Noble Liquid Calorimetry for future facilities

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on behalf of the Future Noble Liquid Calorimetry group

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Noble Liquid Calorimetry: motivation

Very good experience with noble liquid calorimeters in a number of experiments (e.g. D0, H1, NA48/62, ATLAS)

Advantages

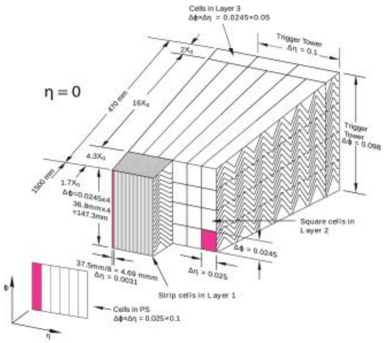
- Very good energy resolution (sampling term of ~10%)
- Linearity, uniformity and stability of the response → Low systematics
- Particle identification capabilities
- Radiation hardness

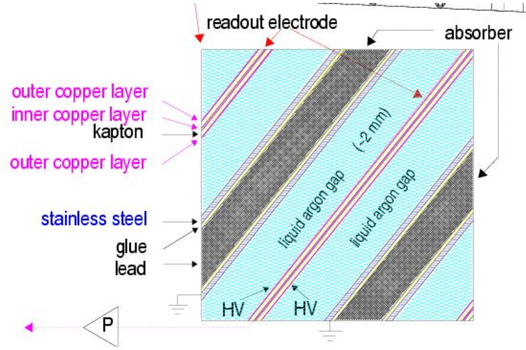
Concept suitable for future experiments (e.g. electron-positron colliders, FCC-hh)

ATLAS LAr calorimeter

ATLAS electromagnetic calorimeter

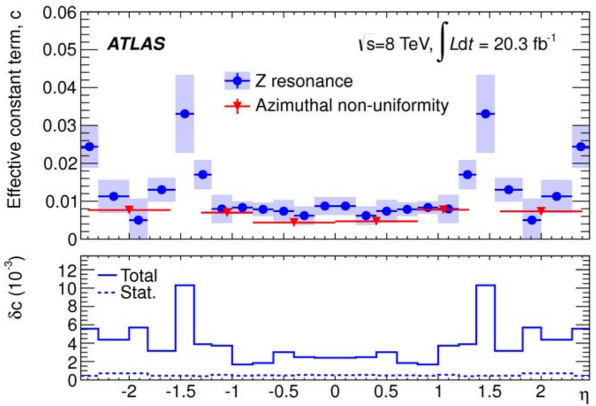
- Lead absorbers/LAr in the gap
- Accordion geometry of the kapton electrodes

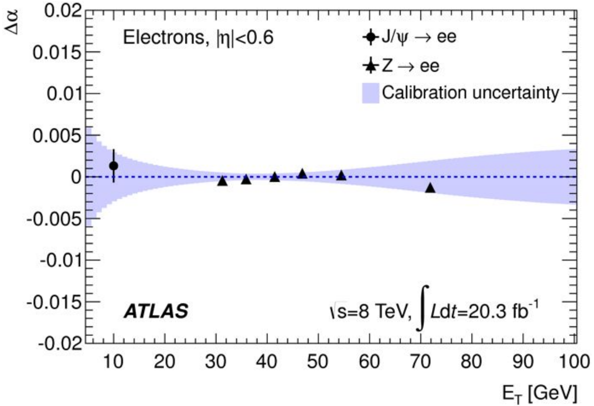


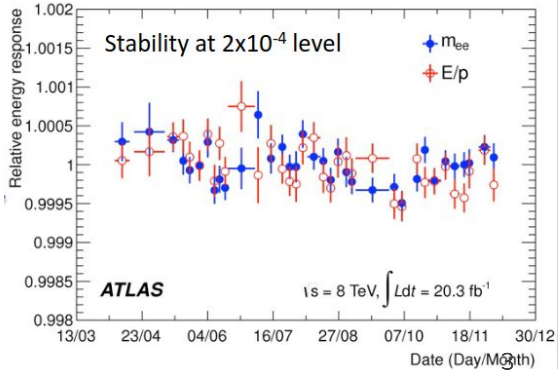


Performance

- 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 response stable at the level of 10^{-4})





