Noble-liquid calorimetry for ALLEGRO FCC-ee detector concept

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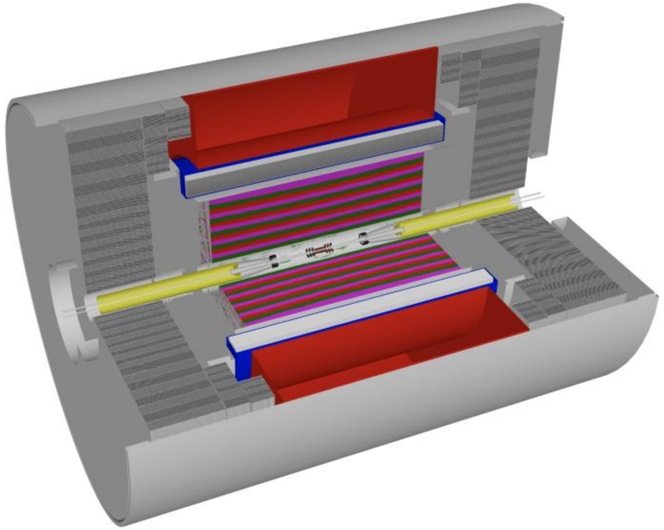
ALLEGRO detector concept

A Lepton co**L**ider **E**xperiment with **G**ranular calorimetry **R**ead-**O**ut: a general-purpose detector for FCC-ee ($\sqrt{s}$=90-360 GeV).

- Key feature: High granularity noble liquid EM calorimeter (ECAL) and tile hadronic calorimeter (HCAL).
  - LAr or LKr with Pb or W.
  - Multi-layer PCB as read-out electrode.
  - ECAL inside the 2 T solenoid sharing the cryostat.
- Other sub-detector systems: vertex detector, drift chamber and muon tagger.
- Designed for full FCC-ee physics program and focusing on particle identification with particle-flow.

Layout of ALLEGRO



3D-view of ALLEGRO

https://allegro.web.cern.ch/

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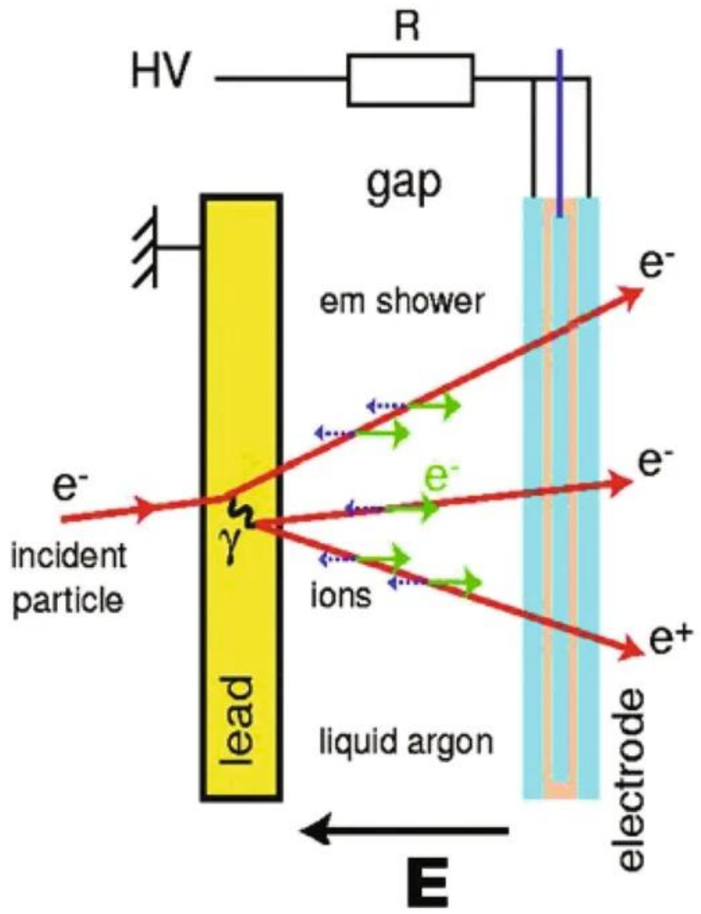
Noble-liquid calorimetry

- Sampling calorimeter technology. Repeated layers of absorber, noble liquid and read-out electrode.
- EM showers start in the absorber. Electrons produced in the showers ionize the liquefied noble gas and induce signals.
- Advantages: Mature technology (D0, ATLAS, …), good energy resolution, linearity, stability and uniformity, timing properties.
- Challenges: signal extraction and complex mechanical structure inside the cryostat.



EM shower and signal induction

C. W. Fabjan, D. Fournier, [Particle Detectors and Detector Systems](#)

This study belongs to DRD6 Collaboration as Work Package 2.

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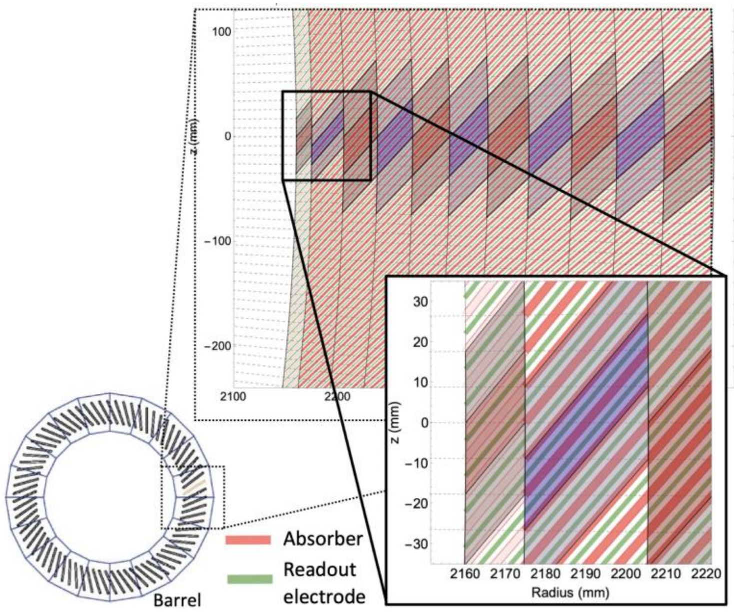
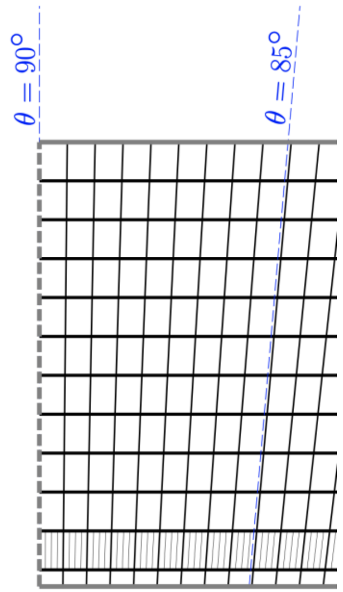
ECAL barrel

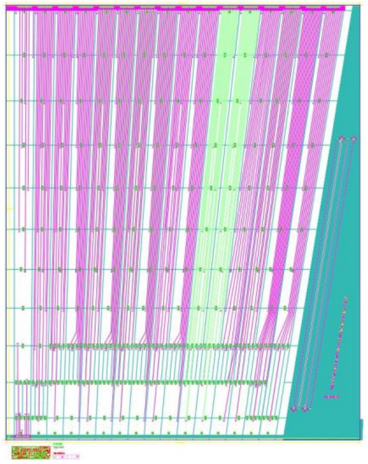
High granularity read-out is allowed b the PCB technology.

- Straight read-out electrode with 50° inclination angle.
- 40 cm in thickness, or 22 χ_0.
- Segmentation in θ and 11 radial layers.
- The second radial layer with narrow strips segmented in θ for π^0 detection.
- Signal traces go inside the electrode toward the edge of θ-tower.



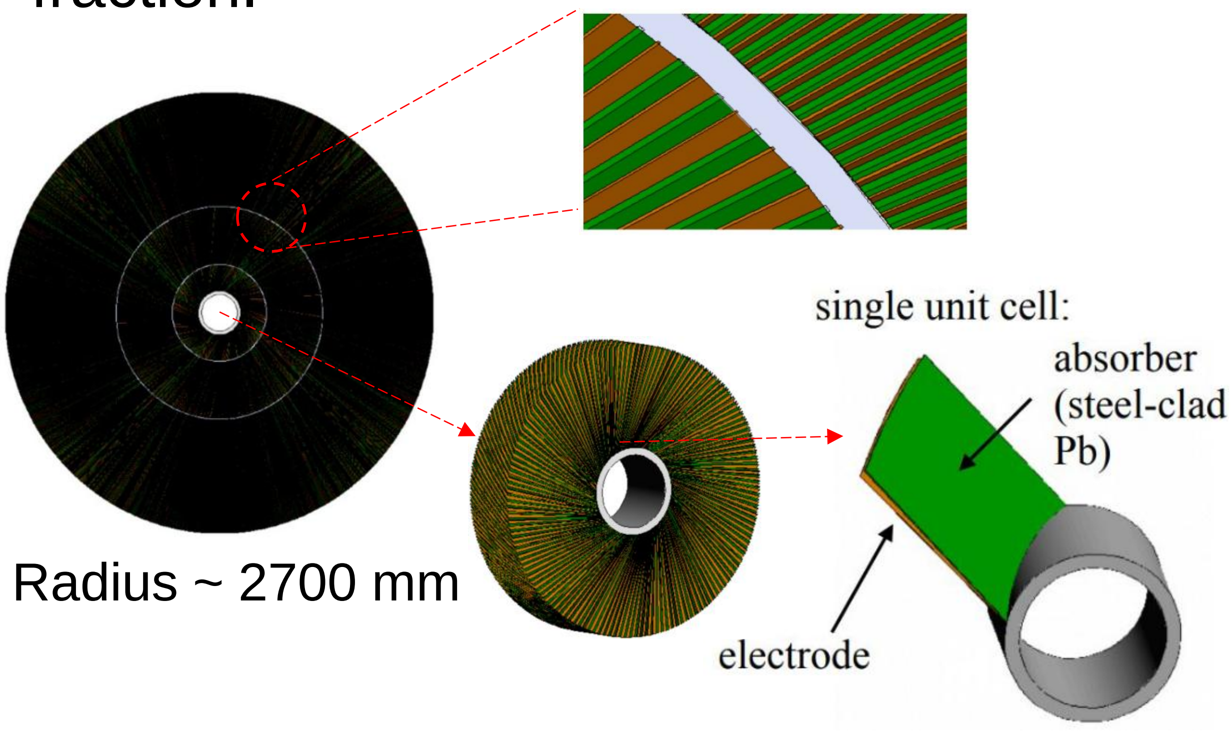


ALLEGRO ECAL barrel read-out. The granularity is 10 times higher than ATLAS.

