Allegro Noble Liquid calo: Design and R&D

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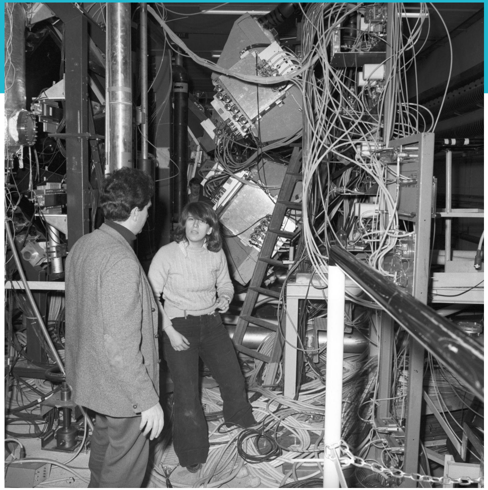
FCC France Workshop, 23/11/2023

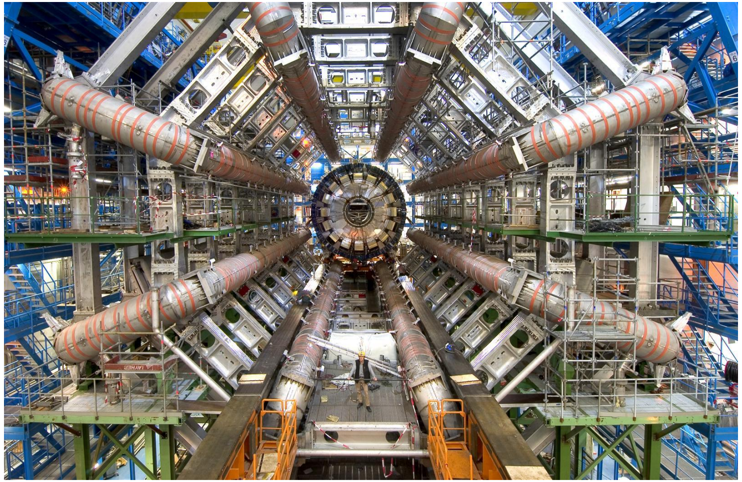
Noble liquid calorimeters



- Decades of success at particle physics experiments: from R806 to ATLAS
  - Mostly LAr, a bit of LKr
- An appealing option for FCC-ee
  - Good energy resolution
  - High(-ish) granularity achievable
  - Linearity, uniformity, long-term stability

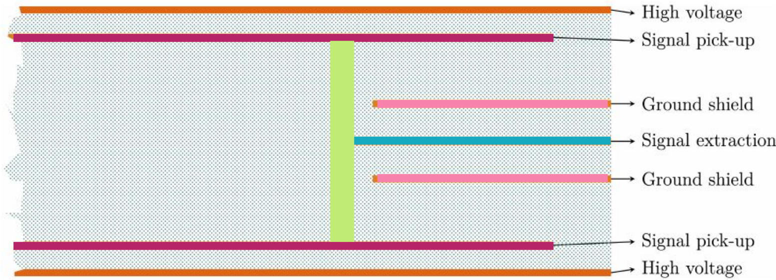
Excellent solution for small systematics

- Lots of interesting studies / R&D to do
  - Optimization for PFlow reconstruction
  - Achieving very low noise
  - Lightweight cryostats to minimize X_0
  - Designing for improved energy resolution



Granularity of Noble Liquid Calorimeters

- Calo 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



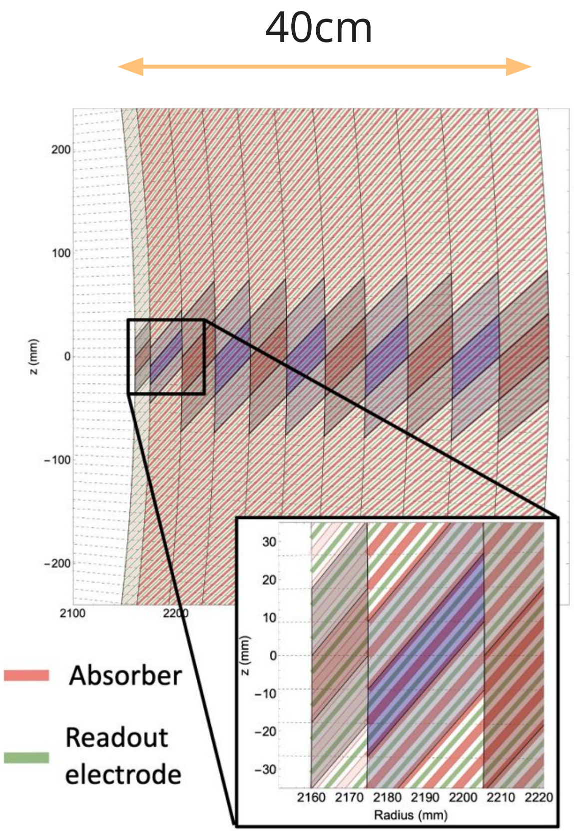
Allegro Barrel Design

Design driven by the solution used for electrodes

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

Copper electrodes: lots of flexibility

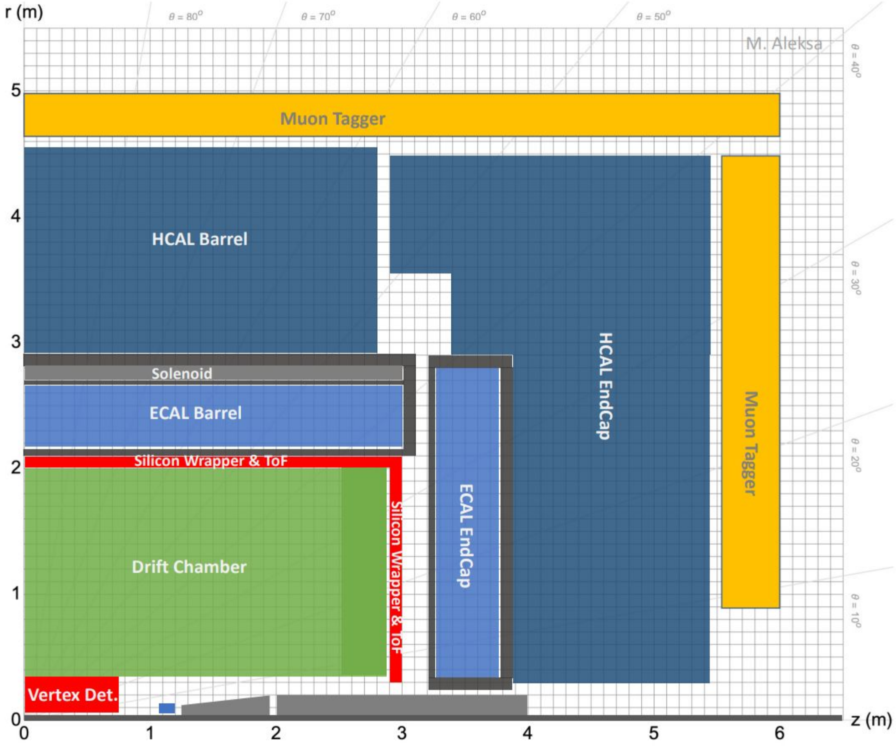
- Number of layers and granularity of layers fully optimizable
- Projective cells



Allegro detector concept

See presentation by Martin Aleksa in the afternoon !

