# Noble Liquid Calorimetry for FCC: ALLEGRO Detector

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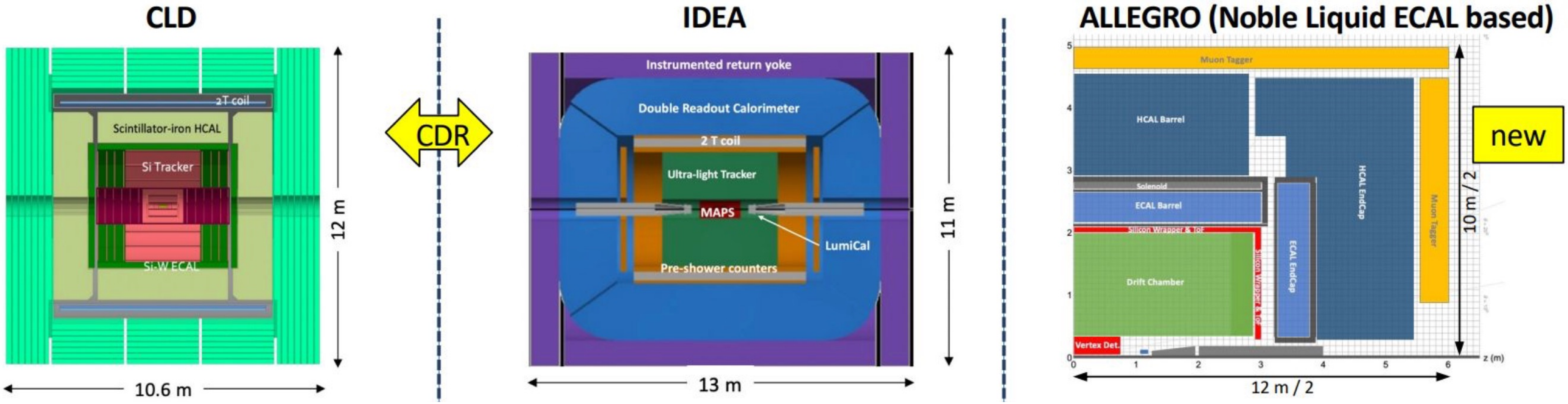
# ALLEGRO detector concept

- ➢ ALLEGRO = A Lepton coLlider Experiment with Granular calorimetry Read-Out
- A Noble-Liquid ECAL Based, general-purpose detector concept for FCC-ee
    - Highly-granular Noble-Liquid ECAL as a central and most studied feature
- Vertex detector, drift chamber and ECAL inside 2 T solenoid, sharing cryostat
- HCAL and Muon System outside the solenoid
- ✓ Optimized for full FCC-ee physics program



# ALLEGRO detector concept

- Vertex Detector:

- MAPS or DMAPS possibly with timing layer (LGAD)

- Drift Chamber (± 2.5 m active)
- Silicon Wrapper + ToF:

- MAPS or DMAPS possibly with timing layer (LGAD)

- Solenoid B = 2T, sharing cryostat with ECAL
- High Granularity ECAL:

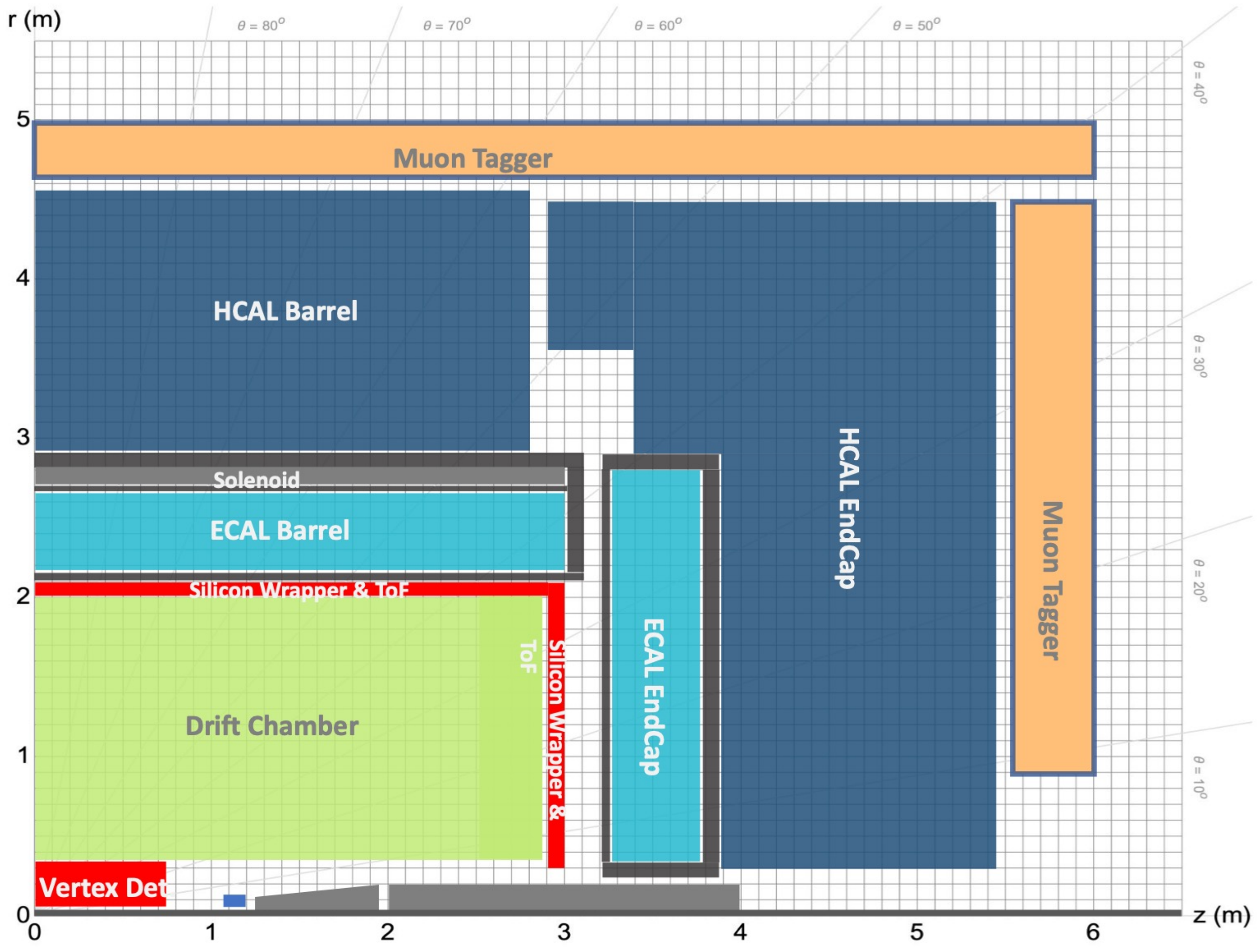
- Noble liquid + Pb or W
- Multi-layer PCB as read-out electrode

- High Granularity HCAL / Iron Yoke:

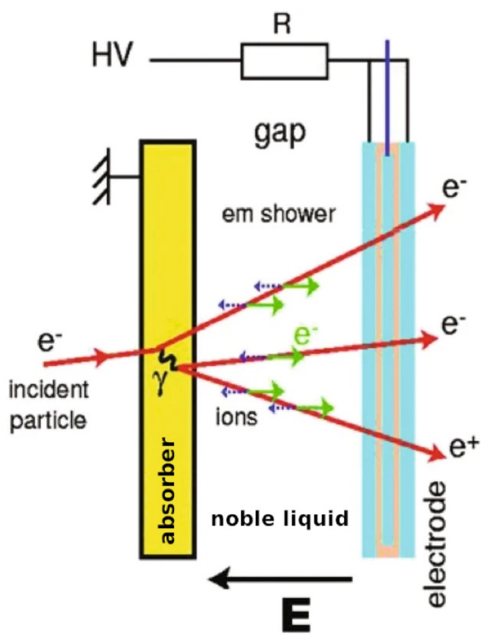
- Scintillator + Iron
- SiPMs directly on Scintillator or
- TileCal: WS fibres, SiPMs outside

