The ALLEGRO detector concept and its full simulation

Giovanni Marchiori (APC-Paris CNRS/IN2P3)
On behalf of, and with many thanks to, many colleagues working on ALLEGRO

8th FCC Physics workshop (CERN, January 2025)

The origin of ALLEGRO

- **2015**: start to think of noble-liquid EM calorimeter for future experiments
  - became part of FCC-hh reference detector (CDR in 2019, input for ESPPU2020)
- **2021**: after ESPPU, focus shifted to FCC-ee: noble-liquid ECAL concept adapted to lepton collider experiment, performance studies showed that it is very competitive compared to other proposals (Si/W, dual read-out)
  - Noble-liquid calorimetry became work-package inside CERN EP R&D and later part of DRD6 as WP2
- **2022**: proposed a detector concept based on noble-liquid ECAL and some "reasonable" choices for other sub-detectors
- **2023**: more teams joined, survey to find a name → **ALLEGRO** (**A L**epton **L**epton collider **E**xperiment with **G**ranular **R**ead-**O**ut) was born
  - ALLEGRO website launched soon after: https://allegro.web.cern.ch/
  - ALLEGRO logo contest

ALLEGRO

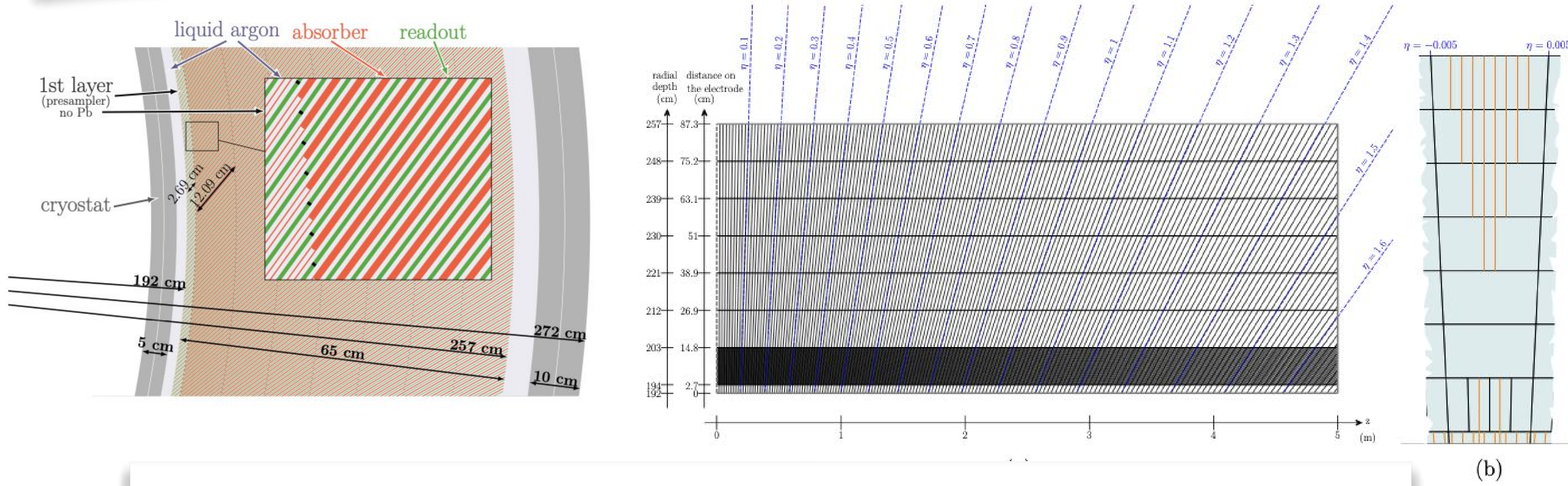
CERN-FCC-PHYS-2019-0003

23 December 2019

20 Dec 2019

Calorimeters for the FCC-hh

M. Aleksa[1], P. Allport[2], R. Bosley[2], J. Faltova[1,3], J. Gentil[4], R. Goncalo[4,5], C. Helsens[1], A. Henriques[1], A. Karyukhin[6], J. Kieseler[1], C. Neubüser[1], H. F. Pais Da Silva[1,4], T. Price[2], J. Schliwinski[7], M. Selvaggi[1], O. Solovyanov[1,8], R. Stein[9], N. Topiline[6], N. K. Watson[2], A. Winter[2], and A. Zaborowska[1]



Calorimetry at FCC-ee

Martin Aleksa[1], Franco Bedeschi[2], Roberto Ferrari[3], Felix Sefkow[4], and Christopher G. Tully[5]

[1] CERN, EP Department, Geneva, Switzerland
[2] INFN, Sezione di Pisa, Italy
[3] INFN, Sezione di Pavia, Italy
[4] Deutsches Elektronen-Synchrotron (DESY), Hamburg, Germany
[5] Princeton University, Department of Physics, Princeton, NJ, United States

Received: September 2, 2021/ Revised version: September 2, 2021

allegro

noun [C] • MUSIC • specialized

UK /əˈleg.rəʊ/ US /əˈleg.roʊ/

plural **allegros**

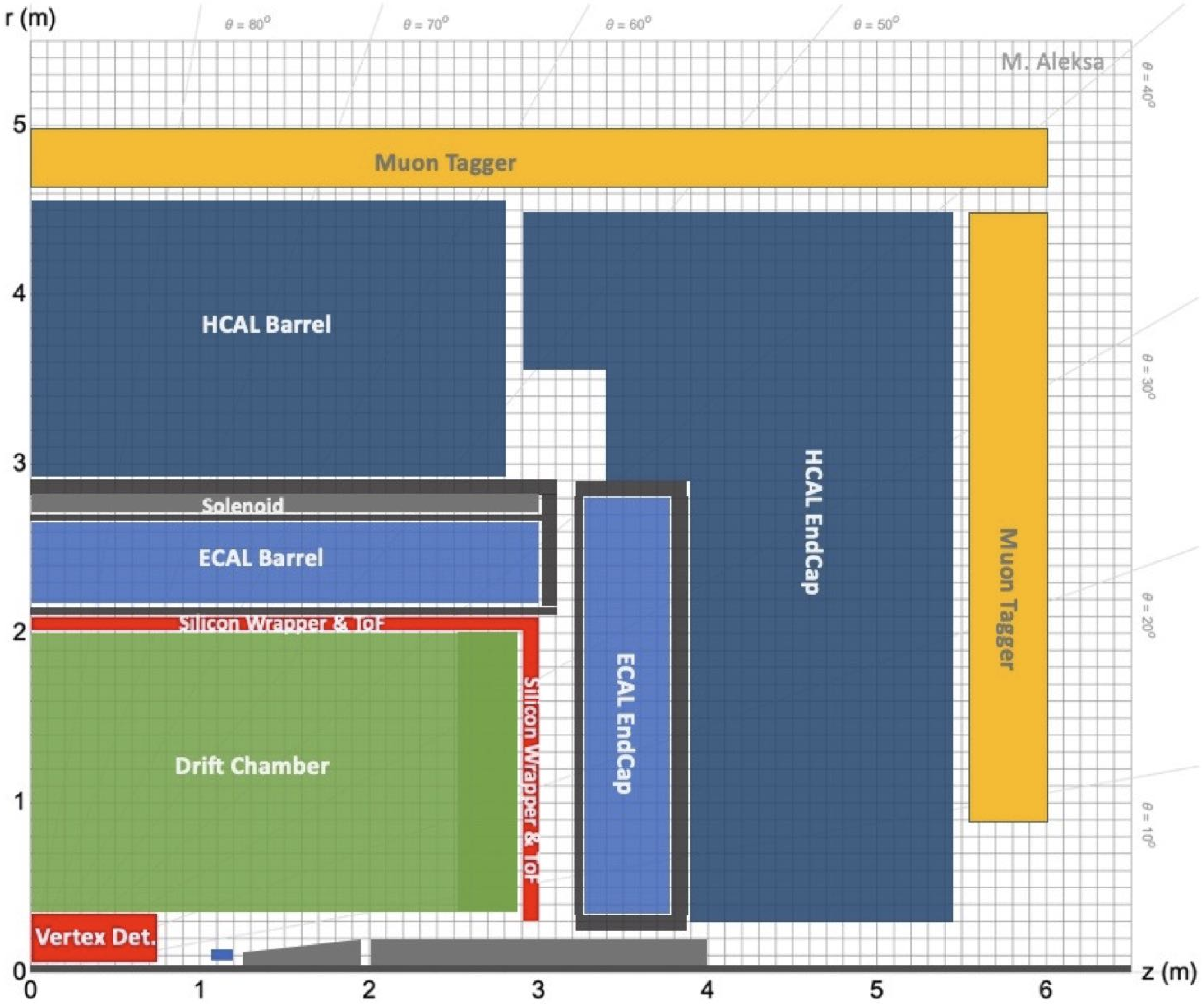
a piece of music that is played in a fast and energetic way

The ALLEGRO detector concept(s)

- From the beginning many different ideas/options → **very open for new ideas**
  - Envelopes need to be optimised/adapted to chosen technologies
  - But had to start with **one version which was implemented into FCC SW**

The ALLEGRO detector concept: common features and reference design

- **Vertex** detector
- **Tracking** system
- **Si wrapper**
- Highly granular **noble-liquid ECAL** inside solenoid
  - Excellent resolution, linearity, stability
  - Optimised for particle flow
- **Solenoid** (B=2T) sharing cryostat with ECAL
  - Light coil (0.76 X_0) + low-material cryostat < $0.1X_0$
- High granularity HCAL
- **Muon** Tagger / Instrumented Iron Yoke
- Detector choices and design optimisation not complete yet



ALLEGRO today

- **Current situation**
  - Strong **noble-liquid ECAL** team collaborating within DRD6 WP2
  - **Other sub-detectors** not yet defined
    - very open for contributions, **many EoIs** received
    - leaning towards gaseous main tracker; various options for muon tagger
  - There is a "reasonable" choice for the other sub-detectors implemented in FCC SW (sketch in previous slide, details in next one), but different choices can be tried due to modularity of FCC SW
- **Next steps**
  - Now: **EoI for ESPPU2025**: ALLEGRO as high-perf. general-purpose detector concept for FCC-ee. While concept is centered around noble-liquid ECAL, technology choices for other sub-detectors are fully open
  - Coming years:
    - **R&D** on subdetectors (optimisation studies, prototypes, testbeams..)
    - **down-selection** to baseline options and formation of a proto-collaboration once a **decision on FCC-ee** has been taken and once we enter the **TDR phase** (possibly in the coming 5 years)

4 Work Package 2: Liquified Noble Gas Calorimeters

4.1 Description

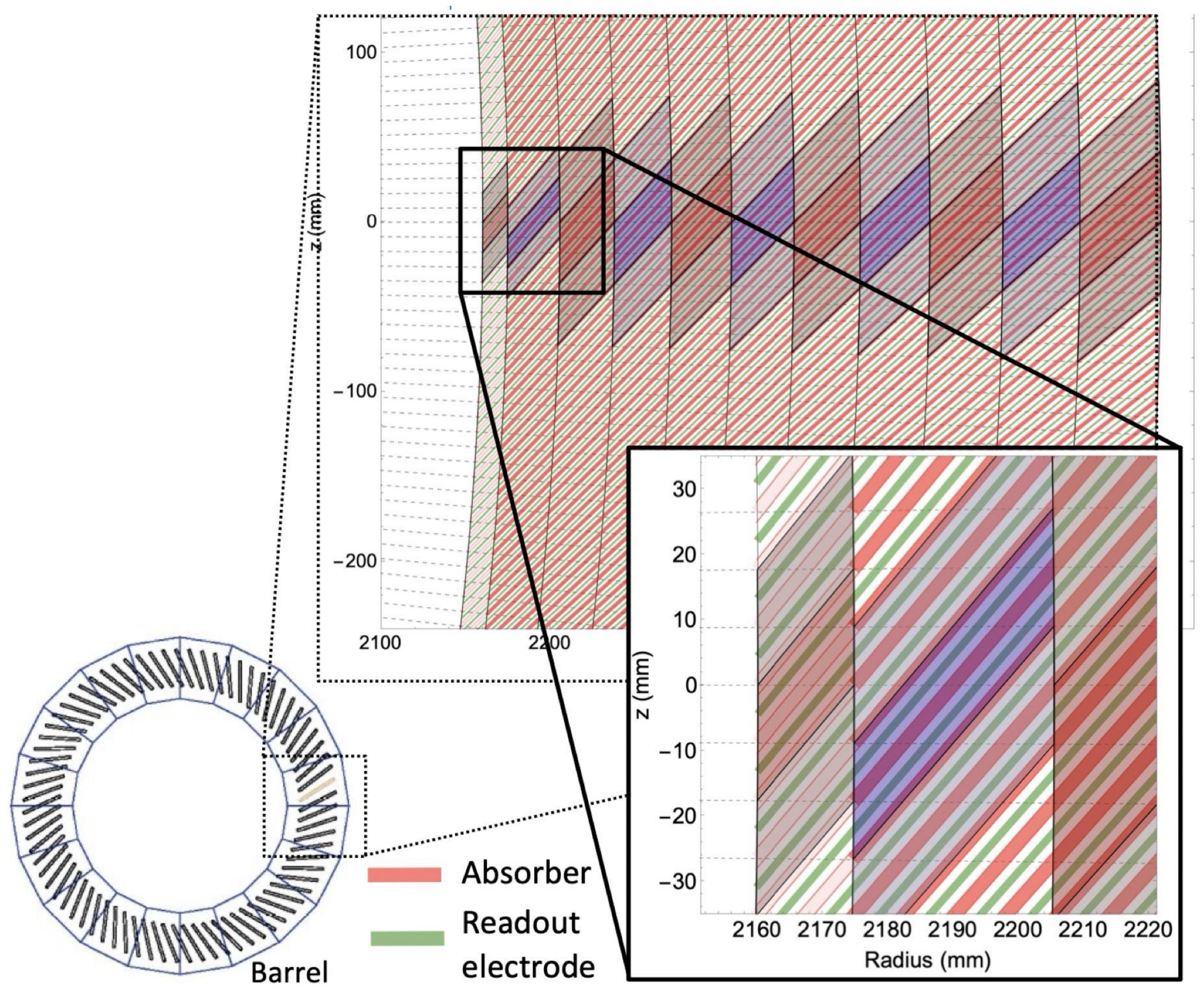
Future experiments at e^+e^-, hadron or muon colliders have an ambitious physics program. The role of calorimetry will be to precisely measure particle energies, complement the tracking system in an optimal particle-flow event reconstruction, contribute to particle identification and - where necessary - provide efficient pile-up rejection. Such functionalities will only be achievable with excellent electromagnetic energy resolution, high lateral and longitudinal granularity and - in some cases (e.g. pile-up rejection) - excellent time resolution. Calorimetry based on liquified noble gases

