Status of calorimeter simulation in the FCC framework

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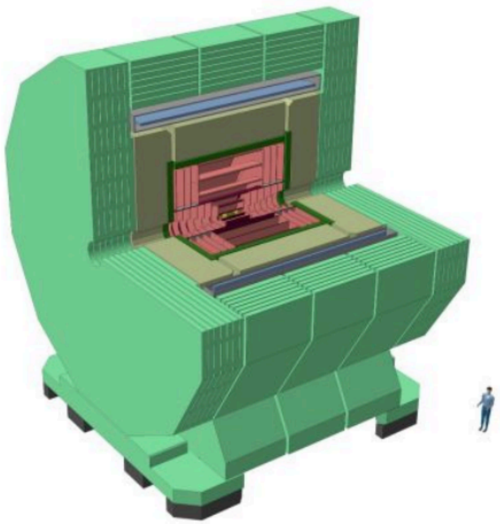
Istituto Nazionale di Fisica Nucleare

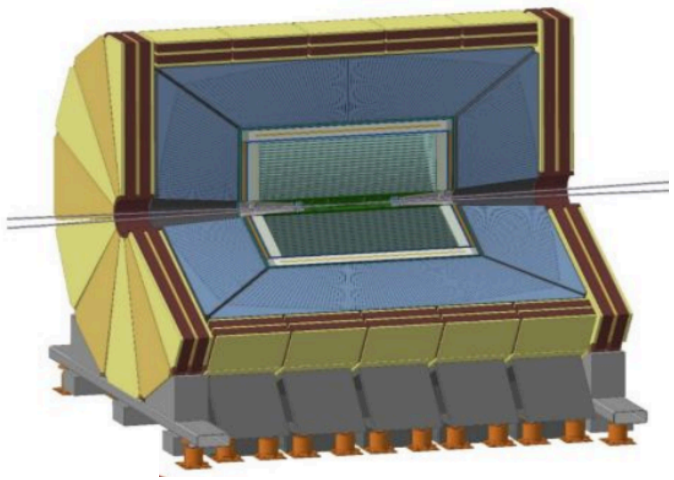
Outlook

- The aim of this short presentation is to spark discussion on calorimetry activities in the FCC software
- This parallel session will cover many calorimetry aspects
  (performances on physics benchmarks, detector designs, test-beam results, …)
- Here the focus is on the FCC software tools:
  namely geometries and reconstruction tools for IDEA, ALLEGRO and CLD

CLD



IDEA



ALLEGRO

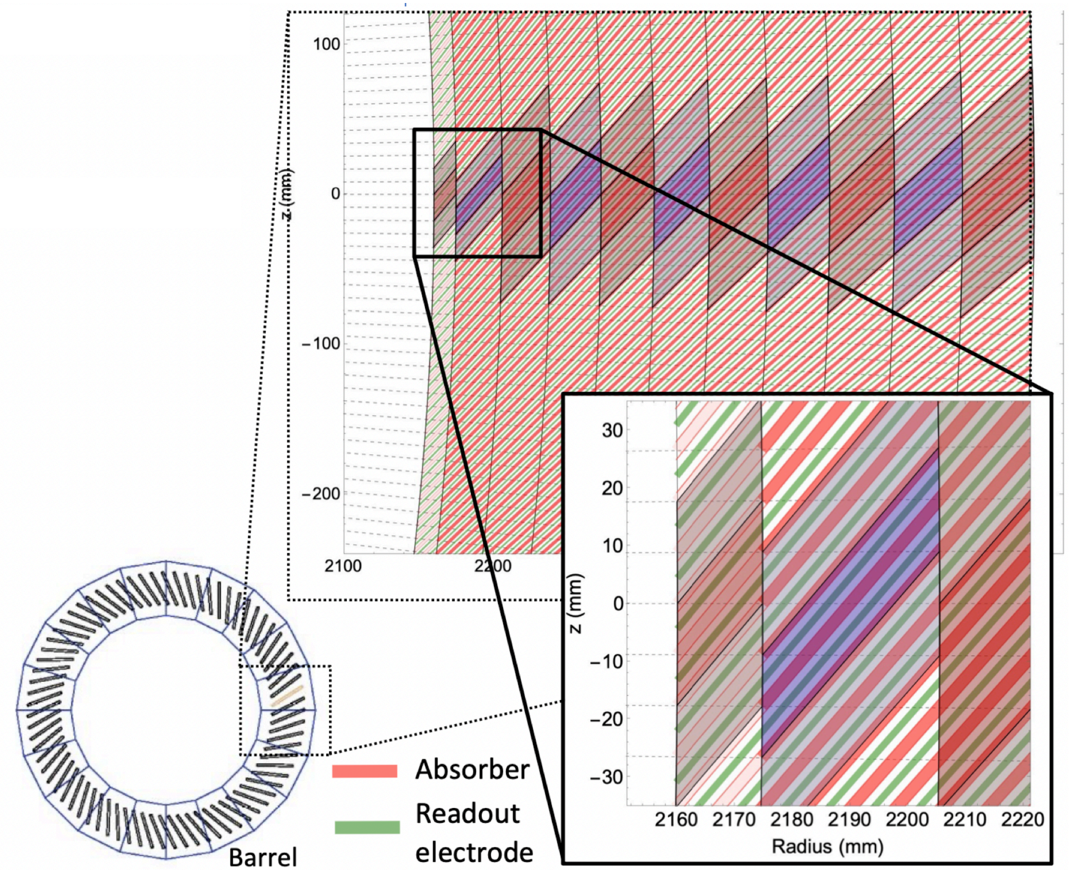
More at M. Mlynarkova 2024 ECFA Workshop talk

Calorimetry @ALLEGRO

- The ALLEGRO calorimeter design
  - Highly-granular LAr calorimeter inside a 2 T solenoid
    - baseline Pb+LAr (with denser option W+LKr)
    - Light coil (0.76 X_0) inside same low-material cryostat (< 0.1 X_0) as ECal
  - TileCal like hadronic calorimeter after the solenoid
    - baseline WLS fibers with SiPM readout at outer radius
    - or with CALICE-like SiPM-on-tile readout
- Status within FCC full-sim
  - DD4hep barrel geometry well established and available in k4geo/ALLEGRO_o1
  - DD4hep endcap geometry also available but more prone to changes

ALLEGRO ECAL

- Barrel:
  - 1536 2-mm-thick straight Pb absorbers (inclined at 50.4°) and 1.2-2.4 mm LAr gaps
  - 11 longitudinal compartments, 40 cm deep (~22 X_0)
  - $\Delta\theta$ ~ 10 (2.5) mrad for regular (strip) cells, $\Delta\phi$ ~ 8 mrad
  - Variations to be explored: LKr active medium, W absorbers, absorber thickness and outer radius, absorber shape (straight or tapered)