- Allegro ECal at core of Allegro detector concept
- Gives typical boundary conditions for the ECal design
  - Overall envelope similar as that of IDEA
- Baseline solution: solenoid outside the ECal (in front of HCal)



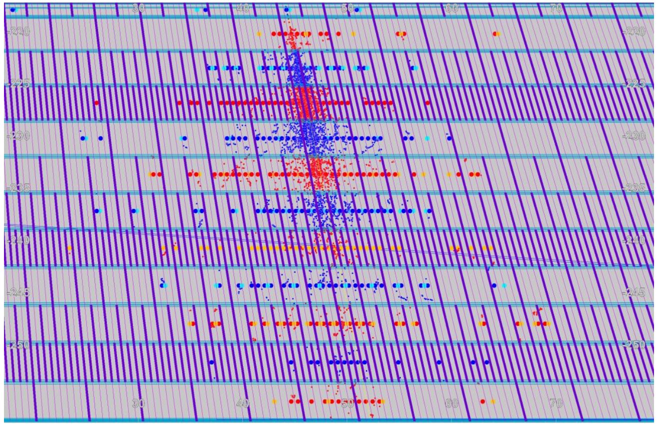
Highlight from 2023

Simulation studies in key4hep

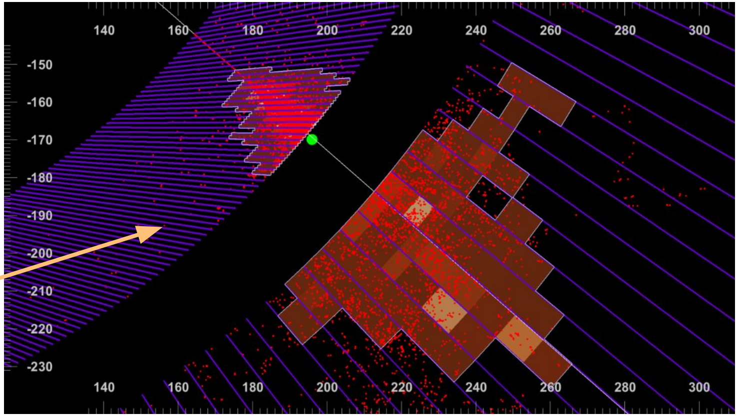
See Tong's talk today !

Lots of ground work in 2023 !

- Correct cells geometry was used in simulation but not in digi/reco
  - Now proper θ/ϕ positions used consistently everywhere
  - Much more flexible fullsim geometry:
    - Can easily change cells and layers sizes
    - Can adapt the granularity per layer



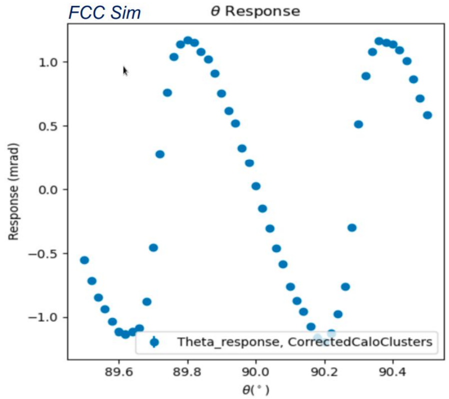
- Improvements in clustering
  - Topo-clustering and fixed-size clusters adapted to new geometry
  - Super nice tool to visualize showers and clusters
  - Topo-clustering using ECal+HCal (Preliminary)

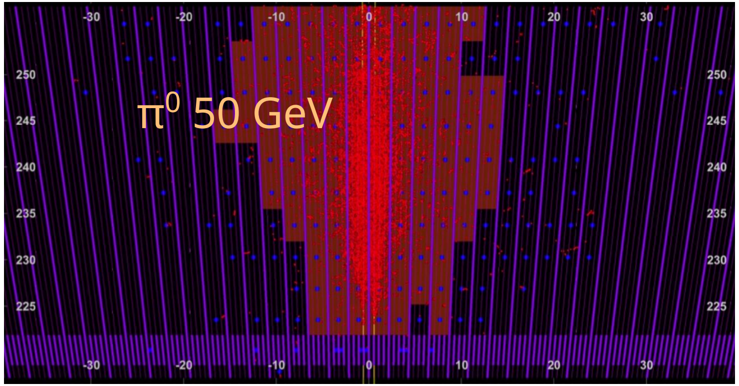


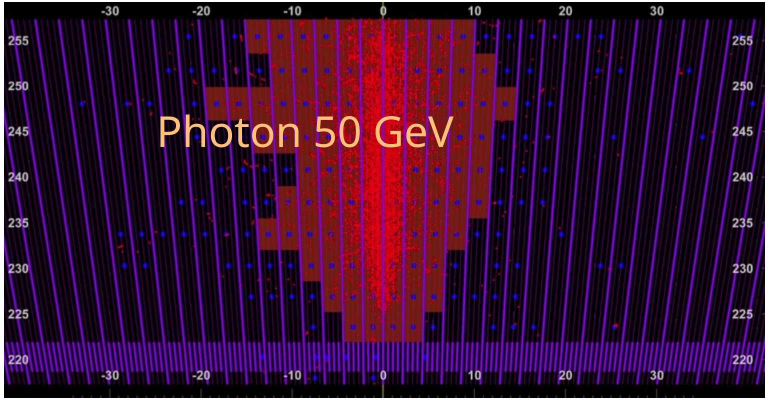
Simulation studies: next steps

Ground work done this year enables performance optimization based on physics

- Finer levels of calibration
  - "Rediscovery" of S-shape effects
- Optimization of cell sizes
  - Event displays show that position of "strip" layer is probably not correct for photon / π^0 separation





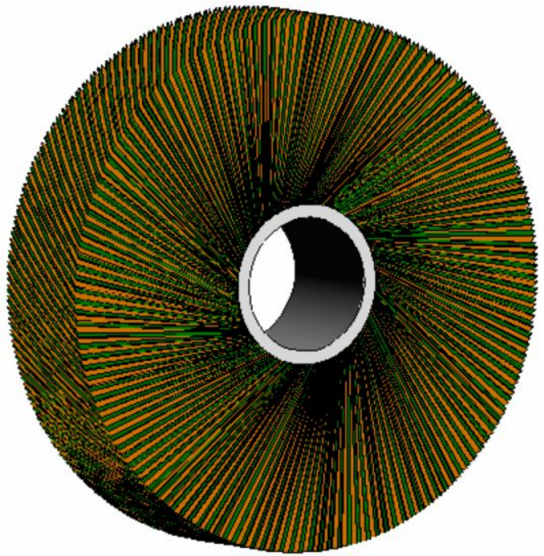


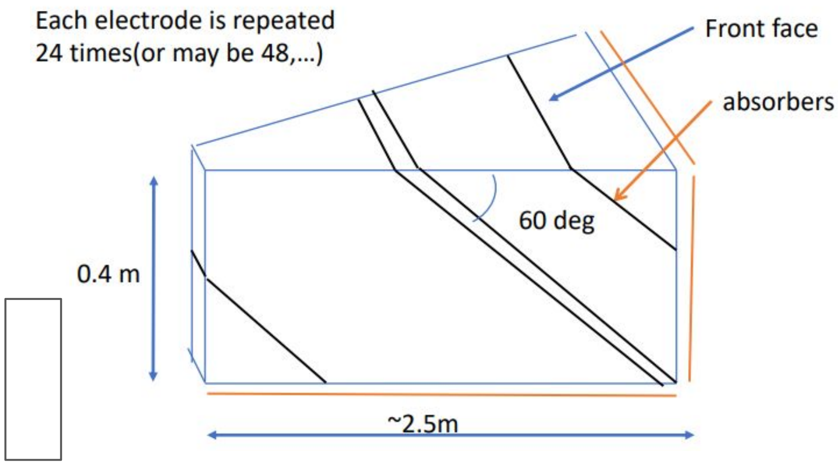
Designs for the endcaps: first ideas

Endcaps designs more complex than that of the barrel: very preliminary ideas !

