Design and performance of the calorimeter system for ALLEGRO FCC-ee detector concept

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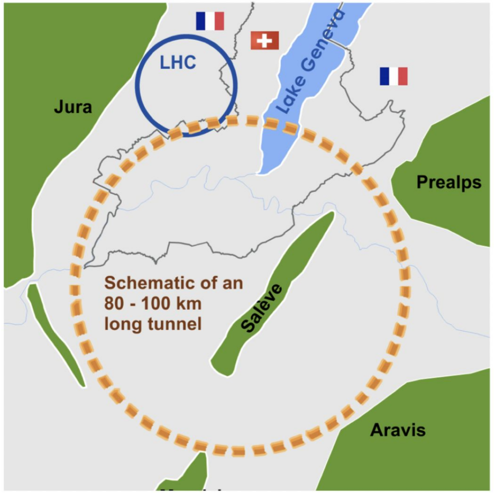
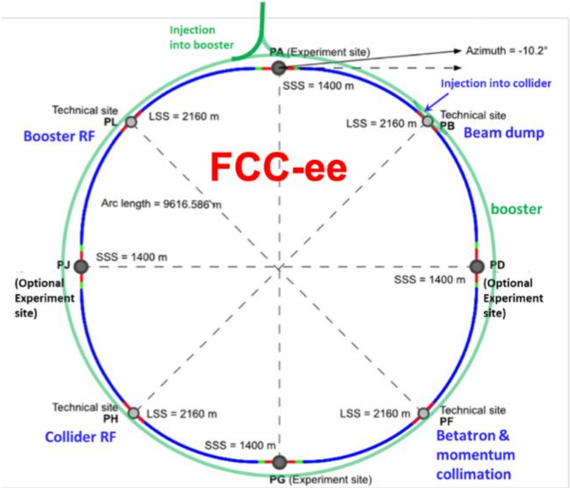
on behalf of the ALLEGRO team

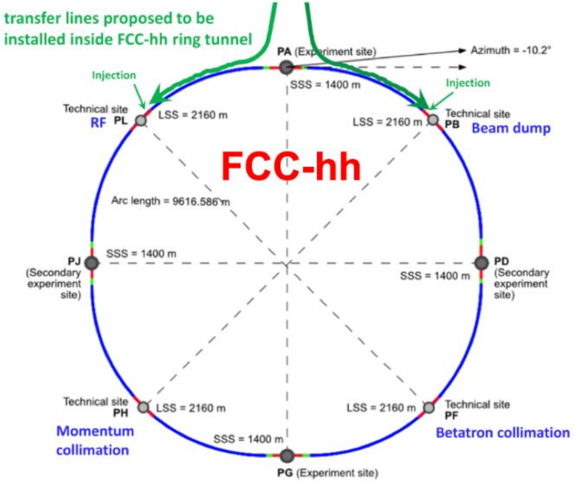
CALOR 2024

The Future Circular Collider

- International FCC collaboration (150 institutes, 34 countries)
- Stage 1: FCC-ee (Z, W, H, tt) as Higgs factory, electroweak & top factory at highest luminosities
- Stage 2: FCC-hh (~100 TeV) as natural continuation at energy frontier
- common civil engineering and technical infrastructures, building on and reusing CERN’s existing infrastructure



