Noble Liquid Calorimeter ALLEGRO Ecal

Nicolas **Morange**, *IJCLab*

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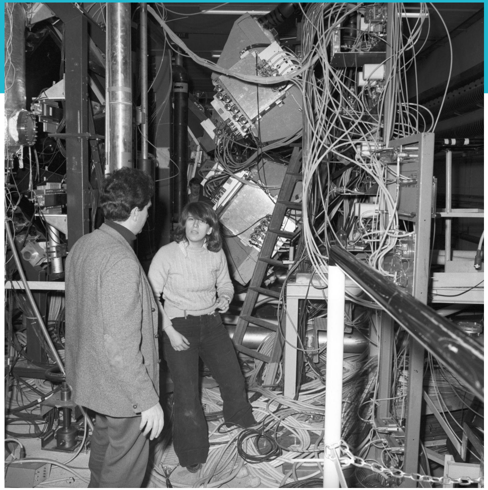
Noble liquid Ecal

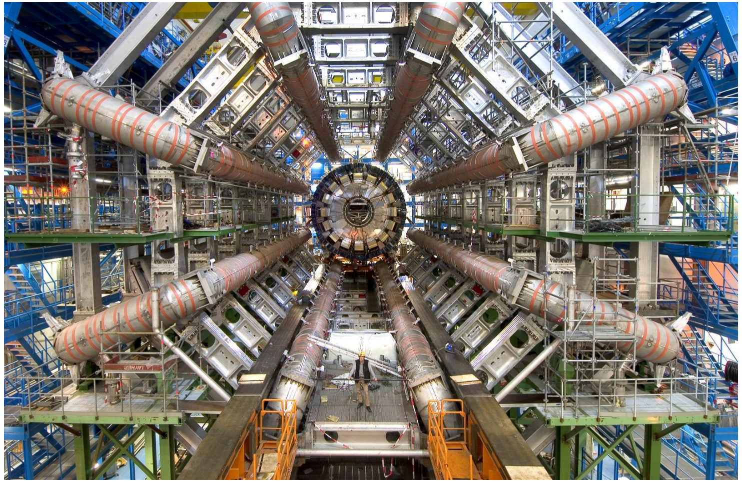
- Decades of success at particle physics experiments: from R806 to ATLAS
  - Mostly LAr, a bit of LKr

- 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

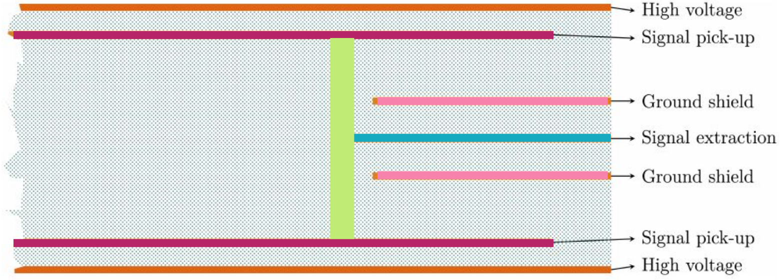
- Lots of interesting studies / R&D to do
  - Optimization for PFlow reconstruction
  - Achieving very low noise
  - Lightweight cryostats to minimize X_0
  - Designing for improved energy resolution





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
  - Allows for ~ ×10 ATLAS granularity



Allegro Barrel Design

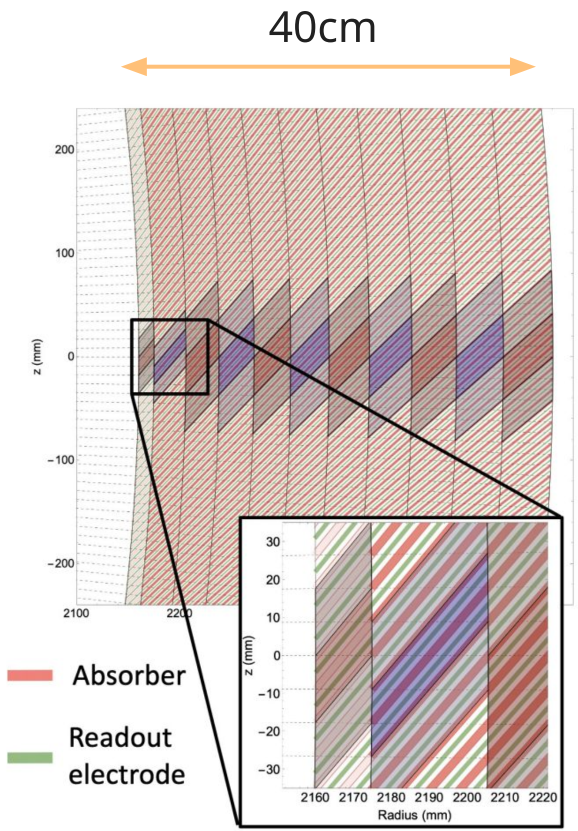
Design driven by the solution used for electrodes

- 1536 **straight inclined** (50º) 1.8mm **Pb** absorber plates
- Multi-layer PCBs as readout electrodes
- 1.2 – 2.4mm **LAr** gaps (**LKr** option): ~20% sampling fraction
- 40cm deep (22 X_0)
- $\Delta\theta$ = 10 (2.5) mrad for regular (strip) cells, $\Delta\phi$ = 8 mrad, 11 longitudinal layers

