Noble liquid calorimeter

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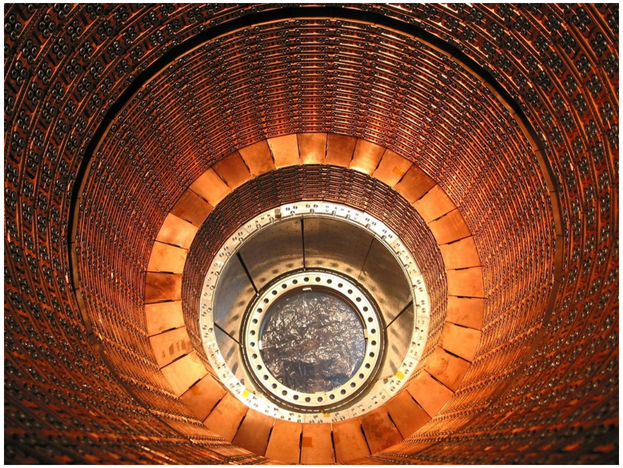
ECFA WG3 Workshop

Content

- Introduction
- R&D projects
  - Multilayer electrodes
  - Lightweight cryostat
  - High density feedthroughs
  - Mechanics
- Software
- Conclusions

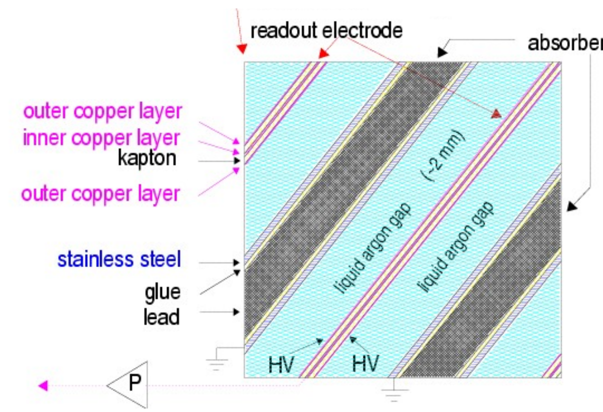
Noble liquid calorimeter

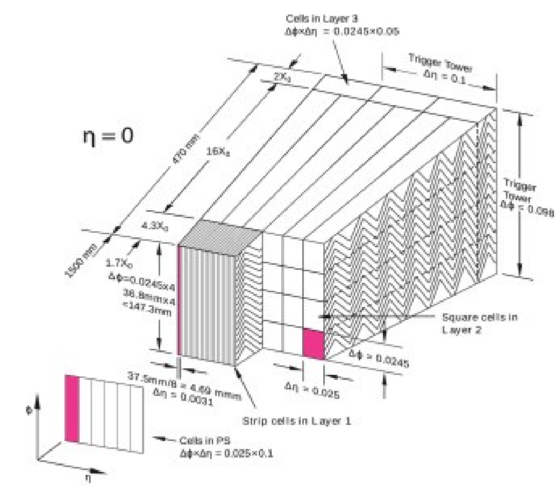
- Good experience with noble liquid calorimeters in a number of experiments (e.g. D0, H1, NA48/62, ATLAS)
- Advantages
  - Very good energy resolution (sampling term of ~10%)
  - Linearity, uniformity and stability of the response → Low systematics
  - Particle identification capabilities
  - Radiation hardness
- Concept suitable for future experiments (e.g. FCC-hh, FCC-ee)
  - R&D projects

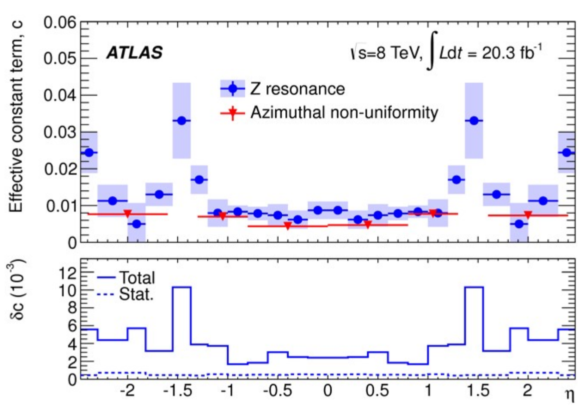


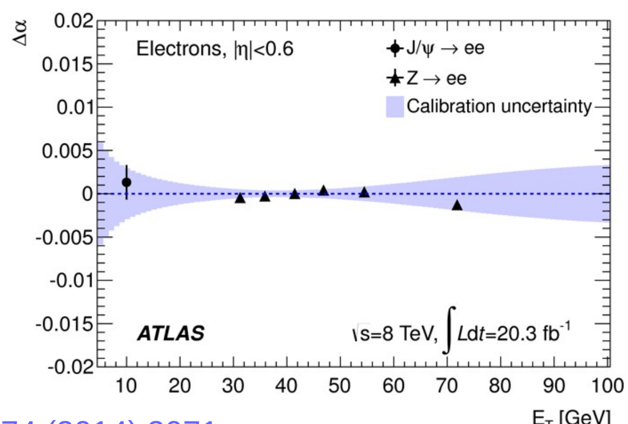
State of art

- ATLAS electromagnetic calorimeter
  - Lead absorbers/LAr in the gap
  - Accordion geometry of the kapton electrodes
- Performance
  - Energy resolution as required $\frac{\sigma(E)}{E} = \frac{10\%}{\sqrt{E}} \oplus \frac{0.2}{E} \oplus 0.2\%$
  - Linearity (variations within 10^{-3})
  - Stability (energy resonse stable at the level of 10^{-4})









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The detector design is not optimised for particle flow algorithm

Towards new design

- Key points for the future experiments
  - High granularity is a necessity for advanced reconstruction techniques (e.g. 4D imaging, particle flow)

    → High density feedthroughs
    → Design of the readout PCBs (cross talk under control)
  - Systematics uncertainties have to be kept as low as possible

    → Precise calibration of the system

    → Considerations for the precision of the mechanics

Towards new design

- Key points for the future experiments
  - High granularity is a necessity for advanced reconstruction techniques (e.g. 4D imaging, particle flow)