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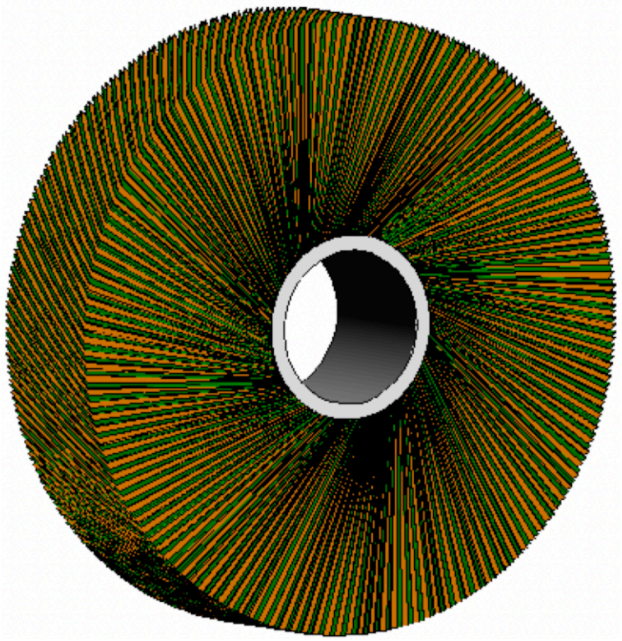
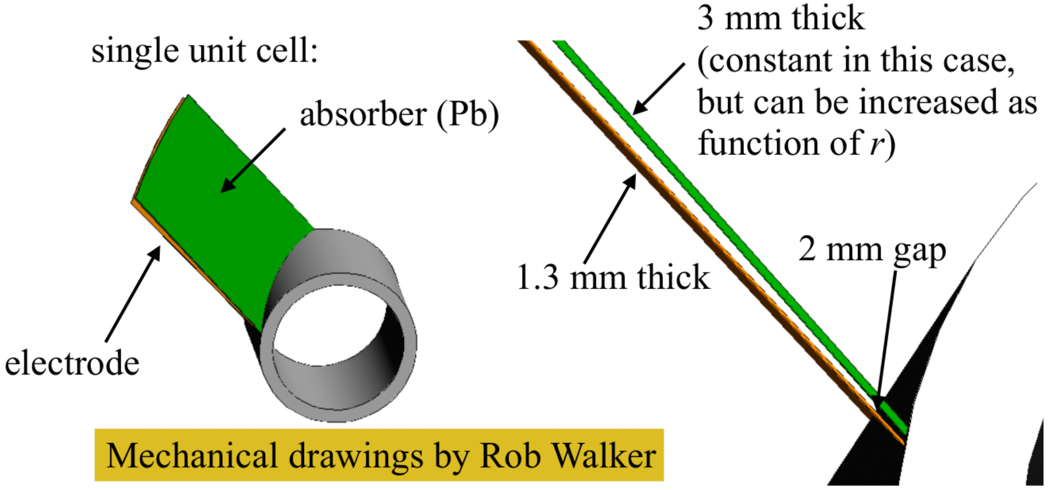
- Endcap:
  - Endcap region more complex than barrel one, a k4geo ϕ-symmetric *Turbine* calo is being implemented
    - LAr gaps thickness increases with the radius → non-uniformity of the sampling fraction and response
    - Possible solutions: three concentric wheels with different number of absorbers or tapered absorbers with increasing thickness

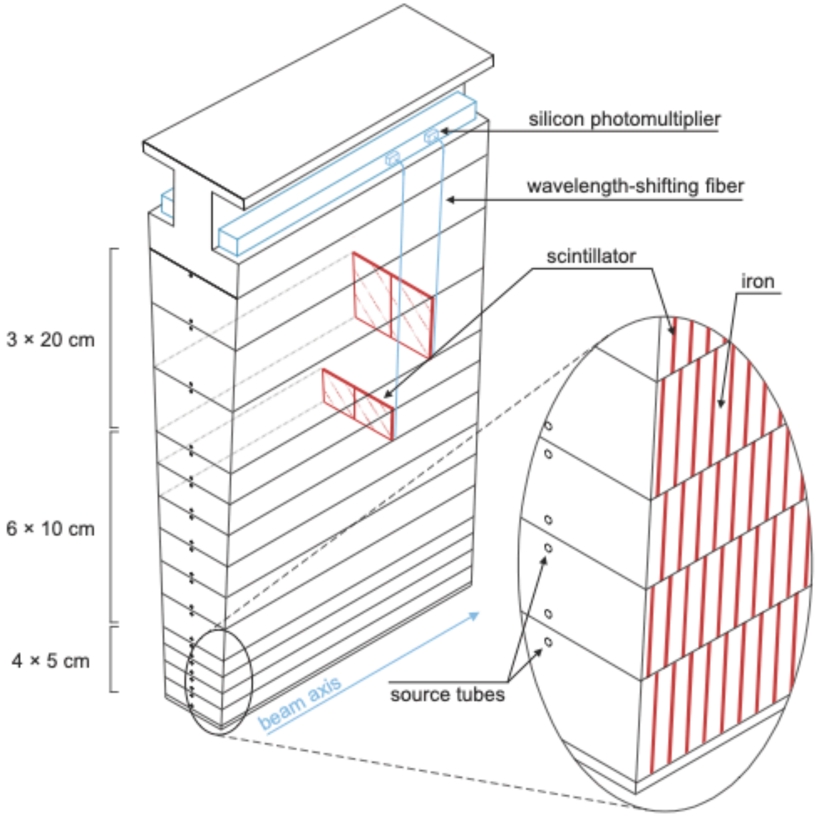




Mechanical drawings by Rob Walker

ALLEGRO HCAL

- TileCal-like design fully implemented in k4geo
  - W.r.t. FCC-hh the Pb plates were removed as the HCAL acts as return yoke for the central solenoid
- Barrel:
  - 5 mm steel absorber plates alternating with 3 mm scintillator plates
  - 13 radial layers in the barrel region, 140 cm length (8-9 λ)
  - segmentation of $\Delta\theta$ ~ 2 mrad (grouping 3-4 tiles along z), 128 modules in ϕ using 2 tile/module $\rightarrow \Delta\phi$ = 25 mrad