16:20 → 18:00 Expressions of Interest — 1h 40m

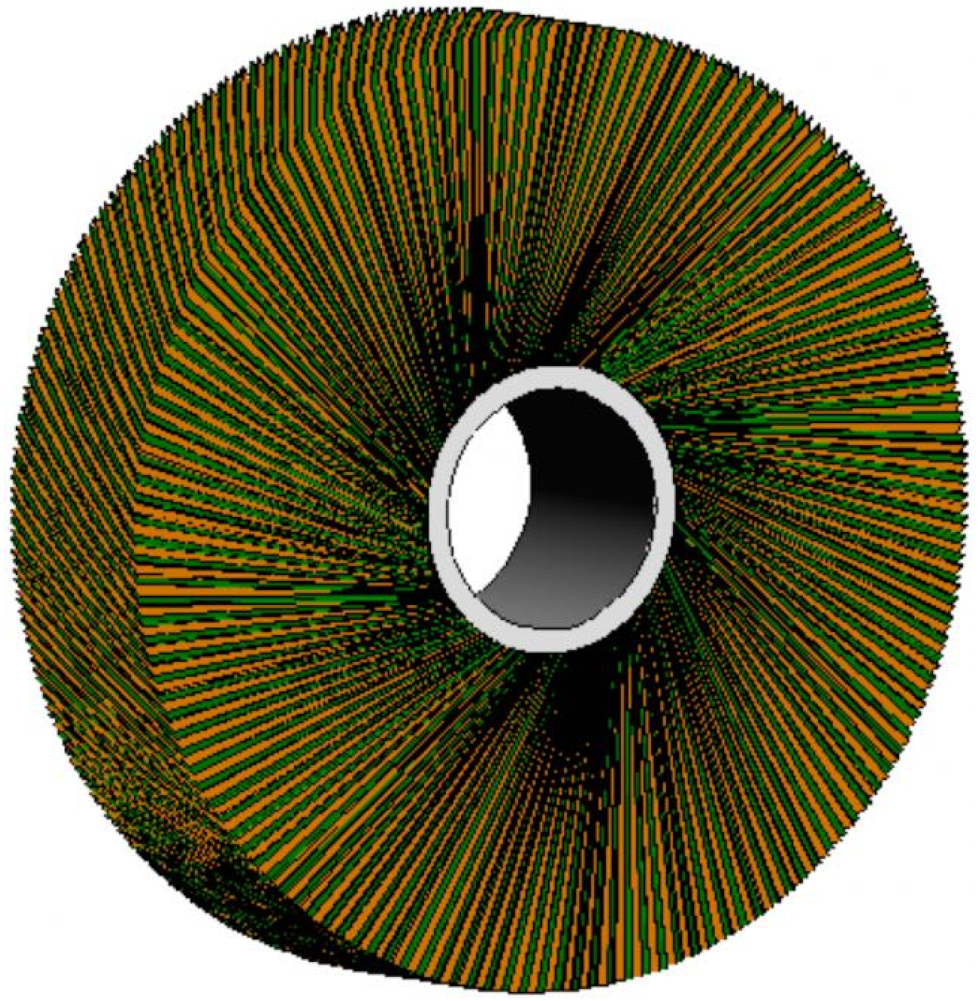
- Interest of Swiss Groups in Several Detector Areas — 10m
  Speaker: Ben Kilminster (University of Zurich (CH))
  Swiss-Inter...
- Interest of MPP Munich Group — 5m
  Speaker: Oliver Kortner (Max Planck Society (DE))
  EOI_2024-...
- Detector Simulations - B.K.C. College Kolkata — 5m
  Speaker: Avinanda Chaudhuri (CERN)
  Kolkata-Ind...
- Straw Tracker - Michigan — 5m
  Speaker: Junjie Zhu (University of Michigan (US))
  Straw-UM-...
- Gaseous Tracking - BNL — 5m
  Speaker: George Iakovidis (Brookhaven National Laboratory (US))
  2024_11_2...
- Wire Chamber - IJCLab — 5m
  Speaker: Gabriel Charles (Université Paris-Saclay (FR))
  Allegro_Ex...
- Silicon Detectors for Allegro - BNL — 5m
  Speaker: Alessandro Tricoli (Brookhaven National Laboratory (US))
  Tricoli_BN...
- Gaseous and Silicon Detectors - Weizmann Institute — 5m
  Speaker: Shikma Bressler (Weizmann Institute of Science (IL))
  WIS.pdf
- Vertex Detector - Strasbourg — 5m
  Speaker: Jeremy Andrea (Centre National de la Recherche Scientifique (FR))
  FCCee-SEE...
- ECAL - UT-Austin — 5m
  Speakers: Peter Onyisi (University of Texas at Austin (US)), Timothy Robert Andeen (University of Texas at Austin (US))
  20241122_...
- TileCal HCAL - CERN — 5m
  Speakers: Henric Wilkens (CERN), Michaela Mlynarikova (CERN), Rute Pedro (Laboratory of Instrumentation and Experimental Particle Physics (PT))
  EoI_ALLEG...
- Muon Drift Tube Detector - Michigan — 5m
  Speaker: Jianming Qian (University of Michigan (US))
  FCCeeMuo...
- MicroMegas Muon Detector - Roma 3 — 5m
  Speakers: Biagio Di Micco (Universita' degli Studi di Roma Tre e Istituto Nazionale di Fisica Nucleare (INFN)), Mauro Iodice (INFN - Sezione di Roma Tre)
  Allegro_Mi...
- MicroMegas Muon Detector - INFN Napoli — 5m
  Speakers: Mariagrazia Alviggi (University Federico II and INFN, Naples (IT)), Massimo Della Pietra (University Federico II and INFN, Naples (IT)), Paolo Iengo (INFN)
- Muon Detector based on Scintillators - Roma 1 — 5m
  Speakers: Claudio Luci (Sapienza Universita e INFN, Roma I (IT)), Fabio Anulli (Sapienza Universita e INFN, Roma I (IT)), Massimo Corradi (Sapienza Universita e INFN, Roma I (IT)), Riccardo Vari (Sapienza Universita e INFN, Roma I (IT)), Stefano Rosati (Istituto Nazionale di Fisica Nucleare Sezione di Roma 1), Stefano Veneziano (INFN e Università Roma Sapienza)
  Roma-I-Mu...
- TDAQ - CERN — 5m
  Speakers: Aimilianos Koulouris (CERN), Rosa Simoniello (CERN)

ALLEGRO full simulation in FCC SW

- ALLEGRO full simulation based on DD4hep & Geant4, fully integrated within FCCSW/Key4hep/EDM4hep ecosystem
- **Full implementation** of “reference" detector **model** in DD4hep/key4hep recently **completed**
  - **Tracking** system taken from IDEA 'as is’
    - vertex detector with curved sensors
    - drift chamber z-extent un-changed (to be optimized)
    - silicon wrapper similar to VTX but with planar sensors
  - **Noble-Liquid ECAL** with inclined absorbers
    - Baseline: straight Pb+Steel absorber, growing sensitive gap
    - Turbine geometry in endcaps
    - Many parameters (geometry, readout, materials) can be customised
  - **Coil** in ECAL outer barrel cryostat
  - **TileCal HCAL** tuned to FCC-ee (barrel and endcaps)
  - **Muon Tagger** as sensitive cylinder/disks (scintillators) - mainly a place holder
- **Next**: reconstruction, physics performance studies, detector design optimisation