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  - Systematics uncertainties have to be kept as low as possible

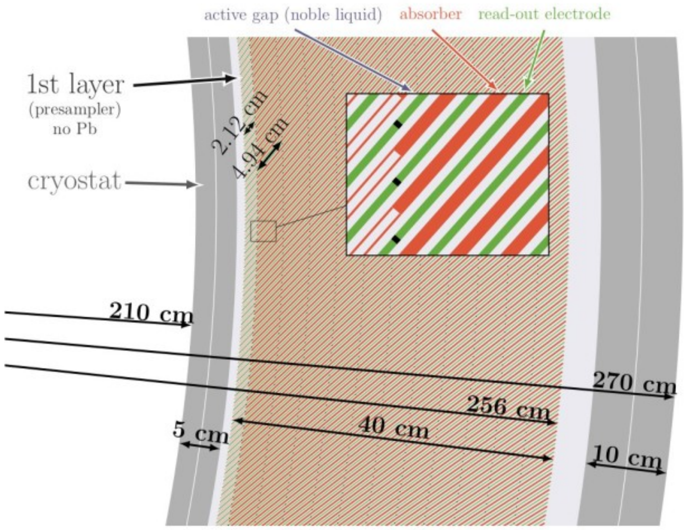
    → Precise calibration of the system

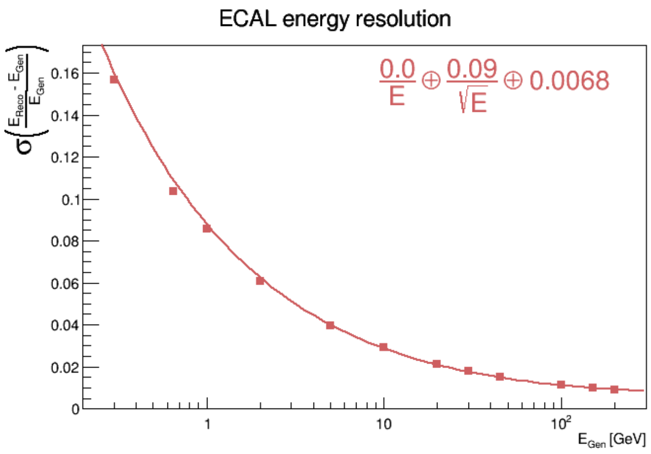
    → Considerations for the precision of the mechanics
- Electron – positron colliders: measurements of photons/electrons down to 300 MeV
  - Low electronic noise
    → Design of the readout PCBs
  - Low material in front of the calorimeter
    → Light weight cryostat

Baseline geometry

- Geometry optimised for experiment at FCC-ee
- 1536 Pb absorbers inclined by ~50.4°, $|z| \leq 2$ m along the beam axis
- Sandwich structure
  - Absorber (2 mm Pb)
  - Active medium (1.2 – 2.4 mm of LAr)
  - Read-out (1.2 mm PCB)
- 22 X_0 (40 cm) of the active ECAL region
- Placed in the aluminium cryostat (5 cm in front, 10 cm in back)

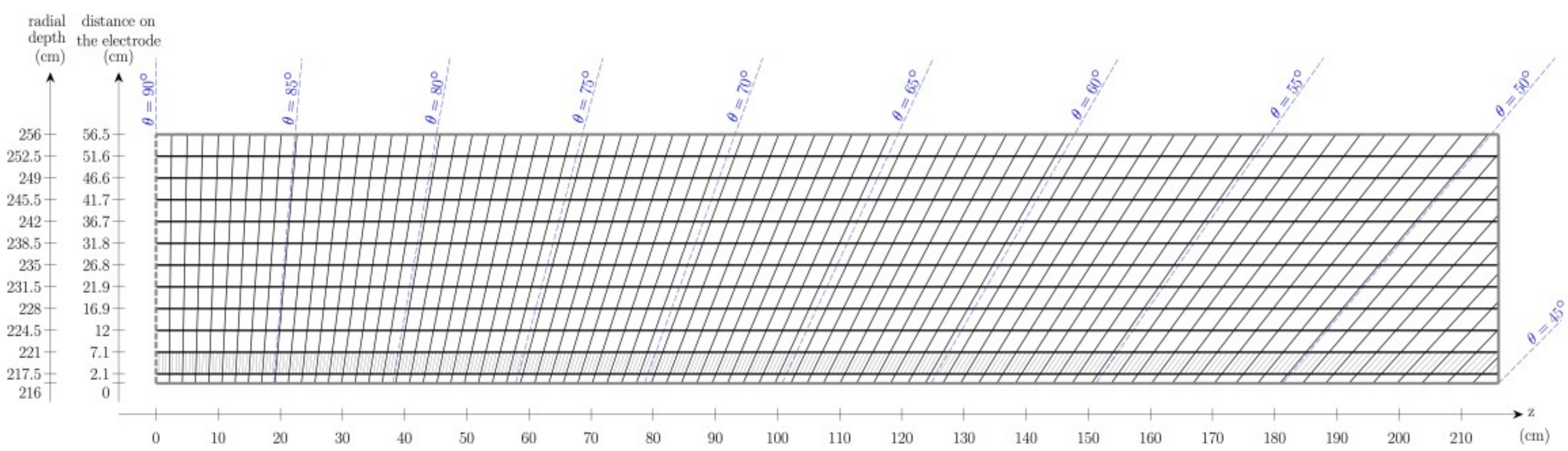
High granularity achieved by usage of straight multilayer readout





Granularity

- Target granularity: 10-15 times more compared to ATLAS LAr calorimeter
- 12 longitudinal compartments in radius
  - 1st layer (pre-sampler) without absorber for energy corrections
  - 2nd layer (strips) for π^0 identification
- Cell sizes
  - $\Delta\theta$ ~ 2.5 mrad in the strips (5.4 mm), 10 mrad in other compartments
  - $\Delta\Phi$ ~ 8.2 mrad in strips (17.7 mm), ~16.4 mrad in other compartments
  - Cell size ~2 cm x 2 cm x 3.5 cm in the 3rd compartment