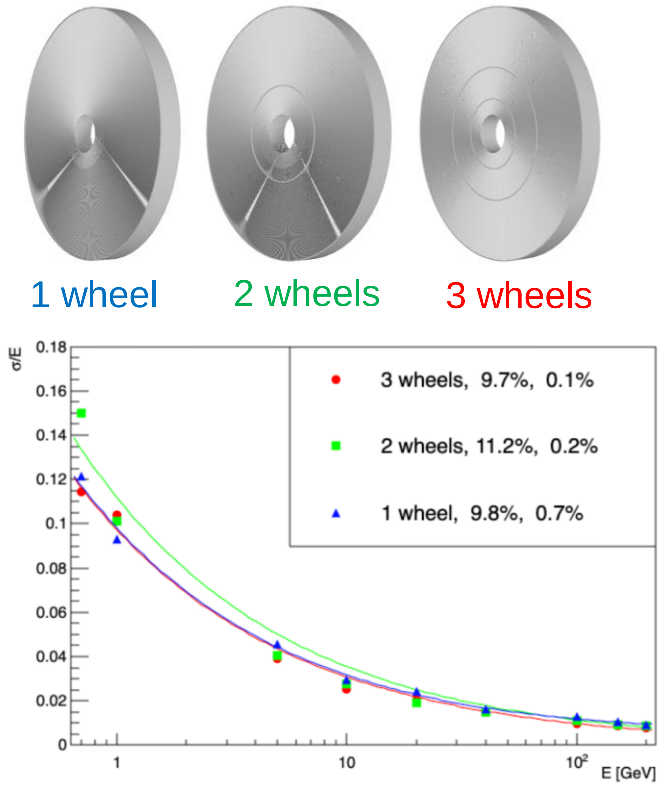


ECAL end-caps

- Baseline design: 3 nested wheels with turbine-like layout.
- Tapered absorbers (varying thickness) are good for uniform sampling fraction.



Structure of baseline end-cap design.



The final choice may be determined by construction practicalities.

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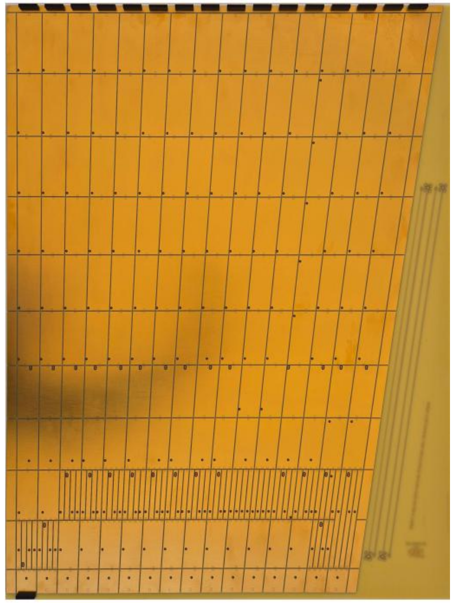
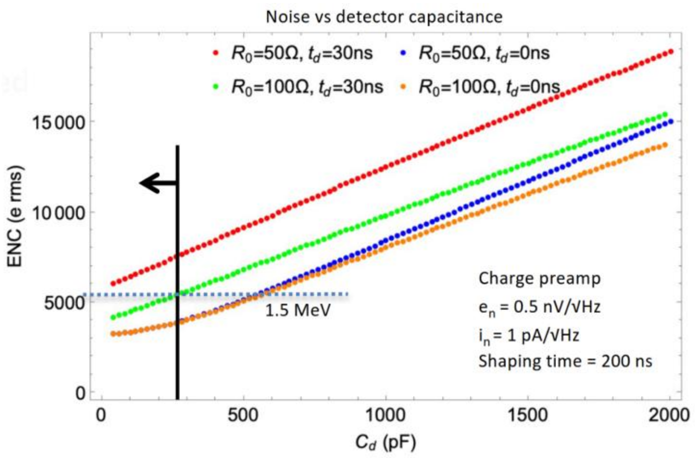
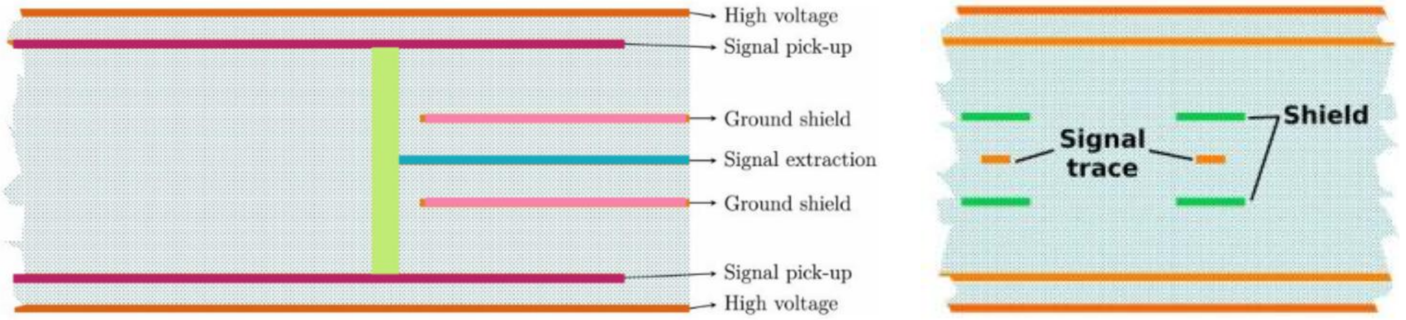
ECAL barrel read-out electrode

- High granularity of read-out cells leads to smaller signal amplitude.
- Use shielding to suppress the cross-talk generated by various coupling between calorimeter cells and signal traces.
- Choose proper size of shielding to limit the increase in noise due to larger detector capacitance.



The latest prototype ALLEGRO ECAL barrel read-out PCB

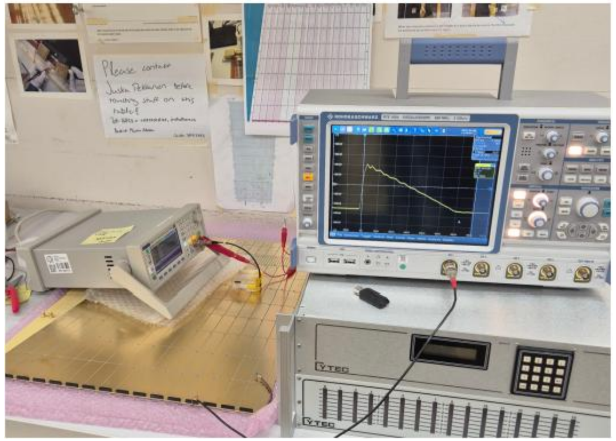


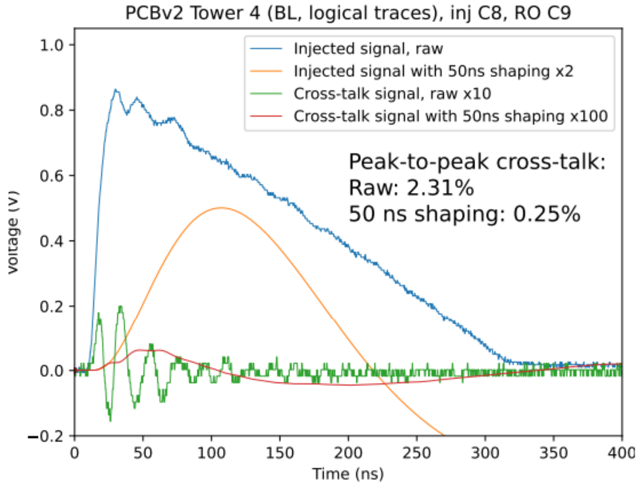


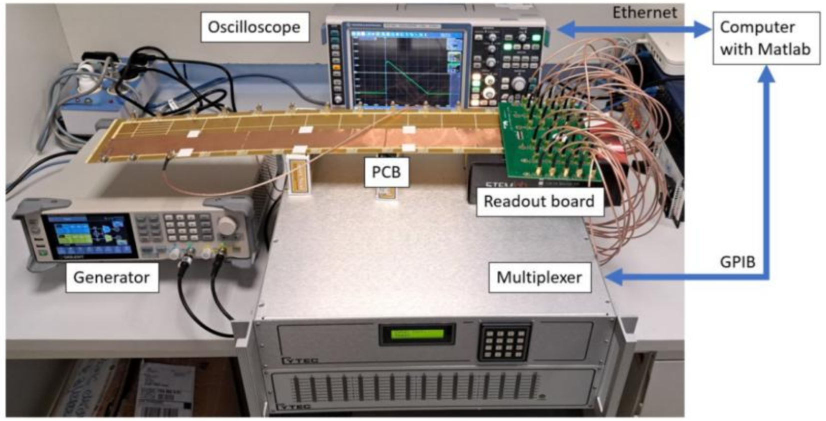
Sectional view of read-out PCB

Test of ECAL barrel electrode prototype

Measurements of electric properties for different electrode designs.

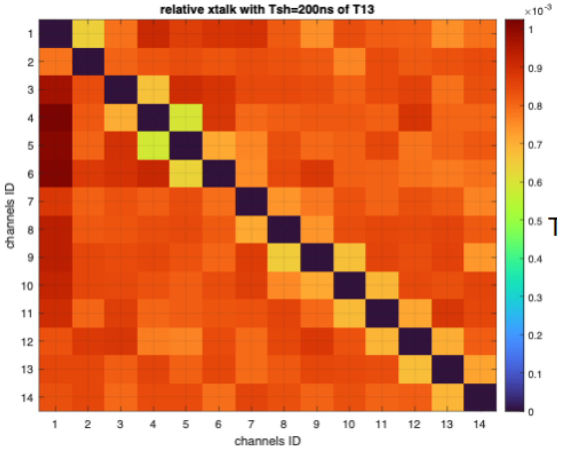






Test of prototype PCB at CERN.

- The cross-talk is measured via pulse shape injection on the electrode.
- The cross-talk can be reduced to 0.25% level with 50 ns pulse shaping.
- Measurement results reproduced in simulation.



Automatic test platform at IJCLab. Relative cross-talk is reduced to <0.1% level with 200 ns pulse shaping.

The measurement of characteristic impedance has started.

