Current Status of Noble Liquid Calorimetry R&D

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ECFA Detector R&D Roadmap,
Calorimetry Community Meeting (TF6)

Jan. 12th, 2023

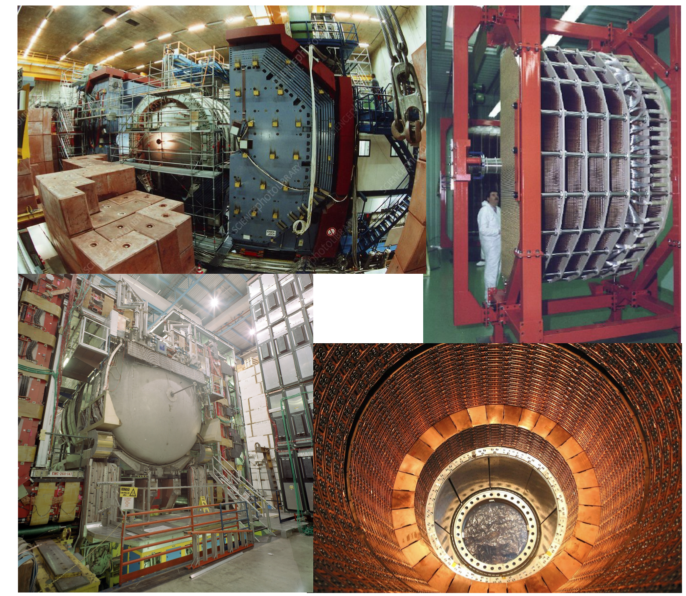
ECFA
European Committee for Future Accelerators

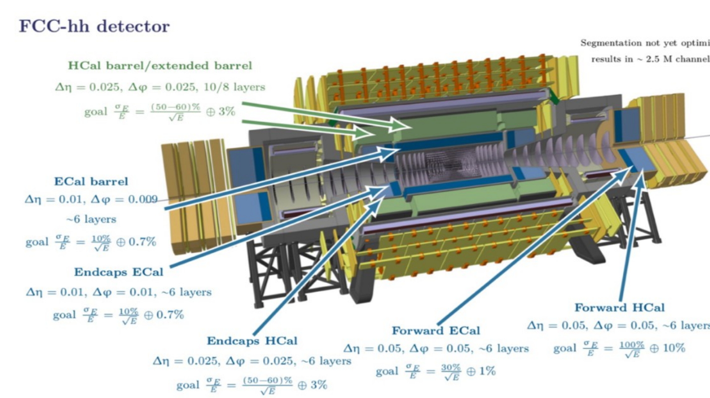
Outline

- State of the art
- Ongoing R&D
  - High granularity
    - Readout electrode design
    - Cross-talk
    - Noise
    - Signal extraction
  - Mechanics
    - Lightweight cryostat
    - Absorbers, support structure
  - Software and performance studies

Introduction

- Noble Liquid Calorimetry is a well proven technology
  - Successful operation in D0, H1, NA48/62, ATLAS
- Suitable for various collider flavors (p-p, e-p, e-e, fixed target, …)
- Proposed for several future collider experiments
  - FCC-hh, FCC-ee, LHeC, HIKE, SCTF, …
- Key features
  - Very good energy/time resolution
  - Radiation hardness
  - Long term stability, linear response, uniformity
    - Easy calibration, high control over systematics
- R&D ongoing to improve upon the state of the art

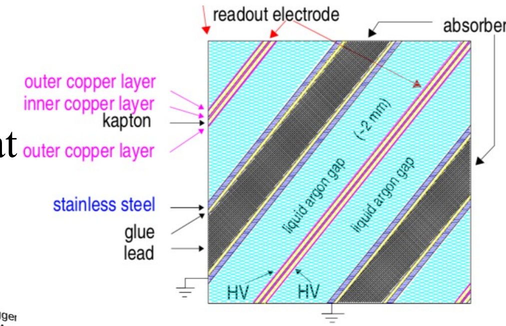


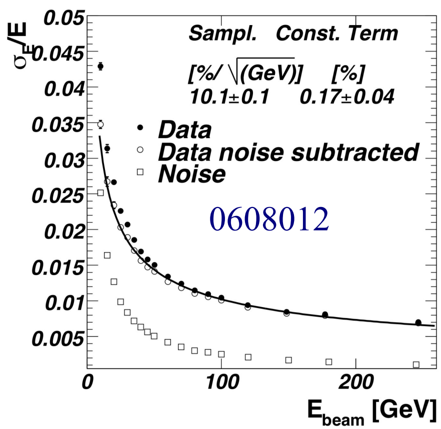


State of the Art

- ATLAS LAr sampling calorimeter: lead absorbers, LAr active gaps, 3-layer Kapton electrodes with accordion geometry, Aluminum cryostat, front-end outside of the cryostat
- Met the designed energy resolution

$$\frac{\sigma(E)}{E} = \frac{10\%}{\sqrt{E}} \oplus \frac{0.2}{E} \oplus 0.2\%$$





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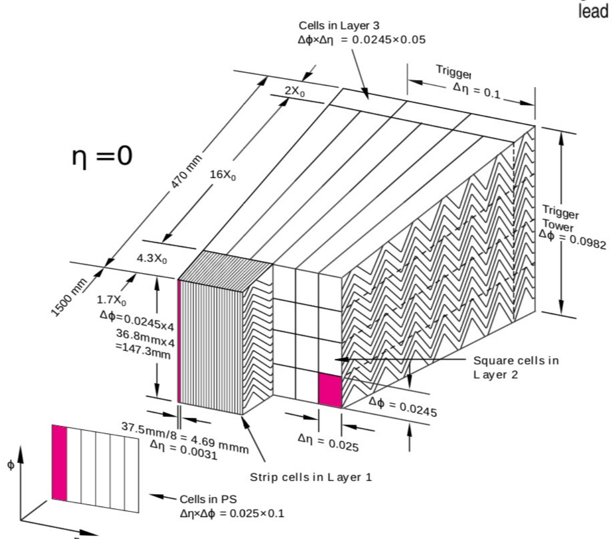

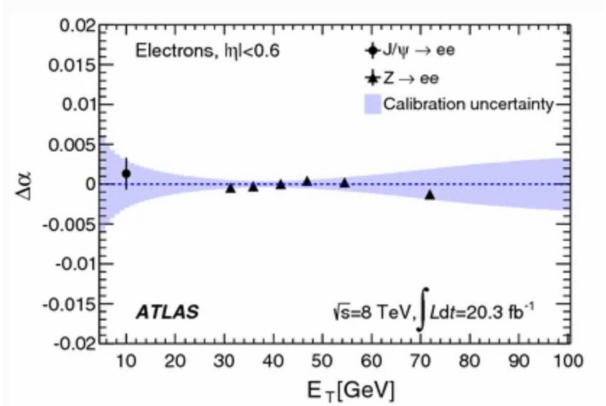

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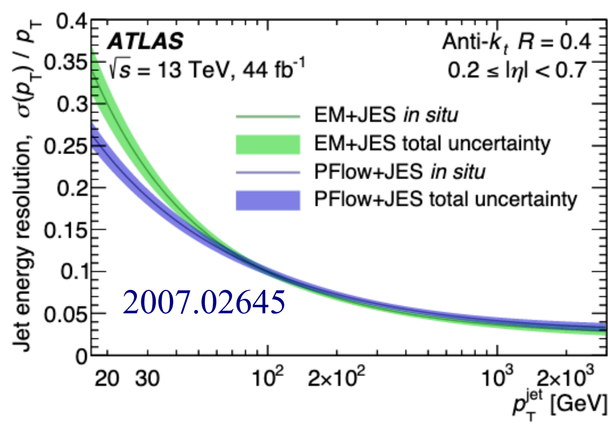
- Linearity: energy scale variation within $\sim 10^{-3}$ over large E_T range
- Stability: energy response stable at $\sim 10^{-4}$ level over a year
- Limited particle flow performance



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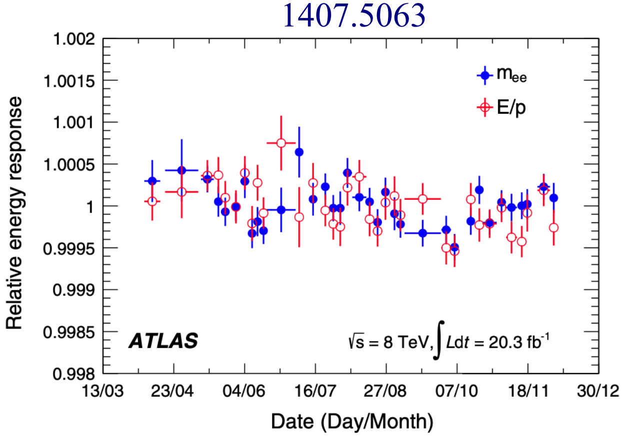
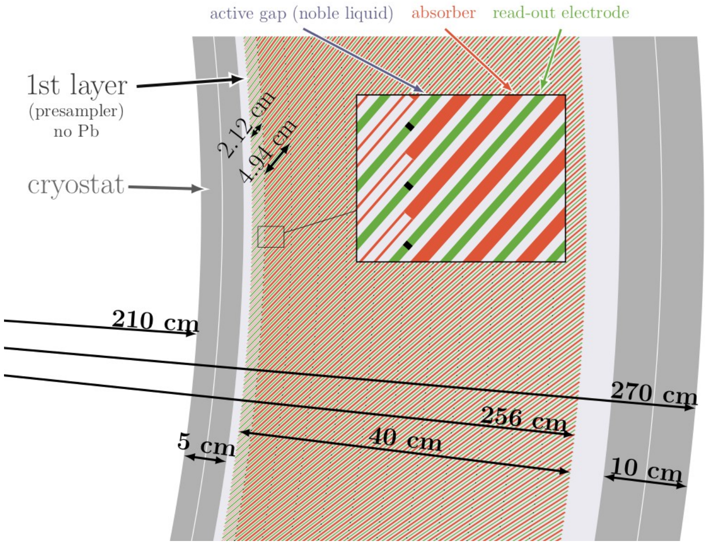
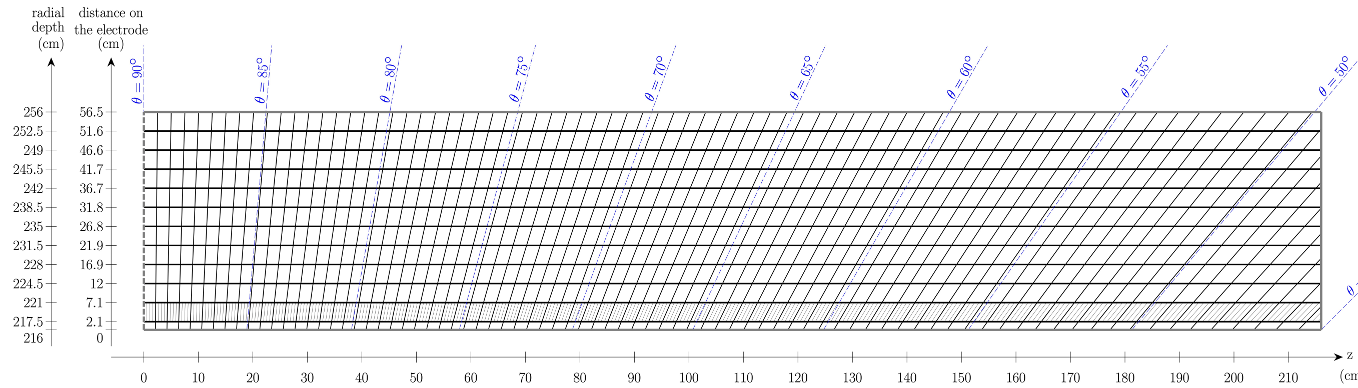


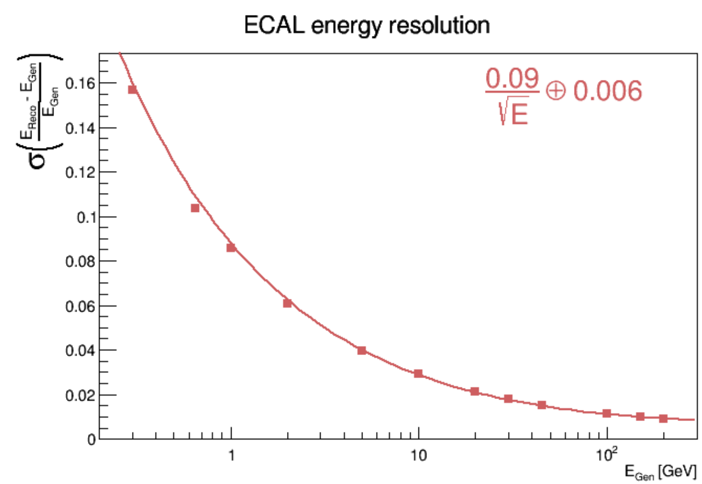
Next Generation Detector Geometry

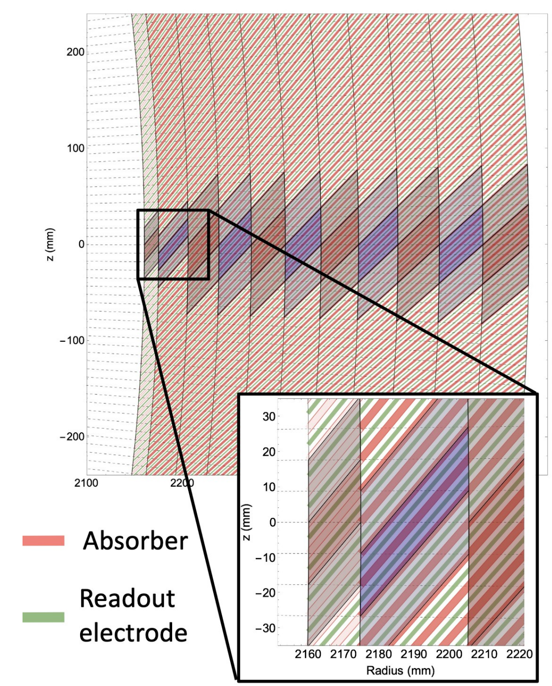




Example of (conservative) implementation for an FCC-ee ECAL

- 1536 **straight inclined** (50°) 2 mm **Pb/Steel** absorber arranged in Φ
- **1.2 - 2.4 mm LAr** sensitive media
- 40 cm deep (22 X_0)
- $\Delta\Phi \geq 8$ mrad, $\Delta\theta = 10$ (2.5) mrad for regular (strip) cells, 12 longitudinal compartments ($\Delta r = 3.5$ cm)
- Aluminum cryostat (5 cm inner, 10 cm outer)

