Noble liquid calorimetry for FCC-ee

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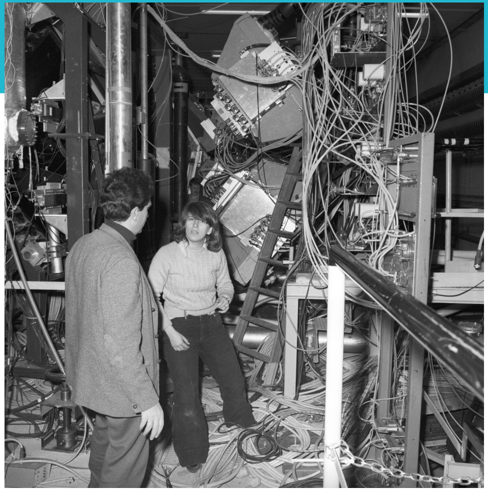
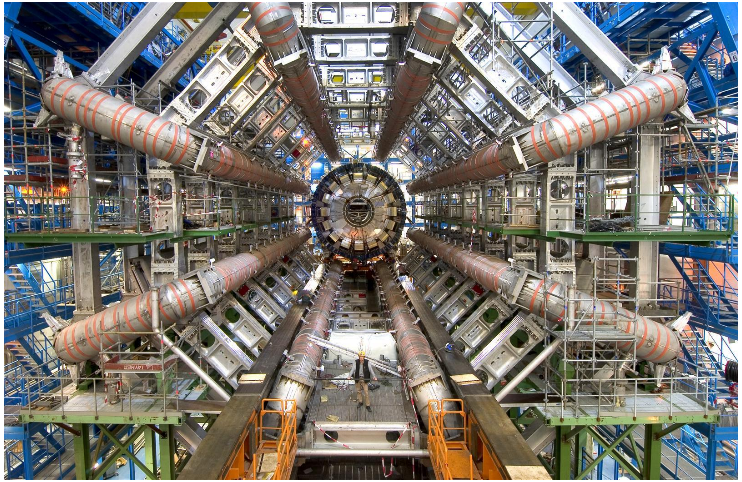
Introduction: noble liquid calorimeters



- 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
- **Significant progress in the past year**