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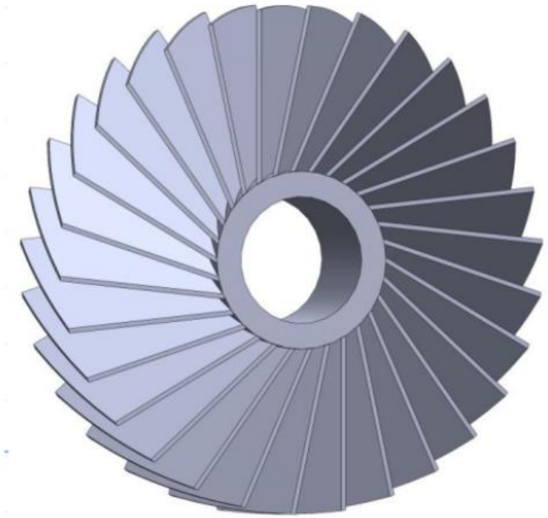
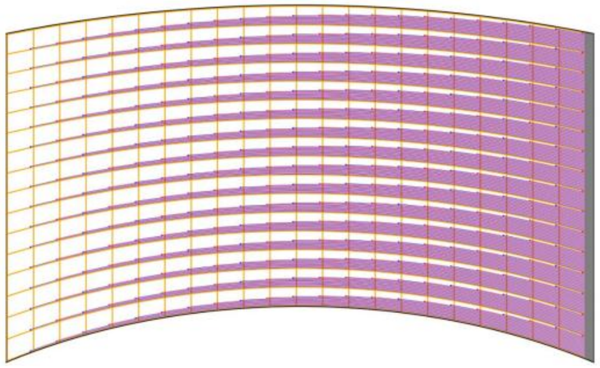
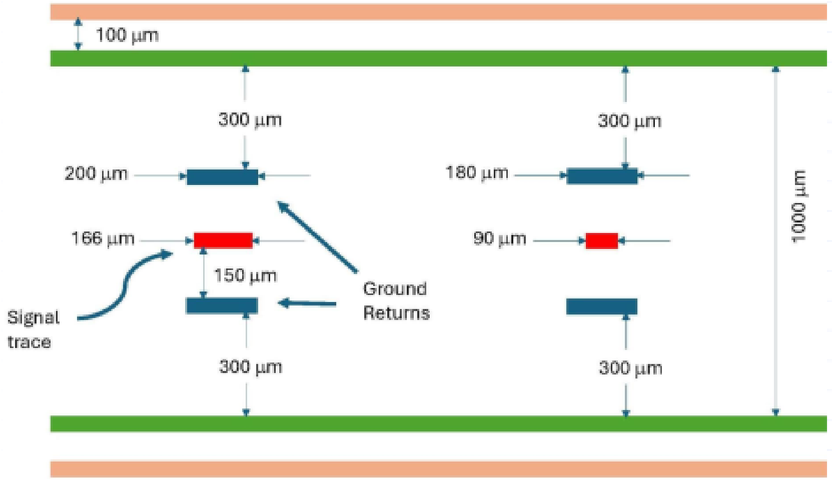
ECAL end-cap electrode design

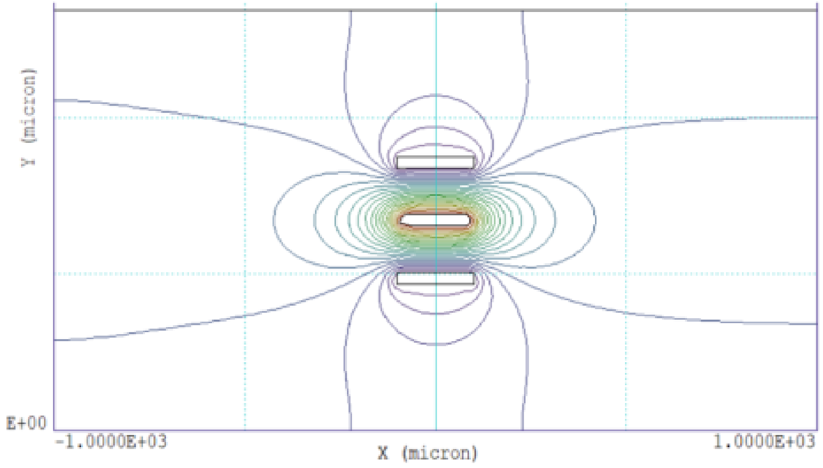
Dedicated PCB design in Arizona:

- Flat PCB with shape adapted to the turbine-like end-cap.
- Signal read-out from high-|z| edge.
- Study of transfer line characteristic impedance: simulation required, backed by measurements.
- Prototype design in progress!









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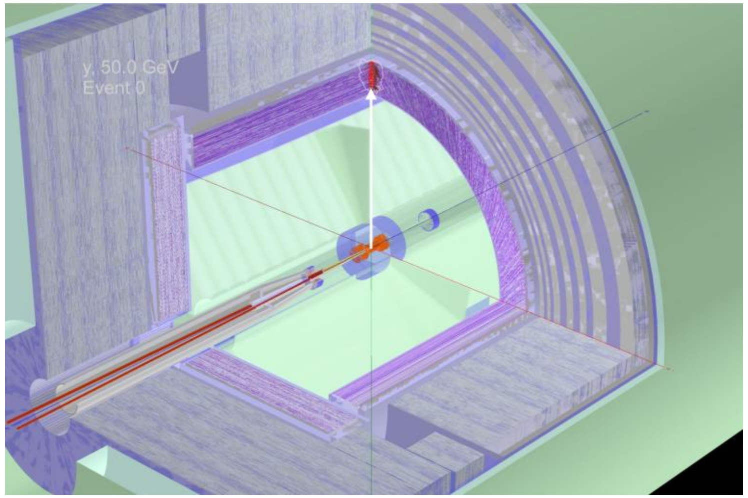
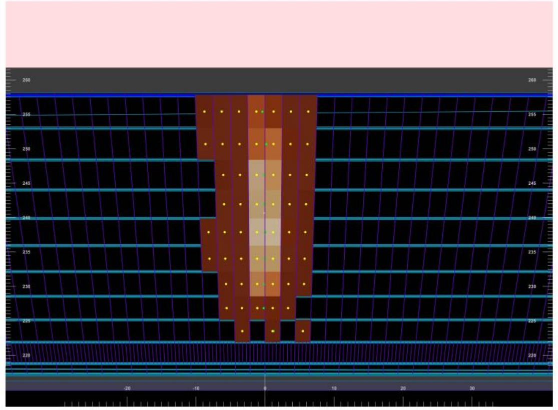
Overall status of full simulation

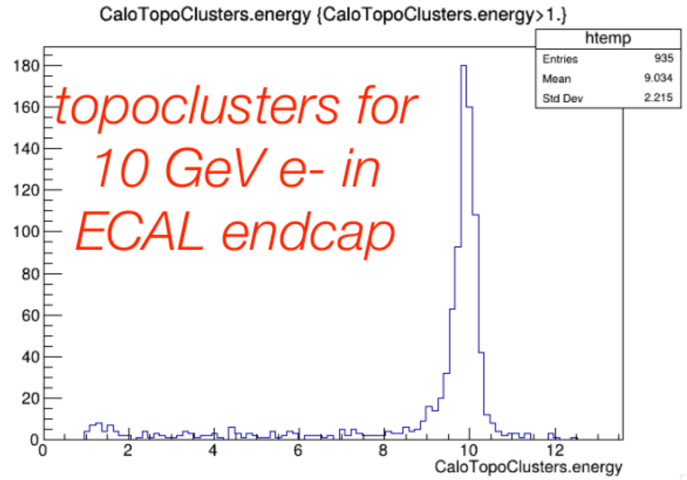
- ECAL detector model is fully implemented in ddsim.
- Simple digitization is taken as a sum of Geant4 energy deposit, corrected by pre-calculated sampling fraction for each layer. -> Realistic digitization on-going.
- Reconstruction is available for both fixed-size sliding window (SW) cluster and topo-cluster.



Response of ALLEGRO calorimetry to a 50 GeV photon.

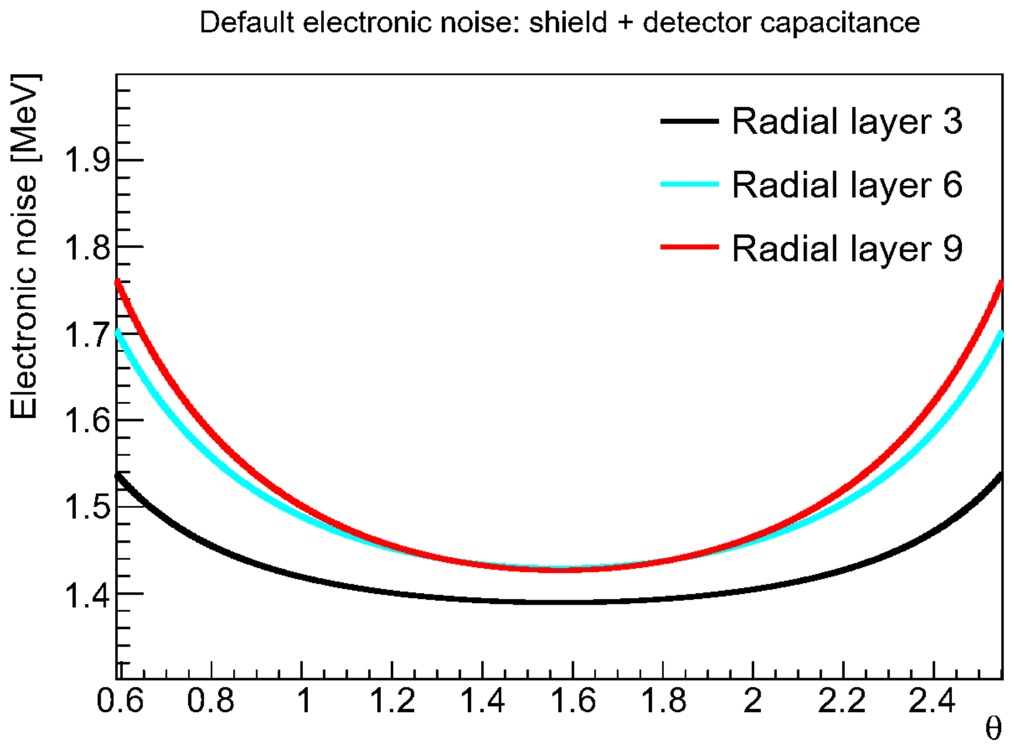


Reconstruction of a photon with ECAL-only SW cluster in the barrel region.



Implementation of electronic noise

- Calculate the average level of electronic noise as a function of radial layer and θ.
- For each event in the full simulation, after the digitization, randomly draw the value of electronic noise for individual ECAL cells, following a Gaussian distribution.
- With the noise filter enabled, cells with energy below a certain threshold are removed from the cell collection, which reduces the input size to clustering algorithms.



Pre-calculated conservative estimation of electronic noise, depending on radial layer and polar angle θ (unit in radian).

Noise level calibrated to MeV.

