LAR CALORIMETERS FOR FUTURE COLLIDERS

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INTRODUCTION

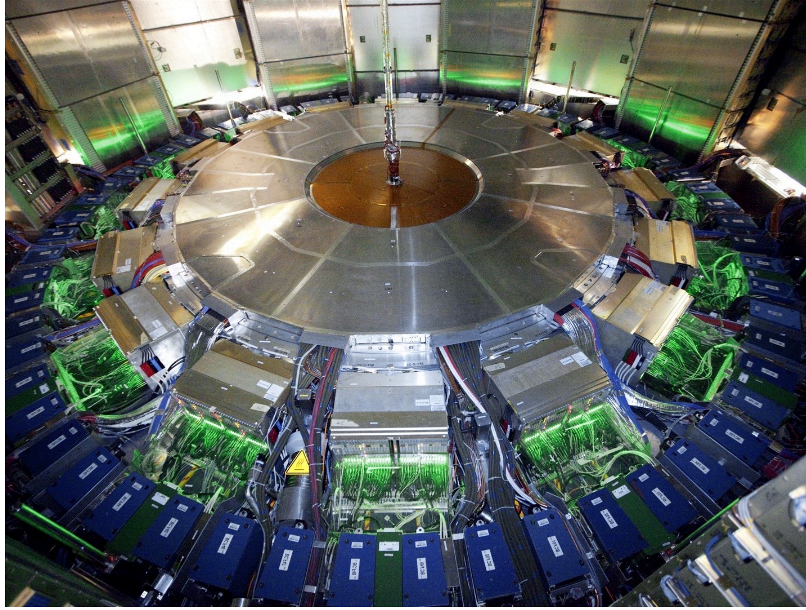
R&D of Noble-Liquid calorimeter for future colliders ongoing since a few years now

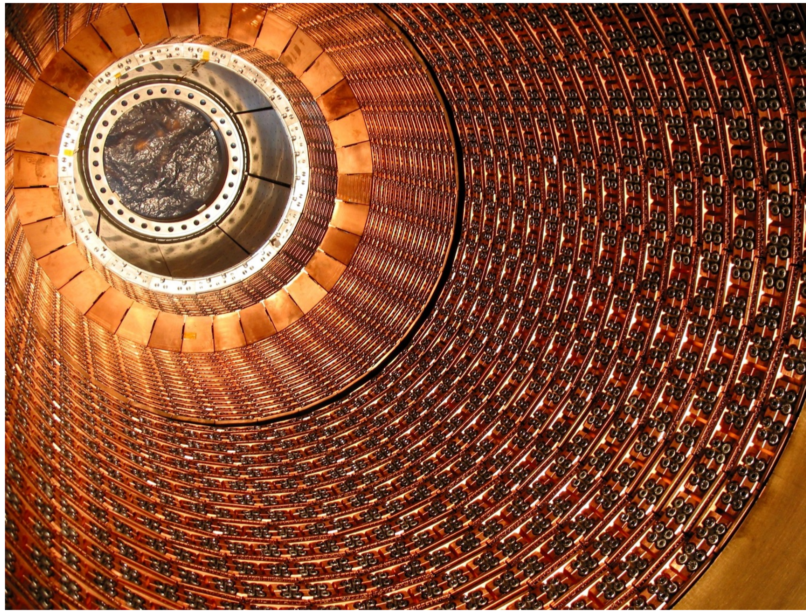
This is the work of a relatively small team of people which is growing!

- Interests of various institutes are still evolving

A Noble-Liquid calorimeter proposal for FCC-ee is nevertheless very advanced

- Expanding and adapting work done for calorimetry at FCC-hh (see arxiv:1912.09962)
- Taking advantage of experience in successful construction and operation of the ATLAS LAr Calorimeter at the LHC
- See also recent talk by Nicolas Morange and elsewhere also by Martin Aleksa, Brieuc Francois and others from which this material was borrowed





WHY USE NOBLE LIQUID CALORIMETRY

Proven technology with successful operation in several experiments

- e.g. ATLAS, D0, H1, NA48/62

Inherently radiation-hard

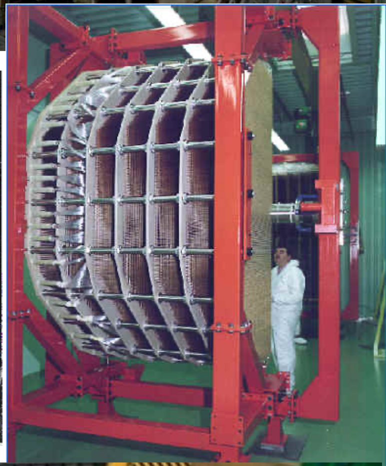
Suitable for experiments at various machines

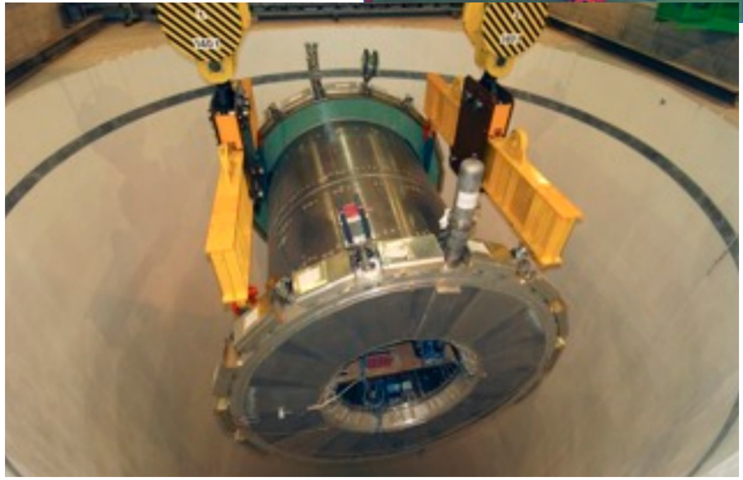
Very good energy resolution

- Sampling term of ~10%

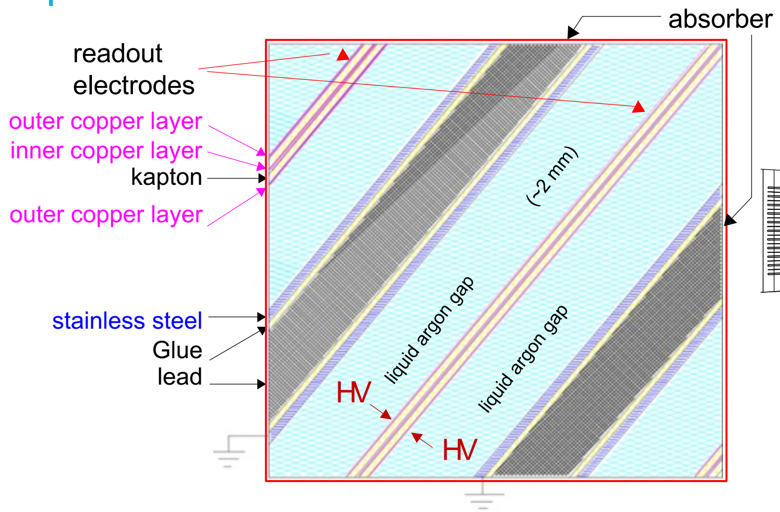
Linearity, uniformity and stability of the response