PCBs as electrodes: great flexibility

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

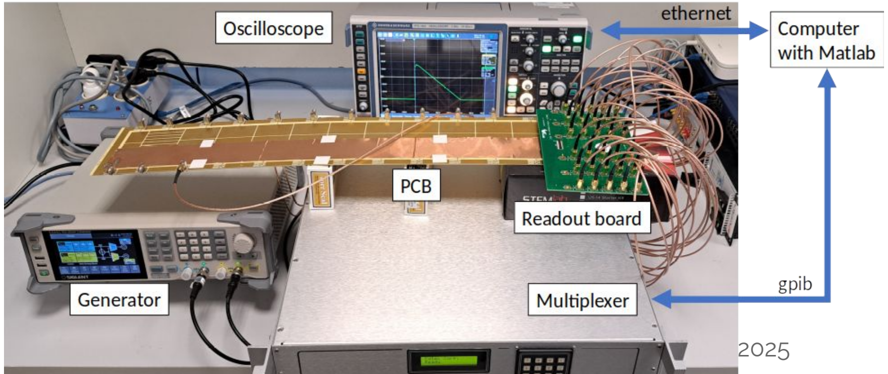
➢ **Lots of room for optimisation !**

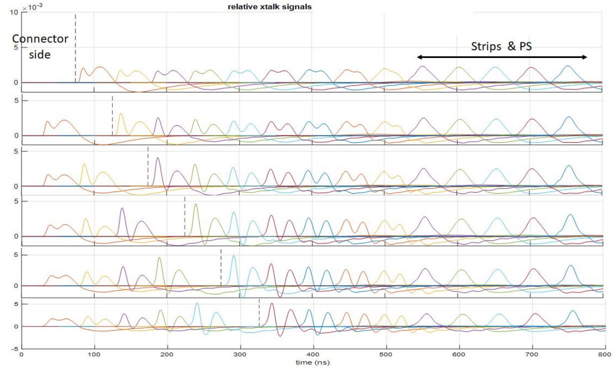


Progress on electrodes prototypes

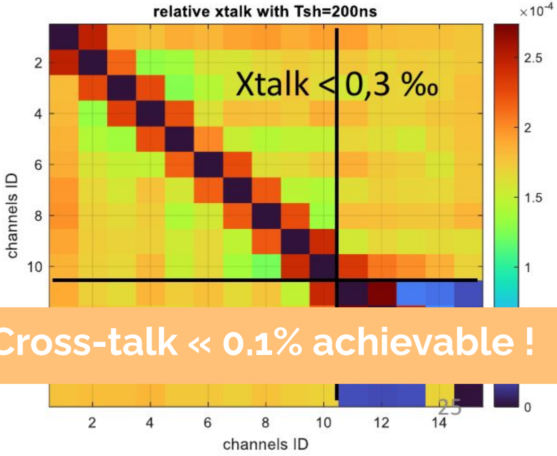
Explore tradeoffs: max granularity / capacitance (noise) / cross-talk

- First large-scale prototype at CERN
  - Explore many options for grounding, for shields
  - Few per-mille cross-talk achievable with long shaping
- Latest prototype at IJCLab
  - All layers readout at the back
    - Best for material budget, worse for noise and cross-talk
  - New shielding ideas
  - Developed system for automated measurements
    - Detailed understanding of cross-talk and capacitances





Tsh = 200ns



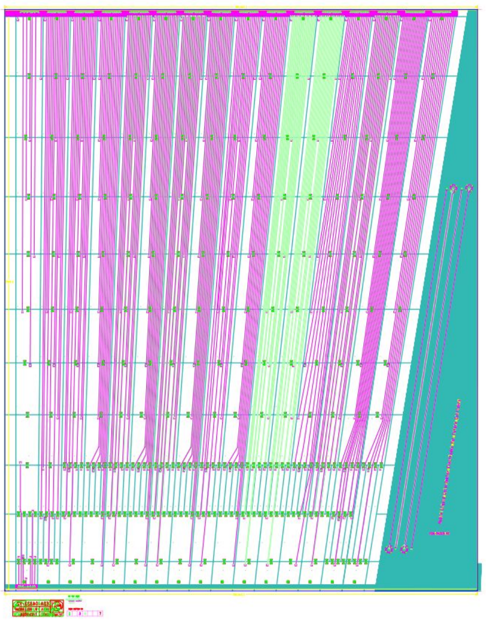
Cross-talk « 0.1% achievable !

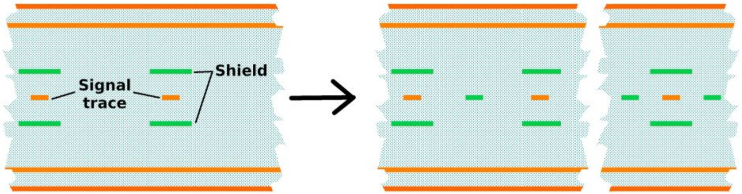
Next generation of electrodes

New large-scale prototype in fabrication at CERN PCB Lab (Jan 2025)

- Based on all lessons learned with previous generations
  - All channels readout at the back
  - Connectors to use same automated test system as IJCLab
  - Tuned widths and thicknesses
  - Optimization of stack-up and line impedance

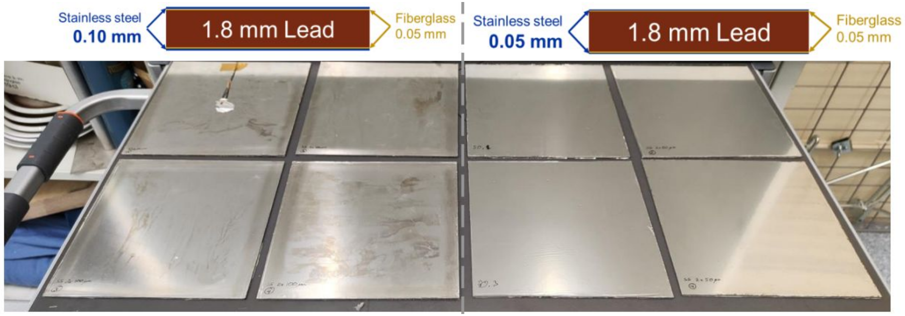
- Still investigating options
  - Many towers are different, varying one parameter at a time (widths, thicknesses)
  - Additional shielding (à la IJCLab)
  - Traces ordering in towers (impact on cross-talk expected)
  - Position of “strip” layer

