The ALLEGRO Noble Liquid Calorimeter for FCC-ee

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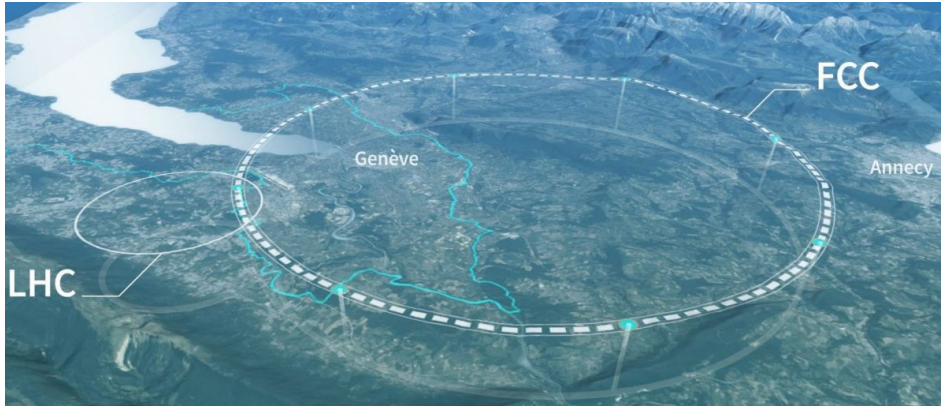
On behalf of the ALLEGRO Ecal Team

The FCC-ee physics case

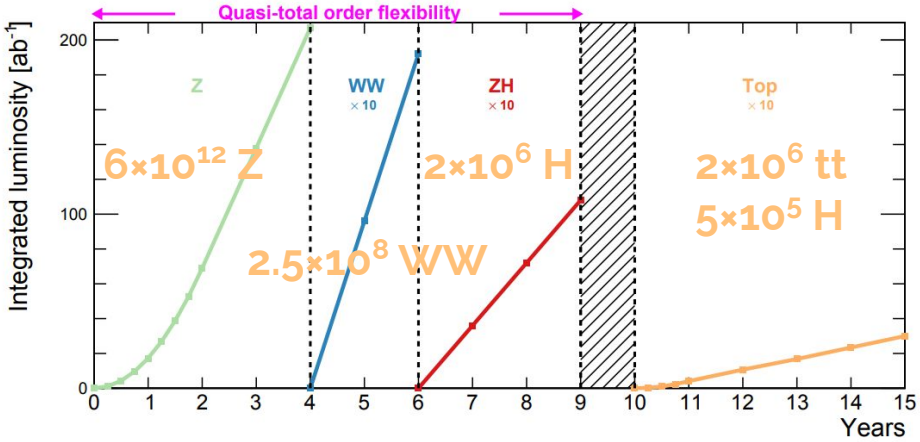
The FCC Project

- 90km circular collider at CERN: e^+e^- as a first stage
- Collisions at 90 GeV (Z), 160 GeV (WW), 240 GeV (ZH), 365 GeV (tt)
- Feasibility Study concluded for ESPPU

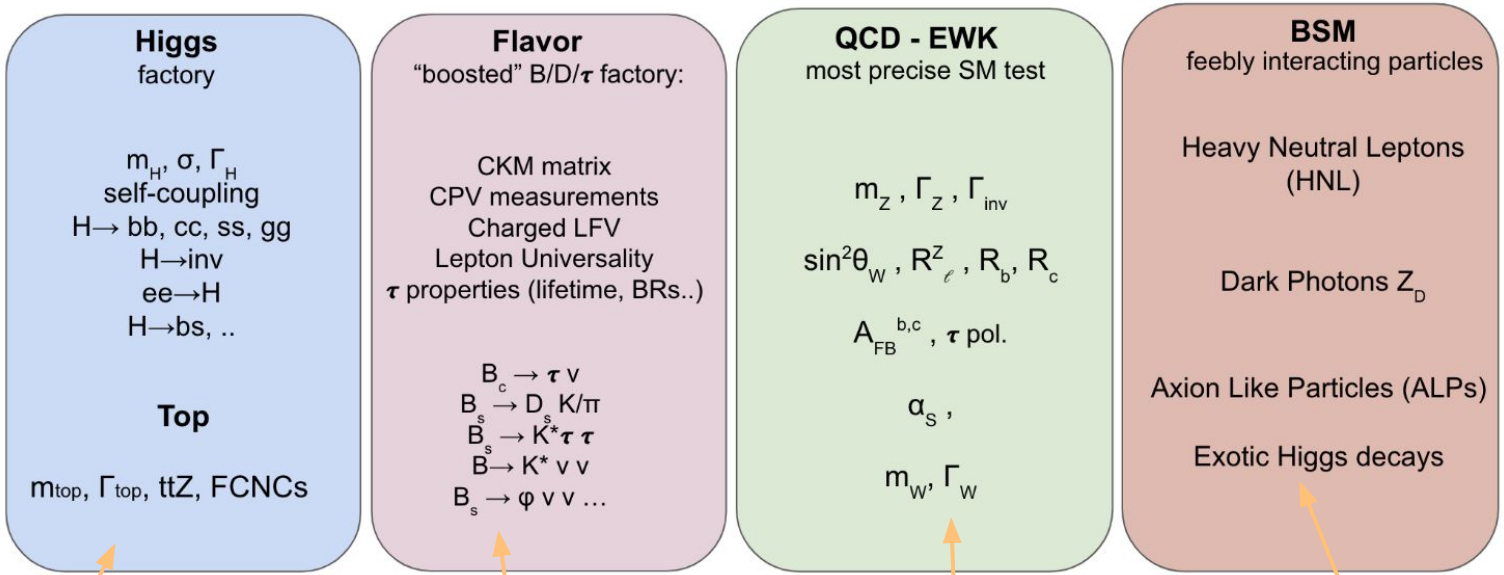


Outstanding physics programme

- Higgs precision physics
  - Complementarity with LHC
- Electroweak and QCD
  - Extraordinary precision
- Heavy flavour factory
- BSM searches



Outstanding Physics ⇒ Strong Requirements on Detectors



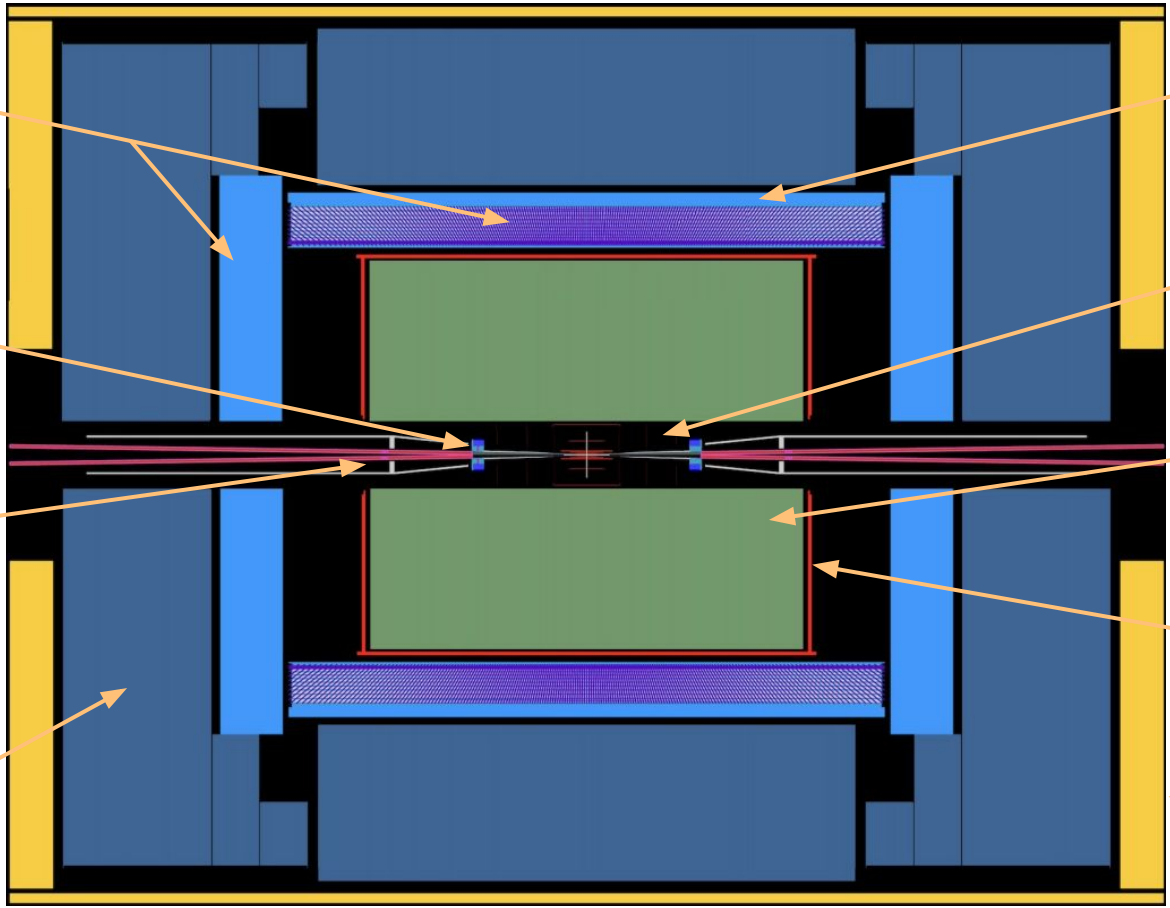
Excellent tracking
Jet energy resolution
at high energies