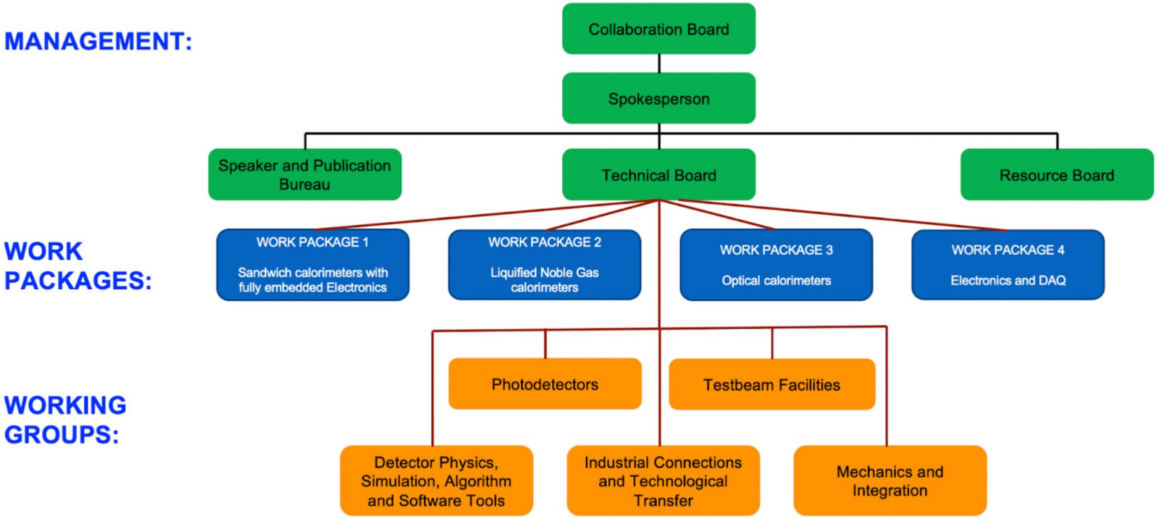




- 2040 | 2045 - 2060 | 2070 - 2095

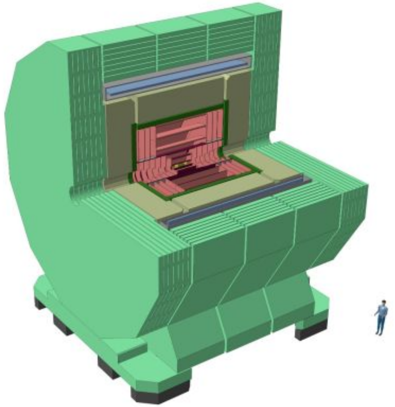
DRD6 Collaboration

- **Detector R&D (DRD) collaborations** being set-up to implement the **ECFA detector R&D Roadmap**
- **DRD6 on calorimetry** with 4 work packages (WP) and several transversal activities
  - Noble Liquid Calorimeter R&D part of WP 2 (18 institutes from 7 countries)
  - TileCal R&D part of WP 3 (7 institutes from 6 countries)
  - CALICE-like AHCAL part of WP 1 (10 institutes from 4 countries)
- DRD Proposal has been submitted, implementation beginning of 2024

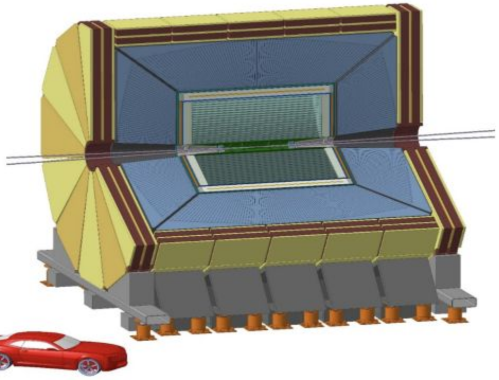


FCC-ee detector concepts under study

CLD



IDEA



ALLEGRO
("Noble-liquid based")

- Well established design
- ILC → CLIC → CLD
- Full Si vtx + tracker; CALICE-like calorimetry; large coil, muon system

- Less established design, but still ~15y history
- Si vtx detector, ultra light drift chamber w powerful PID, compact light coil, monolithic dual readout calorimeter, muon system

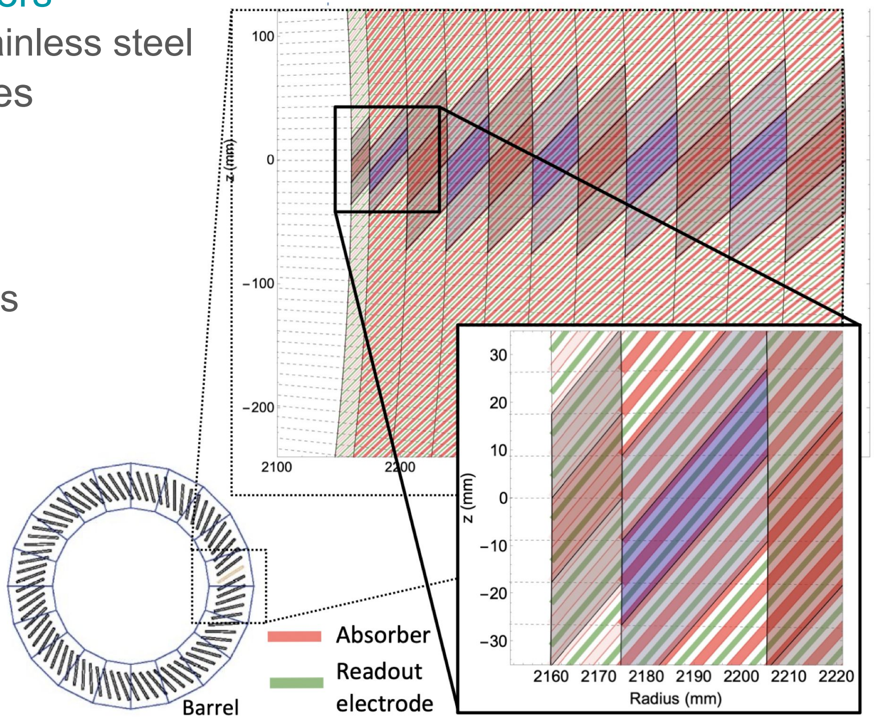
- New kid on the block
- Drift chamber, high granularity Noble Liquid ECal, TileCal-like or CALICE-like HCal, muon system

ALLEGRO detector concept and its calorimeters

- **A L**epton co**L**lider **E**xperiment with **G**ranular **R**ead-**O**ut
- Highly-granular noble liquid ECal inside solenoid
  - Pb/W+LAr (or denser W+LKr)
  - Coil inside same cryostat as LAr
- TileCal-like or CALICE-like HCal outside solenoid
  - Light coil (0.76 X_0) + low-material cryostat < $0.1X_0$
  - WS fibres+SiPMs outside or SiPMs directly on scintillators
- Detector design optimisation not complete → presenting preliminary results that will likely change over time