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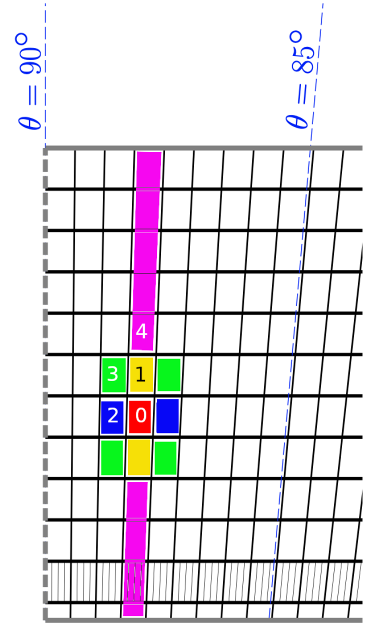
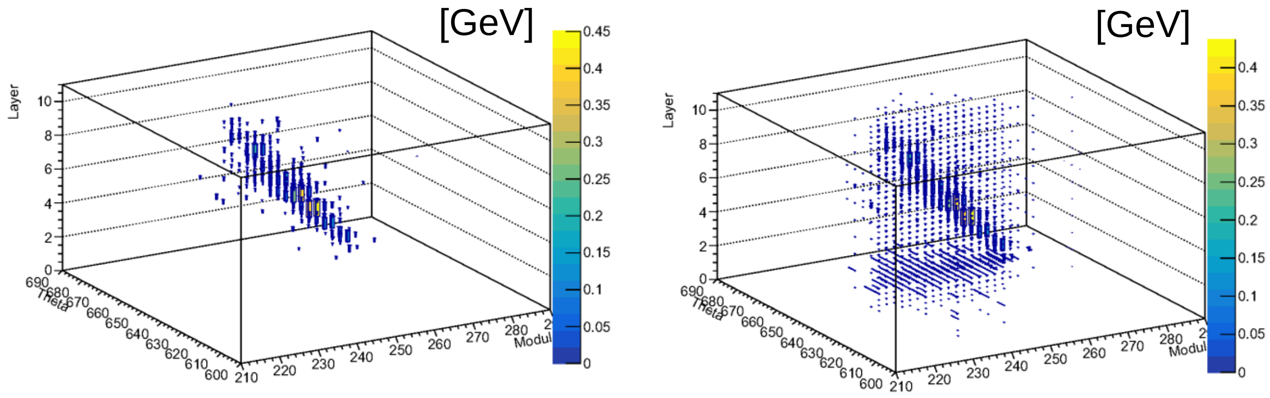
Implementation of ECAL barrel cross-talk

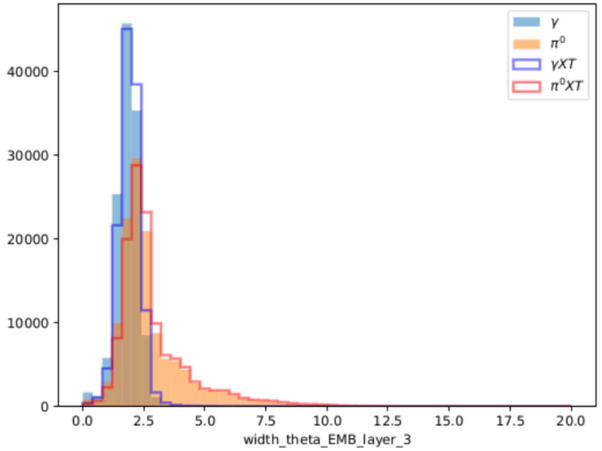
- Assuming four types of cross-talk on the read-out electrode.
- Minor impact on the energy resolution but causes a shift to ECAL shower shape variables, therefore affecting the particle identification performance.



Coefficients of 4 different cross-talk types (0.04%-0.7%) are taken from the measurement with 50 ns shaping.



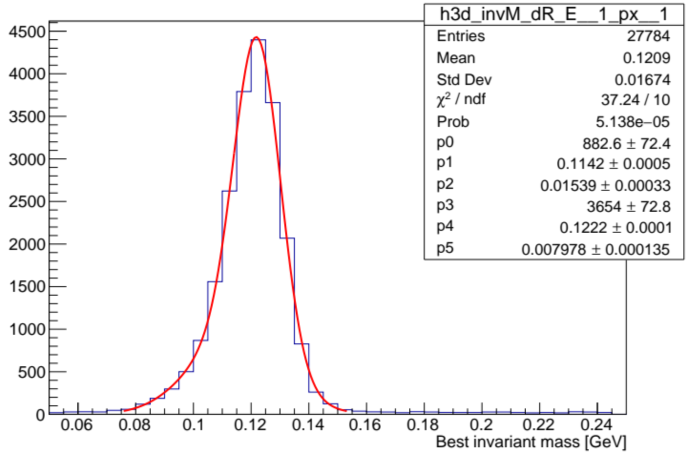
ALLEGRO ECAL signals in each cell for a 5 GeV photon shower, before and after adding cross-talk.



Shower shape variable “θ width” shifted by cross-talk.

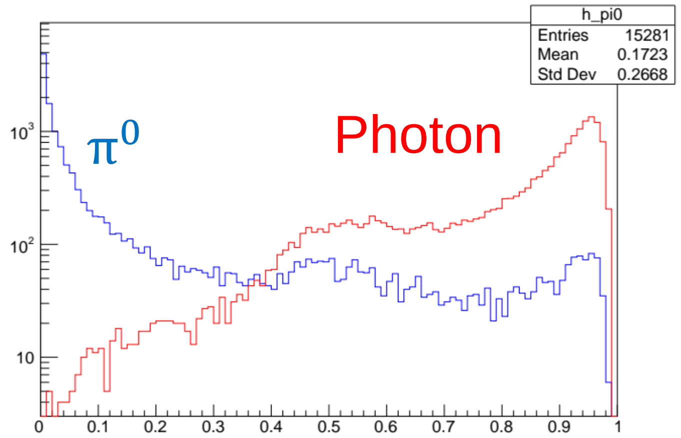
Photon-π^0 separation based on ECAL

- Reconstruction of resolved π^0 by pairing clusters in the π^0 invariant mass window.
- Unresolved π^0 are separated from photons via machine learning method.
- Identification of tau decay mode by counting number of reconstructed π^0 in the ALLEGRO ECAL.

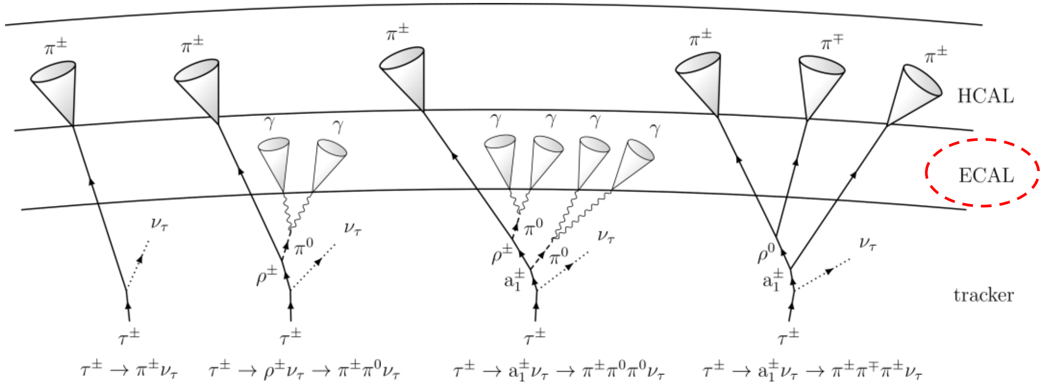


π^0 invariant mass distribution reconstructed by ALLEGRO ECAL.

Calibration not up-to-date.



BDT score of photon-π^0 separation trained with cluster energy and shower shapes.



BDT training uses input π^0 from ee->ZH, H-> ττ process at √s=240 GeV.

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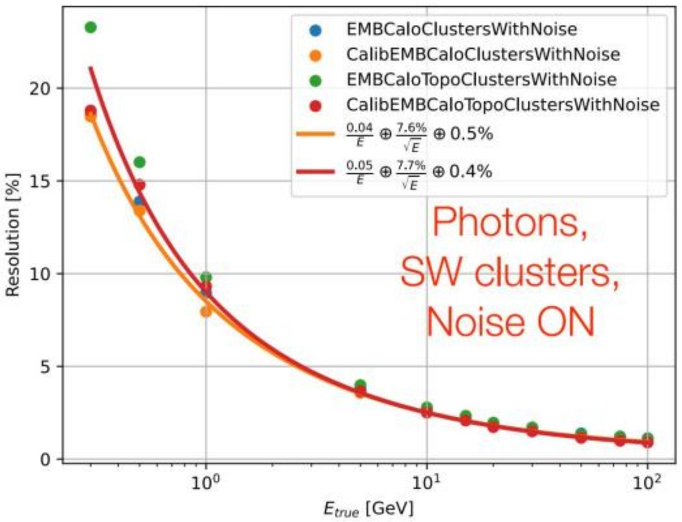
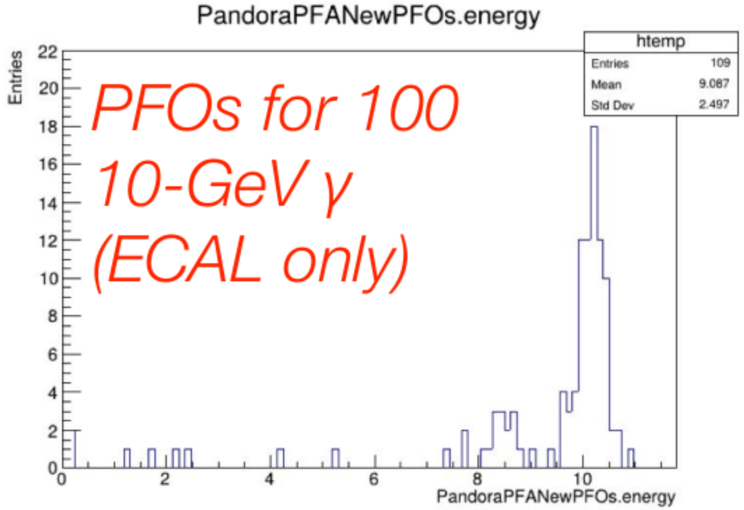
Energy calibration and particle-flow

- ECAL energy resolution to single electrons: a 7% sampling term is achieved for the baseline Pb+LAr combination.
- Machine learning techniques are introduced to improve the energy resolution.
- Particle-flow object (PFO) reconstruction with PandoraPFA is under development.



BDT-regression based calibration implemented in Gaudi improves cluster energy resolution.



Adaptation of PandoraPFA-based tools in Key4hep/FCCSW to ALLEGRO.

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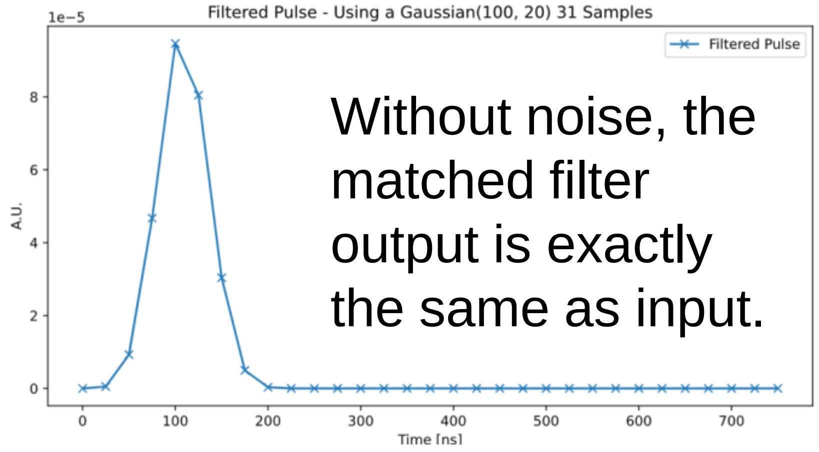
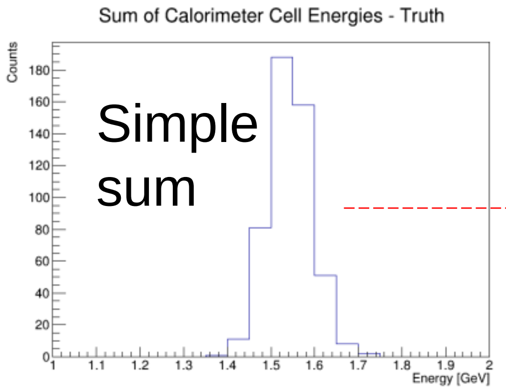
Realistic digitization

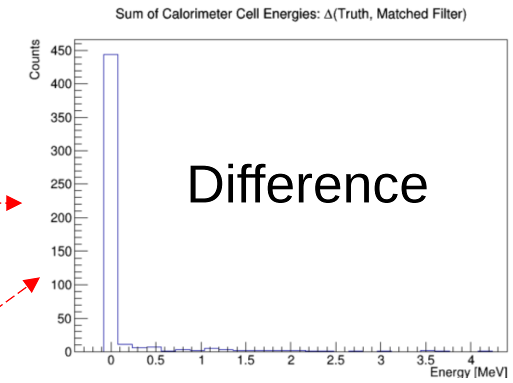
- Digitization of cell hit: simple sum of cell energy -> digitized samples.

