Progress on ALLEGRO calorimeters implementation in full simulation

Giovanni Marchiori
(APC-Paris CNRS/IN2P3)

FCC PED workshop (Annecy, January 2024)

material from T. Li, A. Maloizel, M. Mlynarikova and E. Varnes

The ALLEGRO concept and its calorimeters

- **A** **L**epton co**L**lider **E**xperiment with **G**ranular **R**ead-**O**ut

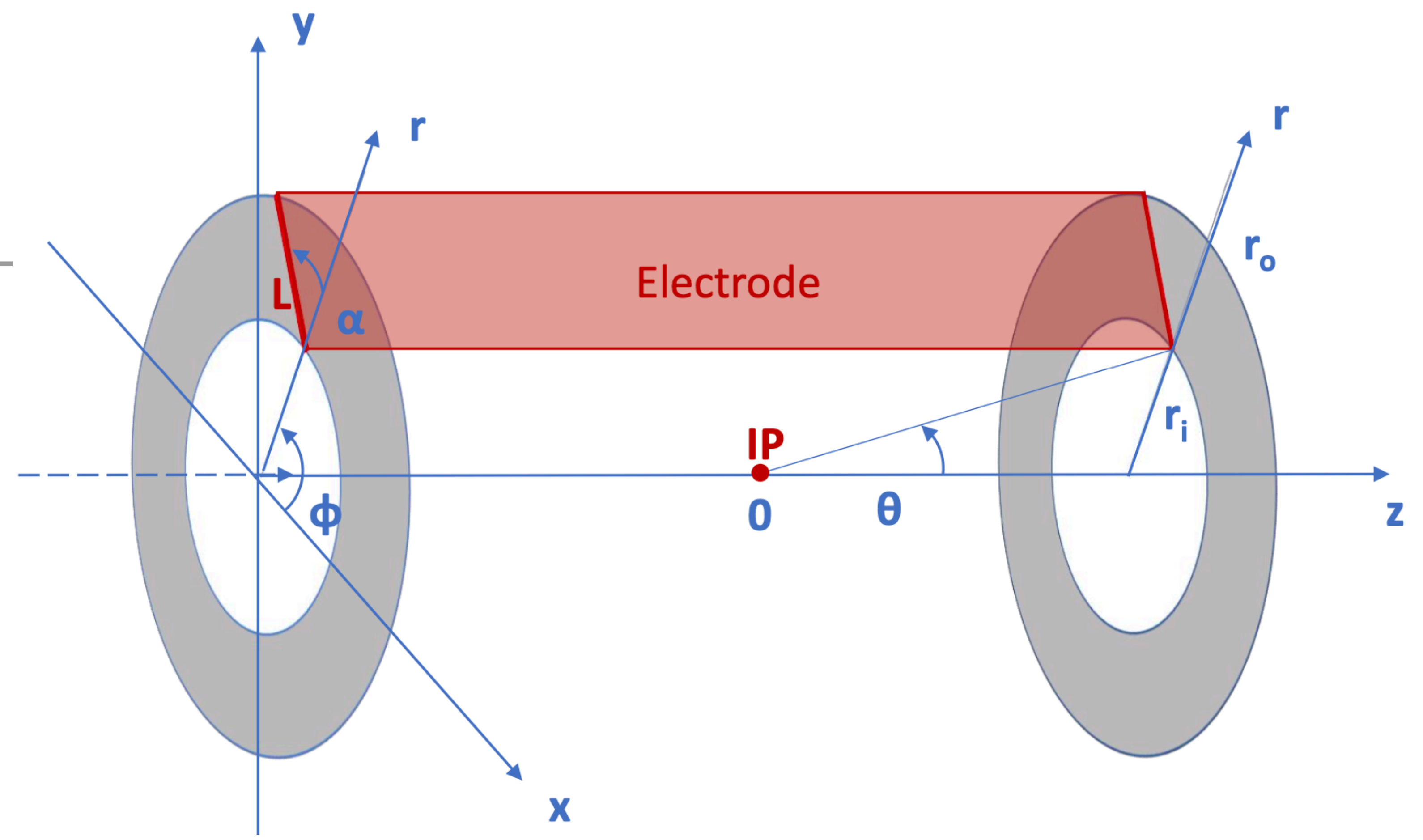
> allegro
> *noun* [C] • MUSIC • specialized
> UK /əˈleg.rəʊ/ US /əˈleg.roʊ/
> plural **allegros**
>
> **a piece of music that is played in a fast and energetic way**

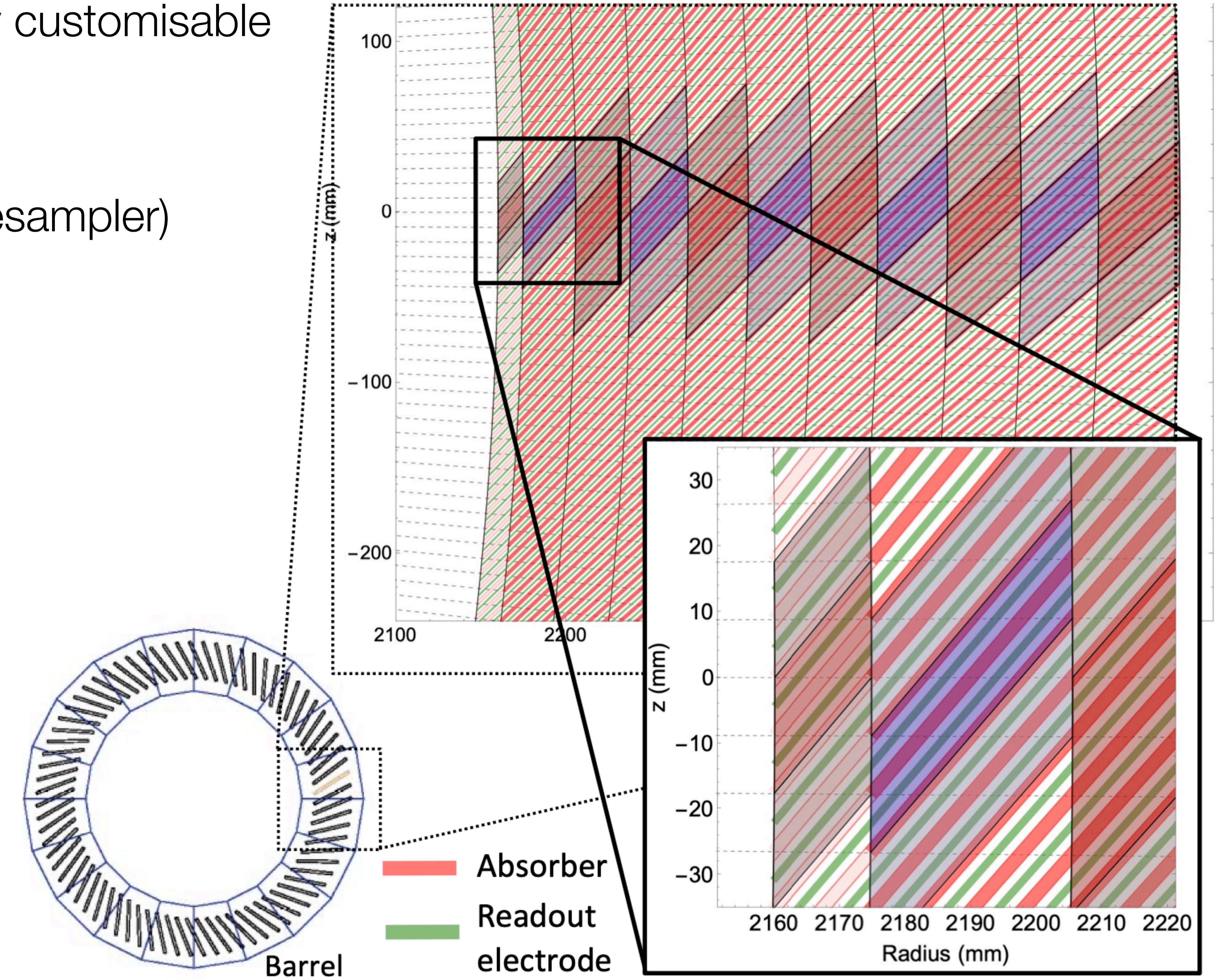
- Highly granular noble liquid EM calorimeter inside solenoid
  - Pb/W+LAr (or denser W+LKr)
  - Coil inside same cryostat as LAr
- CALICE-like or TileCal-like HCAL outside solenoid
  - Light coil (0.76 X_0) + low-material cryostat < $0.1X_0$
  - SiPMs directly on Scintillator or TileCal: WS fibres, SiPMs outside
- Detector design optimisation not complete - needs full simulation beforehand!

See also Juska Pekkanen's talk

ECAL barrel

- Baseline design (exact parameters subject to further optimisation):
  - 1536 straight inclined (50°) 1.8 mm Pb absorber plates
  - R_{in} = 216 cm, R_{out}=256 cm => 40 cm deep (≈ 22 X_0)
  - Multi-layer PCBs as readout electrodes => # layers and granularity customisable
  - 2 x 1.2 mm LAr gaps
  - 12 = 1 (1.5 cm) + 11 (3.5 cm) longitudinal compartments (L0 = presampler)
  - $\Delta\theta$ ~ 10 (2.5) mrad for regular (L1 strip) cells,
  - $\Delta\phi$ ~ 8 mrad
- Possible Options
  - LKr or LAr active medium, W or Pb absorbers,
  - Al or carbon fibre cryostat
  - Absorbers with growing thickness