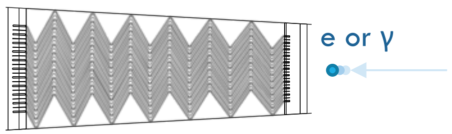
- Easy to calibrate
- Good control of systematic uncertainties

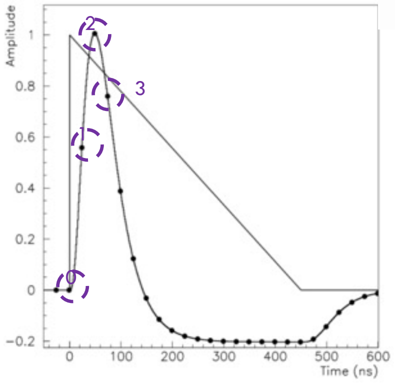


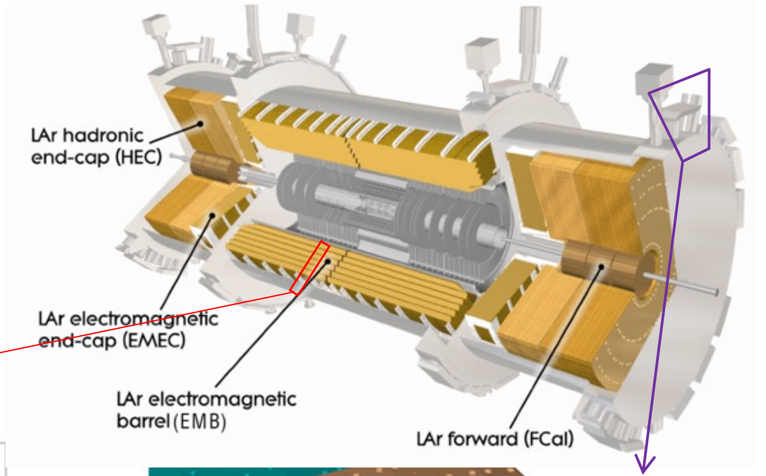


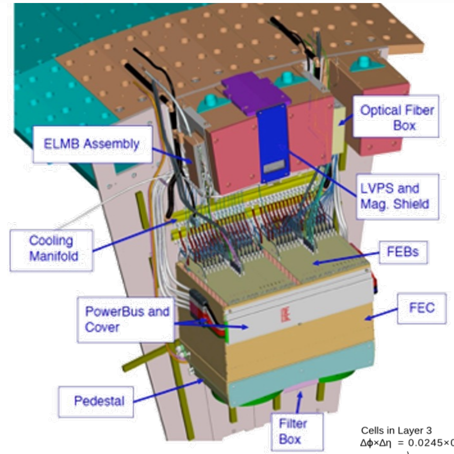
THE ATLAS LAR CALORIMETER

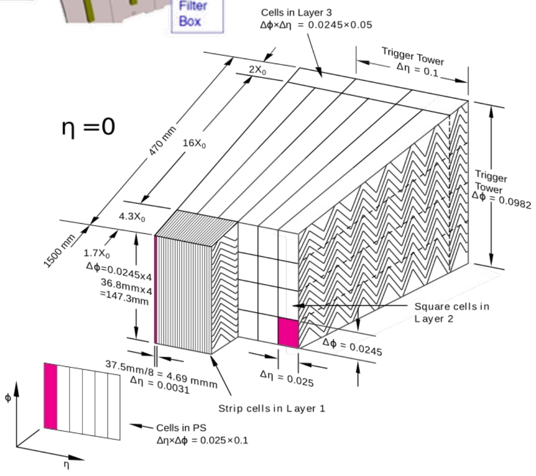












- **On-detector** electronics shape LAr ionization signal and **sample in 4 positions 25 ns** apart in 3 gain scales → **Only one of the gains** digitized and transmitted via optical fibers to **Off-detector Electronics**
  - ***Optimal Filtering Technique*** used to calculate deposited cell energy and pulse peaking time (requires good knowledge of pulse shape)
- **Can we make this technology work with the Particle Flow paradigm?**

HIGH GRANULARITY NOBLE-LIQUID CALORIMETER

Baseline design

1536 straight inclined (50.4°) 1.8mm Pb absorber plates

Multi-layer PCBs as readout electrodes

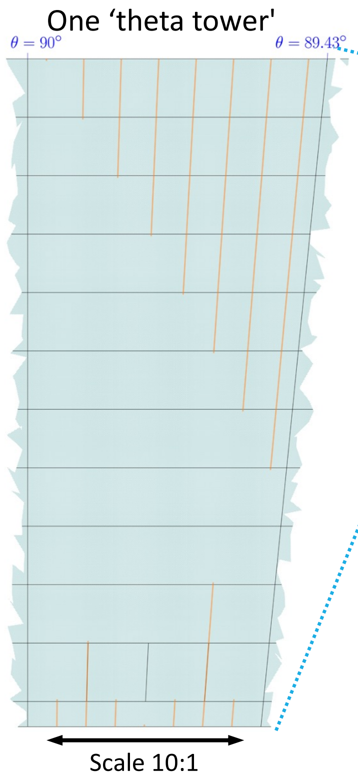
1.2 – 2.4 mm LAr gaps

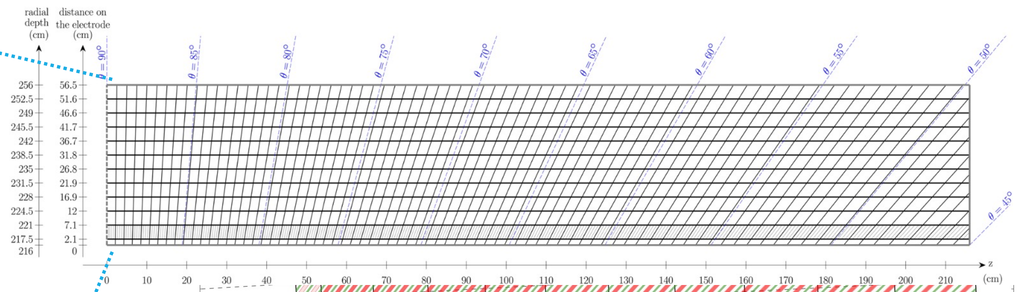
40 cm deep (≈ 22 X_0)