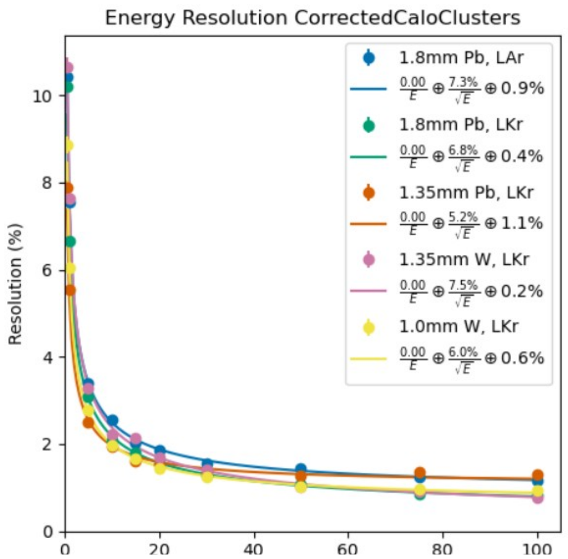


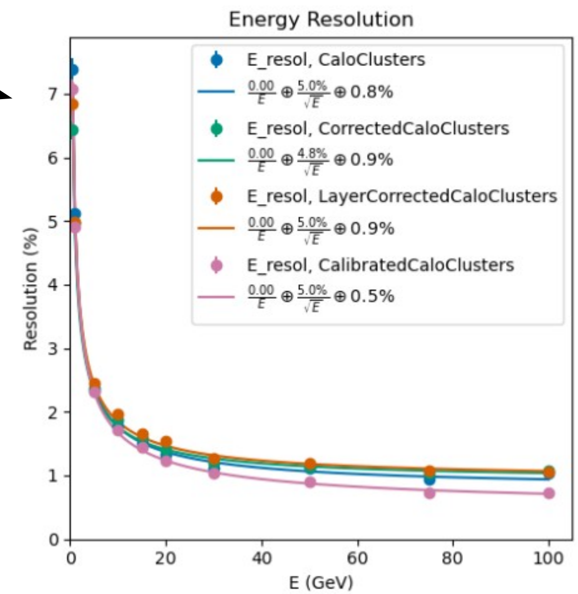
More thoughts about geometry

- Modifications of the geometry to improve performance
  - LKr as the active medium, Pb absorbers
    - 5% sampling term
  - LKr active medium with W absorber
  - Absorbers with trapezoidal shape
    - Constant sampling fraction
    - 5% sampling term, reduction of the constant term

→ “ultimate” performant geometry

- Advanced reconstruction techniques (clustering, energy calibration using MVA) are also options for the performance optimisation

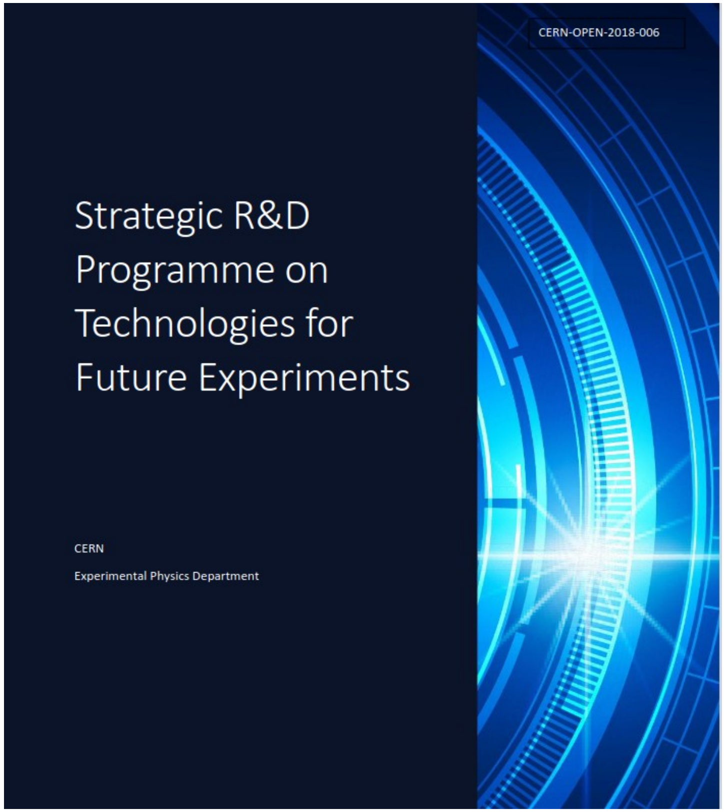




R&D projects

- Multilayer readout (AIDAinnova, WP8.2.2)
- Light weight cryostat (CERN EP R&D)
- High density feedthroughs (CERN EP R&D)
- Mechanical studies

Goal: Module suitable for beam tests (~2028)