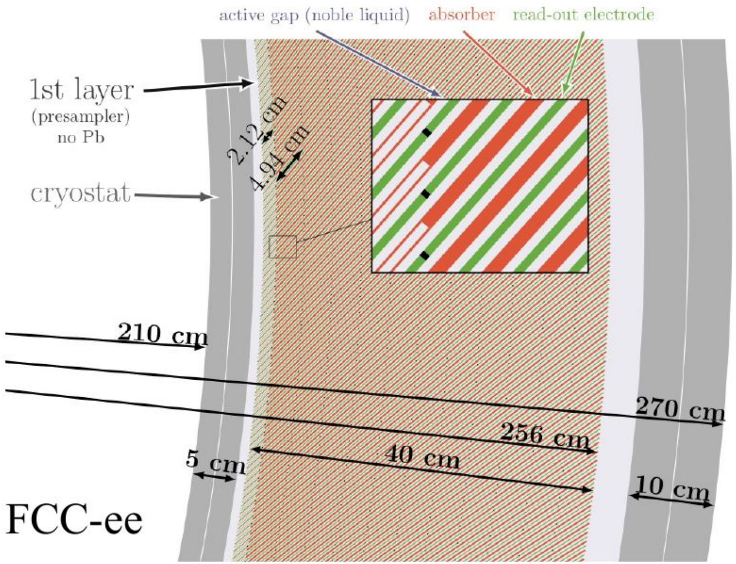


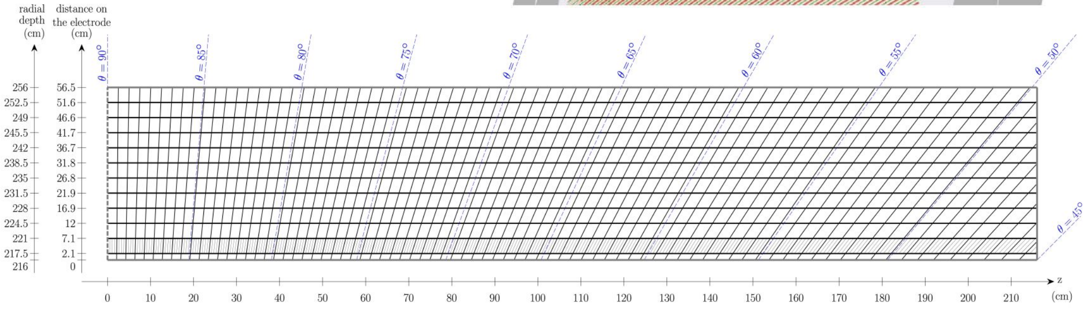
General design: geometry

Design driven by readout electrodes

Baseline (conservative) FCCee ECAL barrel design

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



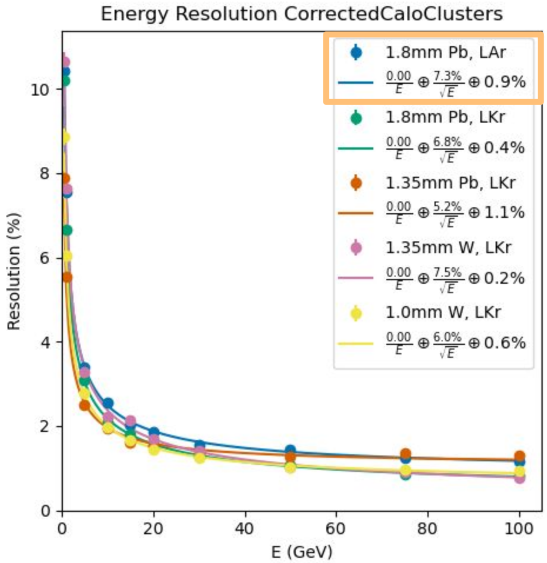


Lots of room for optimization and improvements

Optimizing the energy resolution

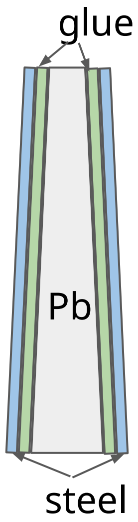
Materials

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



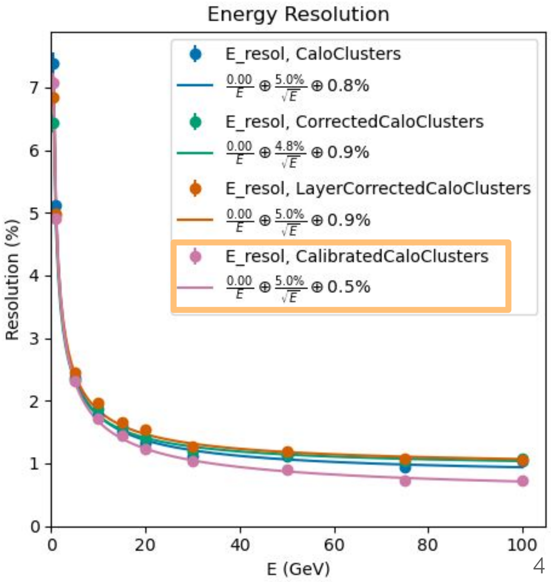
Geometry

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



Software

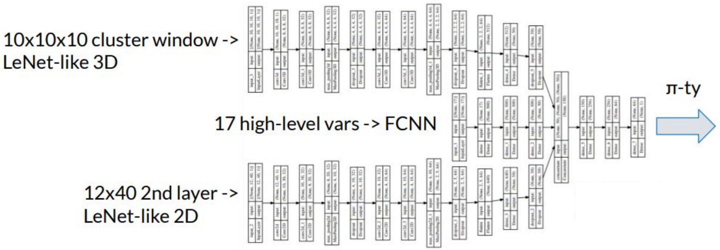
- MVA calibration
  - improves constant term
- Clustering
  - Large effect, to be studied further