- "Turbine" design
  - More similar to barrel design
  - Symmetric in ϕ
  - Issue: increase in the size of the LAr gaps
  - Need to stack several cylinders

- XY / Pie wedge designs
  - Less symmetry in ϕ
  - Increase of LAr gaps under control
  - Many types of electrodes to draw and produce



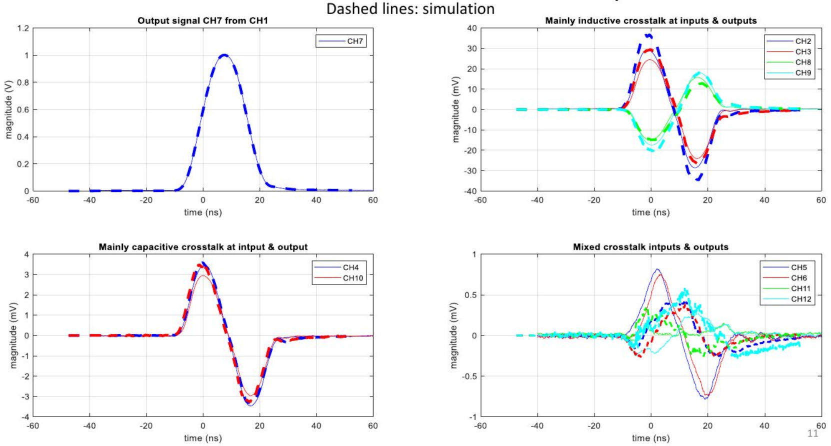


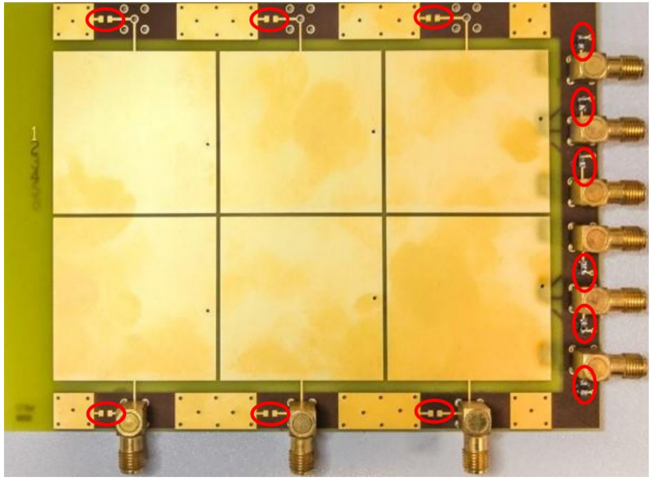
Electrode measurements @ IJCLab

Small-scale prototype designed for precision tests

- Detailed understanding of signal propagation and cross-talk effects
- Building knowledge of Sigrity simulation tool
  - Very good agreement with measurements after tuning !
- Fruitful discussions with PCB manufacturer to understand practical limitations of our design

Dashed lines: simulation

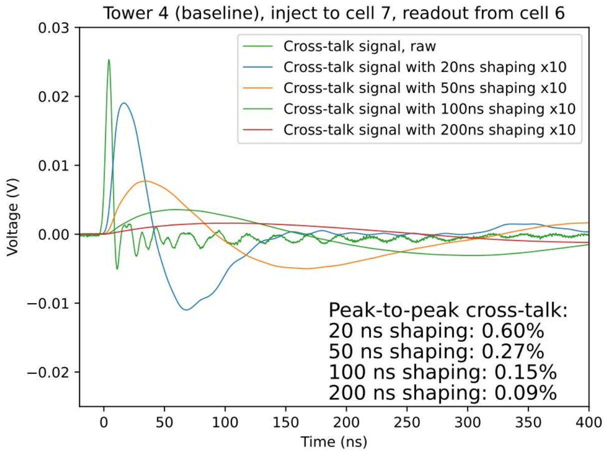


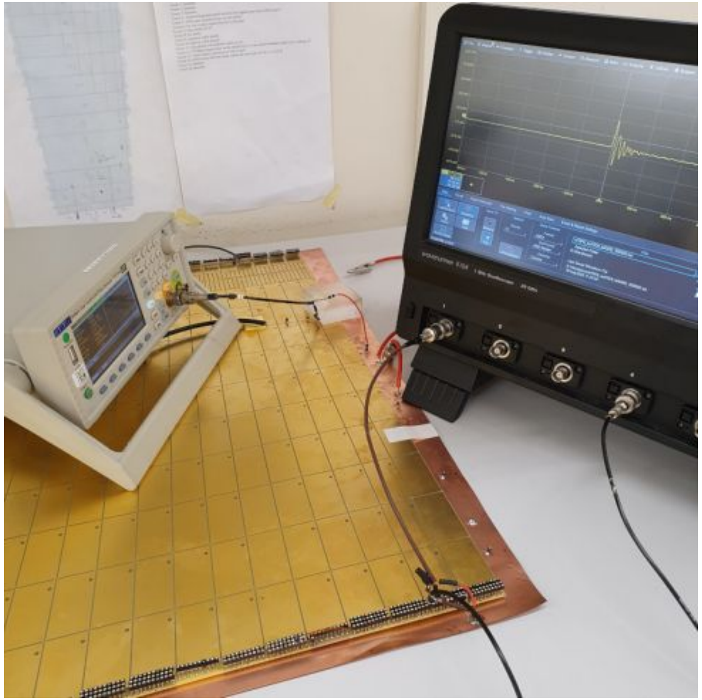


Electrode measurements @ CERN

Full scale electrode !

- Took quite some time and effort to achieve good measurements
  - Fruitful collaboration with IJCLab
  - Proper grounding, terminations, short cables...
- Extraction of cross-talks in several cases
  - Impact of shielding and of shaping time
  - Few per-mille easily achievable