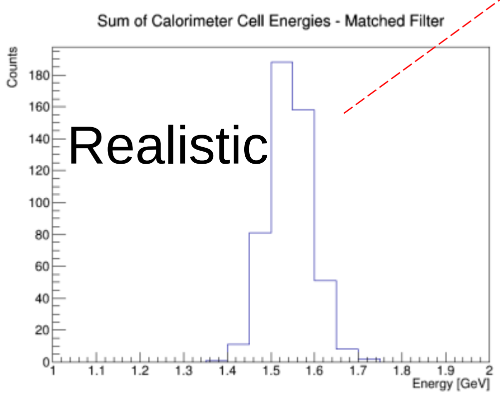
$$S_i = \sum_{\substack{hits\ in \\ a\ cell}} E_h \cdot \left(g_j - \delta t \cdot g_j'\right)$$

- Matched filter pulse is obtained by applying the matched filter to a Gaussian input pulse.
- With correct normalization, the energy and peaking time of the hit are extracted.
- On-going development: realistic digitization with pedestal and noise.









Only minor difference when comparing with the simple sum of cell energy.

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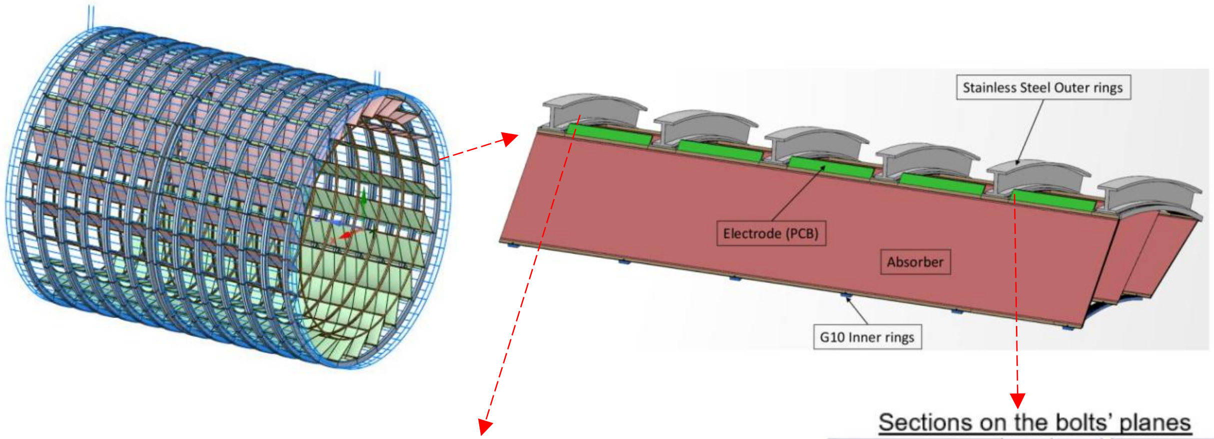
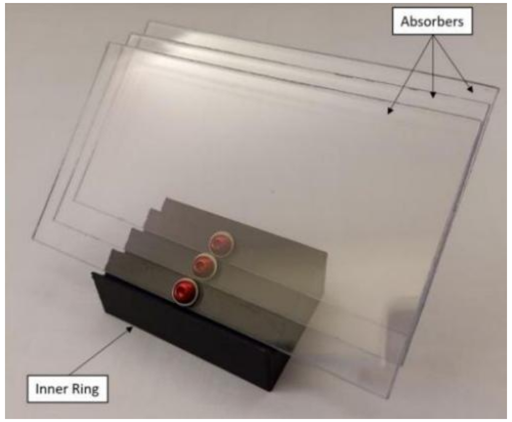
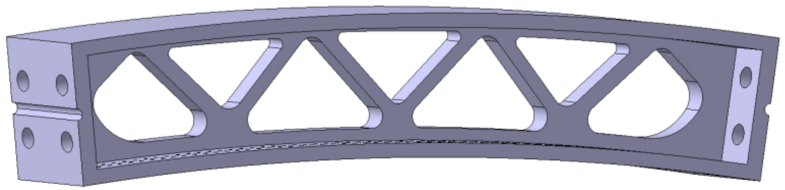
Mechanical structure design

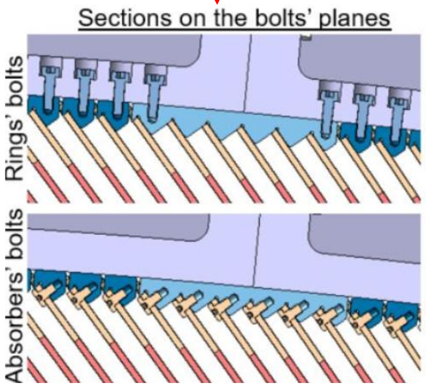
- Key components: external rings, inner rings and connections.
- The finite element (FEM) analysis facilitates the study of mechanical design.



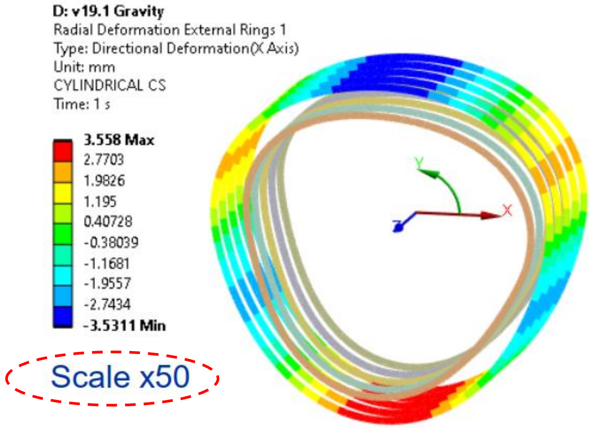


The conceptual model of ECAL inner rings.





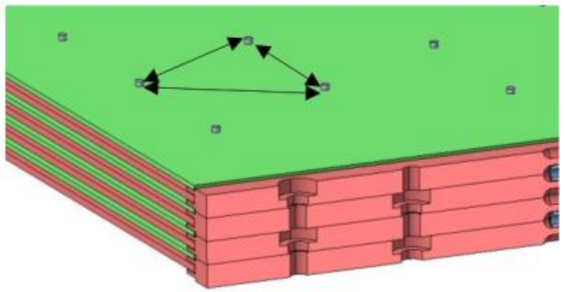
The external rings of ECAL barrel, H-beams and connections to the absorber.

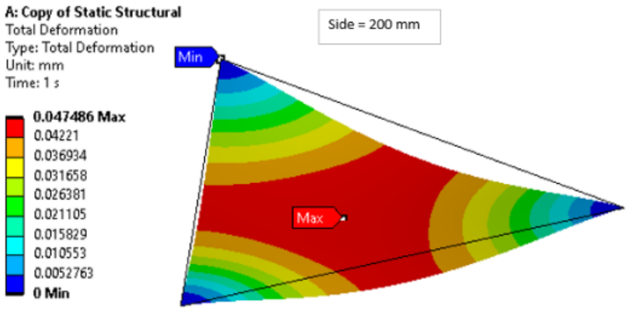


Simulated deformation of external rings due to gravity.

Spacers

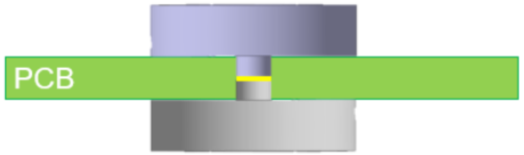
Spacers are placed between read-out electrodes to maintain the gap for the flow of liquefied noble gas.



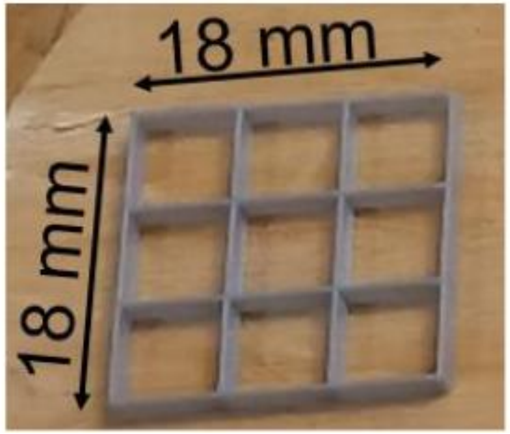


The maximal interval is determined from FEM analysis.

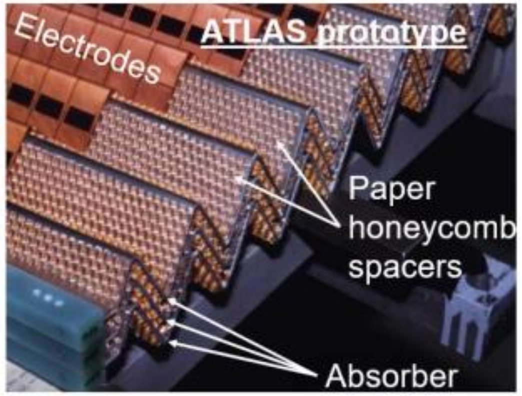
- A distance of 200 mm leads to normal deformation less than 50 μm.