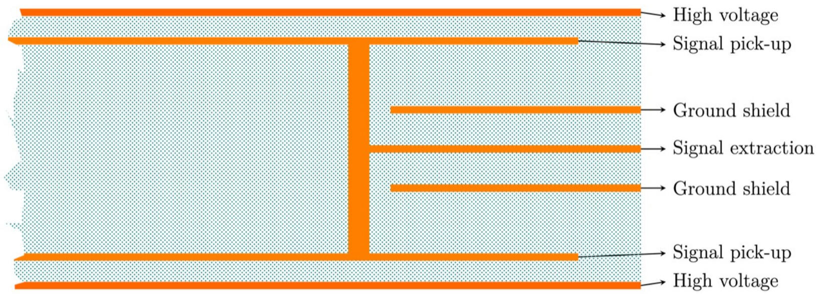


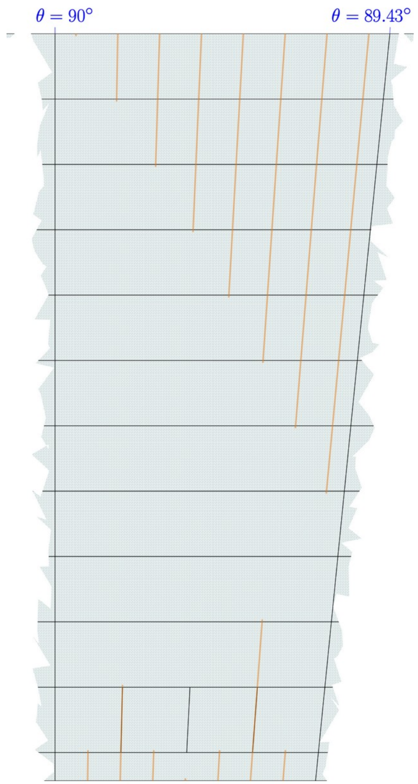
CERN-OPEN-2018-006

Design of readout PCB

- Baseline design for Printed Circular Boards (PCBs)
  - Seven layers: HV, signal pad, shield, signal trace, shield, signal pad, HV
  - Ground shields around the traces to mitigate the cross-talk
  - Signal extraction to the front (three inner most layer) and to the back (the rest)

- PCB allows easily for high granularity
- **Q**: What about cross-talk? Will that be under control?

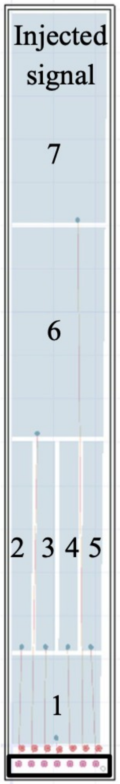




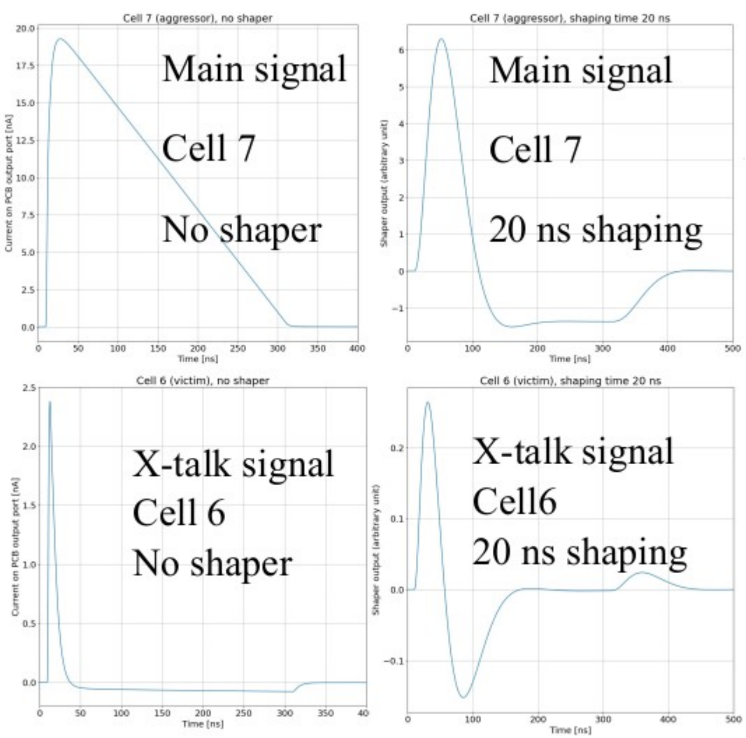
One theta tower
Horizontal axis scale 10:1

Simulations of the PCB

- Goal: find the minimal shielding which leads to low cross-talk (below 1%)
- Finite Element Method calculations in ANSYS
  - Peak-to-peak cross-talk below 1% seems to be easily achievable with a shaper under consideration



Output signals



Simulated peak-to-peak x-talk values (%) VS shaping time

2 shields

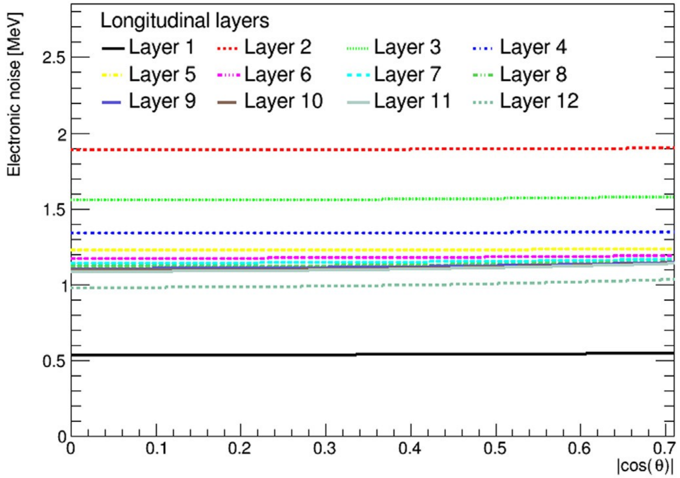
Cross-talk (%) / Shaping time (ns) ↓	Cell 1	Cell 2	Cell 3	Cell 4	Cell 5	Cell 6
No shaper	0.54	0.85	0.85	2.31	2.62	9.11
20	0.03	0.04	0.01	0.09	0.11	0.75
50	0.01	0.02	0.0	0.04	0.05	0.37
100	0.01	0.01	0.0	0.02	0.03	0.23
150	0.0	0.01	0.0	0.02	0.02	0.18
200	0.0	0.01	0.0	0.01	0.02	0.15
300	0.0	0.0	0.0	0.01	0.01	0.13