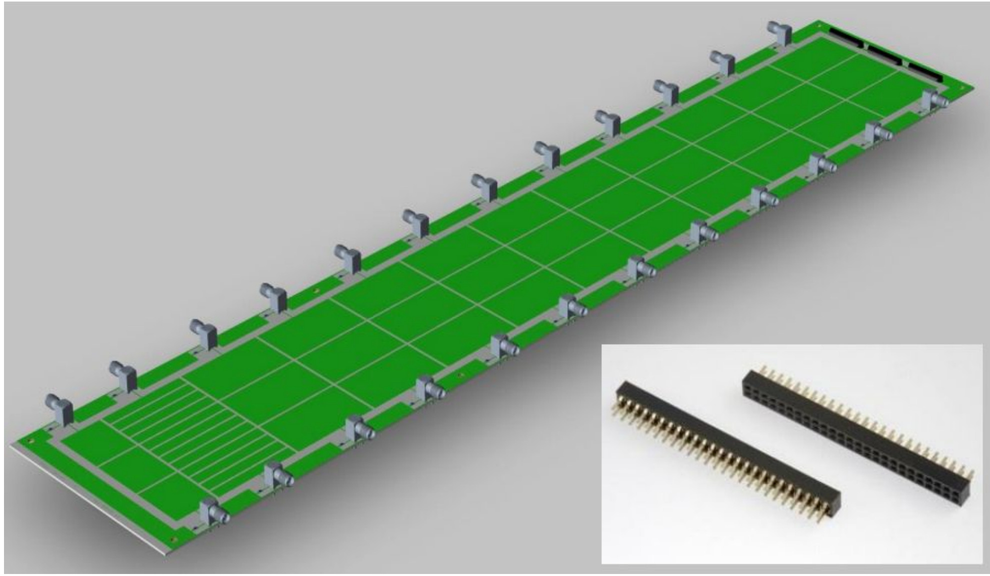




Next generation of prototype electrode

Learning from the previous generation

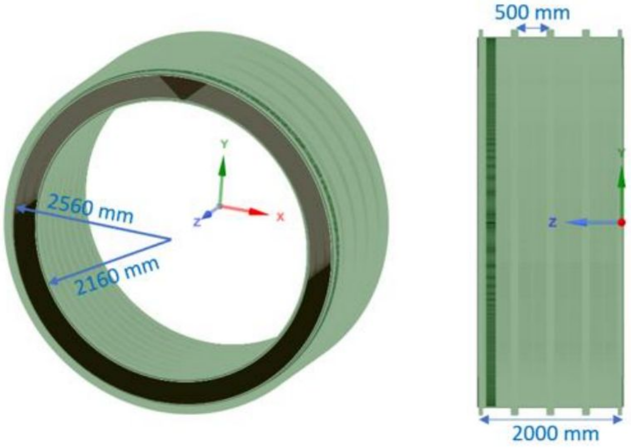
- Next prototype at IJCLab
  - All layers, 3 towers
  - Readout all cells at the back
    - Best for material budget in calo, worst for cross-talk
  - Study options for additional shielding
  - Connectors for easy readout/injection
  - Possibility to merge several PCBs
  - In fabrication

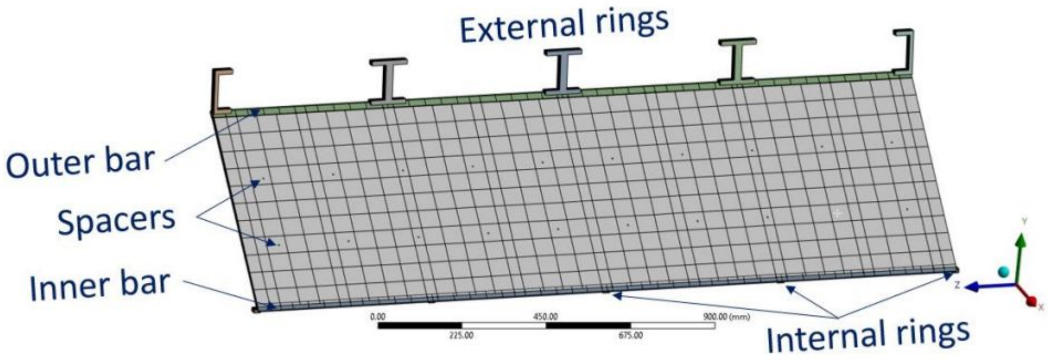


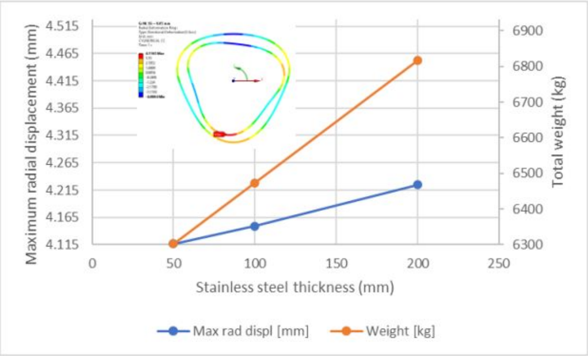
R&D on absorbers: simulations

Find mechanical solutions that could work for a full scale design

- Study thickness of steel sheets
- Numbers of spacers needed
- Support rings
- In warm and in cold



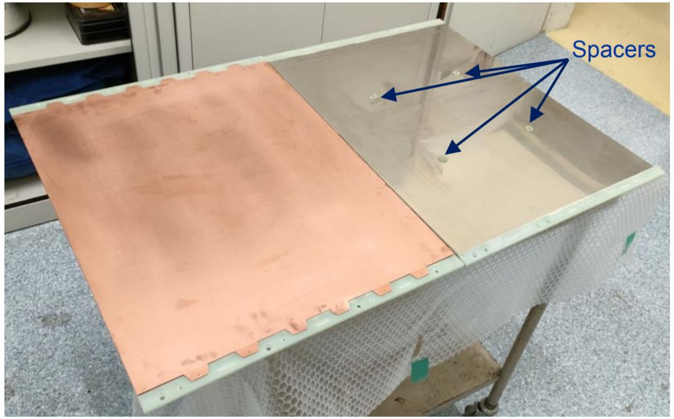


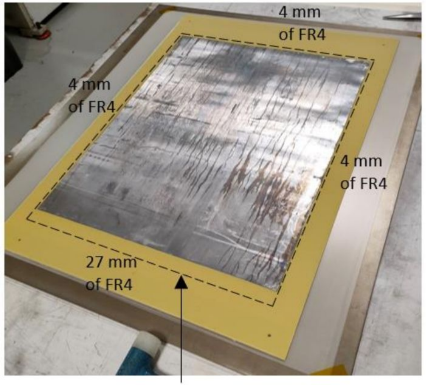


Absorbers: first prototypes

- Use FR4 frame to build the prototype
- Glue steel sheets on top of lead plate
- Then cut by CNC to final dimensions
- Mount absorbers around a fake electrode

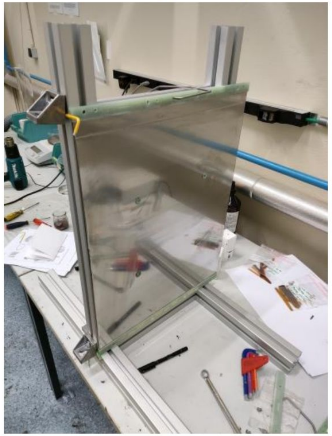
2 absorbers and the fake PCB





Final dimensions

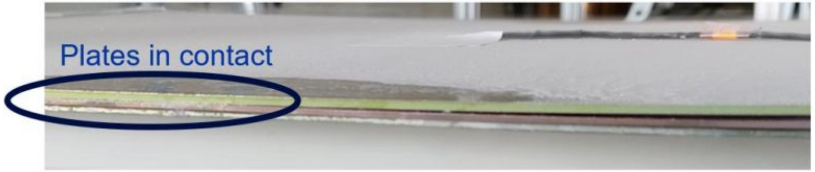
Bars gluing

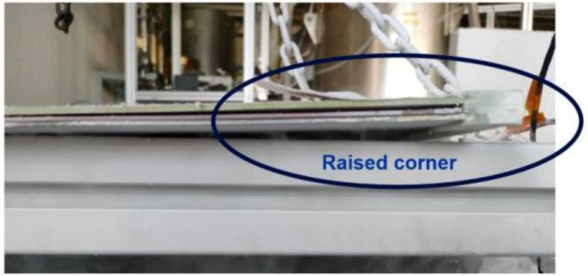


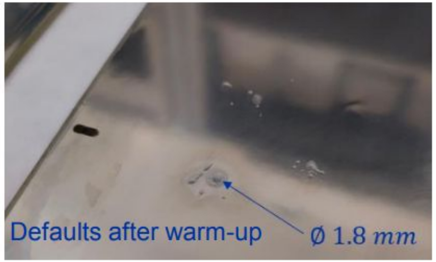
Final assembly

Absorbers: mechanical tests in the cold

- Put structure (2 absorbers + 1 electrode) in cold bath
  - Study deformations and defects
- Many interesting lessons learned !
  - Deflection of the assembly in both directions
  - Measured deformation fits with the calculated for the absorbers but not for the PCB and the bars
  - No cracks found in the steel or the bars and they stayed glued together
  - Some defaults found in the internal part of the lower absorber
  - ➢ More spacers needed, and should improve clamping







Plans for the R&D

Allegro ECal in DRD6

Only project in WP2: the community is united behind this project !