Solution A: pins



Solution B: 3D-printed mesh



Solution C: honeycomb

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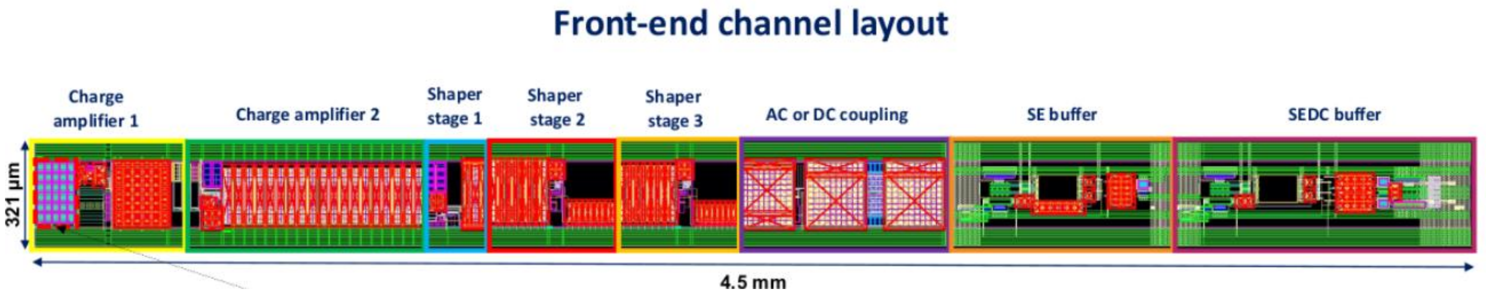
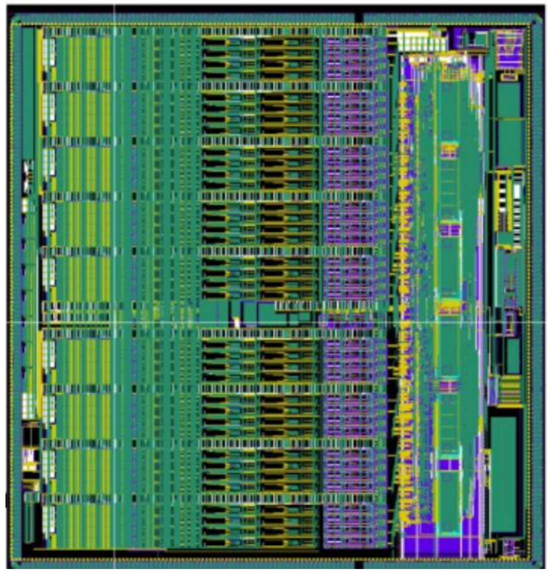
Explore the possibility of cold electronics

ALLEGRO ECAL barrel contains about 2M channels.

- Warm electronics needs to deal with the routing of signal cables.
- Cold electronics requires room for boards+HV, powering and signal cables.



CHARMS250 cryogenic analog front-end ASIC @ BNL



CALOROC1C chip for ALLEGRO ECAL @ Omega Labs

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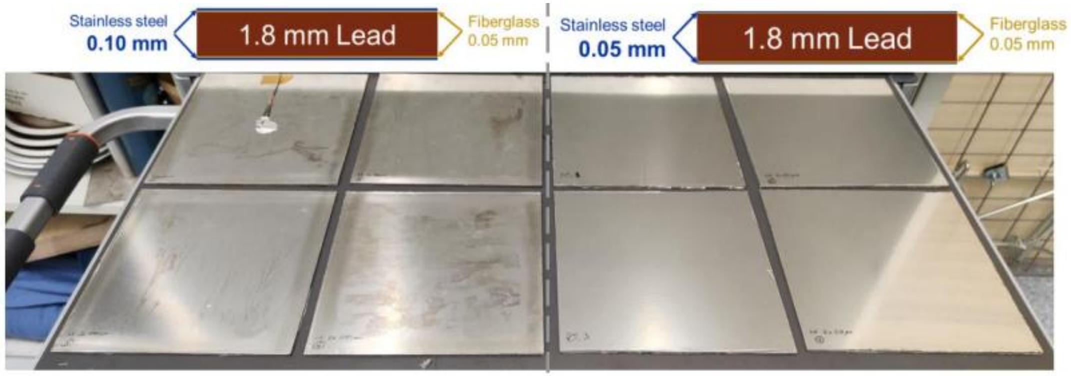
ECAL absorber cold test

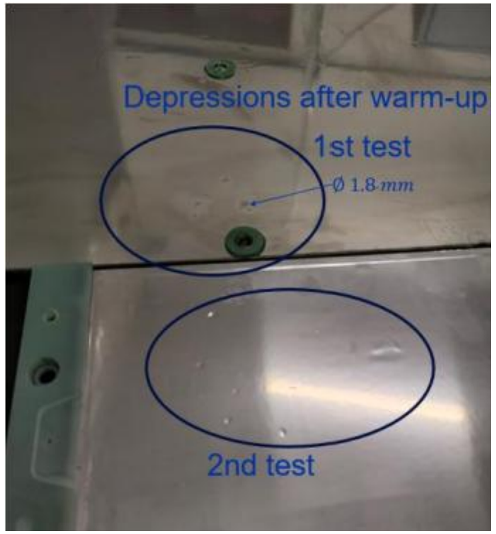
Test of two absorber designs performed with liquid nitrogen bath of 77 K: 0.1 mm steel clad vs 0.05 mm steel clad.

- Deformations appear only on the 0.05 mm steel, because of different thermal expansions of lead and steel.
- Consequently, the absorber with 0.1 mm stainless steel clad is chosen to be the default.



Two absorber designs with different thickness of steel clad.

One setup of cold test: clamped to the frame



Depressions on the absorber with 0.05 mm steel clad after cold tests.

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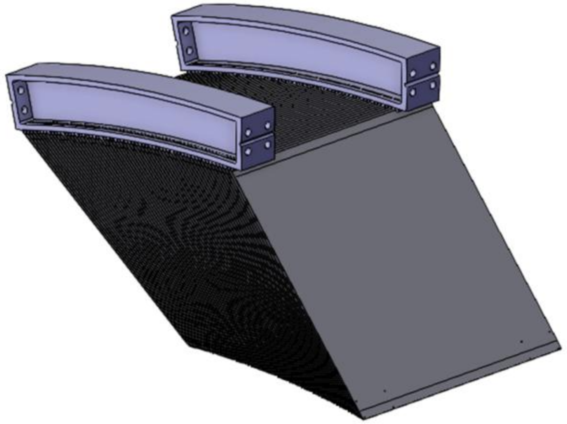
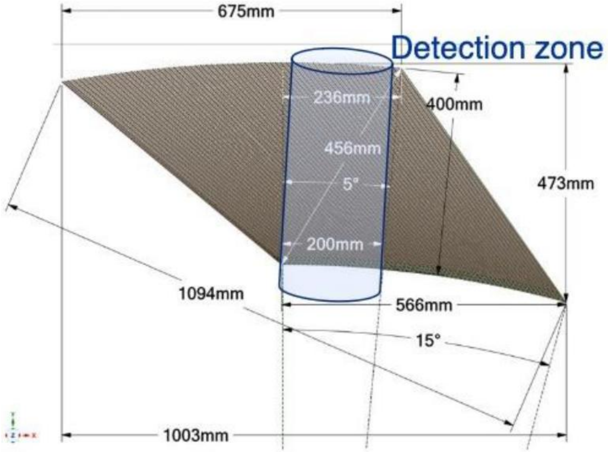
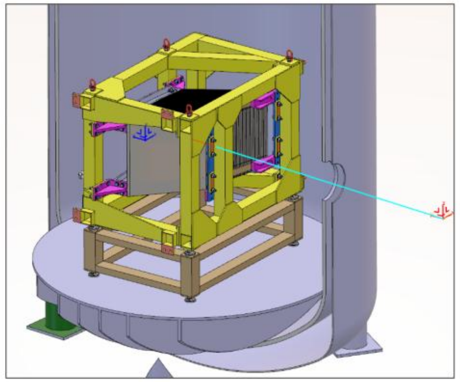
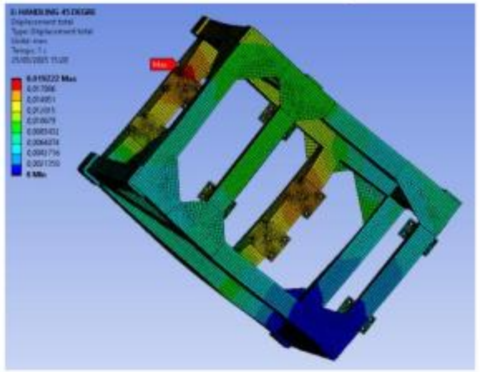
ECAL barrel test-beam prototype

The test-beam prototype: part of the ECAL consisting of around 64 repeats of absorber and read-out electrodes.









- 64 repeats of absorber and read-out electrodes are capable of containing the development of a typical shower.

Progress in prototype mechanics:

- 500 kg prototype and 800 kg total weight.
- Mechanical properties simulated by FEM analysis.

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Summary

Rapid progress in almost all aspects of ALLEGRO ECAL R&D, demonstrating that it is a realistic detector concept for high performance calorimetry designed for FCC-ee.

- Electric properties of electrode prototypes are tested comprehensively, with room for fine-tuning of the barrel region design. Also, efforts have been made to develop the end-cap design.
- Various tools are available in the full simulation for the optimization of the detector design aiming at specific physics goals.
- Some first ideas of cold electronics are under study.
- With the assistance of FEM analysis and lessons learned from cold tests, the mechanical structure for test-beam prototype is quickly converging.