- Muon Tagger:

- Drift chambers, RPC, MicroMegas



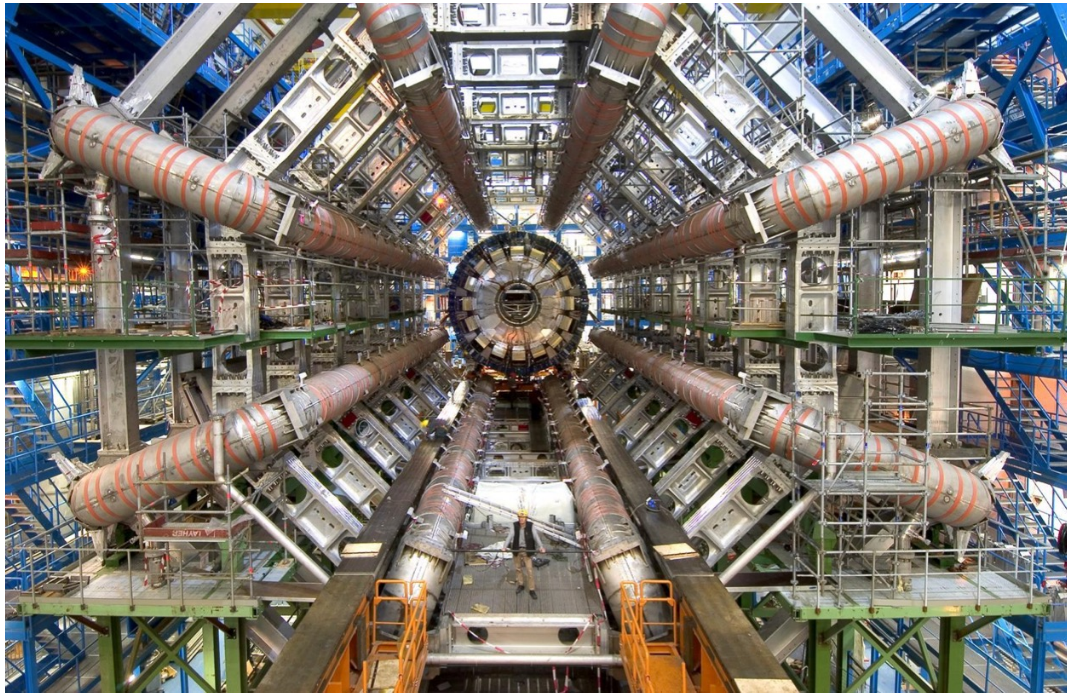
# Noble Liquid Calorimeters




- Sampling calorimetry relying on ionization of liquefied noble gas: based on alternating layers of absorbers, noble liquid and read-out electrodes
  - Voltage applied over noble-liquid gap
  - Incident particle ionizes noble liquid
  - $e^-$ (and ions) drift to electrodes and induce current signal

- Successful in many HEP experiments
  - MarkII, DØ, H1, NA48/62, ATLAS

- An appealing option for FCC-ee
  - Good energy resolution
  - High(-ish) granularity achievable
  - Linearity, uniformity, long-term stability
  - Easy to calibrate
  - ➢ Excellent solution for small systematics

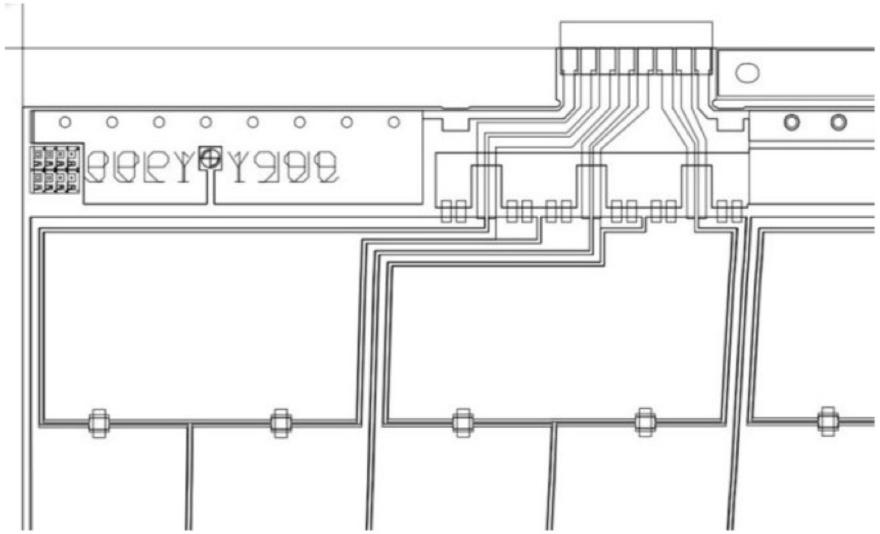


# Granularity of Noble Liquid Calorimeters

- Calorimeter design:
- Granularity of the calorimeter ⇔ granularity of the electrodes

- ATLAS: copper / kapton electrode
- Traces to read out middle cells take real estate on back layer
- Cannot really increase granularity

- FCC-ee requirements
- High jet energy resolution needed
- Particle flow algorithms take advantage of much finer granularity



✓ Solution for Noble Liquid calo for FCC
  - Multi-layer PCB to route signals inside

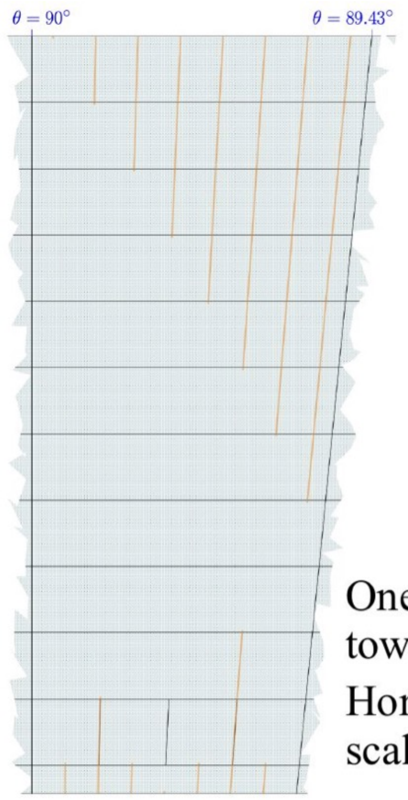
# How to achieve high granularity?

- Aiming for ~ ×10 ATLAS granularity
  - High granularity required for better PFlow performance
  - > 6 compartments to compensate LAr gap widening

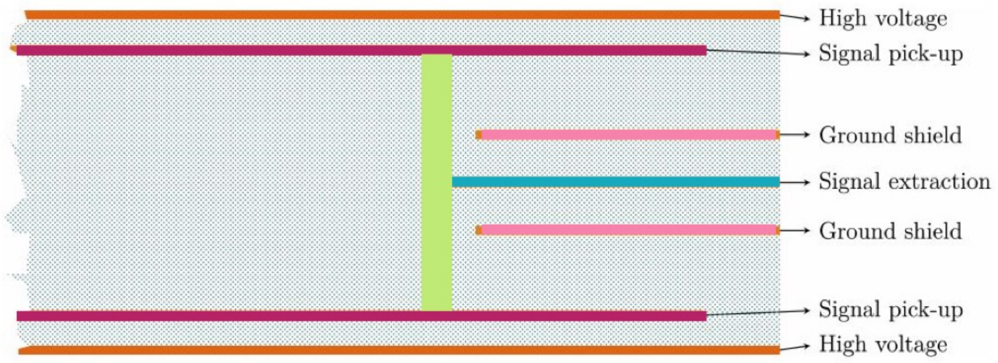
- Implementation of multi-layer PCBs (7 layers):
  - Signal collection on readout planes
  - Transmission through via
  - Signal extraction on trace
  - Ground shields to mitigate cross-talk

- Challenges
  - Trade-off capacitance (noise) / cross-talk
  - Maximum density of signal traces?