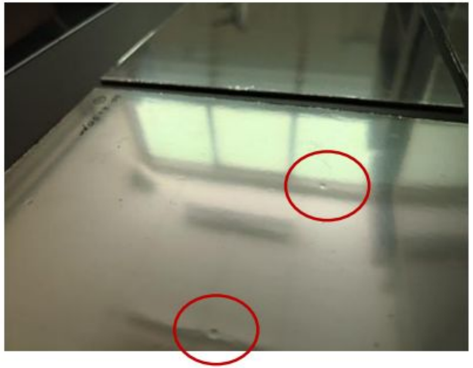




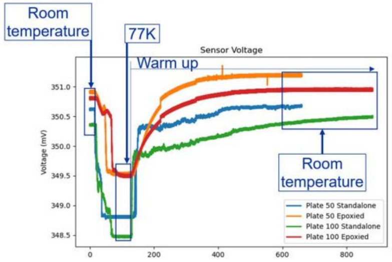
Absorbers

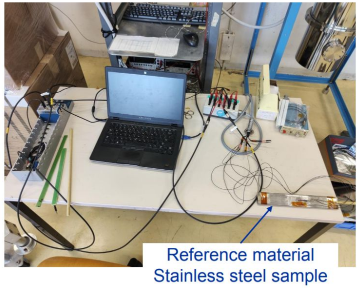
- Absorbers are 1.8mm lead plates sandwiched between stainless steel sheets, glued by prepreg
  - Absorbers fabricated with 0.1mm and 0.05mm SS sheets
  - Deformations appear in cold tests at 77K with 0.05mm sheets only





- CTE investigations
  - Deformations probably due to CTE differences
  - Investigated using strain gauges



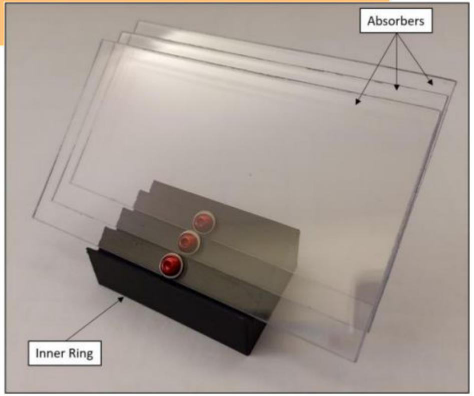


- **0.1mm SS sheets is now default**

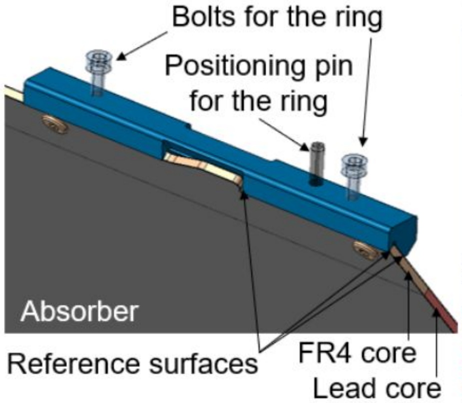
Support structures and general design

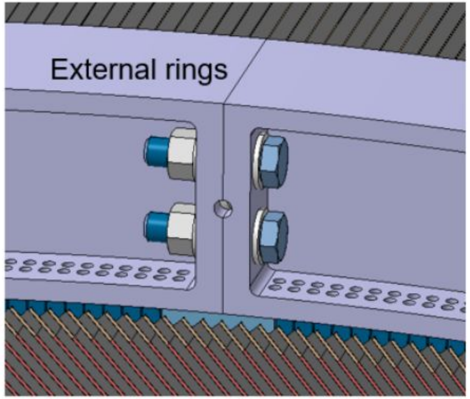
Significant progress on general mechanics design in 2024

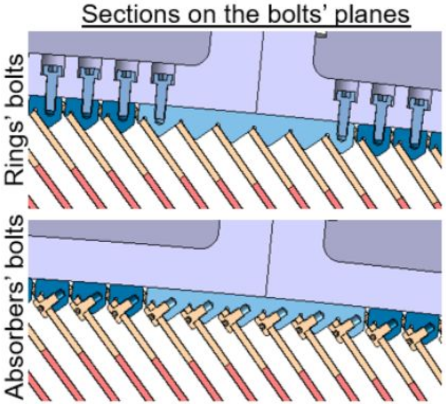
- How to hold the electrodes and absorbers ?
  - Tight space
  - High precision
  - Minimal X_0 in front of calo ⇒ use fiberglass for inner ring



- Design and 3D-printed prototypes to check feasibility
  - Small screws: need Torx over Allen

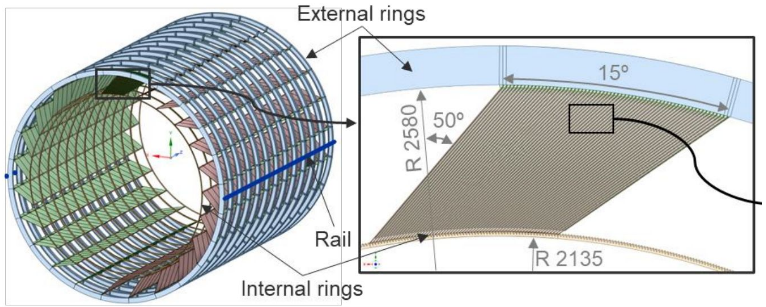


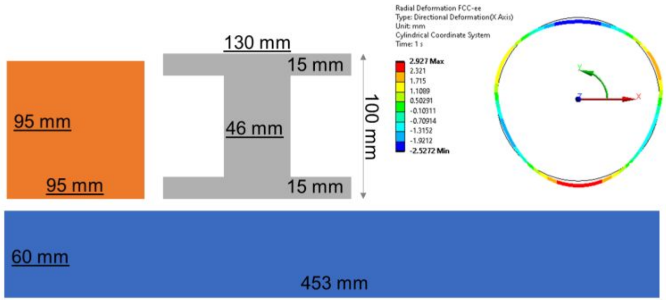




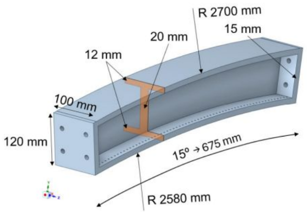
Support structures II

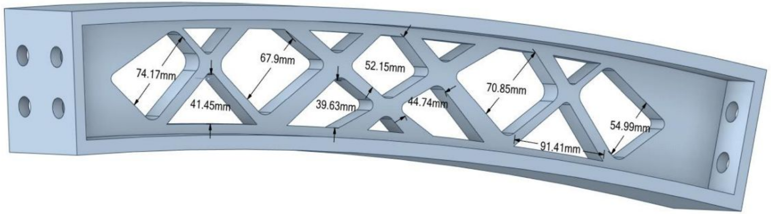
- Overall structure is given by support rings, external and internal
  - Inner ring: mostly positioning, need to be as 'transparent' as possible
  - External ring provides most of the support. Sits on rails in the cryostat
- Calculations on the overall structure inform needed size of the H beams





