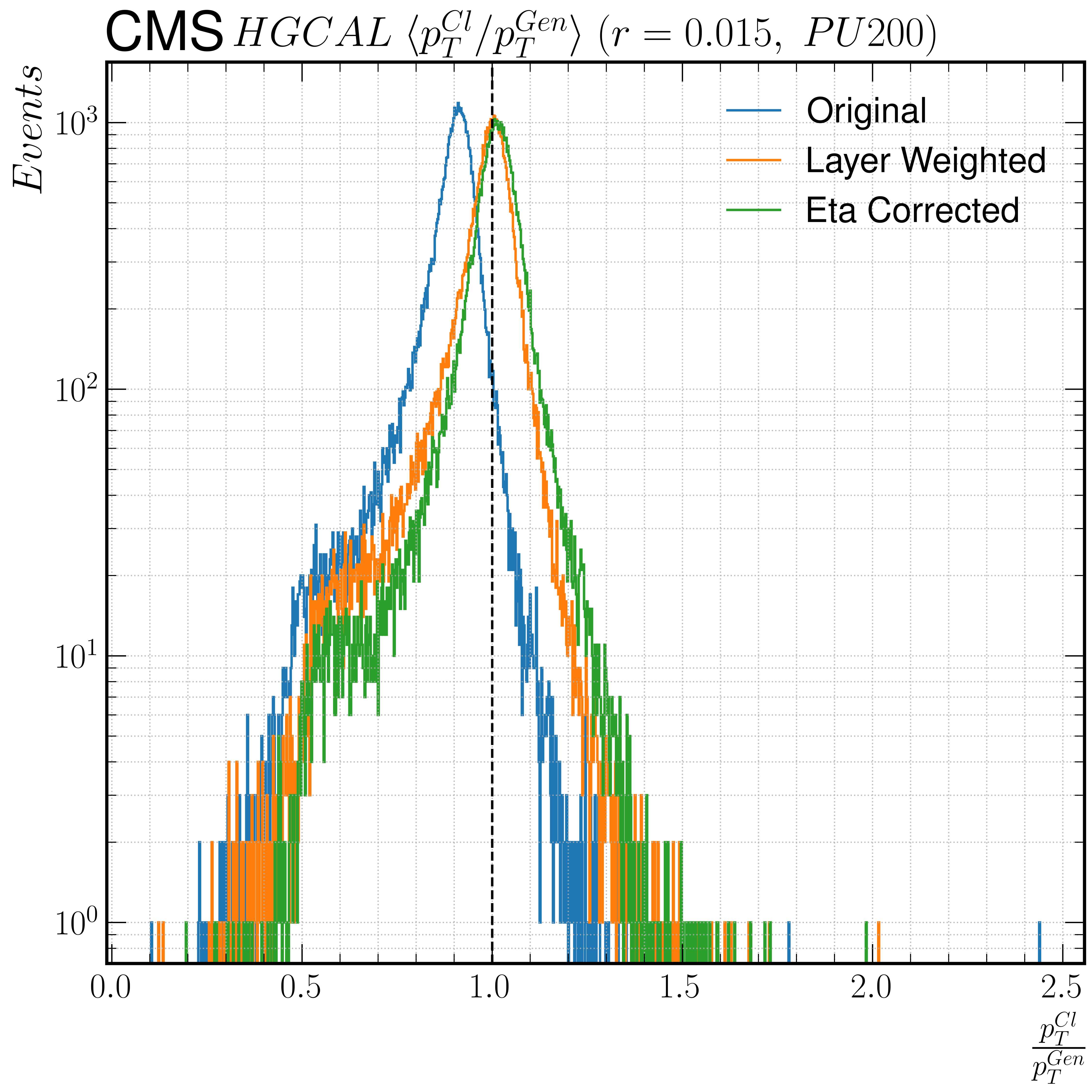
Conclusion and Outlook

- Response and Resolution of 3D clusters have been well optimized
- Optimal clustering radii determined to be $r_{EM}^{Cl} \sim 0.01$, $r_{Had}^{Cl} \sim 0.02$
- Further work should be performed to determine the best energy calibration for hadronic showers
- Vary the radii independently in each layer of the HGCAL to achieve better performance

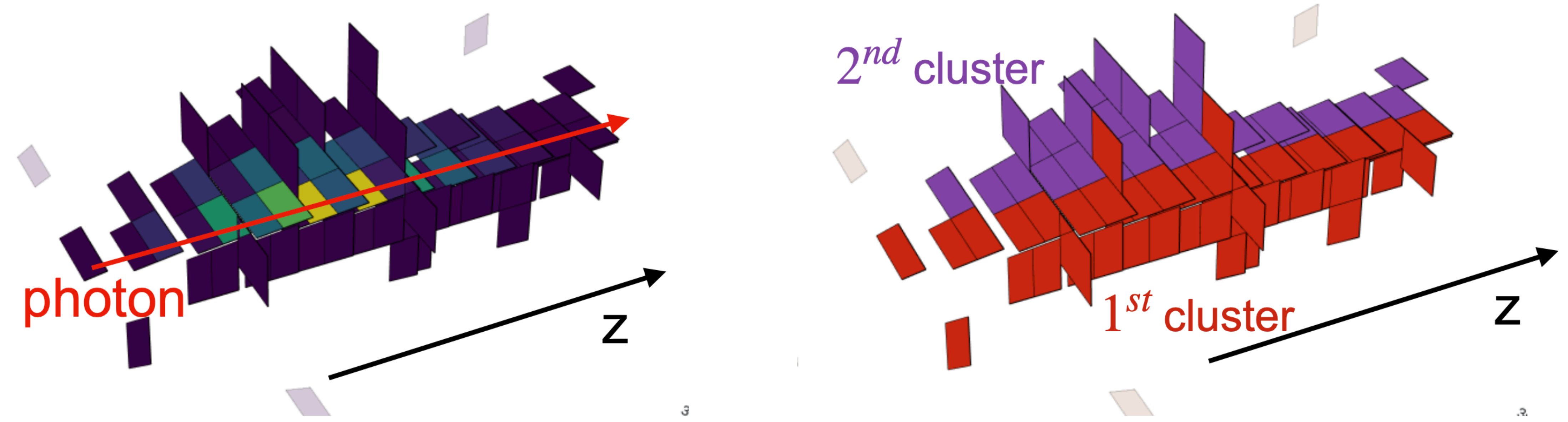
Backup

Backup

Electrons lose part of their energy to bremsstrahlung radiation before interacting in the HGCAL, leading to a low energy tail in the p_T^{Norm} distributions.



Backup



Known issue in the default clustering algorithm leads to excessive cluster splitting in the high-$|\eta|$ region of the detector.