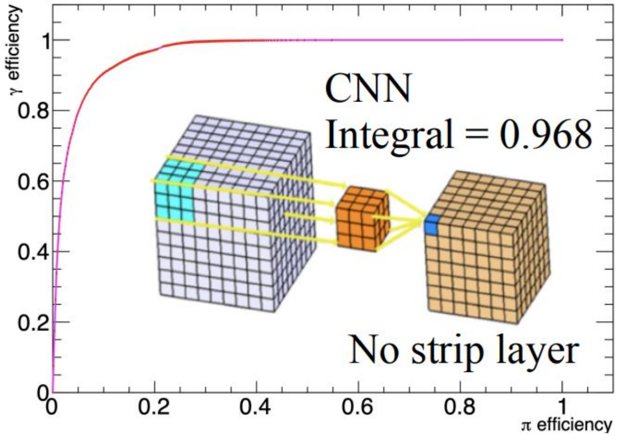


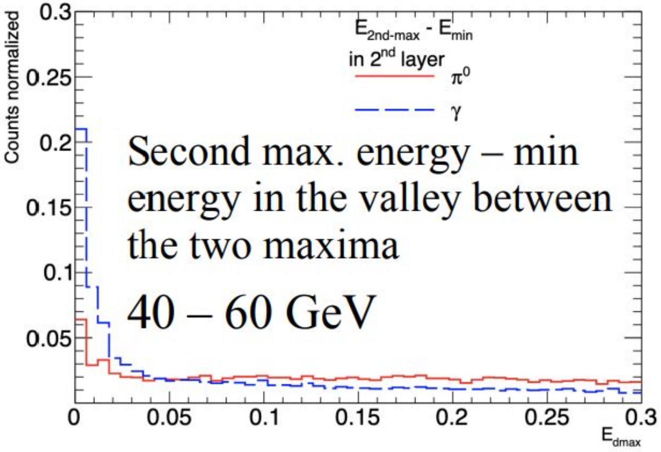
Estimating PID performance

Benchmark for ECAL: π^0/γ separation

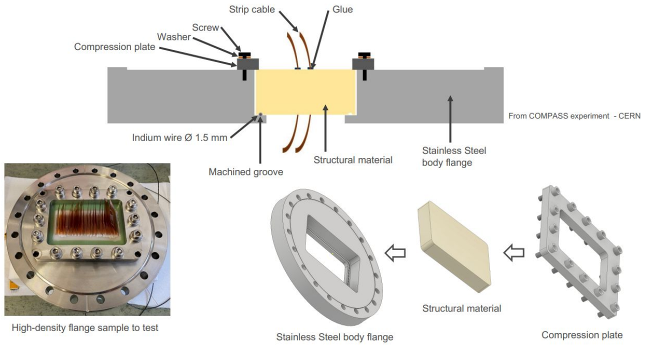
- Use of PCB as readout electrode
  ⇒ large **flexibility on granularity**
- Many cells: use of **ML techniques** for improved performance
  - Based on shower shapes and on raw cells energies
  - Investigate CNN and DNN
  - Investigate role of “strips” layer
- **Very promising results !**
  - 95% γ efficiency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