Excellent tracking
EM Energy resolution
PID at low energies

Excellent knowledge of detectors:
Small systematics

Versatile detector
Photon pointing

The ALLEGRO Detector Concept



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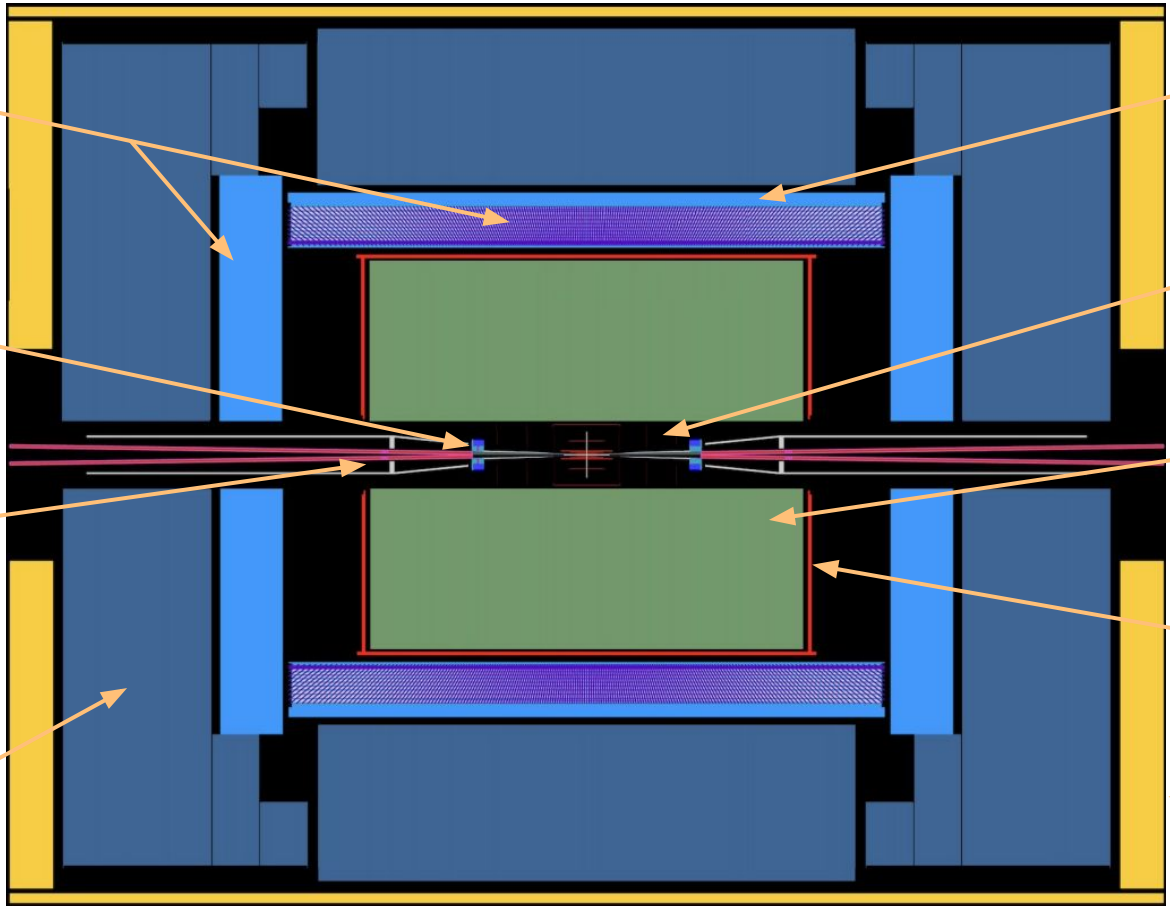
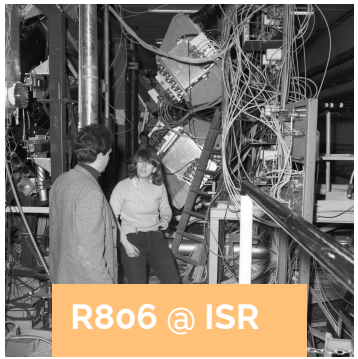
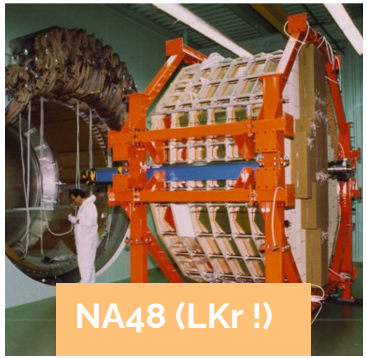


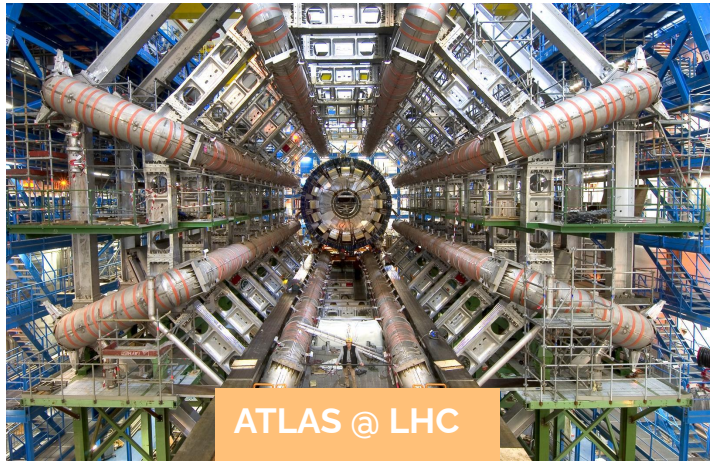
Noble Liquid Calorimetry

Decades of successes in particle physics experiments


R806 @ ISR

Dø @ Tevatron


NA48 (LKr !)


ATLAS @ LHC

Checks all boxes for an excellent calorimeter at FCC-ee

- **Excellent energy resolution**
  - 5 – 8% /√E
- **High granularity** achievable
  - Few 10^6 channels for Particle Flow Reconstruction
- Suitable for **low systematics**
  - Linearity, uniformity, long-term stability
  - Easy to calibrate

→ **90 MeV systematics in H→γγ mass measurement with ATLAS**

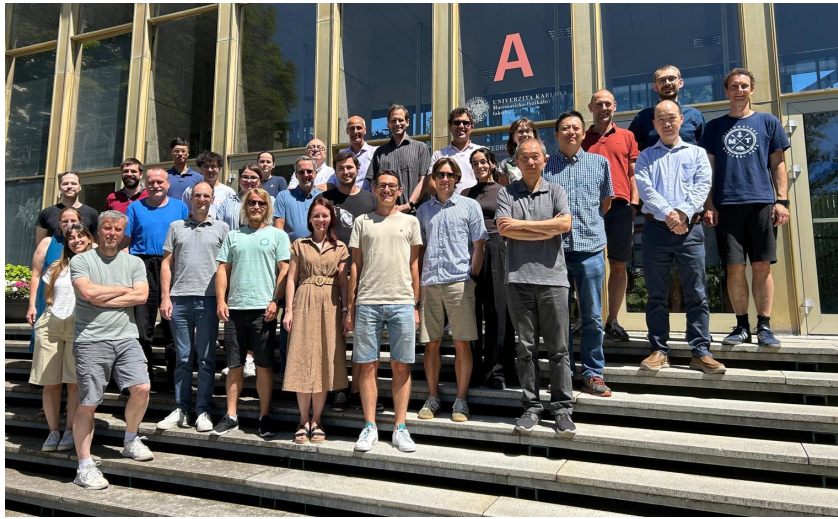
Noble Liquid Calorimetry for FCC-ee

Challenges for a next generation noble liquid calorimeter

- Reach **high granularity**
  - And optimize for physics: photon/π^0 PID ; PFlow reconstruction
- Design for **improved energy resolution**
  - Including achieving **very low noise**
  - "Transparent" cryostat: **minimize amount of X_0** in front of calorimeter