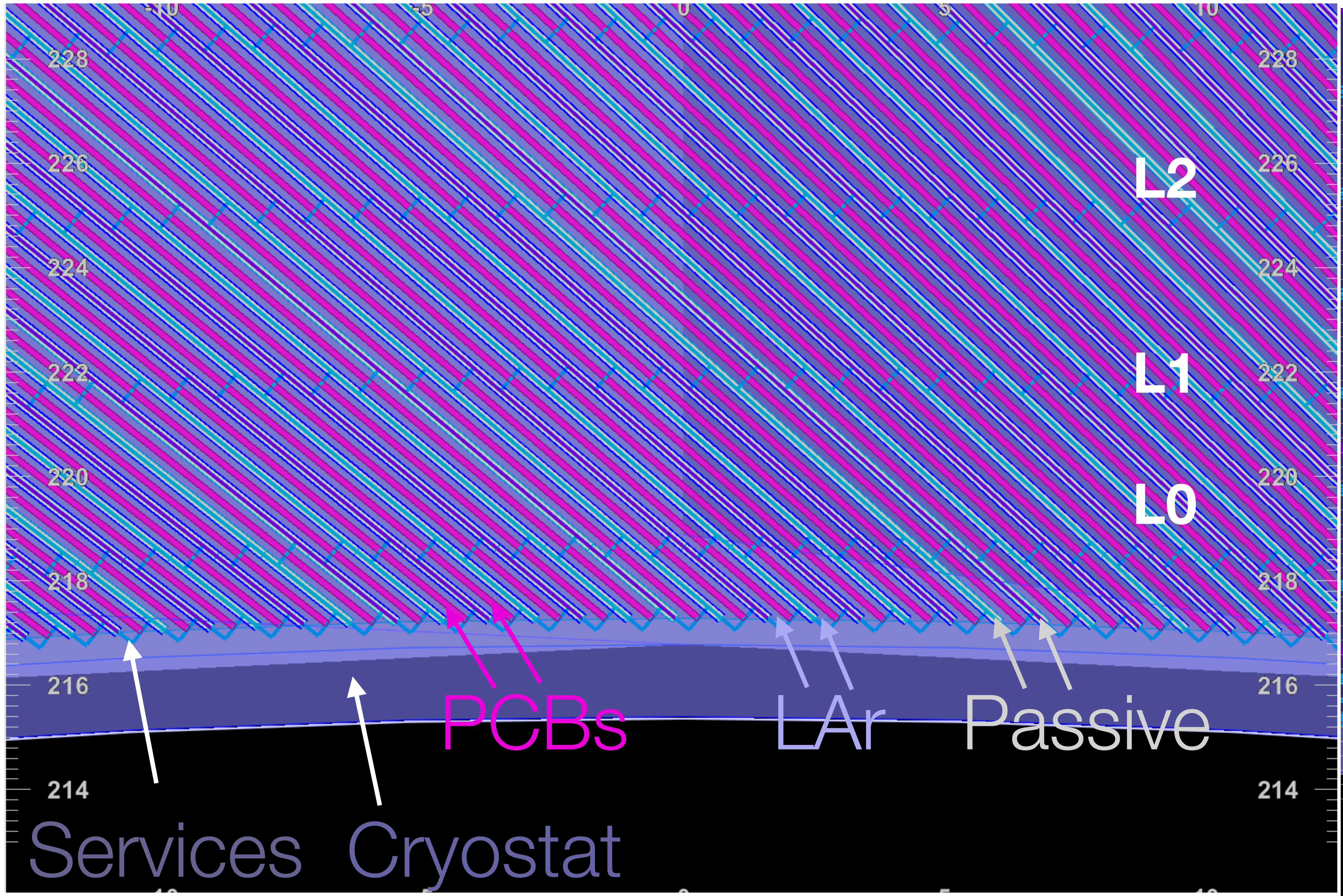




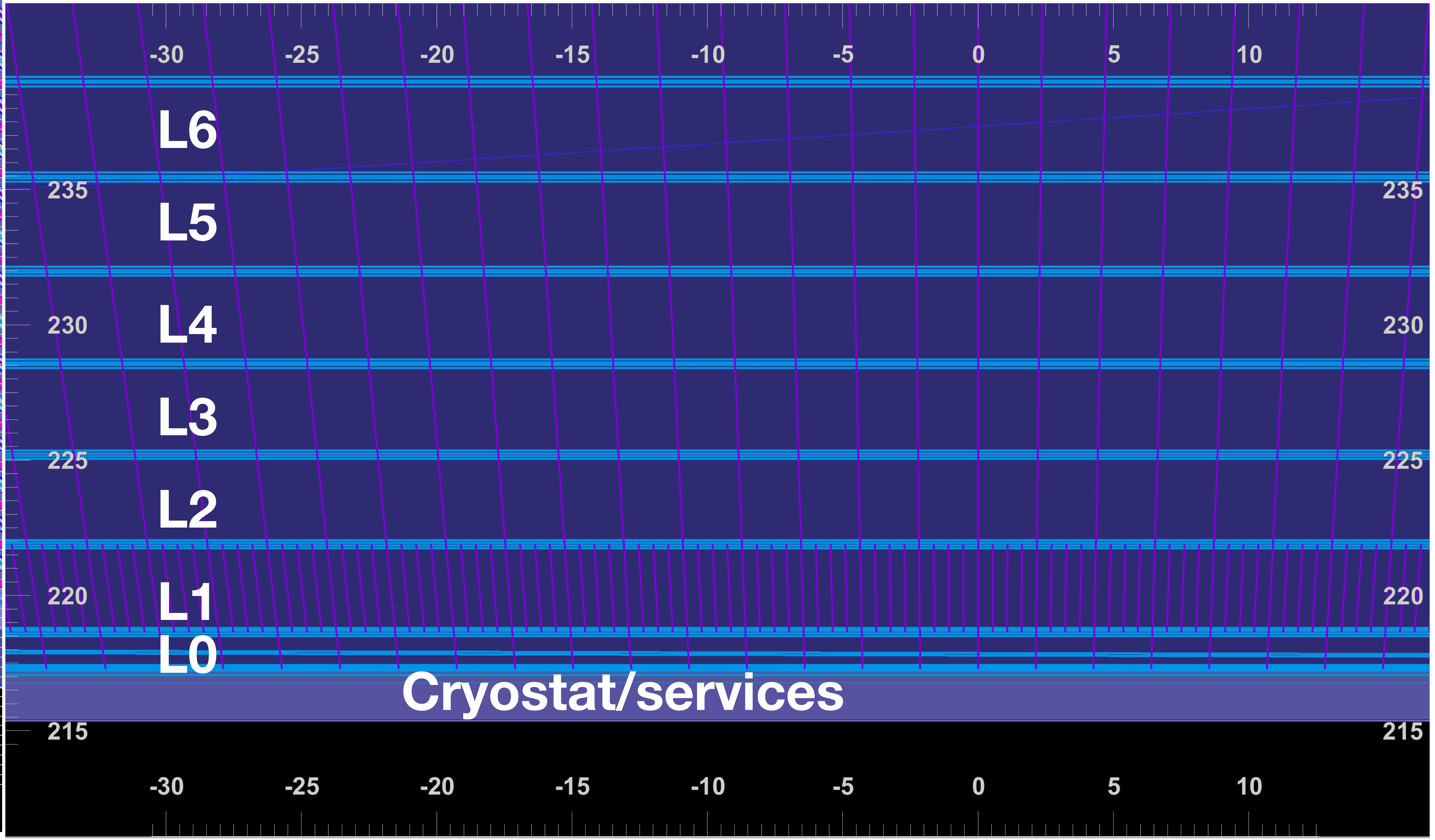
ECAL barrel simulation

- Geometry implemented in FCCSW since quite some time - originally for FCC-hh studies
- Activities of the past year:
  - new segmentation class adapted to detector readout concept (PR #1 #2 #3 - merged)
    - η-ϕ projective cells => θ-projective cells, non-projective in ϕ (following the geometry of the inclined absorbes)
    - customisable per-layer granularity/grouping of cells (baseline corresponds to granularity shown in previous slide)
  - sliding window (PR #1 #2 #3 - under review) and topo-clustering (PR #1 #2 #3) adapted to new segmentation
  - migration of detector geometry and segmentation to k4Geo (PR #1 #2 #3 #4 - merged)
  - ancillary work on development of simple calo event display, to easier debugging (repository)
- Activities ongoing/foreseen
  - Calculation of cluster barycentre (and per-layer), log-weights vs regression
  - Update noise tool to work with new ECAL geometry/segmentation
  - Implement x-talk
  - Use simulations to study physics performance and optimise detector design

ECAL barrel simulation

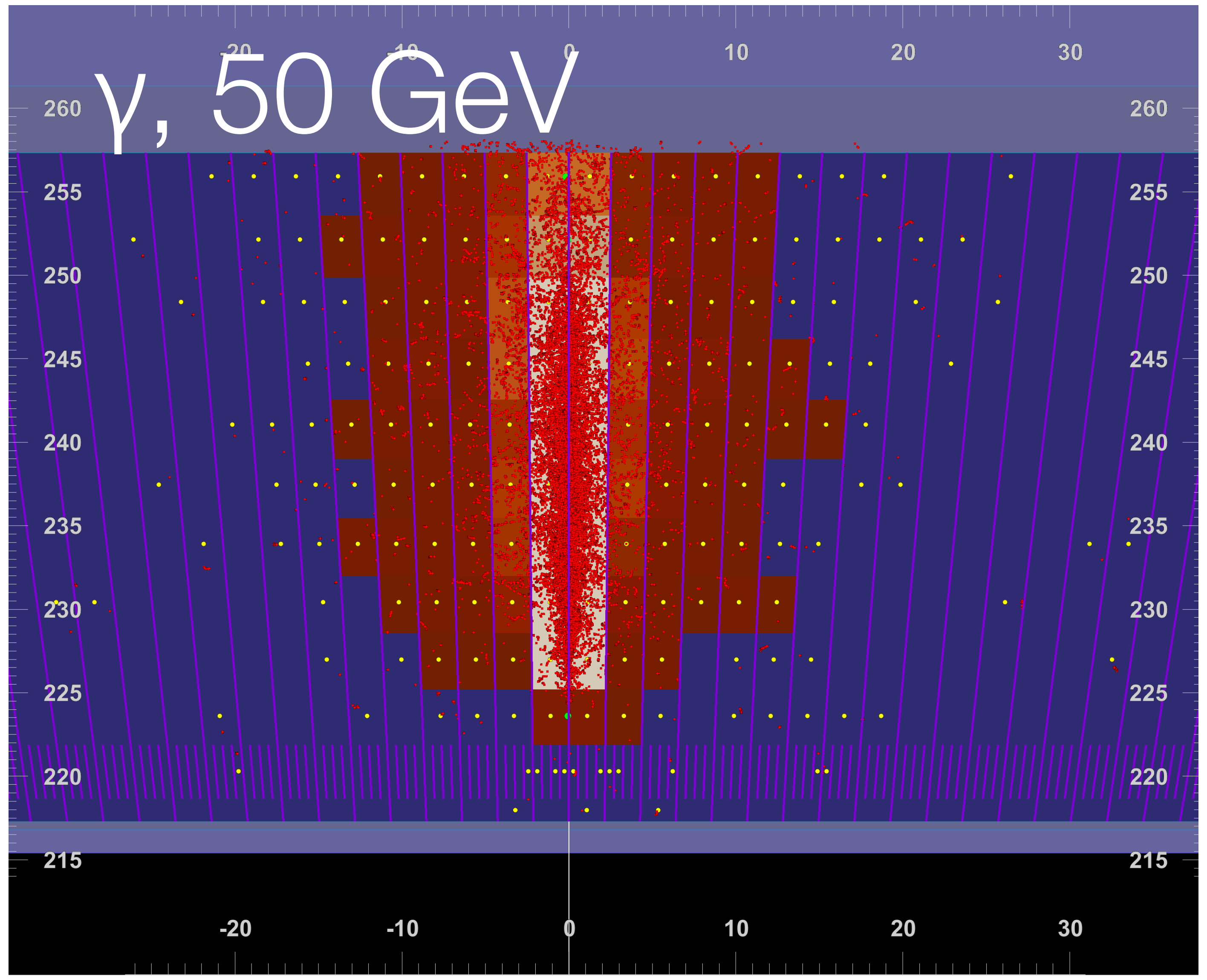


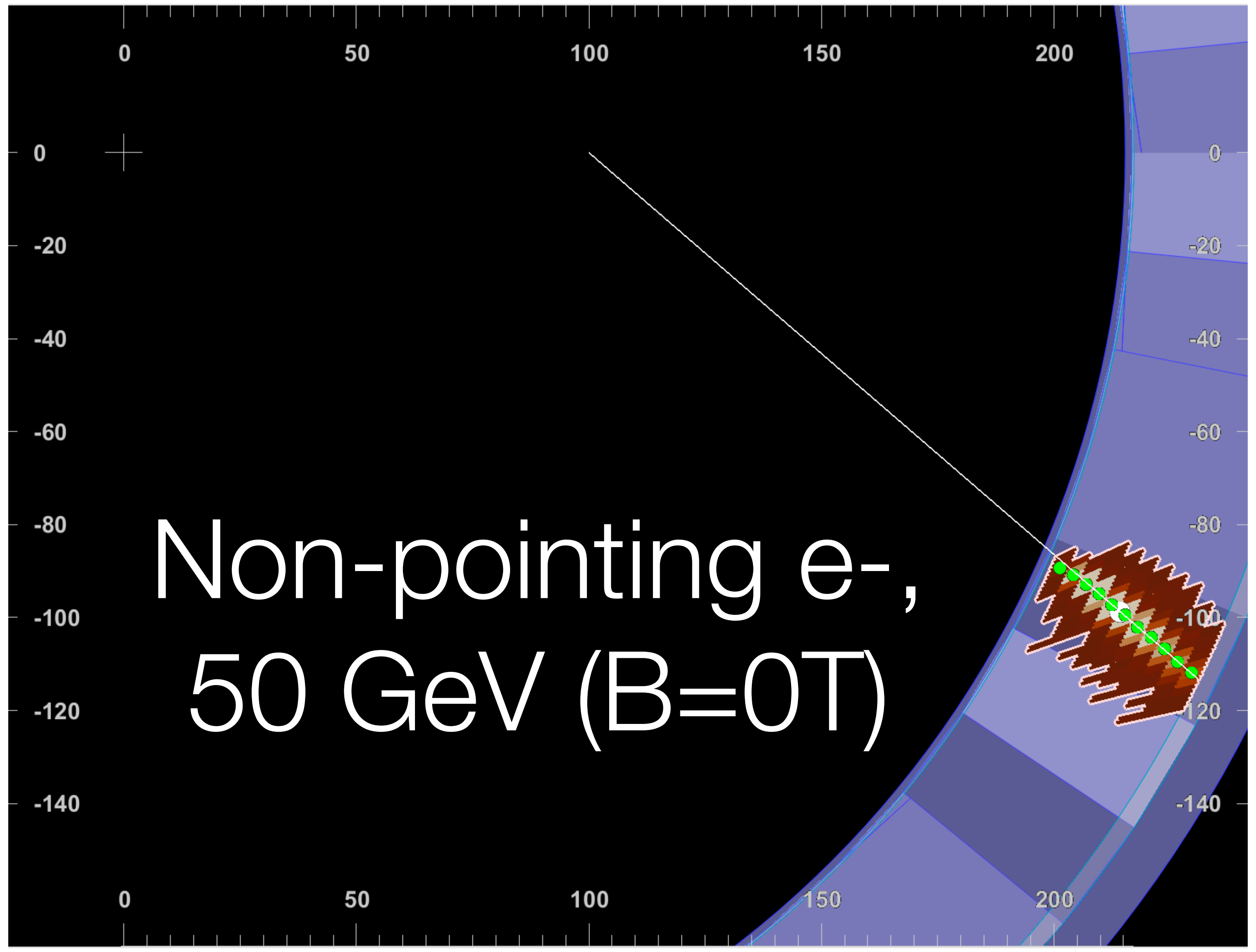
Geant4 geometry (r-ϕ)