- Then: need space for cables and cooling pipes to go through
  - First attempts at using ANSYS to calculate a hollow structure to make room

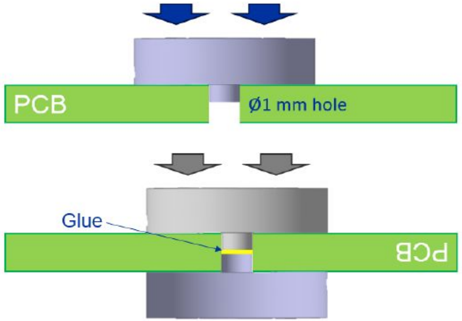


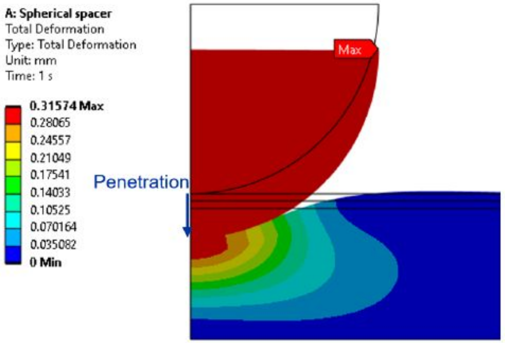


Spacers

- Spacers needed to ensure well controlled liquid argon gap

- First idea studies: simple cylindrical spacers
  - Mechanical simulations: need >6mm spacers, placed in corners of readout cells at most 20cm apart from each other
  - 5 different heights due to LAr gap variation
  - Equivalent of 0.15% of LAr volume



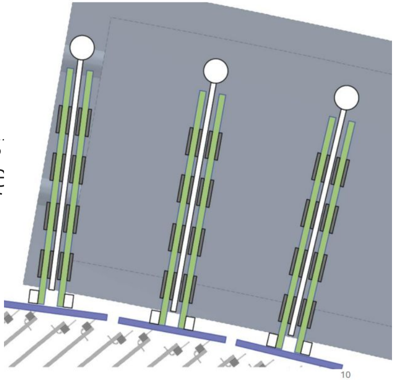


- Alternative ideas (meshes) to be studied

Ideas on cold readout electronics

ALLEGRO Ecal barrel: ~2M channels

- Warm electronics outside of cryostat: 2M signal cables to route
- Cold electronics: need room for boards + HV, powering and signal cables
  - Note: number of cables greatly reduced through multiplexing
  - First idea: cold FEB along radial direction. Adapter boards to connect to electrodes and do the summation (2 electrodes in phi are summed)
  - Opens many new questions !
    - Space needed in support rings
    - Cooling aspects
    - Amount of data trans per channel has large impact on number of cables needed
    - Stresses need for 0-suppression

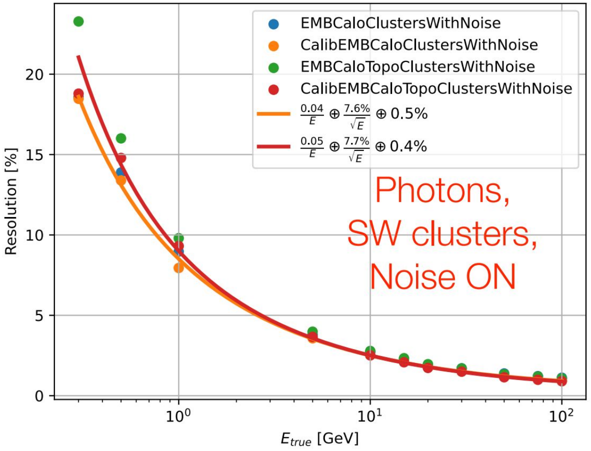


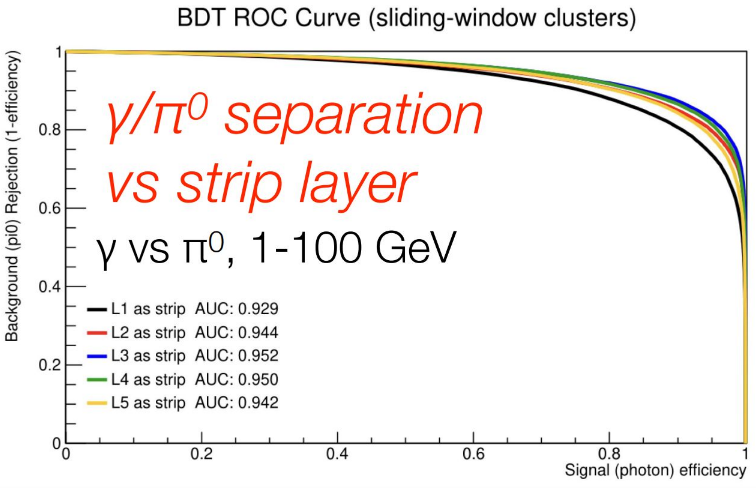
- Cold Preamps: 2024 first design work by 2 teams (based on Dune cold ASIC or based on CMS HGCROC)
  - First 'test structures' should be available in 2025 for testing