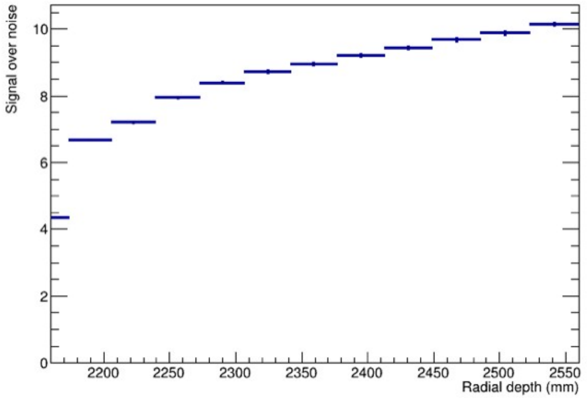
0 shield

Cross-talk (%) / Shaping time (ns) ↓	Cell 1	Cell 2	Cell 3	Cell 4	Cell 5	Cell 6
No shaper	6.27	2.6	3.2	8.75	8.61	15.96
20	0.7	0.1	0.1	0.99	0.92	2.58
50	0.3	0.02	0.02	0.43	0.4	1.14
100	0.17	0.01	0.01	0.24	0.23	0.64
150	0.13	0.01	0.0	0.18	0.17	0.48
200	0.1	0.01	0.0	0.15	0.14	0.4
300	0.08	0.0	0.0	0.12	0.11	0.32

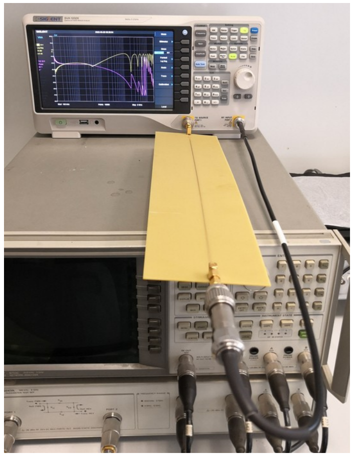
Electronics noise

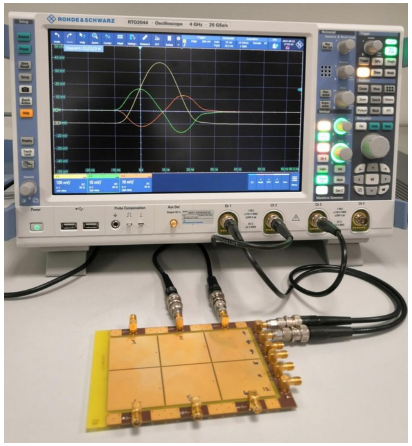
- Cell capacitance derived using FEM tools (ANSYS Maxwell)
  - 25 – 200 pF depending on the longitudinal compartment (2 shields considered)
- From cell capacitances to electronics noise in MeV using the analytical description of the readout chain
  - PCB transmission line (+ coaxial cable) + pre-amp + shaper
  - 0.5 – 2 MeV noise per cell
- Average signal-over-noise ratio for a MIP between 5 and 10 is reached



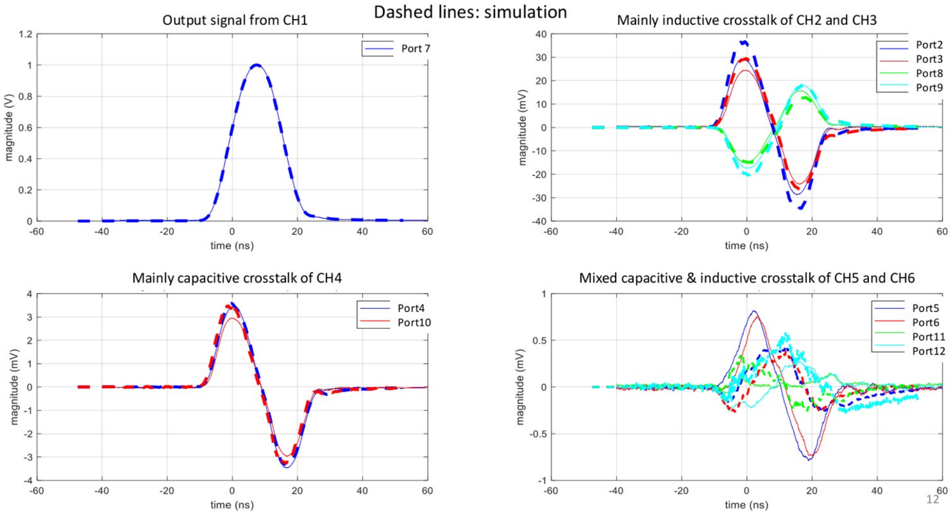


PCB prototypes (IJCLab)

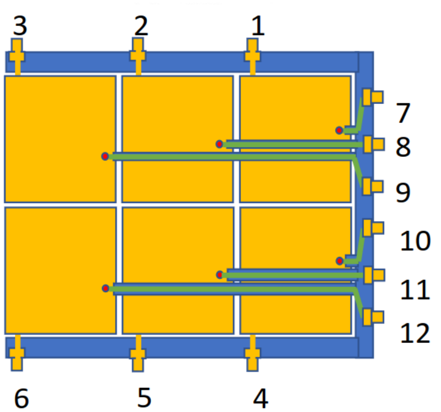


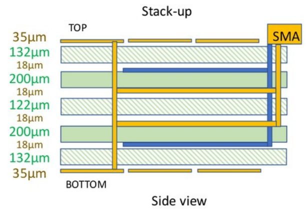


- PCB with even number of layers
- Detailed measurements of the electronic properties
  - Good between measurements and simulations for S-parameters over a large frequency spectrum
  - Total capacitance, inductance and coupling parameters per channel extracted