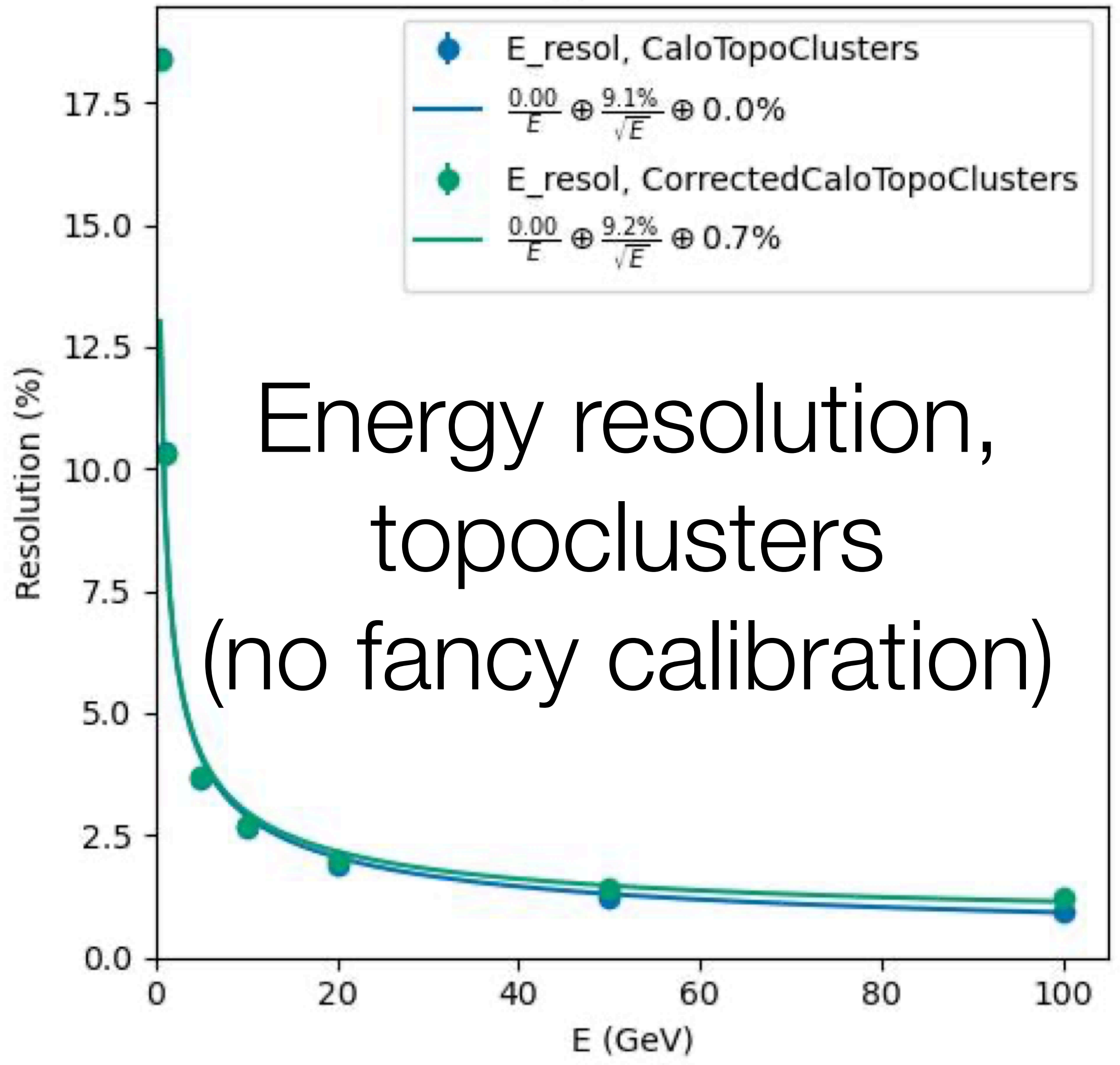


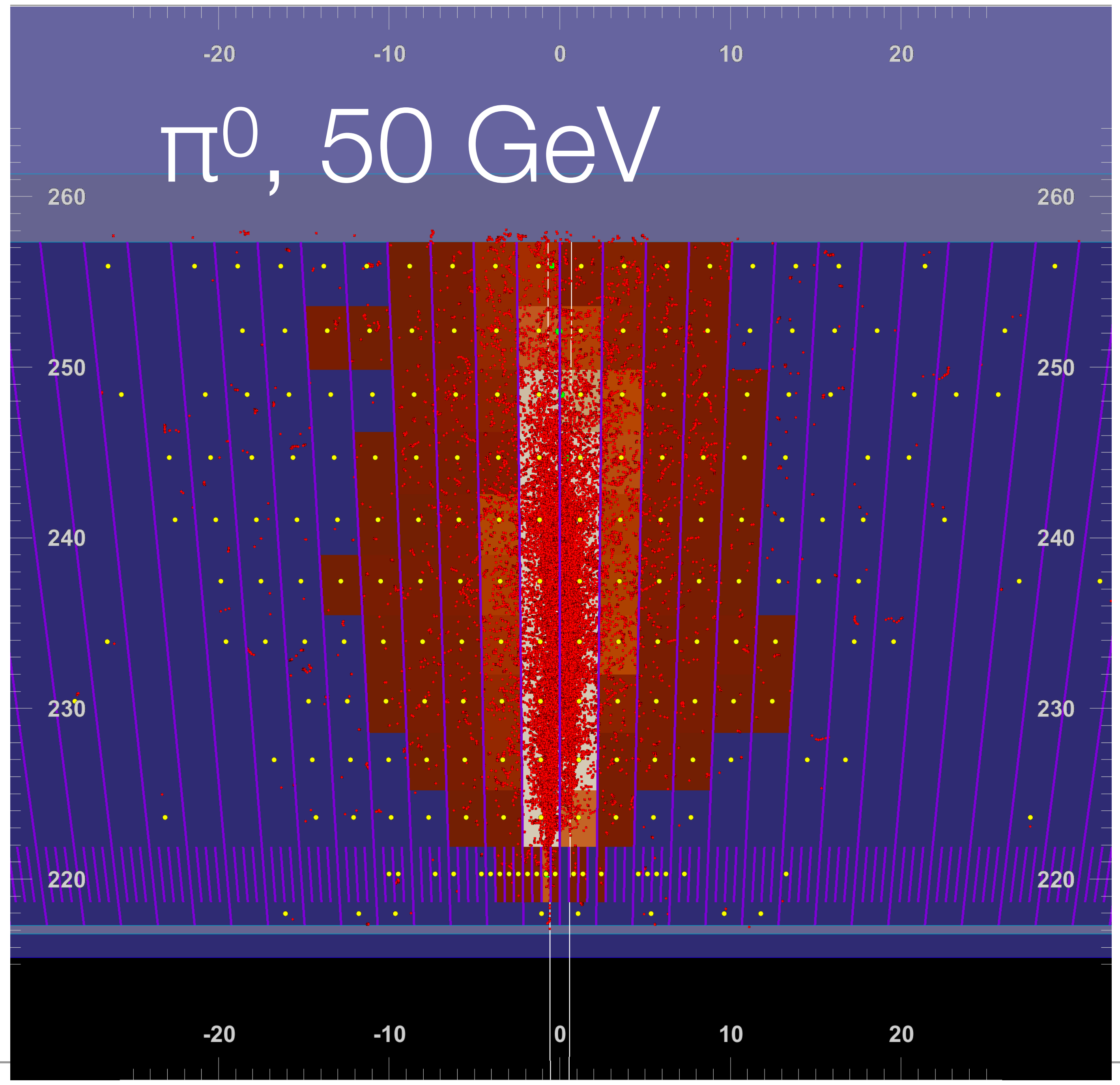
θ segmentation (r-z)