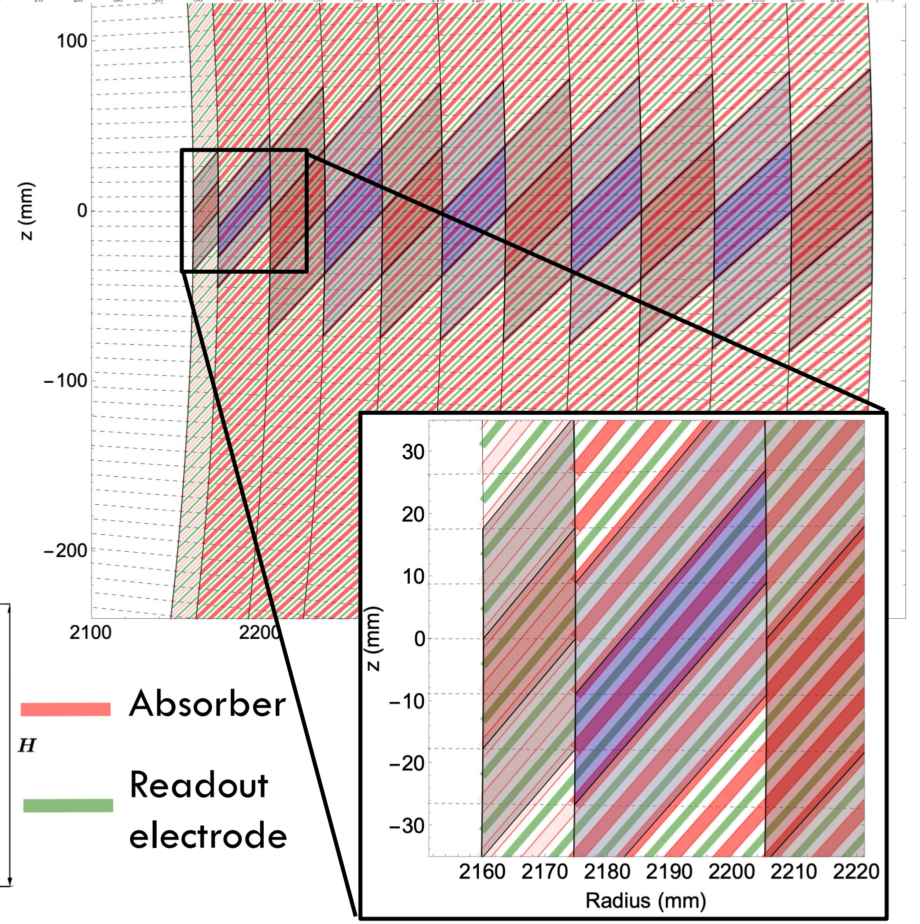
Segmentation:
- $\Delta\theta$ = 10 (2.5) mrad for regular (1st comp. strip) cells,
- $\Delta\phi$ = 8 mrad
- → cell size in strips: 5.4 mm x 17.8 mm x 30 mm