More at M. Mlynarkova FCC Full Sim meeting talk

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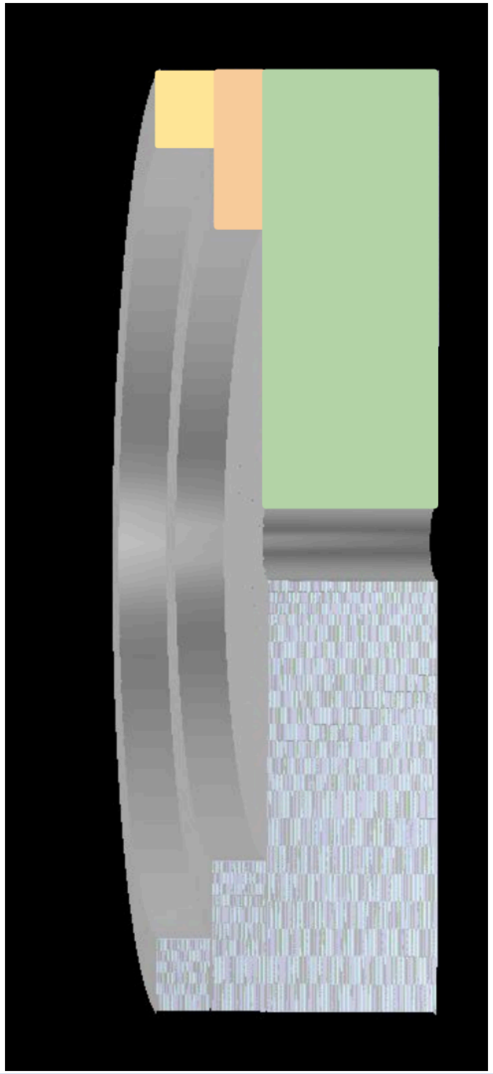
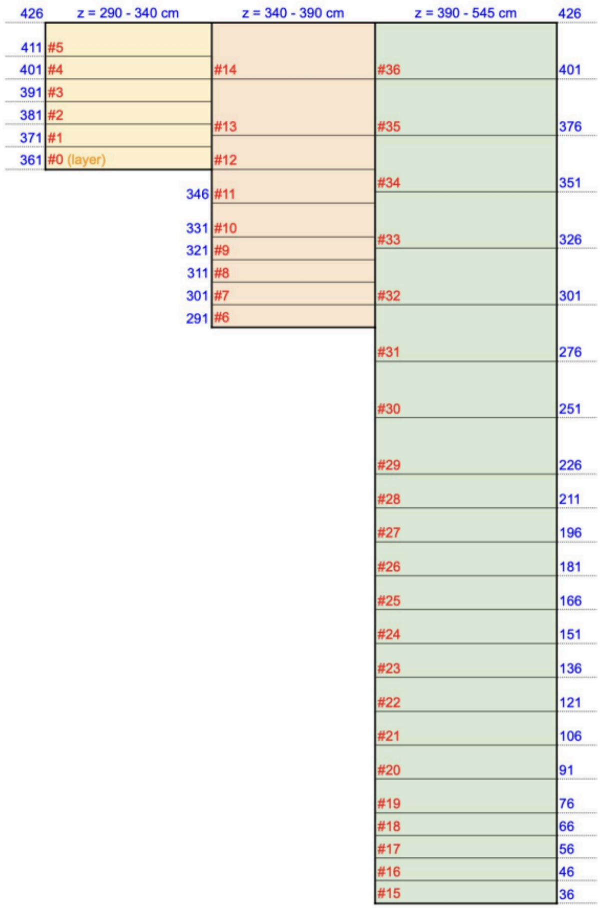
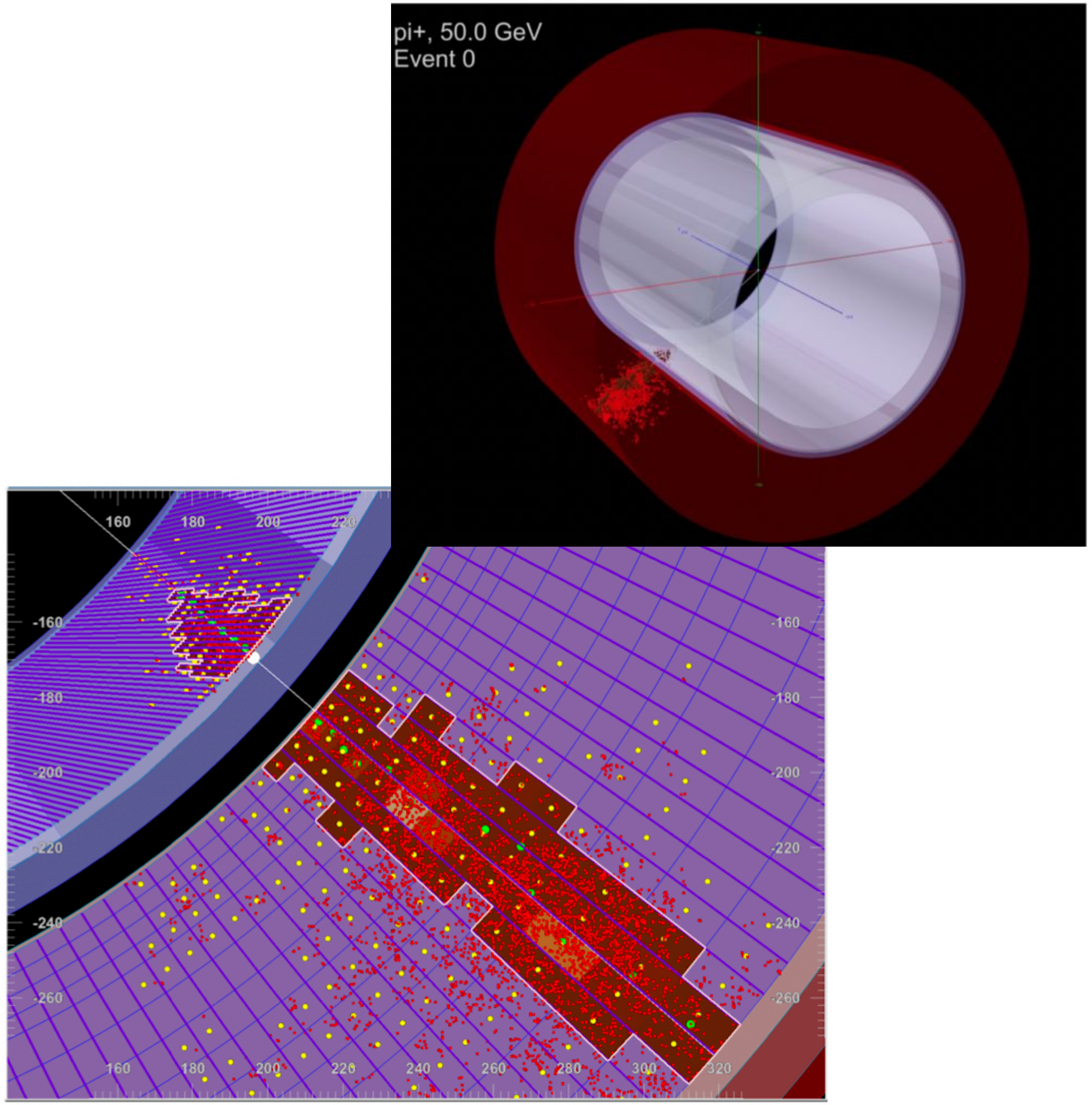
- Endcap:
  - 6 - 9 - 22 radial layers fo the endcap