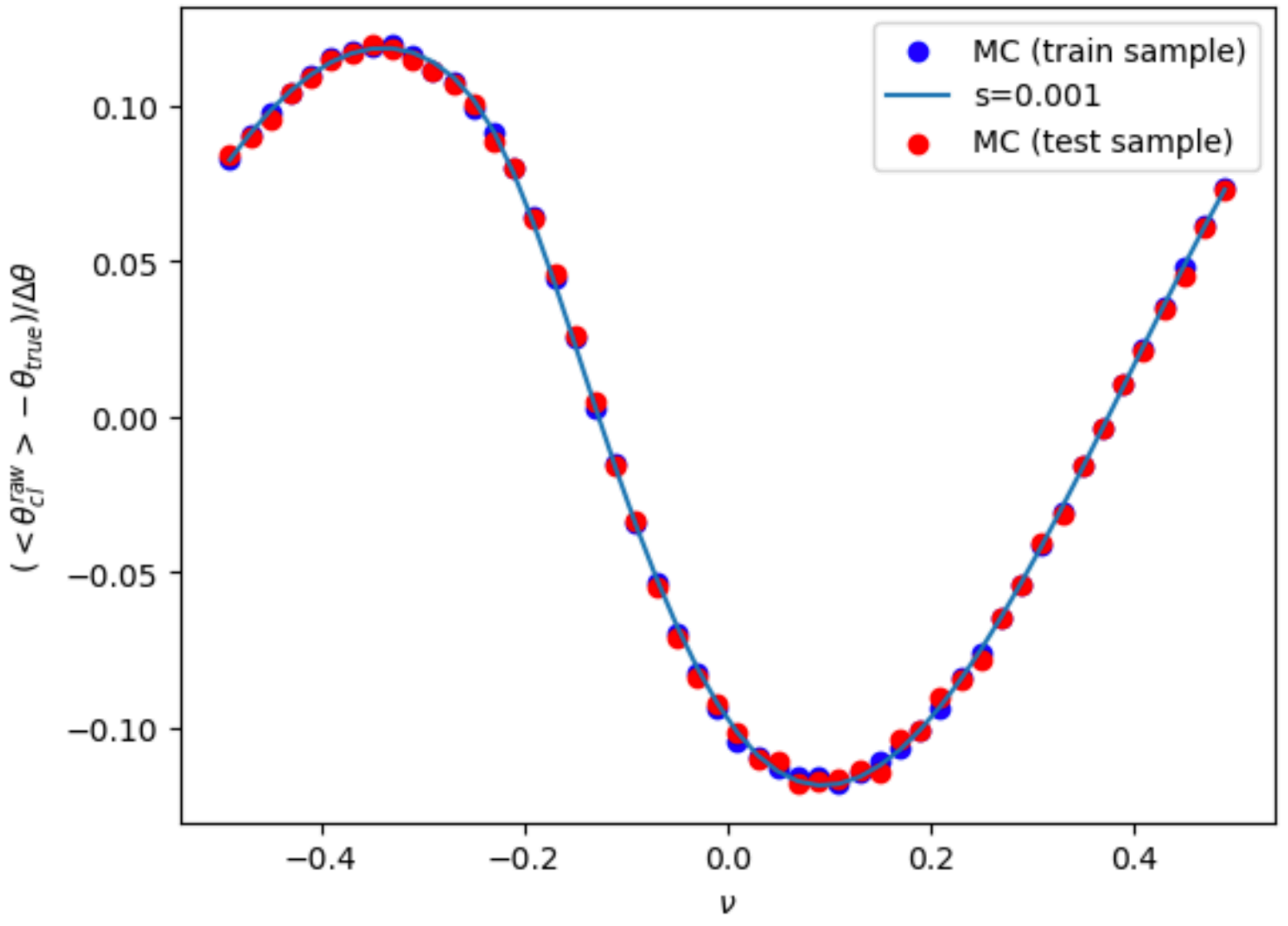
ECAL barrel simulation

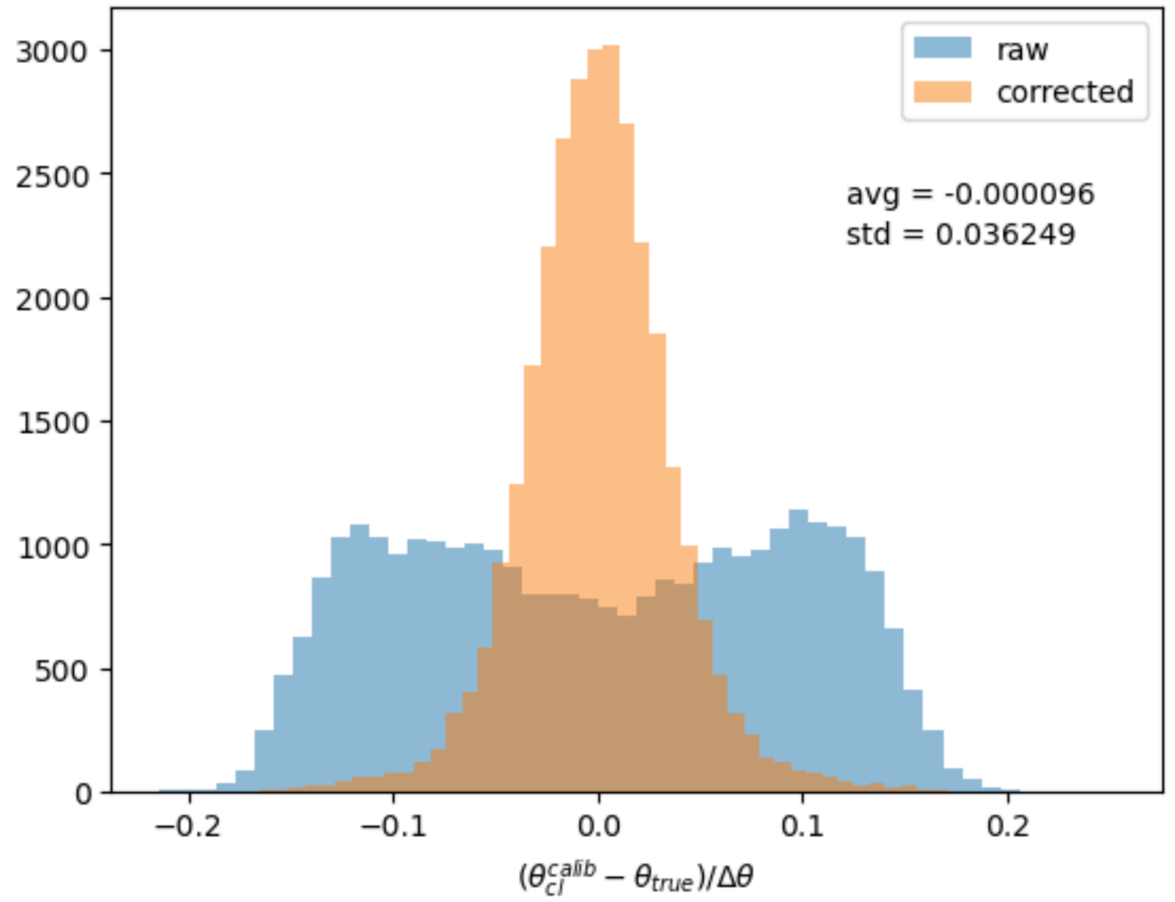








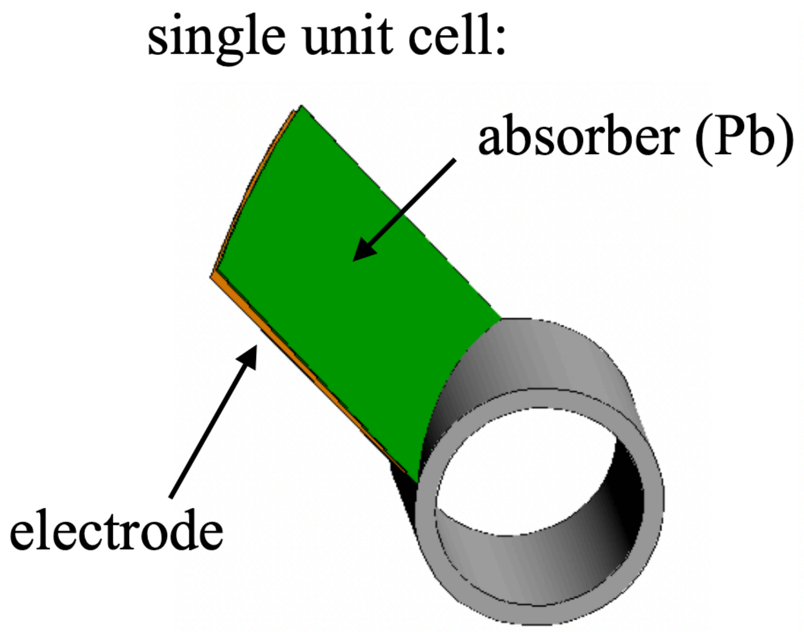


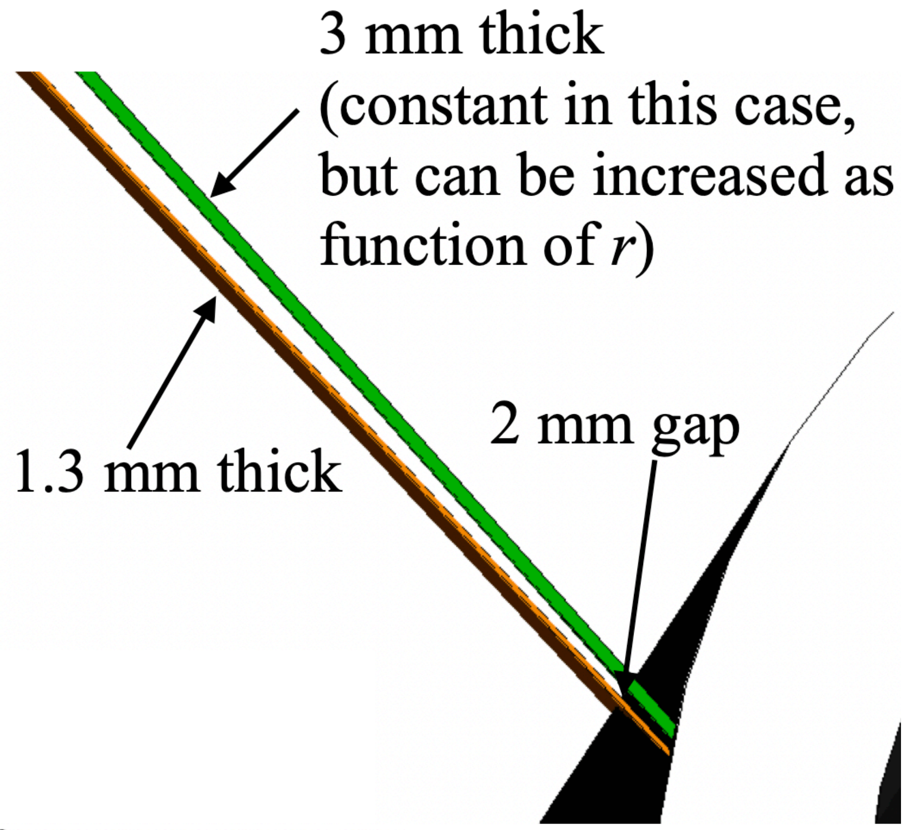


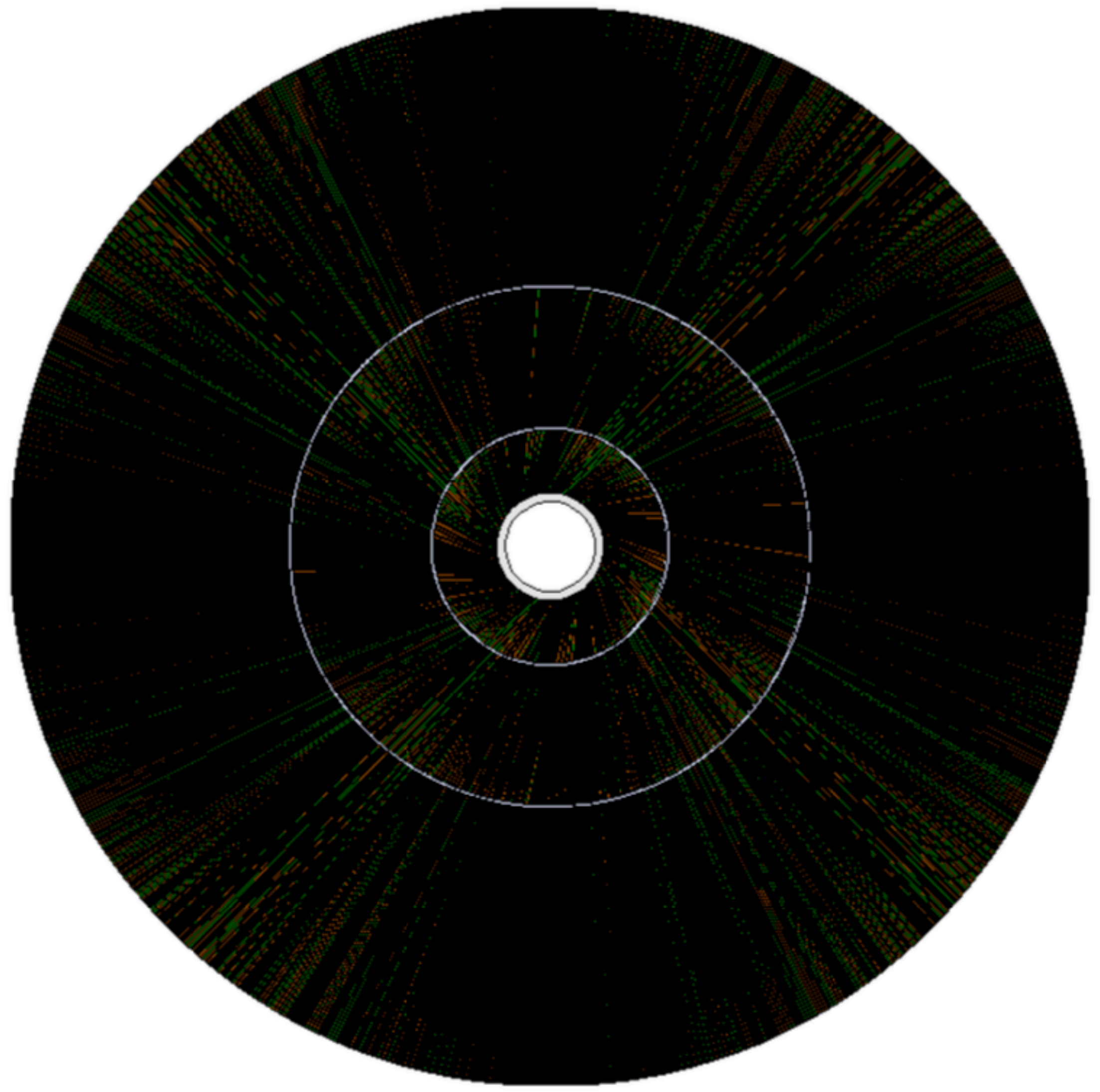
Position/direction reconstruction: S-curve
θ correction and resolution