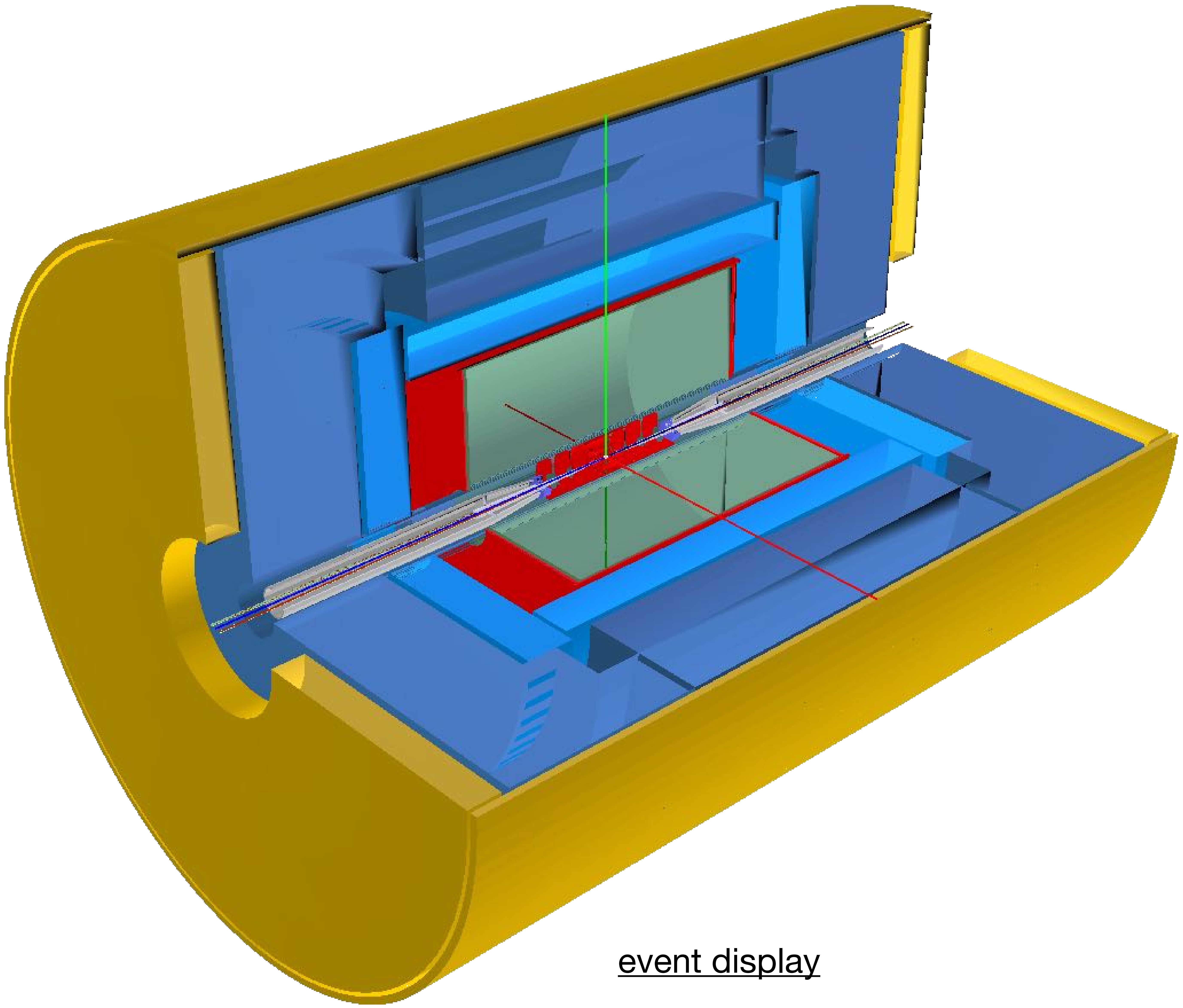


ECAL barrel

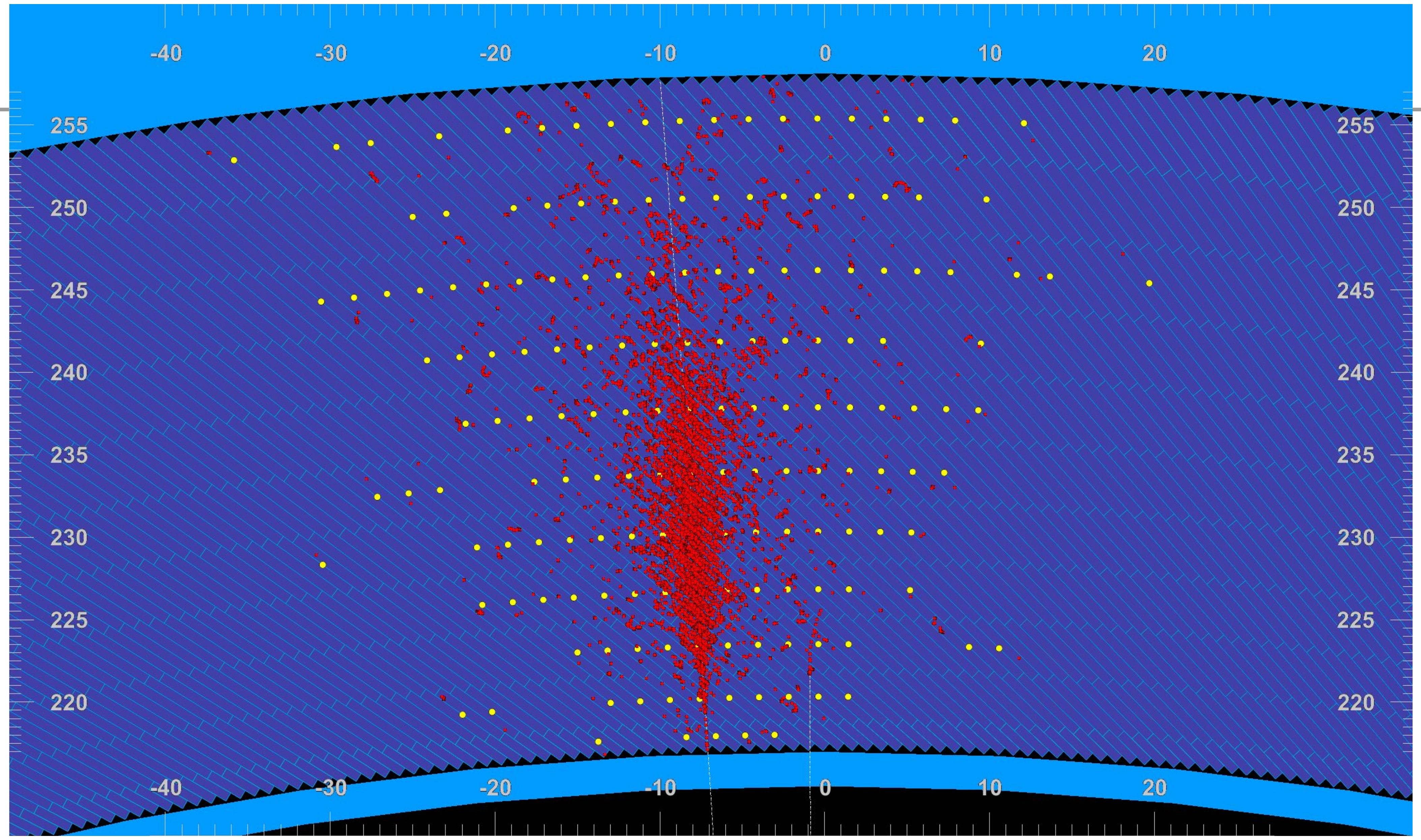


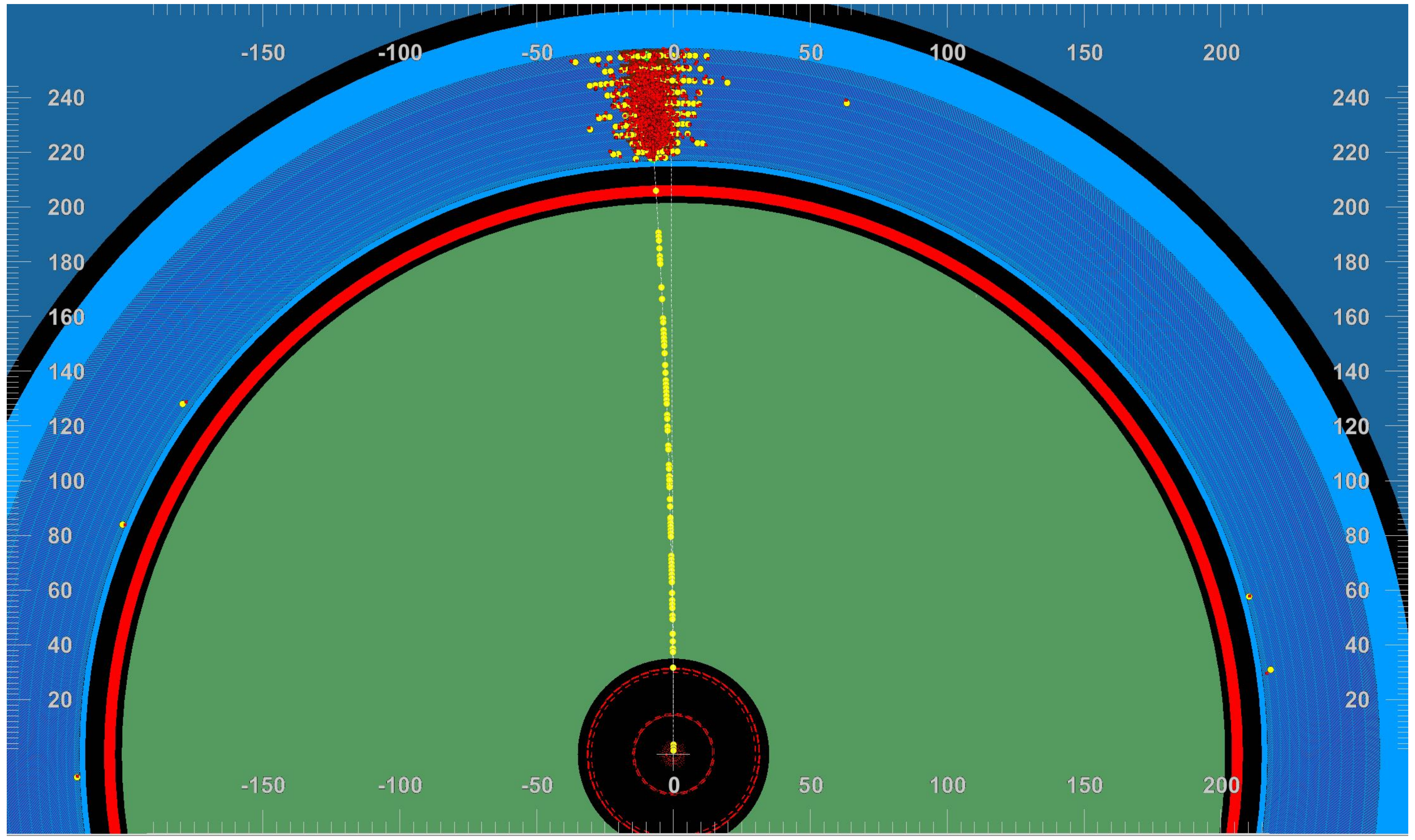
ECAL endcap

ALLEGRO full simulation in FCC SW



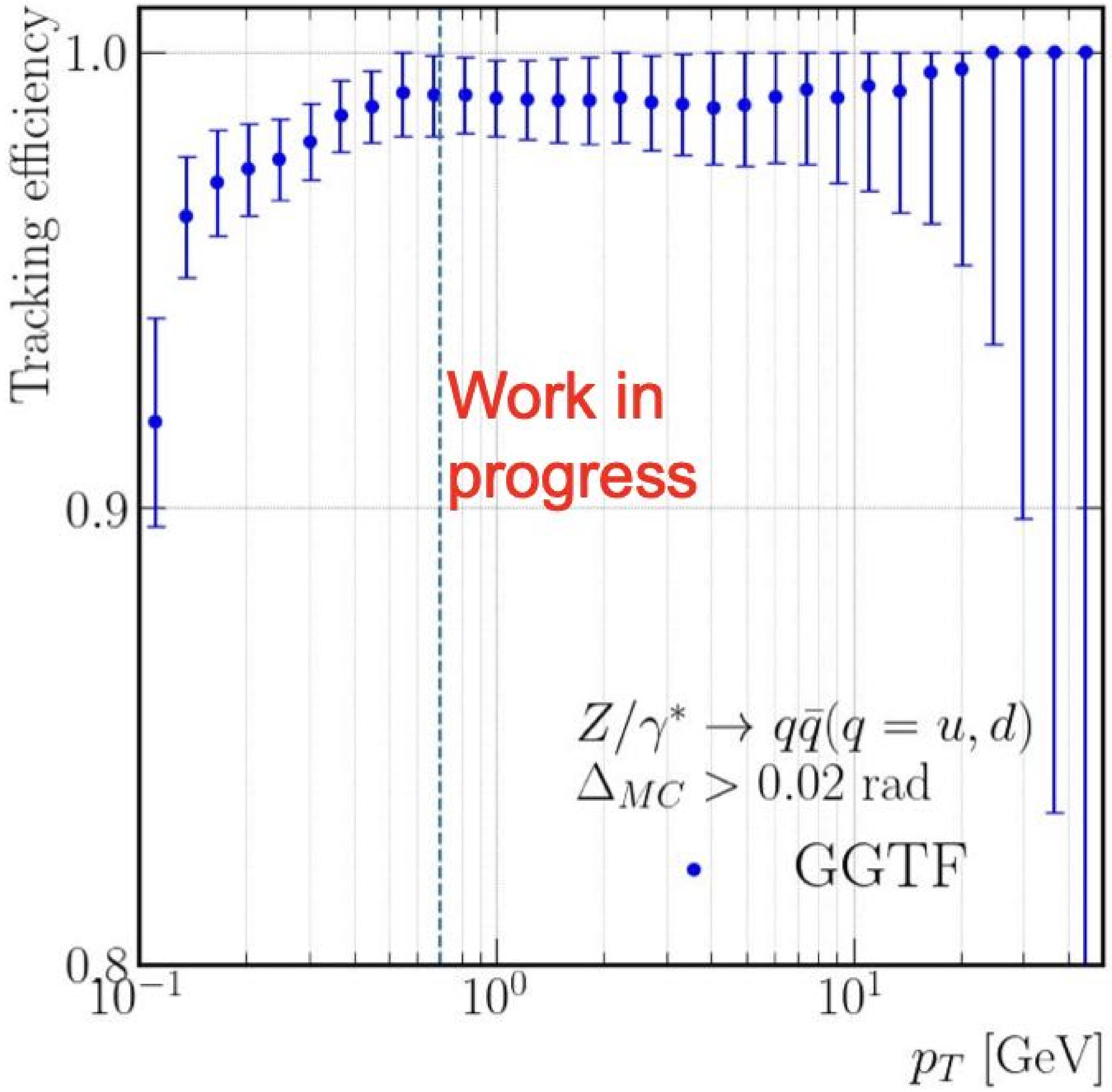
event display





ALLEGRO reconstruction: tracking

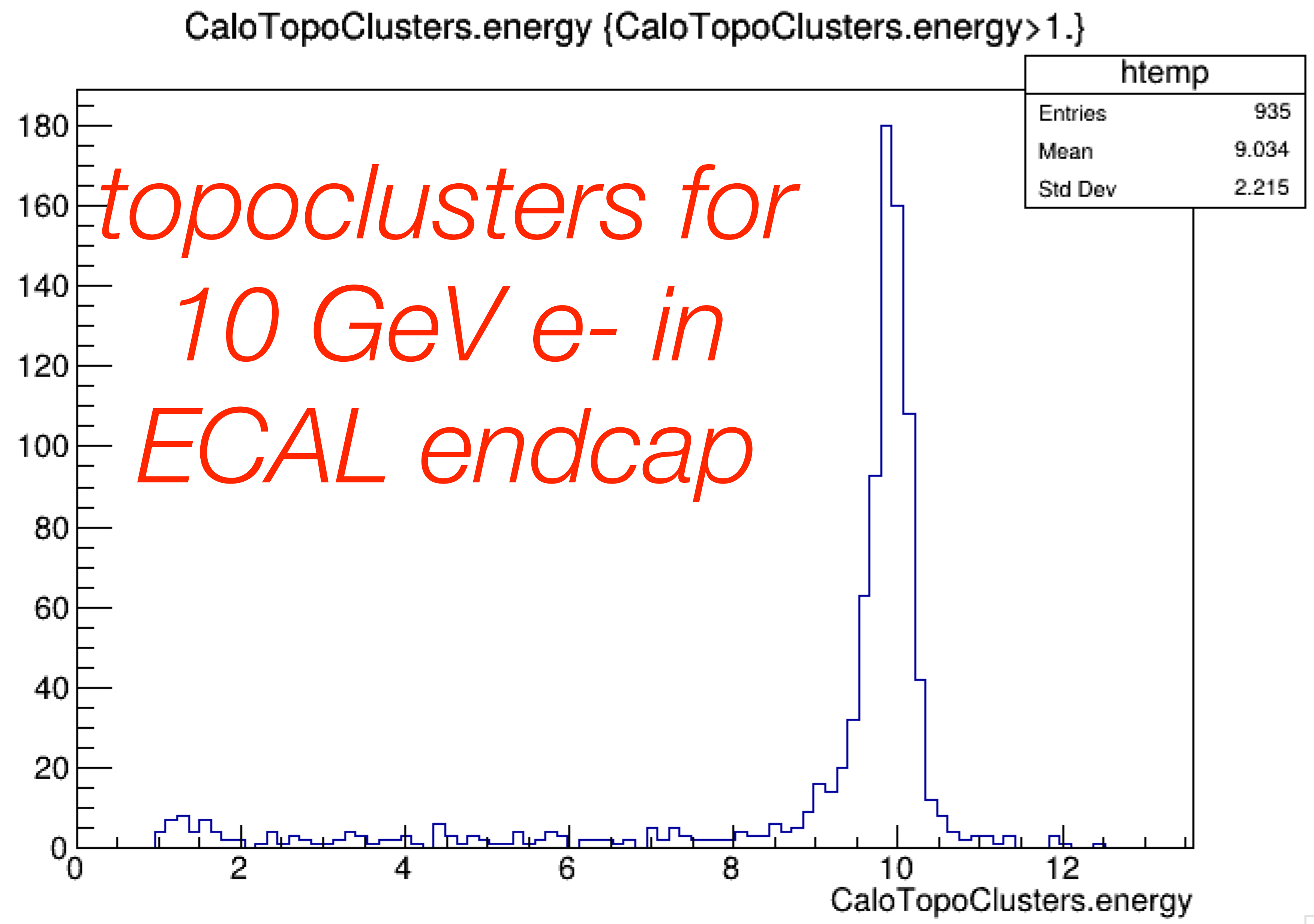
- Tracking in current ALLEGRO simulations is still in the works
  - **Hits** are available, produced by applying Gaussian smearing to truth-level hits in trackers
  - **Track** reconstruction from hits not yet implemented
  - Significant work ongoing on **ML-based tracking** for IDEA, could be ported with little effort to ALLEGRO once finalised