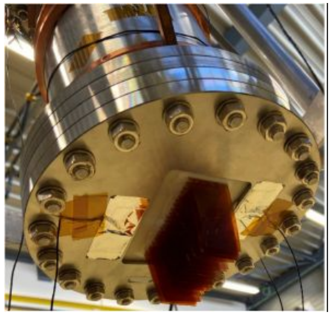


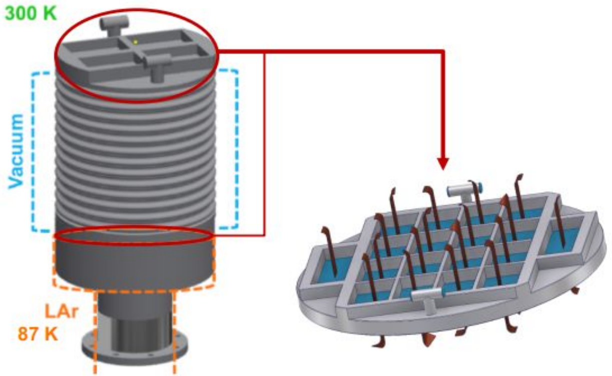




High density feedthroughs





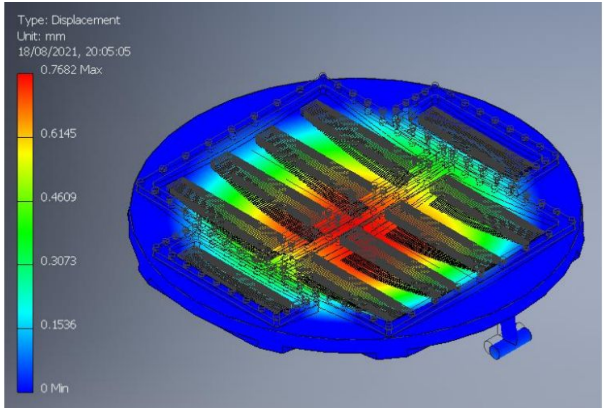


Signal extraction from cryostat

- 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

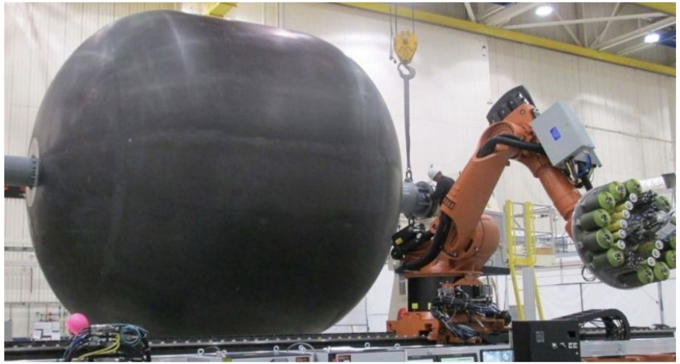


Next generation cryostats

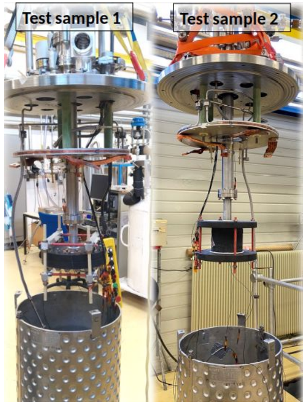
Minimizing dead material in front of calo

- 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 !