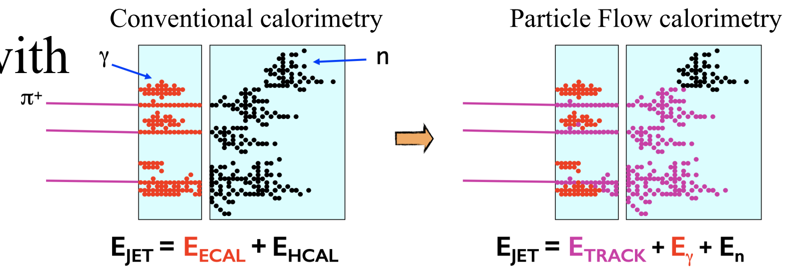


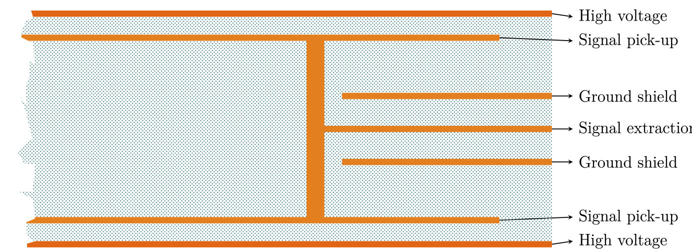


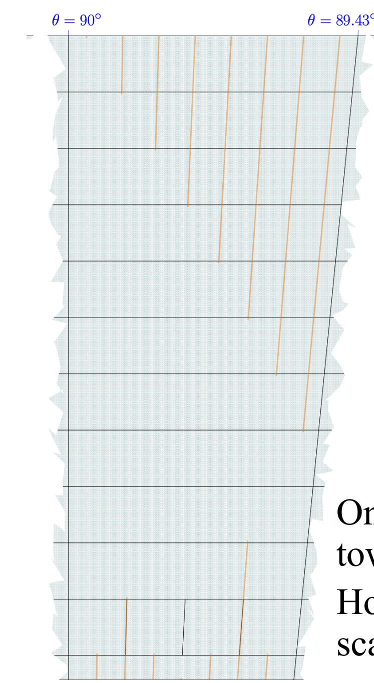
High Granularity

High Granularity Electrode: Design

- Excellent relative jet energy resolution can be achieved with Particle Flow → build future detectors with this in mind
  - Need to avoid double counting and wrong merging
  - Calls for an imaging, high granularity calorimeter
- Target **10 to 15 times higher granularity** w.r.t. the state of the art ATLAS LAr Calo
  - Challenge: **route tiny analog signals** (no avalanche) to the front-end electronics sitting **outside of the sensitive volume,** keeping x-talk under control and high S/N
  - High granularity readout electrode realized as a **7-layer PCB**
    - **Signal extraction** on a **different plane** as the pick up pads
    - **Ground shields** surrounding the trace to mitigate x-talk





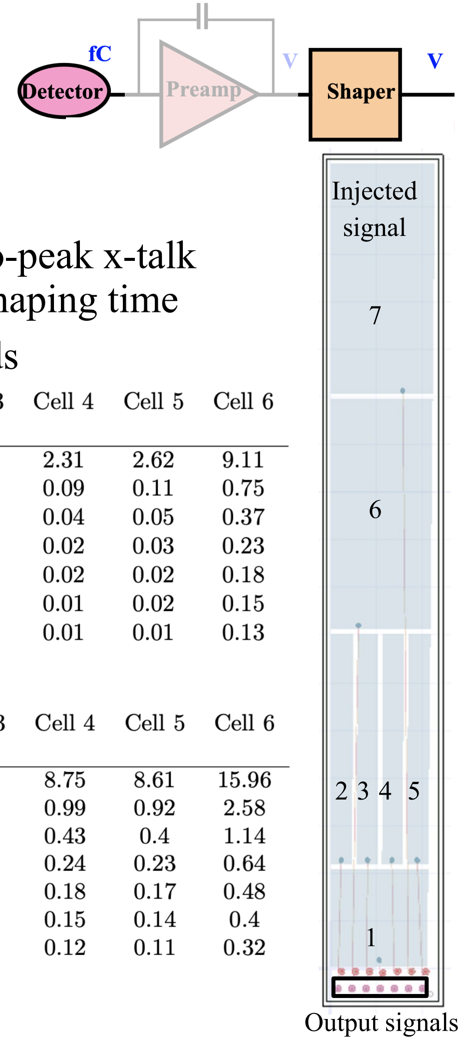


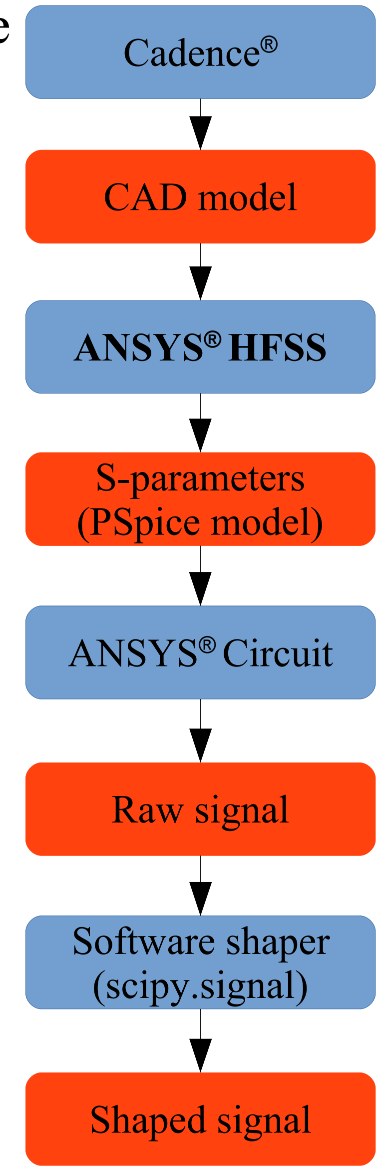
One theta tower

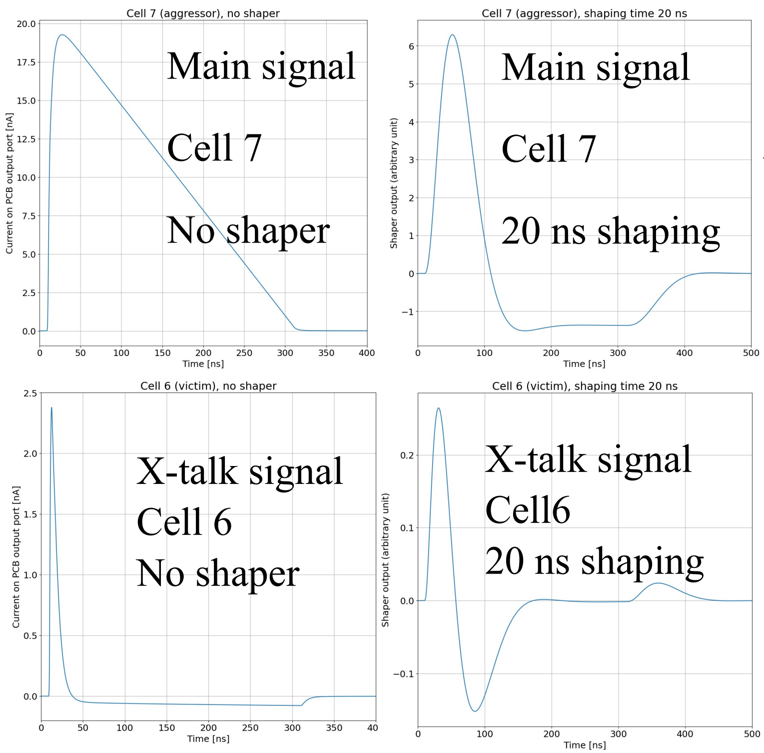
Horizontal axis scale 10:1

High Granularity Electrode: X-talk

- The shields increase detector cell capacitance to ground which impacts noise
  - Target minimal shielding which leads to acceptable x-talk (~1 %)
- X-talk evaluated from **FEM simulations**
  - With signal shaping, **peak to peak x-talk values < 1 % easily achievable**







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

2 shields

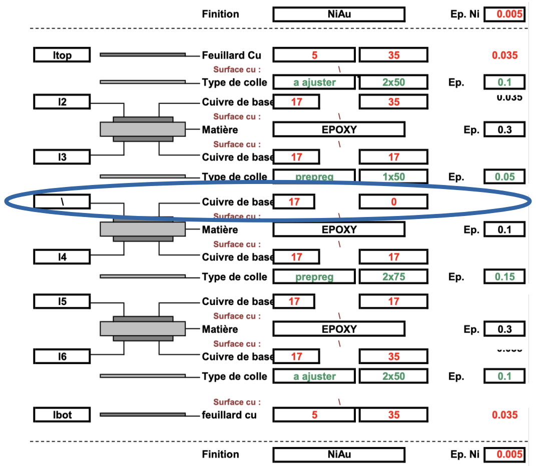
Cross-talk (%) / Shaping time (ns) ↓	Cell 1	Cell 2	Cell 3	Cell 4	Cell 5	Cell 6
No shaper	0.54	0.85	0.85	2.31	2.62	9.11
20	0.03	0.04	0.01	0.09	0.11	0.75
50	0.01	0.02	0.0	0.04	0.05	0.37
100	0.01	0.01	0.0	0.02	0.03	0.23
150	0.0	0.01	0.0	0.02	0.02	0.18
200	0.0	0.01	0.0	0.01	0.02	0.15
300	0.0	0.0	0.0	0.01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

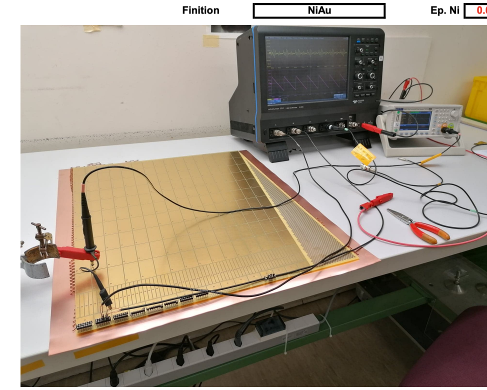
0 shield

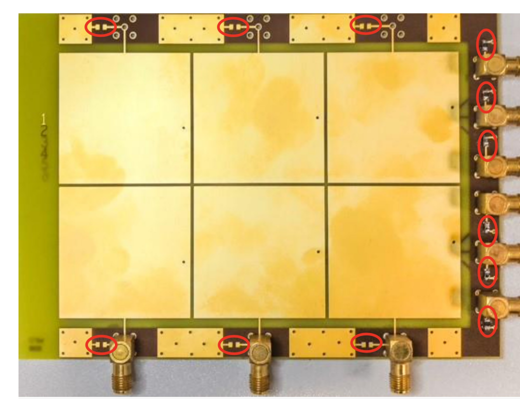
Cross-talk (%) / Shaping time (ns) ↓	Cell 1	Cell 2	Cell 3	Cell 4	Cell 5	Cell 6
No shaper	6.27	2.6	3.2	8.75	8.61	15.96
20	0.7	0.1	0.1	0.99	0.92	2.58
50	0.3	0.02	0.02	0.43	0.4	1.14
100	0.17	0.01	0.01	0.24	0.23	0.64
150	0.13	0.01	0.0	0.18	0.17	0.48
200	0.1	0.01	0.0	0.15	0.14	0.4
300	0.08	0.0	0.0	0.12	0.11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

High Granularity Electrode: Prototyping

- **Real scale prototype produced** to validate the concept
  - Fairly easy manufacturing, even with an odd number of layer
  - Simple **electrical tests** with function generator and scope + software shaper
    - **Confirms that cross-talk < 1% is easily reachable for all cells**
    - Effect of the transmission line on signal attenuation negligible
- All results compared to simulation (see back-up)
  - Same qualitative behavior, values in the same ball-park but quantitative comparison not satisfactory yet
- Small scale simpler electrodes produced for detailed understanding of all the effects at play
  - Fairly good mesurement/simulation agreement for S-parameters over a large frequency spectrum
- Still a lot to be done: connectors for real scale prototype, improve measurement/simulation agreement, optimize electrode segmentation (a lot of freedom!), cell extraction scheme, …