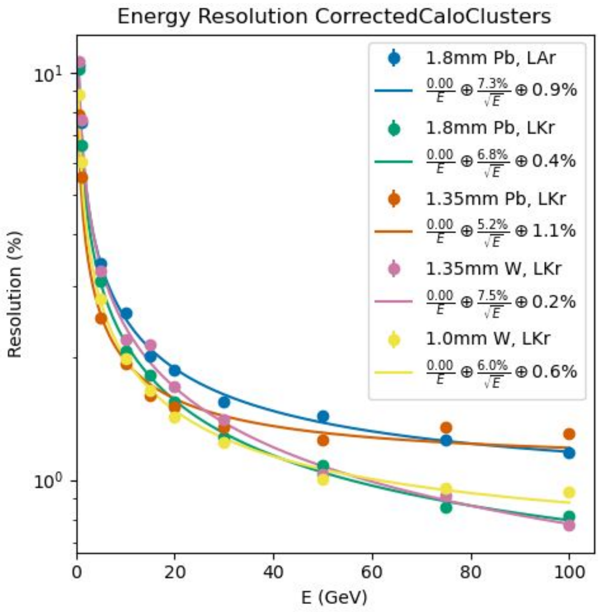
- DRD6: opportunity to build up the community
  - New Europeans partners
  - Inclusion of US institutes
  - IN2P3: involvement of more labs

- Main objective: do R&D up to a prototype that can be put in testbeam
  - Realistic timescales give 2028 as target

1. General design and expected performance

Workplan

- Understand the required granularity
  - Study photon/pion ID (tau physics)
  - Axion searches
  - Jet energy reconstruction
  - Using 4D imaging techniques, ML, PFlow
- Optimize design for EM resolution
  - Electron and photon resolutions
  - Pions, b-physics
  - gap size, sampling fraction, active and passive material…
- Investigate possibility to readout Cerenkov light
  - Design feasibility
  - Possible gains for timing or for DR measurements

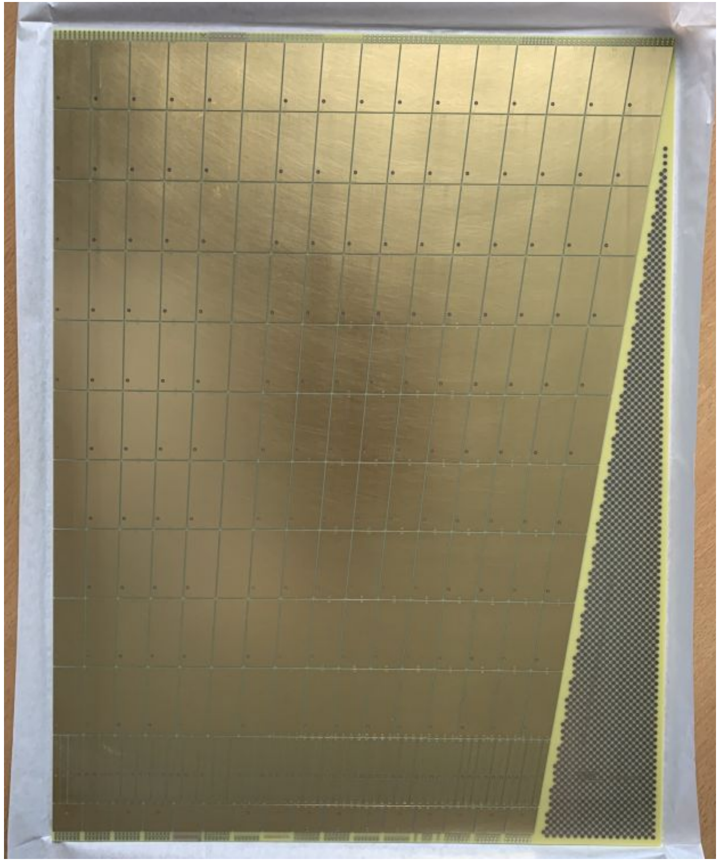


2. Readout electrodes

Workplan

- Barrel electrodes
  - Optimize granularity based on physics simulations
  - Minimise noise (aim for photons down to 300 MeV and S/N>5 for MIP) and cross-talk
  - Readout everything at the back
  - Connectors
  - HV layer, including resistors
  - Aim for “final” prototype end of 2024

- Endcap electrodes
  - Investigate possible geometries
  - Optimize granularity
  - Design prototypes

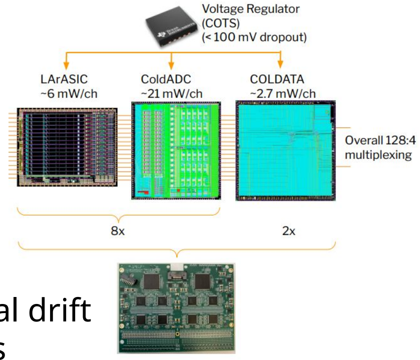


3. Readout electronics

Workplan

- Both Frontend options
  - Take advantage of synergies with existing chips or planned chips for other DRDs
  - Develop frontend boards
- Warm Frontend electronics option
  - Specific work on cables inside the cryostat
- Cold Frontend electronics option
  - Could allow for much lower noise
  - Adapt 'regular' chips to LAr temperatures, or start from Dune experience
  - Specific work on power consumption
- Backend electronics and DAQ
  - Requirements not yet defined

$$N \sim C_d \sqrt{\frac{4kT}{g_m \tau_p}}$$

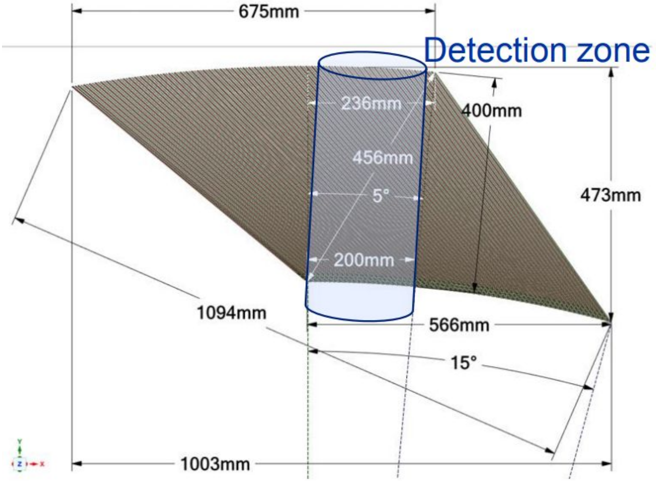


Dune horizontal drift front-end chips

4. Mechanics, and Towards a prototype

Workplan

- Absorbers
  - Find best compromise in feasibility, between thickness, rigidity, support structures
  - Prototypes in 2024 and 2025
- Small module
  - Requires to put everything together
  - Design in 2024 and 2025
  - Assemble and test at warm temperatures in 2027
  - **Cold tests and testbeam in 2028**
- Infrastructure
  - Use of common tools (EUDAQ...) would facilitate the integration in a testbeam facility
  - Strong testbeam expertise from some institutes