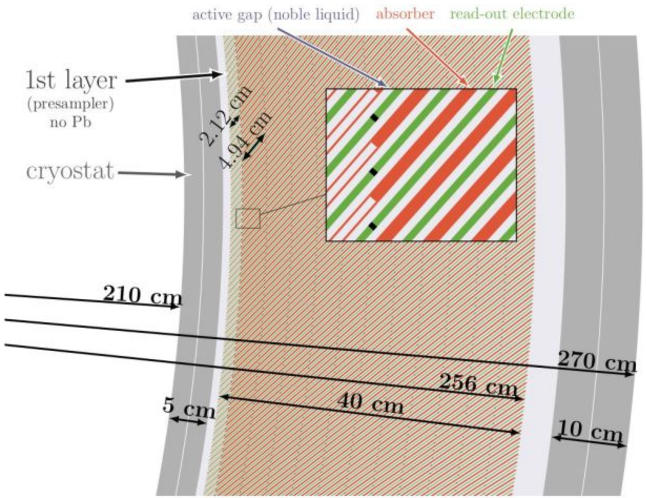


Noble liquid calo for future e+e- collider

Key points

- High granularity is needed for advanced reconstruction techniques (e.g. 4D imaging, particle flow)
- Systematics uncertainties to be kept as low as possible
- High energy resolution down to small energies

-> Possible by the usage of straight multilayer electrodes



Baseline geometry (barrel)

- 1536 Pb absorbers inclined by ~50.4º, |z| ≤ 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 a cryostat: Aluminium (5 cm in front, 10 cm in back)

Ideas and first implementation of the geometry of the endcaps

- Turbine wheel like with radially inclined straight absorbers or parallel plates perpendicular to beam

R&D studies for the feasibility of the detector design with a goal of beam tests (~2028 at cold temperature)

ALLEGRO

ALLEGRO (A Lepton coLlider Experiment with highly Granular calorimeter ReadOut)

Noble liquid calorimeter as a part of the full detector concept

- 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
- Superconducting solenoid placed between ECAL and HCAL in the barrel
- HCAL: TileCal type in barrel & endcaps
- Muon tagger (e.g. drift chamber, RPC, MicroMegas)

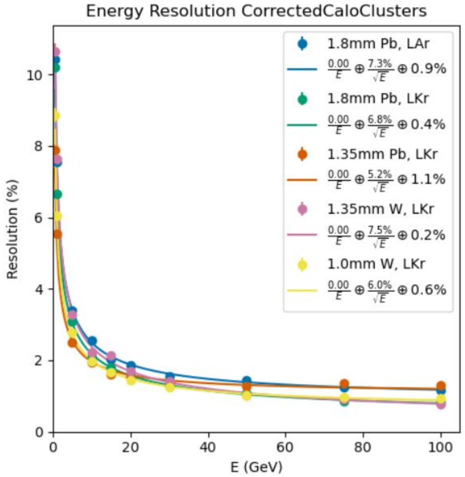
Detector description available in DD4HEP

Performance studies

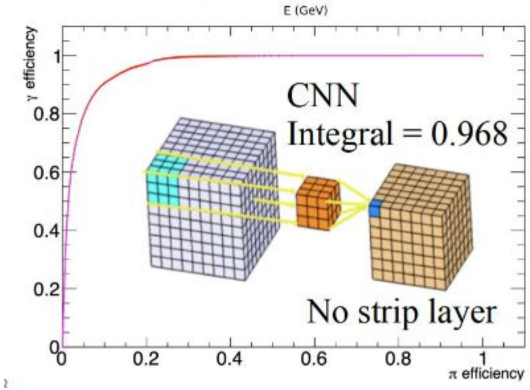
Modifications of the geometry to improve performance

- Baseline geometry (LAr/Pb) leads to a sampling term of 7% and a constant term of 1%
- LKr as the active medium, Pb absorbers -> sampling term of 5%
- LKr active medium with W absorber -> constant term of 0.2%
- Absorbers with trapezoidal shape (constant sampling fraction)

→ “ultimate” performant geometry



Machine learning for photon/π^0 identification (95% γ efficiency for 10% π0 in large energy range)



Work on the improvements of the reconstruction techniques ongoing

Readout electrodes

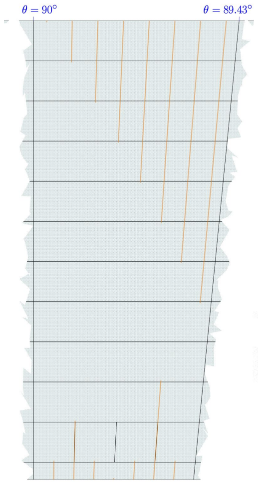
Baseline design for Printed Circular Boards (PCBs)