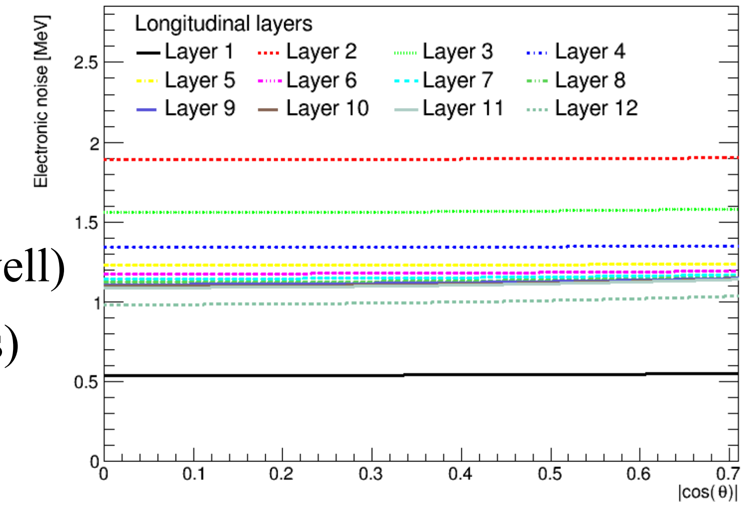




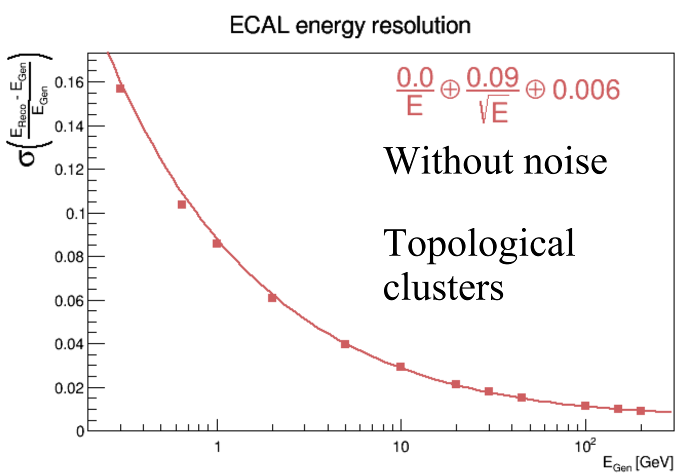


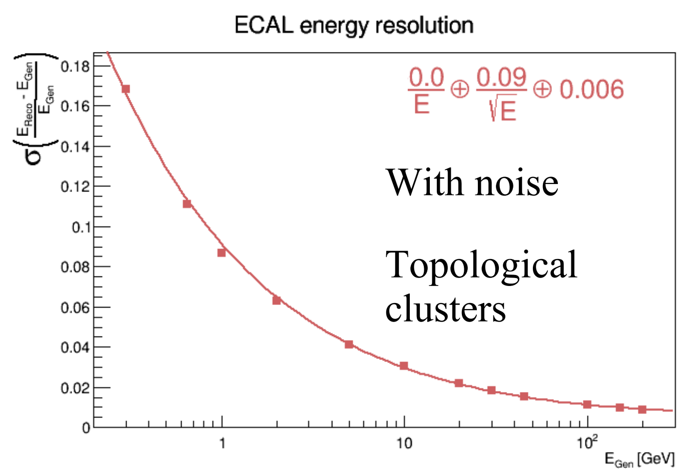
High Granularity Electrode: Noise

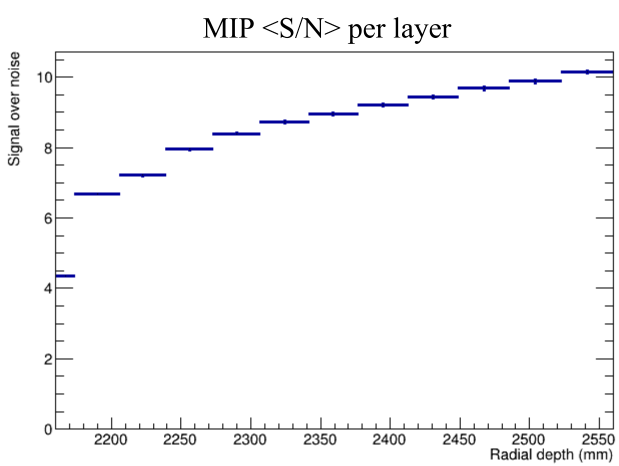
- Electronics noise VS cell capacitance estimated from analytical description of the readout chain
  - Transfer function (Laplace domain) in Mathematica
    - PCB transmission line (+ coaxial cable) + pre-amp + shaper
- Cell capacitance derived from FEM tools (ANSYS Maxwell)
  - 25 - 200 pF depending on the longitudinal layer (2 shields)
  - **0.5 – 2 MeV noise** per cell
- Noise per cell implemented in Full Sim
  - Negligible impact on energy resolution > 1 GeV
  - **MIP S/N > 5** also with warm electronics (next slide)



2 ground shields, 1 readout cell = 2 physical cells, 5 m 100 Ω coax, Charge preamp, $e_n = 0.5\ \mathrm{nV}/\sqrt{\mathrm{Hz}}$, $i_n = 1\ \mathrm{pA}/\sqrt{\mathrm{Hz}}$, shaping time = 200 ns



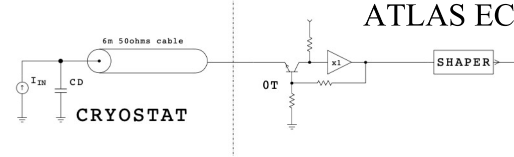




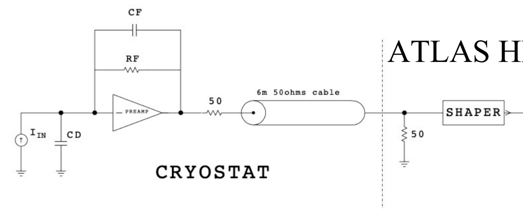
Warm or cold electronics?

- **Electronics** can sit **inside** (cold) **or outside** (warm) the **cryostat**
  - Hybrid solution with only the pre-amplifier inside the noble liquid can also be envisaged
- Noise estimated in both scenarios
  - Cold electronics can bring a **noise reduction factor of *O*(5)**
  - Precise value depends on the final design
    - Transmission line impedance, shaping time, detector capacitance
- All FE electronics inside the cryostat → **easier signal extraction**
  - Analog with cables VS digital with optical fibers
- First trial with HGCROC (CMS HGCAL ASIC) at cold
  - Some adaptation needed but looks promising for first tests
- Not covered yet:
  - Estimate the impact on the cross-talk (better with cold electronics)
  - **Difficult maintenance**/upgrade with cold electronics: risk assessment and mitigation strategy (redundancy) to be established
  - Estimate impact of **power dissipation inside the noble liquid**

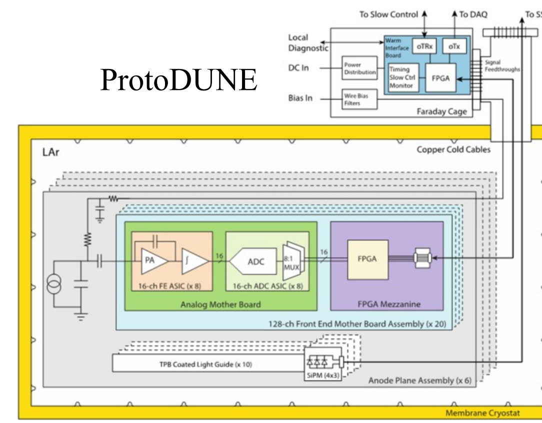
ATLAS ECAL

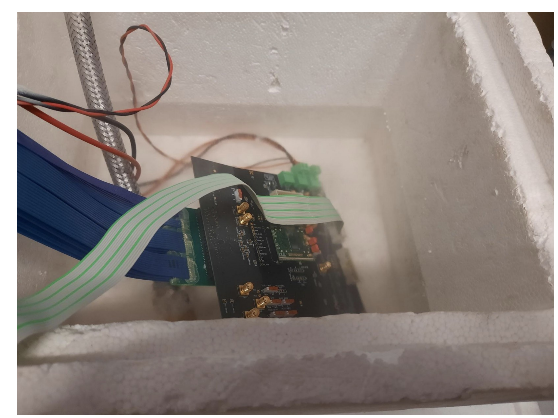


ATLAS HEC



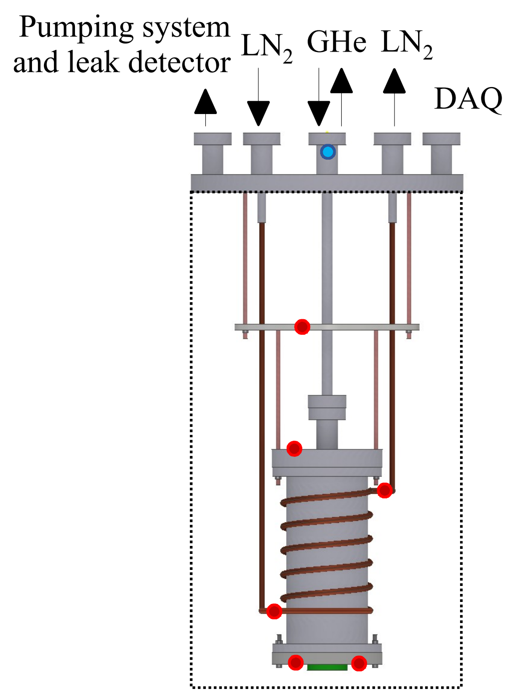
ProtoDUNE



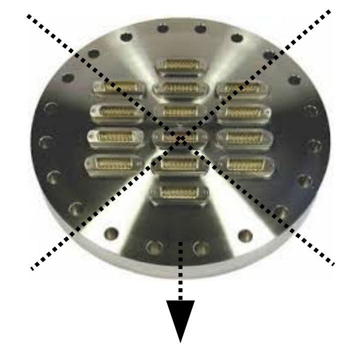


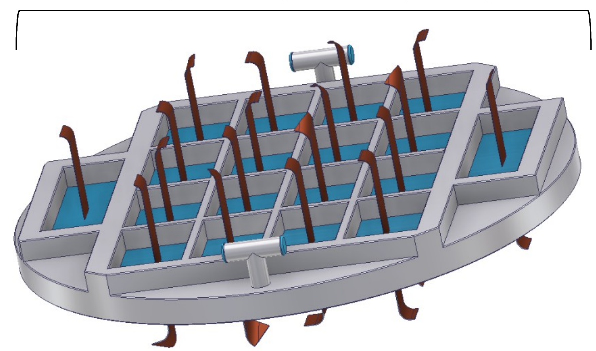
High Density Feedthroughs

- Factor **10-15** more granular than ATLAS → **more channels to extract** (ECAL barrel ~2 M)
- If the electronics sits outside of the cryostat (warm electronics), one needs high density feedthroughs
- Innovative **connector-less feedthroughs**
  - High density flange
  - Higher area dedicated to signal extraction
  - 20 000 wires per feedthrough
  - Reduced size samples development
    - Testing different 3D-printed epoxy resins as structures with slits allowing the passage of cables – glued to the flange
    - 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)

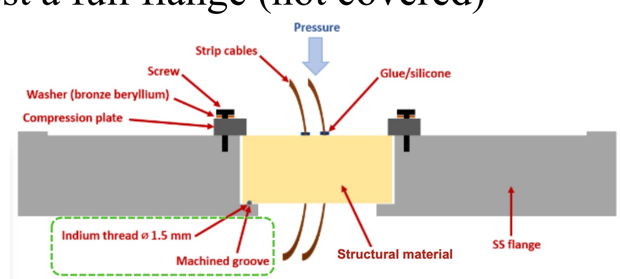


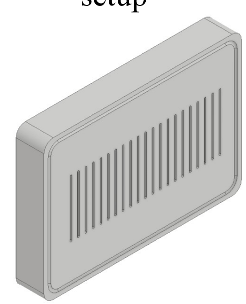
Experimental setup

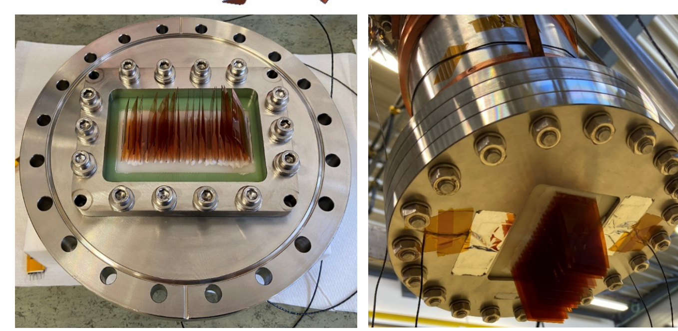




Conceptual high-density flange



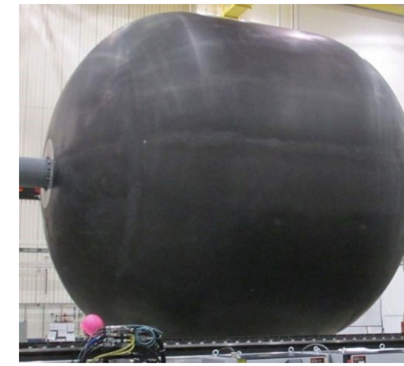




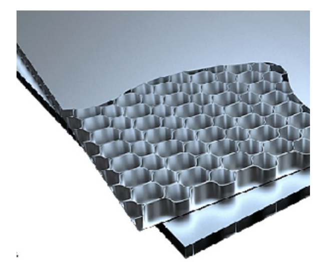
Mechanics

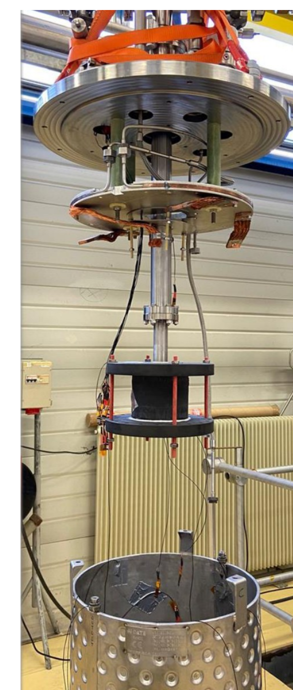
Lightweight Cryostat

- **Minimizing dead material budget** before sensitive areas is profitable for Particle Flow, energy resolution, low energy particle detection, …
- Ongoing R&D on **low mass cryostat**
  - Solid (plain) shell or honeycomb sandwich
  - Aluminum or Carbon Fibre Reinforced Polymer (CFRP)
  - Up to **factor 10 lower material budget** for ICC w.r.t. plain Aluminum
- Small scale CFRP prototype produced and validated (leak-tight at 112 K)
- Next step: establish a large scale manufacturing process