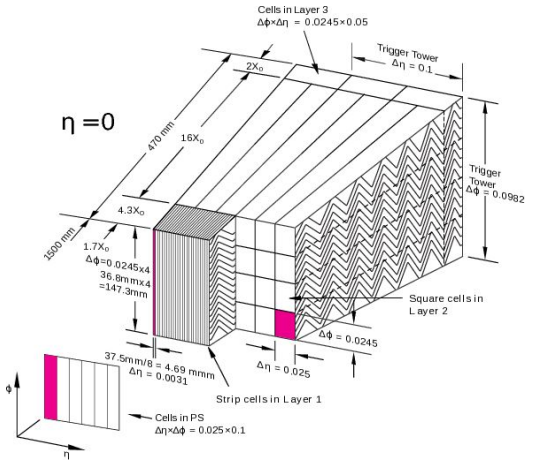
ALLEGRO Ecal R&D

- New design ideas to tackle these challenges
  - Study concepts for a barrel and for endcaps
  - Validate with prototypes in testbeam
    - ➢ Aim for post-LS3 (2029)
- Community of 20 institutes
  - Many already involved in ATLAS LAr
- Part of the DRD6 collaboration
  - WP2 on Noble liquid Calorimetry



Granularity of Noble Liquid Calorimeters

- Calorimeter collects ionization charge
  - Granularity of the calorimeter
    ⇔ granularity of the readout electrodes
- ATLAS: copper/kapton electrode
  - Traces to read out middle cells take real estate on back layer
  - Limits on longitudinal granularity
- FCC-ee requirements
  - High jet energy resolution needed
  - Particle flow algorithms take advantage of much finer granularity



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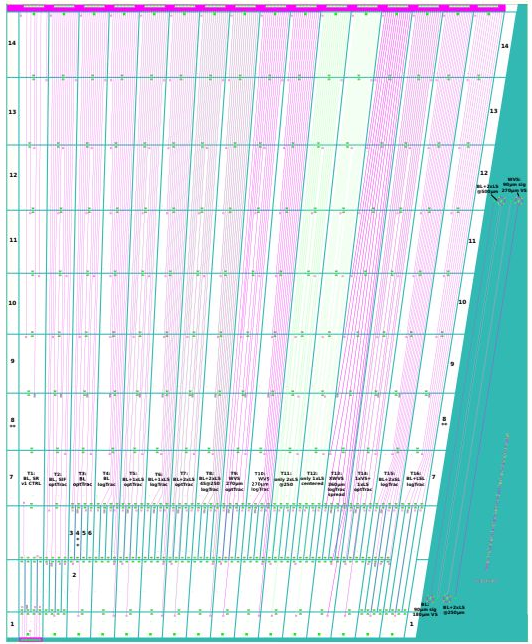
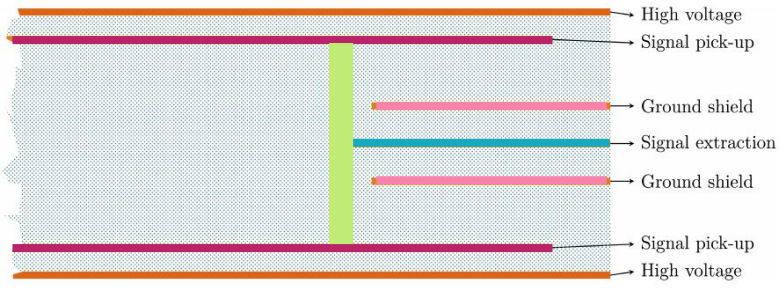
- **Solution for Noble Liquid calo for FCC**
  - Multi-layer PCB to route signals inside
  - Allows for **~ ×10 ATLAS granularity**

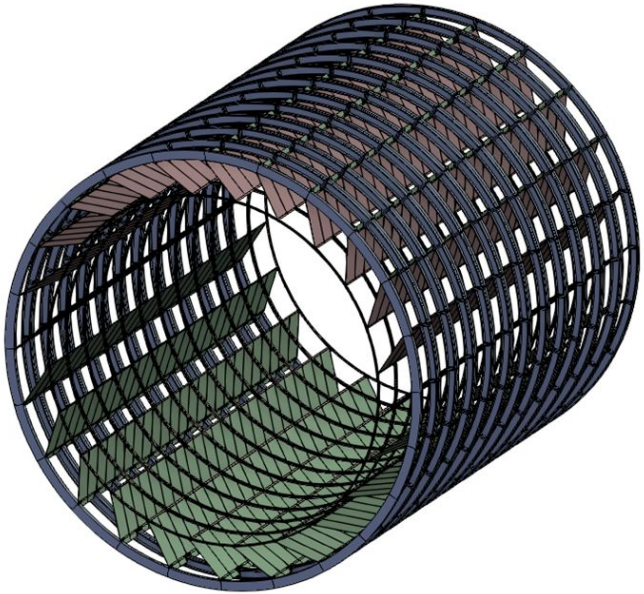




Allegro Barrel Design

Design driven by the solution chosen for the electrodes

- Geometry description
  - 1536 **straight inclined** (50°) 1.8mm absorber plates
  - Segmented multi-layer PCBs as readout electrodes
  - 1.2 – 2.4mm LAr gaps ~20% sampling fraction
  - 40cm deep (**22 X_0**)
  - $\Delta\theta \times \Delta\phi$ = 10 × 8 mrad, 11 longitudinal layers
- PCBs as electrodes: great flexibility
  - Number of layers and granularity of each layer tuneable
  - Projective cells in θ and ϕ
- Active and passive material
  - Baseline: **Pb** for absorbers, **LAr** gaps
  - Options of **W** absorbers and **LKr** being investigated