Conclusions

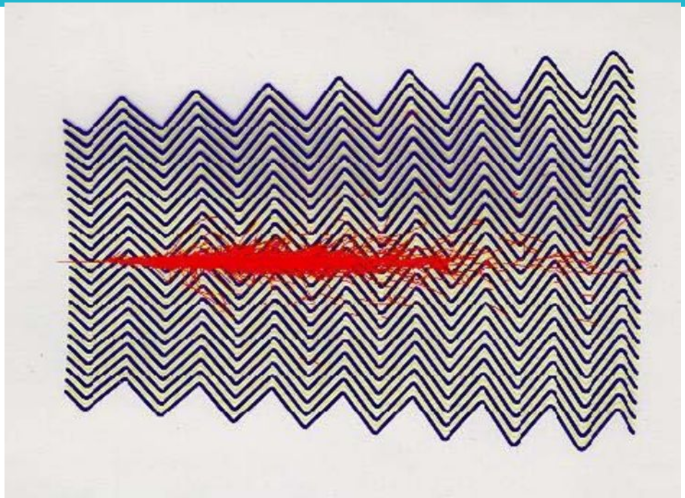
- R&D on Allegro ECal is progressing well
  - 2023 very productive in simulation studies, electrodes measurements, and first absorbers prototypes
- DRD6 is the opportunity to scale up the project
  - Build a community towards a first prototype in testbeam
  - Clear R&D path to get there

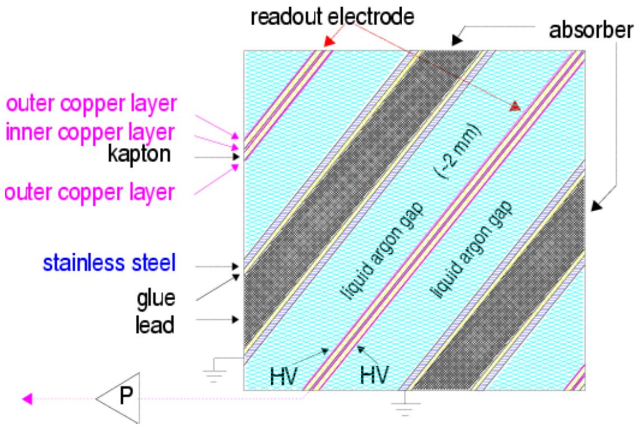
Backup

Sampling Noble liquid calorimeters

Working principles in 30 seconds

- LAr gap between electrodes with HV
- Incoming particle shower develops in the absorbers and ionize the liquid
- Ionization electrons drift in the gap
- Induce current on the readout plane below the electrode
- Proportionality between deposited energy and induced current over orders of magnitude





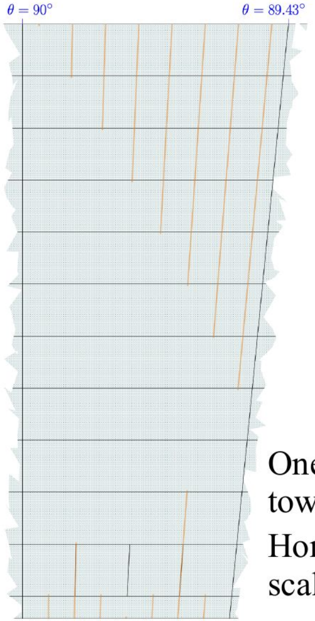
High granularity electrodes

Aiming for ~ ×10 ATLAS granularity

- High granularity required for better PFlow performance (few million cells)
- >6 compartments to compensate LAr gap widening

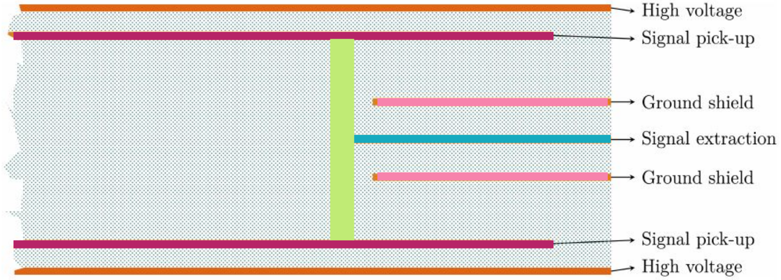
Implementation: multi-layer PCBs

- 7-layer PCB
  - 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



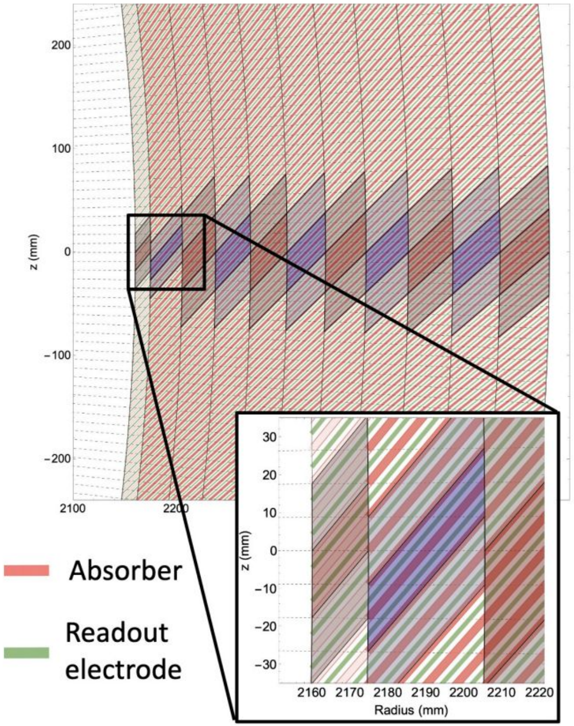
One theta tower

Horizontal axis scale 10:1

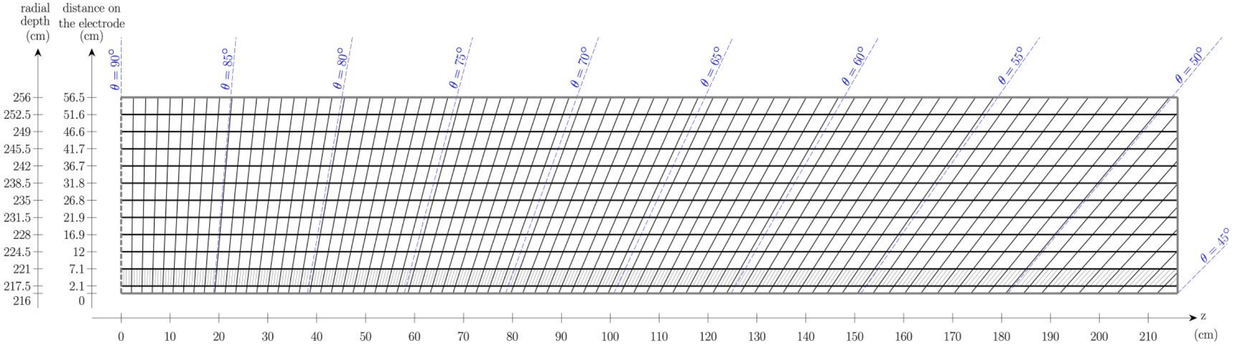


Geometry

Transverse



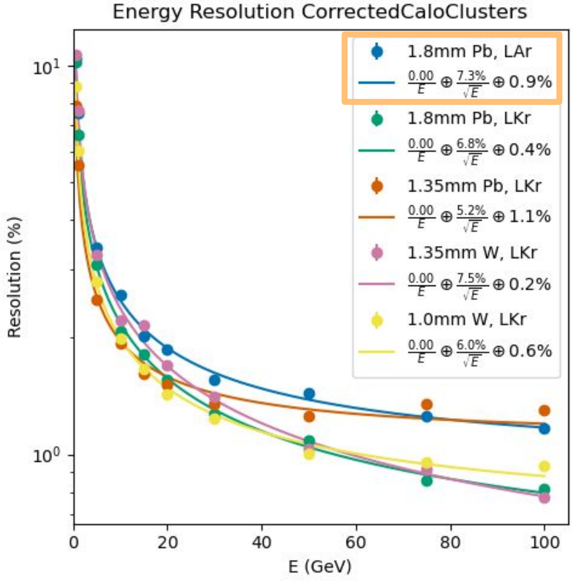
Longitudinal



Optimizing the energy resolution

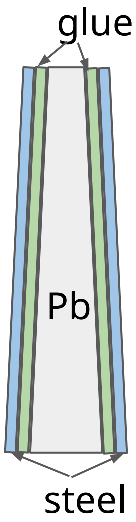
Materials

- LAr → LKr:
  - 8%/√E to **5%/√E**
- Pb → W:
  - No improvement in resolution
  - Expected impact on PID to be studied



