The Allegro Concept

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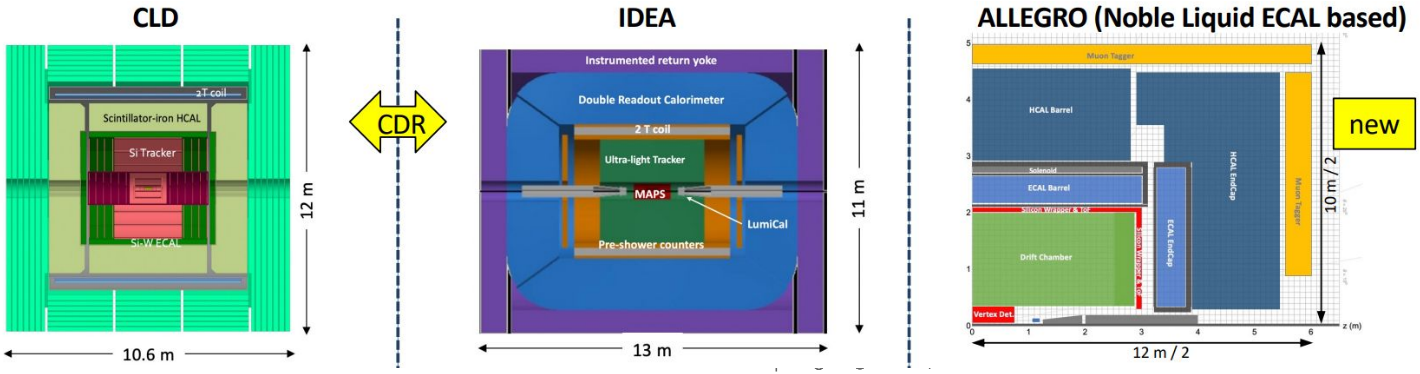
What is Allegro ?

A Noble-Liquid Ecal Based Detector Concept

- Allegro Ecal: Noble liquid calorimeter is a promising solution to fulfil FCC-ee physics requirements
  - Z pole measurements, B and τ physics, Higgs physics
  - From low energy photons to high-energy jets

- Allegro as a detector concept: vision of a high-performance general detector for FCC-ee physics
  - Based on physics requirements and knowledge of performance of proposed sub-detectors
  - Current concept design very open for change
    - **We welcome new ideas !**



FCC-ee physics

Higgs
factory

m_H, σ, Γ_H
self-coupling
H→ bb, cc, ss, gg
H→inv
ee→H
H→bs, ..

Top

m_{top}, Γ_{top}, ttZ, FCNCs

Flavor
"boosted" B/D/τ factory:

CKM matrix
CPV measurements
Charged LFV
Lepton Universality
τ properties (lifetime, BRs..)

$B_c \to \tau \nu$
$B_s \to D_s K/\pi$
$B_s \to K^* \tau \tau$
$B \to K^* \nu \nu$
$B_s \to \varphi \nu \nu$ …

QCD - EWK
most precise SM test

m_Z , Γ_Z , Γ_{inv}

$\sin^2\theta_W$, R^Z_ℓ , R_b, R_c

$A_{FB}^{b,c}$, τ pol.

α_S ,

m_W, Γ_W

BSM
feebly interacting particles

Heavy Neutral Leptons (HNL)

Dark Photons Z_D

Axion Like Particles (ALPs)

Exotic Higgs decays

**Excellent tracking
Jet energy resolution
at high energies**

**Excellent tracking / energy resolution / PID
at low energies**

Small systematics

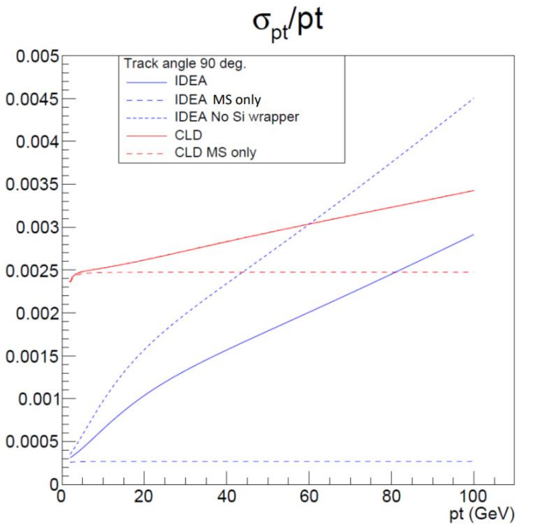
Versatile detector

Detector requirements: tracking performance

- Momentum resolution
  - Avoid large contribution from MS: the lighter, the better
- Flavour tagging: vertex detector
  - Closer to IP
  - Lighter
  - Smaller pixels

$$\sigma(p_\mathrm{T})/p_\mathrm{T}^2 = a \oplus \frac{b}{p\sin\theta}$$

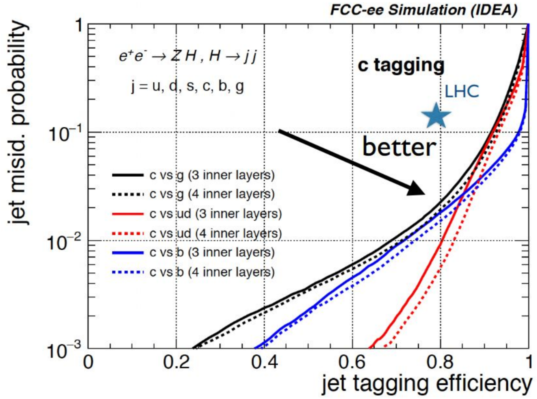
$$\frac{\Delta p_T}{p_T}\Big|_{m.s.} \approx \frac{0.0136\,\mathrm{GeV/c}}{0.3\beta\, B_0 L_0}\sqrt{\frac{d_{tot}}{X_0\,\sin\theta}}$$



$$\sigma_{d_0} = a \oplus \frac{b}{p\sin^{3/2}\theta}$$

$$a \simeq 5\,\mu\mathrm{m}; \quad b \simeq 15\,\mu\mathrm{m\,GeV}$$

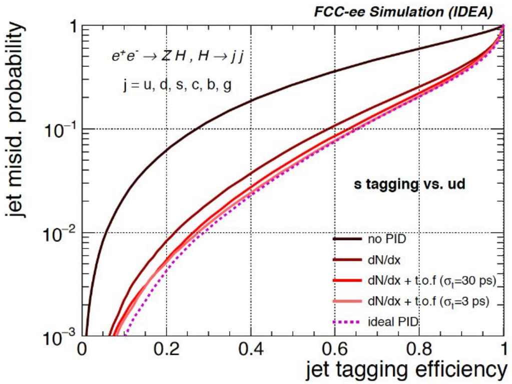
	r beam pipe	1st VTX layer
ILC	12 mm	14 mm
CLIC	29 mm	31 mm
FCC-ee	10 mm	12 mm