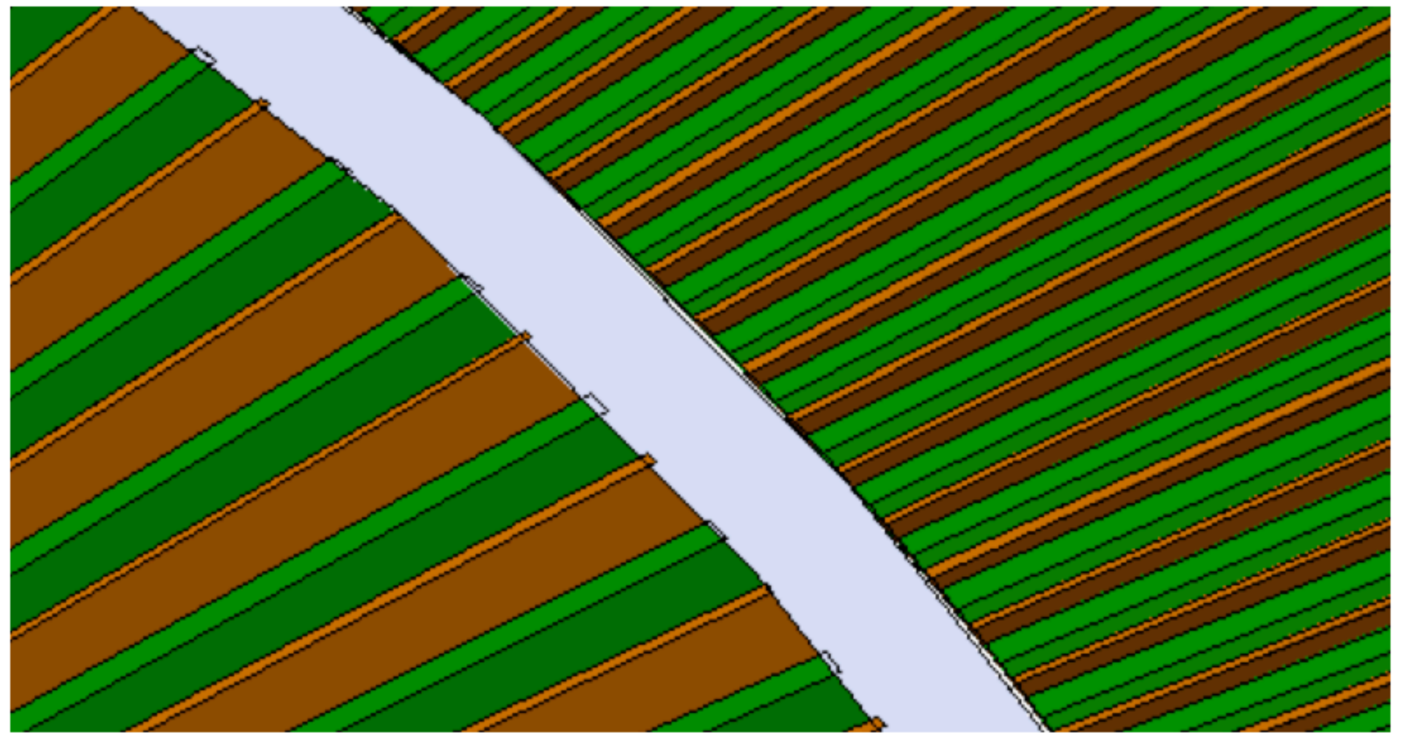
ECAL endcap

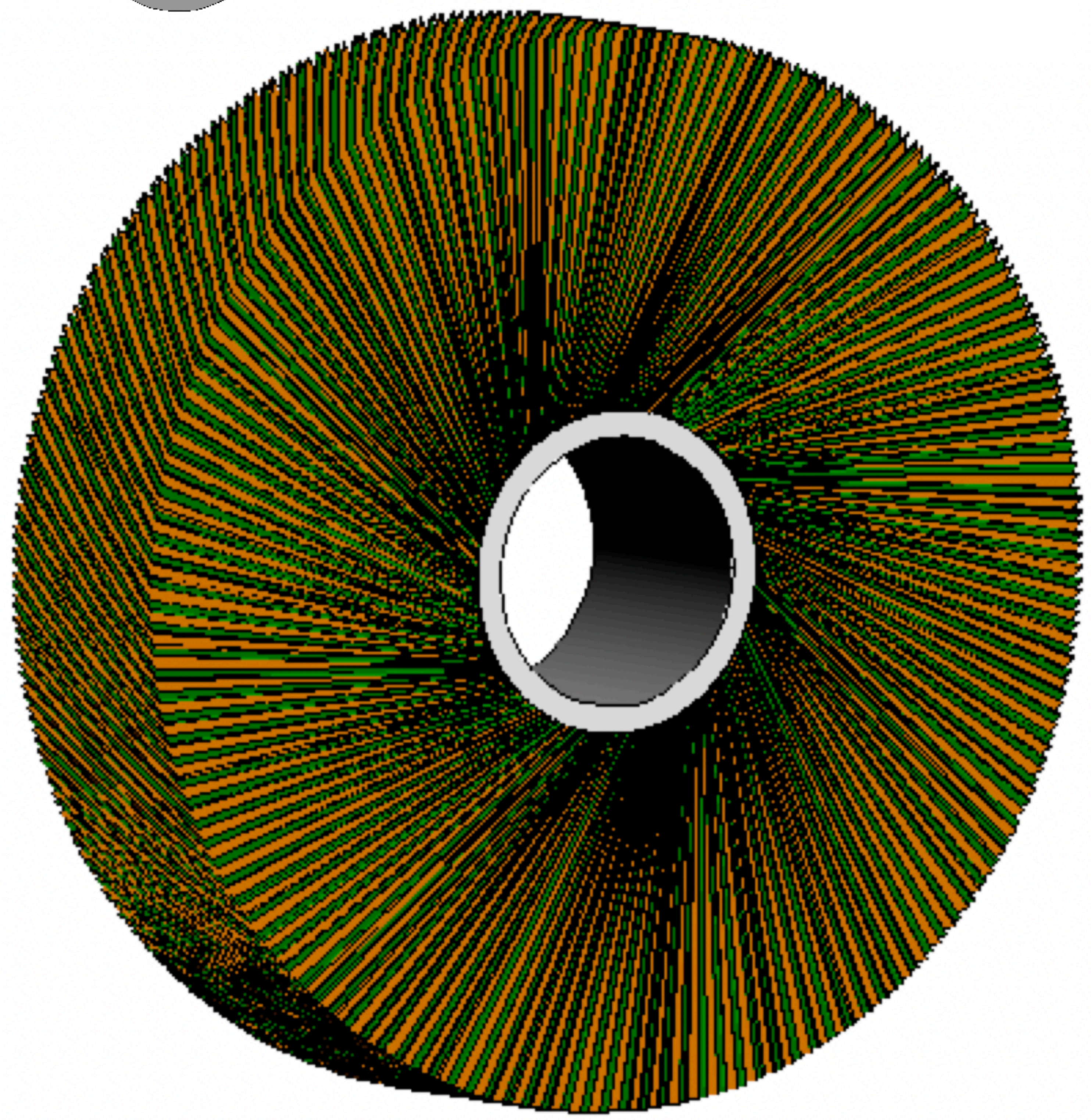
- Endcap design more complex than barrel. A few preliminary ideas on the table. Showing here the one being implemented in the simulation at the moment (“Turbine design”), see <u>here</u> for alternative ideas
    - similar to barrel design, with many thin absorber plates
    - symmetric in ϕ
    - readout from high-|z| face
    - Issue: increase in the size of the LAr gaps
        - mitigated stacking several cylinders