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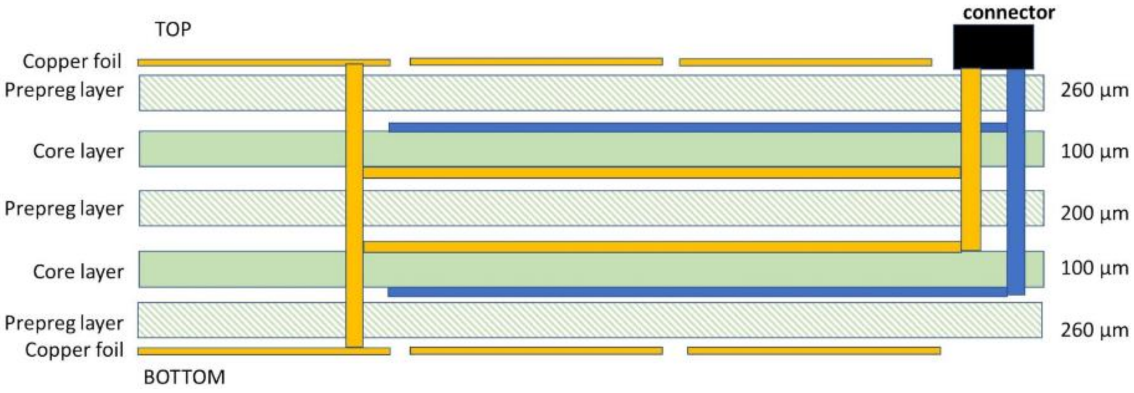
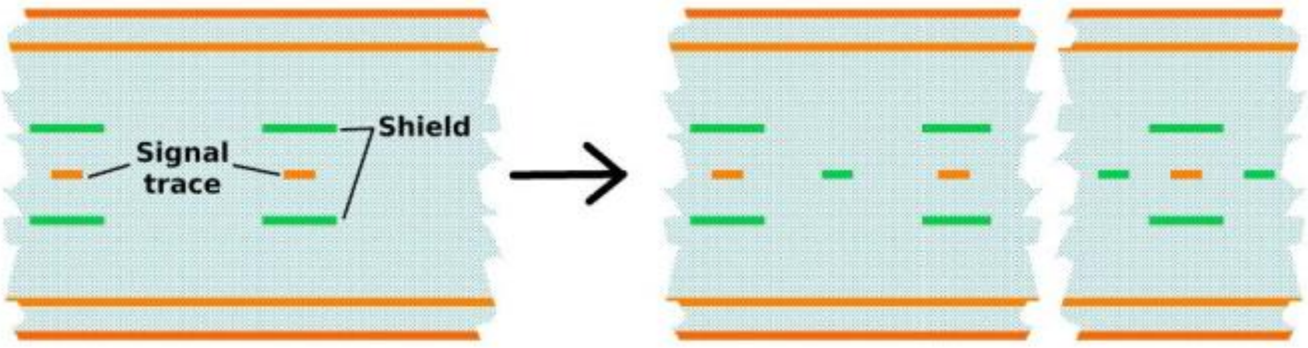
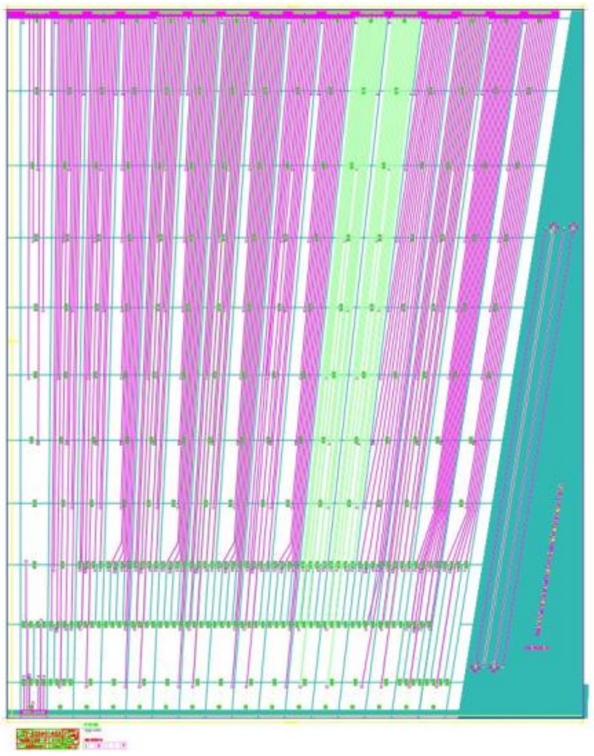
Backup

ECAL barrel read-out electrode

- PCB design







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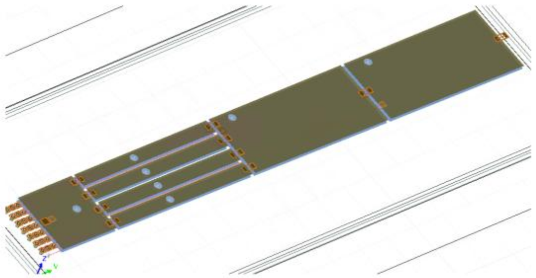
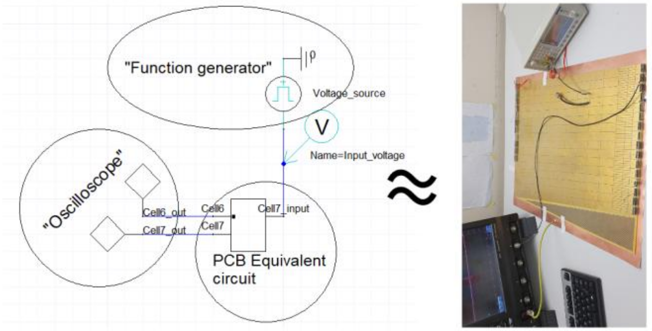
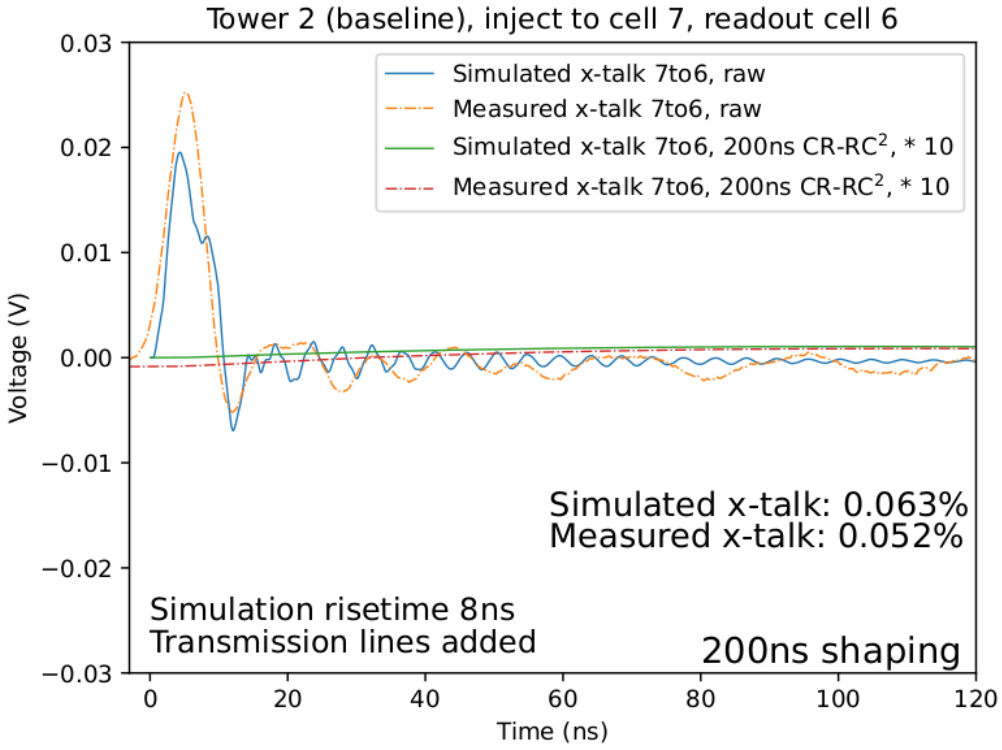
Simulation of read-out electrode

- Electrical properties are also studied by Ansys Electronics Desktop.
- Good agreement of cross-talk shapes between measurement and simulation.





PCB model analysis and conversion to equivalent circuit.



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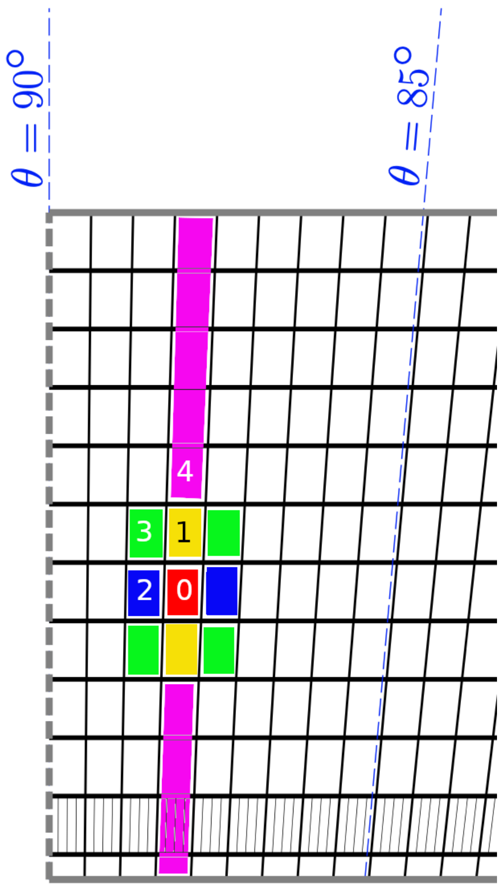
Cross-talk coefficients.

- Taken from measurements with 50 ns shaping time.



Type	1: Radial	2: Theta	3: Diagonal	4: Tower
Crosstalk	0.7%	0.3%	0.04%	0.1%

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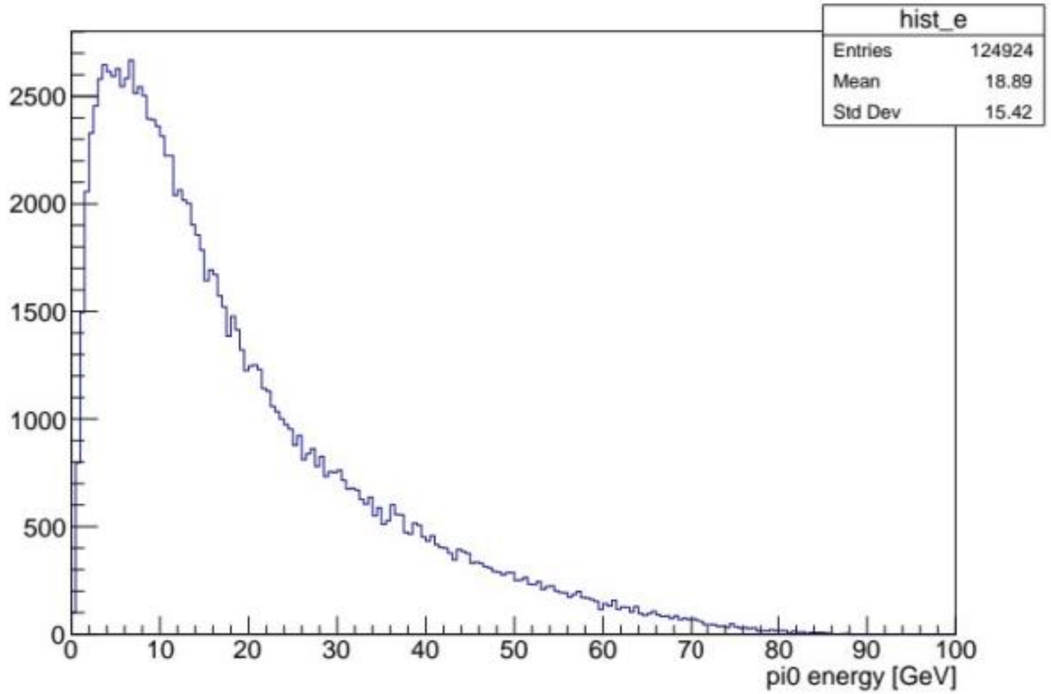
π^0 energy distribution

Distribution of π^0 energy in photon-π^0 separation.



Energy distribution of pi0 from the tau→h+pi0+v decay mode.
ZH production @ 240GeV.