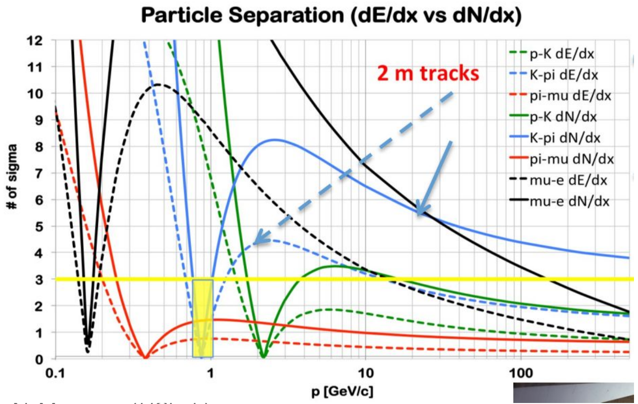


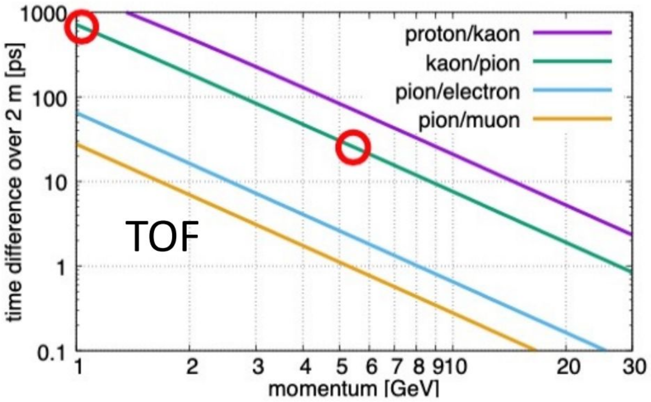
Detector requirements: PID

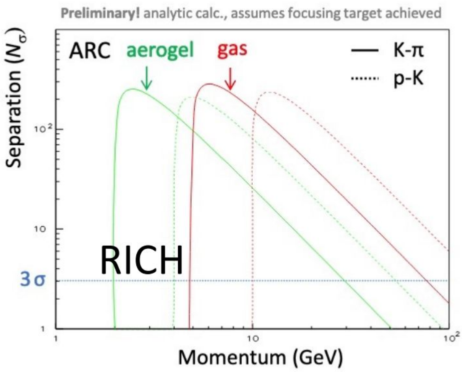
PID capabilities across a wide momentum range is essential: flavour physics, H→ss…

- Drift chamber: dE/dx or cluster counting
  - 3σ for K/π separation up to 100 GeV
  - Can be complemented with simple TOF for hole at 1 GeV
- Time-Of-Flight: ~10 ps resolution over 2m (LGAD, TORCH)
  - 3σ for K/π up to ~5 GeV
- RICH counters (ARC)
  - 3σ for K/π in 5 – 80 GeV range





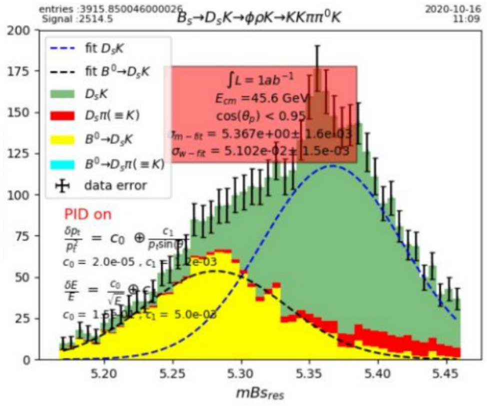


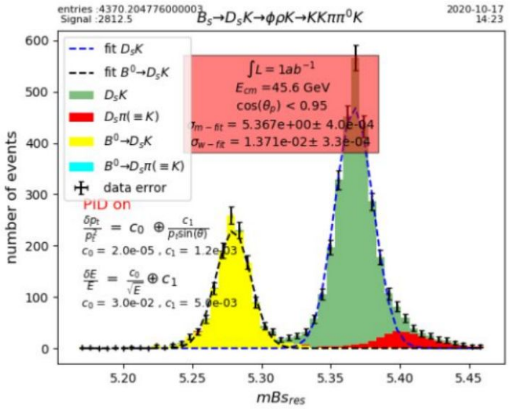


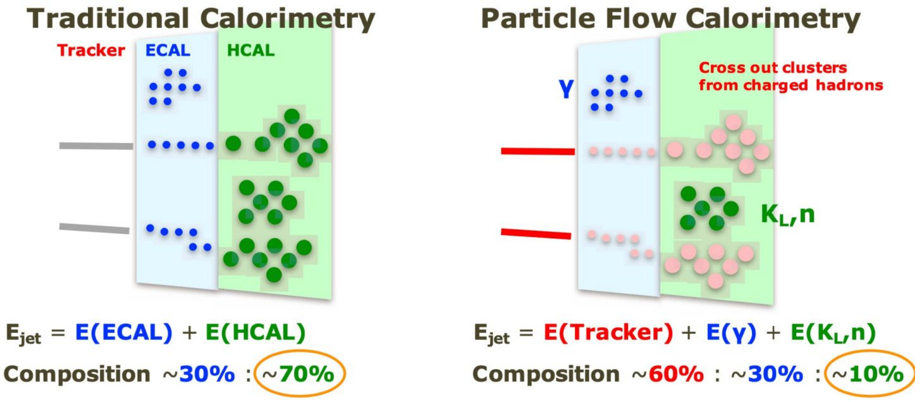
Detector requirements: Calorimetry

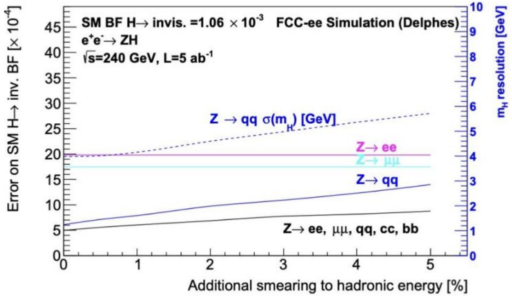
- EM objects
  - PID $e/\gamma/\pi^0$, esp. at low energy
    $\Rightarrow$ Granularity
  - High energy resolution

- Jets
  - Target: $\sigma(E)/E = 30\%/\sqrt{E}$ (GeV)
    - Typical figure of merit: W/Z boson separation
    - Actual use: variety of hadronic measurements
  - Requires high granularity to maximally use PFlow reconstruction
  - Dual Readout as additional handle