ECal barrel

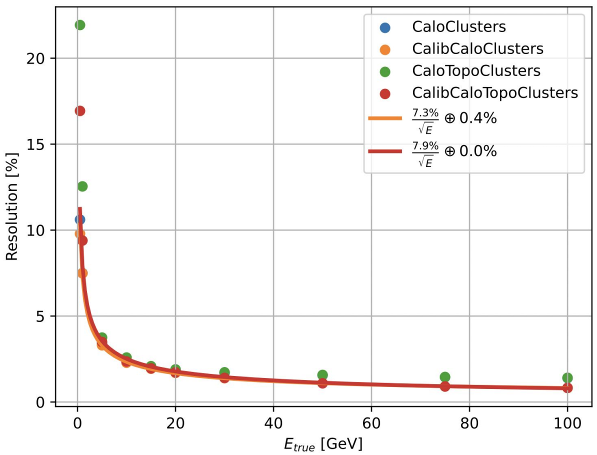
- **Baseline design** (exact parameters subject to further optimisation):
  - 1536 straight inclined (50.4°) 2 mm absorbers
    - 1.8 mm Pb, 0.1 mm glue and 0.1 mm stainless steel
  - Multi-layer PCBs used as readout electrodes
  - 1.2-2.4 mm LAr gaps
  - 40 cm deep (≈ 22 X_0)
  - Segmentation
    - $\Delta\theta$ ~ 10 (2.5) mrad for regular (strip) cells
    - $\Delta\phi$ ~ 8 mrad
  - 11 longitudinal compartments (in depth)

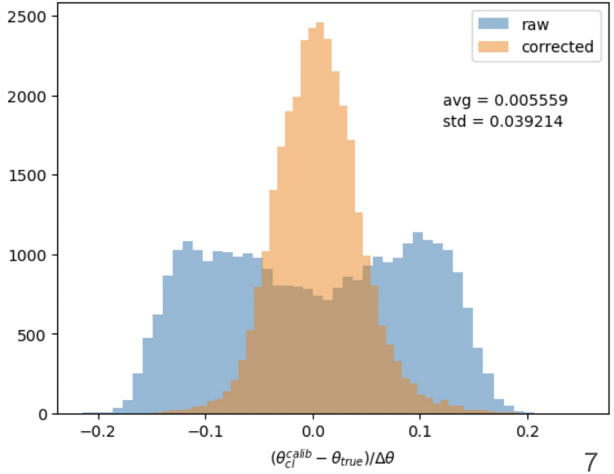


- **Possible Options**
  - LKr or LAr active medium
  - W or Pb absorbers
  - Al or carbon fibre cryostat
  - Absorbers thicker at outer radius

ECal barrel simulation

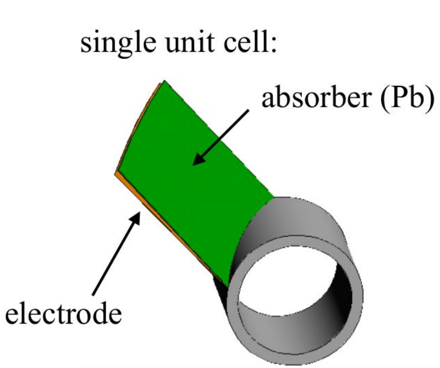
- EM resolution with a sampling term of 7-8%
- Flexible geometry implemented in FCC-SW Full sim
- Benchmark for geometry optimization: photon/π^0 separation
- **Calibrations** of reconstruction
  - Simple MVA energy regression of EM clusters
  - Per layer correction for cluster barycentre position
- First tests ongoing of Pandora **Particle Flow** (arXiv:1308.4537)
  - For technical reasons, pioneered in detector simulation with ALLEGRO ECal + CLD Tracker