12 layers

Implemented in FCC-SW Fullsim

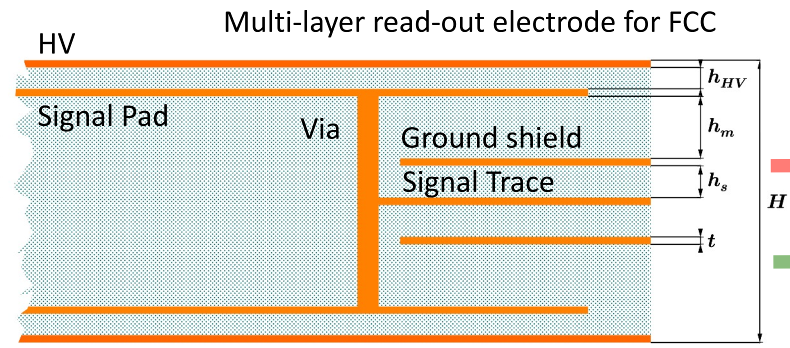




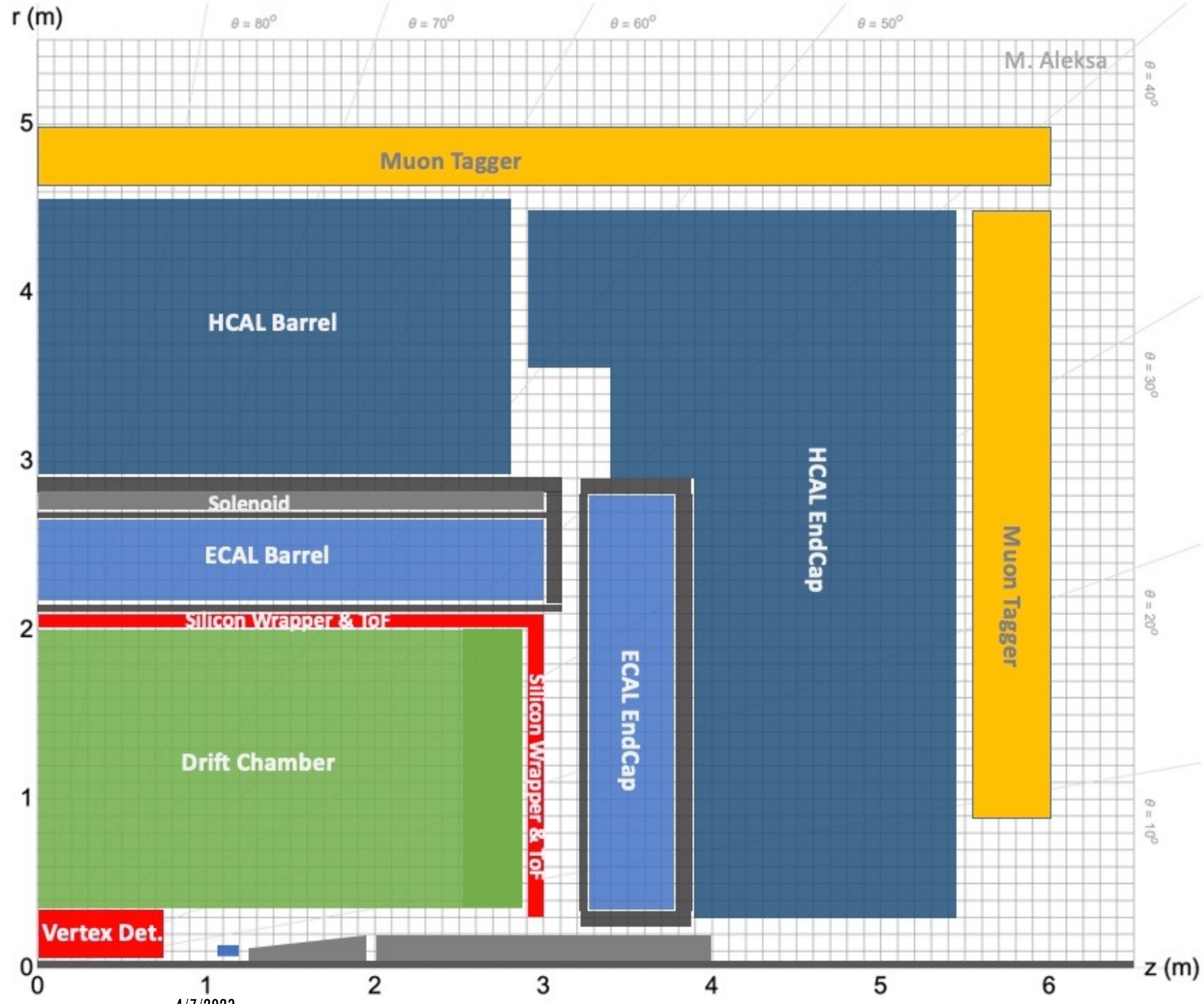


Possible Options

- LAr or LKr, W or Pb absorbers,
- Absorbers with growing thickness
- Granularity optimization
- Al or carbon fiber cryostat
- Warm or cold electronics



NOBLE-LIQUID ECAL BASED DETECTOR CONCEPT



Vertex Detector:
- MAPS or DMAPS possibly with timing layer (LGAD)
- Possibly ALICE 3 like?

Drift Chamber (±2.5m active)

Silicon Wrapper + ToF:
- MAPS or DMAPS possibly with timing layer (LGAD)

High Granularity ECAL:
- Noble liquid + Pb or W
- Particle Flow reconstruction

Solenoid B=2T, sharing cryostat with ECAL, outside ECAL
- Light solenoid coil ≈ 0.76 X_0 (see back-up)
- Low-material cryostat < 0.1 X_0 (see back-up)

High Granularity HCAL / Iron Yoke:
- Scintillator + Iron (particle flow reconstruction)
  - SiPMs directly on Scintillator or
  - TileCal: WS fibres, SiPMs outside

Muon Tagger:
- Drift chambers, RPC, MicroMegas

See e.g talk by M. Aleksa

THE WAY FORWARD

Further develop the overall design and study is performance in full simulation

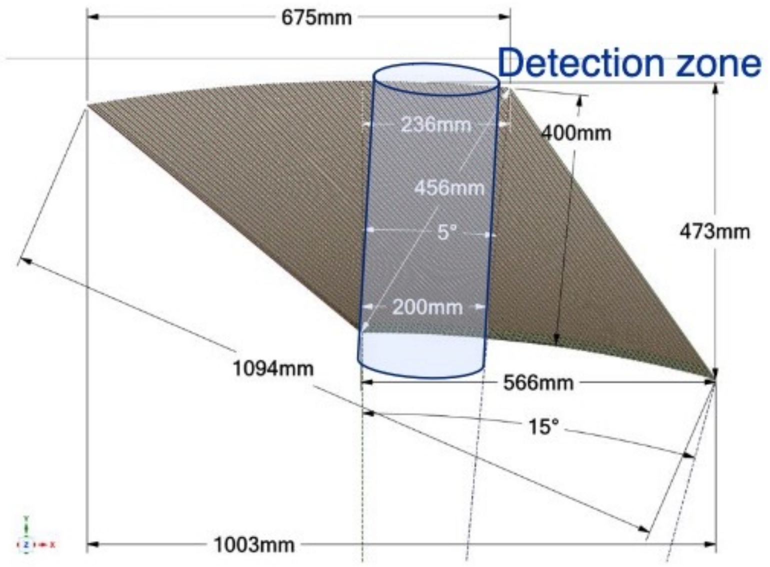
Determine required granularity

Develop and freeze readout electrode design

Investigate and decide on readout electronics (cold vs warm?)

Study mechanics, structural/assembly aspects of calorimeter

Build a prototype module in cryostat and study it in test beam some time in **2028**



COLLABORATION

Many opportunities for contributions

Most of the institutes have experience in the design, construction, and operation of the ATLAS LAr Calorimeter

DESIGN OPTIMIZATION

Performed in **full Geant4 simulation** within the FCC software chain

- First EM physics studies performed in 2022 but much more can be done:
  - LAr vs LKr, Pb vs W, granularity, layer structure, sampling fraction, …

Investigate solutions for Endcaps

- Possibly use "Windmill/turbine" geometry?

Investigate possibility to readout Cerenkov light

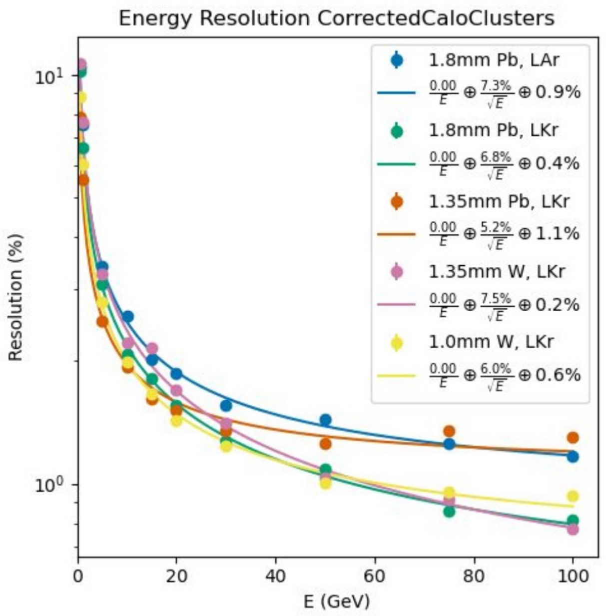
- Feasibility of design?

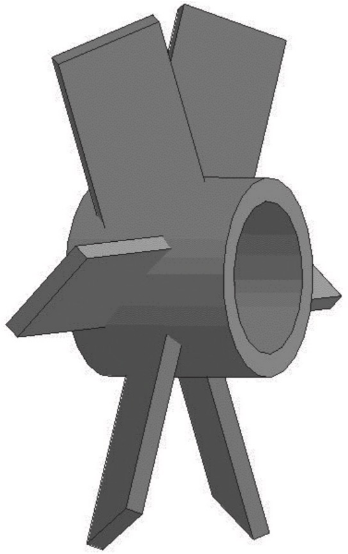
Next studies should be performed with full detector and full reconstruction, including Particle Flow

- At least with HCAL and truth-tracker

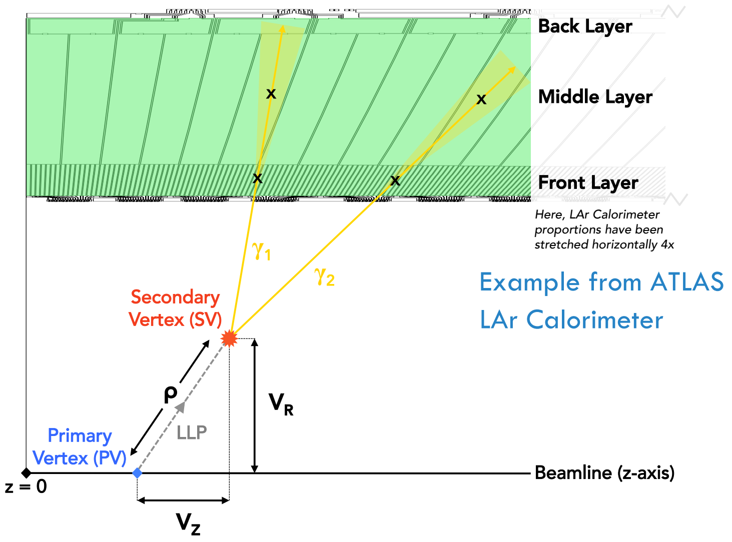
Work needed on reconstruction

- Study shower-shapes, employ cut-based PID, traditional clustering,…
- But also work on more modern ML techniques





GRANULARITY

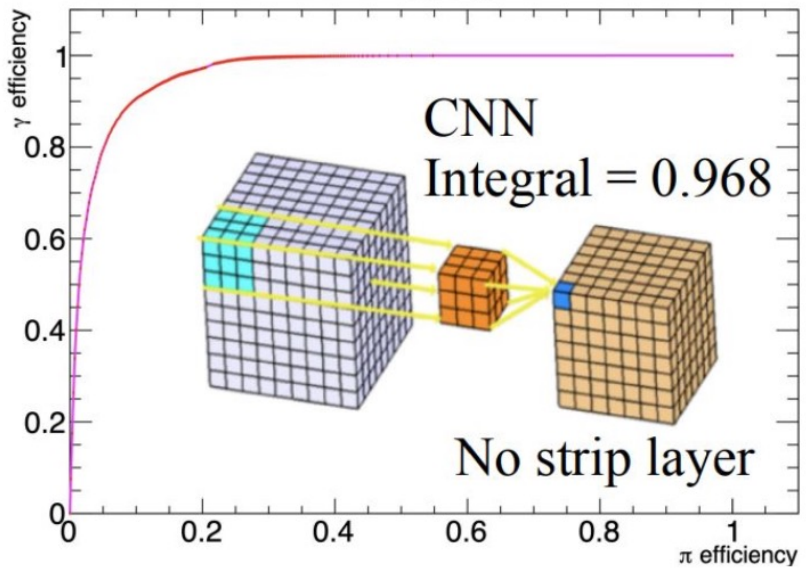


Need to understand the required granularity

- Study pion ID (tau physics)
- Axion-like particle searches
  - Including Long-lived signatures → Employ pointing/diphoton vertex reconstruction
- 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…



ELECTRODES

Continue lab tests with small-scale electrode PCB and first large-scale prototype

- Measurements of x-talk and other cell properties
  - Promising to reach <1% x-talk target
  - Minimize noise aiming for photons down to 300 MeV and S/N>5 for MIPs
- Comparing lab results with Finite Element simulations

Develop endcap design

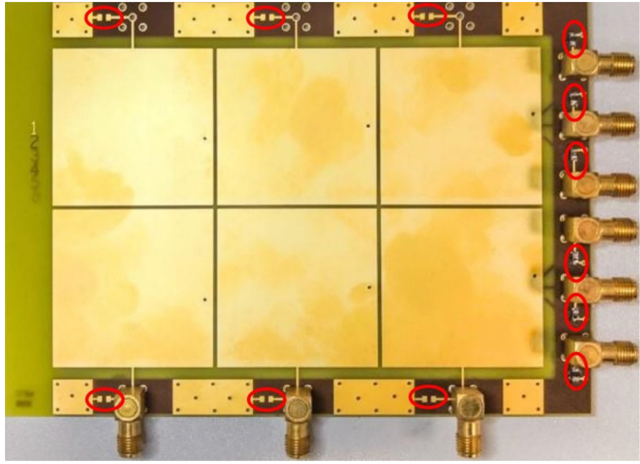
- Depends on geometry
- Optimize granularity

Finalize barrel design and produce prototype (~2024)

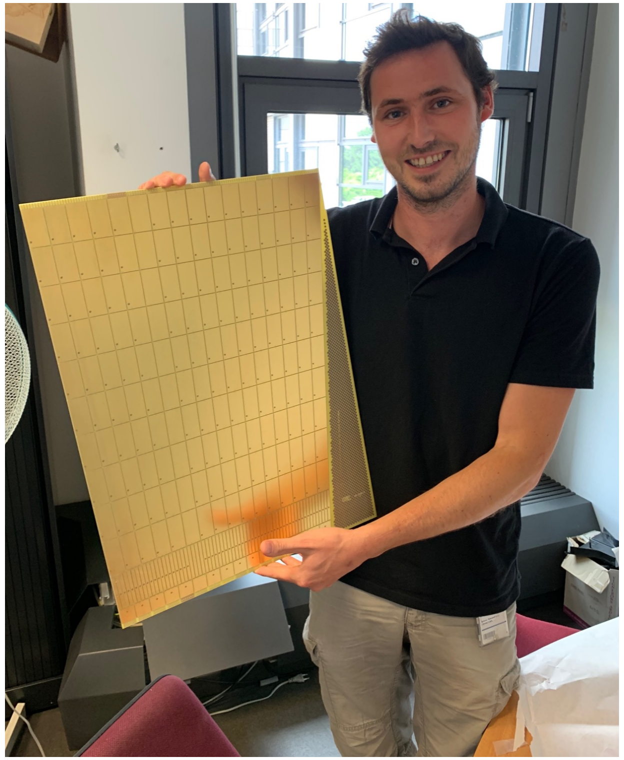
- Readout signals at the back → chose connectors

Manufacture test-module electrodes by 2027

- Potentially foresee half of module read-out by cold electronics, other half send signals outside of cryostat with coaxial cables



Small-scale PCB prototype at IJCLAB

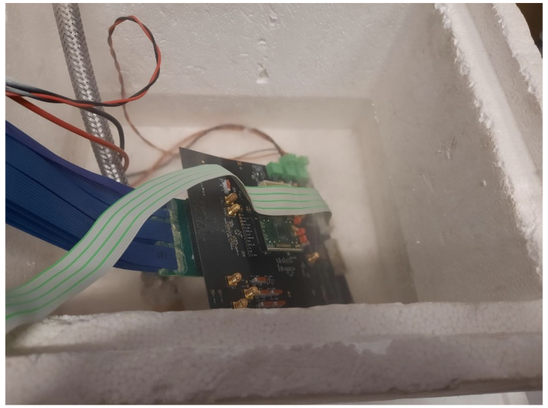


58 cm x 44 cm x 1.2 mm
electrode prototype at CERN

READOUT ELECTRONICS

On-detector Electronics: two options under consideration

- Warm option (outside cryostat)→ requires work on cables inside the cryostat and feedthroughs to get the many signals out
- Cold option (inside cryostat) → very appealing, but also requires work
  - Noise reduction up to factor ~5
  - If all the electronics are inside the cryostat, it is easier to extract the signals
  - Power consumption is a huge challenge

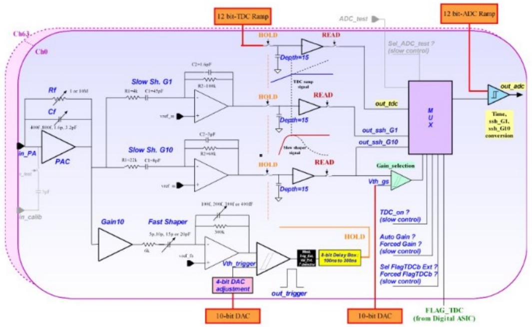


HGROC in cold bath

Intention to reuse/adapt existing readout chips and/or exploit synergies for the test module

- E.g. ATLAS LAr, CMS HGCAL, DUNE, … SKIROC
- Significant interest/work planned at OMEGA, BNL, …

SKIROC



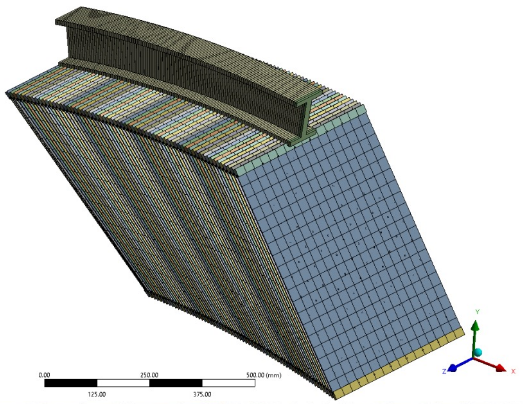
Timing? Requirements not fully defined yet/performance not fully explored

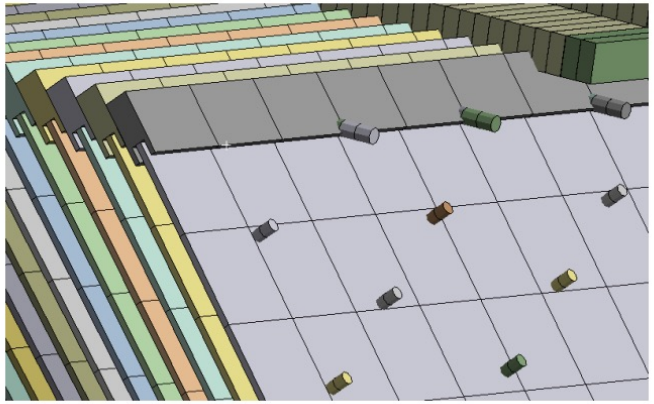
- But heavily depends on choices on the electronics

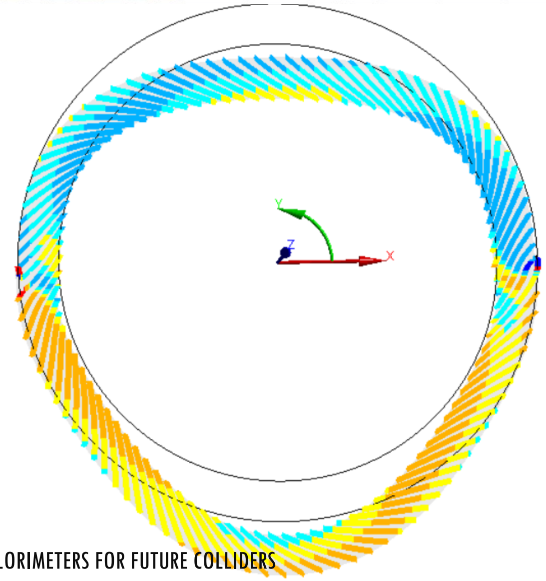
Off-detector electrons/DAQ: requirements not yet defined

- Also try to reuse available electronics for the test-beam

MECHANICS







Challenge: assemble electrodes and absorbers in a rigid structure with relatively light-weight support

- Successful example with ATLAS LAr
  - Though accordion structure contributes to rigidity. On the other hand, assembly of straight plates should be easier

Work recently started in earnest but quite encouraging

- FE analysis, deformation under own weight

But also studying feasibility of additional ideas:

- Trapezoidal absorbers
- 3D-printed pins for precision spacing/maintaining gaps

TEST MODULE

Mechanical design of testbeam module (64 absorbers) has started

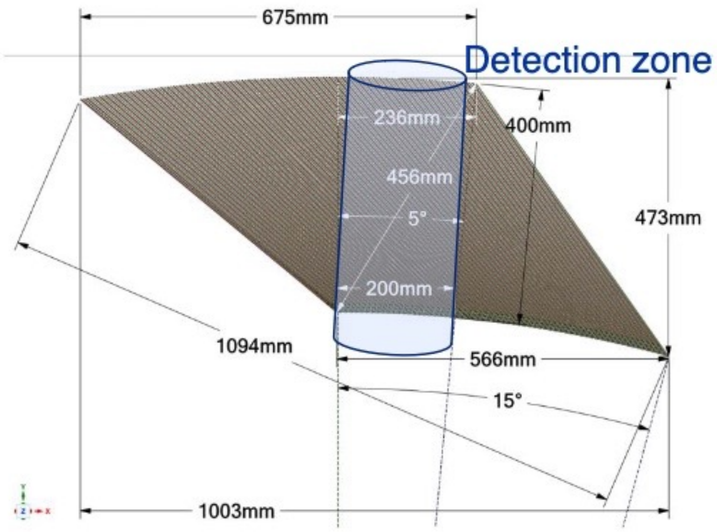
Finite element calculations including

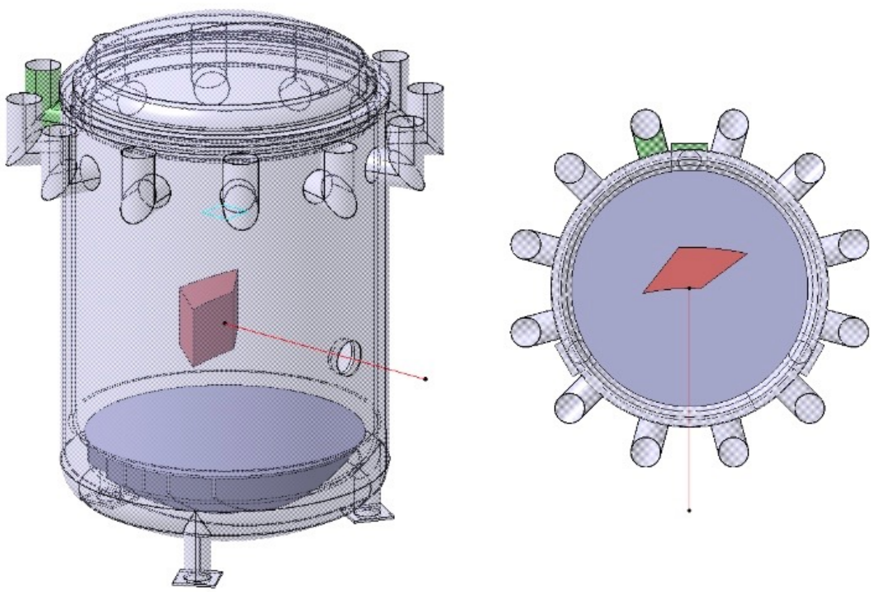
- Rings and G10 bars
- Absorbers and electrodes as shell (2D) elements using layers
- Distance pins
- Six M5 beams join electrodes and absorbers in each side (inner-outer)

Plan to place module into cryostat available at CERN

- But looking into thin carbon-fiber cryostats

Assembly and first tests at warm ~2027, cold tests and test-beam in 2028





CONCLUSIONS

Growing collaboration with new institutes recently joining the effort

- Interests of institutes still evolving

More contributions and ideas welcome!

First definition of milestones and deliverables

Simulation work to define and optimize design

First prototype in test beam by 2028

- **Challenging, but exciting work ahead!**

BACKUP MATERIAL

HIGH DENSITY FEEDTHROUGHS

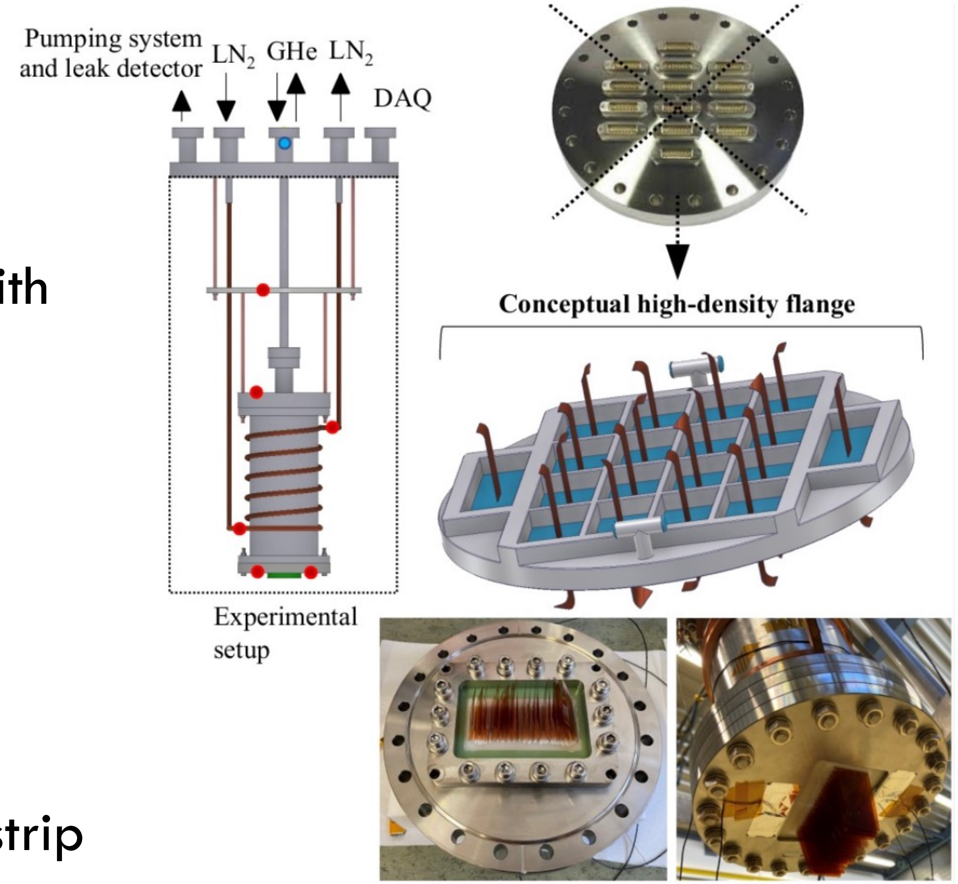
Factor of 10-15 more channels wrt ATLAS (ECAL barrel with ~2 M channels)

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



CALORIMETRY – JET ENERGY RESOLUTION

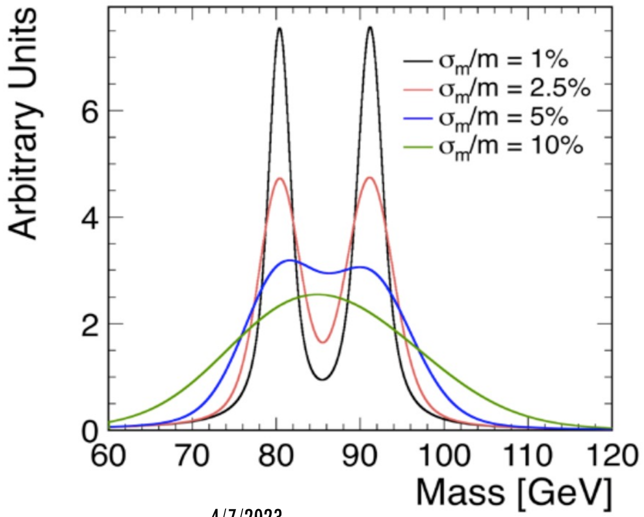
Energy coverage < 300 GeV :   22 X_0, 7λ
Precise jet angular resolution

Jet energy: $\sigma(E_{jet})/E_{jet} \simeq 30\% / \sqrt{E}$ [GeV]   ?

⇒ **Mass reconstruction from jet pairs**

Resolution important for control of (combinatorial) backgrounds in multi-jet final states

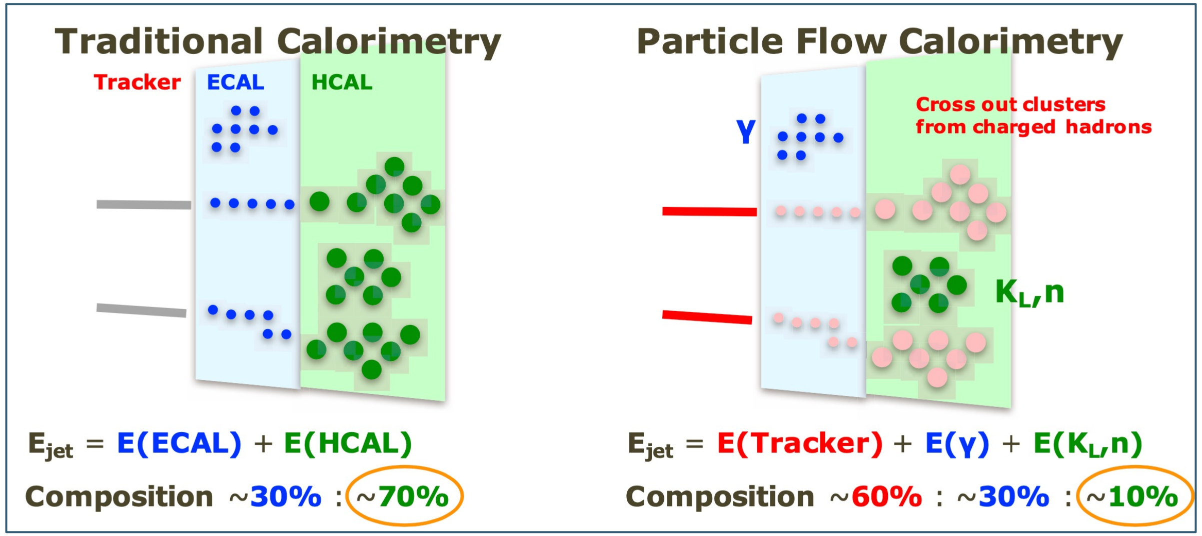
- Separation of HZ and WW fusion contribution to ννH
- HZ → 4 jets, tt events (6 jets), etc.



- At $\sigma E/E \simeq 30\% / \sqrt{E}$ [GeV], detector resolution is comparable to natural widths of W and Z bosons

How to achieve jet energy resolutions of ~3-4% at 50 GeV:

- **Highly granular calorimeters**
- **Particle Flow reconstruction and possibly in addition techniques to correct non-compensation (e/h≠1), e.g. dual read-out**



→ High granularity and/or dual read-out

TARGETS FOR CALORIMETRY

Detector technology (ECAL & HCAL)	E.m. energy res. stochastic term	E.m. energy res. constant term	ECAL & HCAL had. energy resolution (stoch. term for single had.)	ECAL & HCAL had. energy resolution (for 50 GeV jets)	Ultimate hadronic energy res. incl. PFlow (for 50 GeV jets)
Highly granular Si/W based ECAL & Scintillator based HCAL	15 – 17 % [12,20]	1 % [12,20]	45 – 50 % [45,20]	$\approx$ 6 % ?	4 % [20]
Highly granular Noble liquid based ECAL & Scintillator based HCAL	8 – 10 % [24,27,46]	< 1 % [24,27,47]	$\approx$ 40 % [27,28]	$\approx$ 6 % ?	3 – 4 % ?
Dual-readout Fibre calorimeter	11 % [48]	< 1 % [48]	$\approx$ 30 % [48]	4 – 5 % [49]	3 – 4 % ?
Hybrid crystal and Dual-readout calorimeter	3 % [30]	< 1 % [30]	$\approx$ 26 % [30]	5 – 6 % [30,50]	3 – 4 % [50]

Table 1. Summary table of the expected energy resolution for the different technologies. The values are measurements where available, otherwise obtained from simulation. Those values marked with ”?” are estimates since neither measurement nor simulation exists.

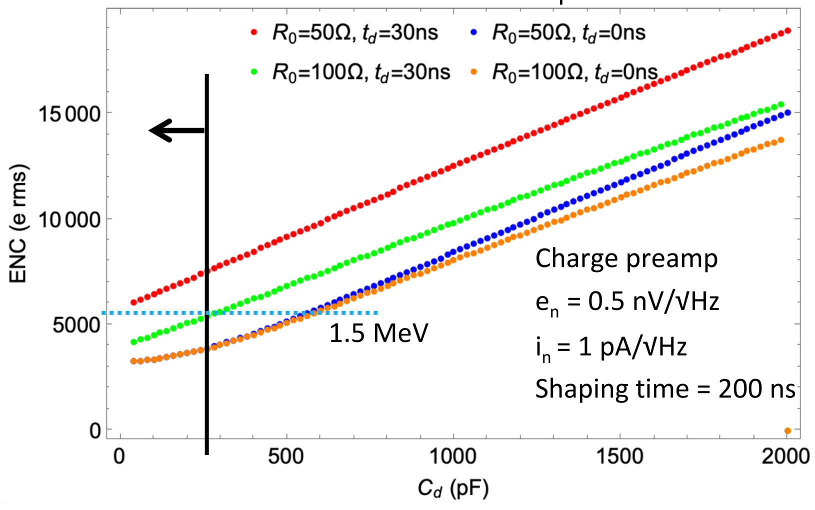
For references and more information see https://link.springer.com/article/10.1140/epjp/s13360-021-02034-2

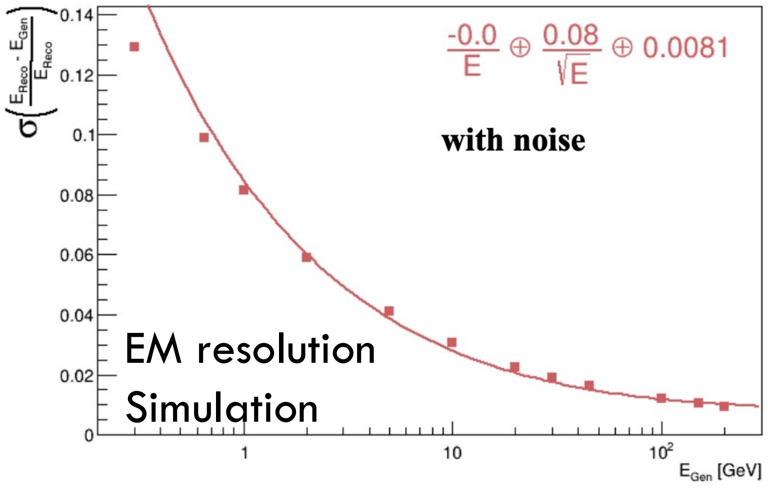
CHALLENGES: RESOLUTION, NOISE AND CROSSTALK

EM resolution with sampling term of 8 to 9%

- **Noise vs cross-talk challenge:** traces need to be shielded to minimize cross-talk → grounded shields increase detector capacitance and hence noise → need to find best compromise – **prototype electrode produced & measured**
  - **Noise** of < 1.5 MeV per cell for warm electronics and transmission lines of R_0 = 100 Ω and τ = 200 ns (C_d ≤ 250 pF)
    - → MIP S/N > 5 reached for all layers
  - **Cross-talk** of < 1% for shaping times τ ≥ 20 ns

Noise vs detector capacitance





Simulated cross-talk 2 shields < 1% for τ ≥ 20 ns confirmed by measurements on prototype

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