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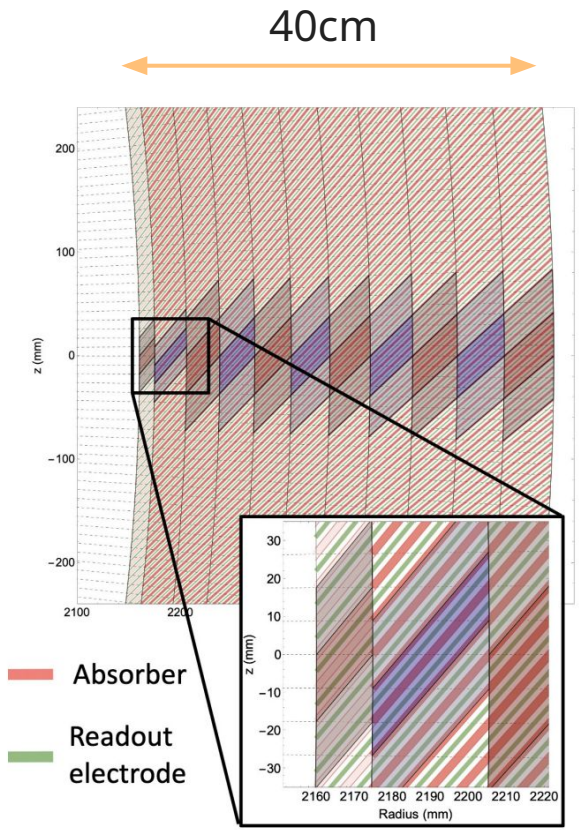
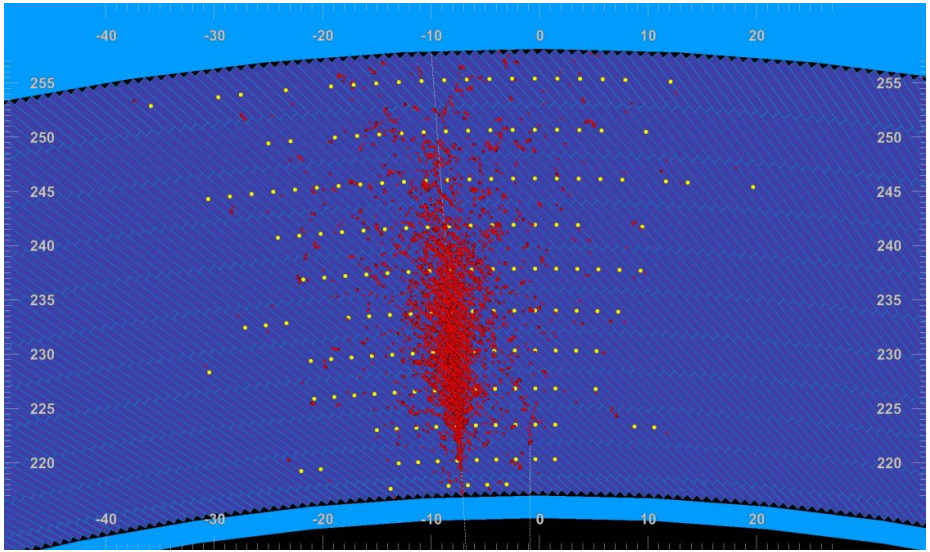
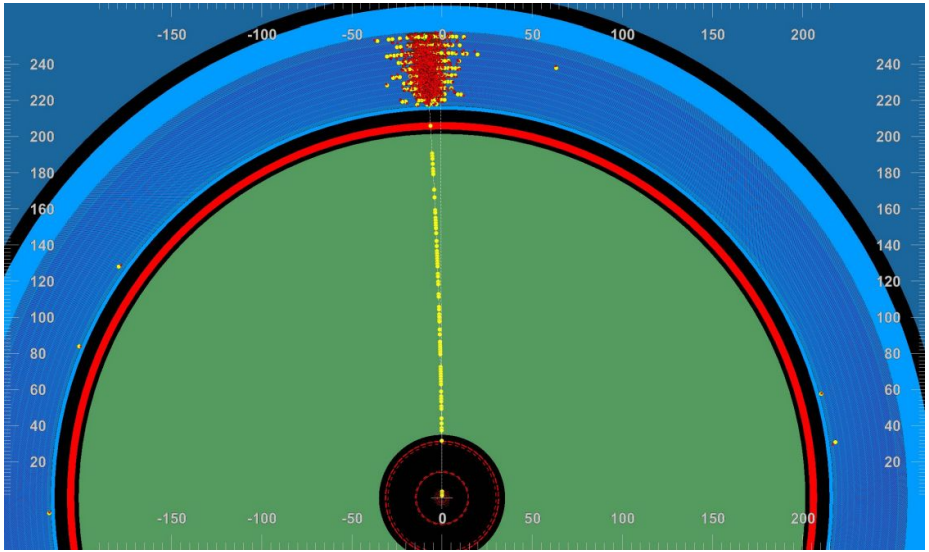


Calorimeter Simulation

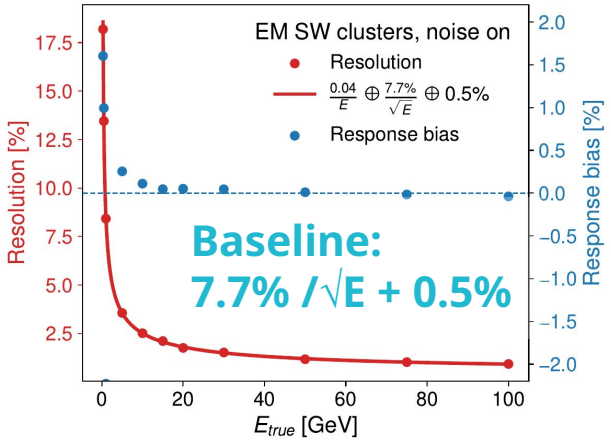
- Full calorimeter simulation implemented in Key4hep
  - (DD4hep/DDSim, EDM4hep, Gaudi)
  - Flexible enough to test easily new ideas

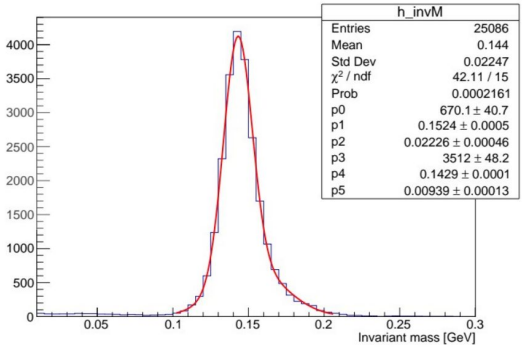




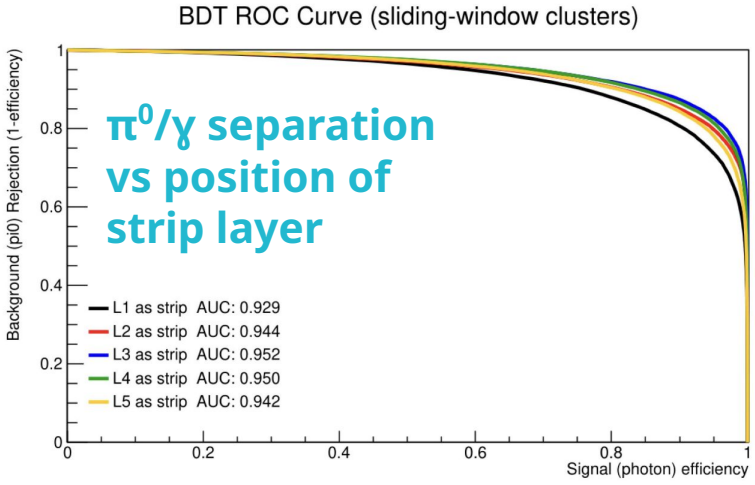
Simulations and design optimisation: granularity

- EM objects reconstruction using fixed-size or topo-clusters
  - Includes electronics noise and cross-talk effects
- Electron and photon energy reconstruction using BDT regression
- Studies on photon / π^0 classification
  - Allows to investigate EM granularity
  - Physics case: hadronic τ decay modes





π^0 peak :
σ = 23 MeV



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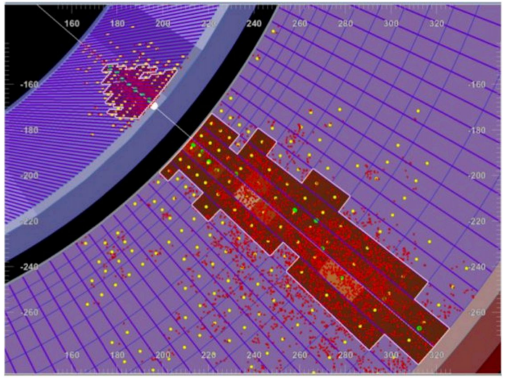
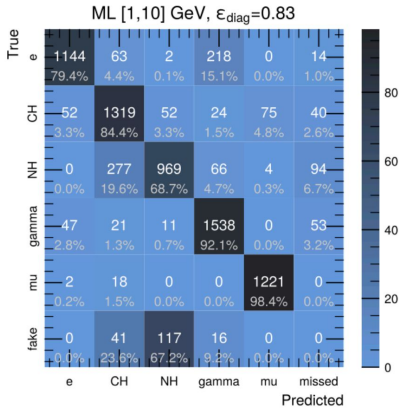
  - Allows to investigate EM granularity
  - Physics case: hadronic τ decay modes
- Next challenge: Particle Flow implementation
  - Key to performance of hadronic final states
  - Preliminary version of Pandora PFA running
  - Will also study state-of-the-art ML-based PFlow approaches



Cluster in ECal + Hcal



ML PFlow in CLD

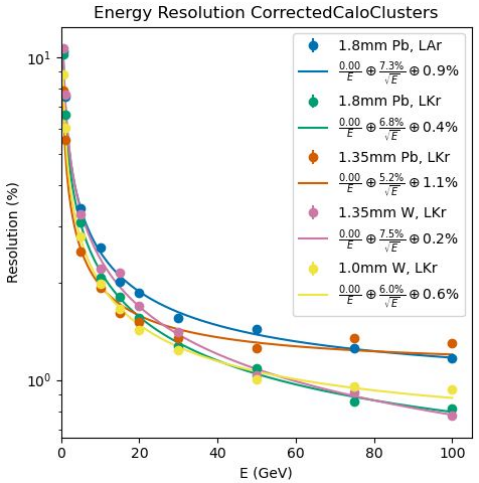
Energy resolution: design options and noise