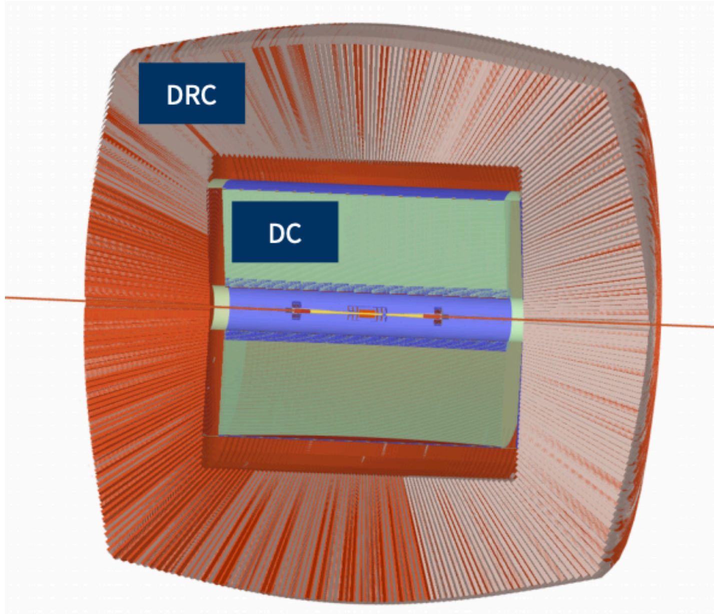
ALLEGRO calorimetry tools

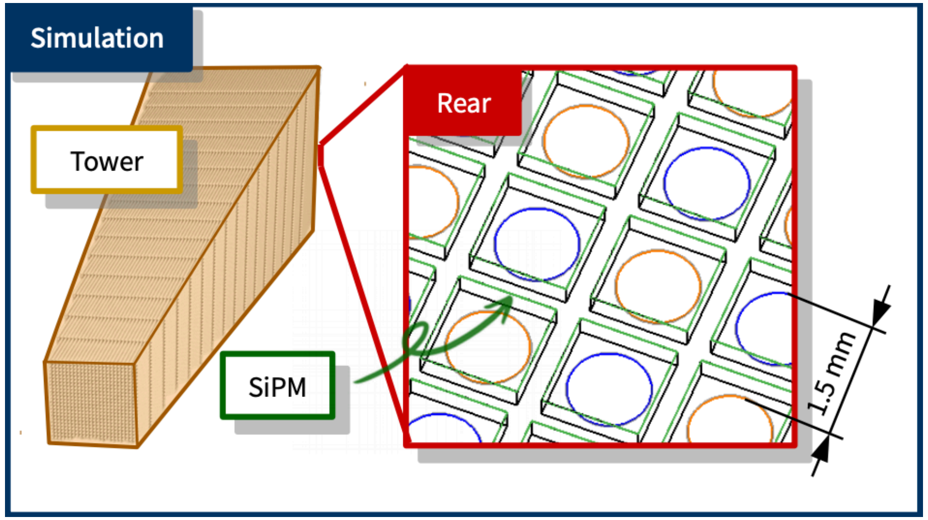
- Reconstruction:
  - Both sliding window and topological clustering working in the barrel region
    - Implemented for standalone HCAL and ECAL+HCAL simulation of single particles
    - Currently the topological clustering is being implemented for the end-cap region
- Calibration:
  - Implemented MVA calibration of cluster energy, using boosted decision tree (BDT), and compared to cell-based approximate calibration using 100 GeV π^- $\rightarrow$ constant term in had energy resolution improved
- To be done:
  - Combine ECal and HCal calorimeter information with particle flow algorithms



Monolithic dual-readout calo @IDEA_o1

- Optical-fiber dual-readout calorimeter implemented in k4geo as IDEA_o1
  - *Monolithic* as fibers are *simply inserted* in copper-based towers (trapezoids)
  - measure both electromagnetic & hadronic components with two different channels
    → excellent energy resolution for hadrons via event-by-event dual-readout correction
  - Projective geometry with a uniform sampling fraction
    - more fibers in the rear than the front
  - Longitudinally unsegmented