NASA lineless CFRP cryotank





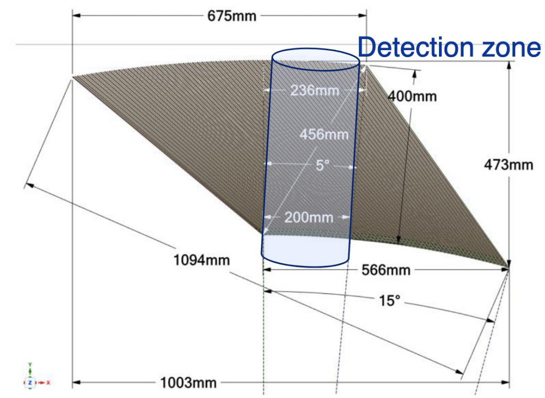
Criteria: Safety Factor = 2	Honeycomb Al				Solid shell			
	HM CFRP		Al		HM CFRP		Al	
	OWC	ICC	OWC	ICC	OWC	ICC	OWC	ICC
Material budget X/X_0	0.03	0.043	0.094	0.17	0.092	0.12	0.34	0.44
X_0 % savings	-68%	-75%	REF	REF	-2%	-29%	262%	159%
Skin Th. [mm]	3.2	4.8	3.9	7.5				
Core Th. [mm]	32	38	40	40				
Total Th. [mm]	38.4	47.6	47.8	55	24	30.4	30	39
Thickness % savings	-20%	-13%	REF	REF	-50%	-45%	-37%	-29%

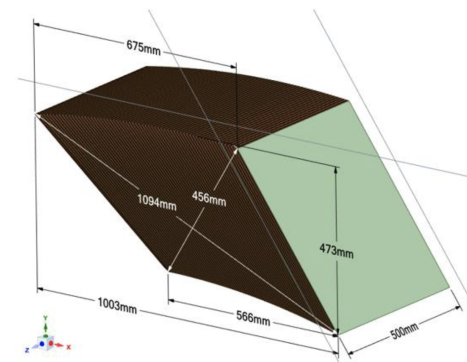
Promising R&D — Baseline — Prototype — ATLAS

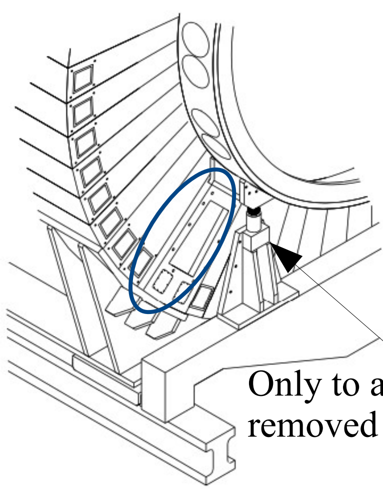
CFRP: Carbon Fibre Reinforced Polymer
OWC: Outer Warm Cylinder
ICC: Inner Cold Cylinder
Al: Aluminum

Mechanics

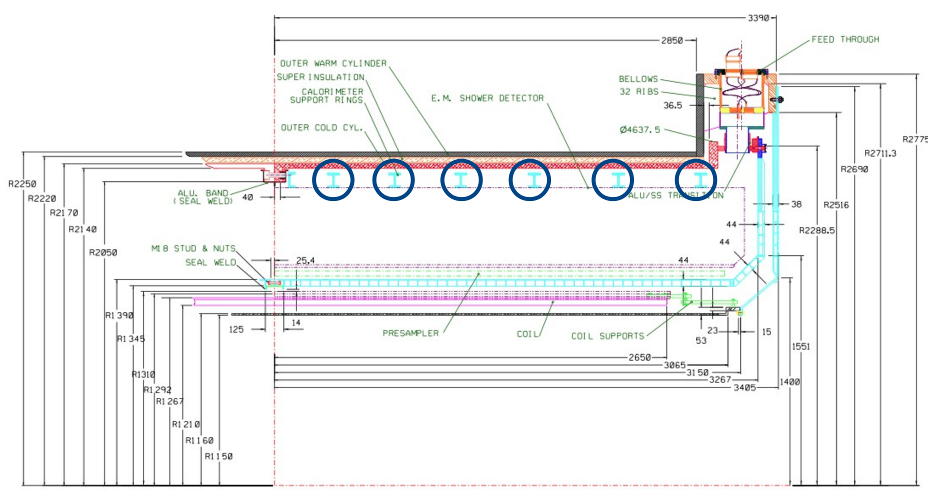
- Starting now a two-fold mechanical engineering campaign
  - Design, price and produce a module for test beam
    - Straight lead/steel absorbers (tolerance on thickness?), cryostat, support structure
  - Design a solution for the whole ECAL
- Many other things to cover
  - Feasibility for trapezoidal absorbers
  - Design for the endcaps
  - How to insert and support the modules in a carbon fibre cryostat
  - Detector integration: how to support the whole calorimeter without jeopardizing hermeticity and with good acceptance knowledge?

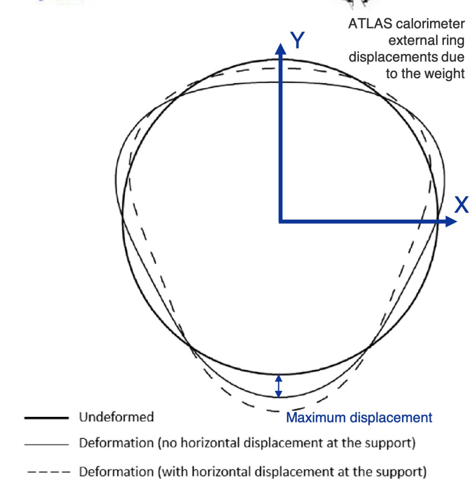






Only to adjust the height, removed after installation

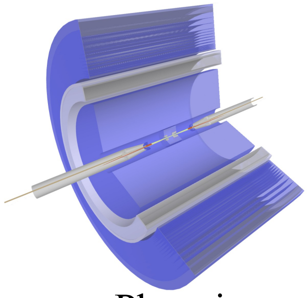


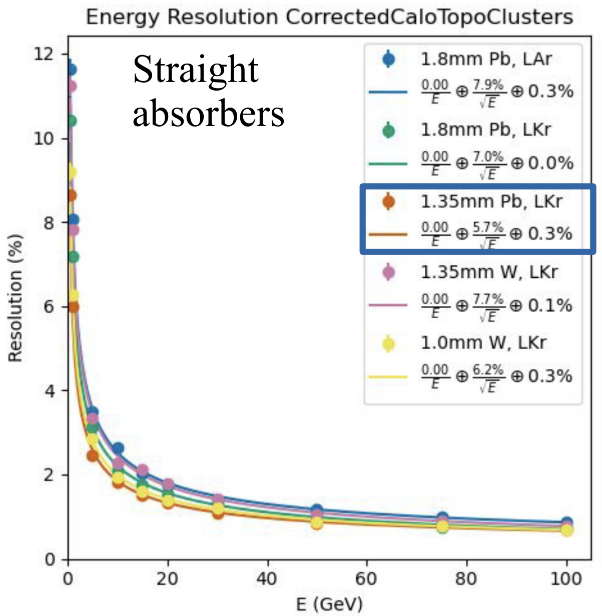


Software and performance studies

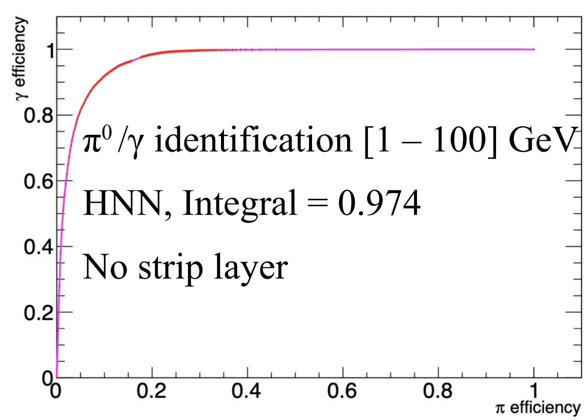
Software Implementation

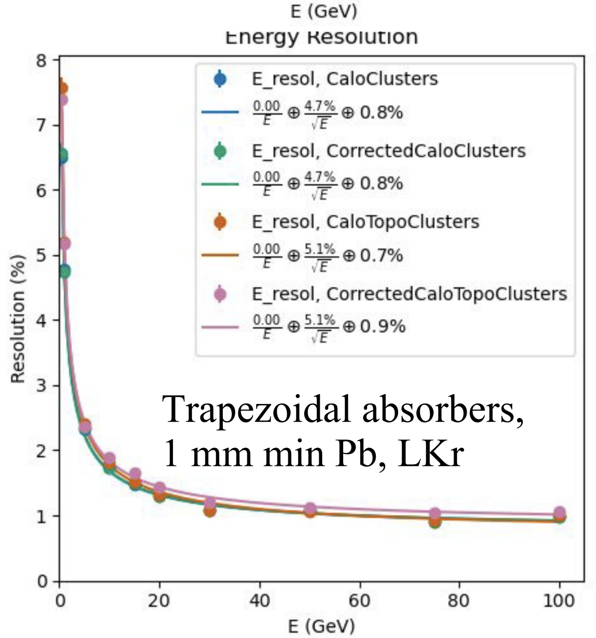
- Detector geometry implementation in **DD4HEP**
  - **Barrel ECAL** layout available and **validated**
    - Possibility to study different absorber material and shape, noble liquid, granularity
    - Fairly accurate description: cryostat walls, space for services, sampling fraction, energy correction, noise
  - Endcap implemented but not fully validated yet
  - Detector simulation and reconstruction integrated in **Key4HEP**
    - Long term support





- First order performance studies available: **5 – 9 % sampling term**, 95 % γ efficiency for 10 % π^0 in the [1 – 100] GeV range
- Can still be greatly improved
  - Detector segmentation (currently a fictive grid) including strip layer
  - Digitization, cross talk
  - Detailed services
  - Particle Flow!





Towards a Full Detector Concept

We are also working on a **full detector concept** for FCC-ee

Still very preliminary and evolving

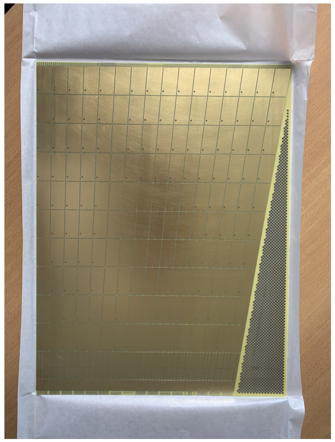
- Vertex detector: (D)MAPS, possibly ALICE 3 like
- Tracker: Drift Chamber with 2.5 m active
- Silicon wrapper and Time of flight
- Highly granular Noble Liquid ECAL
- Superconducting solenoid after ECAL, sharing the same cryostat
- Highly granular HCAL: Scintillator + Iron (return yoke), more in Henric's talk
- Muon ~~Tracker~~ → Tagger
  - Drift chamber, RPC, MicroMegas, …

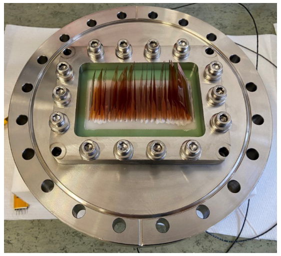
(One of the) Possible layout for the full detector concept*

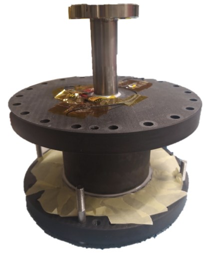
* We still have no name for this detector!

Conclusions

- Noble Liquid calorimeters are required by many future experiments
- Sampling term of 8-9% easily achievable, optimization could bring it down to 5%
- The technology is being adapted for 4/5D calorimetry while preserving its excellent conventional calorimetry properties
- We are now highly confident that it can be done
  - MIP <S/N> estimated to be > 5 also for warm electronics
  - High granularity electrodes produced and tested
    - Cross-talk ~ 1% easily achievable
  - Several options for signal extraction identified
  - Carbon fibre cryostat manufacturing well advanced







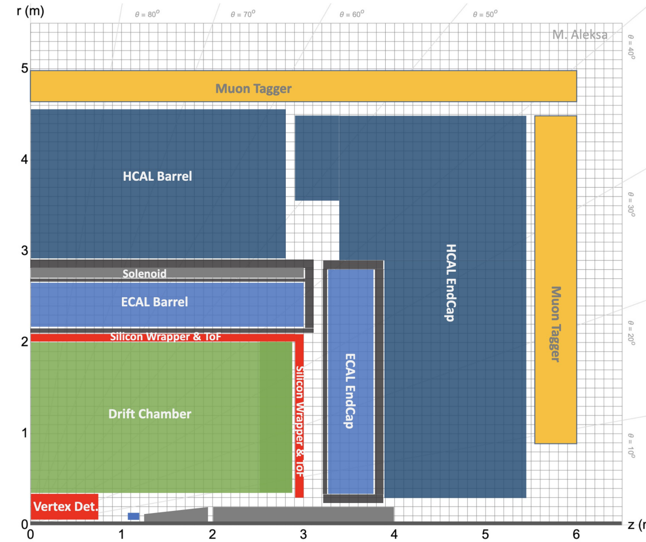
- Software tools already available for first order performance studies
- Most of the results obtained so far are still at the proof of concept level!
  - Tremendous work ahead, **a lot of room for significant contributions!**
    - Move from proofs of concept to a test beam module
    - Optimize all the free parameters
    - …

Additional material

Software Implementation

Full simulation in Key4HEP

- Factorized Detector building (DD4HEP): no need to recompile when changing simple detector parameters
- Includes **all the first order effects**: sampling fraction, dead material correction, noise, clustering, …
- Most of the corrections can be automatically derived upon geometry change
- Working on a **complete detector implementation**
  - ECAL endcap and HCAL almost there, tracker from IDEA, muon tagger as sensitive plates for now



FCCDetectors (DD4HEP)

k4Gen → k4SimGeant4 → k4RecCalorimeter → FCCAnalyses → User Code

k4Gen
Monte Carlo Generation
Physics collision or Particle Gun

k4SimGeant4
Detector description
Particle interaction and propagation
Energy deposits

k4RecCalorimeter
Energy deposits per physical cells/readout channel
Noise
Corrections (sampling fraction, dead material correction)
Clusterings

FCCAnalyses
Plain ROOT n-tuple production
High-level variable computation
Originally used to make analysis macros 'dataformat agnostic' but turned out to bring way more!