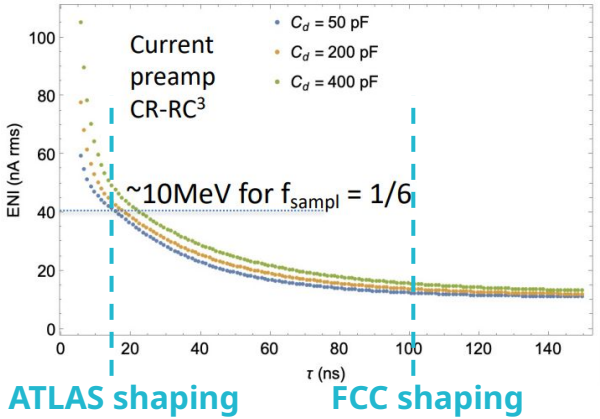
Energy resolution: σ(E)/E = a/E + b/√E + c ⇒ 3 terms to optimise !

- 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
  - Req.: measurement of 200 MeV photons, S/N>5 for MIPs

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

  - Longer shaping time wrt ATLAS (200 ns)
  - Cold frontend electronics in the cryostat will provide **noiseless readout**

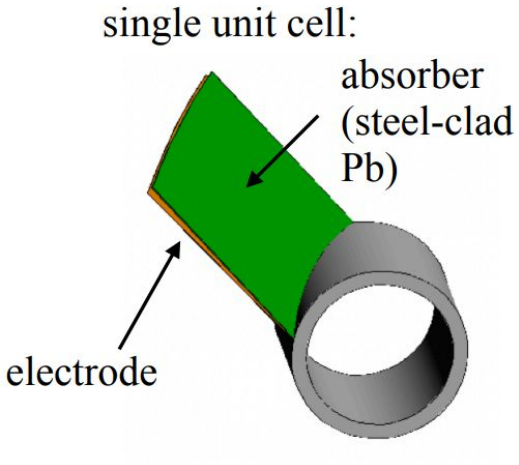


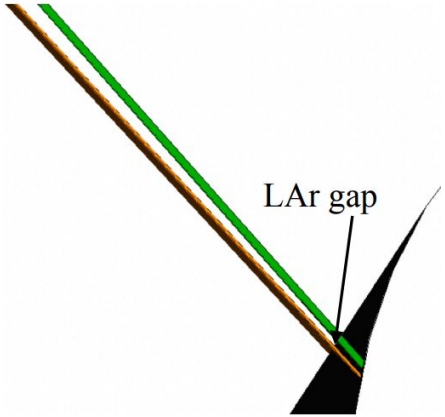


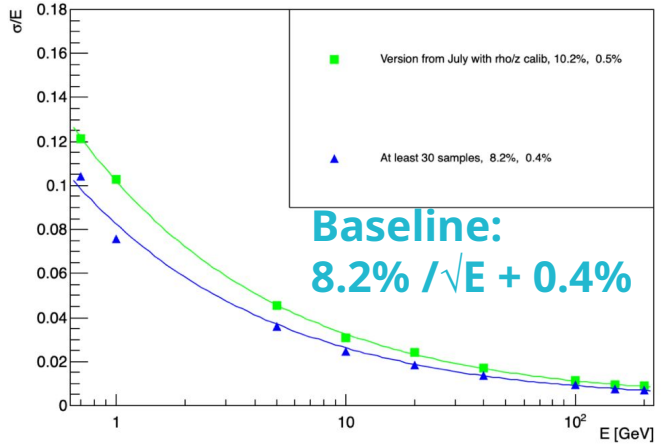
End-caps: turbine design

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

- Nice properties:
  - High sampling frequency
  - 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



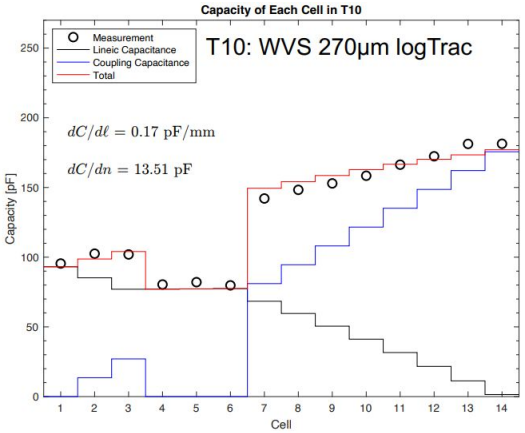


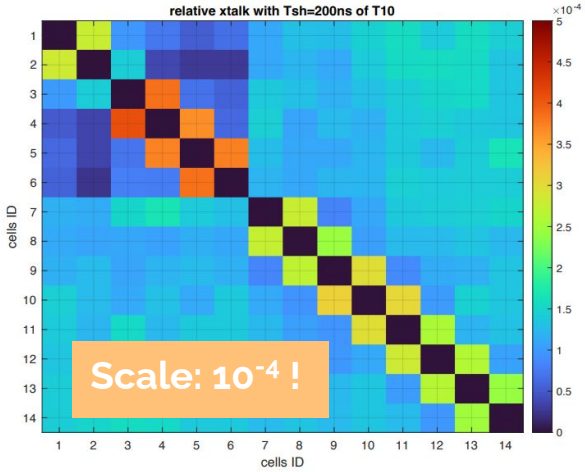


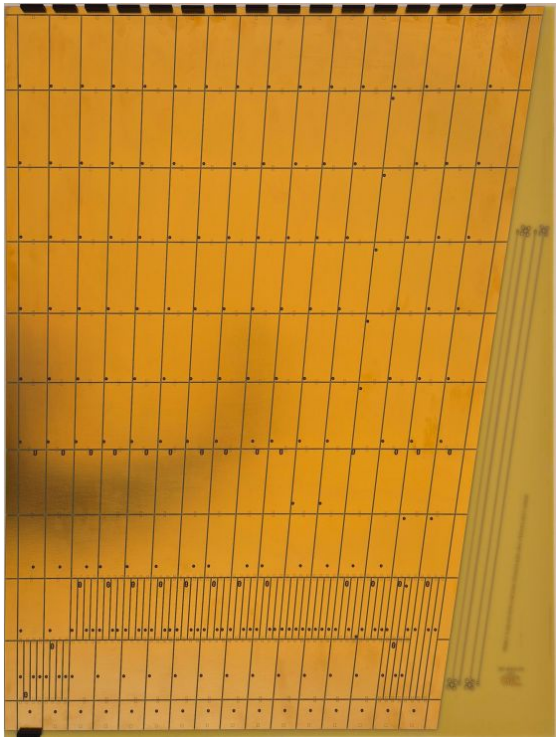
R&D on Electrodes

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

- Large-scale prototypes built with many design options
  - Especially for shielding of signal traces
- Conclusions so far
  - (sub)-**per-mille cross-talk achievable**
  - while keeping reasonable cell capacitances
  - Good agreement with FEM simulations