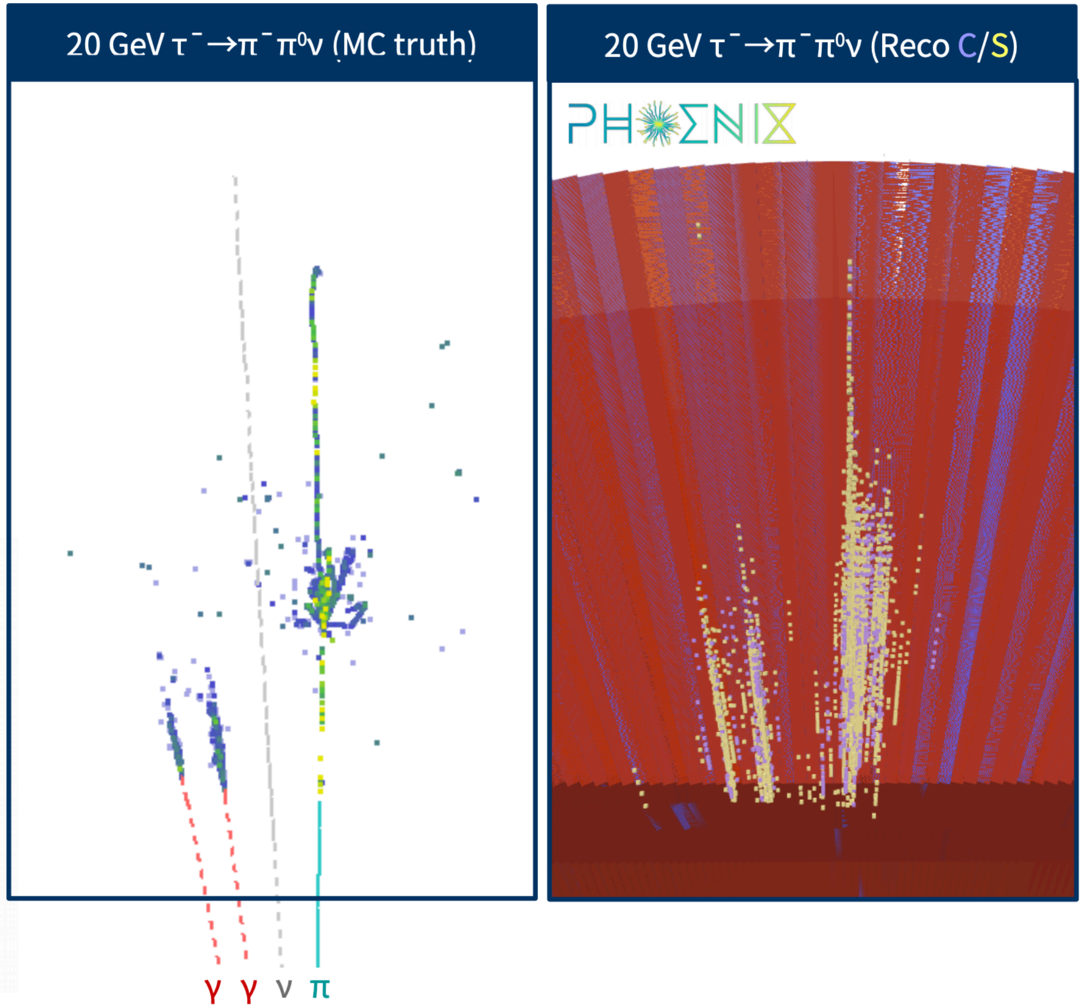




More at S. Ko 2023 FCC Week talk

Monolithic dual-readout calo @IDEA_o1

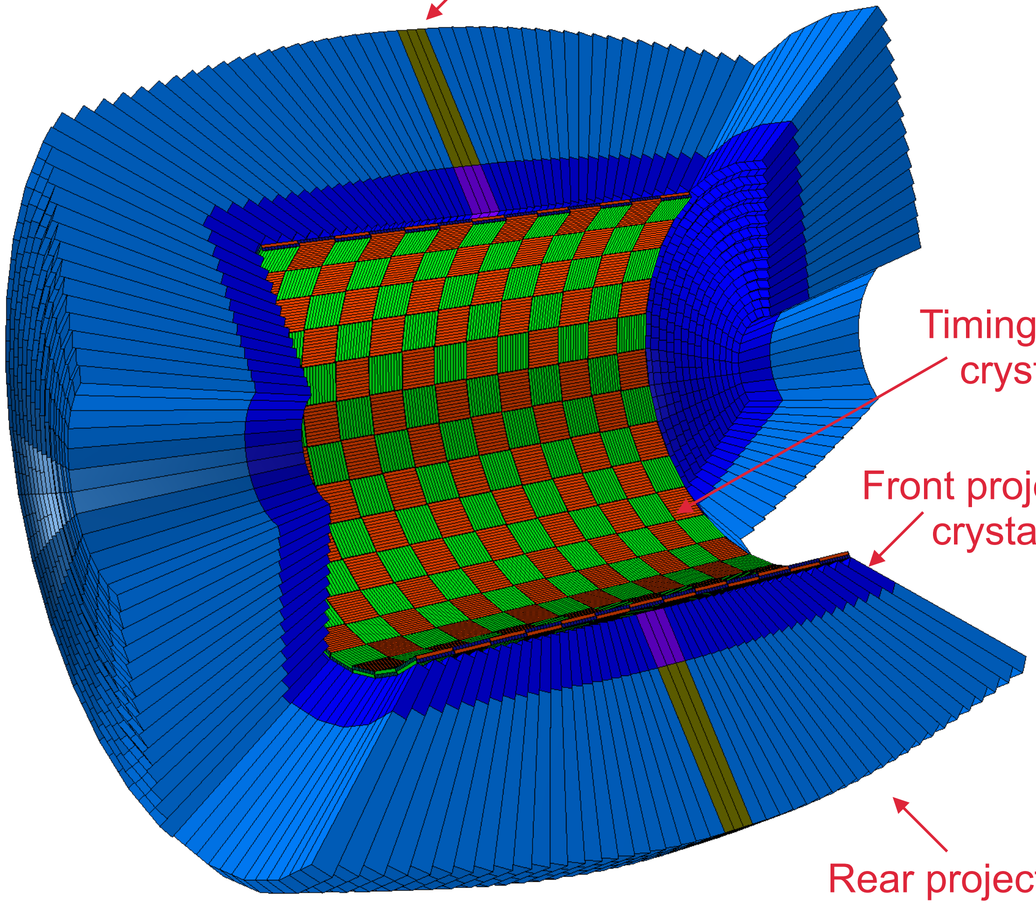
- Digitization:
  - A SiPM simulation library is developed using
  - parameterized inputs from the datasheet (dark counts, crosstalk, afterpulses, saturation, noise, …) and
  - included in the key4hep stack as an external library
- Reconstruction:
  - Reconstruction codes are implemented as Gaudi algorithm including a novel 3D reconstruction using Fourier analysis with timing information from SiPM signals
  - Isolated hits position successfully reconstructed along fibers → excellent example of timing in calorimetry



Dual-readout crystals @IDEA_o2

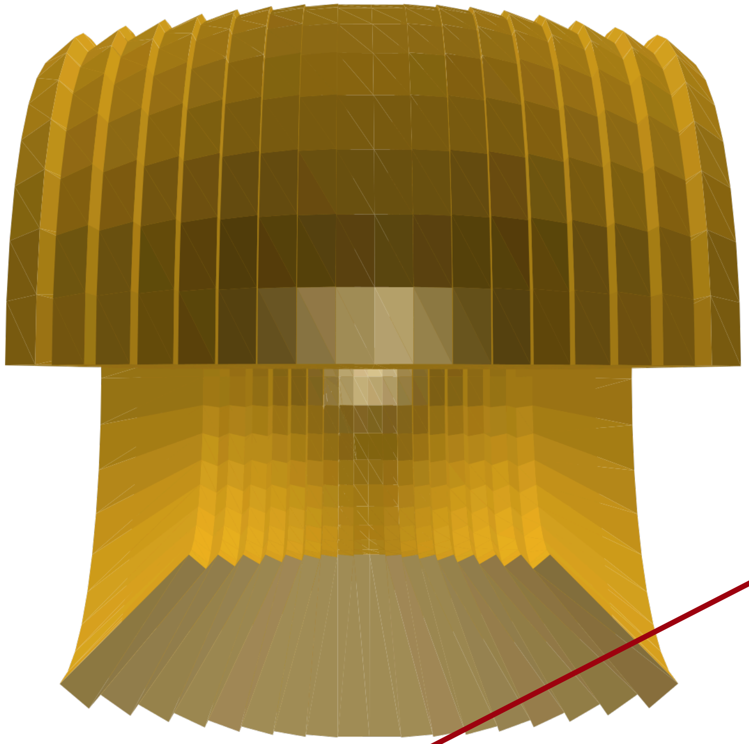
Segmented Crystal Electromagnetic Precision Calorimeter (SCEPCal):