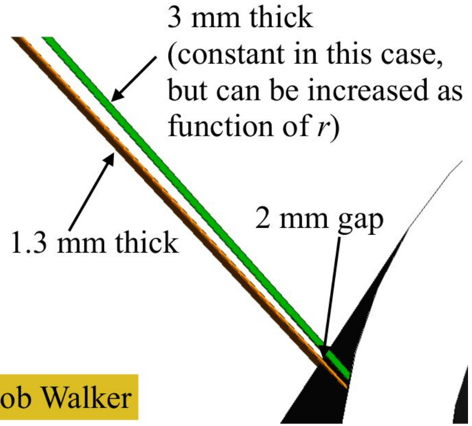




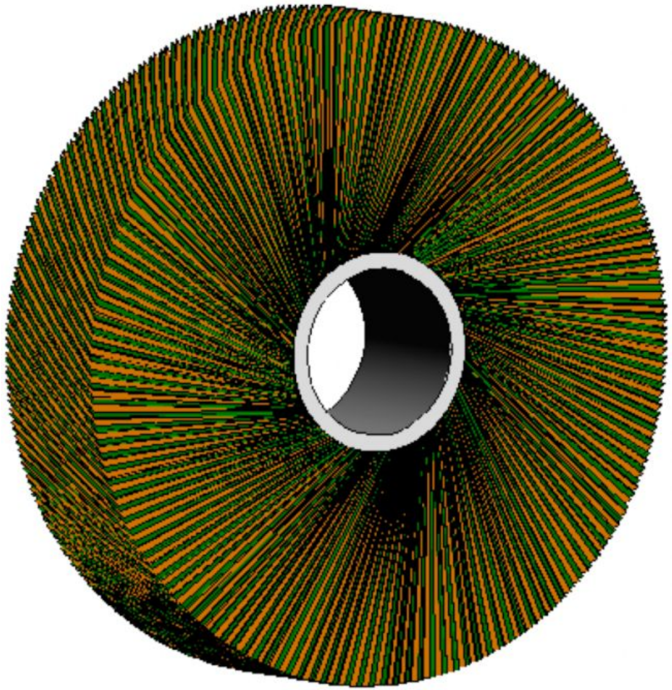
ECal endcap

- Endcap design more complex than barrel. A few preliminary ideas on the table. Showing here one being implemented in the simulation ("Turbine design")
  - Similar to barrel design, with many thin absorber plates
  - Symmetric in ϕ
  - Readout from high-|z| face
  - Exact parameters are subject to optimization
  - Issue: increase in the size of the LAr gaps
    - Mitigated by nesting several cylinders





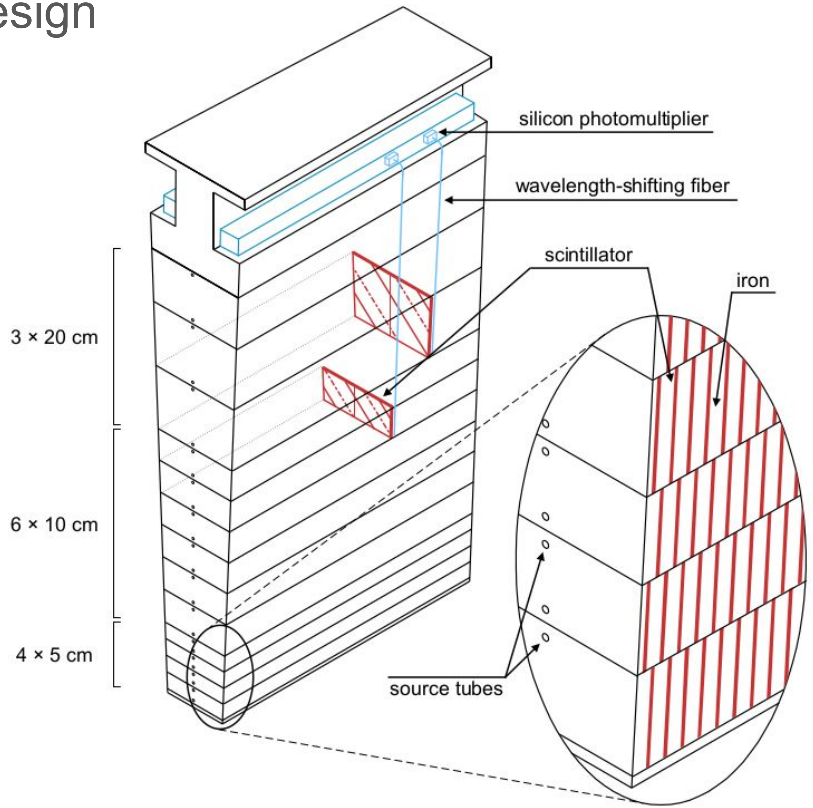
Mechanical drawings by Rob Walker



HCal barrel

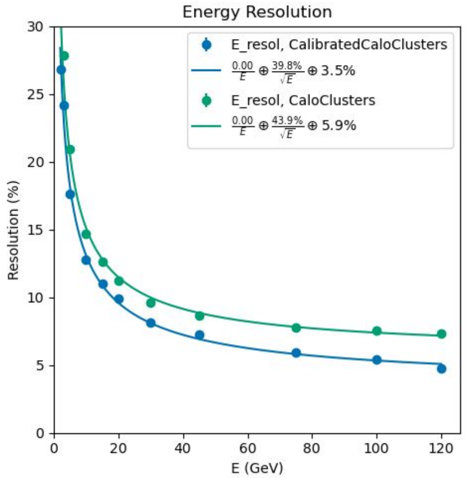
- Currently being simulated: **TileCal-like** design
  - 5mm steel absorber plates alternating with 3mm scintillator plates
  - 1400mm deep (8-9 λ)
  - Segmentation
    - $\Delta\theta$ ~ 22 mrad (grouping 3-4 tiles)
    - 128 modules in ϕ,

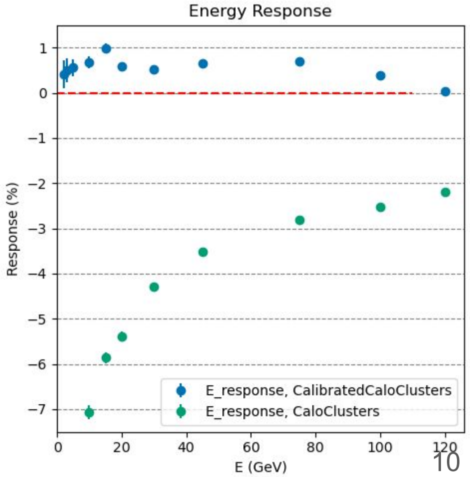
      2 tile/module → $\Delta\phi$ = 25 mrad
  - 13 radial layers (4x5 cm, 6x10 cm, 3x20 cm)
  - Removed the Pb plates compared to FCC-hh design (HCal acts as return yoke for the central solenoid)