➢ Studies on simulations and prototypes

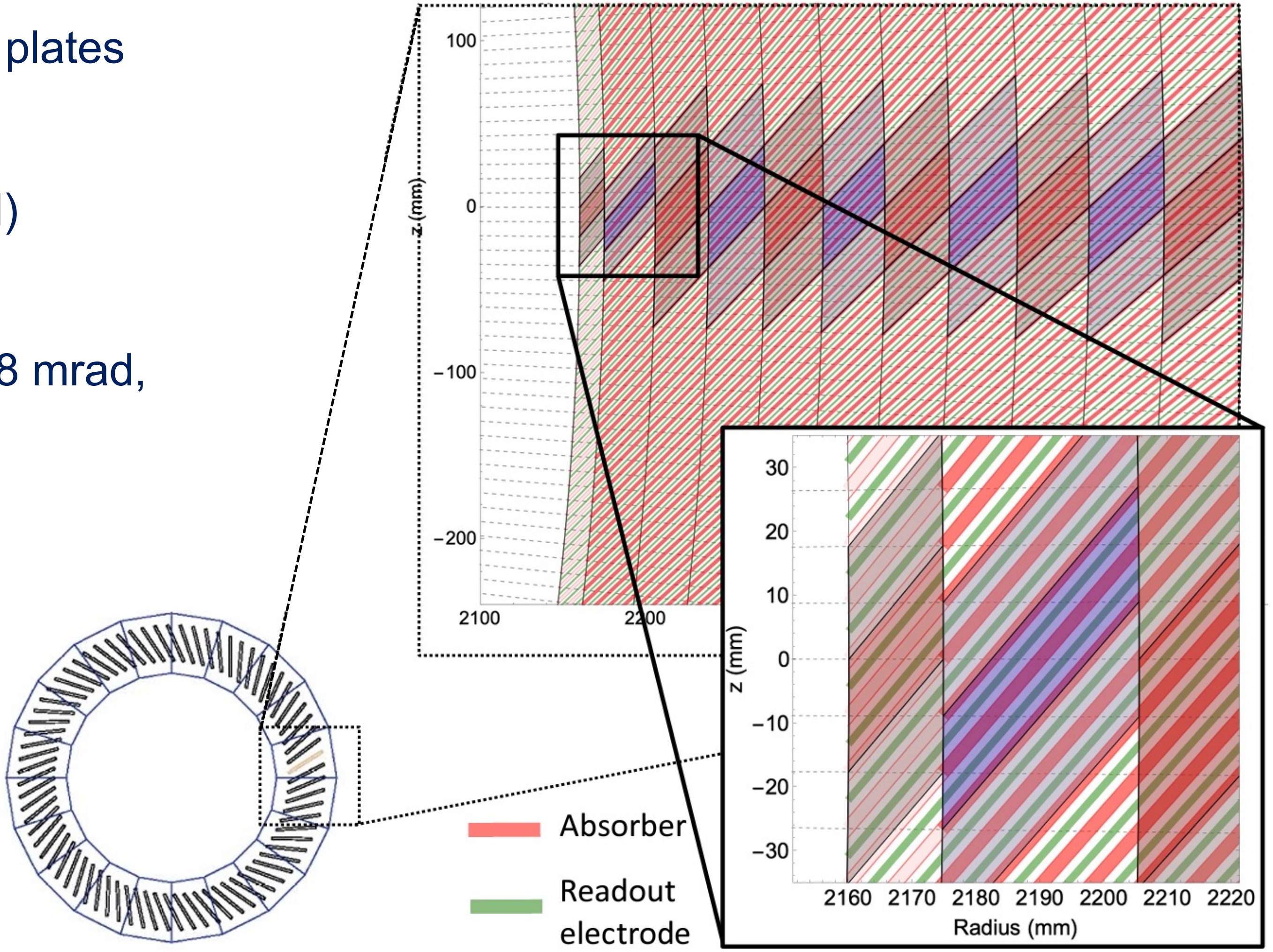



One theta tower
Horizontal axis scale 10:1



# ALLEGRO ECAL barrel design

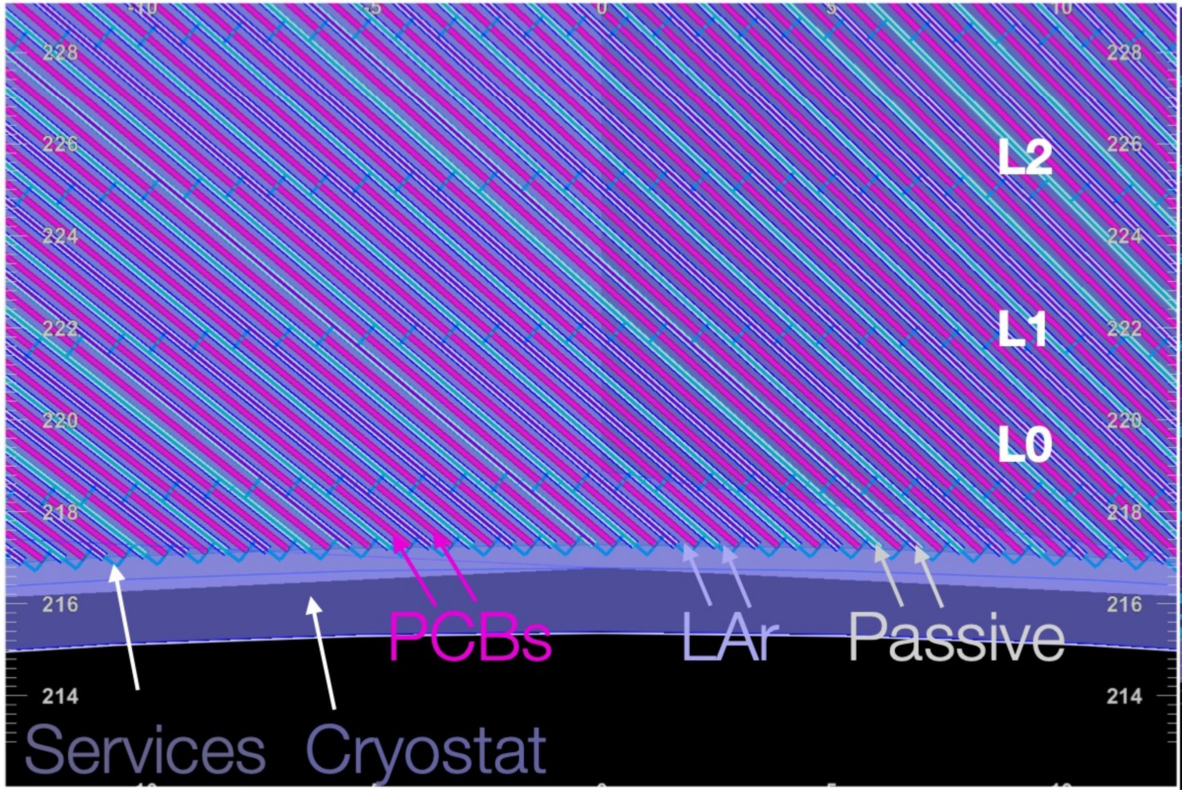
- Design driven by the solution used for electrodes
- 1536 straight inclined (50°) 1.8 mm Pb absorber plates
- Multi-layer PCBs as readout electrodes
- 1.2 - 2.4 mm LAr gaps (LKr seriously considered)
- 40 cm deep (22 $X_0$)
- $\Delta\theta$ = 10 (2.5) mrad for regular (strip) cells, $\Delta\phi$ = 8 mrad, 11 longitudinal layers