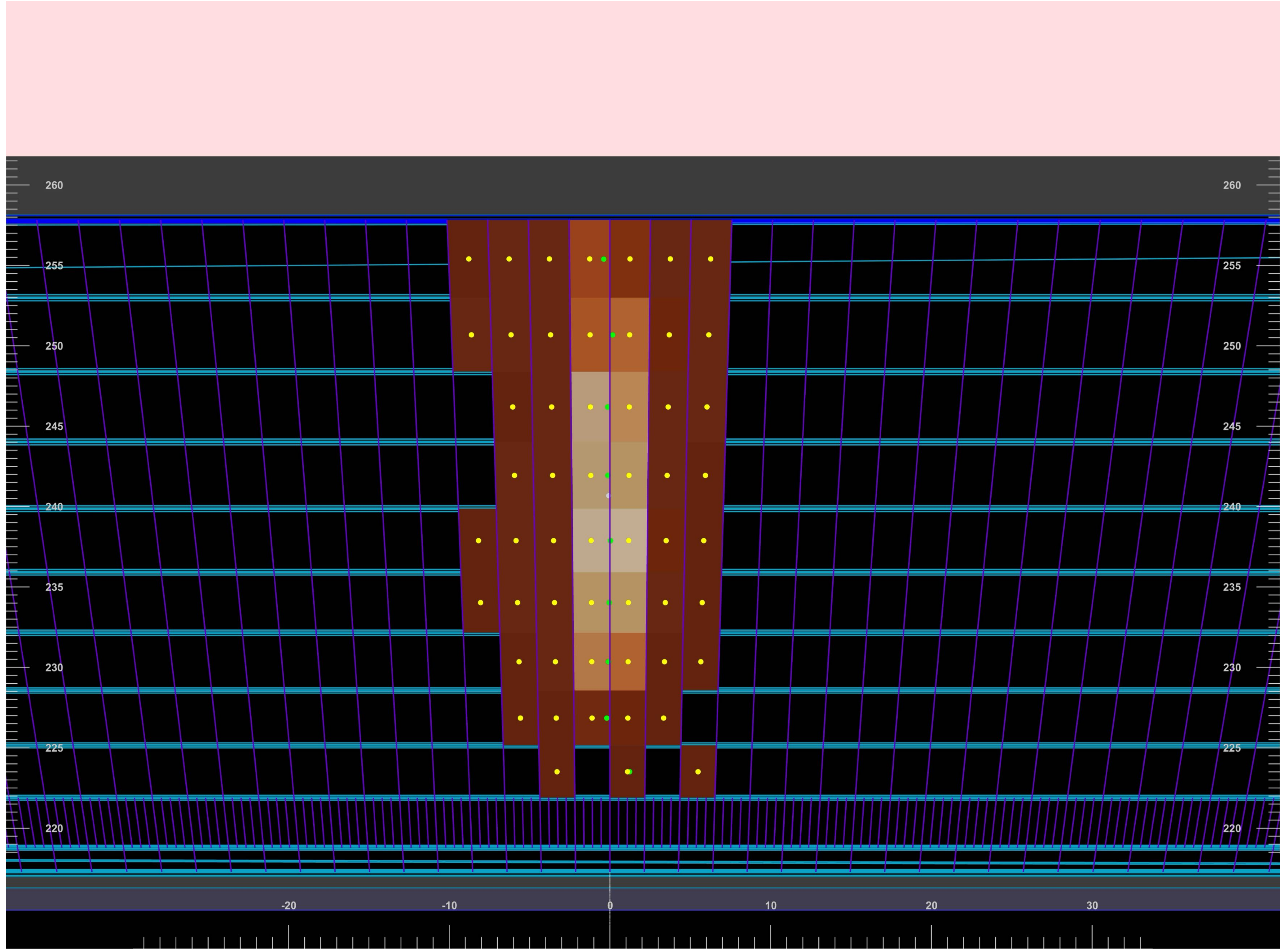
- **As a proxy**, for the time being, to enable starting p-flow reconstruction studies, reconstruction-level tracks are produced by cloning the generator-level tracks

ALLEGRO reconstruction: calorimetry

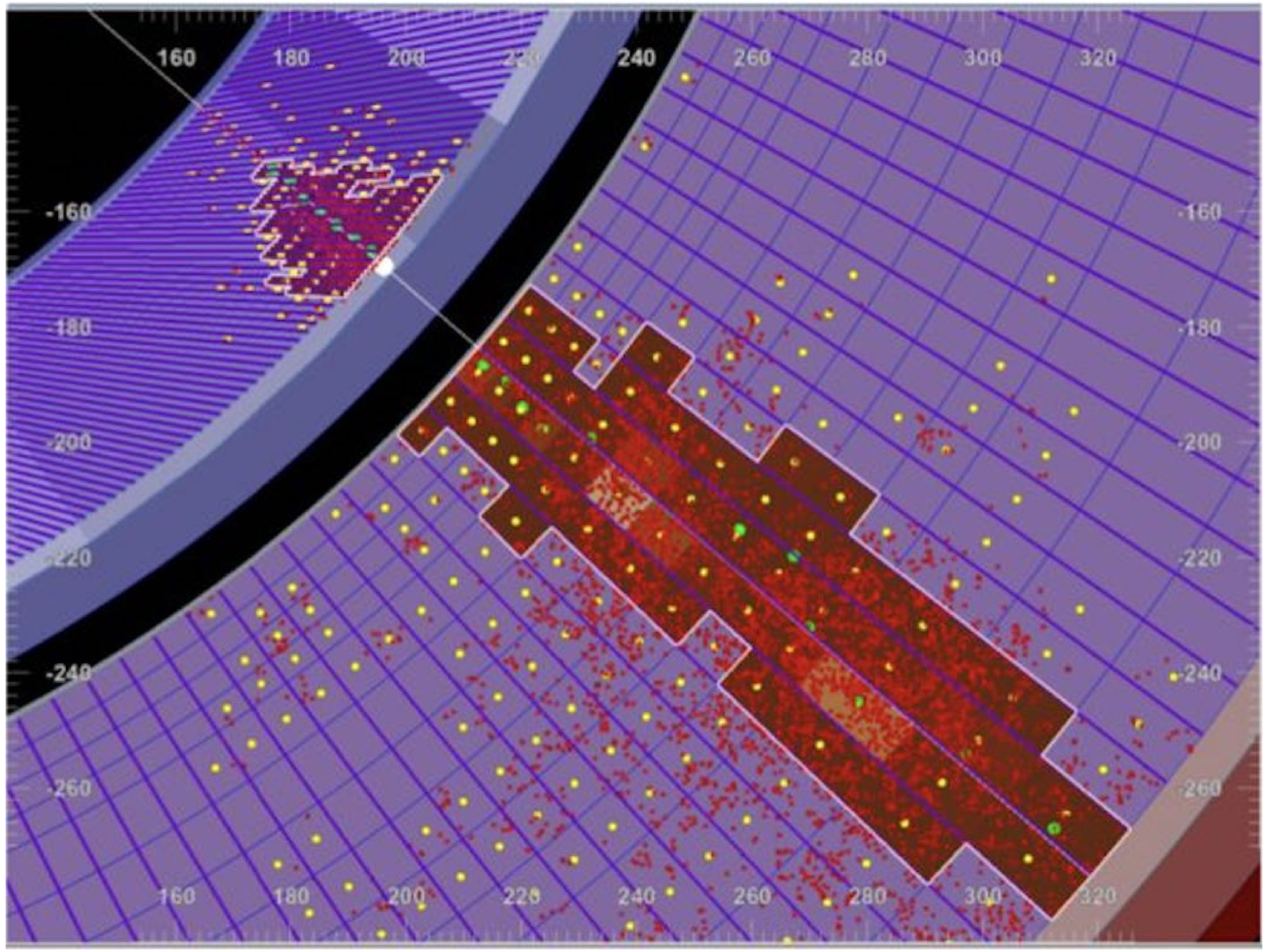
- **Digitisation:** simple sum of G4 hits within given readout cell (defined by the detector readout granularity), rescaled by a sampling fraction correction
  - Same algorithm works for all calorimeter sub detectors (ECAL and HCAL barrel and endcaps)
  - Recent addition of past months: emulation of noise and x-talk in ECAL barrel (to be followed soon by other sub detectors)
    - Noise: addition of random Gaussian-distributed noise energy per cell, starting from calculations of expected noise based on detector geometry and detailed electric field simulations of the cells
    - Crosstalk: redistribute energy among neighbouring cells based on crosstalk measured in PCB prototypes
- **High-level reconstruction**: two clustering algorithms implemented so far, fixed-sized and topological clusters
  - Fixed-size: scan $\theta \times \phi$ space with sliding window to identify local maxima in energy deposition => build clusters of fixed size
  - Topological: find seed cells ($S/N>T_{seed}$) attach neighbouring ones ($S/N > T_{neighbours}$) => build connected clusters of variable size
  - Both can use cells from only one subsystem (e.g. ECAL-only => “EM" clusters) or both (ECAL+HCAL => seeds for jet reconstruction)
  - SW implemented for all configurations; topoclustering working for ECAL/HCAL barrels since long, implementation for endcaps converging recently
  - CLUE algorithm has also been ported to ALLEGRO but not much tested



ALLEGRO reconstruction: calorimetry



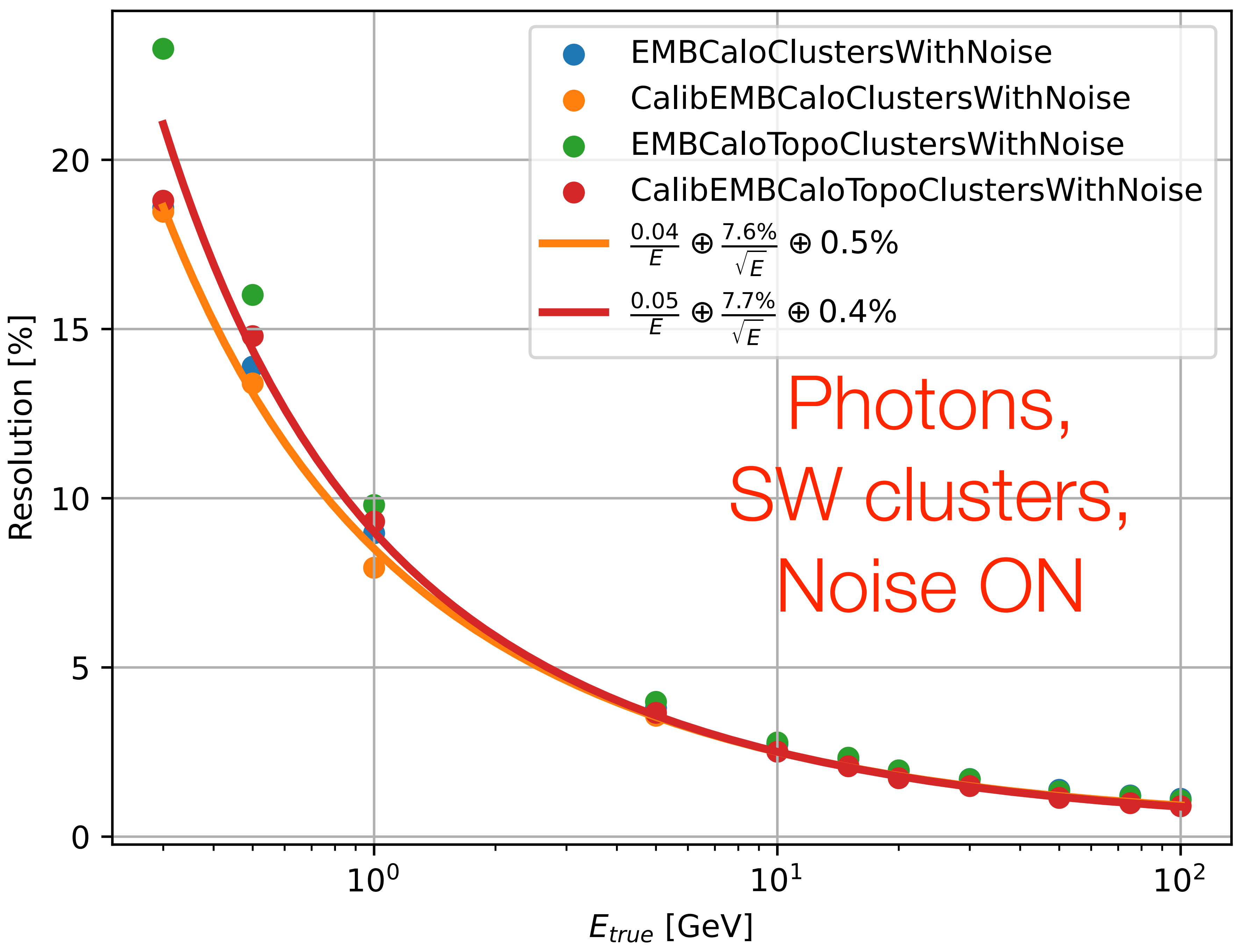
ECAL-only SW cluster (photon)