HCal barrel simulation

- Implemented MVA calibration of cluster energy, using boosted decision tree (BDT)
  - Inputs: total cluster energy $E_{cluster}$ and energy per layer → $E_i/E_{cluster}$
  - Regression target: $E_{true}/E_{cluster}$
  - Trained on 1M single π^-, flat energy distribution (100 MeV-120 GeV)
  - Tested on samples (10k each) of π^- of fixed energy (2-120 GeV)
  - Optimised BDT hyperparameters and event weights for training
  - Run over sliding window 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 $(E_{cluster}-E_{true})/E_{true}$ → within 1%



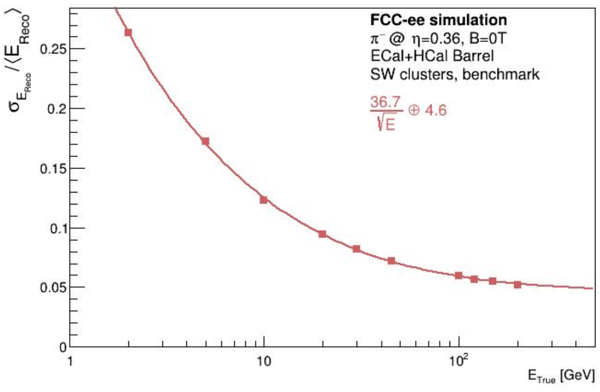


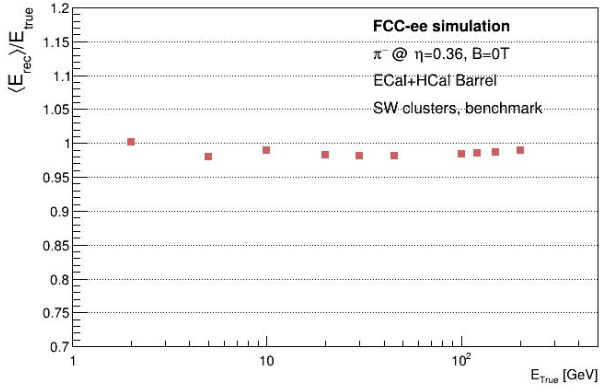
ECal+HCal barrel combined simulation (I)

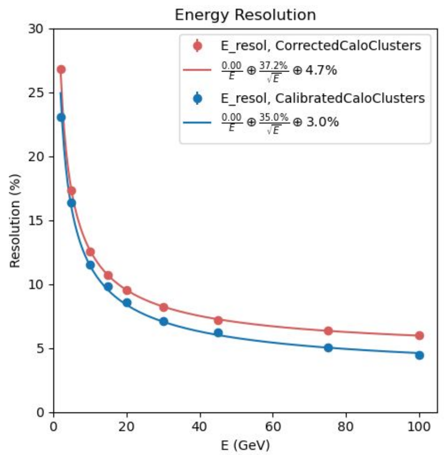
- The goal is to combine ECal and HCal calorimeter information (and later add tracker and do particle flow)
- Tested two approaches for energy calibration of sliding window clusters
  - Using cell-based calibration developed for ATLAS test-beams

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

  - Using MVA calibration (similar to HCal standalone)
    - Constant term decreases from 4.7% to 3.0%, response linearity within 1%