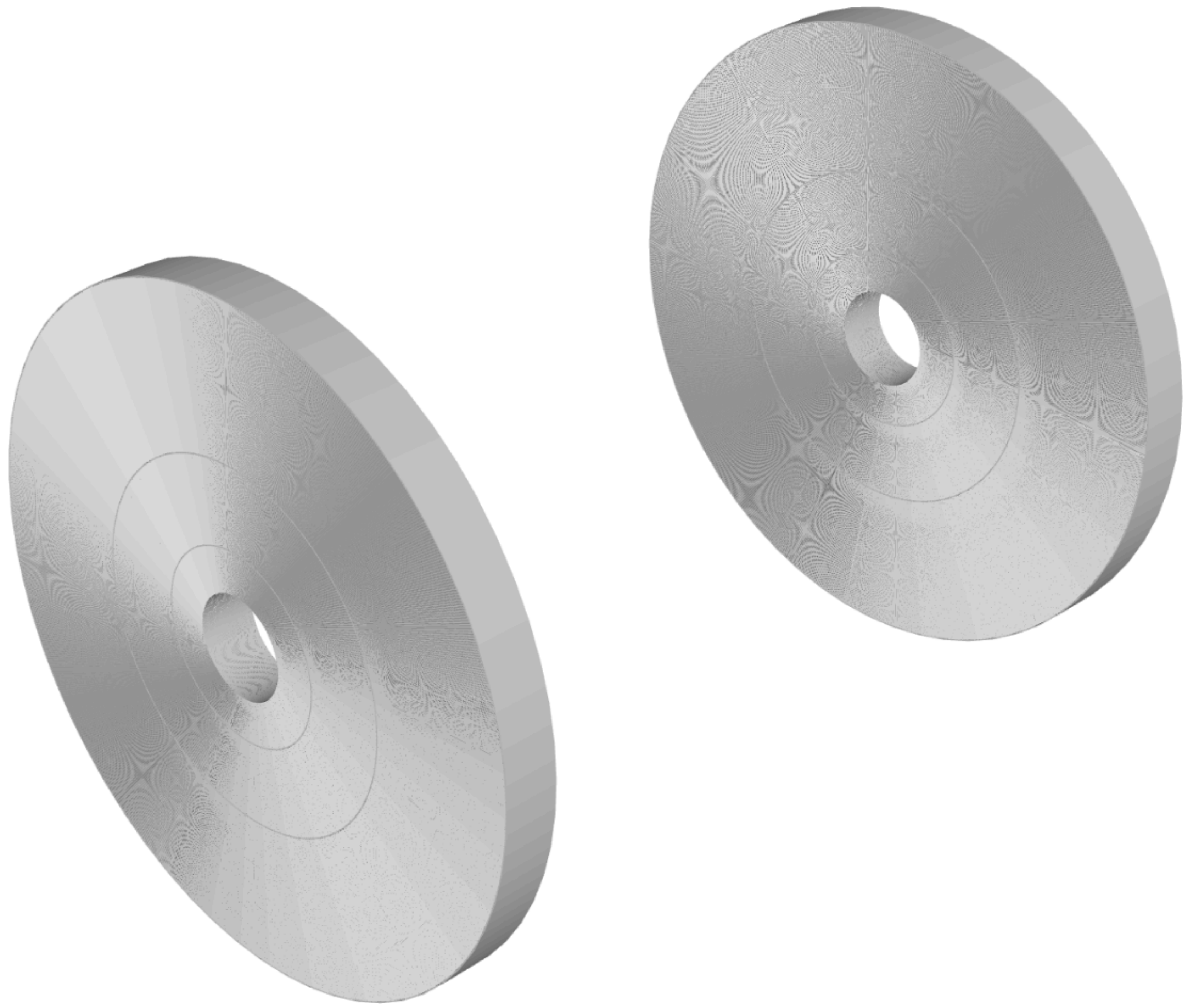




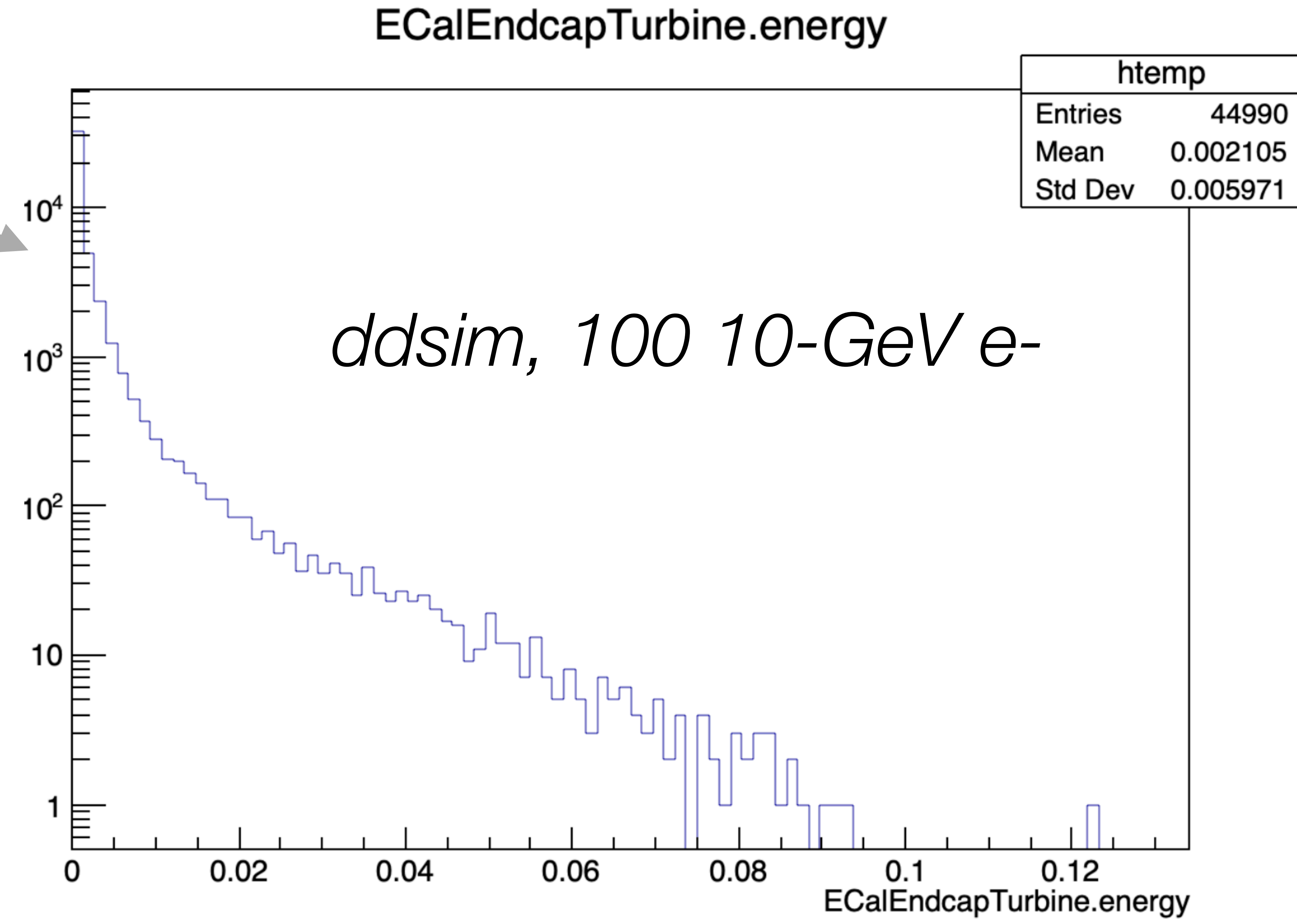


ECAL endcap simulation

- Geometry ported to dd4hep/k4geo (currently in separate fork, not merged yet)
    - Here as seen in JSROOT viewer after running dd4hep2root



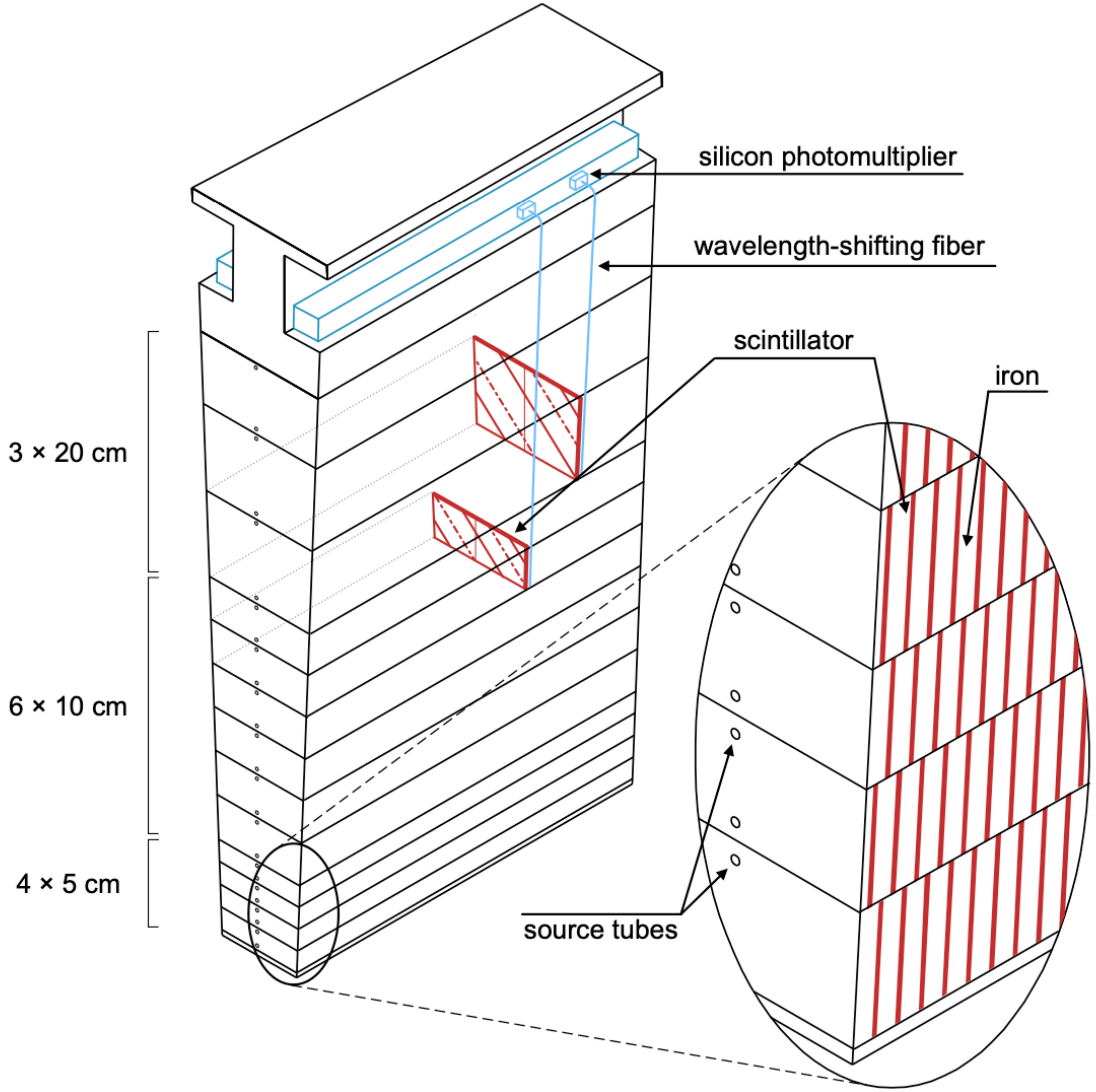
- Initial version of dedicated segmentation class for digitisation written
    - Can run G4 successfully, reconstruct energy deposited in the cells and save it as part of output ROOT file



- Next steps
    - Implement cell positioning tool
    - Calculate sampling fractions and correct for them
    - Implement clustering