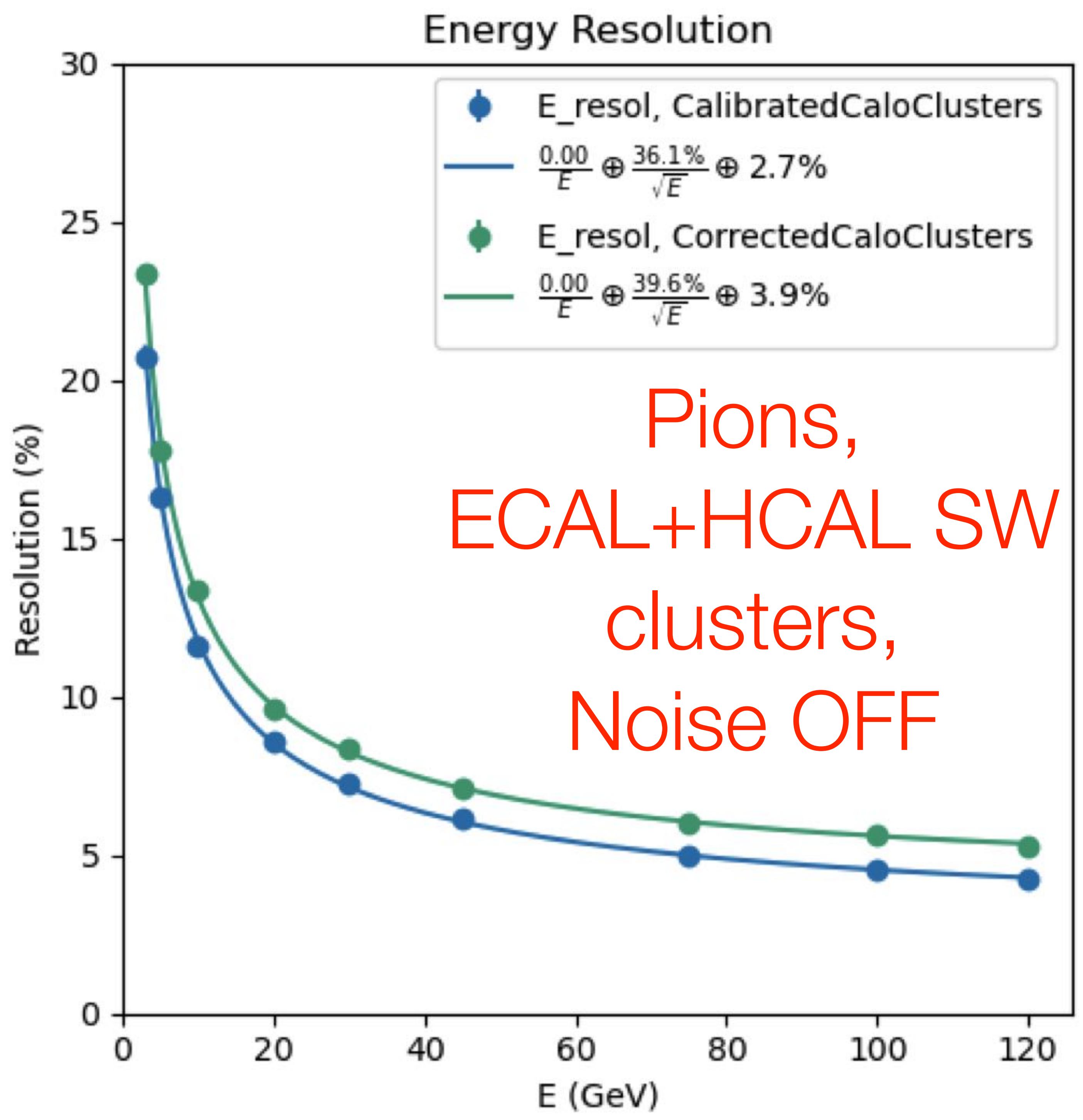


Joint ECAL+HCAL topocluster (pion)

Calorimeter performance: energy calibration

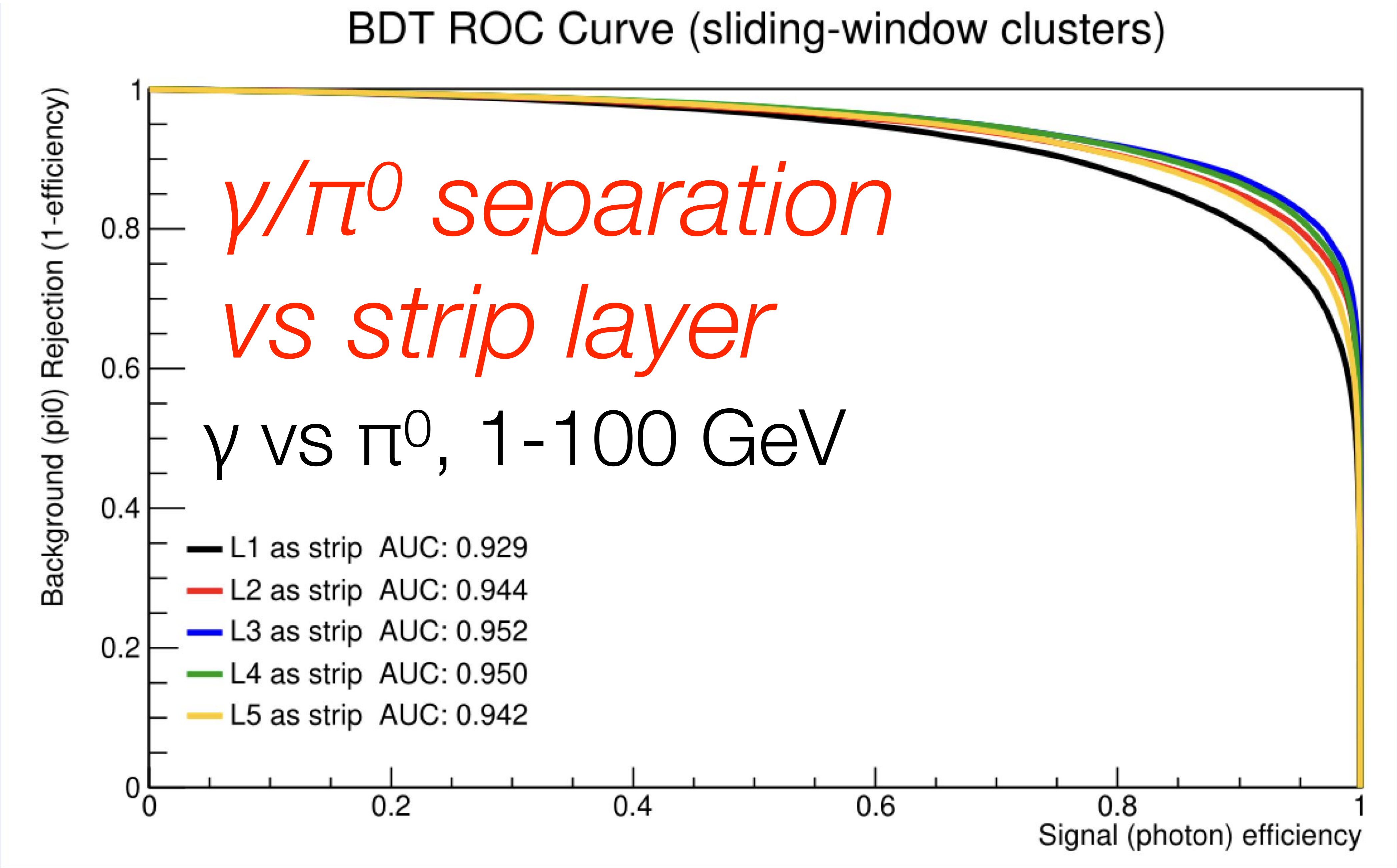
- **BDT-regression**-based calibration implemented **in Gaudi**
  - Inputs: energy fraction in each layer, total energy, cluster barycentre theta-phi;   target: E_cluster/E_particle
  - Inputs calculated directly within Gaudi algorithm, saved as cluster decorations => no need to persist cell-level info
  - BDT trained with external tool, output saved to portable ONNX format, that can be read out in Gaudi
  - Calibration can be applied by another Gaudi algorithm in all subsequent simulations and saved as cluster decoration

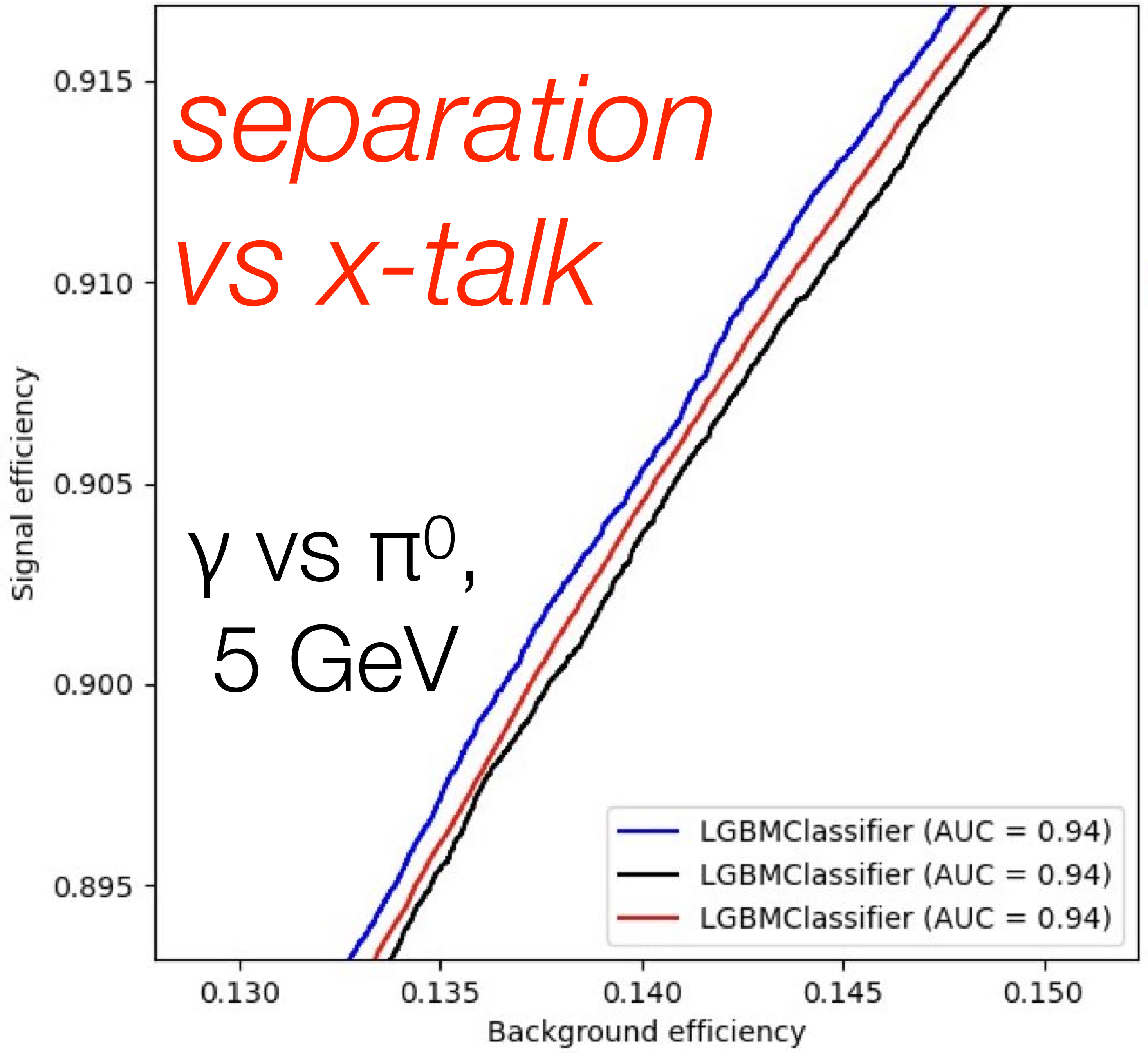




Calorimeter performance: photon identification

- **BDT-based** photon ID algorithm implemented **in Gaudi**
  - Inputs: longitudinal/lateral shower shapes from cell energies, calculated/saved as shape parameters by Gaudi algorithm
  - Target: binary classification with maximum area under curve
  - BDT trained with external tool, output saved to portable ONNX format, that can be read out in Gaudi
  - Inference applied by another Gaudi algorithm in subsequent simulations and BDT score saved in output
  - Work ongoing to assess impact of detector design, crosstalk, noise ..