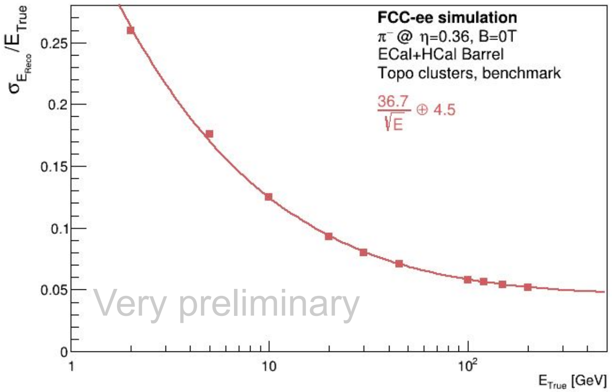


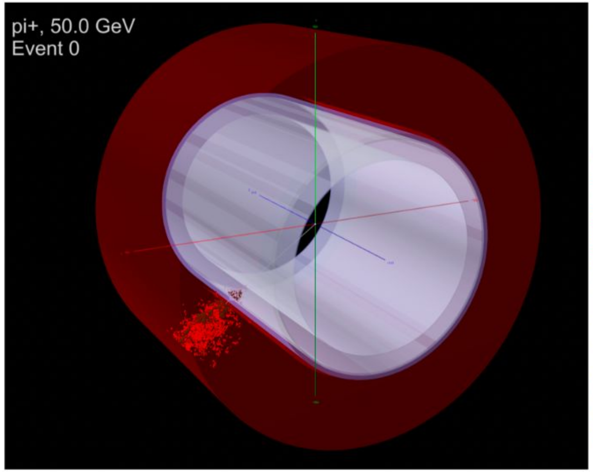


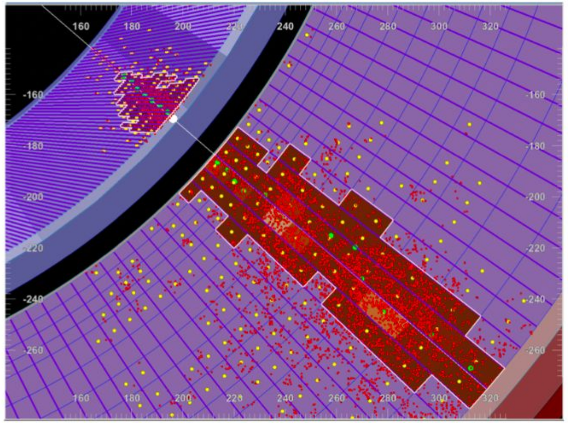


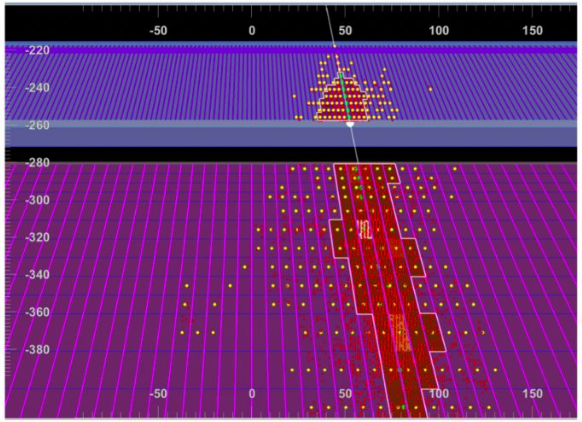
ECal+HCal barrel combined simulation (II)

- Topological clustering has been recently implemented
  - Requires to find out neighbouring relations among cells of outermost ECal layer and innermost HCal layer
  - The algorithm selects cells based on their E/noise ratio
    - Need expected noise per cell







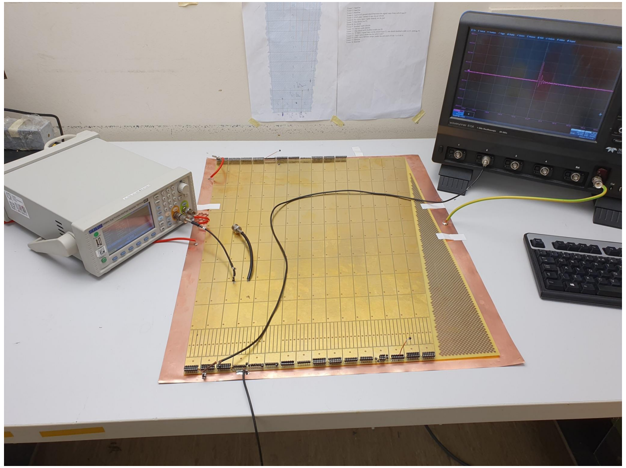


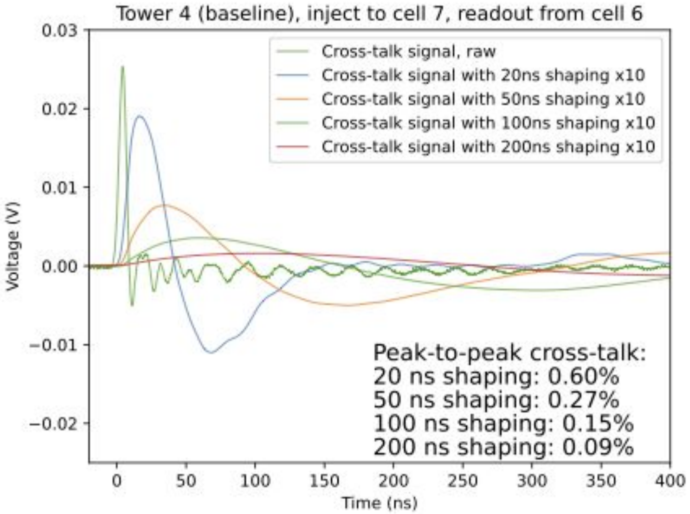
The road towards ECal test beam prototype

- Printed circuit board (PCB) technology allows "arbitrarily" high granularity
  - Signal traces inside the electrode
- First large-scale prototype PCB 58cm×44cm was built
  - Split to 16 θ-towers & 12 depth layers
  - Narrow strips in front for π^0 detection
  - 240 cells in total in the first prototype
  - Read-out from inner and outer edge
- First prototype of two absorbers built as well
  - Tested in liquid nitrogen bath
- Test-beam prototype with 64 layers by 2027-28
  - 64 electrodes and absorbers
  - Placed in a cryostat for beam tests
  - Design to be frozen by September 2025