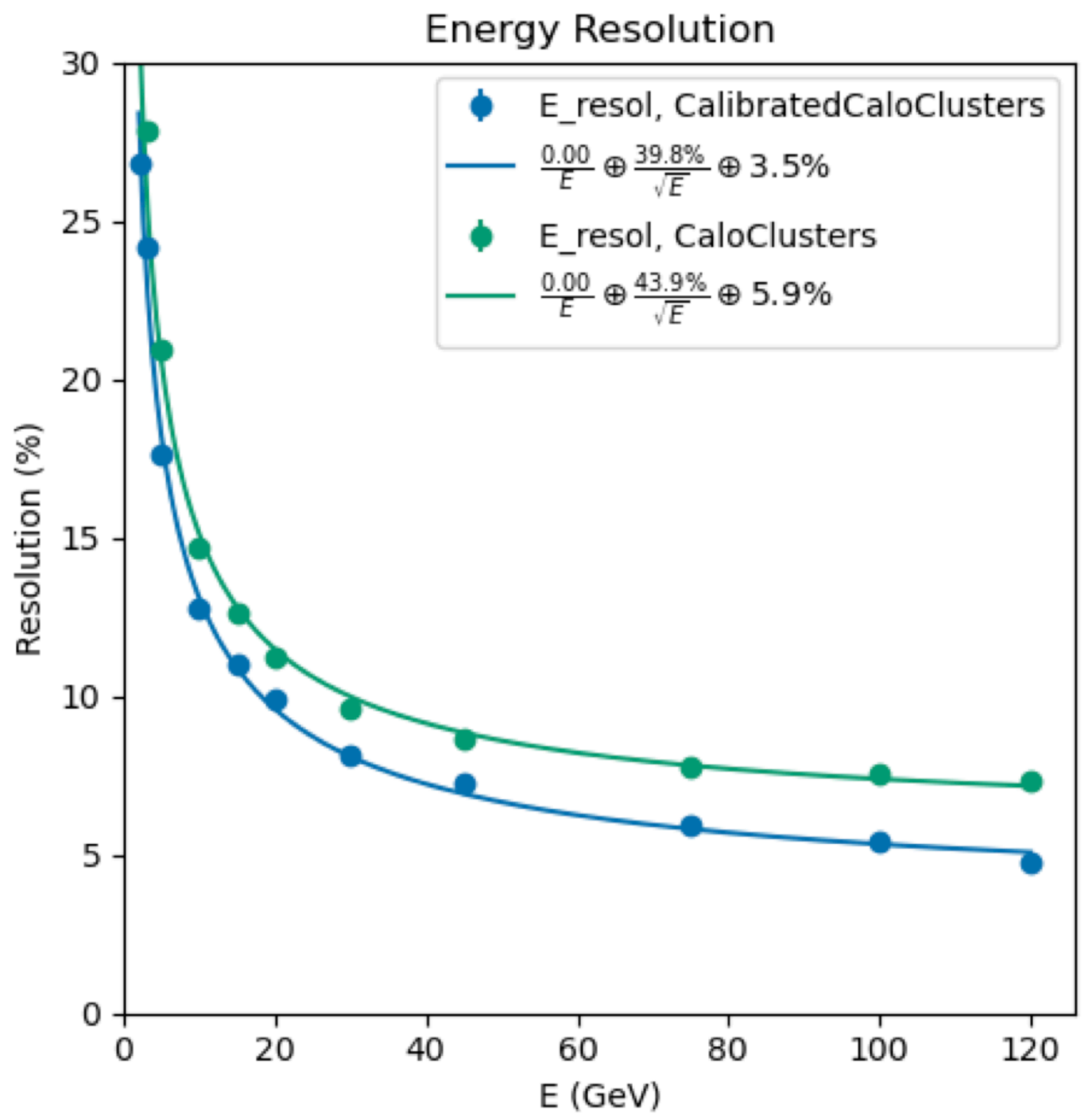
HCAL barrel

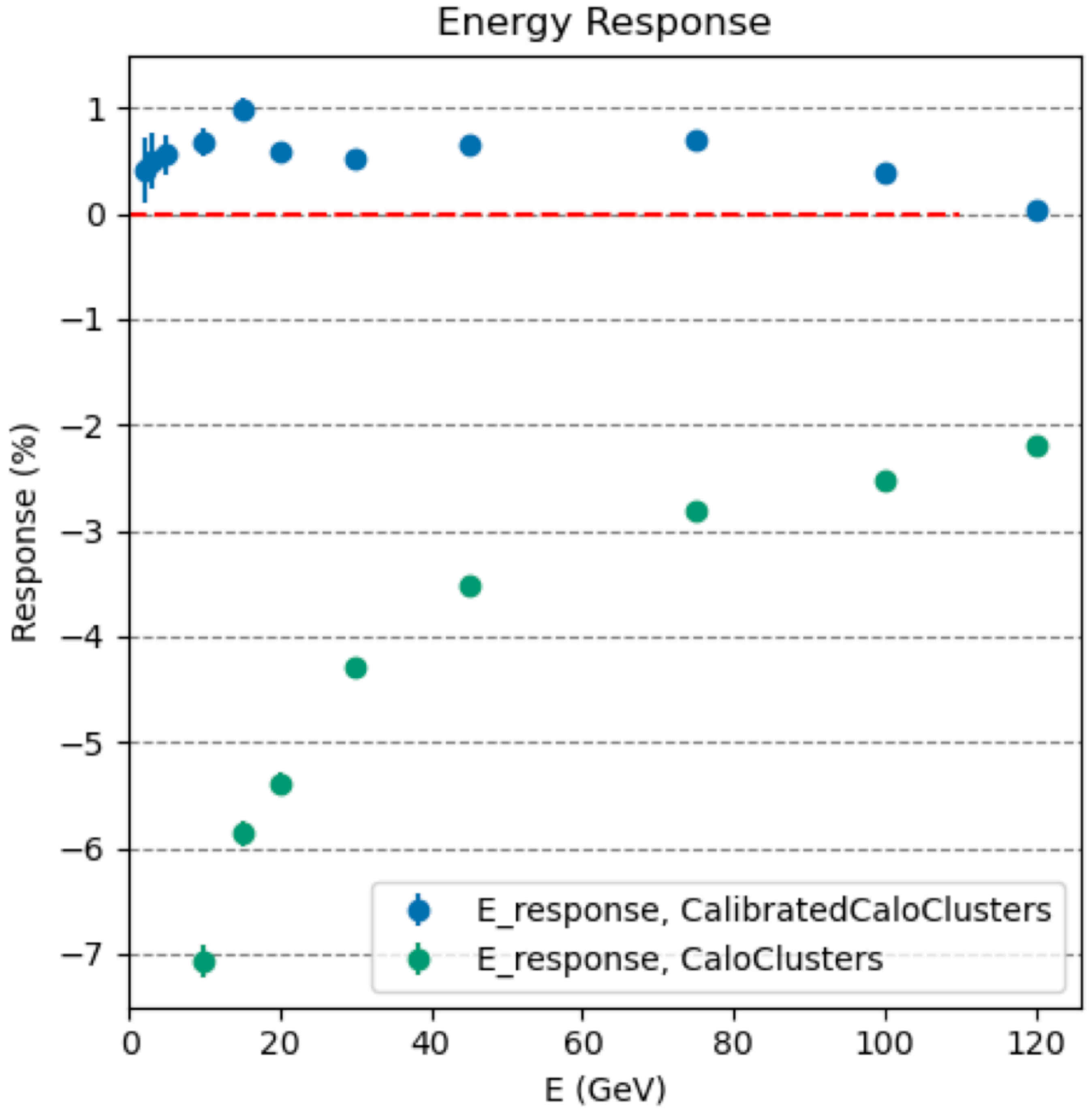
- Currently being simulated: TileCal-like design
  - 5mm steel absorber plates alternating with 3mm scintillator plates
  - 128 modules in ϕ, 2 tile/module → Δϕ = 0.025
  - Δθ ~ 0.022 (grouping 3-4 tiles),
  - 13 radial layers (4x5 cm, 6x10 cm, 3x20 cm)
  - Removed the Pb plates compared to FCC-hh design (HCAL acts as return yoke for the central solenoid)
  - FCC-ee TileCal geometry and segmentation is available in k4geo
  - Work ongoing on the geometry optimisation (different scintillating materials, different absorbers, and dimensions/segmentations - in progress, won't report about it today) and calibration



HCAL barrel simulation

- Inspired by similar previous work for the ECAL, Implemented MVA calibration of cluster energy, using boosted decision tree (XGBoost)
  - Inputs: total cluster energy $E_{cluster}$ and energy per layer over sum $E_i/E_{cluster}$
  - Targets $E_{true}/E_{cluster}$
  - Trained on 1M single π, flat energy distribution 100 MeV to 120 GeV
  - Tested on samples (10k each) of π of fixed energy starting from 2 GeV up to 120 GeV
  - Optimised BDT hyperparameters and event weights for training
  - Run over SW clusters
- Compared to cell-based approximate calibration using 100 GeV π
  - Constant term decreased from 5.9% to 3.5%
  - Big improvement in the energy response E_{reco}/E_{true} → within 1%

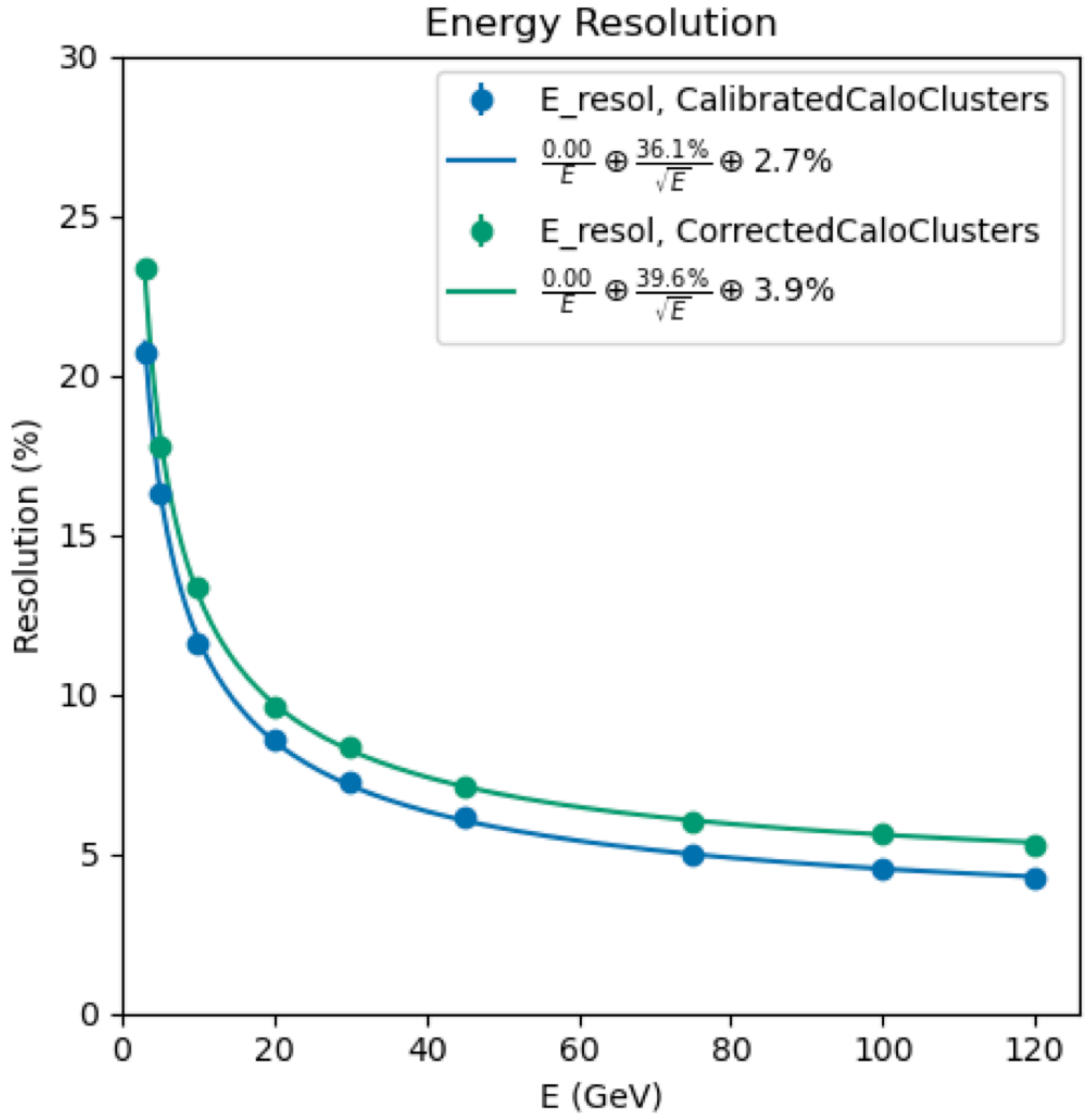


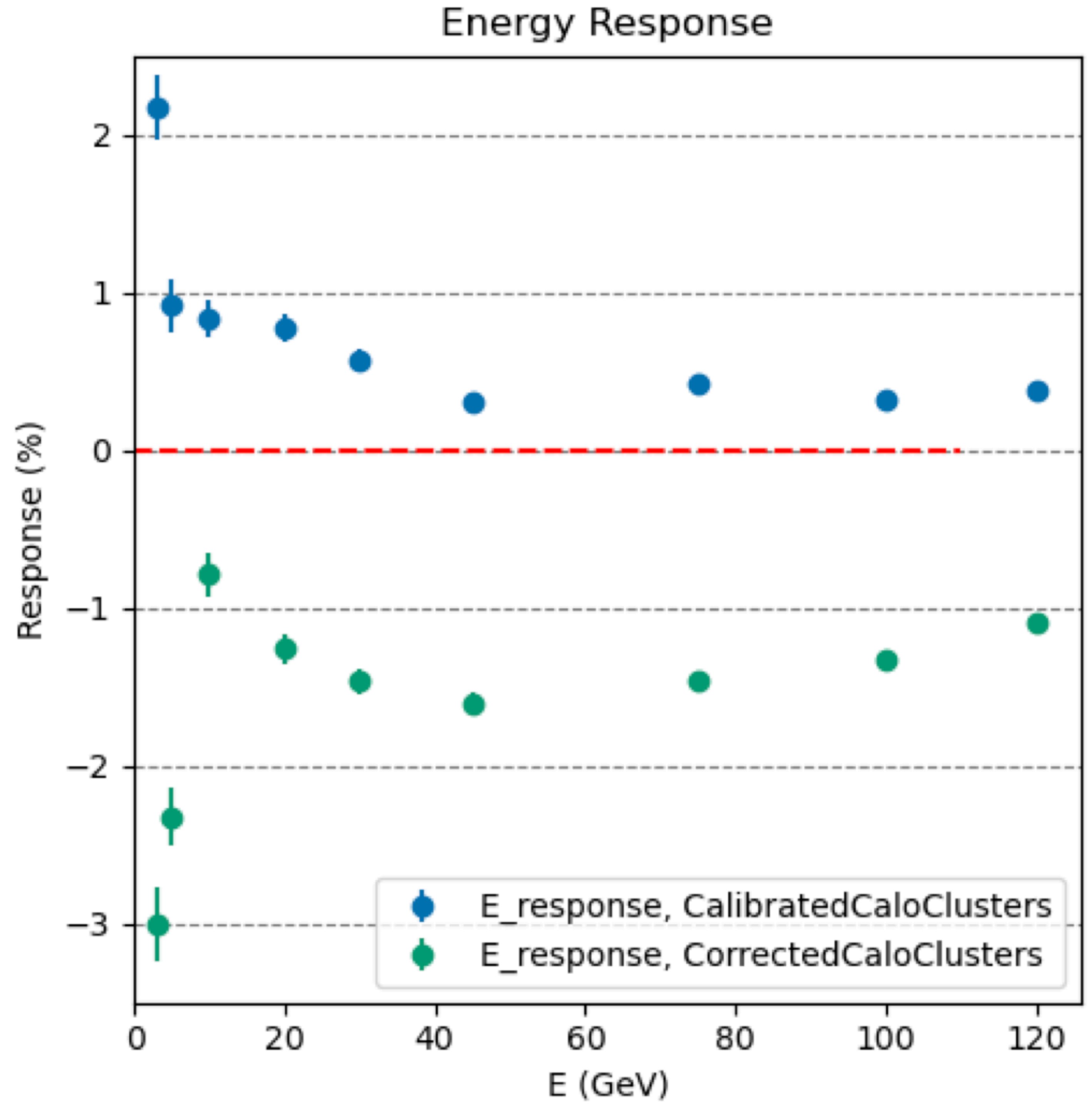


Putting things together

- Of course the goal is to combine the information from both calorimeters (and, later, with the tracker and do p-flow)
- Some work on calibration of ECAL+HCAL barrel SW clusters performed
  - Using **MVA calibration** (similar to HCAL standalone one of previous slide)
  - Using **cell-based calibration** developed for ATLAS test-beams and implemented in k4RecCalorimeter

$$E_{\text{rec}}^{\text{bench}} = p_0 \cdot E_{\text{EB}}^{\text{EM}} + p_1 \cdot E_{\text{HB}}^{\text{HAD}} + p_2 \sqrt{\left| p_0 \cdot E_{\text{EB}}^{\text{last layer}} \cdot E_{\text{HB}}^{\text{first layer}} \right|} + p_3 (p_0 \cdot E_{\text{EB}}^{\text{EM}})^2 + p_4 \cdot E_{\text{EB}}^{\text{first layer}}$$