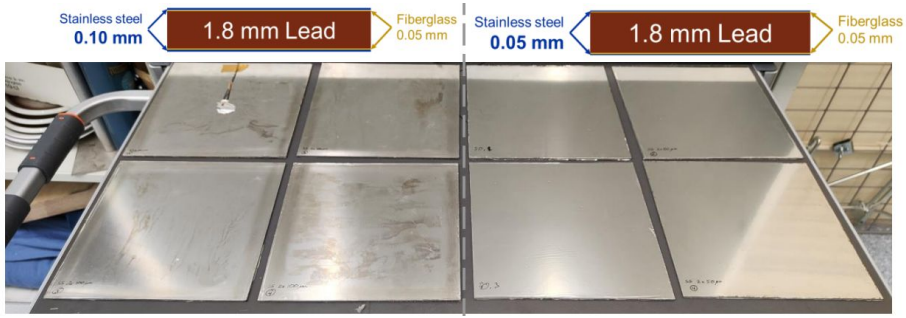


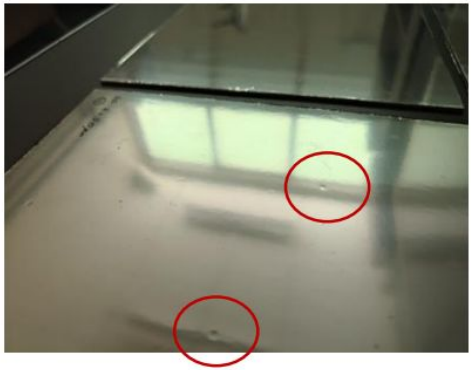




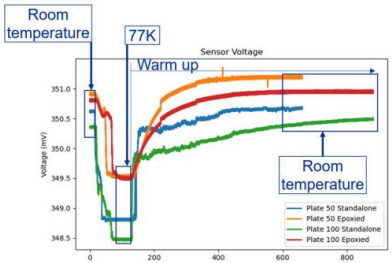
R&D on Absorbers

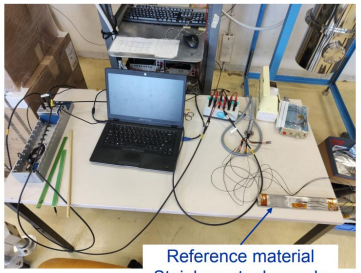
- Absorbers are 1.8mm lead plates sandwiched between stainless steel sheets, glued by prepreg
  - Absorbers fabricated with 0.1mm and 0.05mm SS sheets
  - Deformations appear in cold tests at 77K with 0.05mm sheets only





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



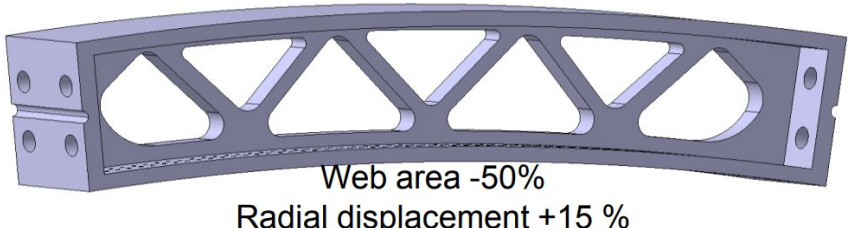


- **0.1mm SS sheets is now default**
- **R&D conclusive !**

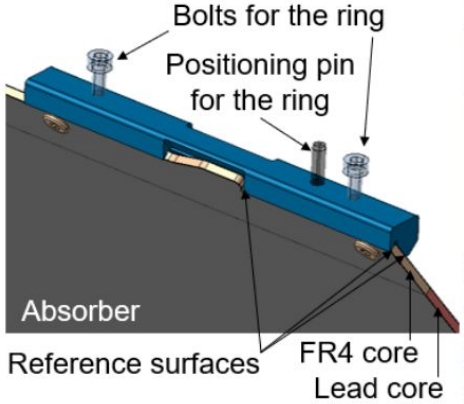
Support structures and general design

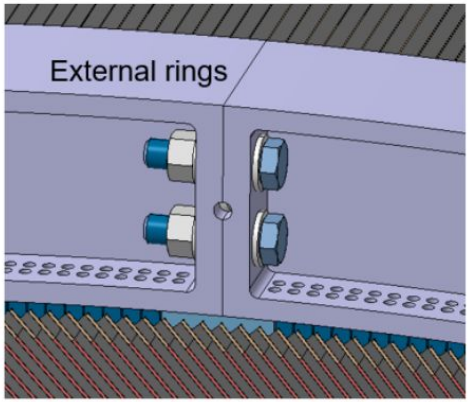
Compactness, rigidity, high precision in positioning

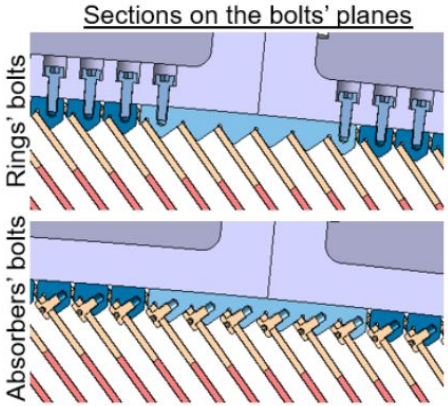
- How to hold the electrodes and absorbers ?
  - Overall structure is given by support rings, external and internal
  - Calculations to chose minimal beam size
  - High precision: need uniform LAr gaps

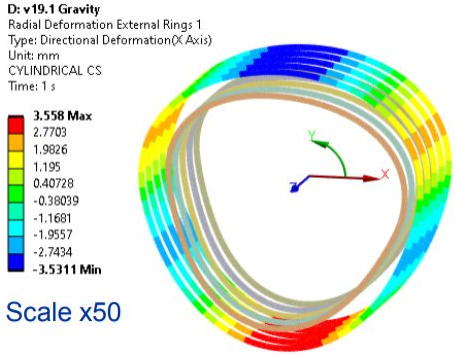


- Add constraints to route cables and pipes
  - ANSYS studies for hollow structure



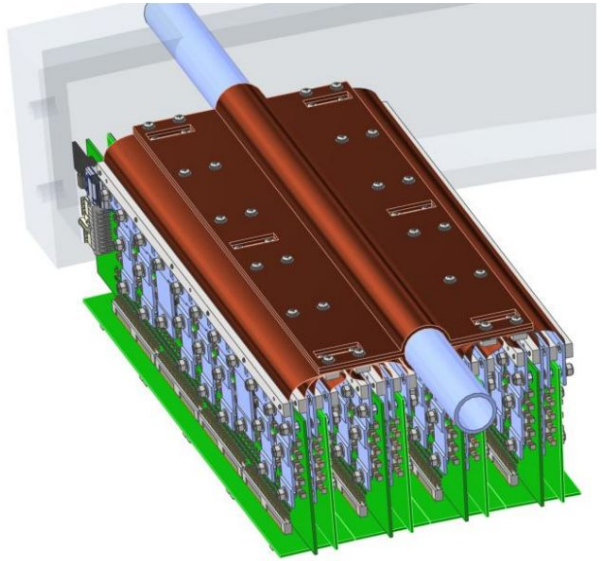






Readout electronics in the cold

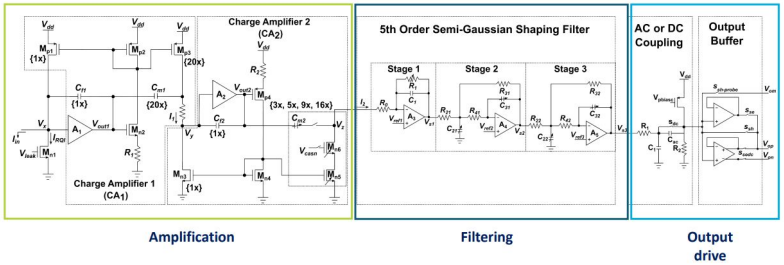
ALLEGRO Ecal barrel: ~2M channels



- Warm electronics outside of cryostat:
  2M cables to route ⇒ avoid if possible

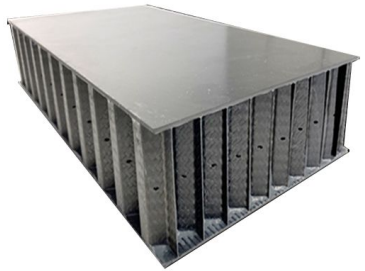
- Cold electronics: fewer cables, digital signals
  - But: needs room for boards + HV, powering and signal cables
  - Proposed solution inspired by DUNE electronics
  - Requires cooling system to dissipate heat

- Cold Frontend ASICs: two designs, based on Dune LArASIC or on CMS HGCROC
  - DUNE: turn a cryogenic-ready design into calorimeter application
  - CMS: turn a calorimeter chip into a lower-power, cryogenic-ready design
  - **Designs submitted for fabrication**