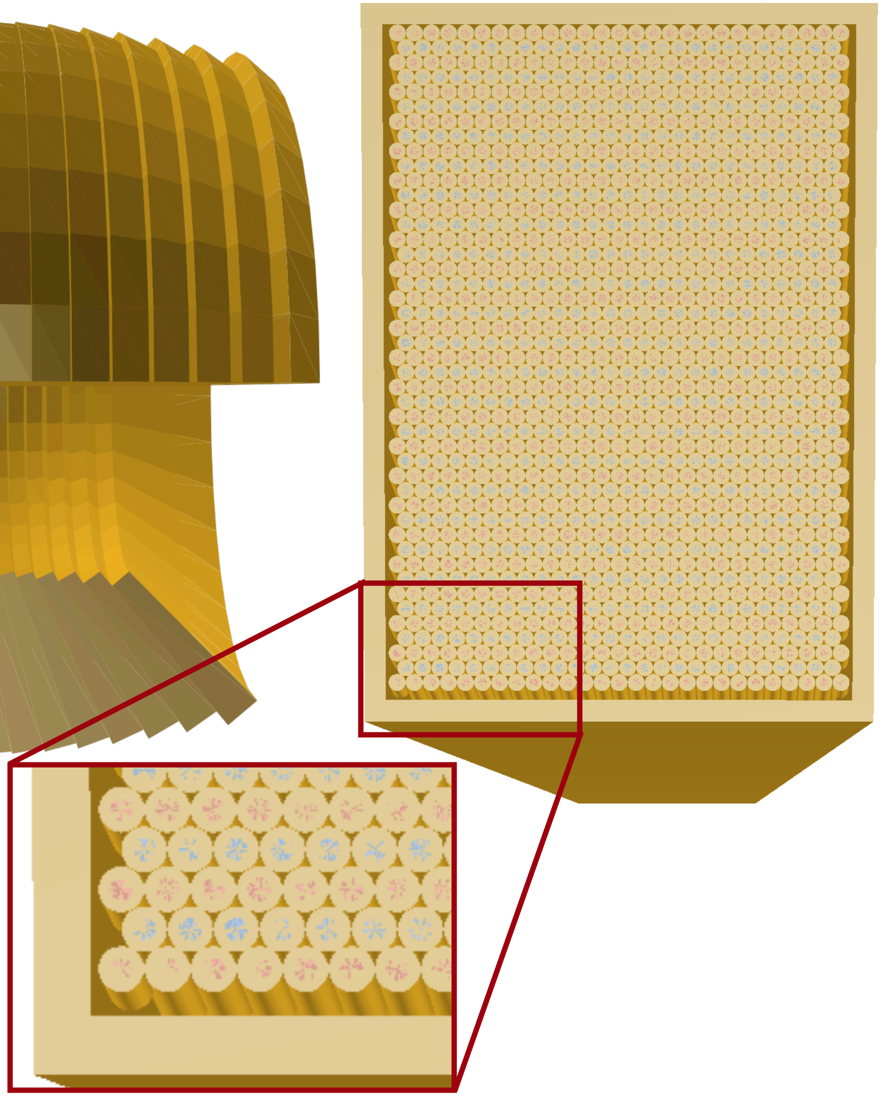
- ✦ Projective homogeneous ($PBWO_4$) crystal calorimeter:
  - Each crystal is longitudinally segmented with front/rear section (6:16 ratio 22 X_0 (~20 cm))
  - Dual-readout capability ensured by two dedicated SiPMs instrumented on the rear section
  - Timing layer placed in front comprises two layers of fast-scintillating LYSO crystals with opposite orientation
  - New DD4hep implementation recently carried out [github]
    - To be added together with the dual-readout tubes calo in k4geo towards IDEA_o2



Tubes-based dual-readout calo @IDEA_o2

- Novel dual-readout calorimeter design using
  - a new construction technique housing optical-fibers into capillary-tubes
  - A first prototype was tested at CERN and used to validate em-shower simulation [article]
  - A new prototype, named Hidra, is being built and tested at CERN (see A. Pareti's talk)