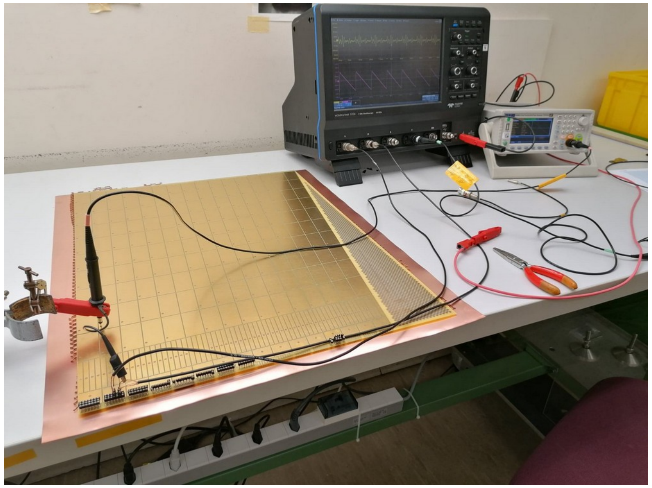
Proto2 design

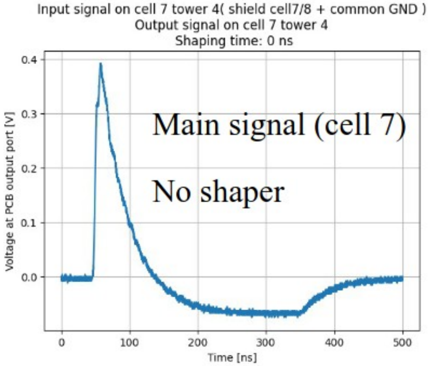


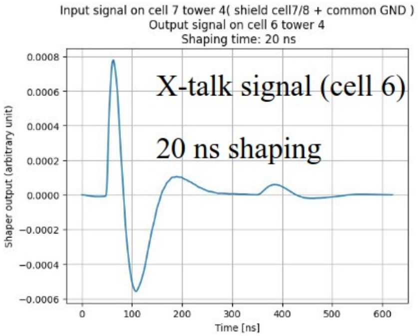


PCB prototype (CERN)

- Prototype with 1:1 scale in the radial direction with 16 'theta towers' with different layouts (58 cm x 44 cm)
- Electrical tests with a scope and a software shaper
  - Confirms the cross-talk goal easily reachable
- Good agreement with the simulations
  - Could be improved especially for small signals and short shaping times







Sub-percent cross-talk reachable for all cells with a single ground shield and shaping time > 50 ns

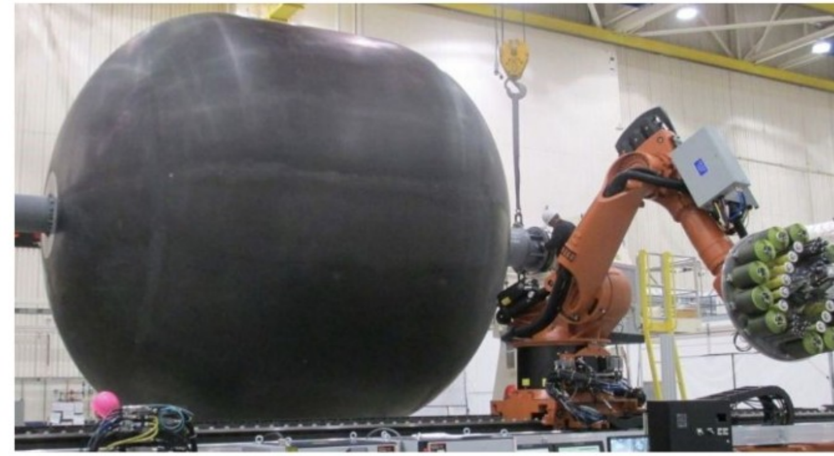
PCB lessons

- Cross-talk under control
- Two ground shields not necessary, one is enough to mitigate the cross-talk
  → PCB with even number of layers
- Open questions
  - Readout all cells at the back?
    - Less material in front of the detector
  - Realisation of the HV layer?
  - Optimisation of the segmentation of the electrode

Cryostat

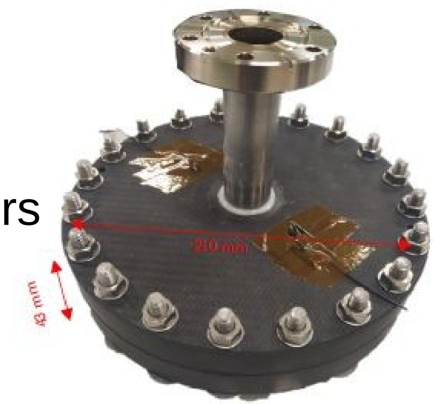
- Carbon fiber materials for low material cryostat
  - Sandwich of Carbon Fibre Reinforced Polymer (CFRP) shell and Al honeycomb

    → Very low X_0 (10% compared to Al solid)
- Ongoing R&D at CERN
  - CFRP / metal interfaces, sealing methods