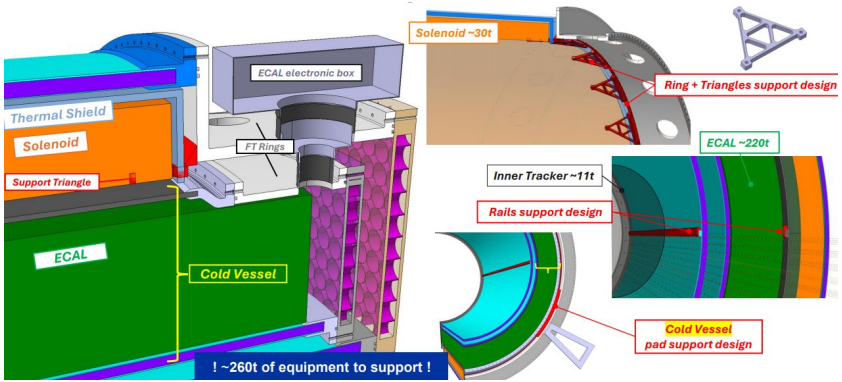


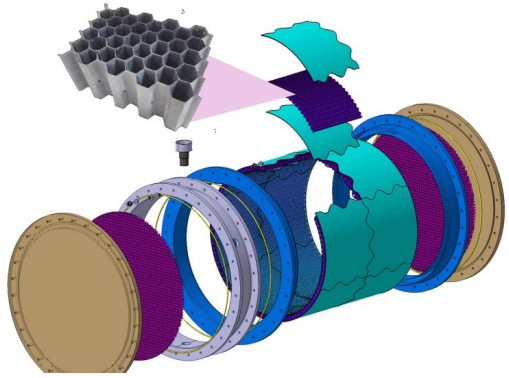
Transparent Cryostat for ALLEGRO Ecal

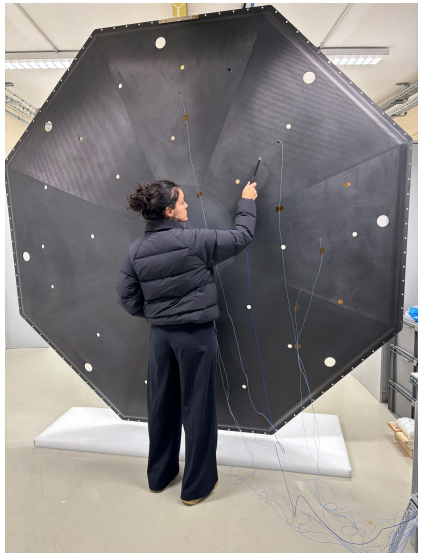
Minimal amount of X_0 ⇒ Investigate solutions based on carbon fiber



- Carbon cryostats developed for aerospace applications
  - But requirements quite different !
- R&D from component level to Engineering Models
  - **Sandwich Carbon layers + honeycomb: 3% X_0 / wall !**
- Design of a cryostat suitable for ALLEGRO in progress
  - With plans for demonstrators



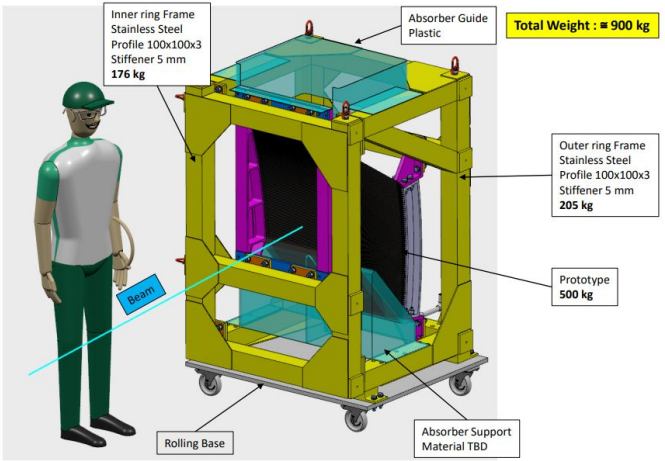


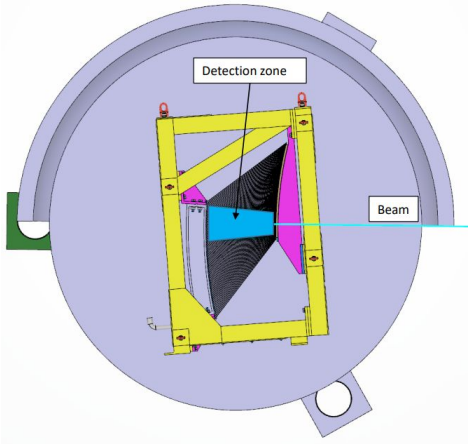


Putting it all together: prototype module

Main goal of the R&D within 5 years

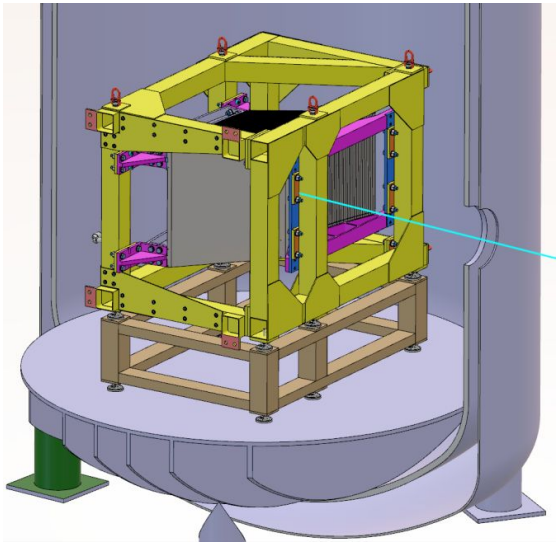
- Prototype representative of a calorimeter section
  - Full **containment of EM showers**
  - Realistic size of support beams
  - 64 electrodes, 65 absorber plates
  - ~5000 channels
- Advanced design of structure used for assembly and support
- Testbeams at CERN
  - Using existing cryostats
  - Post-LS3: 2029 – 2030
  - Coordination of calorimeter testbeams at DRD6 level





Conclusions

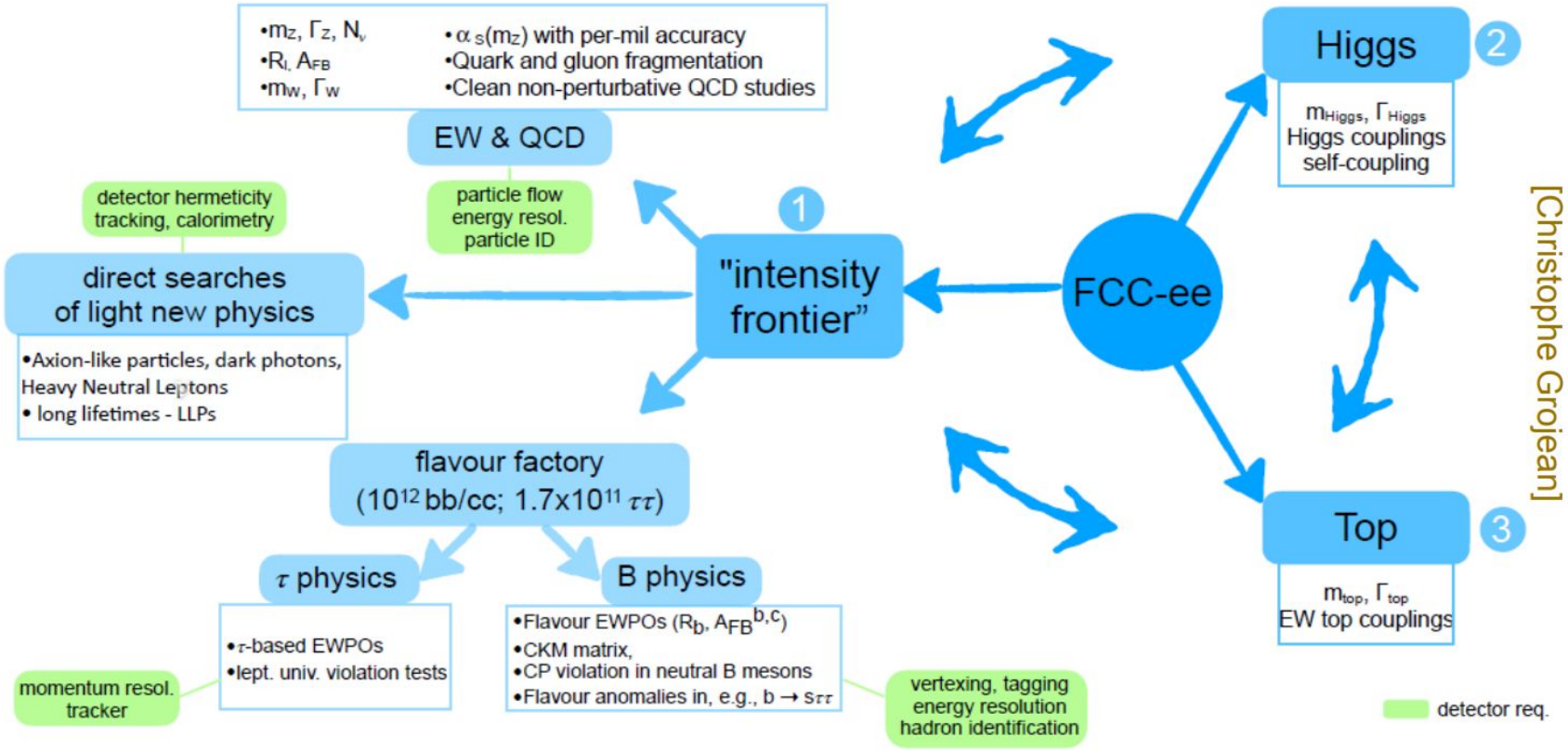
- Noble Liquid EM calorimetry is a very appealing solution for FCC-ee
  - Fulfils **all requirements** of the physics programme
  - Cost-effective
  - Significant progress in simulations to prove all important metrics
- Very active ALLEGRO Ecal R&D
  - As part of DRD6 collaboration
  - Working on all challenges to reach our performance goals
  - Design to be demonstrated by a prototype within 5 years
  - There is still plenty to do !
  - We are **always open to new collaborators !**