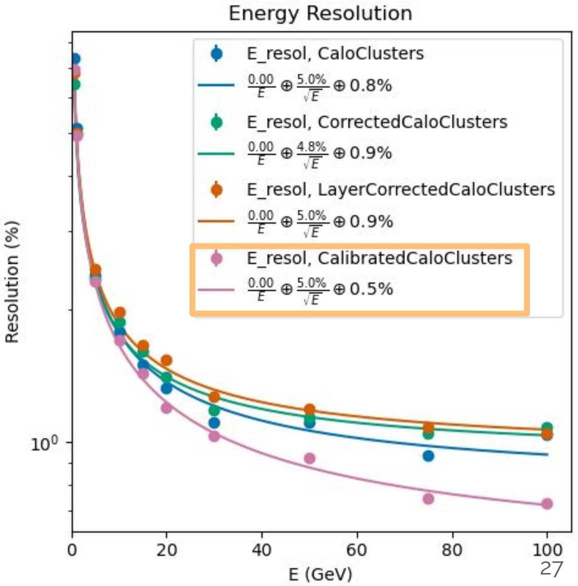
Geometry

- Straight planes → trapezoidal absorbers
  - Better sampling fraction in first layers
  - Small gain in resolution
  - Feasibility to be evaluated



Software

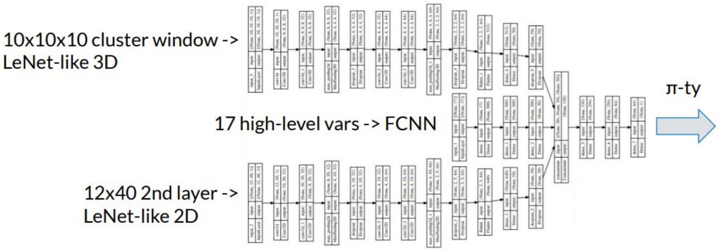
- MVA calibration
  - improves constant term
- Clustering
  - Large effect, to be studied further

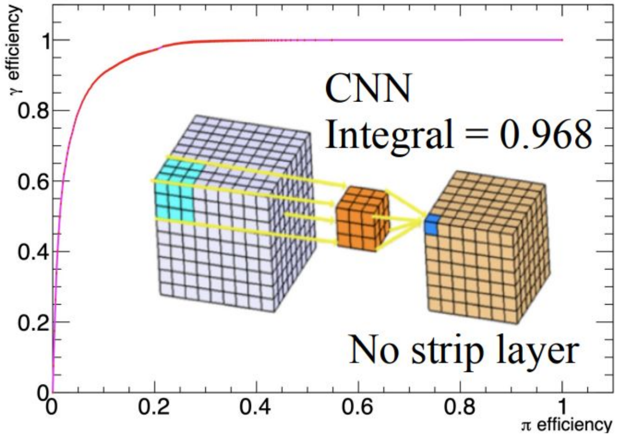


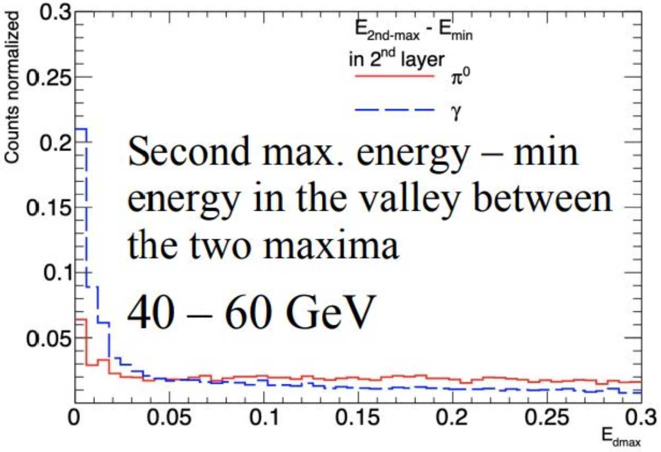
Estimating PID performance

Benchmark for ECAL: π^0/γ separation

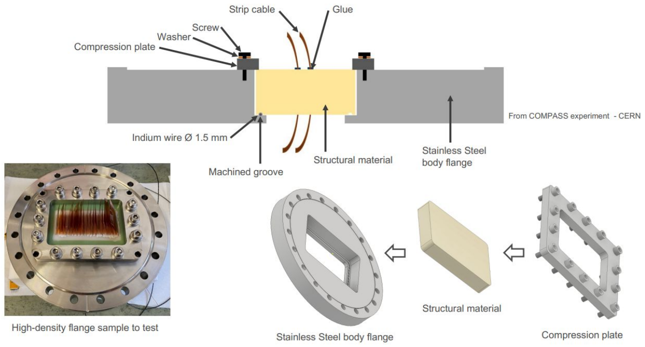
- Use of PCB as readout electrode
  ⇒ large **flexibility on granularity**
- Many cells: use of **ML techniques** for improved performance
  - Based on shower shapes and on raw cells energies
  - Investigate CNN and DNN
  - Investigate role of “strips” layer
- **Very promising results !**
  - 95% γ efficiency for 10% π^0
- Next is use of GNN
  - Probably better suited for our use-case

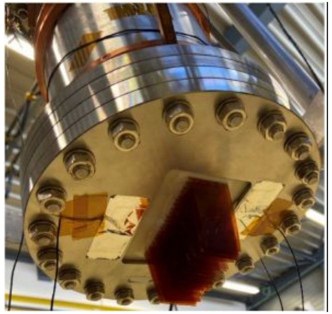


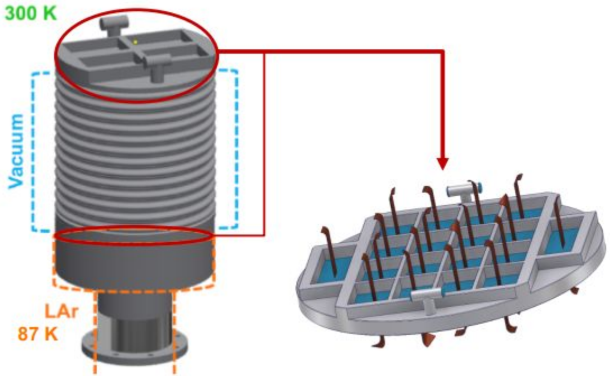




High density feedthroughs





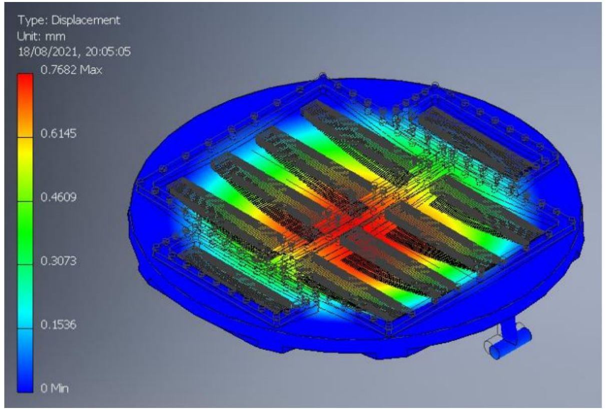


Signal extraction from cryostat

- High density feedthroughs needed in case readout electronics outside of cryostat
- Aim for ~ ×5 density and ~ ×2 area wrt ATLAS