ECal PCB measurements

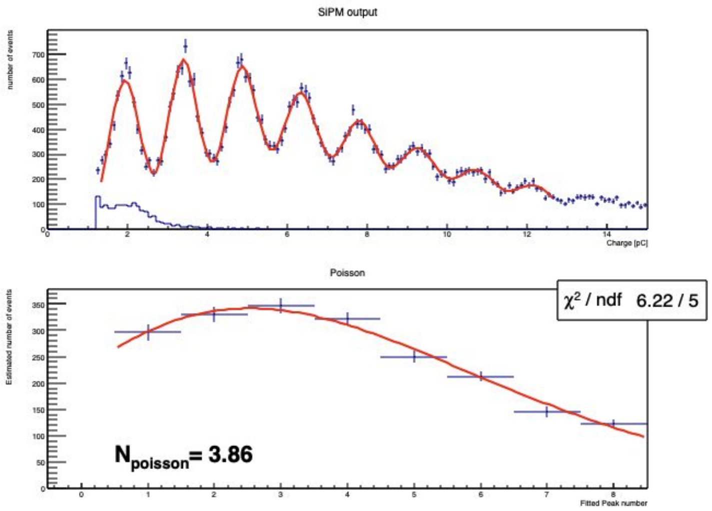
- Signal traversing under other cells induces cross-talk
  - Traces need to be shielded to minimize cross-talk
  - Grounded shields increase detector capacitance and hence noise
  - Need to find the best compromise
- Electrical properties of the PCB measured with a simple table-top setup
- Function generator used for injecting sharp-edged triangular signal
- Signal read with oscilloscope, analyzed offline
- Cross-talk down to 0.1% and less with long shaping time

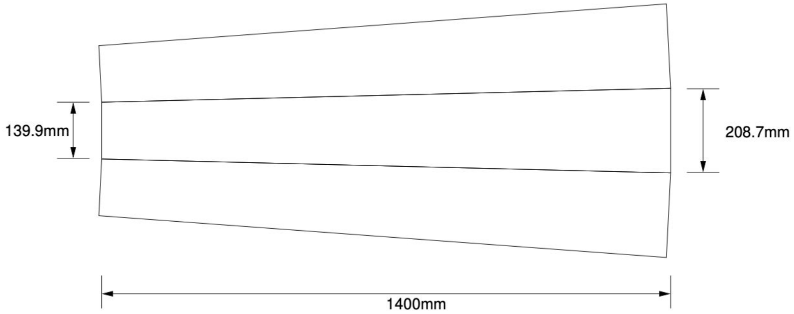




The road towards HCal test beam prototype

- Extensive studies of the light response of plastic-scintillator tiles with SiPM readout done in 2017-2019
  - One SiPM and one scintillator tile, used cosmic muon events to get single photon spectrum
- Aim to build several (3-4) test beam modules within the next 5 years
  - Mechanical design studies ongoing
  - Restarted SiPM readout studies in the lab

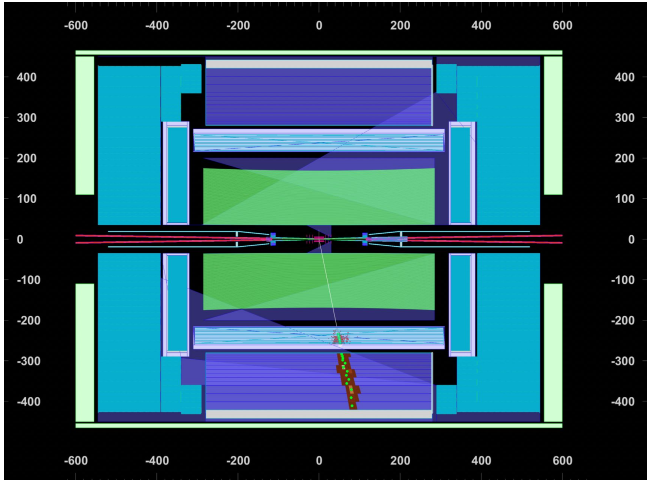


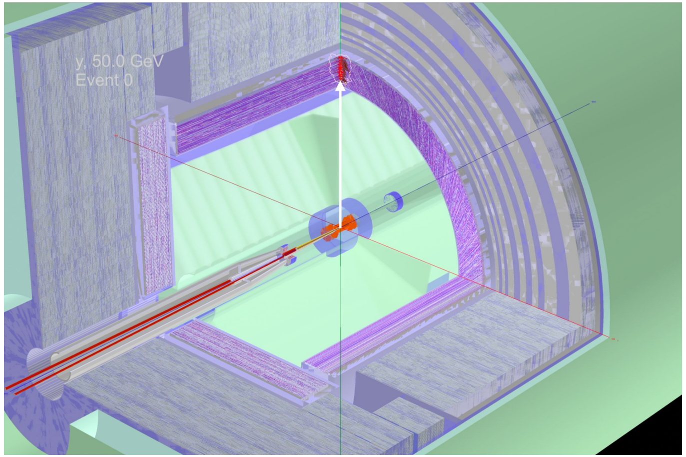


For 1 module 13 layers in depth, 39 periods:
- 0.134 m3 of steel (0.173m3 total)
  - 1.055 Tons
- 507 scintillators/channels
- 79 master plates (5mm)
- 507 filler plates (4mm)

Conclusions

- Detector R&D for FCC-ee is a rich field totally orthogonal to challenges at HL-LHC!
- Strong International effort on setting up Detector R&D Collaborations (DRD6 on Calorimeters)
- Many interesting questions and research topics ahead of us!
- ALLEGRO is a new detector concept for FCC-ee
- A lot of progress towards the full detector simulation of ALLEGRO done over the past years
- Both, ECal and HCal communities plan to build a test-beam prototype(s) in coming years
- Come and join ALLEGRO!