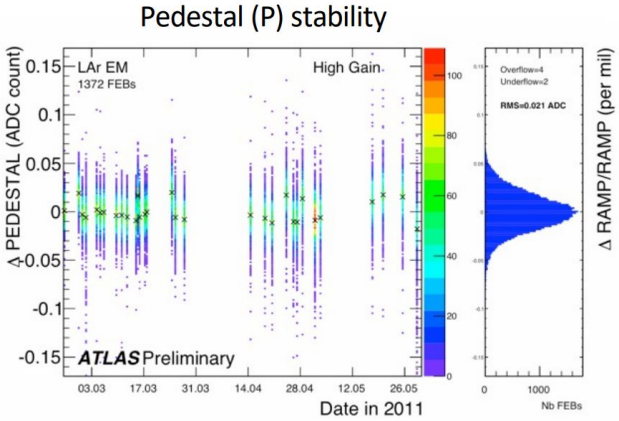
Additional Material

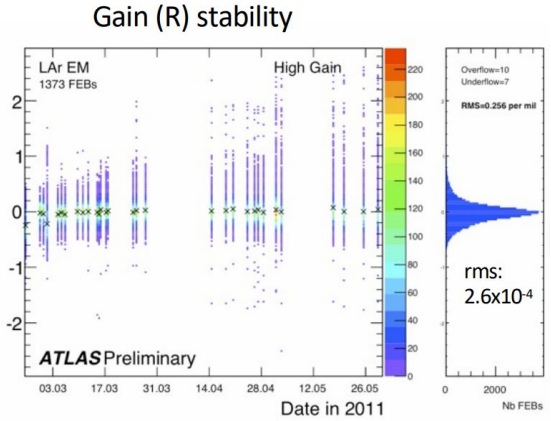
FCC-ee Physics Programme

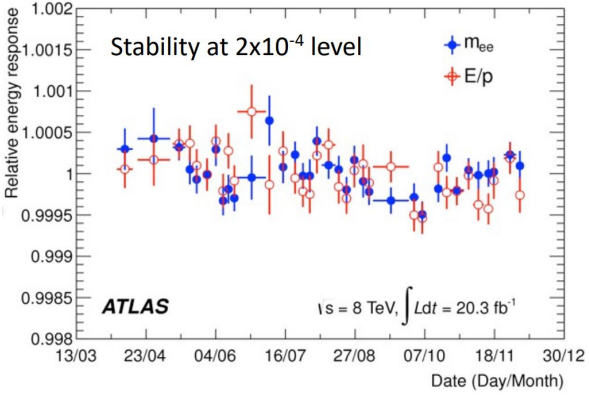
Extremely broad ! Excellent complementarity with HL-LHC



Example: Stability of ATLAS LAr Energy Scale





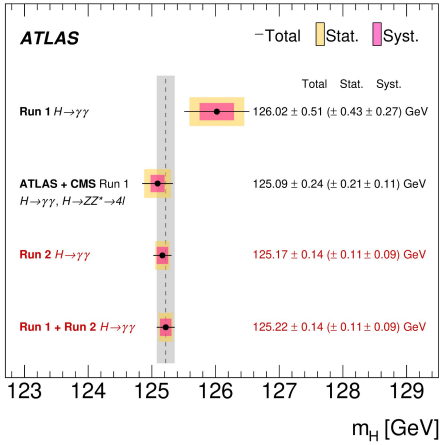


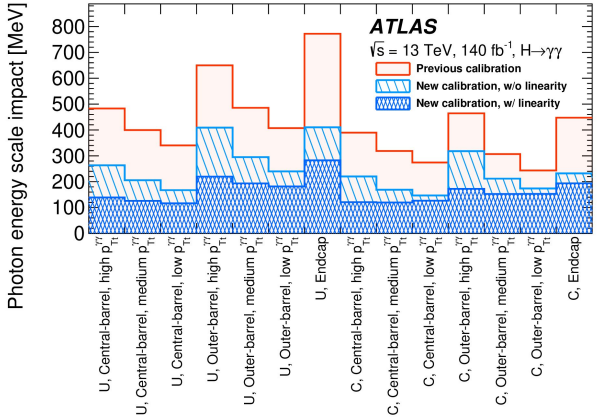
Pedestal stability 100 keV

Gain stability 2.6x10^{-4}

Energy scale stable at 2x10^{-4}

Key to measurement of Higgs mass with 140 MeV precision in H→γγ

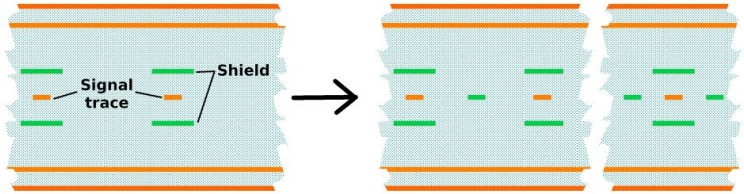


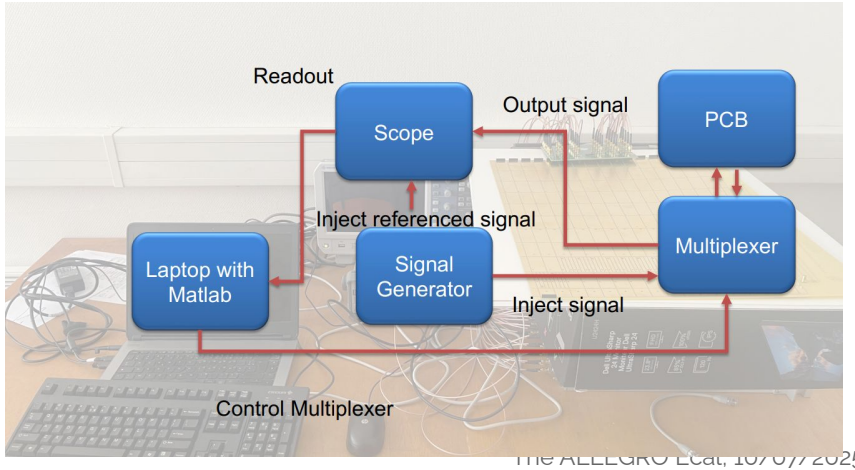


R&D on Electrodes

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

- Large-scale prototypes built with many design options
  - Especially for shielding of signal traces
  - Measured at CERN, IJCLab, BNL





R&D on Electrodes

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

- Large-scale prototypes built with many design options
  - Especially for shielding of signal traces
- Conclusions so far
  - (sub)-**per-mille cross-talk achievable**
  - while keeping reasonable cell capacitances
  - Good agreement with FEM simulations
- Next challenges
  - Distribution of High Voltage (1 – 2 kV)
    - Will investigate resistive layers or resistive ink
  - Design of large electrodes at the end of the barrel
    - Do we still need projectivity ?