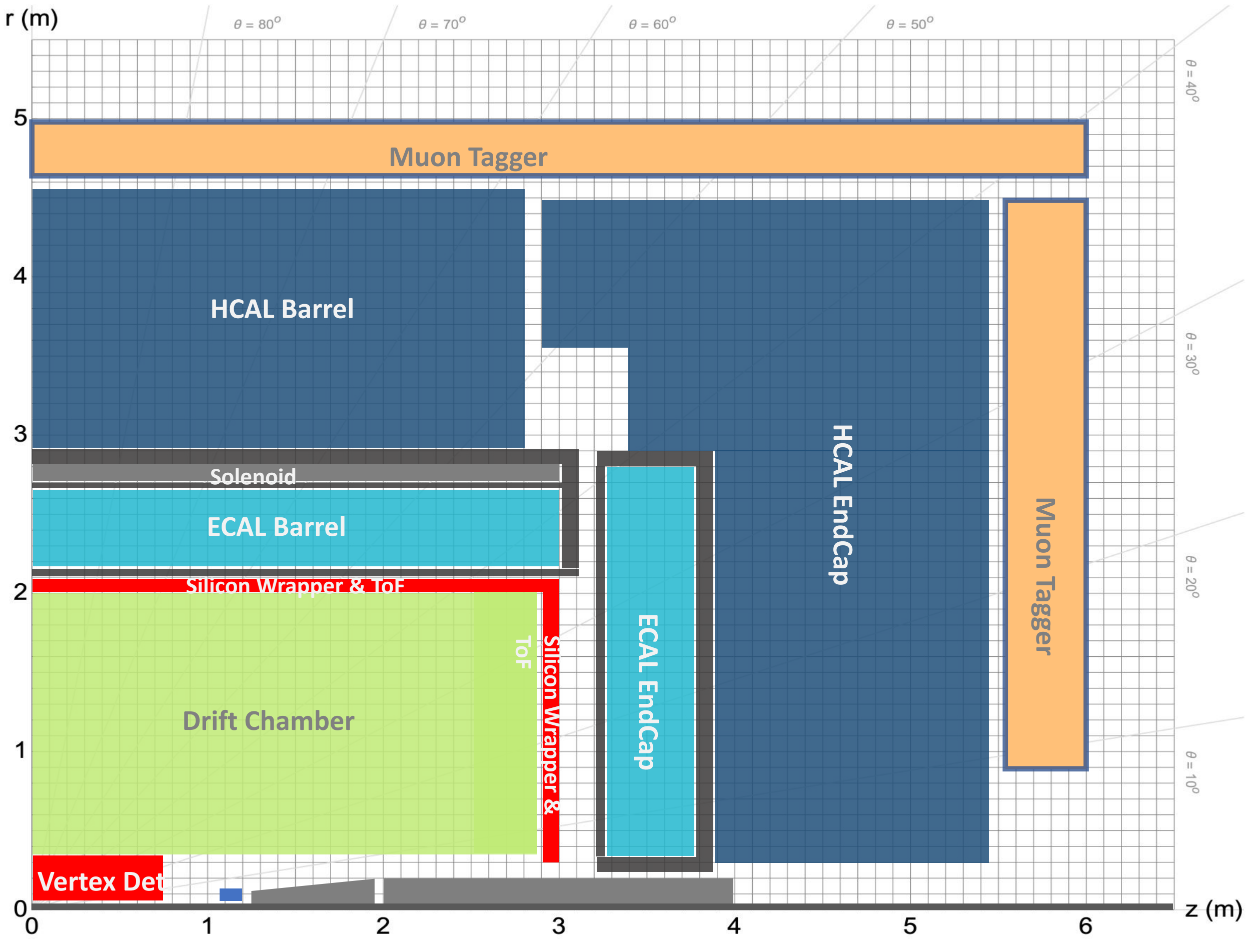
Calorimetry options

Many options on the table, for both Ecal and Hcal

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]	≈ 6 % ?	4 % [20]
Highly granular Noble liquid based ECAL & Scintillator based HCAL	8 – 10 % [24,27,46]	< 1 % [24,27,47]	≈ 40 % [27,28]	≈ 6 % ?	3 – 4 % ?
Dual-readout Fibre calorimeter	11 % [48]	< 1 % [48]	≈ 30 % [48]	4 – 5 % [49]	3 – 4 % ?
Hybrid crystal and Dual-readout calorimeter	3 % [30]	< 1 % [30]	≈ 26 % [30]	5 – 6 % [30,50]	3 – 4 % [50]

- All options feature good jet energy resolution
- Varying Ecal resolution ⇒ Highest EM resol required for B physics
- Varying segmentation: PFlow, shower shapes, cluster pointing
- Other characteristics: Operational stability, cost

Allegro detector concept



ALLEGRO

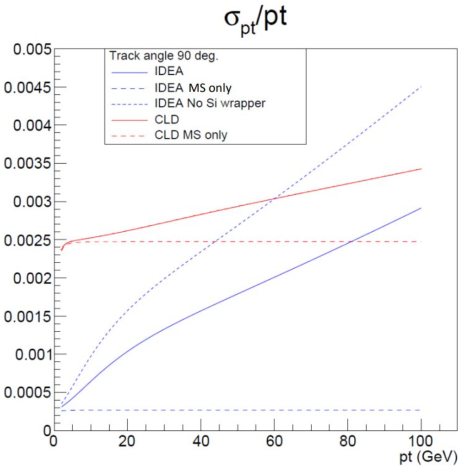
A Lepton co**L**lider **E**xperiment with **G**ranular **R**ead-**O**ut

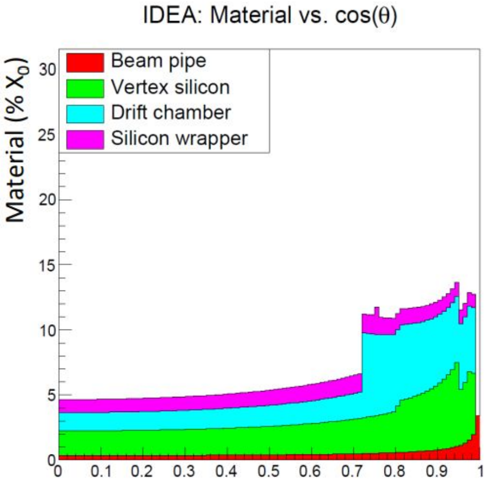
- **Vertex Detector**:
  - MAPS or DMAPS possibly with timing layer (LGAD)
  - Possibly ALICE 3 like?
- **Drift Chamber** (±2.5m active)
- **Silicon Wrapper + ToF**:
  - MAPS or DMAPS possibly with timing layer (LGAD)
- **Solenoid B=2T**, sharing cryostat with ECAL, outside ECAL
- **High Granularity ECAL**:
  - Noble liquid + Pb or W
- **High Granularity HCAL** / Iron Yoke:
  - Scintillator + Iron
    - SiPMs directly on Scintillator or
    - TileCal: WS fibres, SiPMs outside
- **Muon Tagger**:
  - Drift chambers, RPC, MicroMegas

Vertex detector and momentum measurement

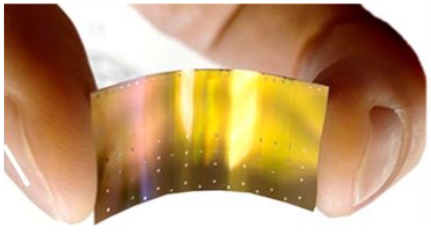
Transparency key for high resolution

- Light vertex detector and tracker
  - Particle energies < 100 GeV: lower MS contribution required
- Vertex detector: MAPS-based
  - Similar to e.g Belle 2 or ALICE ITS3
  - Typically: 5 layers, 33 x 33 μm^2 pixels
  - Extremely light: Inner layers: 0.1% X_0 / layer
  - Outer layers: 0.5 – 1% X_0 / layer
  - IP resolution ~10 μm