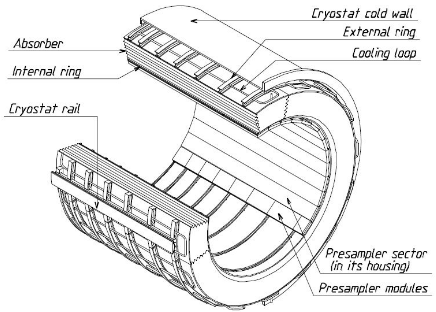




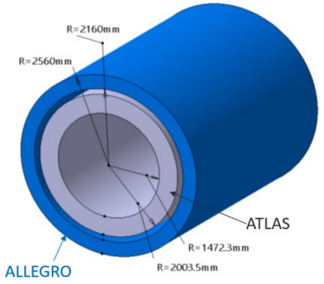
BONUS SLIDES

Mechanical studies

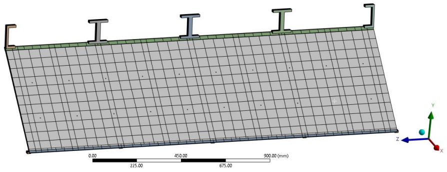
- Calorimeter in ATLAS experiment is taken as reference.
  - Bigger, heavier (≈ +40%) and different geometry of the electrodes.
- Finite element analysis are performed to size the structural elements.
- First prototype of two absorbers and one electrode was build.
- The prototype was tested by immersing it into liquid nitrogen bath.

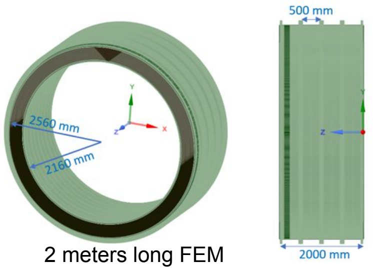


ATLAS liquid argon calorimeter general layout

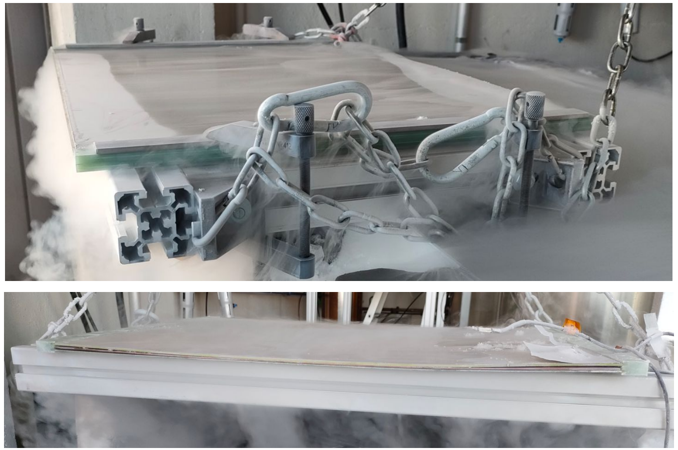


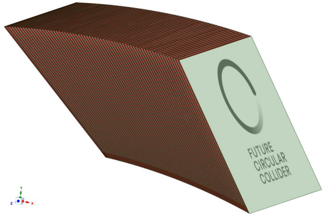
Detection zones size comparison


Finite elements model which is multiplied 1536 times

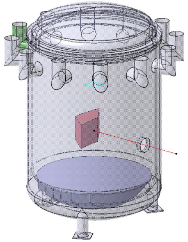


2 meters long FEM


First cold test. Liquid nitrogen bath was used.



Test beam prototype. 64 electrodes and absorbers.


Test beam in the cryostat

Mechanical results

- Section of the external rings chosen to expect about 3 mm of radial deformation.
- Spacers between absorbers and electrodes separated 200 mm. They are needed in the edges.
- The FEM of 2 meters long returns relative deflections in the absorbers of 2.7 mm due to gravity at room temperature.
- Assuming 2.9 Mpa as yielding point of the lead, the stainless-steel plates reach 107 MPa in compression just because of the cooling down to 77 K. If the value of the yielding point of the lead is higher, the stress in the steel is also bigger (8 MPa □ 183 MPa). Adding the effect of the gravity, the stainless steel could also reach the yield point.
- In the cold tests, where the assembly was subjected to thermal shocks, some depressions were found after warming up. Some more studies will be done to understand this phenomena (local buckling, steel yielding…? Due to the thermal shock or it appears also when it´s slowly cold?).