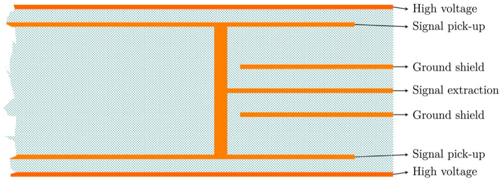
- Seven layers: HV, signal pad, shield, signal trace, shield, signal pad, HV
- Ground shields around the traces to mitigate the cross-talk
- Signal extraction to the front (three inner most layer) and to the back (the rest)

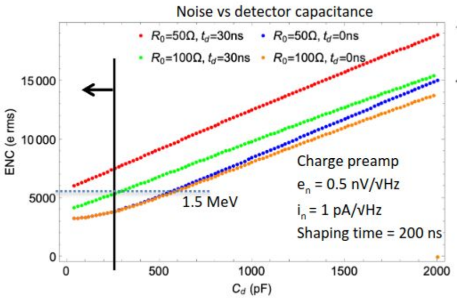
Finite Element Method calculations (ANSYS)

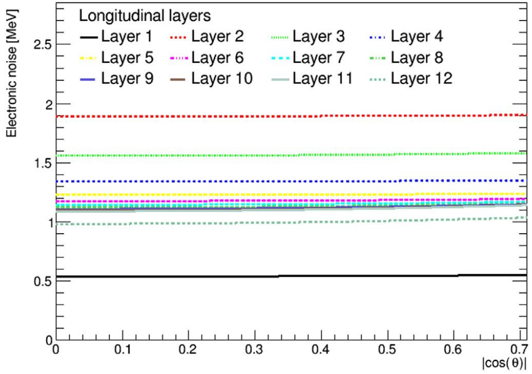
- Peak-to-peak cross-talk below 1% seems to be easily achievable with a shaper under consideration
- Capacitance of the cell 25 – 300 pF depending on the longitudinal compartment
- Electronics noise per cell in 0.5 – 2 MeV (analytical description of the readout chain: PCB transmission line + pre-amp + shaper)

Average signal-over-noise ratio for a MIP between 5 and 10 is reached









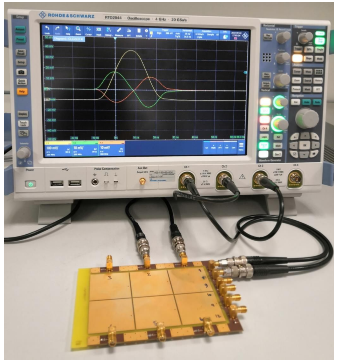
Prototypes of the readout electrodes

Small dimension prototype (CRNS-IJCLab)

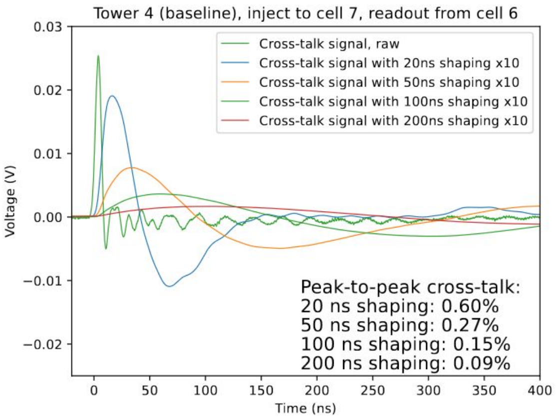
- Detailed measurements of cell properties and cross-talk effects
- Good overall agreement with simulations on large frequency range

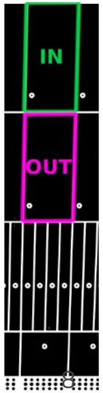
Larger scale prototype (CERN)

- 1:1 scale with 16 towers - different layout of the towers
- Electrical tests with a scope and a software shaper
- Good agreement with the simulations
- Sub-percent cross-talk easily achievable with shaping times larger than 50 ns



Note: Cross-talk signals with a shaper magnified by a factor of 10





R&D studies

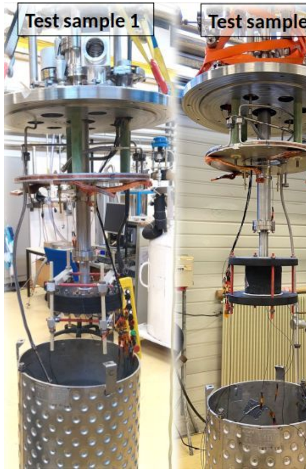
Carbon fiber materials for low material cryostat

- Sandwich of Carbon Fibre Reinforced Polymer (CFRP) shell and Al honeycomb

  → Very low X_0 (10% compared to Al solid)