No cabling, no piping in the active area



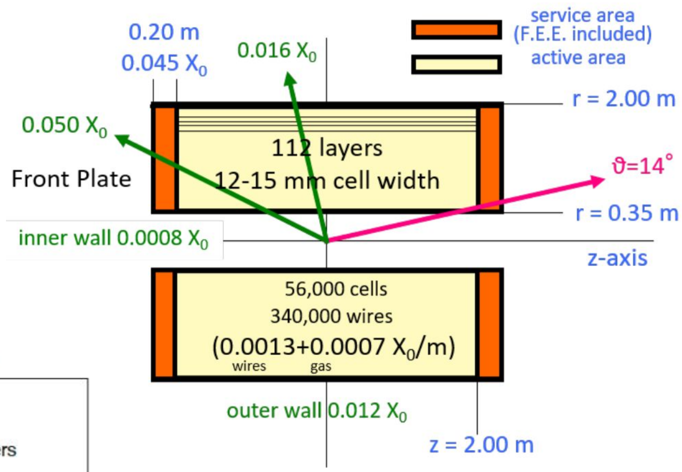
Curved MAPS sensor

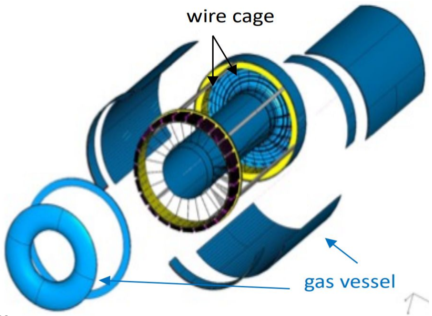
Drift chamber: IDEA design

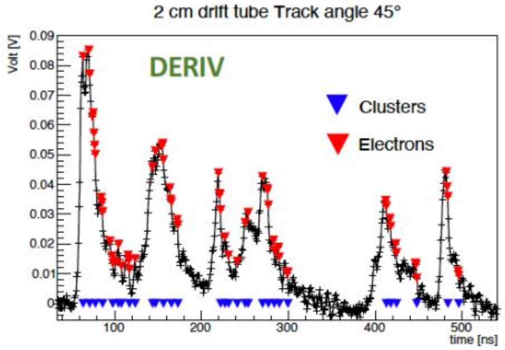
IDEA: Extremely transparent Drift Chamber

- Large volume:
  - Rin = 0.35 m, Rout = 2 m, L = 4 m
- Operating gas: He 90% - iC_4H_{10} 10%
- Full stereo:
  - 112 co-axial layers, at alternating-sign stereo angles ranging from 50 to 250 mrad
  - **Allegro**: Longer DC ⇒ fewer layers
    - **Careful optimisation needed**
- Expected resolution $\sigma_{xy} < 100$ μm, $\sigma_z < 1$ mm
- Cluster counting for PID

tracking efficiency ε ≈ 1 for ϑ > 14° (260 mrad) 97% solid angle	0.016 X_0 to barrel calorimeter 0.050 X_0 to end-cap calorimeter







δ_{cl} = 12./cm for He/iC_4H_{10}=90/10 and a 2m track → **σ ≈ 2.0%**

$$\frac{\sigma_{dN_{cl}/dx}}{(dN_{cl}/dx)} = (\delta_{cl} \cdot L_{track})^{-1/2} = N_{cl}^{-1/2}$$

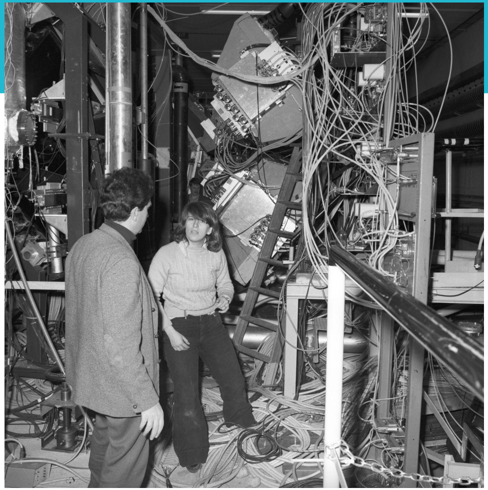
Poisson

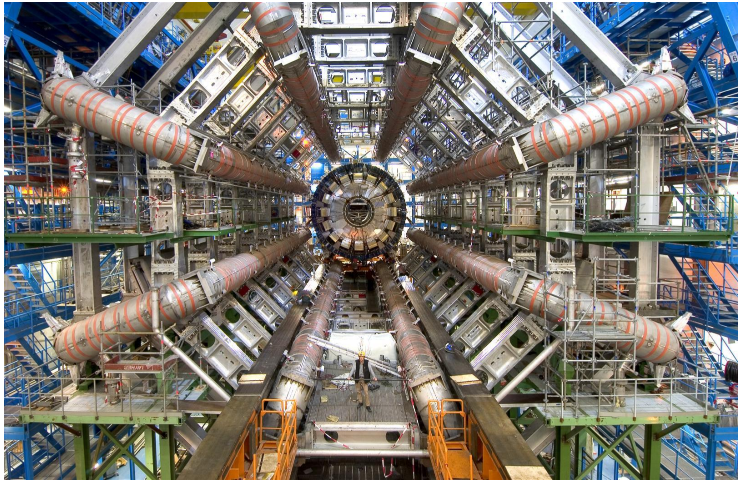
Noble liquid based Ecal

- 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
  - Easy to calibrate

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



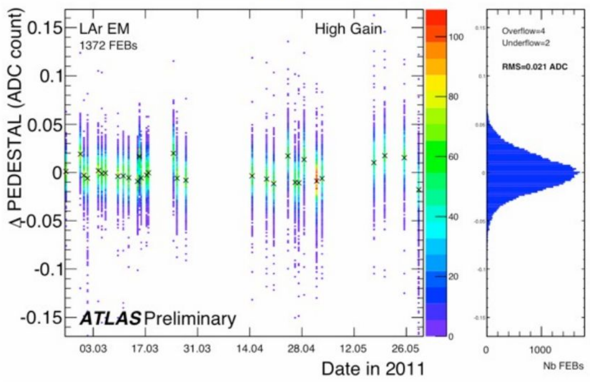


Example: Stability of ATLAS LAr Energy Scale

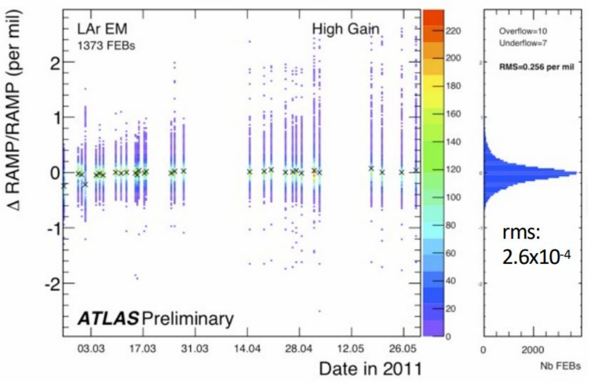
Noble-liquid calorimetry: High intrinsic stability

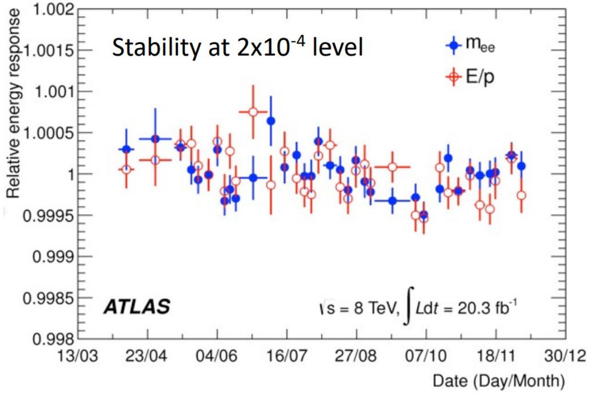
- Pedestal stability < 100 keV
- Gain stability 2.6×10^{-4}
- Parameters monitored in daily calibration runs
  - Changes in constants needed only about 1 / month
- ➢ Stability of the energy scale of 2×10^{-4}
  - Visible on Z→ee invariant mass and E/p