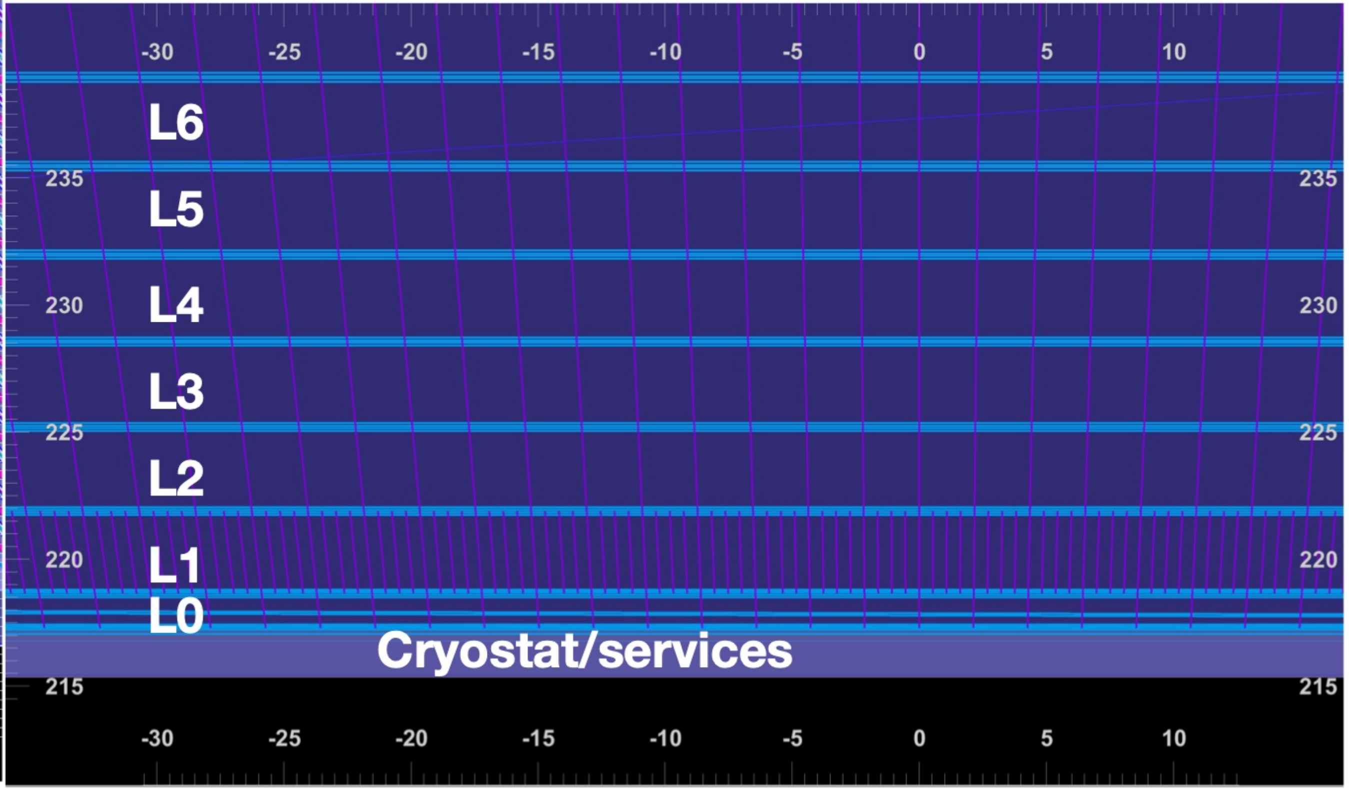

- Copper electrodes: lots of flexibility
- Number of layers and granularity of layers fully optimizable
- Projective cells

➢ Lots of room for optimization!

# ECAL barrel simulation

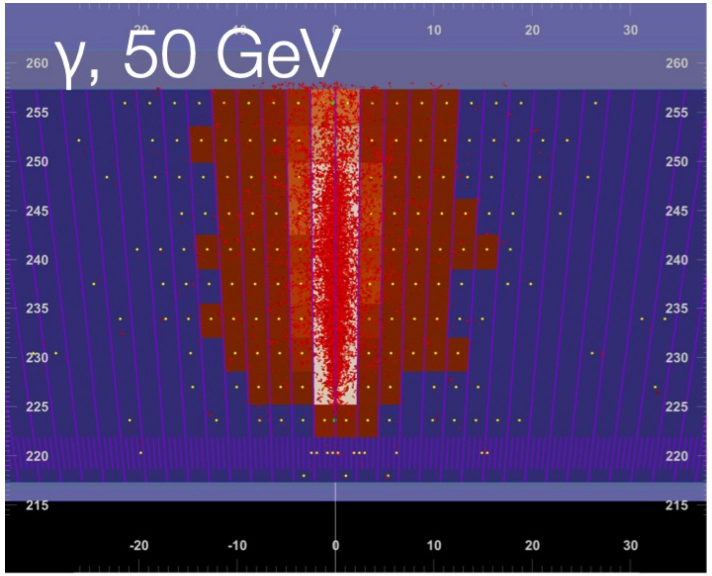


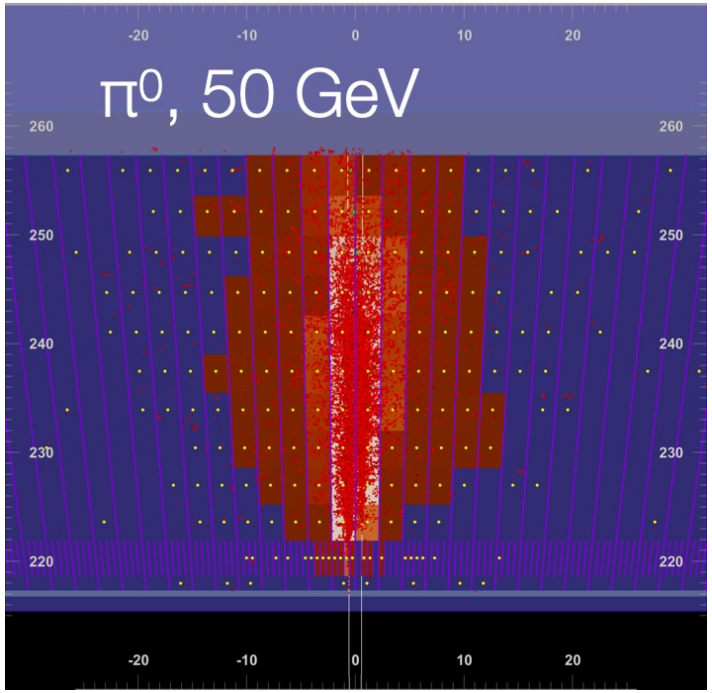

Geant4 geometry (r-ϕ)

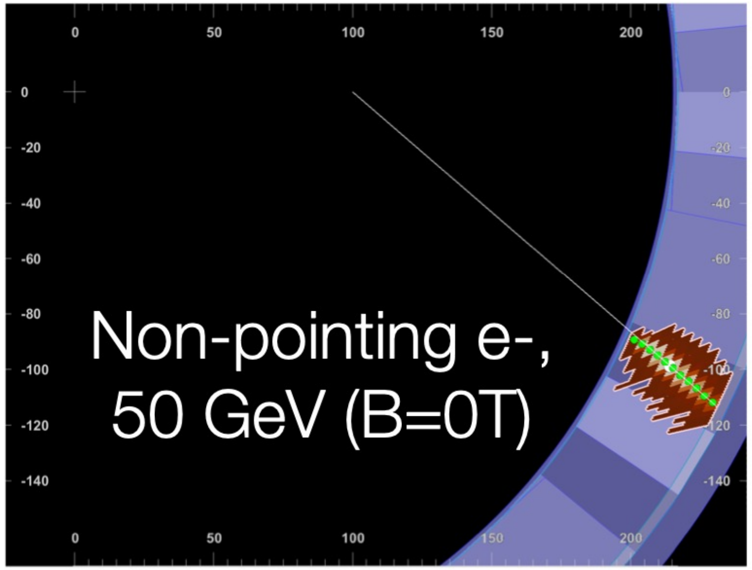


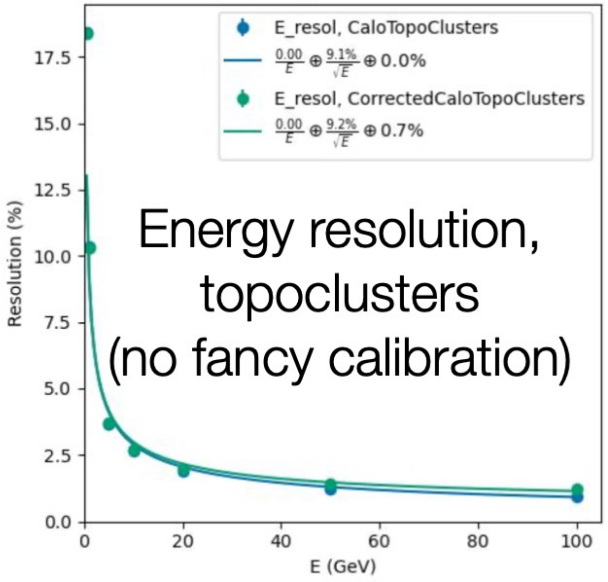

θ segmentation (r-z)