Simulations and design optimisation: granularity

See also Giovanni's talk

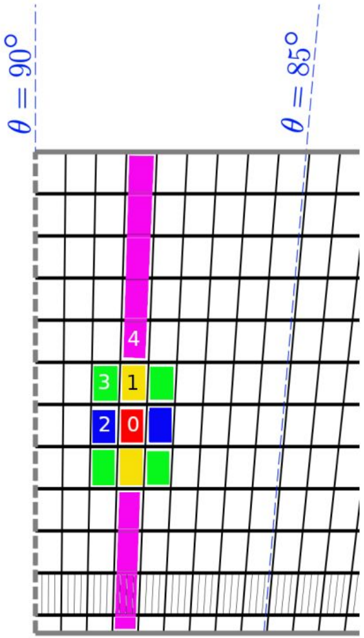
- Fixed-size and topo-clustering available for a while
- Electron and photon energy reconstruction using BDT regression
- 2024: BDT for photon / π^0 classification
  - Allows to investigate EM granularity
  - Indicates that "strips" layer would be better placed in 3rd or 4th layer instead of 2nd layer (shower has not started enough yet)

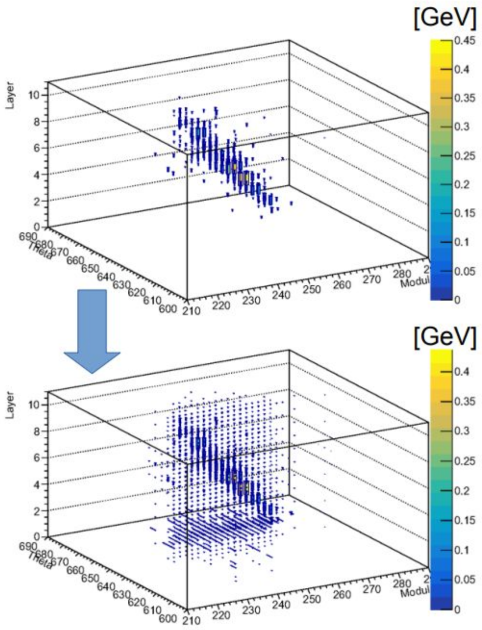


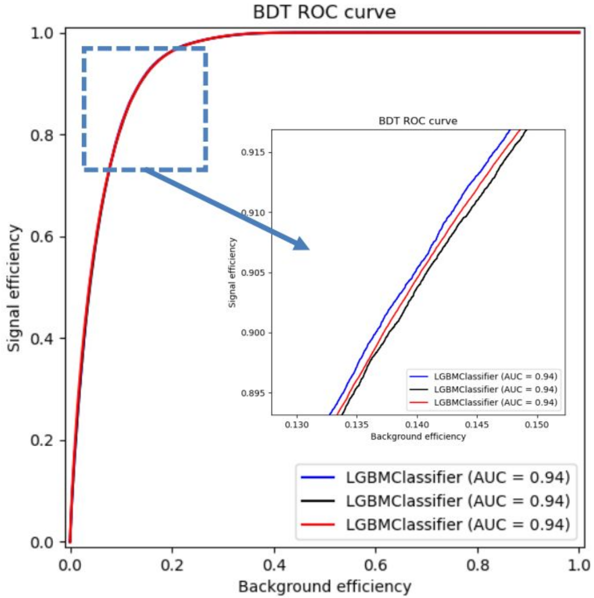


Simulations and design optimisation: improvements

- Inclusion of noise and crosstalk (energy sharing) in the digitization
  - **Tiny impact** on photon / π^0 classification, even with pessimistic cross-talk figures !





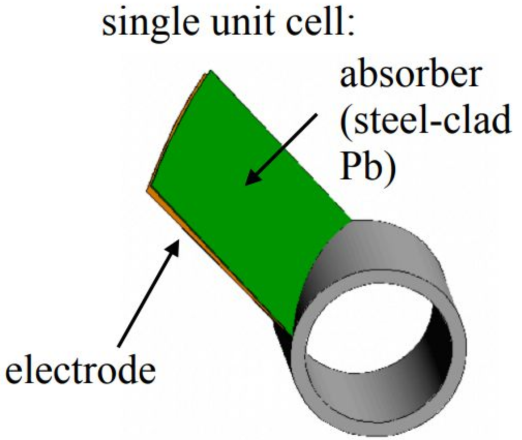


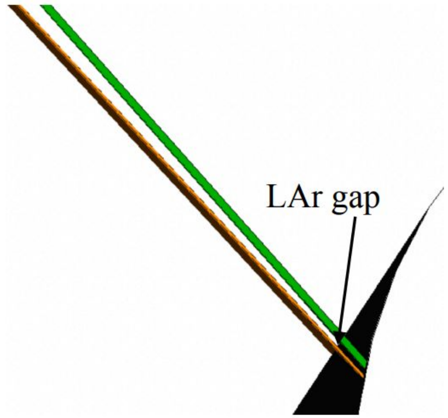
Type	1: Radial	2: Theta	3: Diagonal	4: Tower
Crosstalk	0.7%	0.3%	0.04%	0.1%

End-caps: turbine design

Turbine design: adaptation of barrel idea to end-caps regions

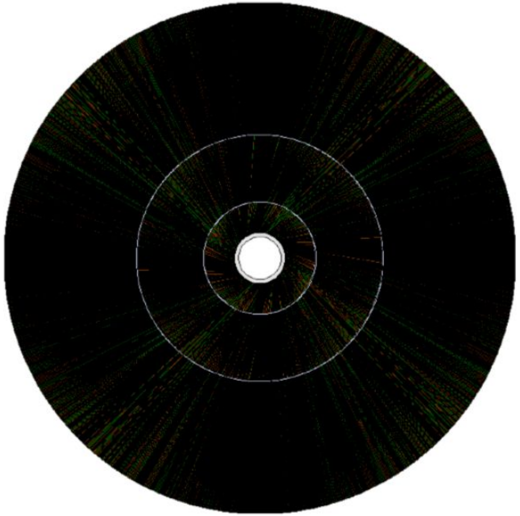
- Nice properties:
  - Particles should traverse many thin absorber/sampler/ electrode unit cells (for spatial and energy resolution)
  - Uniformity in ϕ
  - Ability to read out solely from the high-$|z|$ face
  - Can be constructed with multiple copies of a small number of electrode/absorber designs