User Code
Automation
Reco/Gen comparison
Plots!

\+ k4FWCore for Podio services and very generic tools

Gaudi based

High rate mitigation

- HiLum/FCalPulse R&D project
  - Understand/quantify space charge effects under high rate: targets ATLAS HL-LHC but is interesting for any high rate experiment (e.g. FCC-hh)
    - Anode screening (HV drop), recombination
  - Impact on current pulse (degradation, distortion)
    - Affected regions: FCal1, FCal2, EMEC at high η
  - Planning a test beam to measure LAr drift and recombination parameters
  - At fixed high ionization rate, is the pulse height still linearly proportional to the energy deposit?
  - Develop software corrections to recover energy response
- Other handles: reduced sensitive gap thickness, adapted HV distribution

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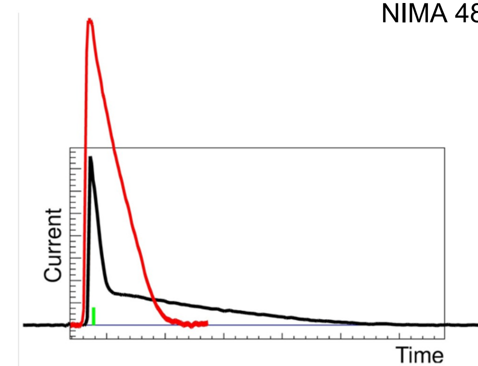
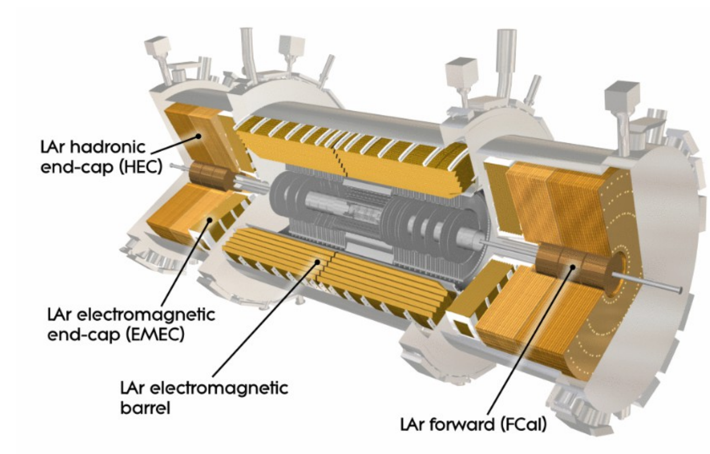
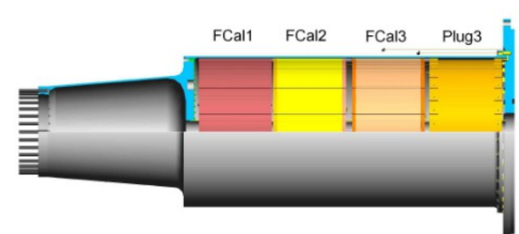


HiLum R&D project: EMEC normal pulse (red) and degraded pulse (black)

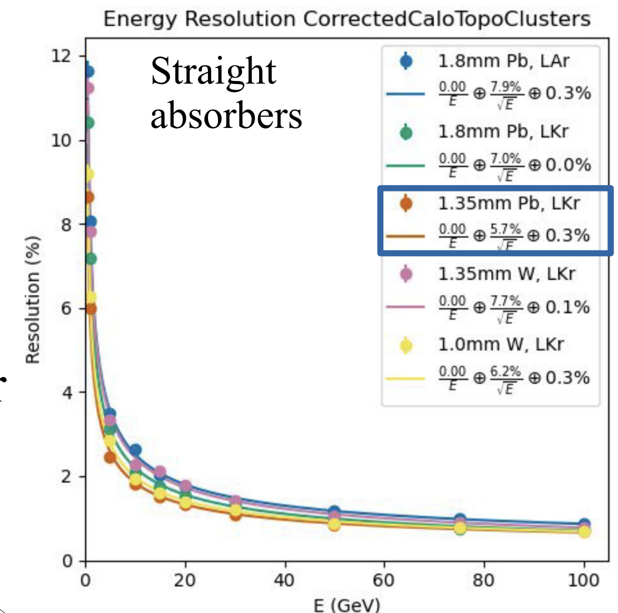


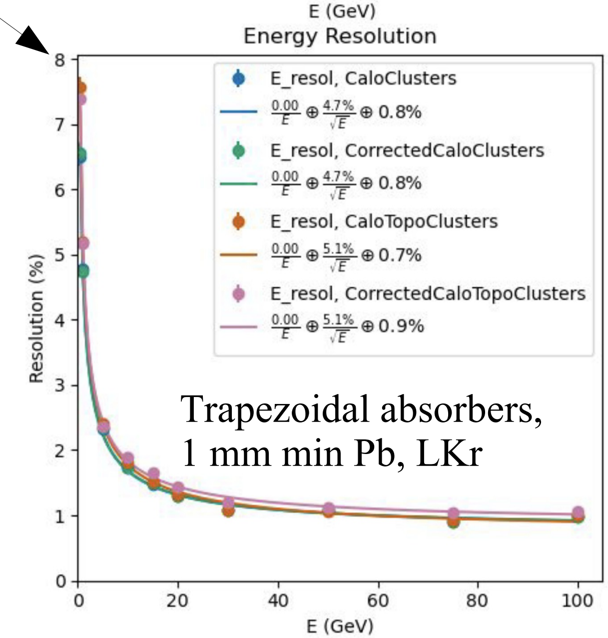


Further Possible Geometries

Other geometries are under consideration

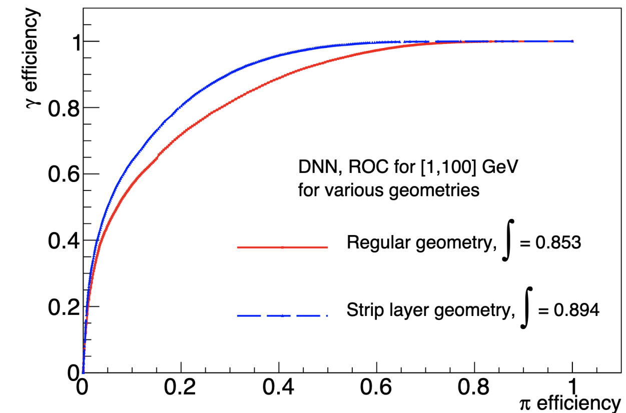
- **LKr** sensitive media
  - Better sampling term: 7% w/o touching absorber, 6% w/ thinner absorbers (keeping same total #X_0's)
- **Trapezoidal absorber** → constant sampling fraction per layer
  - 5% sampling term
  - Easier high voltage distribution
- Thinner Pb absorbers + higher radial extent (not shown here)
  - Increased sampling fraction
- **W absorbers** instead of Pb
  - Smaller R_M and radial extent
- Many handles to bring the **sampling term down to $\mathcal{O}$(5%)!**
  - **Mechanical engineering campaign** started to investigate those options
- Further performance squeezing (esp. constant term) possible through improvement of clustering and calibration (MVA calibration)

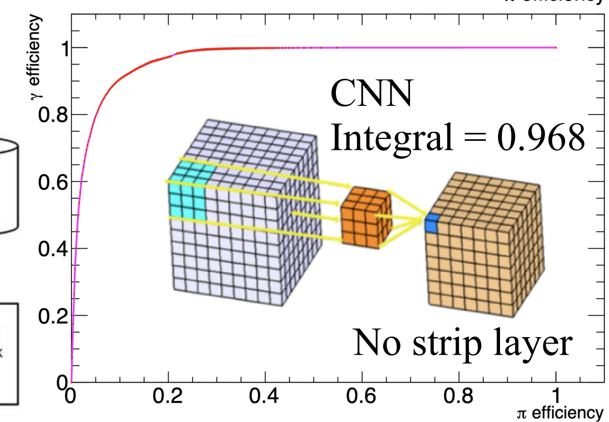


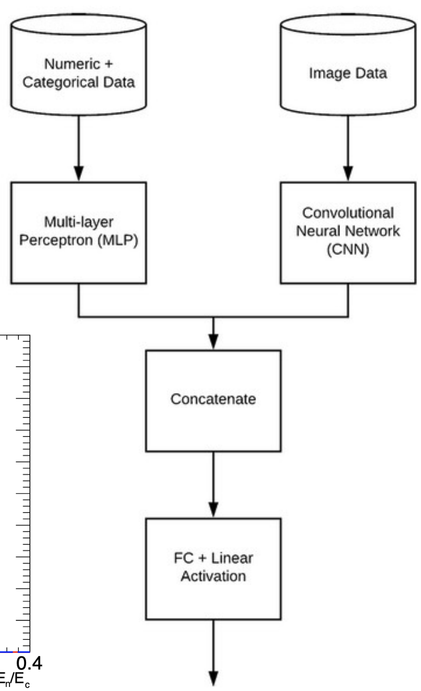


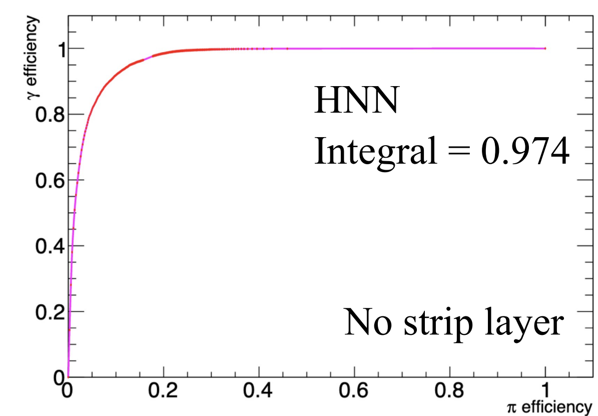
Particle Identification

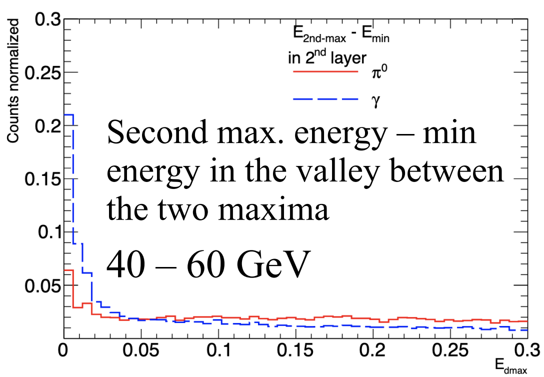
- π^0/γ separation studied with different MVA and geometries
  - π^0 and γ particle gun, 100 k events each, [1 – 100] GeV uniformly distributed in Φ and θ, with and without strip layer
  - DNN with ~15 variables
    - No loss of perf. w/ one training for the whole energy range w.r.t. energy specific trainings (parametrized DNN with $E_{Cluster}$)
  - 3D Convolutional NN (CNN) with 10 x 10 x 12 window
    - Tremendous improvement w.r.t. DNN
  - Hybrid NN (**HNN**) with both DNN and CNN
    - **95% γ efficiency for 10% π^0 contamination** for the whole energy range (**no strip layer** + baseline **conservative** geometry)

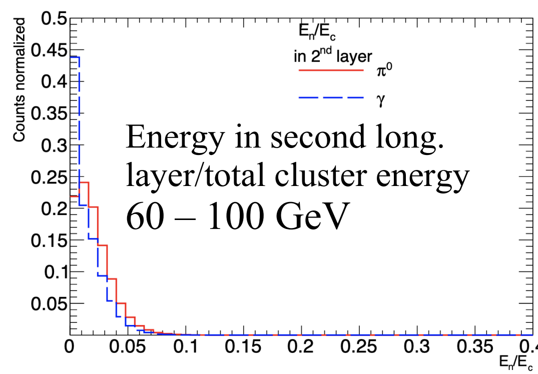






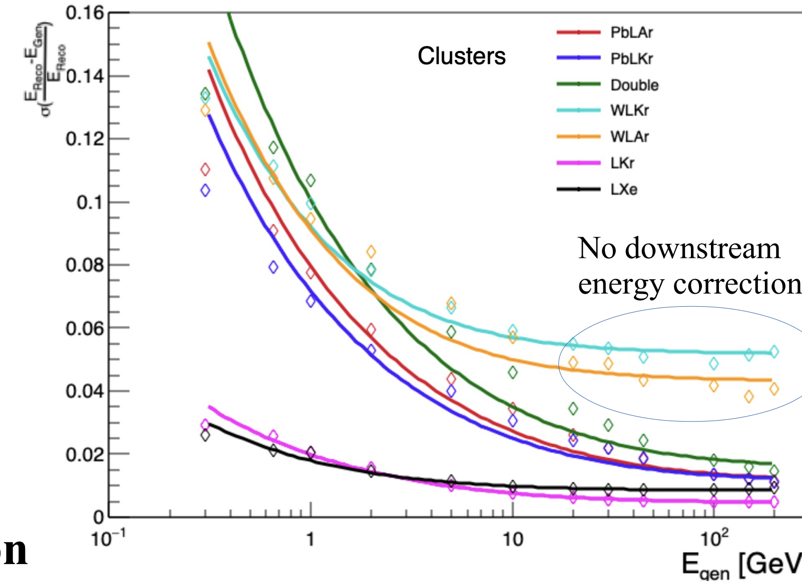




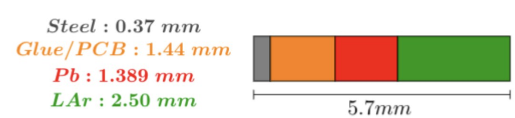


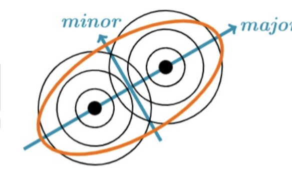
Performance Studies

- Performance studied for **different absorber/Noble Liquid scenarios** with, in most cases:
  - Absorber/sensitive thicknesses kept untouched
  - Calo length adapted to have ~ 22 X_0 in each scenario