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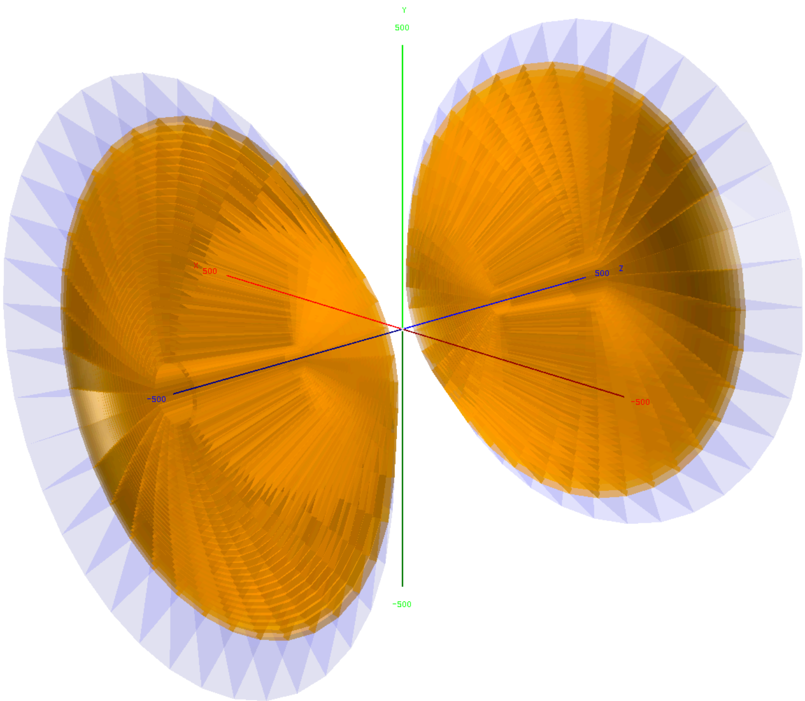
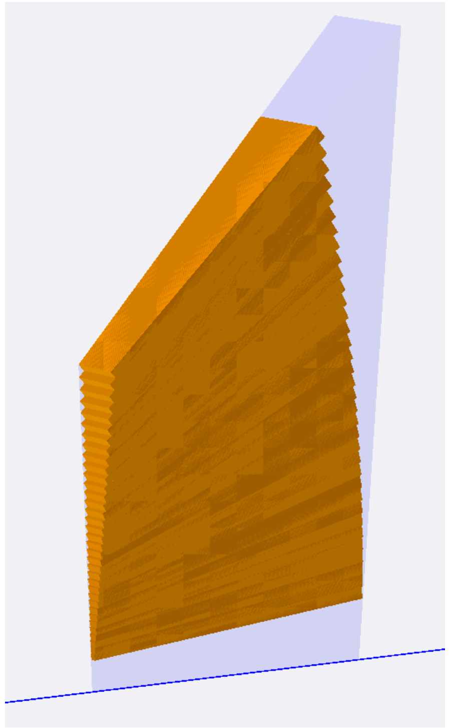
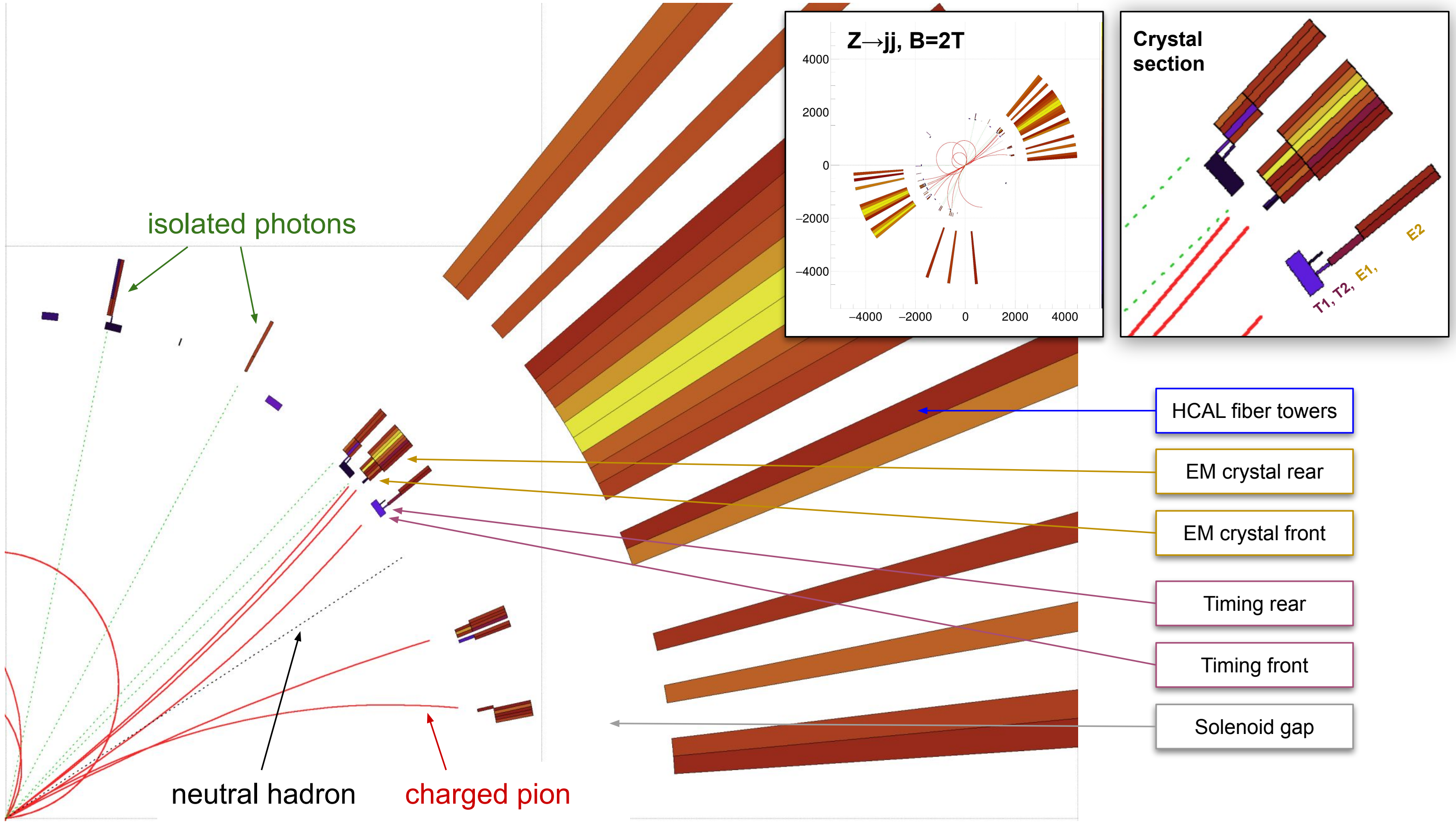
  - A new prototype, named Hidra, is being built and tested at CERN (see A. Pareti's talk)
- DD4hep geometry leveraging this design has been proposed for both the barrel and the endcap
  - Extensive cpu time to propagate showers in this geometry has been reduced to $\simeq 7$ s/evt for 100 GeV e^-
  - Next goal is to explore clustering with available algorithms





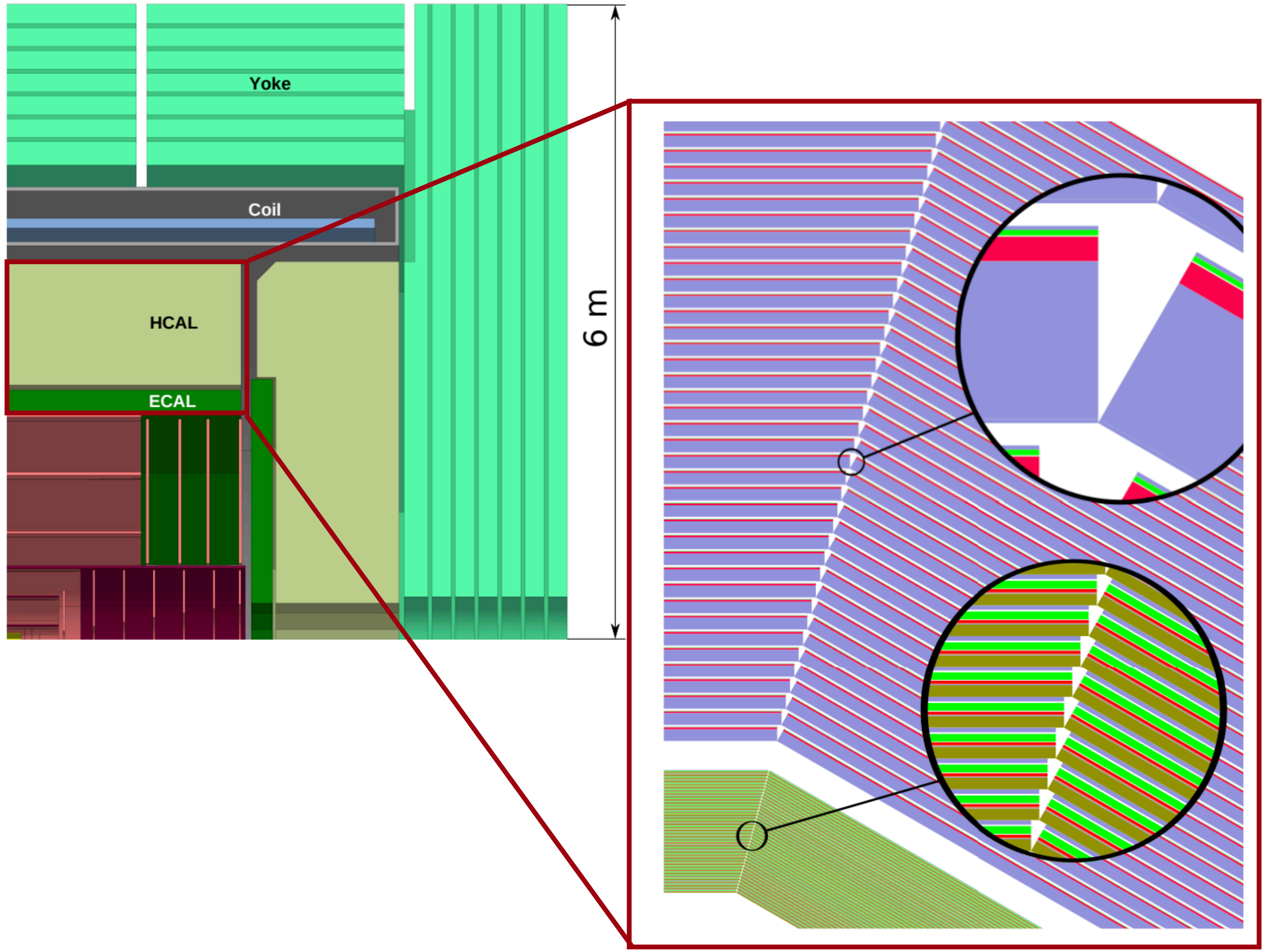
Dual-Readout Particle Flow studies for IDEA_o2