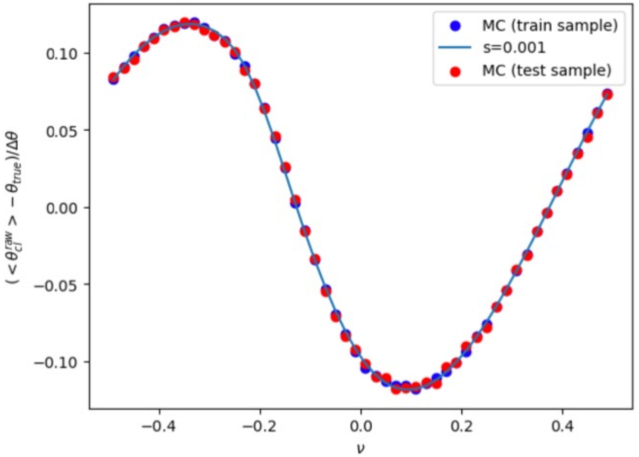
# ECAL barrel simulation

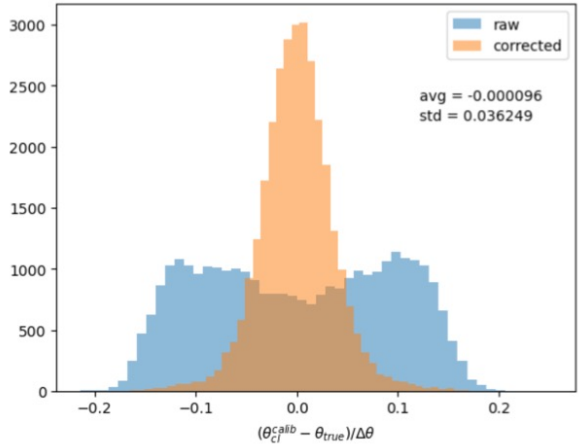


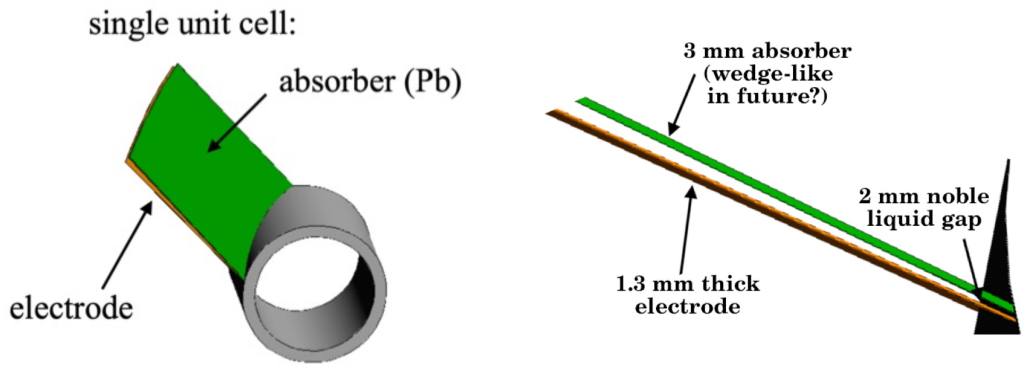




Position/direction reconstruction: S-curve
θ correction and resolution

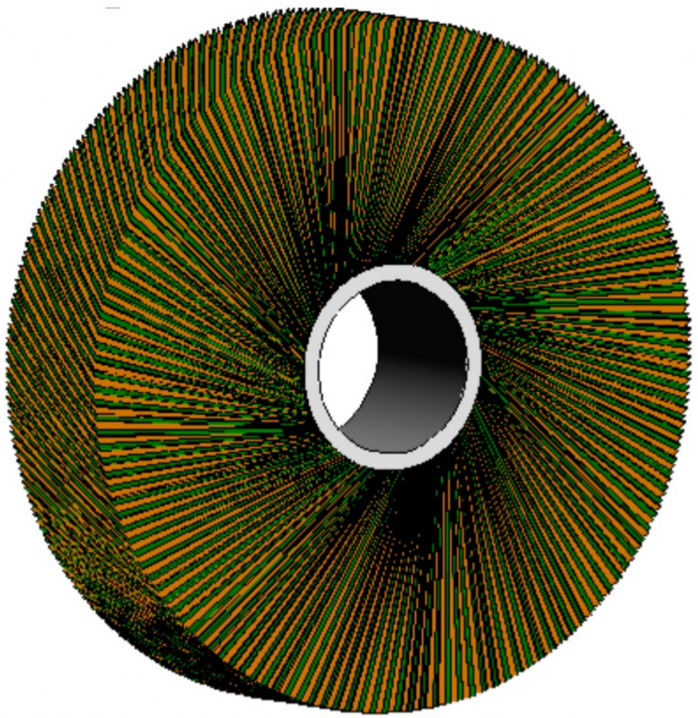
# ALLEGRO ECAL endcap design

- 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")




- Similar to barrel design, with many thin absorber plates
- Symmetric in $\phi$
- Readout from high-|z| face