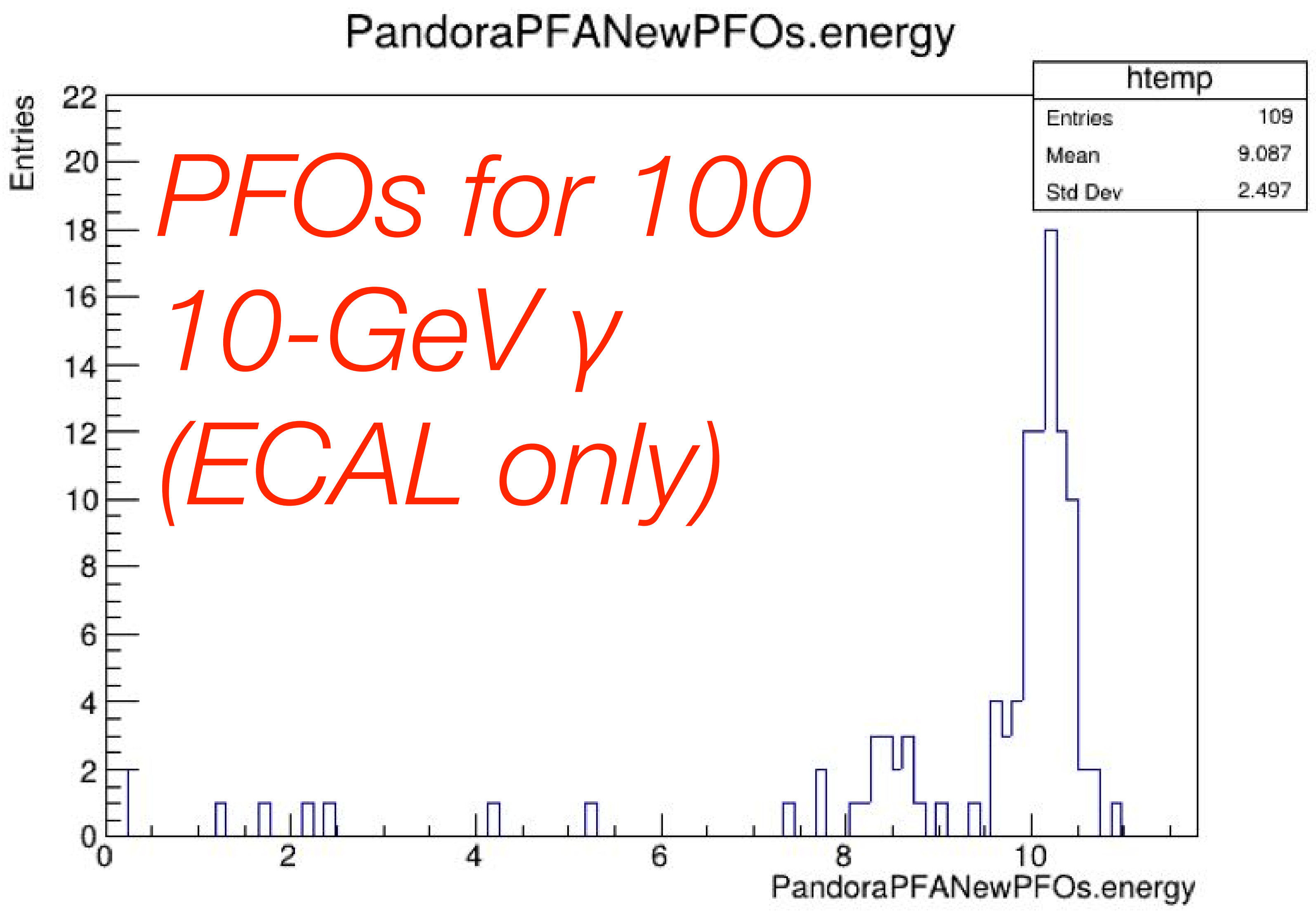


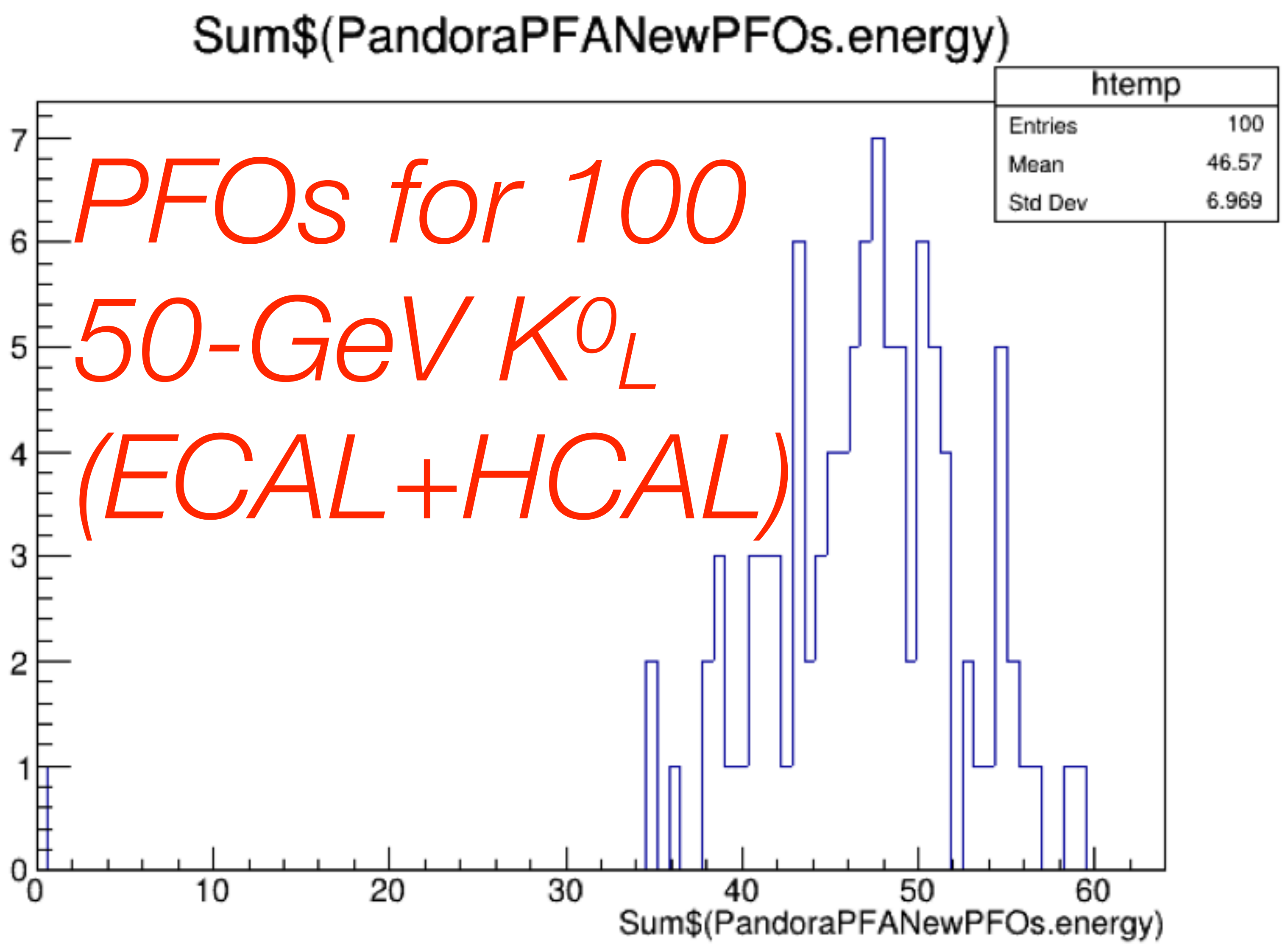


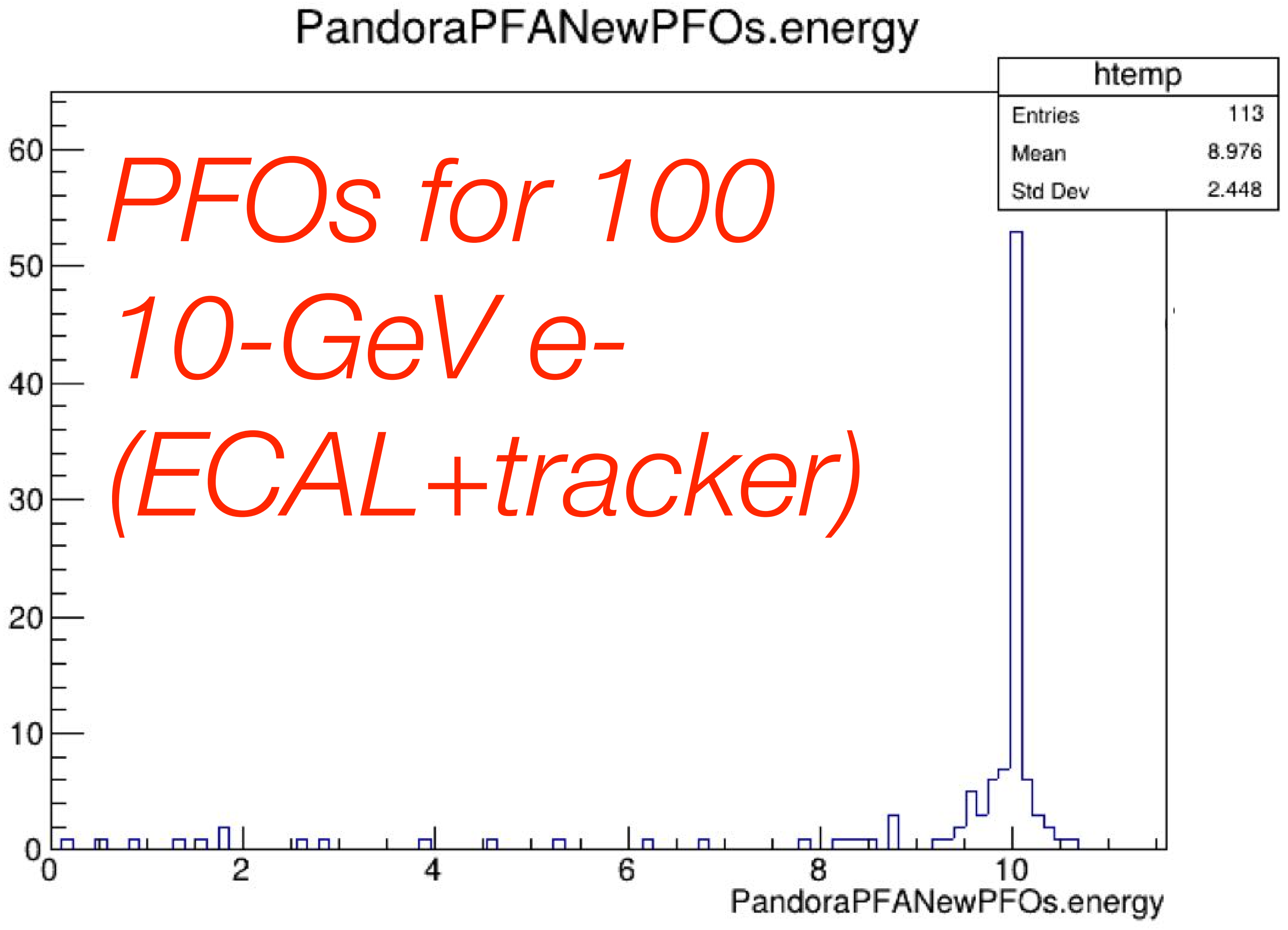
- Blue: No cross-talk in training or test.
- Black: Cross-talk in both training and test.
- Red: No cross-talk in training but cross-talk in test.

ALLEGRO reconstruction: towards particle-flow

- **Next major milestone:** exploit all sub detectors at once within **particle-flow** approach
  - Work ongoing in this direction adapting PandoraPFA-based tools in Key4hep/FCCSW to ALLEGRO
  - Currently, use charged gen-level particles instead of (not available yet) reco particle
  - Started with ECAL and HCAL barrels
  - Used CLD working implementation as a starting point and reference for comparing to
  - Many details (settings, calibrations, identification criteria …) to be fully understood/properly set/adapted to
  - Encouraging initial results on e/γ/KL PFO objects, calibration/identification to be improved