- A 2022 article explored a dual-readout Particle Flow algorithm to combine calo-clusters and tracks in a longitudinally segmented dual-readout calorimeter (almost identical to the IDEA_o2 design)
- Even with just two sections, clear cluster-tracks matching was possible and an improvement in the energy resolution (w.r.t. dual-readout performance) was found
- It would be nice to repeat this study in key4hep using IDEA_o2



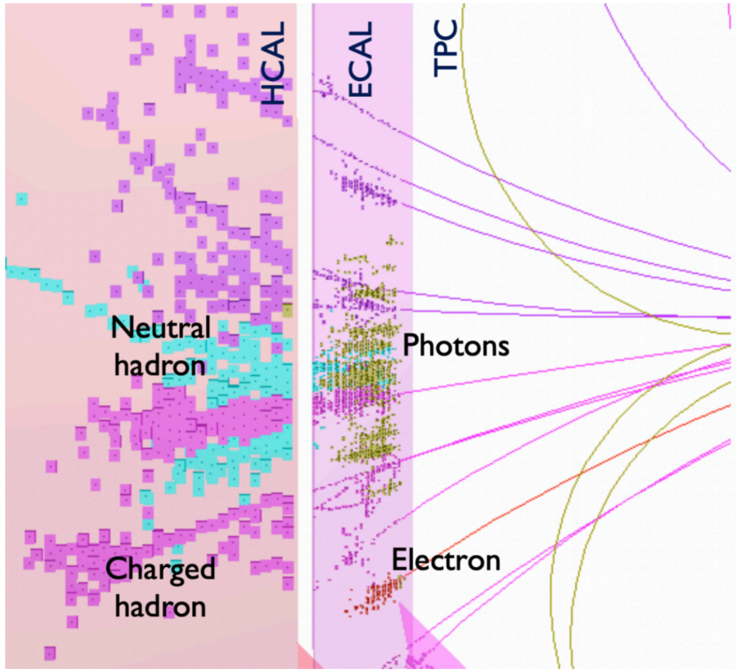
Calorimetry @CLD

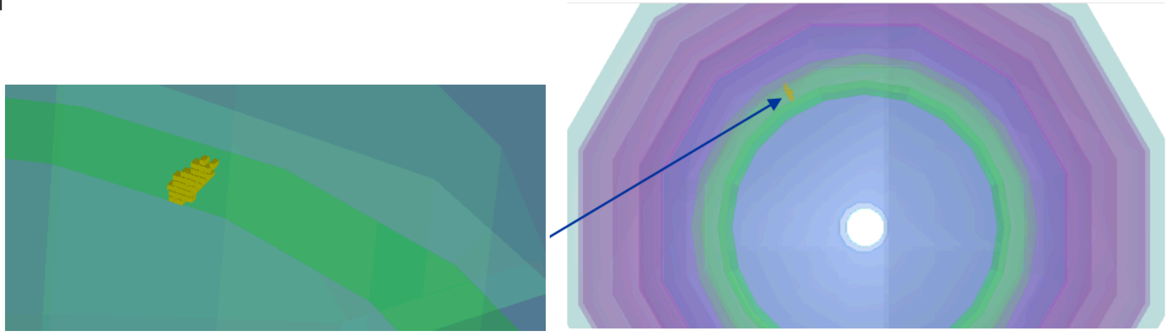
- Well-established calorimeter simulation in key4hep optimized for reconstruction with Particle Flow Algorithms
  - Short calo fully inside the solenoid
- ECAL:
  - 40 layers (22 X_0 deep) of 1.9 mm tungsten absorber, and
  - 0.5-mm-thick silicon sensors with 5×5 mm^2 granularity
- HCAL:
  - 44 layers (5.5 (+1) λ) of 19 mm steel absorber, and
  - 3-mm-thick scintillator tiles with 3×3 cm^2 granularity



Pandora Particle Flow @key4hep

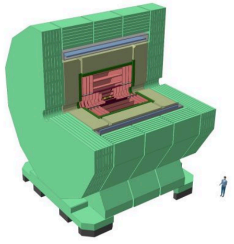
- CLD calo reconstruction uses the Pandora Particle Flow Algorithm (PandoraPFA) by CALICE
- Integration of PandoraPFA in key4hep is ongoing in order to use it across multiple detector models
  - Study of PandoraPFA are being conducted on Nobel Liquid Argon Calorimeter of FCC, with some delicate aspects, *e.g.*
    - Pandora uses radiation lengths and other material properties to determine shower shapes, but
    - ALLEGRO ECAL has a very different geometry w.r.t. CLD → dynamic methods are used to retrieve such information
  - First PandoraPFOs could be observed for the LAr Calorimeter but more work is needed to correctly reconstruct its energy





Status of calorimetry in the FCC framework*

CLD



Geometry → Single particle reco → Full reconstruction using PandoraPFA

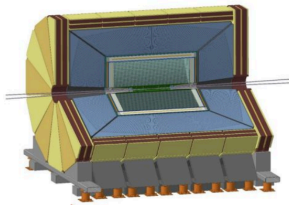
ALLEGRO

Geometry → Single particle reco → Next(?)

endcap geometries might need additional work

Improve energy reconstruction of PFObjects, combine ECAL and HCAL information with tracks information

IDEA



o1: Geometry → Single particle reco → Next(?)

Efficient usage of $O(10^8)$ fibers

o2: Geometry → Next(?)

Clustering on dual-readout ECAL and HCAL sections, maybe porting DR Particle Flow to key4hep?