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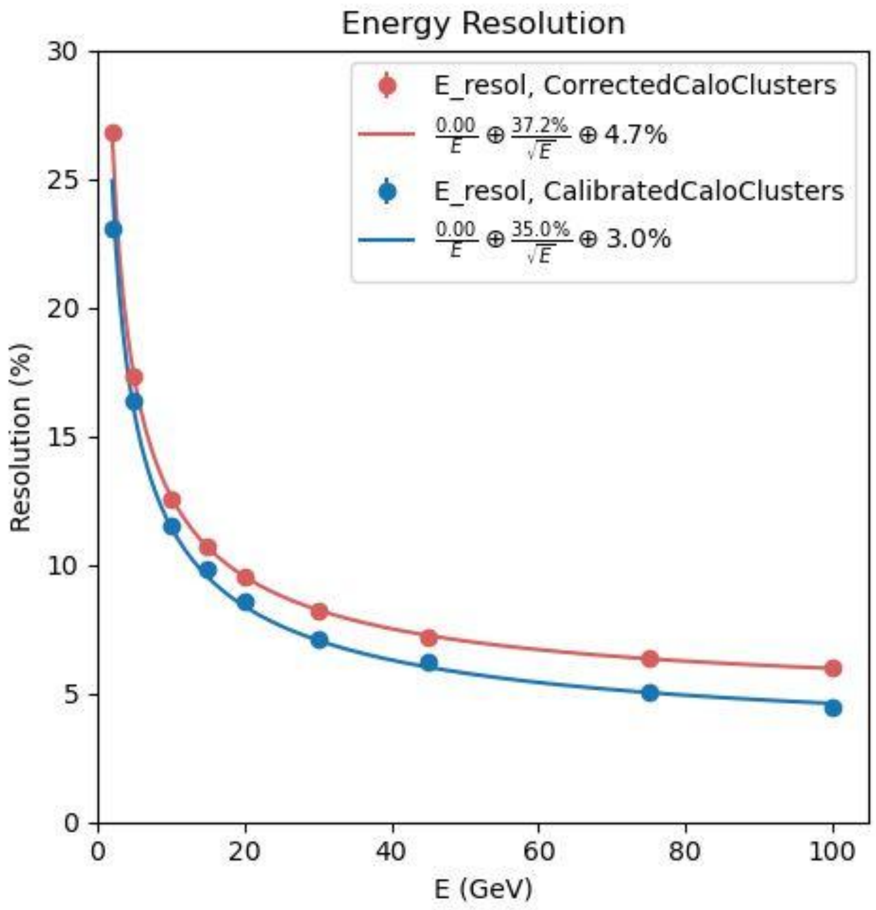
ECAL+HCAL combined performance



Energy resolution to single negatively-charged pions with ECAL+HCAL cluster reconstruction after different calibrations.

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Realistic digitization

- From a hit (pair of energy E_h and time t_h) of a shower deposition, emulate the electronics behavior for a digitized sample S_i in a cell

$$S_i = K \cdot \sum_{\substack{hits\ in \\ a\ cell}} E_h \cdot \left(g_j - \delta t \cdot g'_j\right) + Pedestal + Noise$$

$$j \equiv i - rint\left(\frac{t_h}{t_s}\right)$$

$$\delta t = t_h - t_s \cdot rint\left(\frac{t_h}{t_s}\right)$$

- K: Constant comes from the sampling fraction and the ADC to MeV conversion factor
- g and g' represent the pulse shape and its derivative
- Noise is defined as the autocorrelated expression of the electronic noise
- t_s is the sampling time – 25 ns in LAr

Matched filter pulse given by convolving the received pulse with the time-reversed conjugate of the known signal pulse

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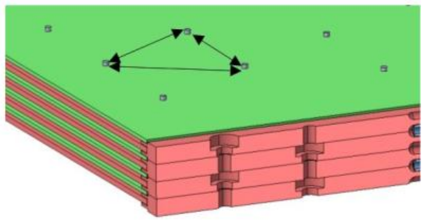
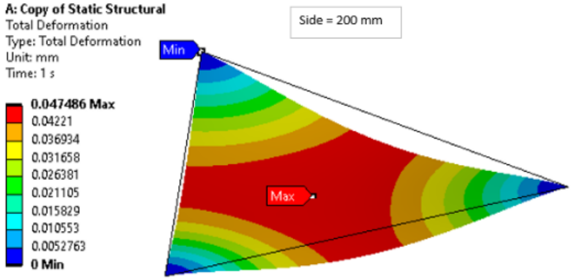
Spacers

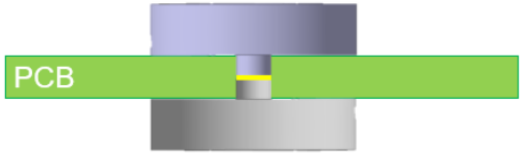
Spacers are placed between read-out electrodes to maintain the gap for the flow of liquefied noble gas.



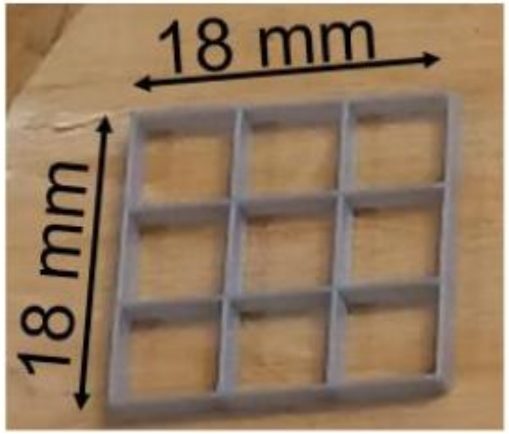


The maximal interval is determined from FEM analysis.

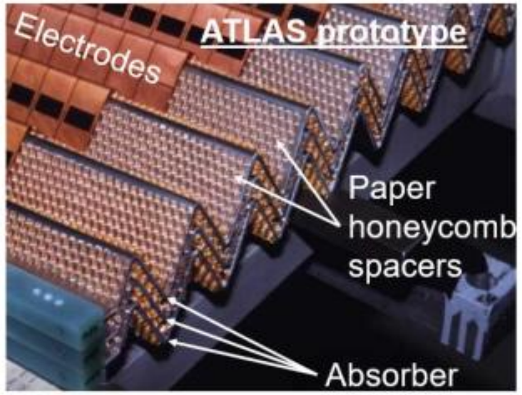
- A distance of 200 mm leads to normal deformation less than 50 μm.



Solution A: pins
Exact position and good tolerance, but concentrated force.



Solution B: 3D print mesh
Distributed force and easy to build, but burring needed, and difficulty in material characterization.



Solution C: honeycomb
Distributed force, easy assembly, but expensive, tolerance unknown.

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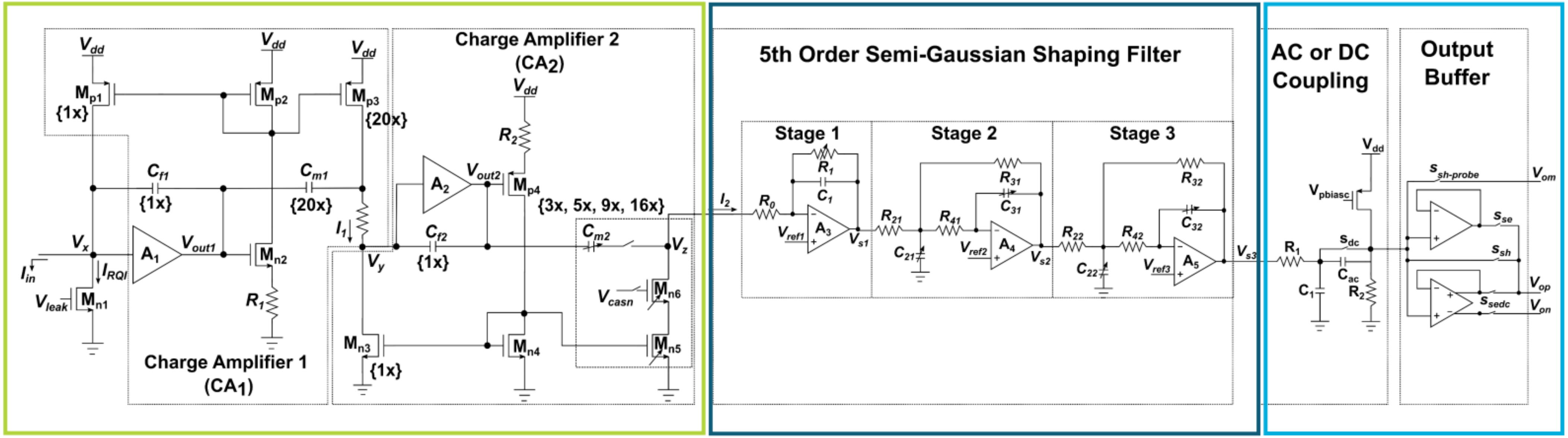
Explore the possibility of cold electronics

CHARMS250 core channel circuits



Amplification

Filtering

Output drive

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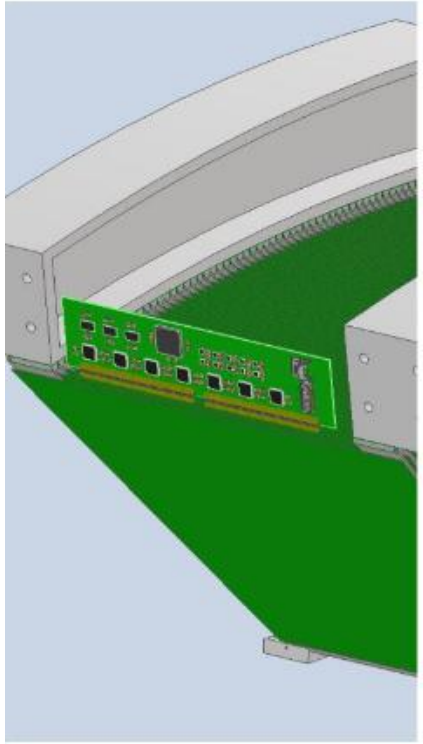
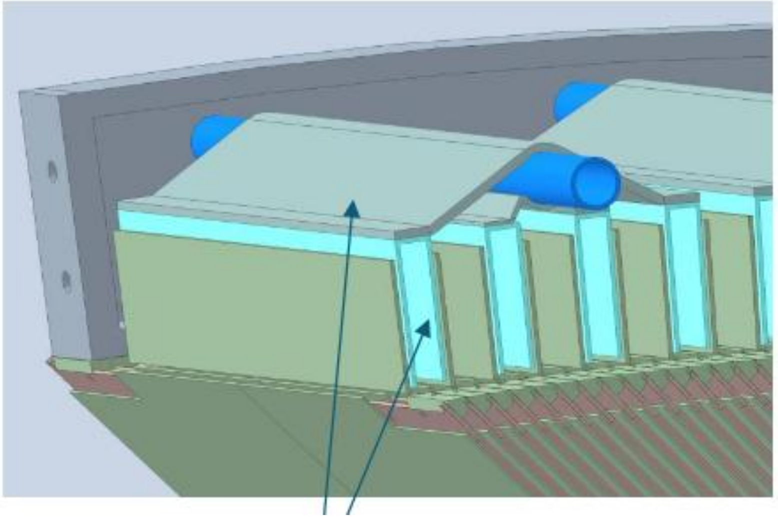
Explore the possibility of cold electronics

ALLEGRO ECAL barrel contains about 2M channels.

- Warm electronics needs to deal with the routing of signal cables.
- Cold electronics requires room for boards+HV, powering and signal cables.

One option of 3 data cables + power cable for the front-end board of cold electronics.





Installation of cold electronics along the electrode and thermal management.

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