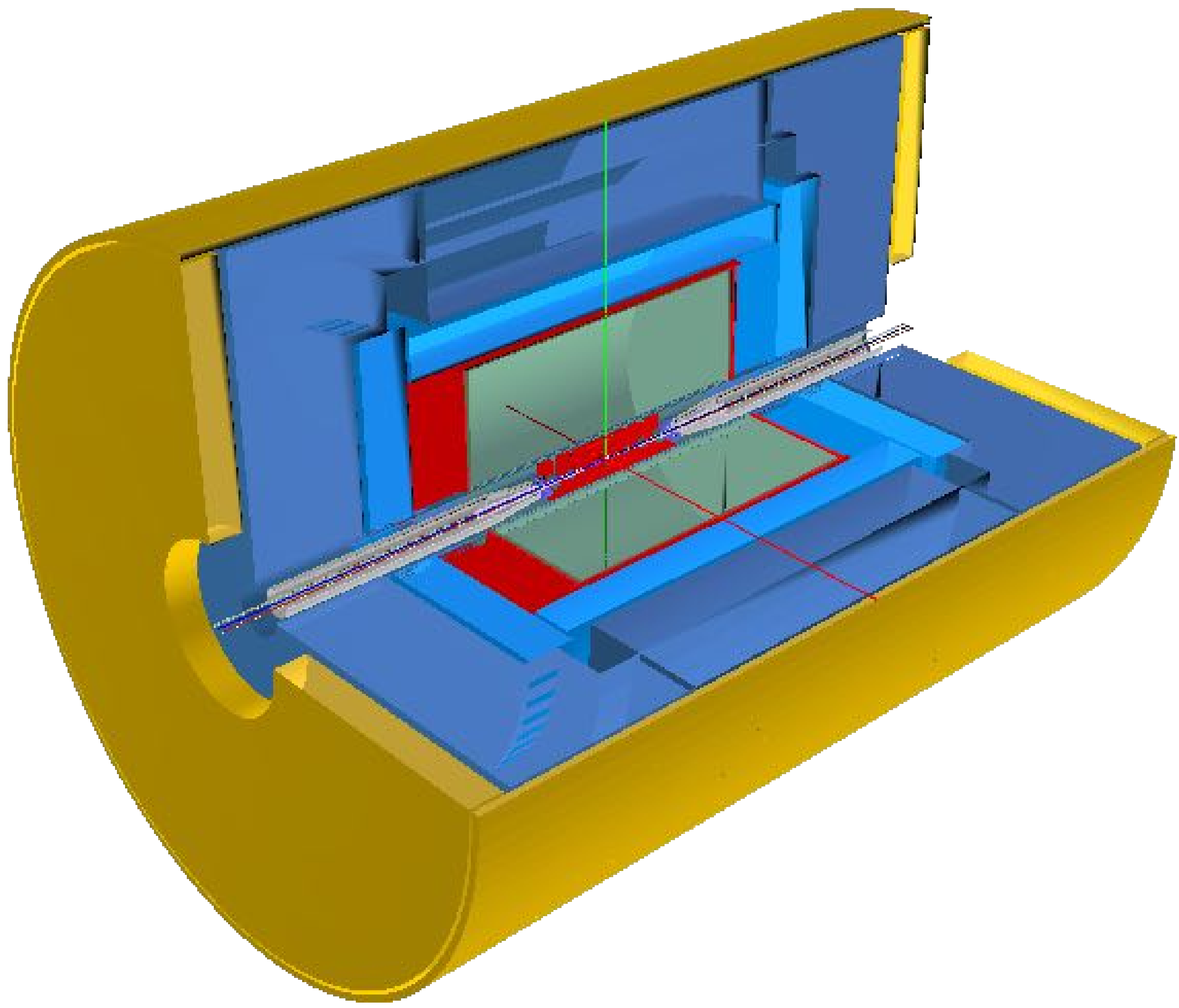






Conclusion

- ALLEGRO proposed as high-performance general-purpose detector concept for FCC-ee
  - we will submit an EoI for the ESU
  - a strong noble-liquid ECAL team (20 institutes) + lots of interest on other subdetectors
  - in coming years we should further develop ideas keeping physics requirements in mind, build prototypes & implement them into FCC SW with realistic performance
- "Paper" version of reference design is now implemented in full-sim within FCCSW
  - Can emulate detector response and (overlay effects such as noise / x-talk
  - Alternative subdetector ideas can be easily implemented
- Reconstruction is actively being developed with very good recent progress
  - Tracking in drift chamber (IDEA), ML-based tracking
  - Basic reconstruction algorithms for calorimeters in place, effort on p-flow ramping up
- **With realistic full-sim and reconstruction in place, we can spend less time on software and more on physics, and have more stable results, in coming years**



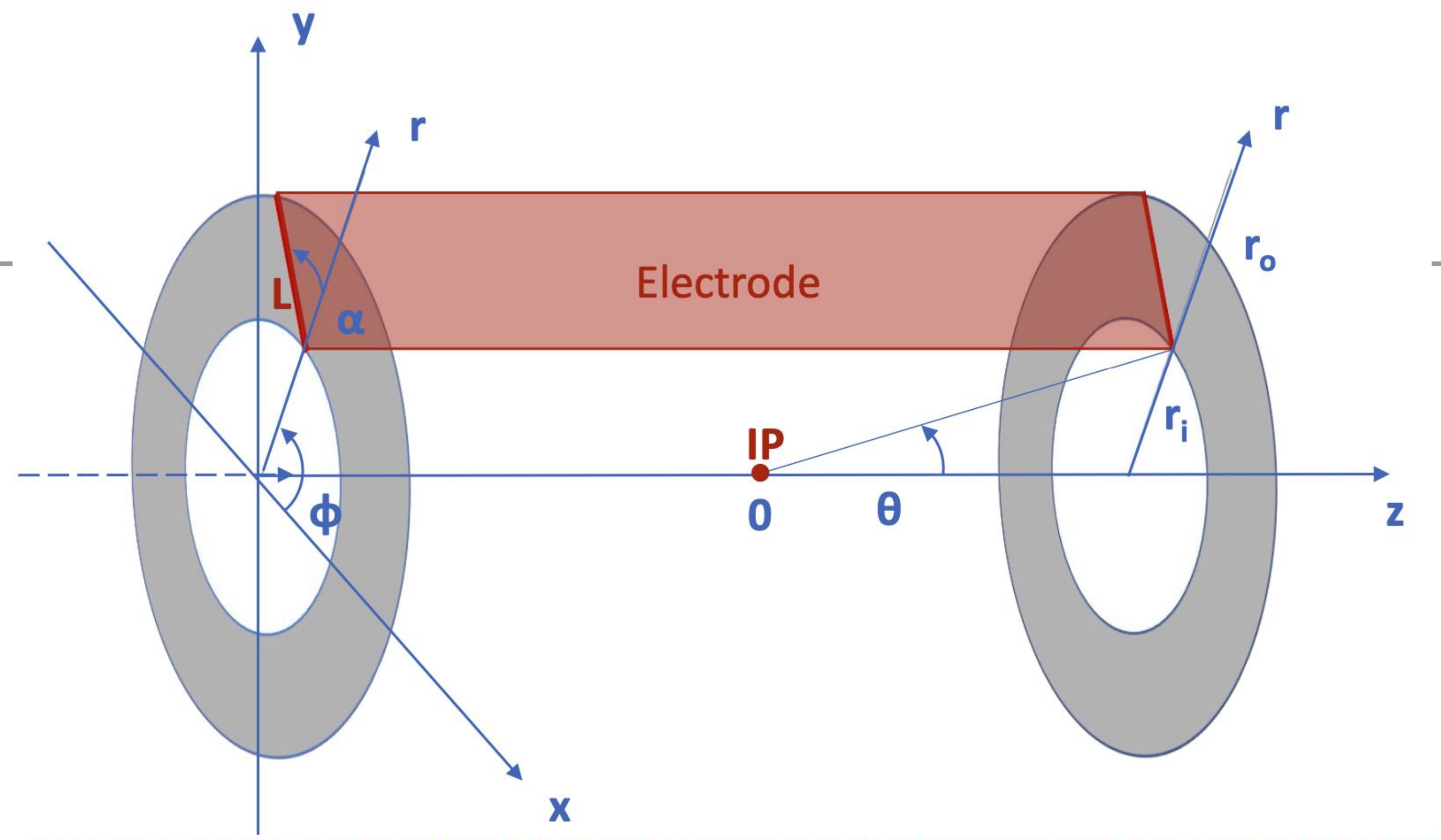
M. Aleksa, N. Morange, M.A. Pleier :

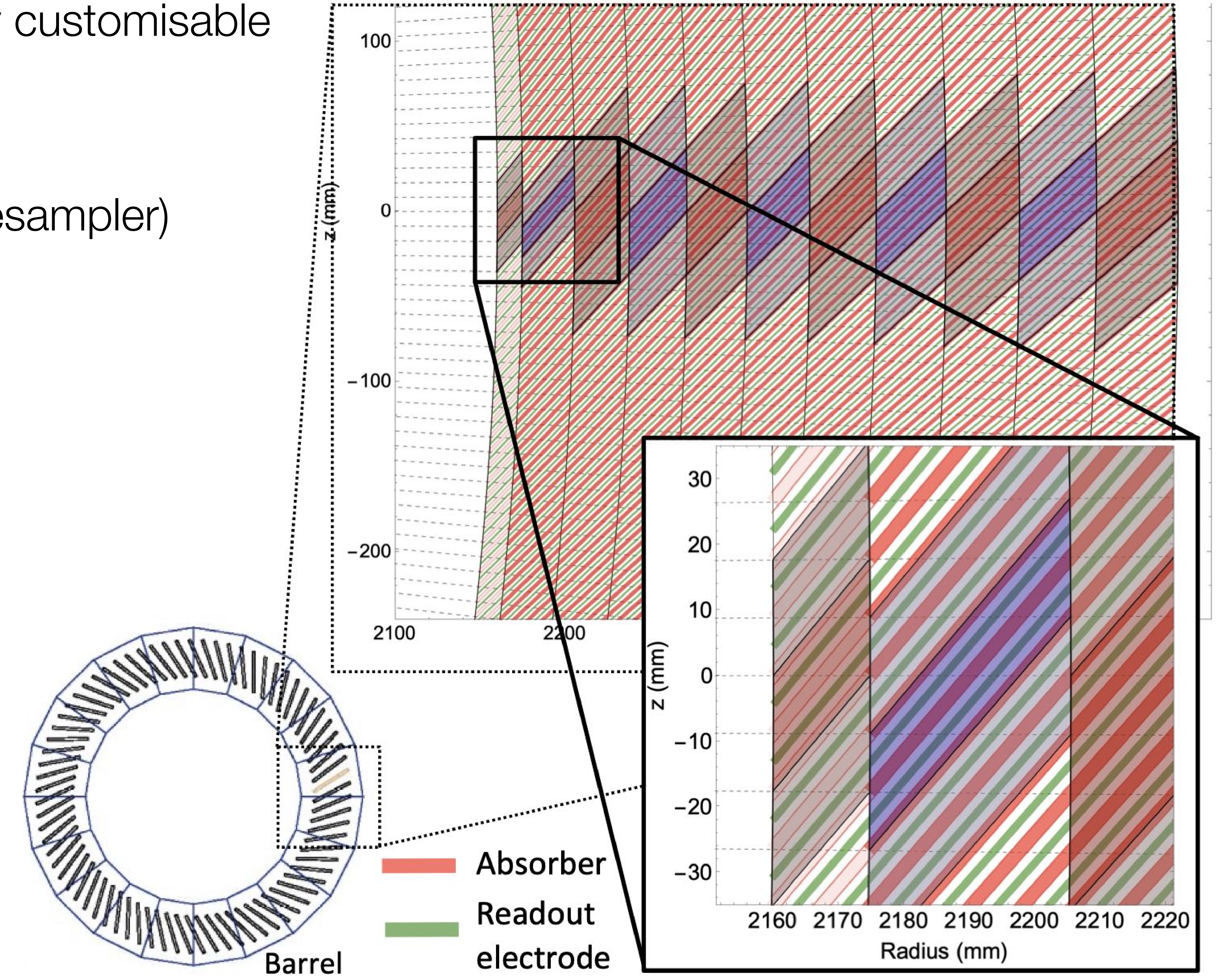
→ Working on ALLEGRO is building our future!
Many interesting challenges ahead of us!
Come and join us!

More details

ECAL barrel

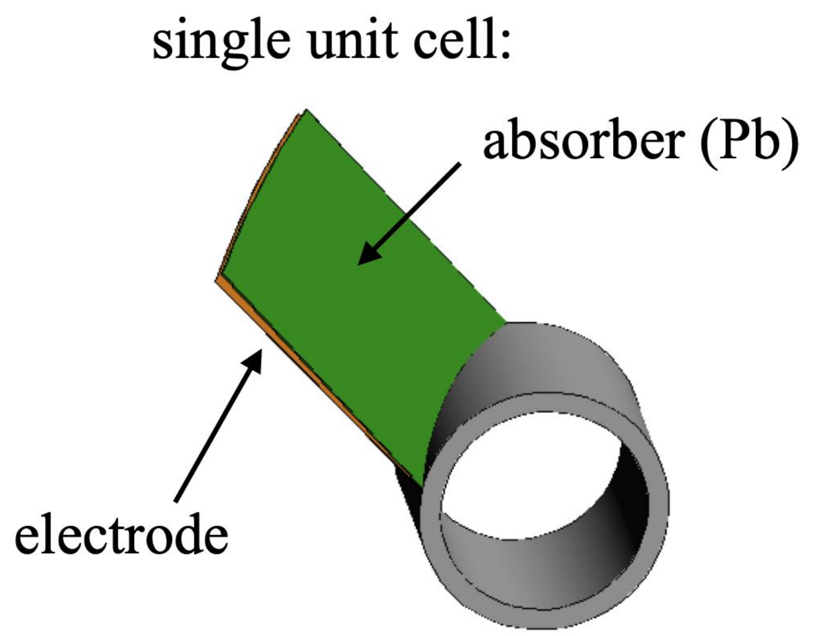
- Baseline design (exact parameters subject to further optimisation):
  - 1536 straight inclined (50°) 1.8 mm Pb absorber plates
  - R_{in} = 216 cm, R_{out}=256 cm => 40 cm deep (≈ 22 X_0)
  - Multi-layer PCBs as readout electrodes => # layers and granularity customisable
  - 2 x 1.2 mm LAr gaps
  - 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