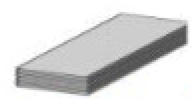
NASA cryotank

Sealing with Belleville washers



Sandwich Shell

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



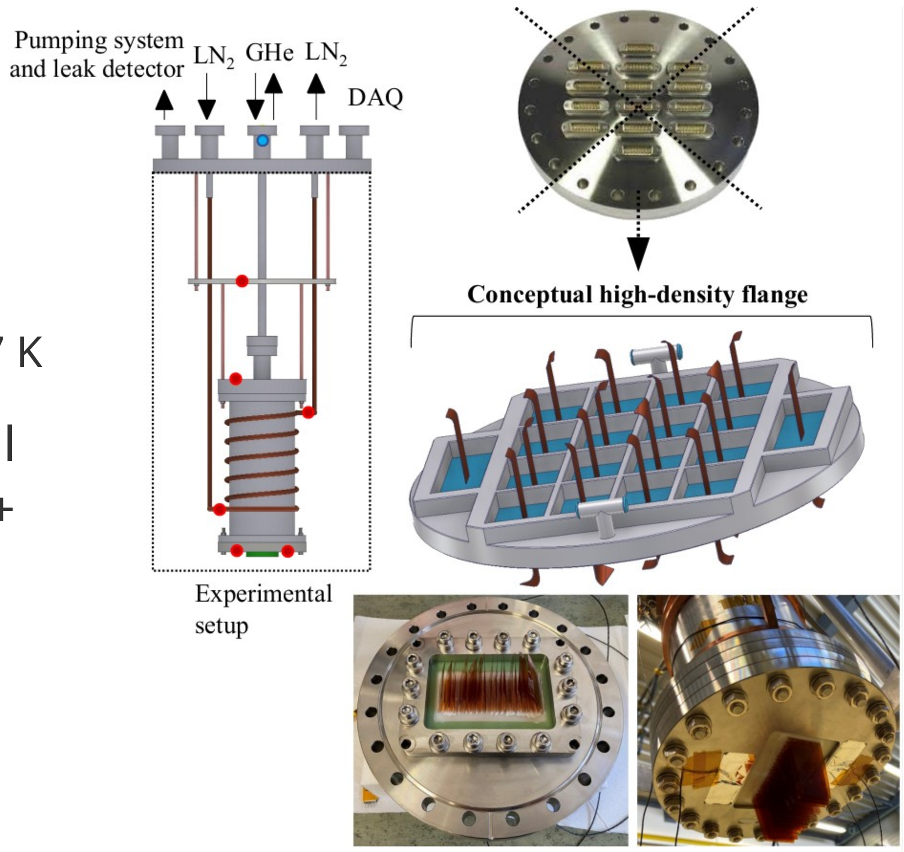
Solid Shell

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%

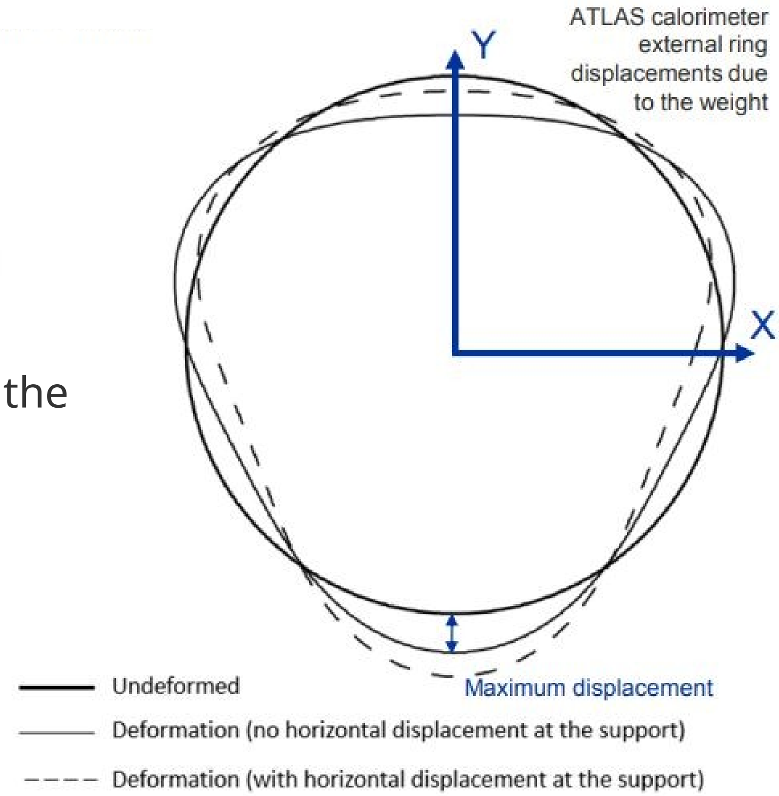
High density feedthroughs

- Factor of 10-15 more channels wrt ATLAS (ECAL barrel with ~2 M channels)
- Innovative connector-less feedthroughs
  - High density flange
  - Higher area dedicated to signal extraction
  - 20 000 wires per feedthrough
  - Leak and pressure (3.5 bar) tests at 300 and 77 K
- Identified a solution surviving several thermal cycles (G10 structure with slits + indium seal + Epo-Tek glued Kapton strip cables)
- To be done: design and test a full flange (not covered)



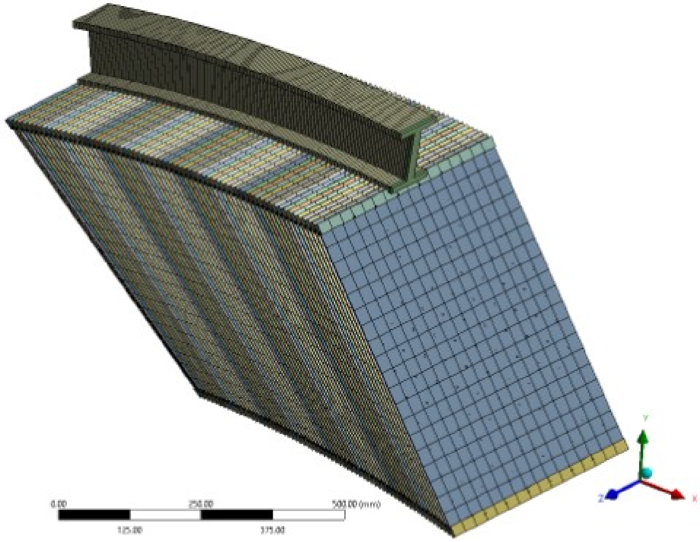
Mechanical studies

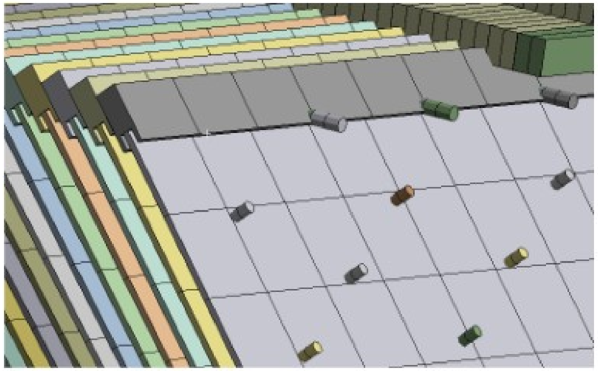
- Small systematics bring strict limits on the precision of the mechanical structure of the calorimeter
- Studies started recently
  - Idea: Identify our requirements with the usage of the knowledge from ATLAS
  - First preliminary results with FEM
- Differences wrt ATLAS to be considered
  - FCC-ee barrel calorimeter about 40% heavier
  - From accordion absorbers to straight sheets
  - Absorbers for FCC-ee: 1.8 mm Pb, 0.05 mm glue and 0.05 mm stainless steel on both sides
  - Electrodes for FCC-ee: 1.2 mm PCB