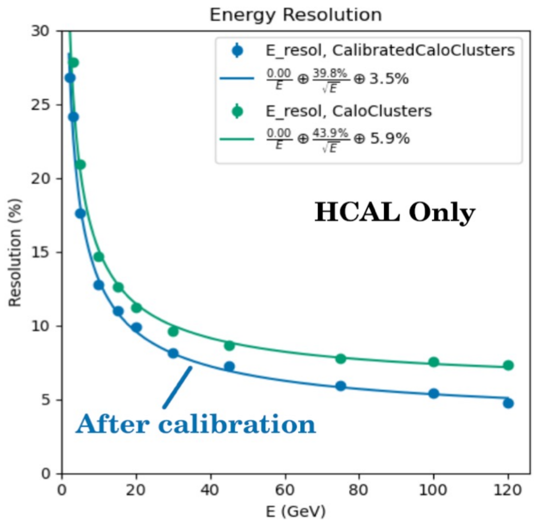


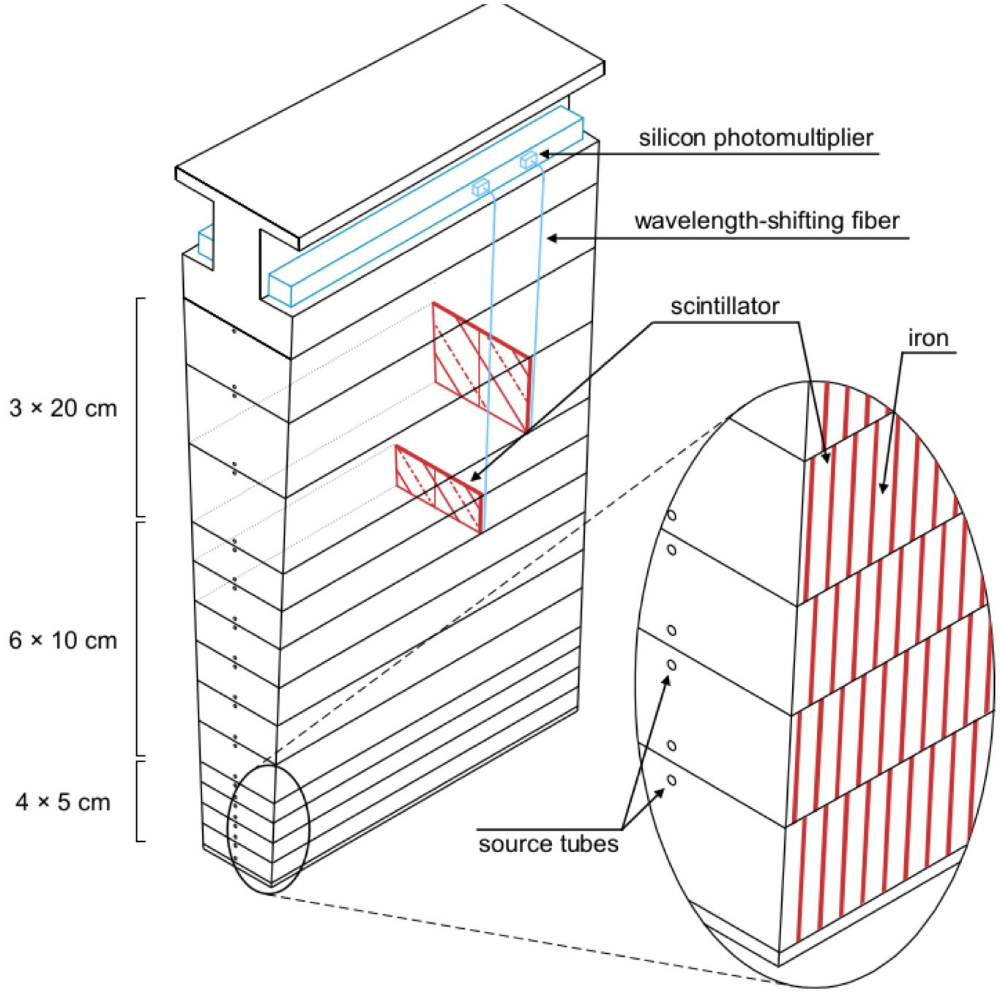
- Issue: increase in the size of the LAr gaps
  - Mitigated stacking several cylinders

# ALLEGRO HCAL design

- HCAL design based on alternating steel and scintillator layers
- Well studied and tested design (similar to ATLAS TileCal)
- 5 mm steel absorber plates alternating with 3 mm scintillator plates

- 13 radial layers (4 x 5 cm, 6 x 10 cm, 3 x 20 cm)
- 128 modules in φ, 2 tiles per module → Δφ = 0.025
- Δθ ~ 0.022 (grouping 3 - 4 tiles)
- Also acts as return yoke for solenoid
- Geometry optimization & calibration studies ongoing



# HCAL simulation

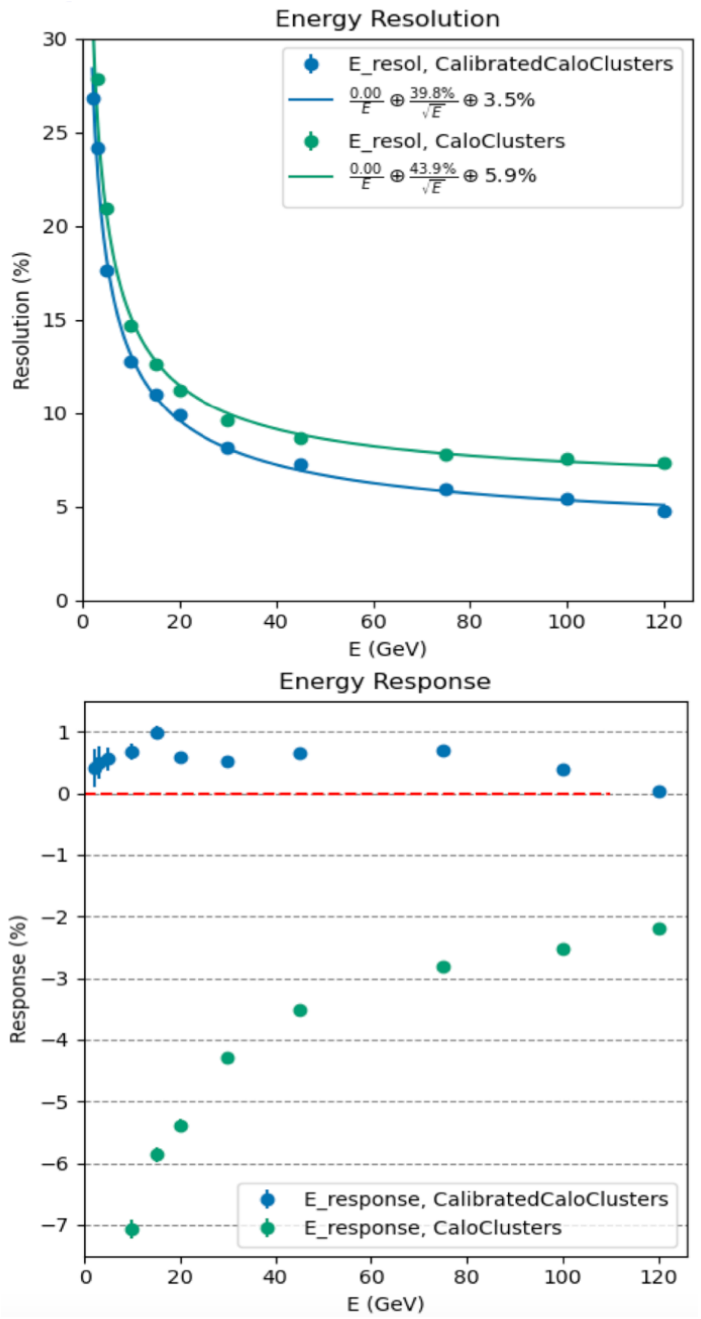
- Implemented MVA calibration of cluster energy, using BDT

- Inputs:

  Total cluster energy $E_{cluster}$ and energy per layer over sum $E_i$ / $E_{cluster}$
- Targets $E_{true}$ / $E_{cluster}$

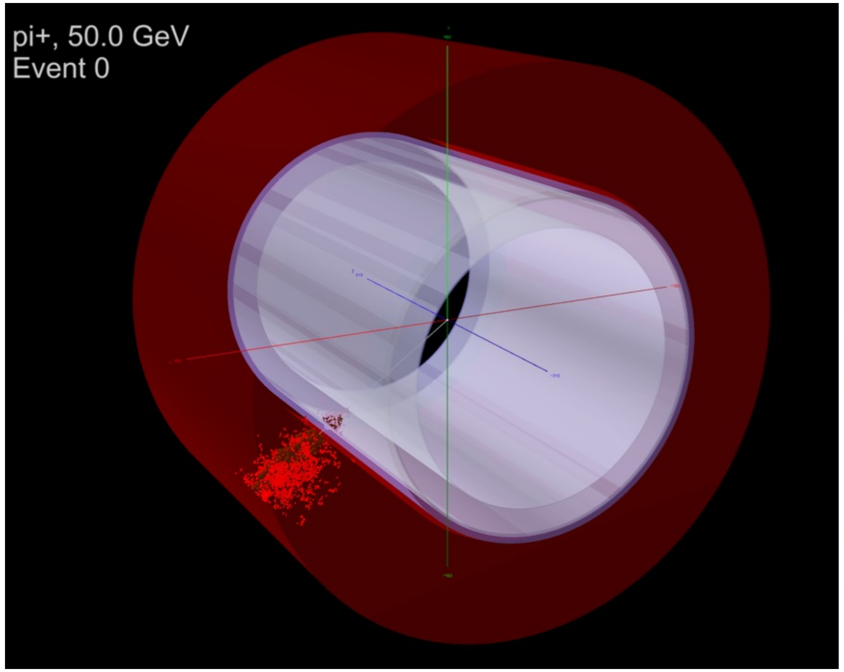
- Trained on 1M single π, flat energy distribution 100 MeV to 120 GeV
- Compared to cell-based approximate calibration using 100 GeV π