Pedestal (P) stability



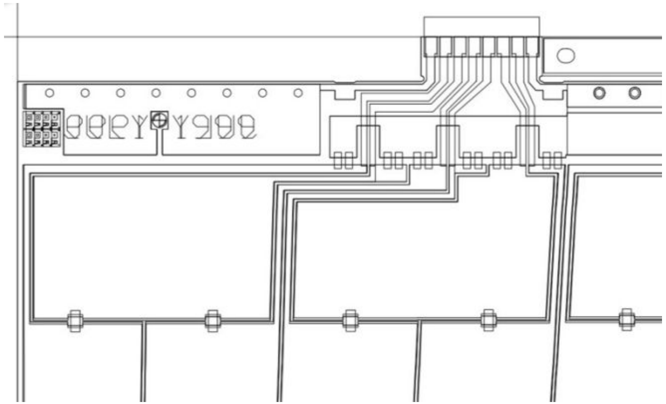
Gain (R) stability





Granularity of Noble Liquid Calorimeters

- Calorimeter design:
  - Granularity of the calorimeter
    ⇔ granularity of the electrodes
- ATLAS: copper/kapton electrode
  - Traces to read out middle cells take real estate on back layer
  - Cannot really increase granularity
- FCC-ee requirements
  - High jet energy resolution needed
  - Particle flow algorithms take advantage of much finer granularity
- **Solution for Noble Liquid calo for FCC**
  - Multi-layer PCB to route signals inside



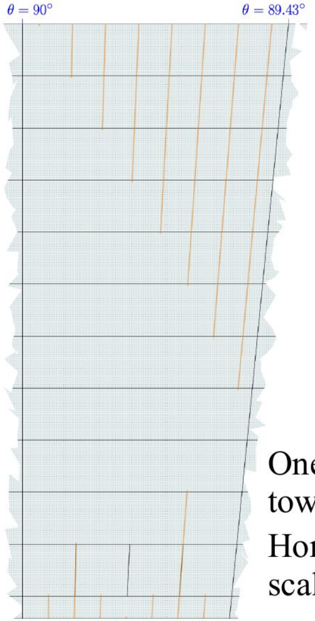
How to achieve high granularity ?

Aiming for ~ ×10 ATLAS granularity

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

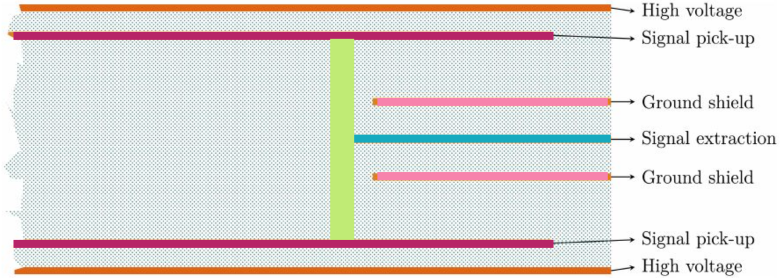
Implementation: multi-layer PCBs

- 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



Allegro Barrel Design

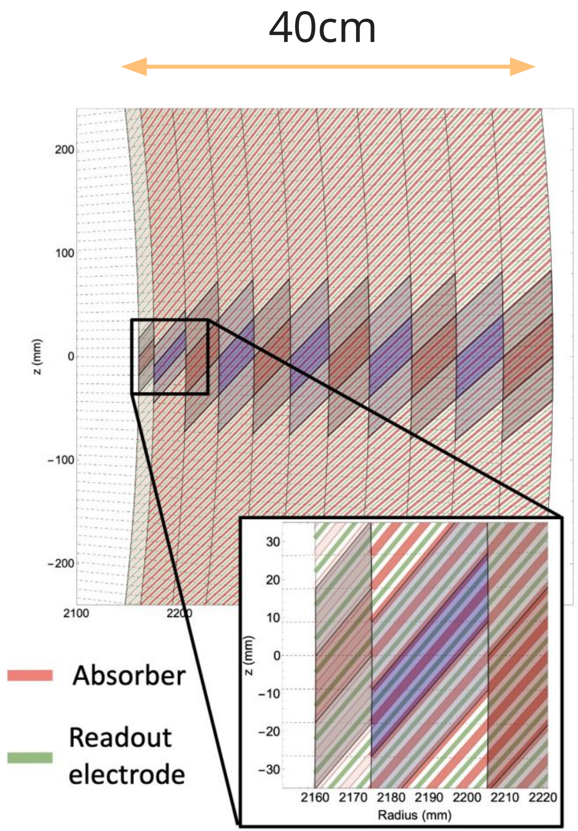
Design driven by the solution used for electrodes

- 1536 **straight inclined** (50°) 1.8mm **Pb** absorber plates
- Multi-layer PCBs as readout electrodes
- 1.2 – 2.4mm **LAr** gaps (**LKr** seriously considered)
- 40cm deep (22 X_0)
- $\Delta\theta$ = 10 (2.5) mrad for regular (strip) cells, $\Delta\phi$ = 8 mrad, 11 longitudinal layers

Copper electrodes: lots of flexibility

- Number of layers and granularity of layers fully optimizable
- Projective cells

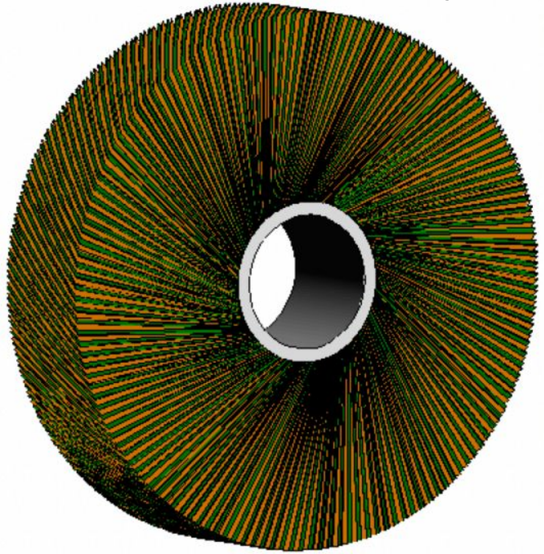
➢ Lots of room for optimisation !



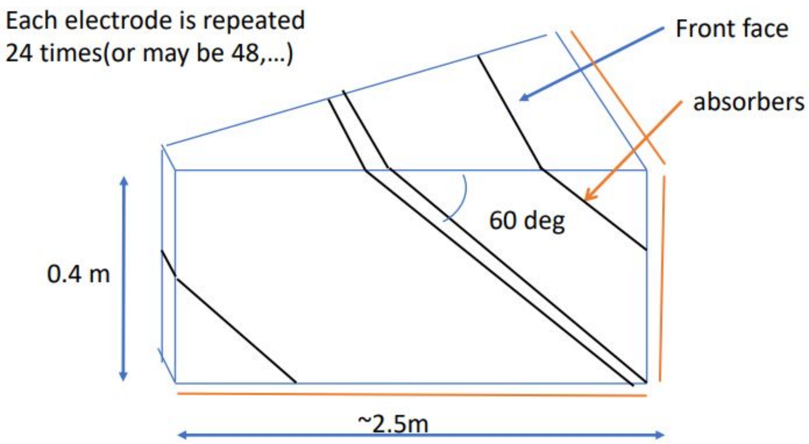
Designs for the endcaps: first ideas

Endcaps designs more complex than that of the barrel: very preliminary ideas !