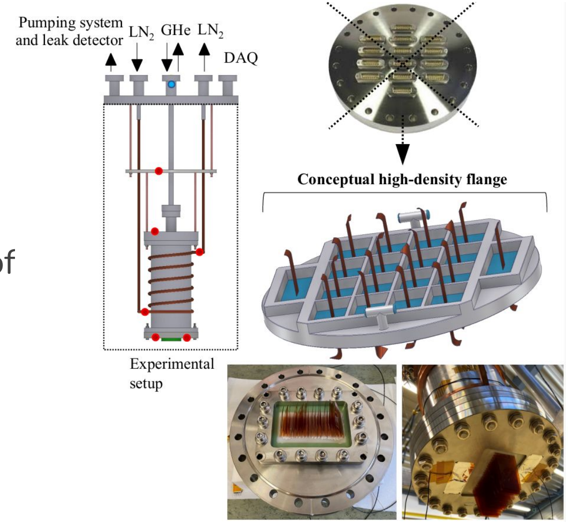
- Tests being performed at CERN

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 with the usage of the high density flanges, 20 000 wires per feedthrough
- Leak and pressure (3.5 bar) tests at 300 and 77 K performed



Mechanics studies

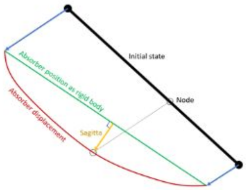
Requirement of small systematics bring strict limits on the precision of the mechanical structure of the calorimeter

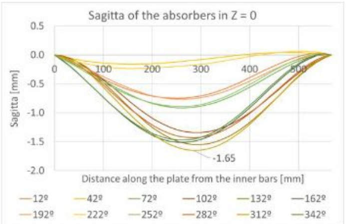
Finite element calculations for the absorber configuration (1.8 mm of lead and different stainless-steel thickness : 50 μm, 100 μm, 200 μm)

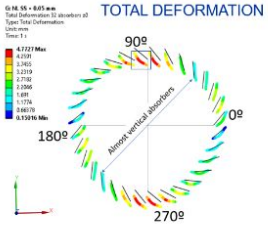
Configuration of the spacers studied

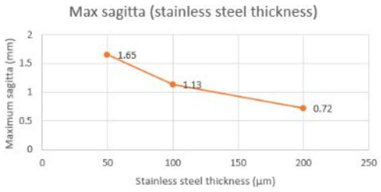
First cold (liquid nitrogen) tests of the feasibility prototype

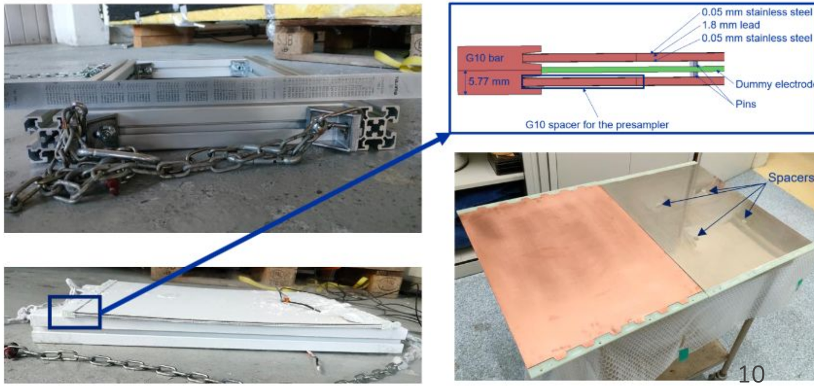
- Two absorbers and one dummy electrode, four spacers between each absorber and the electrode
- Absorber: Stainless steel (50 μm), lead (1.8 mm)
- Goal: check the gluing of the absorbers, measure the contraction of the materials











Software development

Full simulation of the detector available in Key4HEP

- Detector description (DD4HEP)
- Reconstruction
  - Corrections: sampling fraction, dead material correction
  - Emulation of electronics noise
  - Cells → clusters (various clustering algorithms)

Development of SW still ongoing

- Improved description of the endcap geometry
  - Testing various option, optimisation of the layout
- Advanced reconstruction techniques (e.g. machine learning for energy reconstruction, PID)

Software ready to be used for physics studies

Conclusions

Noble liquid calorimeter project is evolving over the past years

- Participation in ECFA DRD6 on calorimetry
- ECAL in the full detector concept ALLEGRO suitable for e+e- collider

The calorimeter barrel is now optimised for the experiments at the e+e- colliders

- Baseline concepts are defined, “ultimate scenarios” to enhance the performance
- Development of the endcaps geometry is ongoing

Tests with small scale prototypes (feedthroughs, cryostat, PCBs, absorbers) ongoing

Goal of beam tests under cold temperature in 2028

BACKUP

Cold electronics