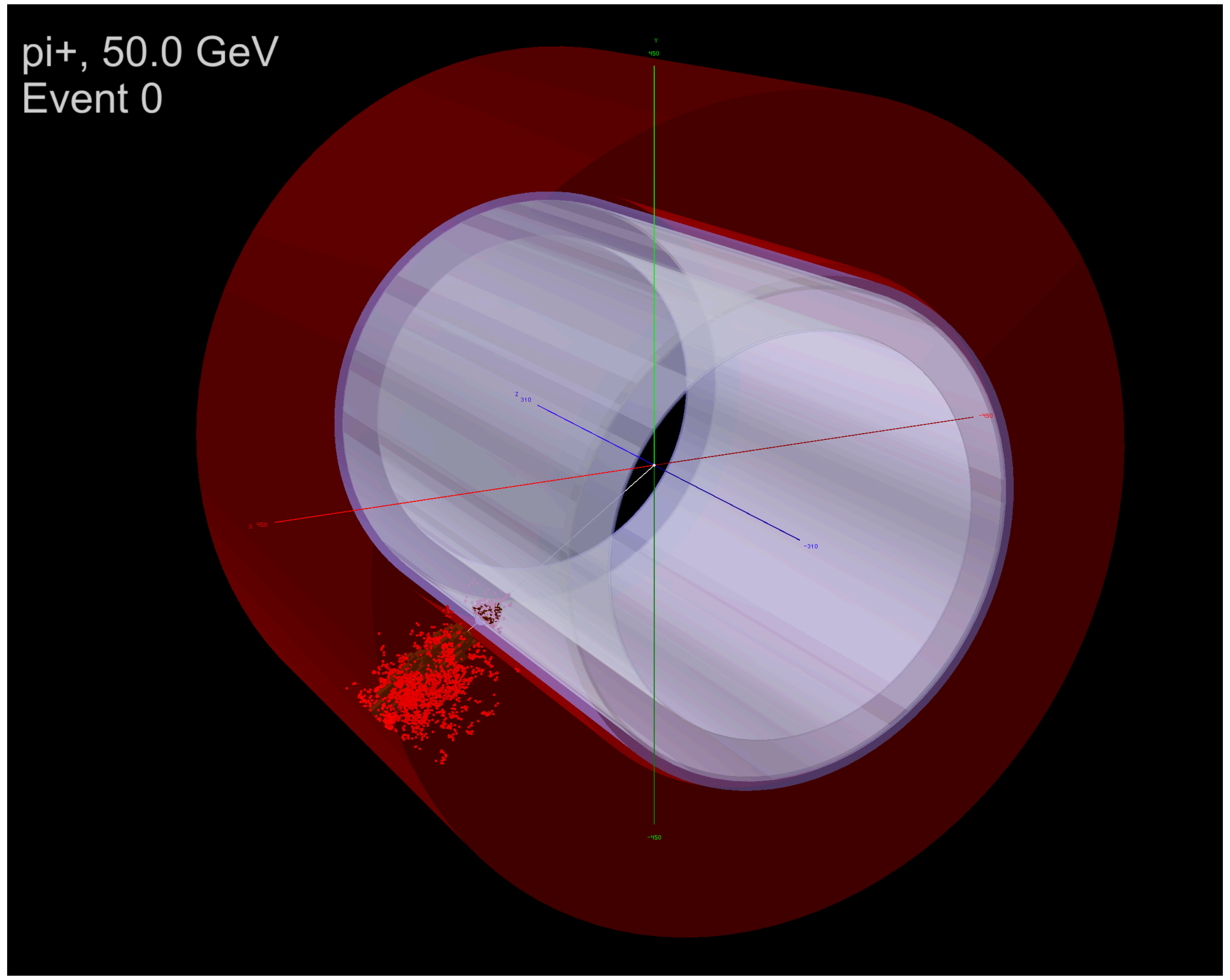


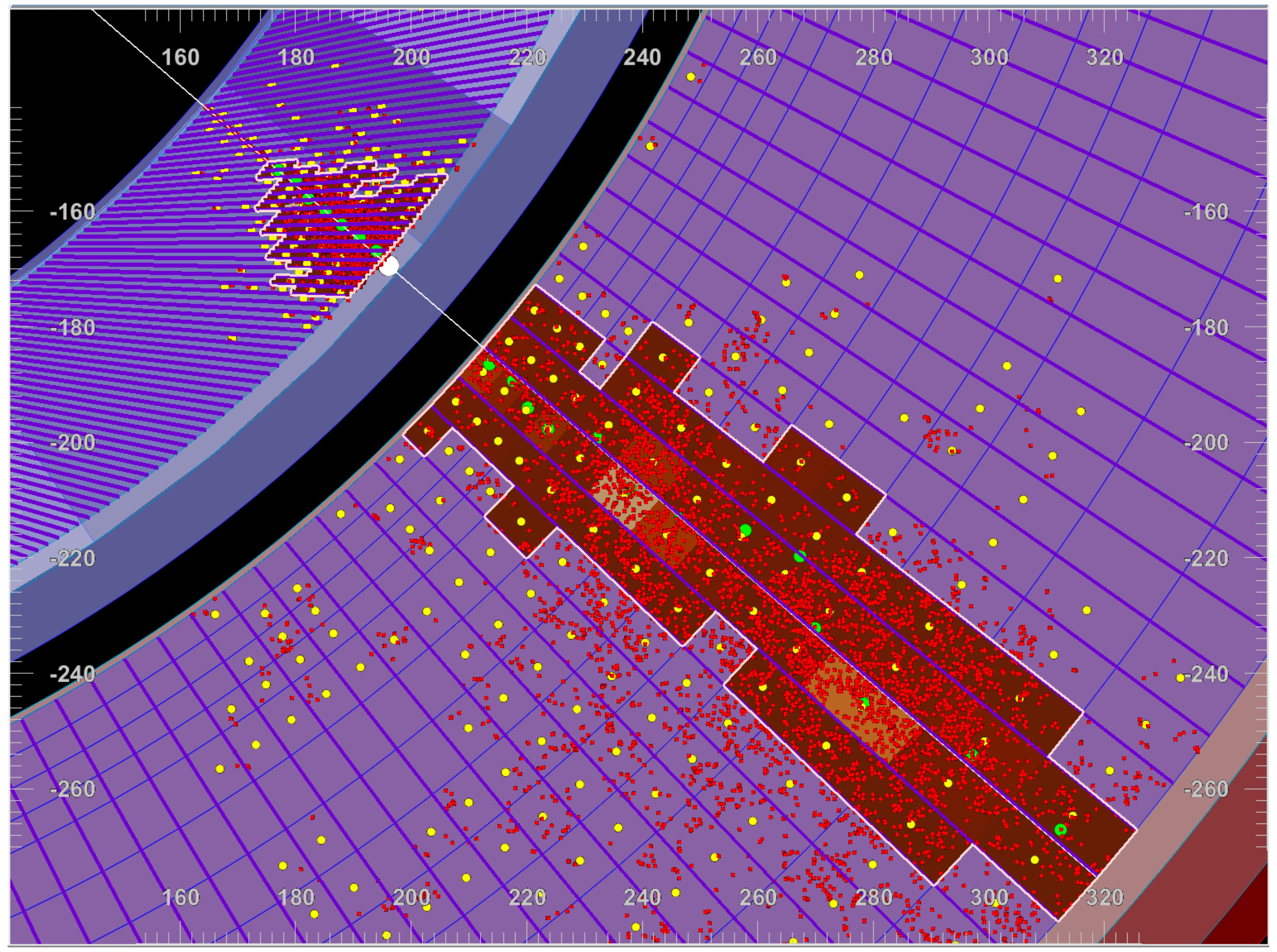


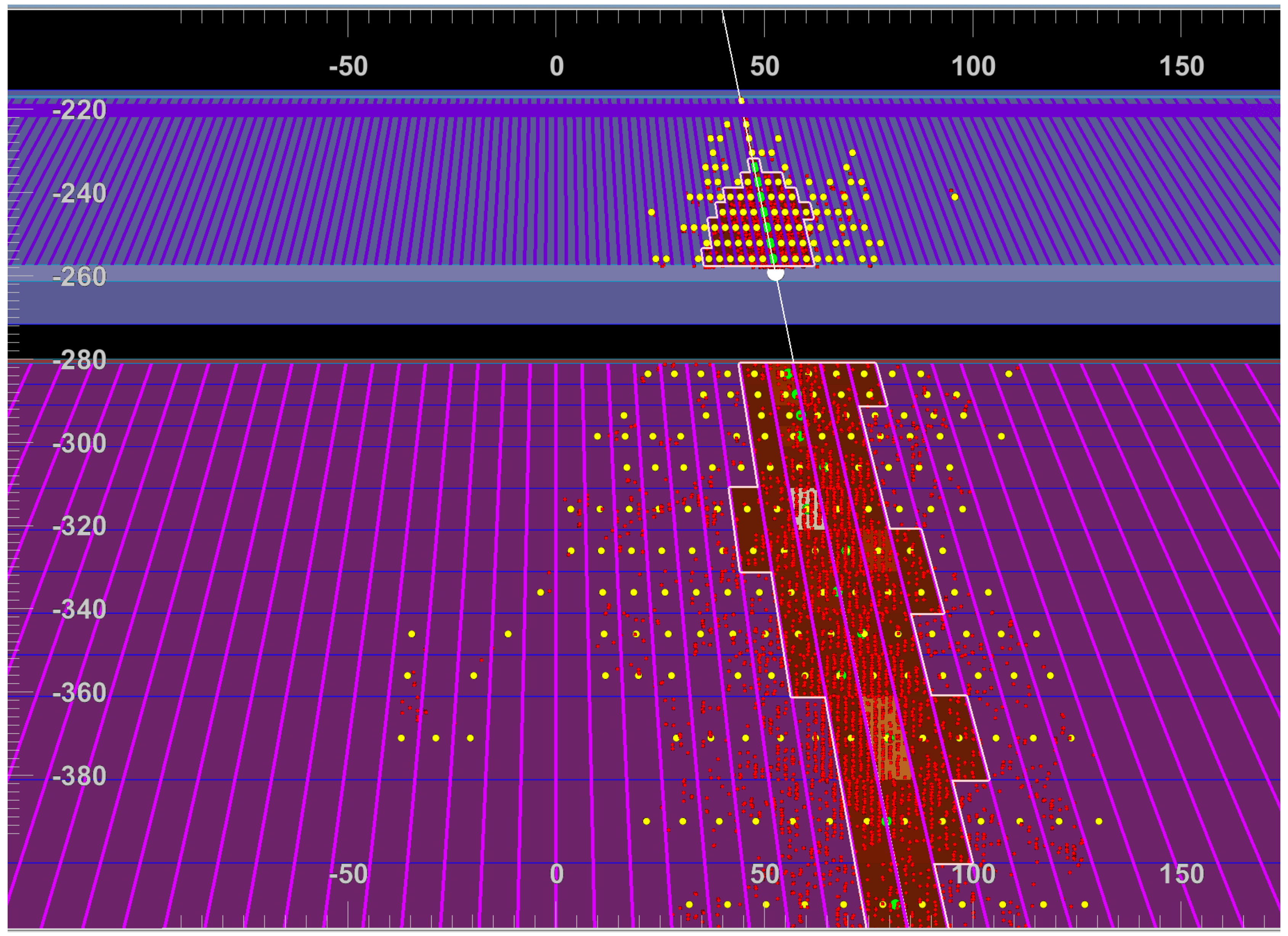
- Constant term decreased from 3.9% to 2.7%
- Energy response within 1% except @ 2 GeV
- Plan to investigate more advanced ML techniques in future

Putting things together

- In parallel, topological clustering for ECAL+HCAL barrel has recently been implemented (PR #1 #2, in review)
  - Basically requires to find out neighbouring relations among cells of outermost layer of ECAL and innermost layer of HCAL
  - As topological clustering selects cells based on their E/noise ratio, expected noise per cell is needed
    - Use most recent noise calculations/simulations for ECAL barrel (script)
    - Use constant noise ~30 MeV for HCAL barrel (can be updated if more realistic estimates are available)







Conclusion

- **Good progress in past year on full simulation of ALLEGRO calorimeters**
    - ECAL endcap simulation coming along
    - Initial version of ECAL+HCAL (barrel) clustering implemented
- **HCAL endcap model also available, to be revamped/included in reconstruction**
- **Plan to make simulation even more realistic including eg noise and x-talk**
- **Calorimeter simulation getting mature enough for studying physics performance and optimise detector design,** e.g.
    - energy and direction resolution
    - particle ID (eg γ vs π^0)
    - optimisation for p-flow reconstruction (possible also thanks to inclusion of other ALLEGRO subdetectors in full simulation)