- “Turbine” design
  - More similar to barrel design
  - Symmetric in ϕ
  - Issue: increase in the size of the Noble liquid gaps
  - Need to stack several cylinders



- XY / Pie wedge designs
  - Less symmetry in ϕ
  - Increase of LAr gaps under control
  - Many types of electrodes to draw and produce

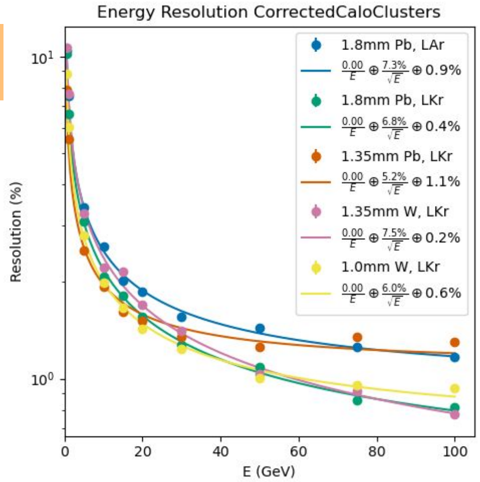


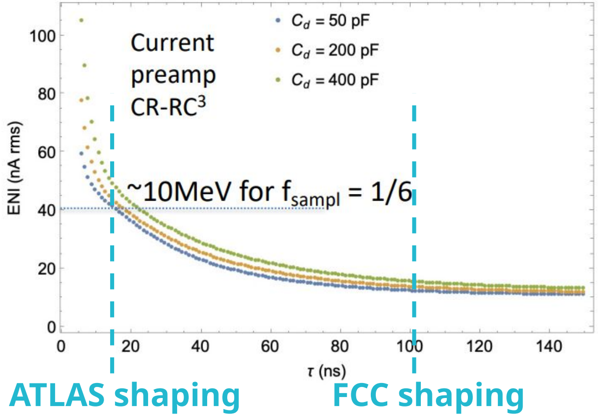
Energy resolution: design options and noise

Energy resolution: σ(E)/E = a/E + b/√E + c ⇒ 3 terms to optimise !

- Constant term
  - Hermeticity, low dead material, uniformity
- Sampling term: improve sampling fraction
  - Optimise gap size, sampling fraction, active and passive material
  - Explore LAr ⇒ LKr, Pb ⇒ W
    - between 5% and 7.5%
- Noise term: readout electronics
  - Want: measurement of 200 MeV photons, S/N>5 for MIPs
  - Longer shaping time wrt ATLAS (200 ns) helps a lot
  - Cold frontend electronics in the cryostat would provide noiseless readout

$$N \sim C_d \sqrt{\frac{4kT}{g_m \tau_p}}$$

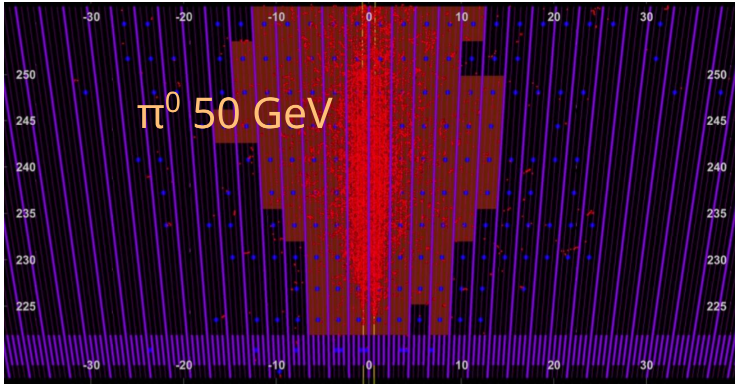


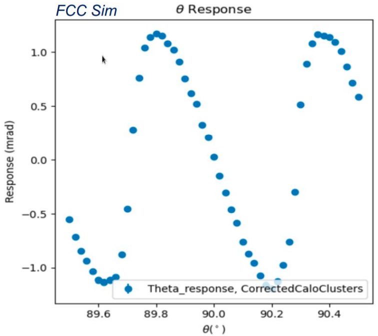


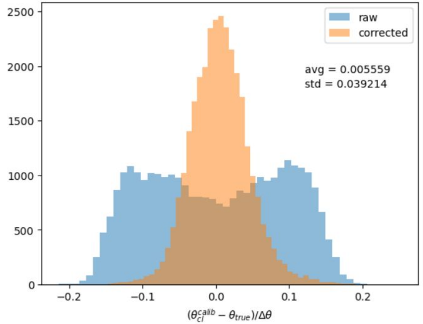
PID/PFlow: granularity optimisation

2023: important groundwork. ⇒ 2024: granularity optimisation studies possible

- Flexible geometry implemented in Full sim
  - Can study EM shower shapes
  - Benchmark: photon / π^0 separation
  - Ongoing: implementation of cross-talk effects
- Calibrations of reconstruction
  - Simple MVA energy regression of EM clusters
  - Cluster position calibration per layer
    - Allows pointing studies (⇒ ALPs)
- Particle Flow on its way
  - Using Pandora toolbox
  - For technical reasons, pioneered in detector sim with Allegro Ecal + CLD Tracker
  - Hope for first results in 2024 !

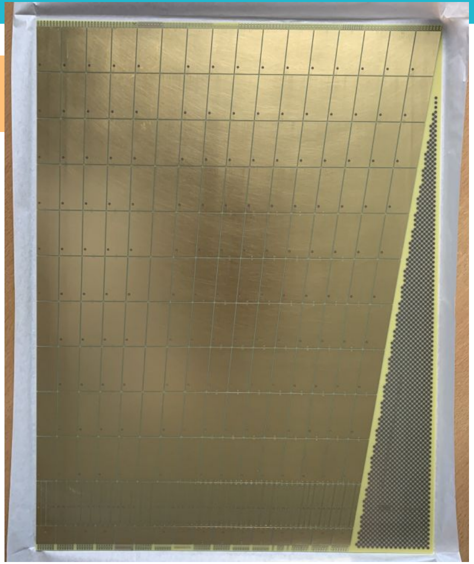






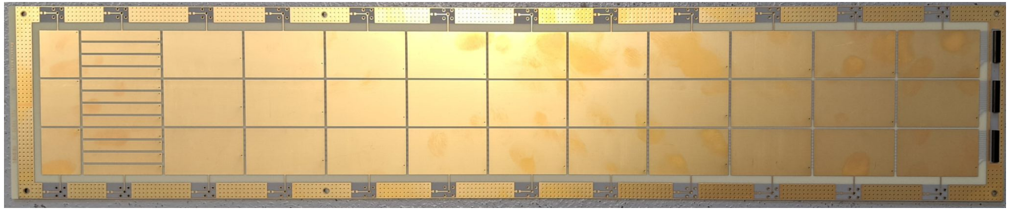
Electrodes prototypes

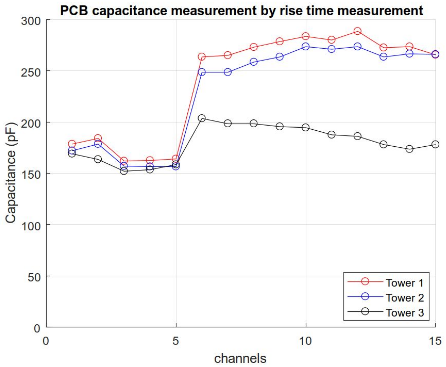
Explore tradeoffs: max granularity / capacitance (noise) / cross-talk