- τ polarization measurements ($\sin^2(\theta_W)$ and lepton universality)
  - Precision measurements need **τ final state categorization**
  - Studied in a simplified geometry (concentric cylinders) – no strip layer (pessimistic)
    - LAr + Pb (R_M=4.1 cm), cell size 2 x 2 x 4 cm^3
  - $e^+ e^- \rightarrow Z \rightarrow \tau^+ \tau^-$, one τ forced into μ channel
  - Categorization based on π^0 counting
    - γ/π^0 separation from simple cluster shape variables





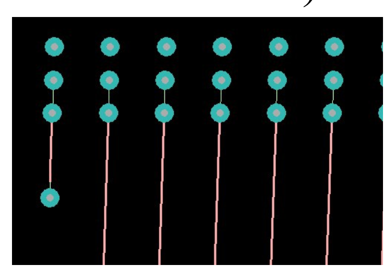
Recon → / Gen ↓	$\pi^\pm \nu$	$\pi^\pm \pi^0 \nu$	$\pi^\pm 2\pi^0 \nu$	$\pi^\pm 3\pi^0 \nu$	$\pi^\pm 4\pi^0 \nu$
$\pi^\pm \nu$	**0.9560**	0.0425	0.0010	0.0003	0.0002
$\pi^\pm \pi^0 \nu$	0.0374	**0.9020**	0.0586	0.0016	0.0002
$\pi^\pm 2\pi^0 \nu$	0.0090	0.1277	**0.7802**	0.0808	0.0022
$\pi^\pm 3\pi^0 \nu$	0.0036	0.0372	0.2679	**0.5972**	0.0910

  - LKr + W scenario (R_M=2.7 cm) shows better performance on π^0 ID
  - Machine learning approach + inclusion of strip layer will further improve these results

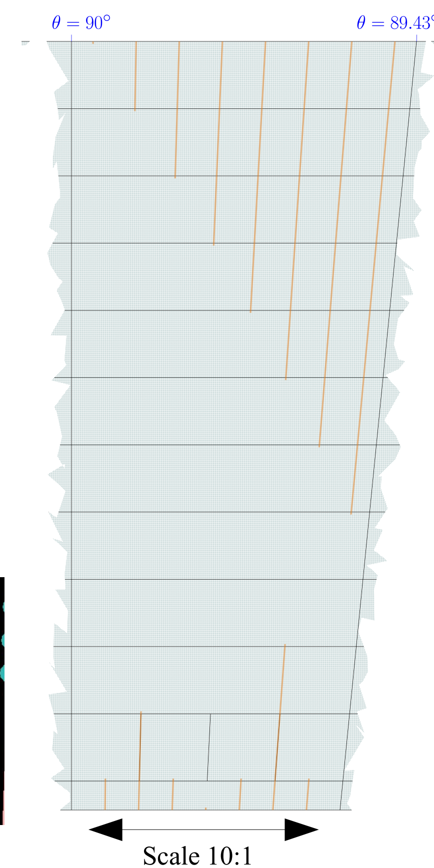
PCB CAD

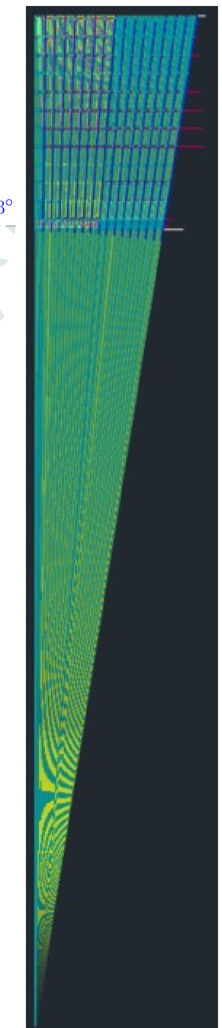
Computer Aided Design with AutoCAD® and Cadence®

- Readout electrode implementation done with the CERN PCB Design office
  - The edges of the tower and the transmission lines point to the interaction point
  - Each tower can be obtained by **rotational symmetries** of the first one + application of a **cutting mask**
    - Structural layout done in AutoCAD, imported in Cadence to place the various components
  - One via per copper trace to distribute the GND and read the signal (will be replaced by connectors for the final design)
  - Signal extracted from front until layer 4, then from the back
    - Constant spacing between traces (can be optimized)
  - 16 'theta' towers (maximum allowed for 'standard' dimensions)
    - Different layout per tower (see back-up)
      - Number of shield, shield width, …
    - Allows us to study several effects with a single prototype (cost effective)



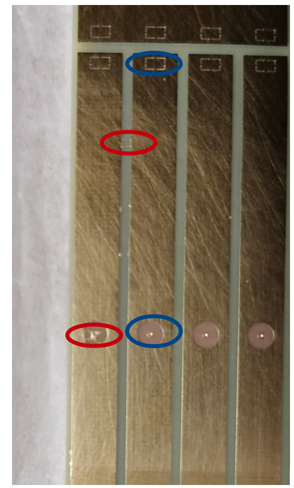
Top edge of the PCB

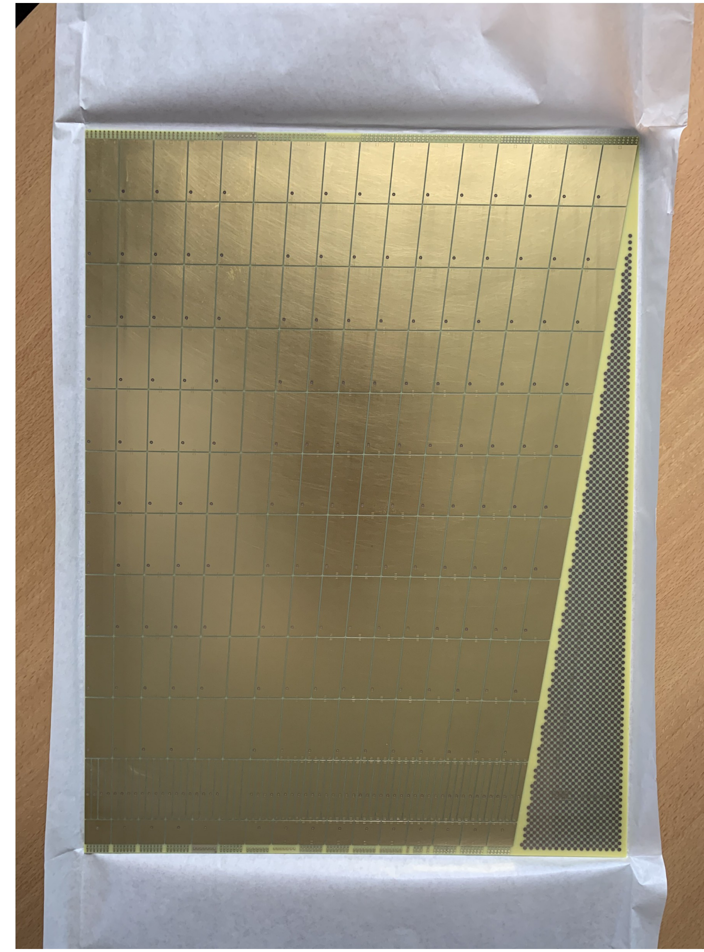


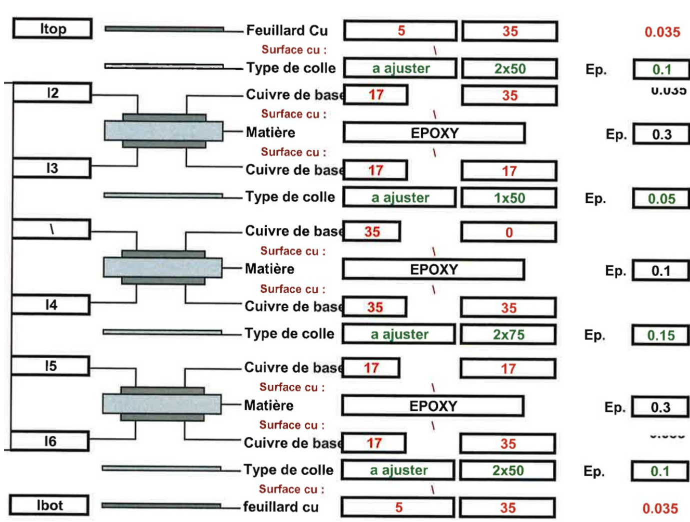


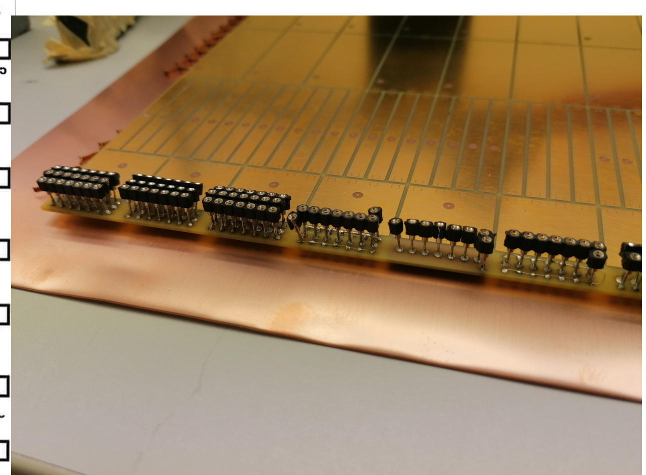
Electrode Prototype

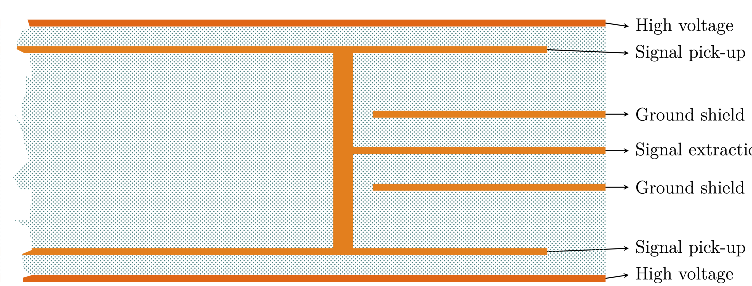
- Readout electrode prototype
  - 7-layer PCB, 1:1 scale, 58 cm x 44 cm x 1.2 mm
  - Soldering pads between HV cells (study resistive x-talk), via to allow injection on pick-up plane
  - Few trials to get manufacturing right but no show stopper for a mass production
    - Visual inspection showed spurious short-cuts → easily removed with a scalpel
  - No connectors (needed something custom) → solder ourselves SIL pins on the vias







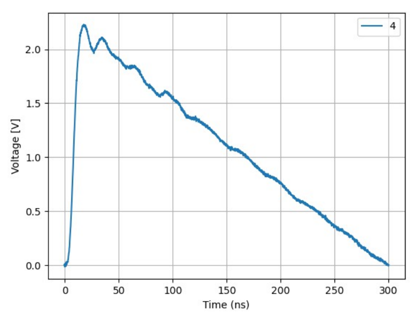


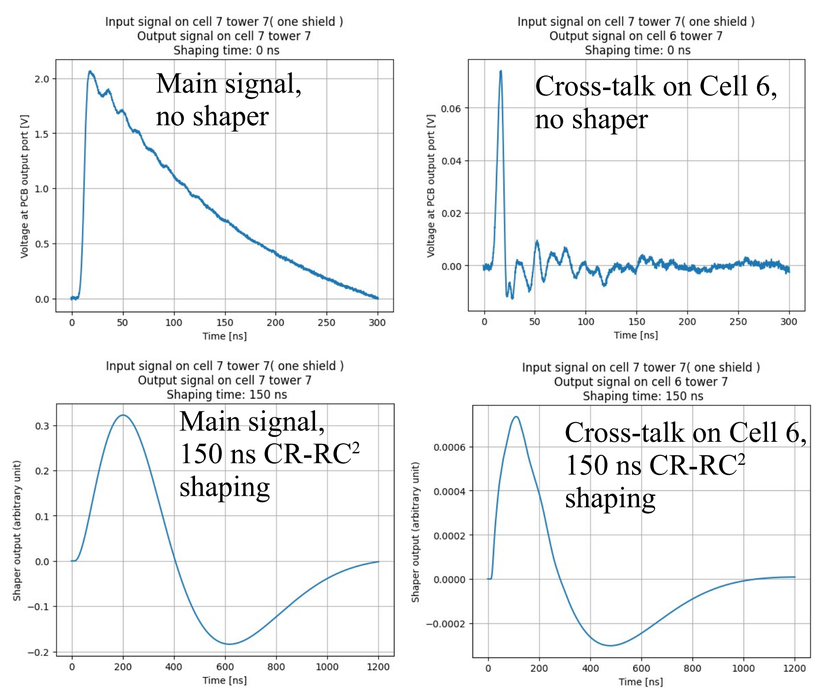


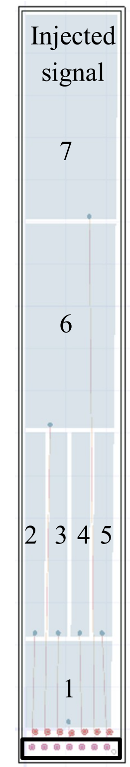
X-talk Measurement Results

- Example of measurements with **1 ground shield**
  - Signal injected on Cell 7, all inner channels read out → signal attenuation and x-talk
    - Peak-to-peak raw signal attenuation: 4%
    - X-talk discussed in next slide
  - Some reflections observed
    - Mostly wiped out by the shaping (except for tiny signals)

Input signal bypassing the PCB (probe on probe)



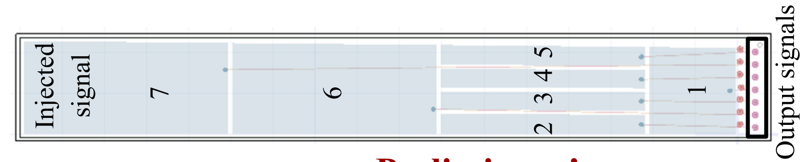




Output signals

X-talk: simulation VS measurement

Comprehensive x-talk measurements with 2, 1 and 0 shields



Preliminary!