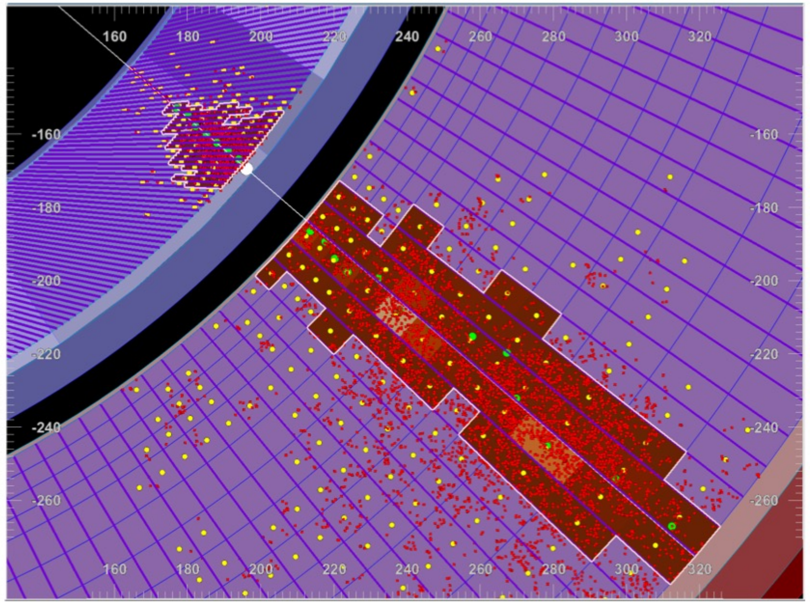
- Constant term decreased from 5.9 % to 3.5 %
- Big improvement in the energy response $E_{reco}$ / $E_{true}$ → within 1 %

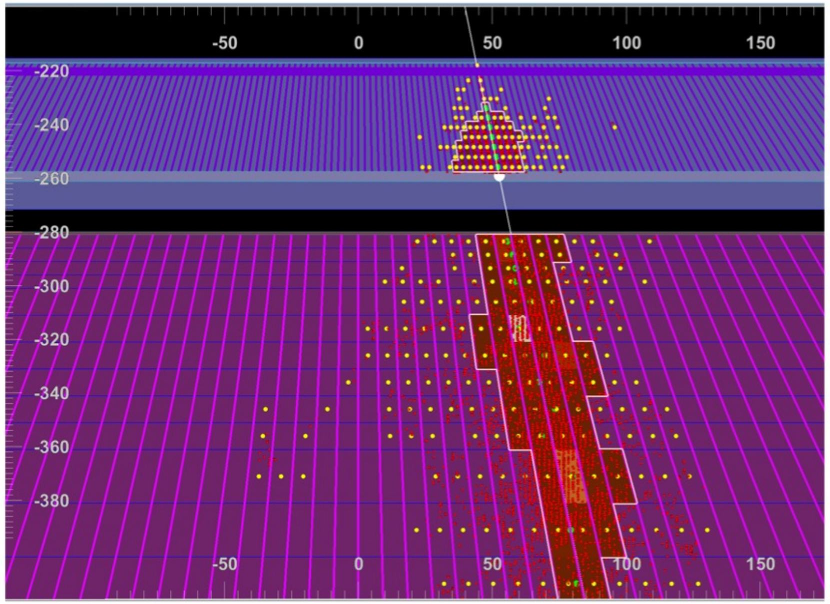


# ECAL + HCAL simulation

- Clustering for ECAL + HCAL barrel has been implemented in ALLEGRO simulation





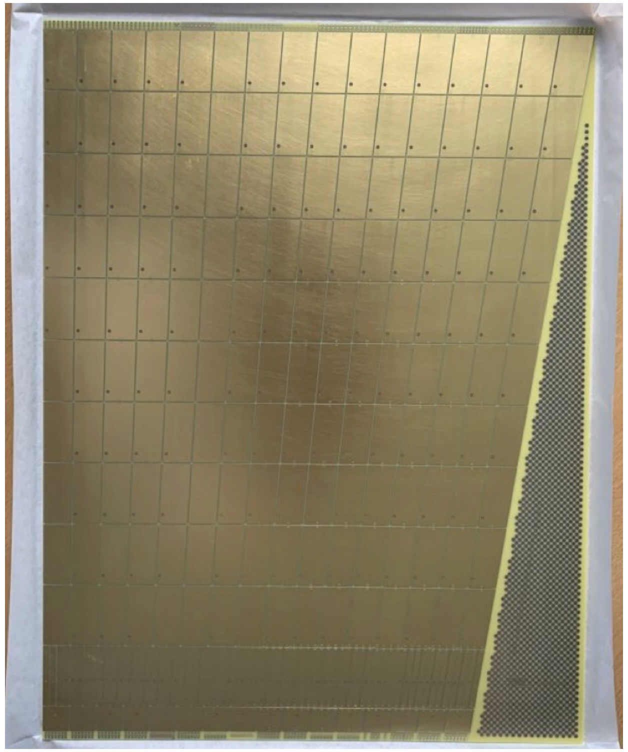
# Electrodes prototypes

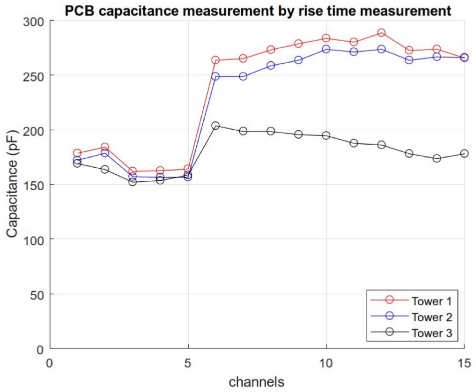
➢ Explore tradeoffs between max granularity / capacitance (noise) / cross-talk

- First large-scale prototype at CERN *
- Explore many options for grounding, for shields
- First-layer readout at the front
- Few per-mille cross-talk achievable with long shaping

- Next prototype at IJCLab **
- All layers readout at the back
  - Best for material budget, worse for noise and cross-talk
- Use of connectors for easier measurements
- Development of system for automated measurements

*



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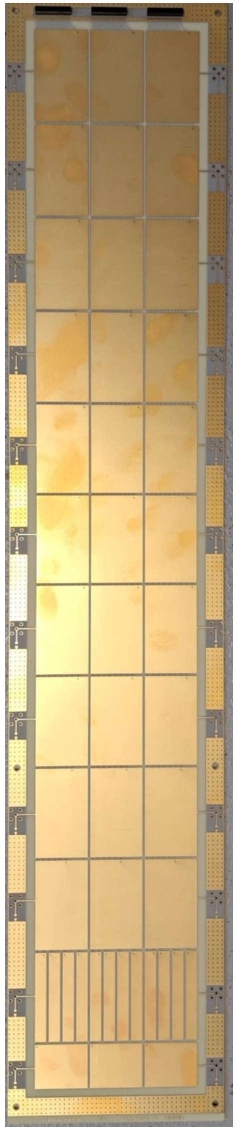
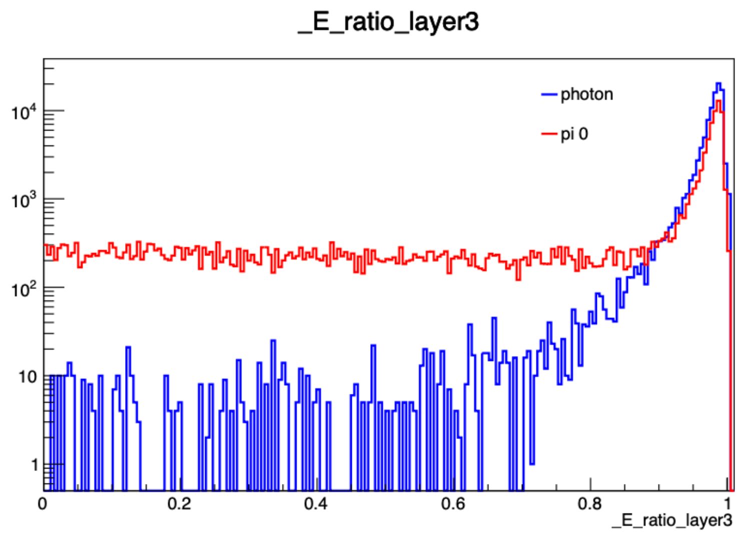