- First large-scale prototype at CERN
  - Explore many options for grounding, for shields
  - First layers readout at the front
  - Few per-mille cross-talk achievable with long shaping

- Next prototype at IJCLab
  - All layers readout at the back
    - Best for material budget, worse for noise and cross-talk
  - Use of connectors for easier measurements
  - New shielding ideas
  - Development of system for automated measurements

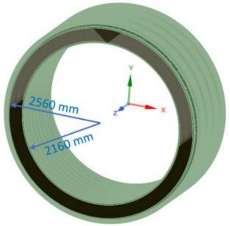


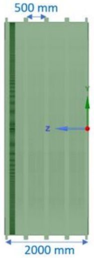


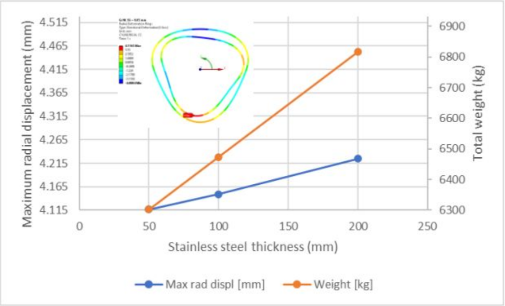
Mechanical studies

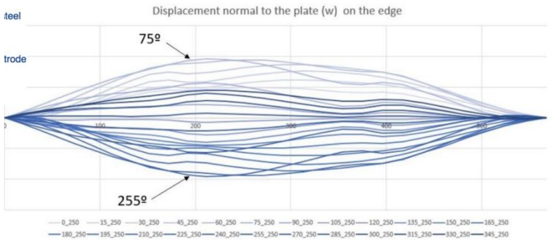
Simulation studies

- Model the full barrel
  - Define support structures, spacers
  - Study thickness of steel sheet
  - Simulations in warm and in cold



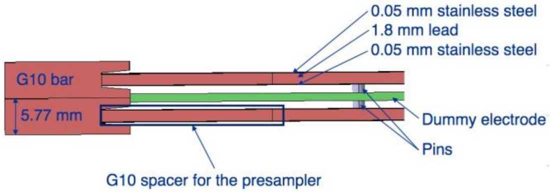


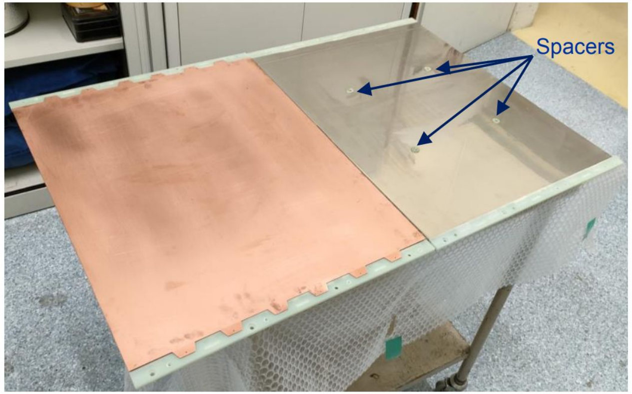




Absorbers prototypes

- First feasibility prototypes
  - Verify assumed rigidity
  - Thermo-mechanical tests in liquid nitrogen

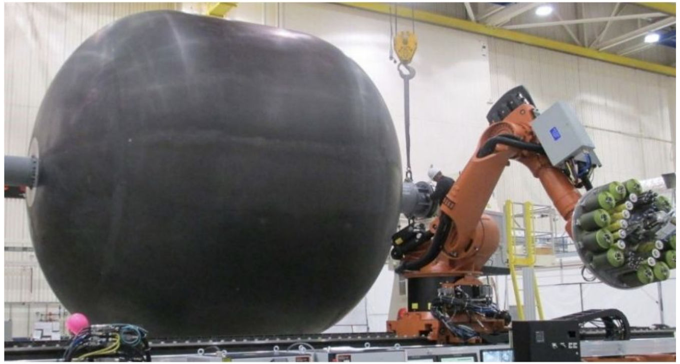




Cryostat and feedthroughs

Low mass cryostats

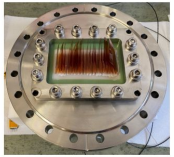
- Minimise dead material in front
  - Use of sandwiches with carbon fiber + Al honeycomb
  - Synergy with progress in aerospace
- CERN R&D: address CFRP/Metal interfaces
- Promises for **"transparent" cryostats**: few % of X_0 !



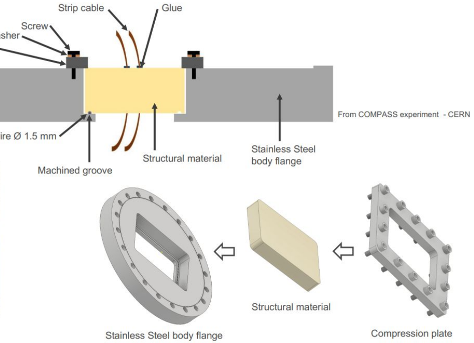
NASA's lineless cryotank

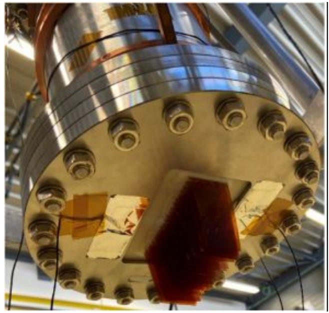
High-density feedthroughs

- Aim for ~ ×5 density and ~ ×2 area wrt ATLAS
- Successful R&D on connector-less feedthroughs at CERN
  - 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



High-density flange sample to test

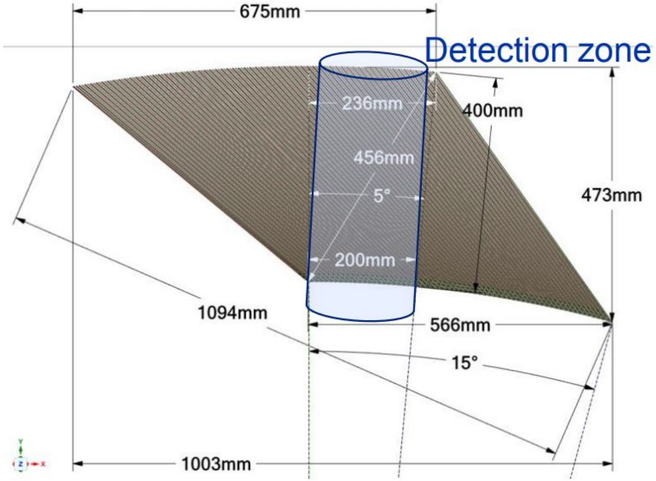




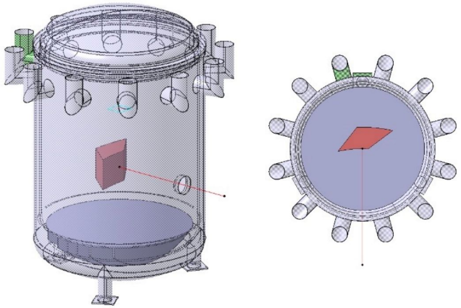
Towards a testbeam module

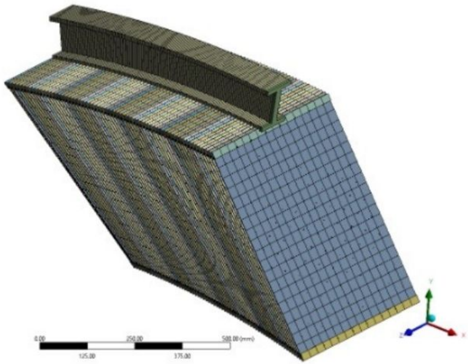
Plan to produce testmodule in the next four years