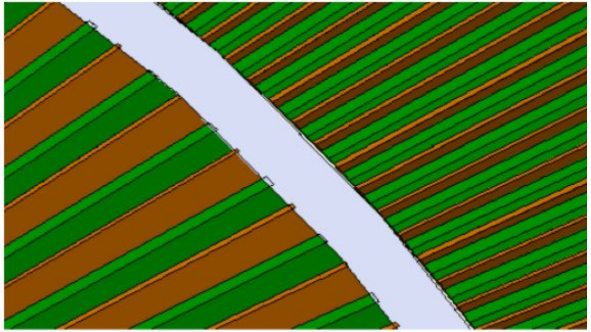


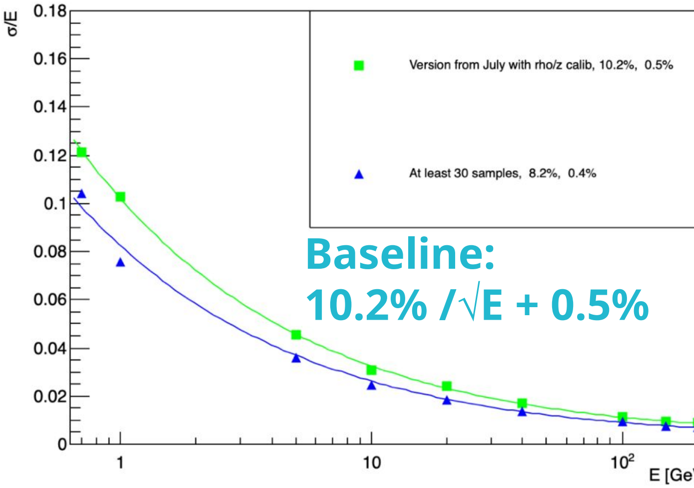


End-caps design progress

- Require 3 nested wheels to limit gap widening effect
  - $r_o/r_i = (275/42)^{1/3} \approx 1.9$
- Use tapered (variable-thickness) absorbers for more uniform sampling fraction
  - Exploring further ideas to improve resolution
- Progress in computation of calibration constants







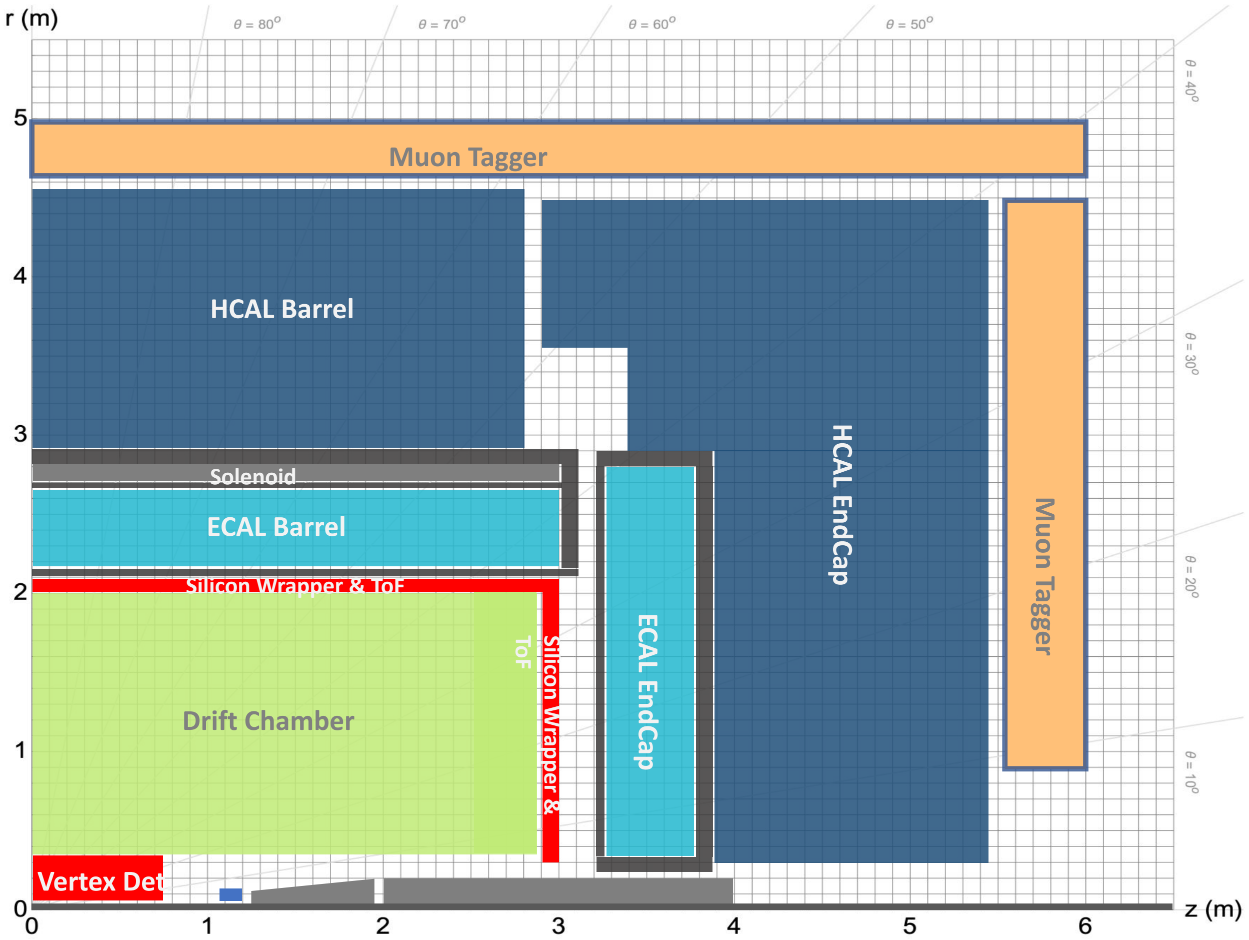
Baseline:
10.2% /√E + 0.5%

Conclusions

- Impressive progress on **all fronts** of the ALLEGRO Ecal R&D in 2024
  - Strengthens the idea that it is a **realistic** concept for **high-performance** calorimetry at FCC-ee
- Electrodes: Noise / cross-talk trade-offs quite well understood
  - Next prototypes will allow to finetune final choices for the barrel
- Mechanics: lessons on absorbers stackup and developed concepts for the support structures and the assembly process
  - Can be readily adapted to our first testbeam module
- Simulations: full simulation is now fairly complete
  - First lessons for granularity optimization
  - Further studies require integration with HCal / PFlow
  - Progress on mechanics and cryostat and solenoid require some changes to the ddsim description
- End-caps concept is developing
  - Studies on e.g specific electrode designs can now be started