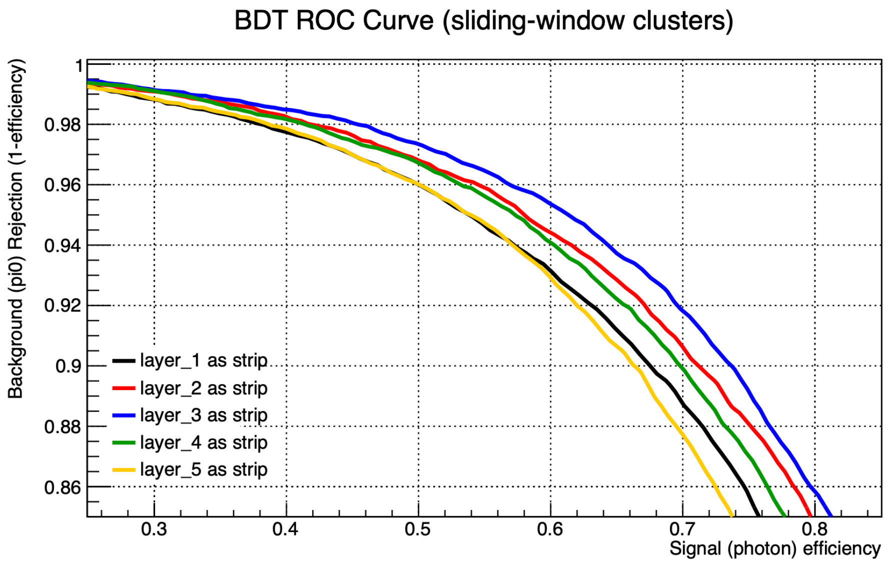
# Particle ID: $\gamma$ vs. $\pi^0$

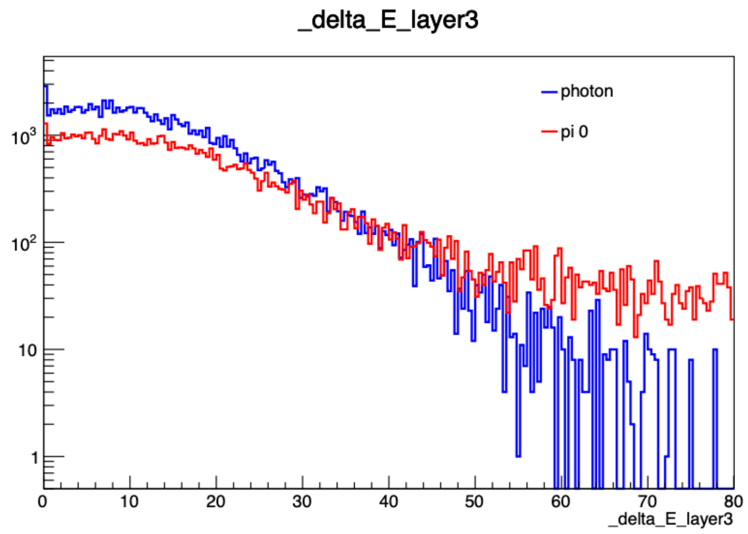
- Good performance of $\gamma$ vs. $\pi^0$ separation plays an important role in physics analysis

- A list of variables related to shower shapes calculated
- BDT trained as a start point, will implement NN as well

- Also considering a shift of the strip layer:
  - which layer is better / the best ?



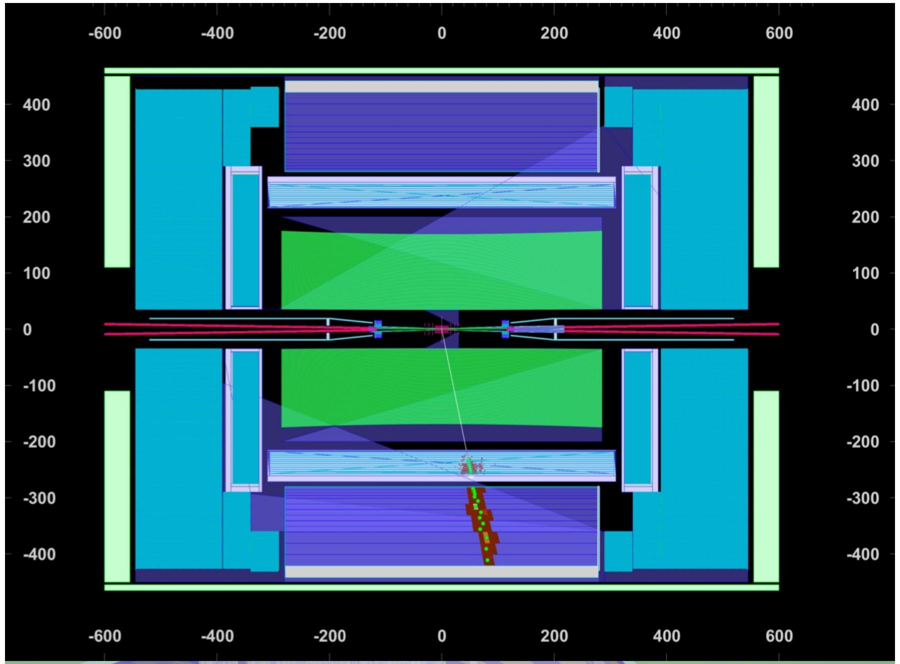
# Conclusions & Outlook

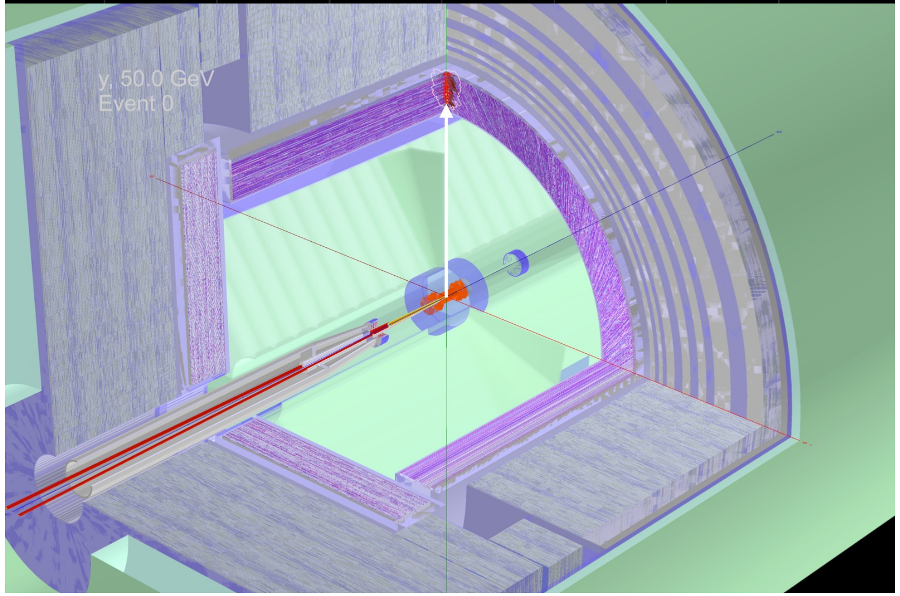
- ALLEGRO is a general-purpose FCC-ee detector concept
  - Now main activity on the calorimetry, magnet & cryostat
- High-granularity Noble-Liquid ECAL with multi-layer PCB
  - Good option for future $e^+ e^-$ experiments

- The project is progressing fast
  - Active and motivated group
  - Progress on all fronts: simulation, electrodes, mechanics
- New prototype PCB to be produced by summer 2024
- Planning for a test-beam module in 2028

➢ Materials taken from Ref_1, Ref_2, Ref_3

➢ ALLEGRO webpage online:
  - https://allegro.web.cern.ch



# Back Up