Absorbers and spacers

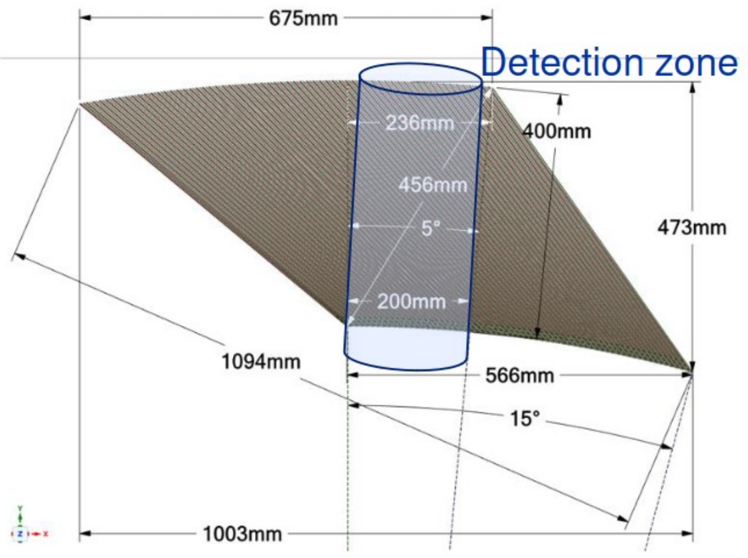
- Absorber design
  - Feasibility studies
  - What is the needed tolerance?
- Trapezoidal shape of absorbers (alternative geometry)
  - Is that technically possible?
  - What is the needed precision?
- Support structure being investigated
- Spacers: honeycomb used in ATLAS
  - Good experience
- Idea: use 3D-print pillars to be placed regularly





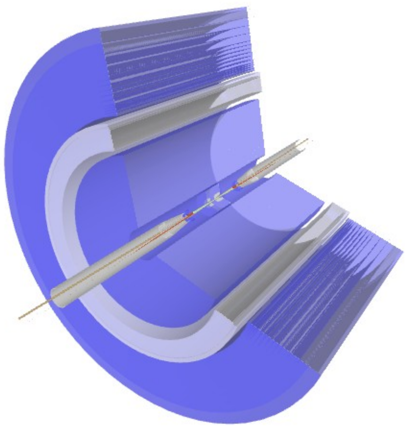
Towards a prototype module

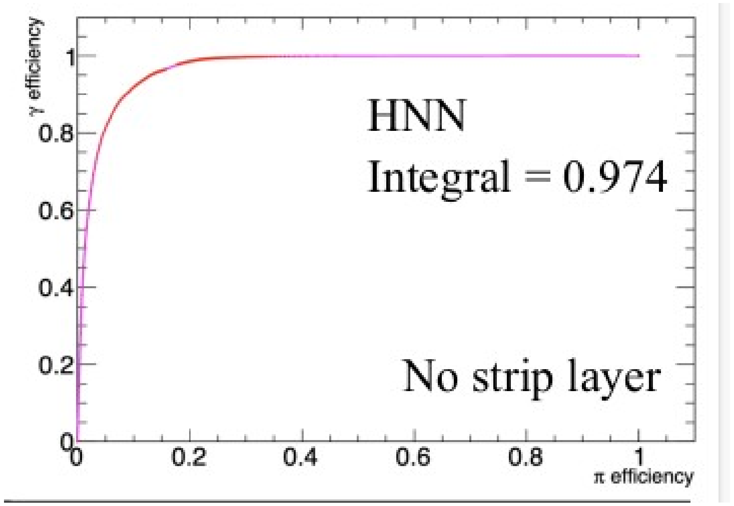
- Test module
  - Prototype as a sector of 15º (64 absorbers)
- Workplan
  - Preparation of the design in 2024/2025
  - Assemble and test at warm temperatures in 2027
  - Cold tests and beam tests in 2028



Software

- Full simulation available in Key4HEP
  - Detector description (DD4HEP)
  - Reconstruction
    - Corrections: sampling fraction, dead material correction
    - Emulation of electronics noise
    - Cells → clusters
- Software ready to be used for physics studies
  - Performance studies: 95% γ efficiency for 10% π^0 in large energy range
- Developement of SW is ongoing
  - Missing parts are e.g. digitization, particle flow reconstruction





Full detector concept

- Noble liquid calorimeter as a part of the full detector concept for FCC-ee
  - Vertex detector: (D)MAPS, ALICE 3 like
  - Tracker: drift chamber (2.5 m)
  - Silicon wrapper and time of flight detector
  - ECAL: noble liquid in ECAL barrel & endcaps
  - Superconfucting solenoid placed afer ECAL in the barrel
  - HCAL: TileCal type in barrel & endcaps
  - Muon tagger (e.g. drift chamber, RPC, MicroMegas)
- Open to other possibilities

Integration of the full detector concept in the Key4Hep simulations is ongoing

What is next

- Design of the front-end electronics
  - Synergies with existing chips, front-end boards to be developed
- Back-end electronics and DAQ to be defined
- Finalize the design of the electrodes (barrel, endcaps)
  - Optimize the granularity based on physics simulations
  - Shields, HV layer
- Continue in the mechanical studies
  - Cryostat
  - Absorbers, spacers and the support
- Software development
  - Digitization of the signal
  - Advanced reconstruction techniques

Conclusions

- Noble liquid calorimeter project is evolving over the past years
  - Small, but active community
- Baseline concepts defined
- Tests with small scale prototypes (feedthroughs, cryostat, PCBs) ongoing
- Goal of beam tests in ~2028
- Project is a part of DRD Calorimetry
- New ideas are welcome

We are looking forward to welcome new members to our team

BACKUP

Cold electronics

- The read-out electronics situated fully or partially inside the cryostat
  - Preamplifier, ADC, multiplexer?, optical conversion?
- 5 to 10 times smaller noise compared to the warm electronics
- Caveats
  - No possibility of repairs
  - Heat dissipation in the liquified noble gas
  - Power consumption
- First test at IJCLab with HGCROC (CMS HGCAL ASIC) in liquid nitrogen

ProtoDUNE