Supplementary Material

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

Outstanding Physics ⇒ Strong Requirements on Detectors

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

Calorimeters for HET factories

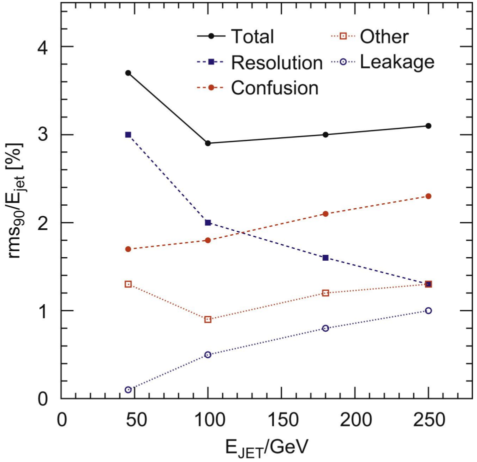
An extensive set of requirements

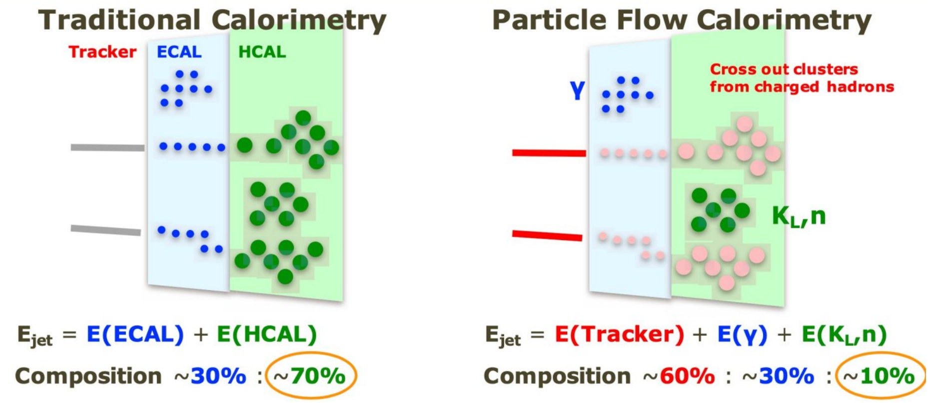
- Energy resolution: “only” for photons and neutral hadrons
  - But: ideally photons as low as 200 – 300 MeV
- Dynamic range: 200 MeV – 180 GeV
  - vs LHC: 6 TeV jets !
- Granularity: PID, disentangle showers for PFlow
  - But: how granular exactly ?
- Hermeticity, uniformity, calibrability, stability
  - Low systematics for precision measurements
  - Complex system-level engineering questions
- No need to be particularly fast
  - But: can precise timing help in reconstructing showers more accurately ?

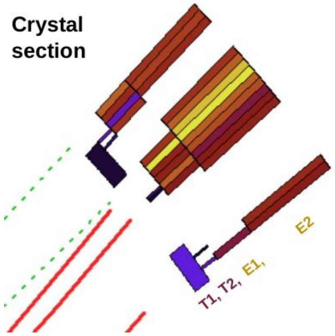
A quest for ultimate jet energy resolution

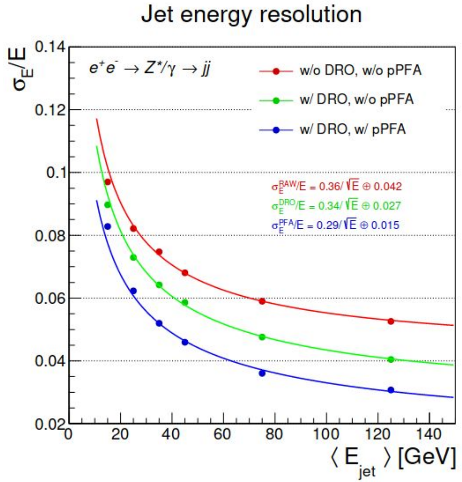
PFlow PFlow PFlow

- Target: σ(E)/E = 30%/√E (GeV)
  - Typical figure of merit: W/Z boson separation
  - Actual use: variety of hadronic measurements
- What granularity do we really need at HET Factories ?
- New calos concepts bring new ideas (crystals DR study)





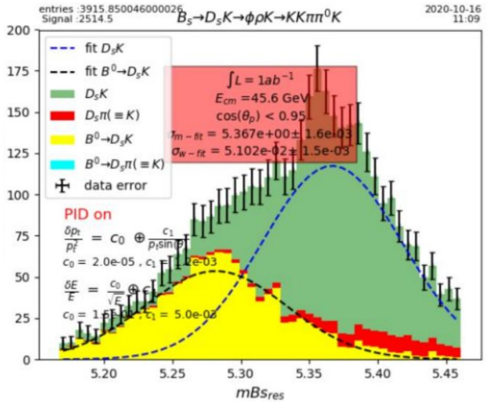




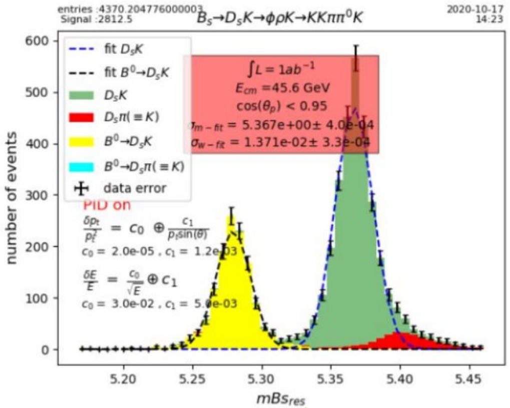
EW factories unique challenges

FCC-ee: O(10^{11}) B and τ at 45 GeV !!!