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

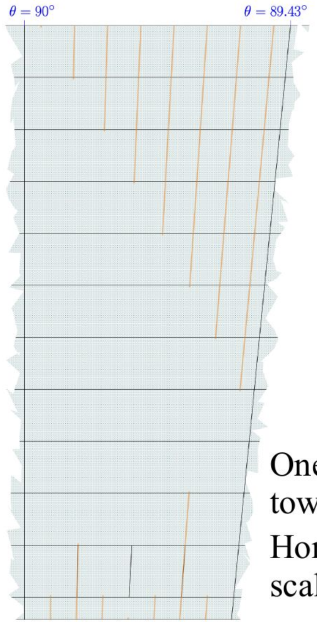
High granularity electrodes

Aiming for ~ ×10 ATLAS granularity

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

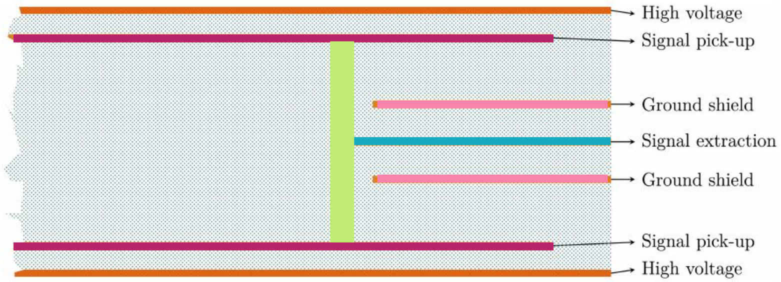
Implementation: multi-layer PCBs

- 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



Noise and cross-talk considerations

Goals

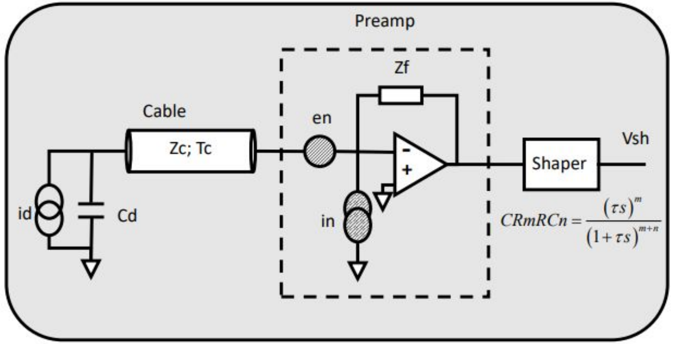
- Low noise to measure photons **down to 200 MeV**
- Measure MIPs with good S/N
- **Sub-percent** cross-talk

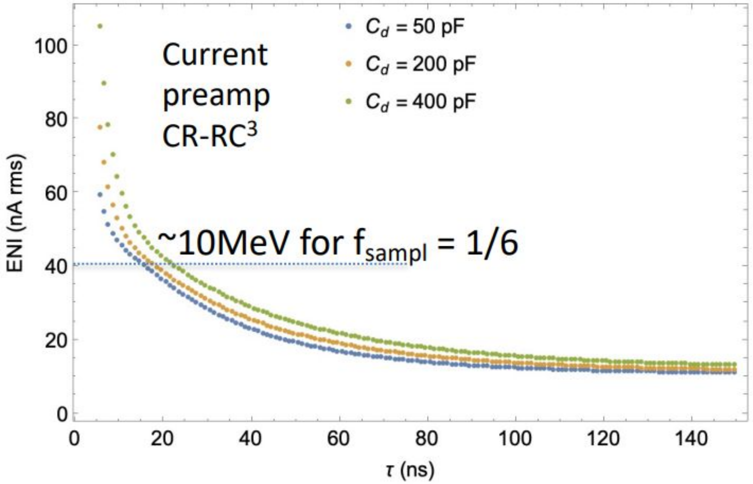
Performance estimation

- 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)

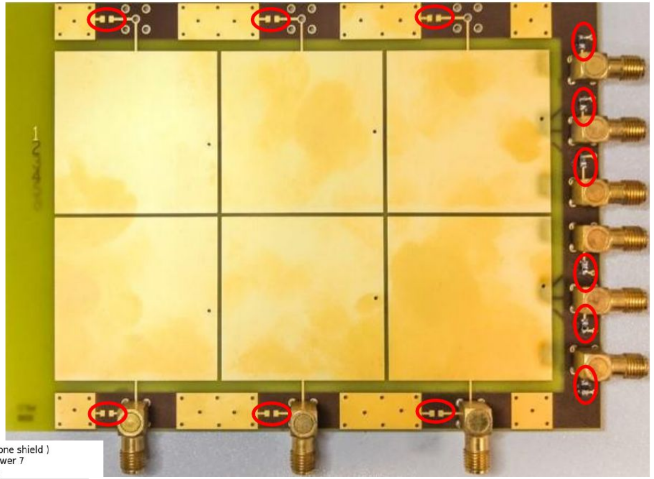
Results

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





Readout electrodes prototypes

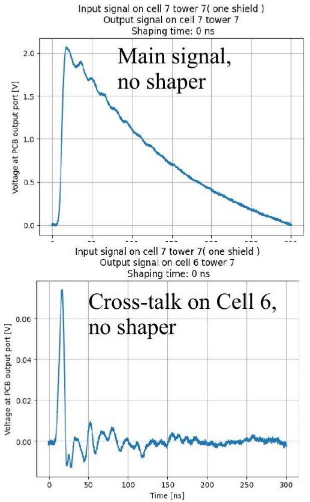


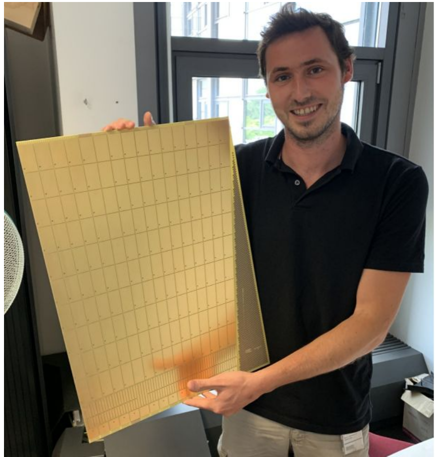
Small scale electrode @ IJCLab

- Detailed measurements of cell properties and cross-talk effects
- Frequency behaviour
- **Good overall agreement with simulations on large frequency range**