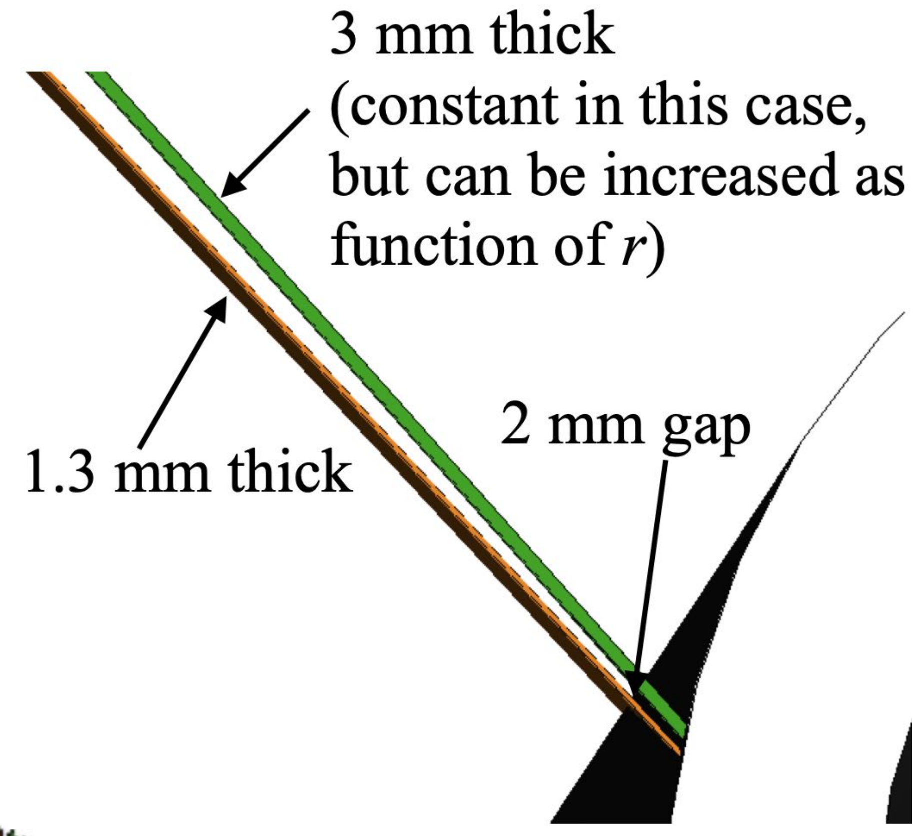


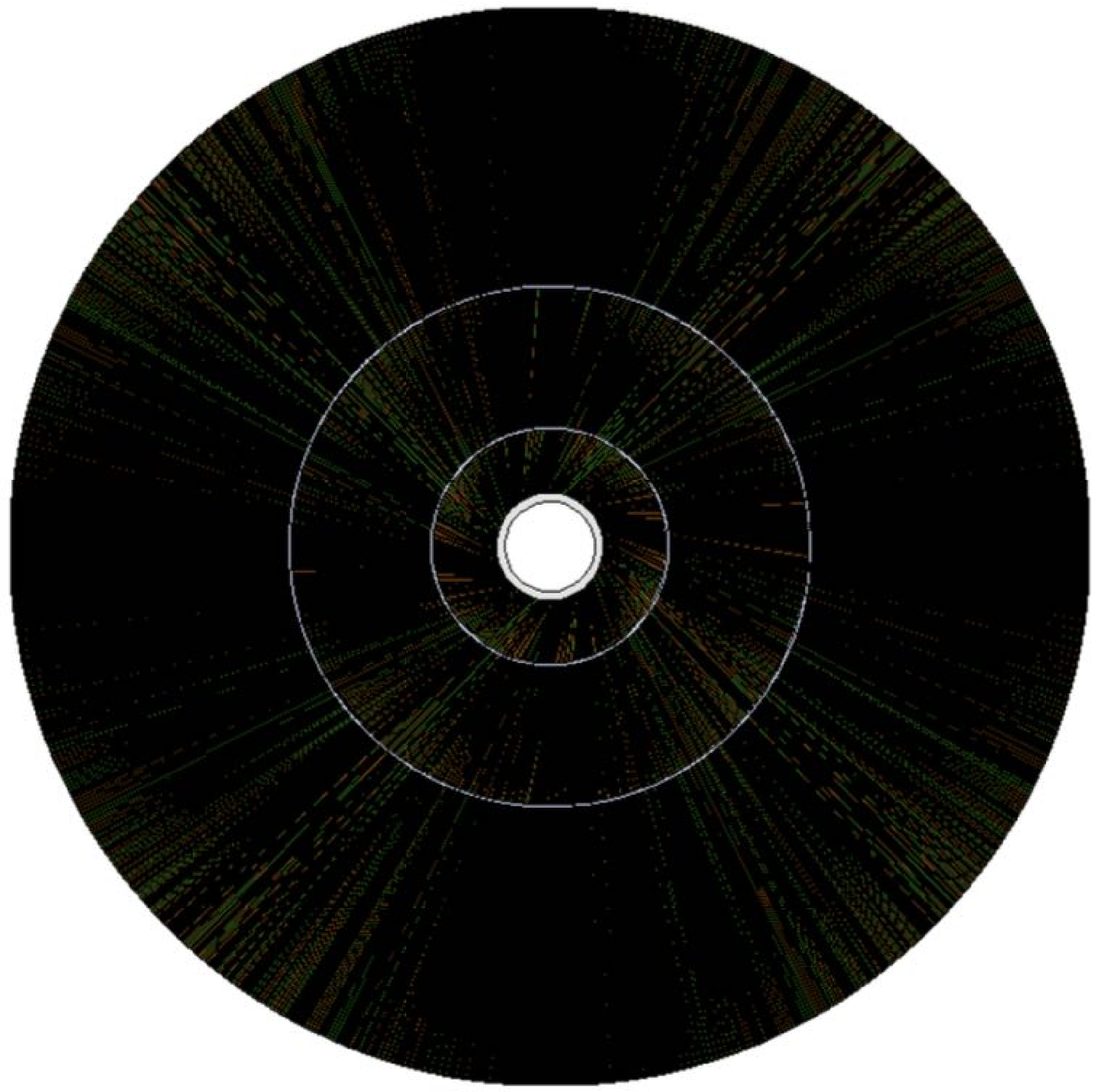


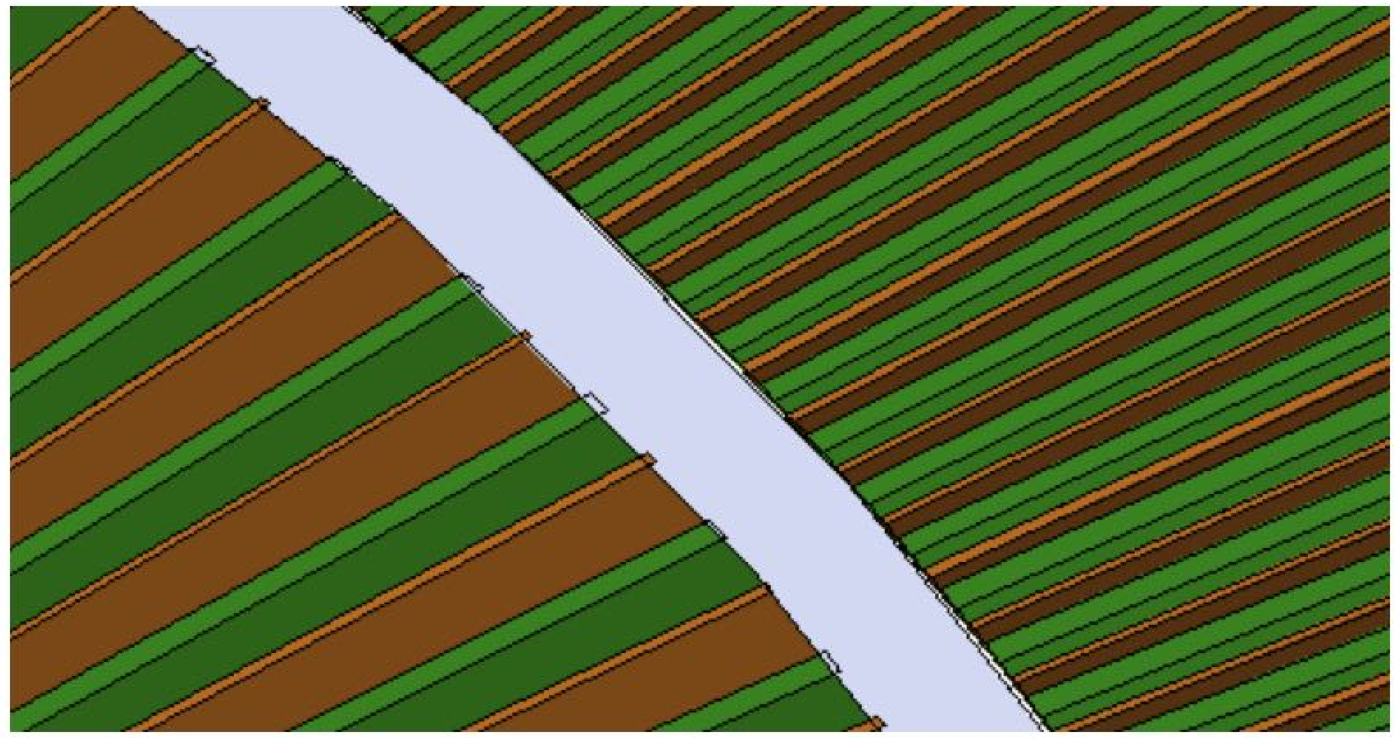
ECAL endcap

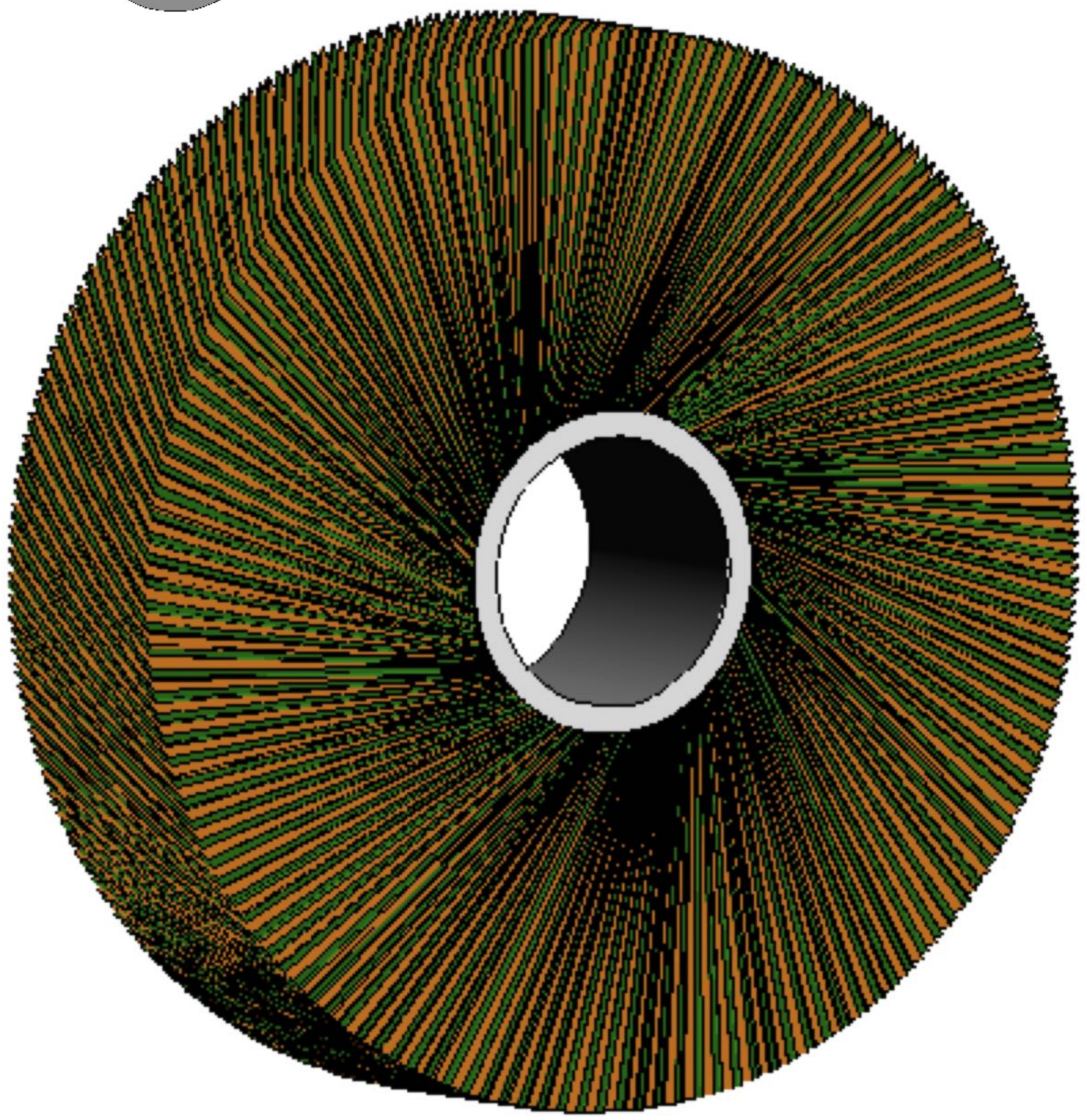
- Endcap design more complex than barrel. A few preliminary ideas on the table. Showing here the baseline one, implemented in the simulation ("Turbine design"), see <u>here</u> for alternative ideas
    - similar to barrel design, with many thin absorber plates
    - symmetric in ϕ
    - readout from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











HCAL barrel

- Currently being simulated: TileCal-like design
    - 5mm steel absorber plates alternating with 3mm scintillator plates
    - 128 modules in ϕ, 2 tile/module → $\Delta\phi = 0.025$
    - $\Delta\theta \sim 0.022$ (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