- Some physics channels require very high EM resolution
- τ physics: reconstructing the decays
  - Means π^0 reconstruction and ID
  - Count close-by π^0
  - Granularity
- BSM, e.g ALP searches
  - Photon resolution, photon pointing



15%/√E



3%/√E

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

Table: Each row shows the fraction of e.g. $\tau \to \pi^\pm \nu$ decays classified as each of the considered channels

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]

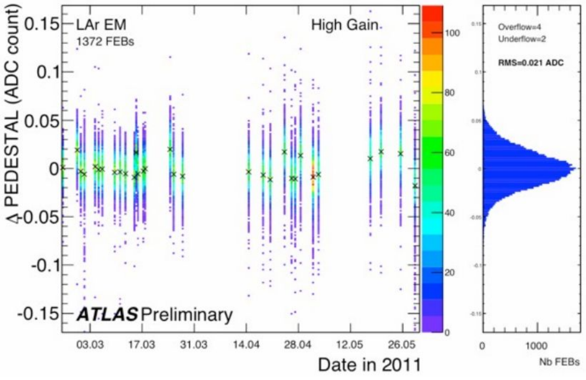
- All options feature good jet energy resolution
- Varying Ecal resolution ⇒ Highest EM resol required for B physics
- Varying segmentation: PFlow, shower shapes, cluster pointing
- Other characteristics: Operational stability, cost

Example: Stability of ATLAS LAr Energy Scale

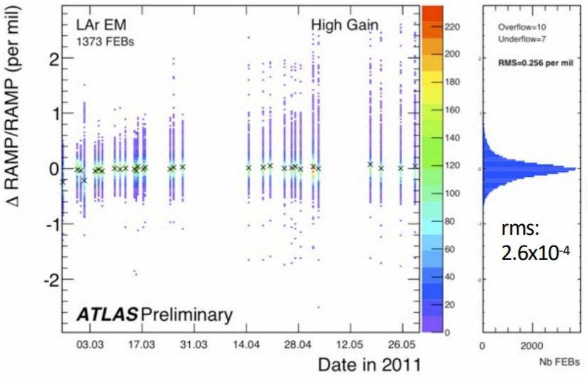
Noble-liquid calorimetry: High intrinsic stability

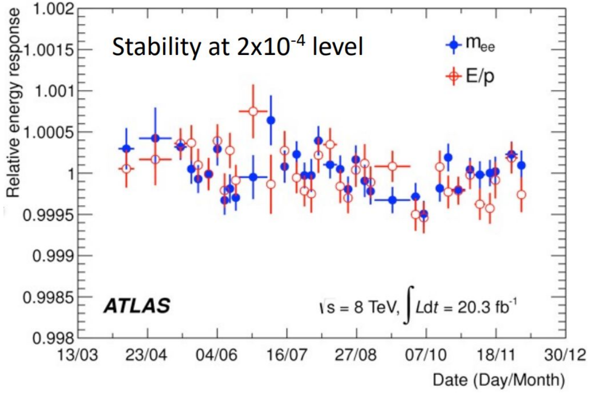
- Pedestal stability < 100 keV
- Gain stability 2.6x10^{-4}
- Parameters monitored in daily calibration runs
  - Changes in constants needed only about 1 / month
- **Stability of the energy scale of 2x10^{-4}**
  - Visible on Z→ee invariant mass and E/p

Pedestal (P) stability



Gain (R) stability

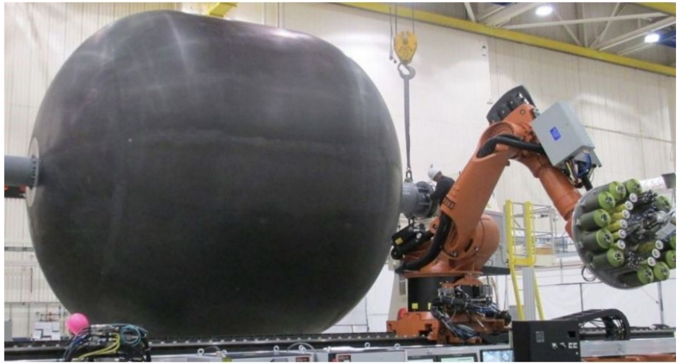




Cryostat and feedthroughs

Low mass cryostats

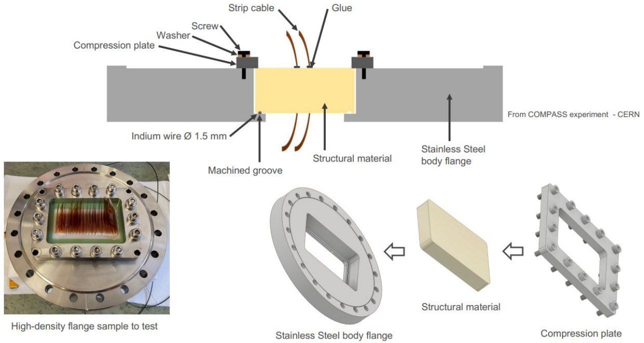
- Minimise dead material in front
  - Use of sandwiches with carbon fiber + Al honeycomb
  - Synergy with progress in aerospace
- CERN R&D: address CFRP/Metal interfaces
- Promises for **"transparent" cryostats**: few % of X_0 !



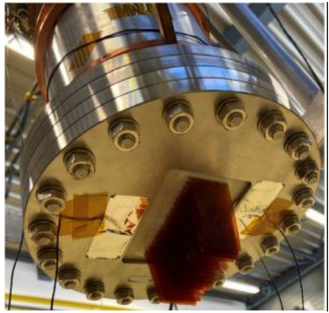
NASA's lineless cryotank

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



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

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