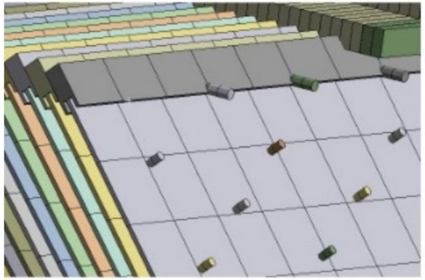
- Mechanical design of module (64 absorbers) has started
  - First finite element calculations performed
- Work on finding / adapting testbeam cryostat
- Common tools (e.g EUDAQ) should facilitate integration in testbeam facility



The cryostat available to make the test beam is the CRRP-00563.

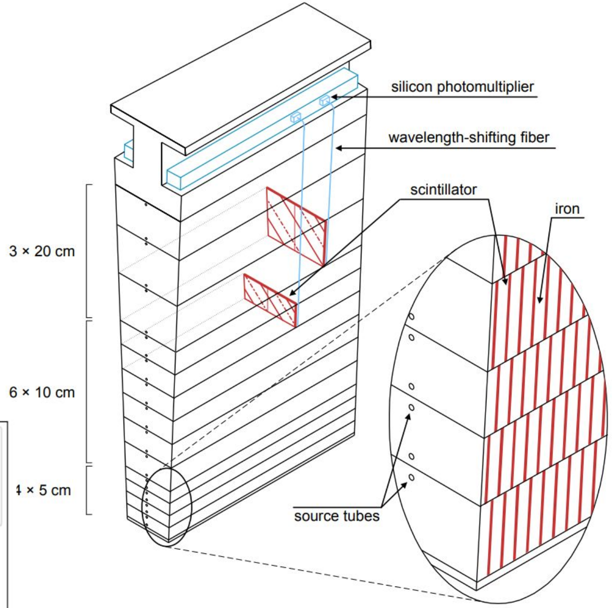


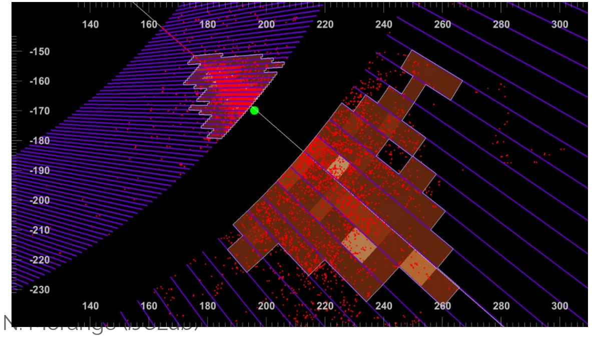


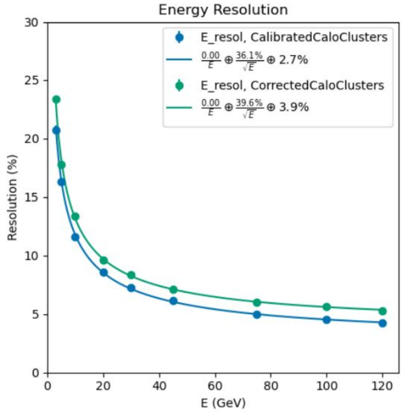


HCal for noble liquid based concept

- HCal inspired by ATLAS TileCal implemented in FCC Fullsim and studied so far
  - Other Sci/Steel options, e.g CALICE AHCAL will be studied as well
- Design
  - 5mm steel absorber plates alternating with 3mm Scint.: 8 - 9.5λ
  - 128 modules in ϕ, 2 tiles/module, 13 radial layers
  - Work on optimisation of segmentation and reconstruction is in full swing
  - Started testing Sci tile + WLS fibre + SiPM readout
- Performance
  - Ecal + Hcal combined clustering implemented
  - Single-pion resolution: 36%/√E



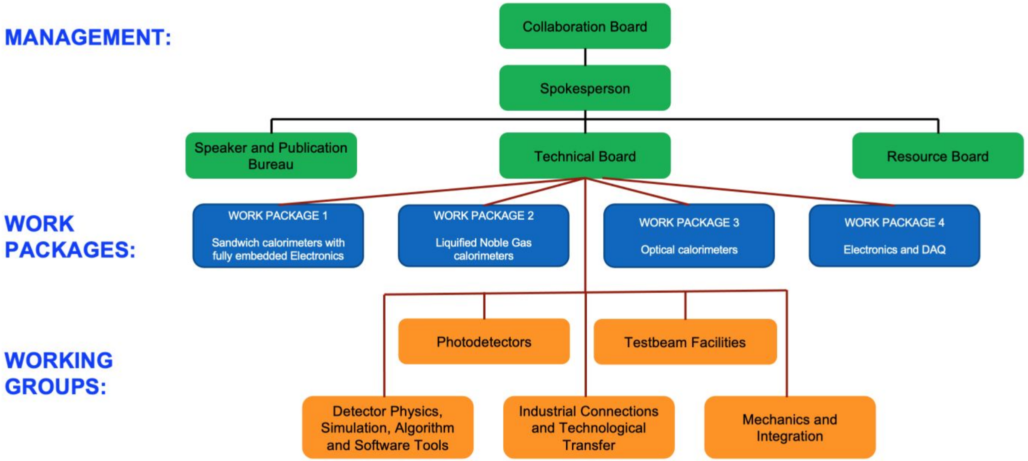




The Allegro Ecal team in DRD6

Detector R&D (DRD) collaborations implement the ECFA Detector R&D Roadmap

- DRD6 on Calorimetry with 4 work packages and several transversal activities (TB, Materials, SW, …)
  - First Collaboration meeting: April 9-11 at CERN
- Noble liquid calo is the WP2
  - 20 institutes from 7 countries
    - Of which **7 US institutes** !
- 4 main goals
  - Performance studies and optimisation
  - Study of readout electrodes
  - Development of readout electronics
  - Mechanical studies of a full calo, and for a testbeam module



Conclusion: Towards an Allegro detector

- The Allegro Noble-liquid Ecal project is progressing fast
  - Active and motivated group, that is expanding thanks to the creation of DRD6
  - Progress on all fronts: simulation, electrodes, mechanics
  - Planning for a testbeam module in 2028
- The rest of the detector is so far mostly a sketch on paper
  - Our take at what an excellent detector for FCC-ee could be, based on the stringent detector requirements to fulfil the FCC-ee physics programme
  - First discussions with colleagues interested in other sub-detectors
  - The design is **fully open to new ideas** and significant changes

Come talk with us to make this detector more than a concept !

End-plugs design idea