Observations from meas.

- Good qualitative behavior
  - Highest x-talk on cell 6
  - The shield mitigate x-talk
  - Cell 4 and 5 show similar values, idem for cell 2 and 3
  - …
- **Confirms that it is easy to get x-talk < 1 %, even without shields!**
- After signal shaping, most of the measured x-talk values are within the same ball-park as the simulated ones
- Quantitative agreement is sometimes poor (especially for small signals or short shaping)

Simulation, 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

Measurement, 2 shields

Cross-talk (%) / Shaping time (ns) ↓	Cell 1	Cell 2	Cell 3	Cell 4	Cell 5	Cell 6
No shaper	1.66	0.69	0.84	0.78	0.5	2.9
20	0.2	0.07	0.08	0.24	0.21	0.61
50	0.08	0.03	0.03	0.1	0.09	0.28
100	0.04	0.02	0.01	0.06	0.05	0.2
150	0.04	0.02	0.01	0.04	0.04	0.17
200	0.03	0.03	0.01	0.04	0.03	0.15
300	0.02	0.03	0.01	0.03	0.03	0.14

Simulation, 1 shield

Cross-talk (%) / Shaping time (ns) ↓	Cell 1	Cell 2	Cell 3	Cell 4	Cell 5	Cell 6
No shaper	2.42	0.82	0.87	3.86	4.14	10.36
20	0.4	0.05	0.04	0.58	0.58	1.72
50	0.18	0.02	0.01	0.26	0.26	0.79
100	0.1	0.01	0.0	0.14	0.14	0.45
150	0.07	0.01	0.0	0.11	0.11	0.34
200	0.06	0.0	0.0	0.09	0.09	0.28
300	0.05	0.0	0.0	0.07	0.07	0.23

Measurement, 1 shield

Cross-talk (%) / Shaping time (ns) ↓	Cell 1	Cell 2	Cell 3	Cell 4	Cell 5	Cell 6
No shaper	2.91	1.36	1.5	2.16	1.98	3.59
20	0.62	0.22	0.28	0.52	0.46	0.99
50	0.26	0.08	0.11	0.23	0.2	0.43
100	0.19	0.08	0.09	0.14	0.14	0.27
150	0.17	0.07	0.08	0.12	0.12	0.23
200	0.15	0.08	0.08	0.11	0.11	0.2
300	0.17	0.09	0.09	0.1	0.12	0.16

Simulation, 0 shield

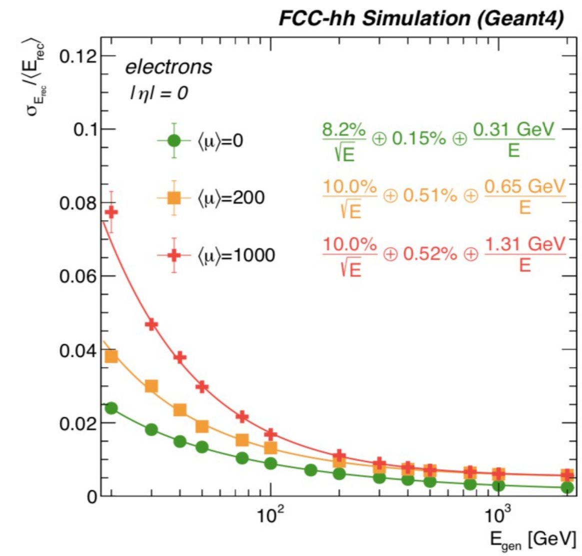
Cross-talk (%) / Shaping time (ns) ↓	Cell 1	Cell 2	Cell 3	Cell 4	Cell 5	Cell 6
No shaper	6.27	2.6	3.2	8.75	8.61	15.96
20	0.7	0.1	0.1	0.99	0.92	2.58
50	0.3	0.02	0.02	0.43	0.4	1.14
100	0.17	0.01	0.01	0.24	0.23	0.64
150	0.13	0.01	0.0	0.18	0.17	0.48
200	0.1	0.01	0.0	0.15	0.14	0.4
300	0.08	0.0	0.0	0.12	0.11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

Measurement, 0 shield

Cross-talk (%) / Shaping time (ns) ↓	Cell 1	Cell 2	Cell 3	Cell 4	Cell 5	Cell 6
No shaper	3.41	1.35	1.73	2.96	2.79	5.36
20	0.87	0.3	0.45	0.79	0.73	1.49
50	0.36	0.11	0.19	0.35	0.32	0.65
100	0.2	0.05	0.13	0.21	0.19	0.39
150	0.17	0.04	0.11	0.17	0.16	0.32
200	0.14	0.04	0.1	0.14	0.14	0.28
300	0.11	0.03	0.1	0.12	0.12	0.23

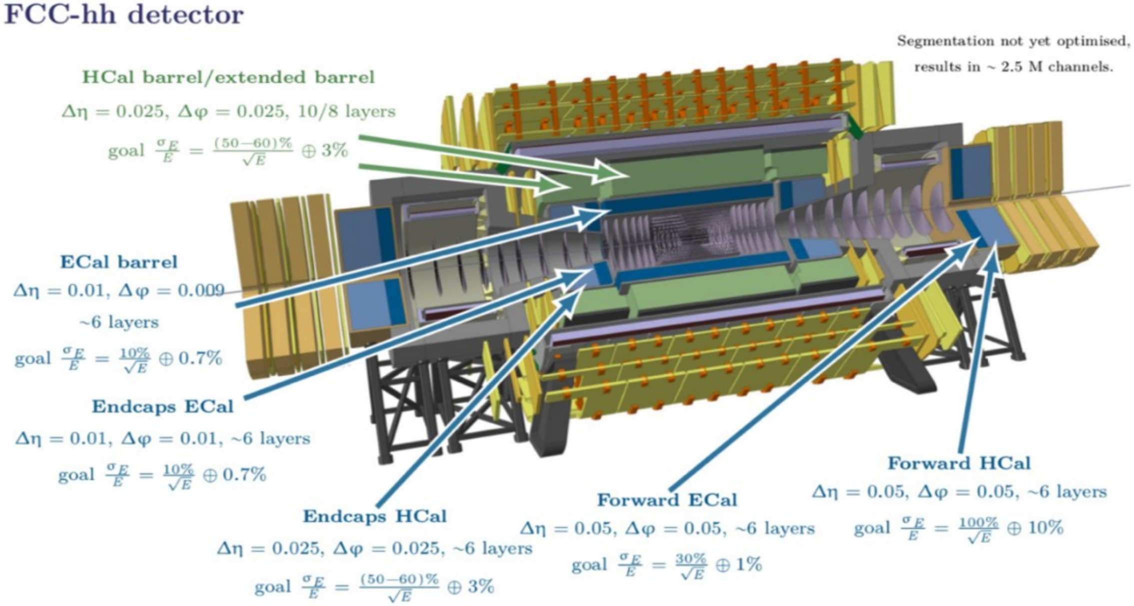
FCC-hh calorimeter

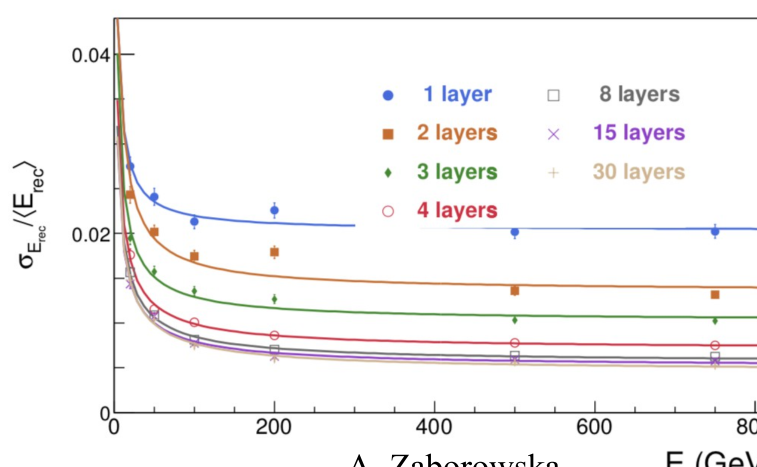
- FCC-hh reference calorimeter inspired by ATLAS Calo and CMS HGCal
  - ECAL, Hadronic Endcap and Forward Calo: LAr/Pb (Cu)
    - Conventional high precision calorimetry made highly granular to allow for 4D imaging and particle flow
    - Barrel ECAL
      - Δη=0.01 (0.0025 strip layer), ΔΦ=0.009, 8 longitudinal layers
      - Meets energy resolution requirements (10%/√E + 0.7%)
  - HCAL Barrel and Extended Barrel: Scintillating tiles/Fe(+Pb) with SiPM
    - Lower radiation behind ECAL barrel, lower cost



CERN-FCC-PHYS-2019-0003

FCC-hh detector





A. Zaborowska

FCC-hh Calorimeter Performance

- Excellent jet energy resolution (30%/√E) needed to separate W and Z decays
  - Already close !
    - 37%/√E achieved for pions in FCC-hh simulations with calo-only information
    - Particle Flow will be used for a more realistic estimation (and will improve)
- Angular resolution

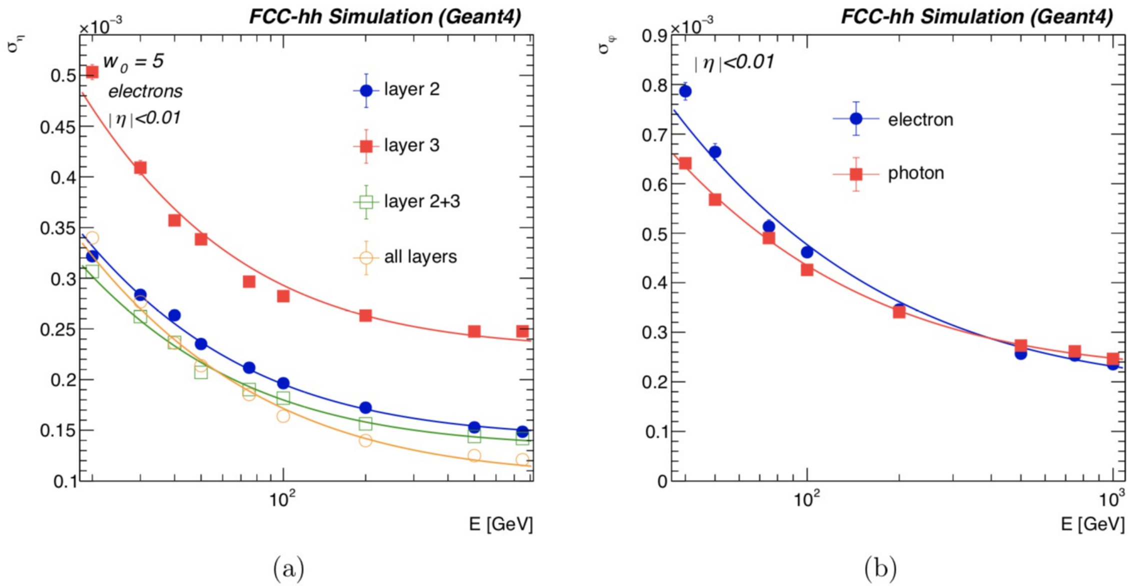
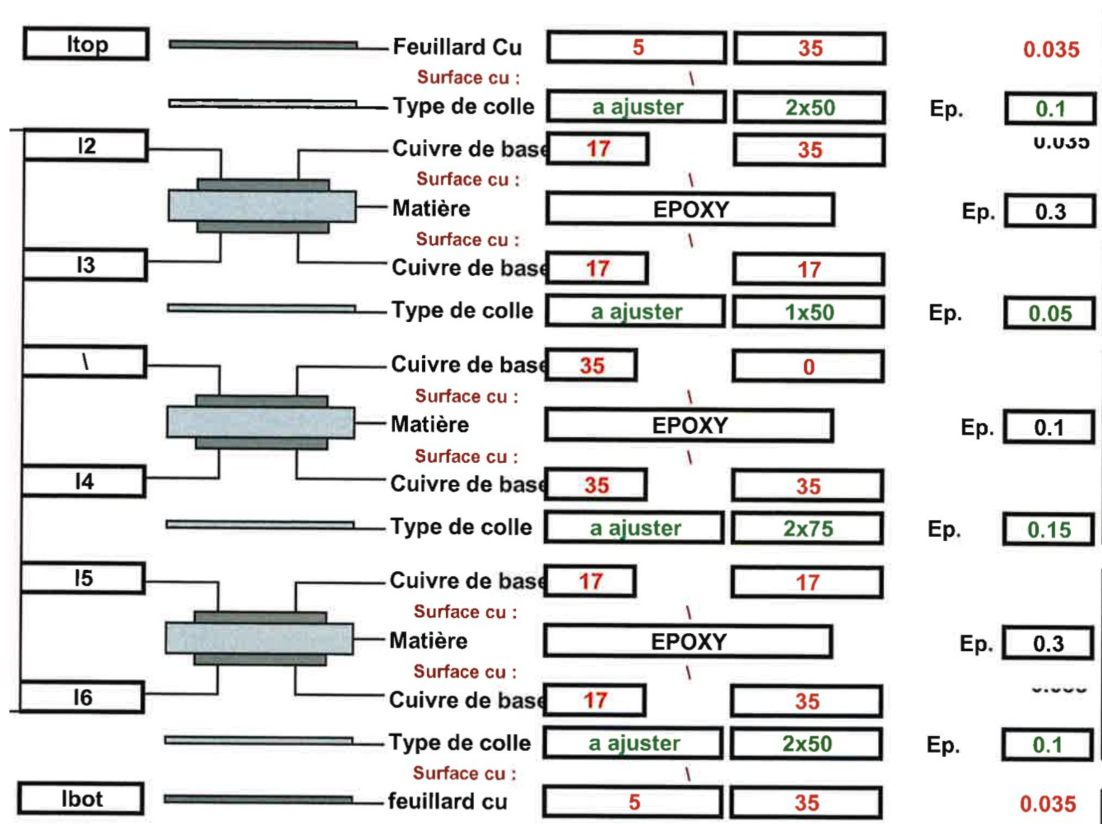


Figure 51: (a) Pseudorapidity resolution for two best calorimeter layers: second (red full circles) and third (blue full squares), as well as combined measurements of those two layers (green hollow squares) and from all EMB layers (yellow hollow circles). (b) Azimuthal angle resolution for electrons (blue circles) and photons (red squares).