Successful R&D on connector-less feedthrouhgs at CERN

- Prototypes of 3D-printed epoxy resins structures with slits for strip cables, glued to the flange
- Leak tests and pressure tests at 300 K and 77 K
  - **Suitable materials identified: G10 structure with slits + indium seal + Epo-Tek glued Kapton strip cables**
- Stress simulations of complete designs at 300 K and 77 K



Next generation cryostats

Minimizing dead material in front of calo

- Crucial for low energy measurements at FCCee
- Ongoing R&D for cryostats using new materials and sandwiches
  - Generic R&D at CERN as cryos will be used for solenoids in all experiments
  - Synergy with progress in aerospace
  - Test microcrack resistance, sealing methods, leak and pressure tests
  - Address CFRP/Metal interfaces
- Promises for **"transparent" cryostats**: few % of X_0 !

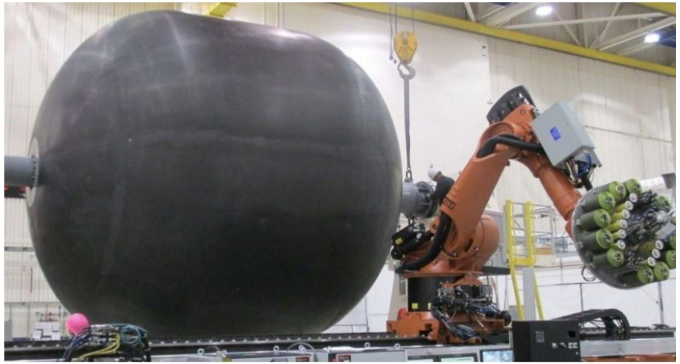
Sandwich Shell

Skin [0,45,-45,90]s
Core : Al Honeycomb
Skin [0,45,-45,90]s

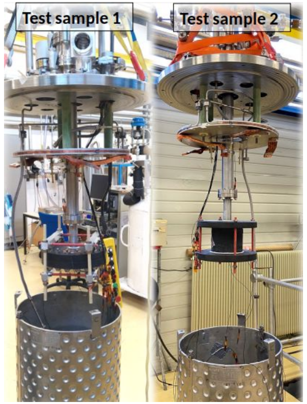
Solid Shell

Radiation length X_0[mm]
Al = 88.9
HM CFRP = 260
Honeycomb Al= 6000

Criteria: Safety Factor = 2	Sandwich shell				Solid shell			
	HM CFRP		Al		HM CFRP		Al	
	OWC	ICC	OWC	ICC	OWC	ICC	OWC	ICC
Material budget X/Xo	0.03	0.043	0.094	0.17	0.092	0.12	0.34	0.44
Xo % savings	-68%	-75%	REF	REF	-2%	-29%	262%	159%
Skin Th. [mm]	3.2	4.8	3.9	7.5				
Core Th. [mm]	32	38	40	40				
Total Th. [mm]	38.4	47.6	47.8	55	24	30.4	30	39
Thickness % savings	-20%	-13%	REF	REF	-50%	-45%	-37%	-29%



NASA's lineless cryotank



Sealing with Belleville washers

Noise and cross-talk considerations

Goals

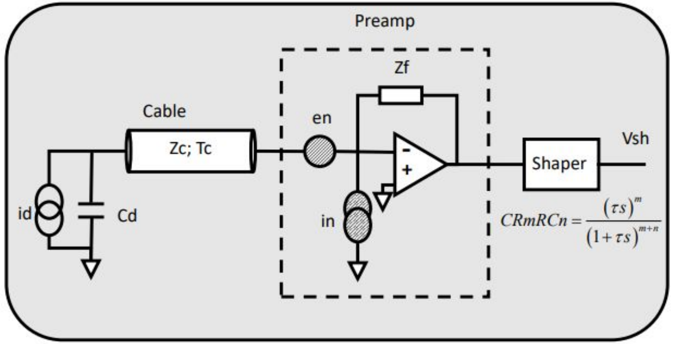
- Low noise to measure photons **down to 200 MeV**
- Measure MIPs with good S/N
- **Sub-percent** cross-talk

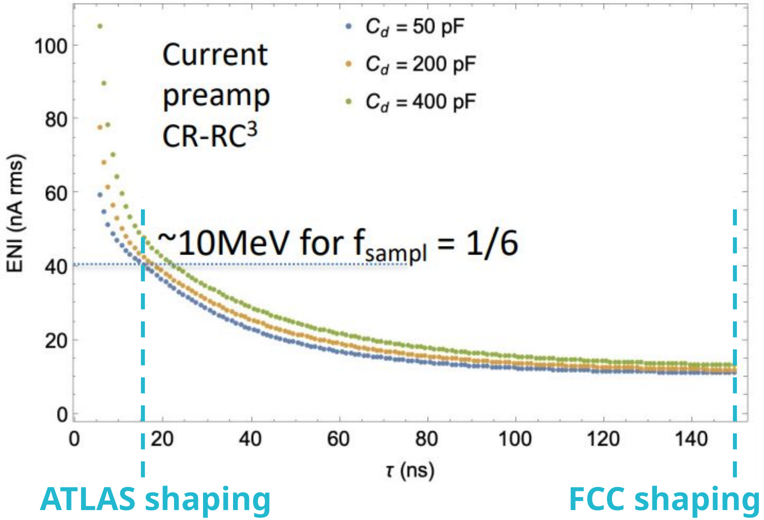
Performance estimation

- Performance depends on **electrodes** and **transmission line** properties, and on choices made for **readout electronics**
- Cell capacitances computed using FEM tools (ANSYS)
- Electronics noise from analytical description of readout
- Cross-talk from FEM calculations (Cadence Sigrity or ANSYS HFSS)

Results

- **Long** (200 ns) **shaping times** help a lot
- Suitably low noise and cross-talk achievable





Cold electronics ?

- Noise master formula: $$N \sim C_d \sqrt{\frac{4kT}{g_m \tau_p}}$$
- Cold electronics: gain on C_d, T and g_m
- **Extremely low noise easily achievable**

$$C_{cable} = \frac{\tau_{delay}}{Z_c}$$

	ENC (keV)	Peaking time = 500 ns
Warm electronics L = 5 m C_{cable} = 500 pF / 1 nF	Cd = 100pF – 50/25 Ω	1400 / 2500 keV
	Cd = 200pF – 50/25 Ω	1600 / 2800 keV
	Cd = 400pF – 50/25 Ω	2100 / 3200 keV
	Cd = 800pF – 50/25 Ω	2900 / 4100 keV
Cold electronics L=10 cm C_{cable} = 10 pF / 20 pF	Cd = 100pF – 50/25 Ω	140 / 150 keV
	Cd = 200pF – 50/25 Ω	250 / 260 keV
	Cd = 400pF – 50/25 Ω	470 / 470 keV
	Cd = 800pF – 50/25 Ω	910 / 910 keV

How ?

- Challenges:
  - Heat dissipation
  - Difficulty for repair
- We know how to do it:
  - DUNE example
- Very first studies
  - HGCROC in Liquid N at IJCLab
  - Check behaviour of analogue and digital parts