Larger scale electrode @ CERN

- 1:1 scale θ chunk: 16 towers with different layouts
- Simple electrical tests with scope and software shaper
- **Sub-percent cross-talk easily achievable with > 50 ns shaping**





Cold electronics ?

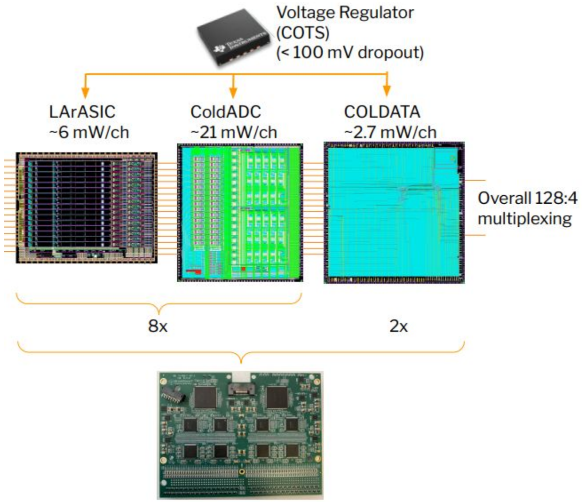
- Noise master formula: $$N \sim C_d \sqrt{\frac{4kT}{g_m \tau_p}}$$
- Cold electronics: gain on C_d, T and g_m
- **Extremely low noise easily achievable**

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

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

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



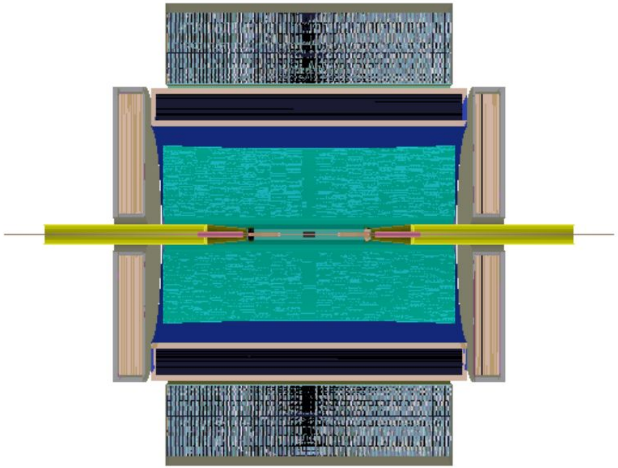
More than the ECAL barrel

Towards a detector concept

- Based on IDEA design but using Noble Liquid for ECAL
- Performance impact of position of solenoid to be studied in simulation

Implementation in FCCee Fullsim

- ECAL endcaps
  - Parallel disks, 1.5mm Pb, 2mm LAr gaps
  - Total thickness 45cm
- HCAL barrel
  - Based on Iron-Scint Tile design for FCChh
  - 13 compartments, $\Delta\theta \times \Delta\phi$ = 0.025 × 0.025
- Cryostat: more realistic implementation



Conclusions

- Significant progress in the past year on Noble Liquid calorimetry for FCC-ee
  - EM resolution and PID optimization in simulation studies
  - Cryostat and feedthroughs R&D
  - Measurements of electrode prototypes
- Very fruitful GranuLAr workshop at IJCLab
  - Welcoming new and prospective collaborators
- Prospects for next year
  - Whole concept in fullsim + Pandora PFA in FCCee software ⇒ **first look at hadron performance**
  - Further EM performance studies
  - Start of **R&D on absorbers**