Odd number of layer PCB



Noble Liquid/Absorber study

Absorber	Liquid	Gap size [mm]	Absorber size [mm]	Phi bins	Radial extend [mm]	Radial length 22 X0 [mm]
Pb	LAr	1.239 * 2	1.8	1536, 768, 512, 384, 256	400	
	LAr	3.079 * 2	3.8	768	400	
	LKr	1.239 * 2	1.8	768	400	~337.5
W	LKr	1.239 * 2	1.8	768	~207.5	
	LAr	2.156 * 2	1.8	576	~323.9	
none	LKr (homo)	~4.2	0.001	768	~1034	
	LXe (homo)	~4.2	0.001	768	~647.5	

	Avg sampling fraction
Pb + LAr baseline	0.17
Pb + LKr	0.23
Pb + LAr double	0.17
W + LKr	0.15
W + LAr	0.16
LKr	0.97
LXe	0.97

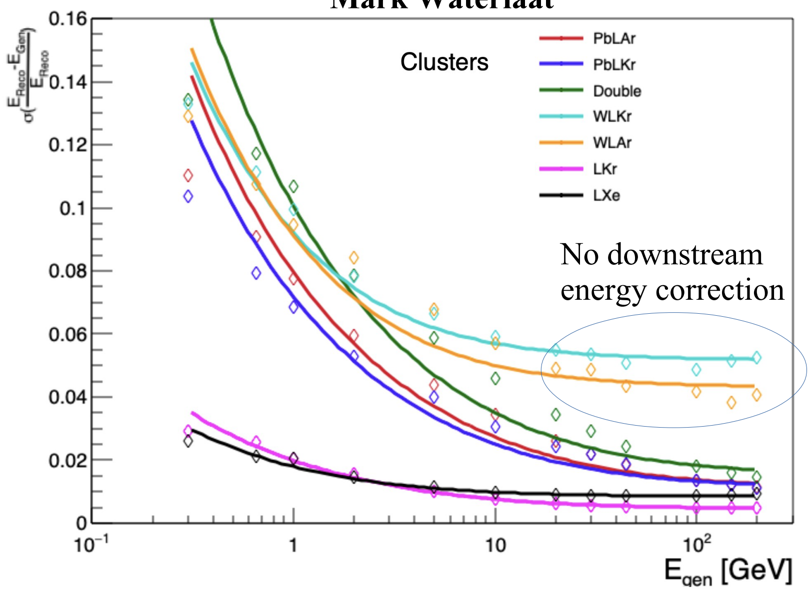
Clusters

	A/E	B/sqrt(E)	C
Pb + LAr	0	0.079	0.011
Pb + LKr	0	0.071	0.011
Double	0	0.099	0.015
W + LKr	0	0.075	0.052
W + LAr	0	0.086	0.041
LKr	0	0.019	0.005
LXe	0	0.016	0.008

Cells

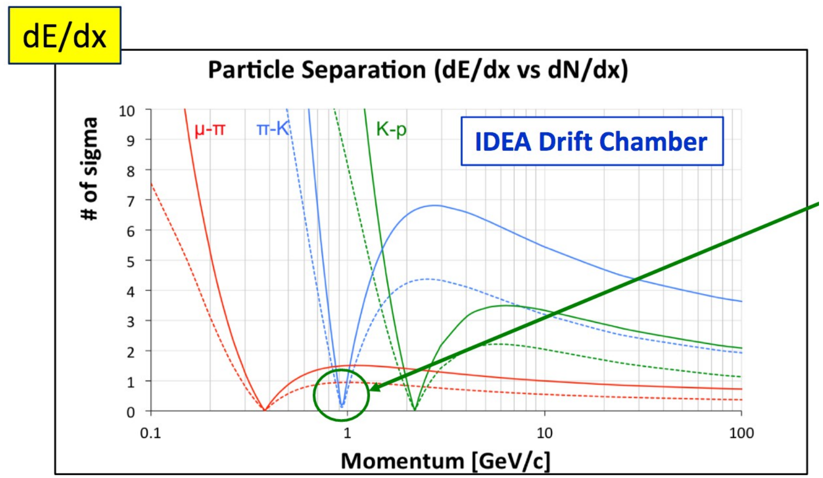
	A/E	B/sqrt(E)	C
Pb + LAr	0	0.077	0.021
Pb + LKr	0	0.070	0.050
Double	0	0.098	0.027
W + LKr	0	0.083	0.050
W + LAr	0	0.085	0.041
LKr	0.004	0	0.008
LXe	0	0.007	0.010

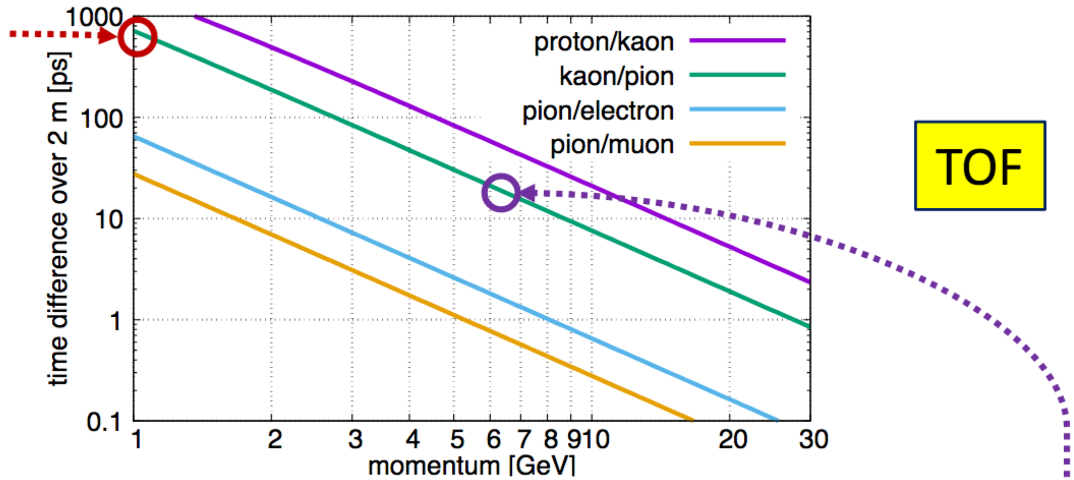
Mark Waterlaat



Particle ID

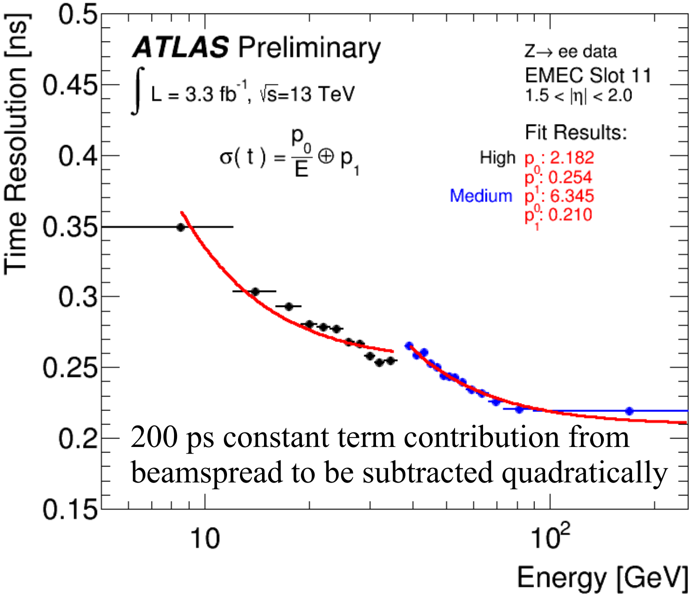
- dE/dx or dN/dx performs very well for particle ID, except in a few points where timing could help (low energy)





Timing

- Timing will play an important role in future colliders (PU removal, particle identification, heavy stable charged particles, …)
- Time resolution achieved by ATLAS
  - ~260 ps for EM showers ≥ 20 GeV, ~130 ps for EM showers ≥ 100 GeV
- **Time resolution needs to be evaluated and optimized with the new designs (and full readout chain)**
  - Depends on the shaping time
    - Which will mainly be driven by noise considerations for lepton colliders
  - Limitations: time-walk, stochastic ionization, cell inter-calibration
  - To be considered with the big (detector) picture in mind
    - Jitter from external sources
    - Do we have dedicated timing layers or not?
    - Do we have dE/dx or dN/dx for particle ID?



FCC-ee CLD calorimeter

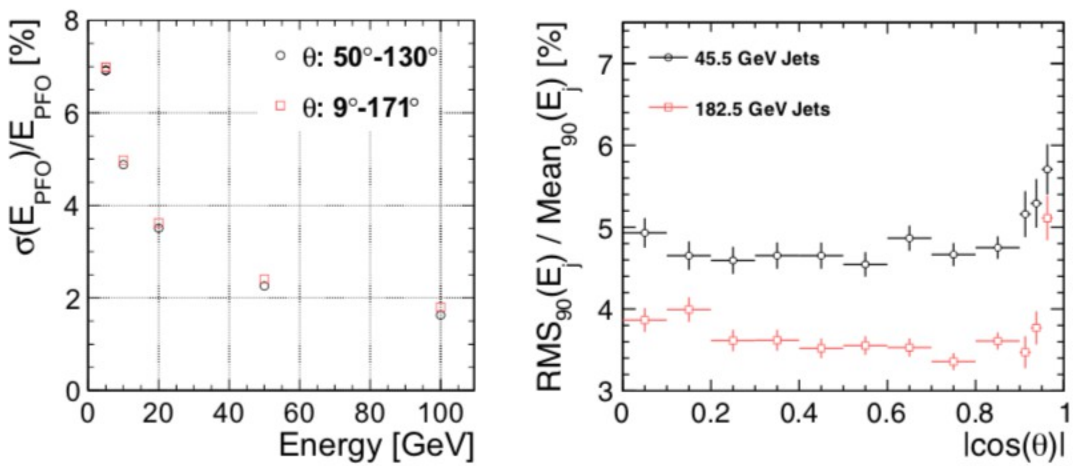


Fig. 7.8. CLD calorimeter performance. Photon energy resolution as a function of energy (left), comparing the barrel region with the full detector acceptance. Jet energy resolution for light quark jets as a function of polar angle (right).

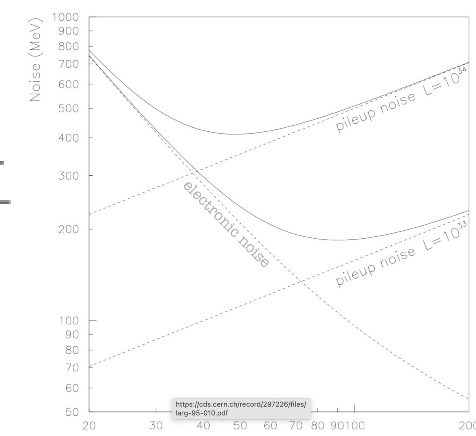
Table 16: W- and Z-boson mass peak resolution and separation power calculated with different values of R of the VLC jet clustering algorithm. The energy of the bosons is 125 GeV.

background overlay	R	$\sigma_{m(W)}/m(W)$ [%]	$\sigma_{m(Z)}/m(Z)$ [%]	Separation [σ]	Separation (fixed mean) [σ]
no BG	0.7	5.94	5.75	2.19	2.16
with BG	0.7	5.95	5.90	2.13	2.13
no BG	0.9	5.26	5.11	2.46	2.43
with BG	0.9	5.18	5.19	2.43	2.43
no BG	1.1	4.99	4.94	2.58	2.54
with BG	1.1	5.36	4.96	2.50	2.45

Noise for Charge Preamp & CR²-RC²

- **Series noise:** Case of charge preamp and CR²-RC² shaper
  - ideal transmission line of length *L* with $t_d = L/v$ the line delay
    - no attenuation, no skin effect, but these effects are small (negligible) at cryogenic temperatures
  - charge preamplifier, CR²-RC² shaper (different to ATLAS LAr!),
  - see NIM A330 (1993) 228-242
- **Similar procedure for parallel noise** (not shown here)

$$V_n^2 = \int_0^\infty \frac{e_n^2}{|R_0 + Z|^2} \frac{1}{\omega^2 C_f^2} |H(i\omega)|^2 \frac{\mathrm{d}\omega}{2\pi}$$



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$$V_n^2 = \int_0^\infty \frac{e_n^2}{|R_0 + Z|^2} \frac{1}{\omega^2 C_f^2} |H(i\omega)|^2 \frac{\mathrm{d}\omega}{2\pi} \quad \text{with} \quad Z = \frac{iR_0 \tan(\omega t_d) - \frac{i}{\omega C_d}}{\frac{\tan(\omega t_d)}{R_0 \omega C_d} + 1}$$

$$V_n^2 = \frac{\tau^4 C_d^2 e_n^2}{2\pi \tau_p^2 C_F^2} \int_0^\infty \frac{\omega^2 \left(\tau_p \omega \cos(\omega t_d) + \sin(\omega t_d)\right)^2}{\left(\tau^2\omega^2 + 1\right)^4 \left(\tau_p^2 \omega^2 + 1\right)} \mathrm{d}\omega \qquad \tau_p = R_0 C_d$$

- This series noise needs to be normalised to signal response V(x) of unit charge Q_0:
  - either Dirac delta-function $Q_0\delta(t)$,
  - or triangular signal (t_{dr} is the e⁻-drift time): $2Q_0/t_{dr}(1 - t/t_{dr})$

$$\mathrm{ENC} = Q_0 \frac{V_n}{\max|_x(V(x))}$$

Warm electronics: