Simulation of Noble Liquid Calorimetry Performances

Jiashun Luo[1,2], Farès Djama[1], Emmanuel Monnier[1]

[1]CPPM, [2]IHEP

for the ALLEGRO ECAL team

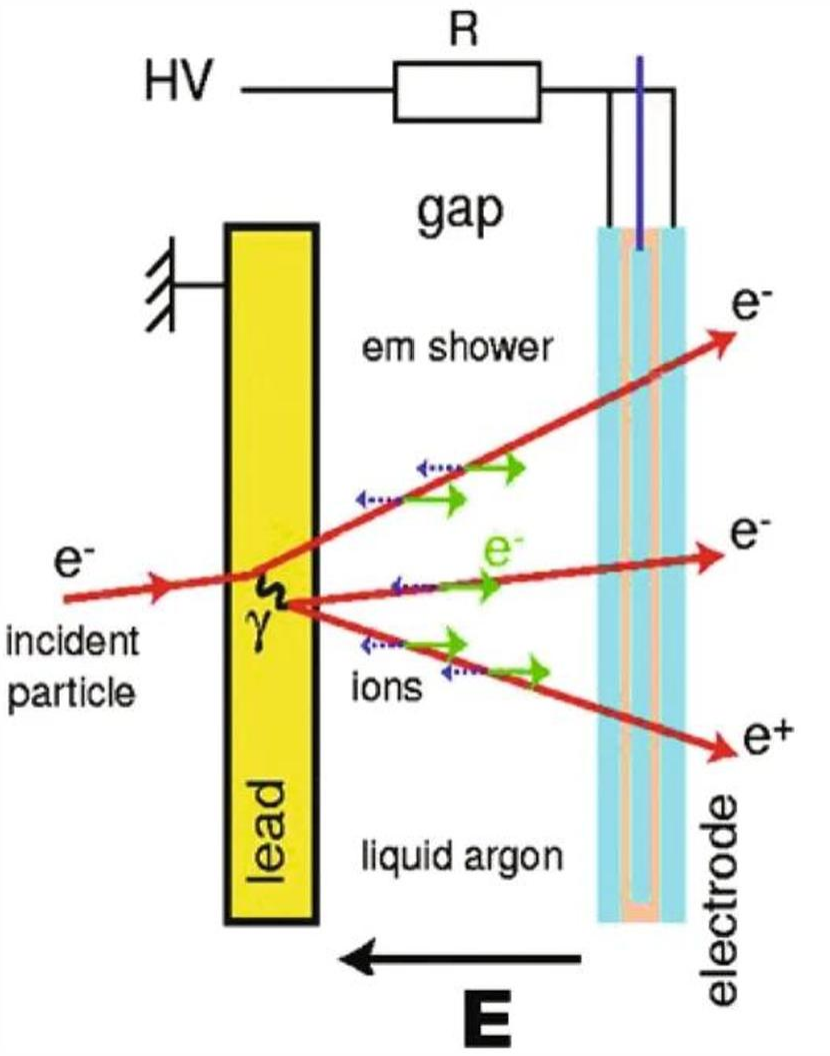
Noble Liquid Calorimeter

Sampling calorimeter: absorber + noble liquid active gap + read-out electrode

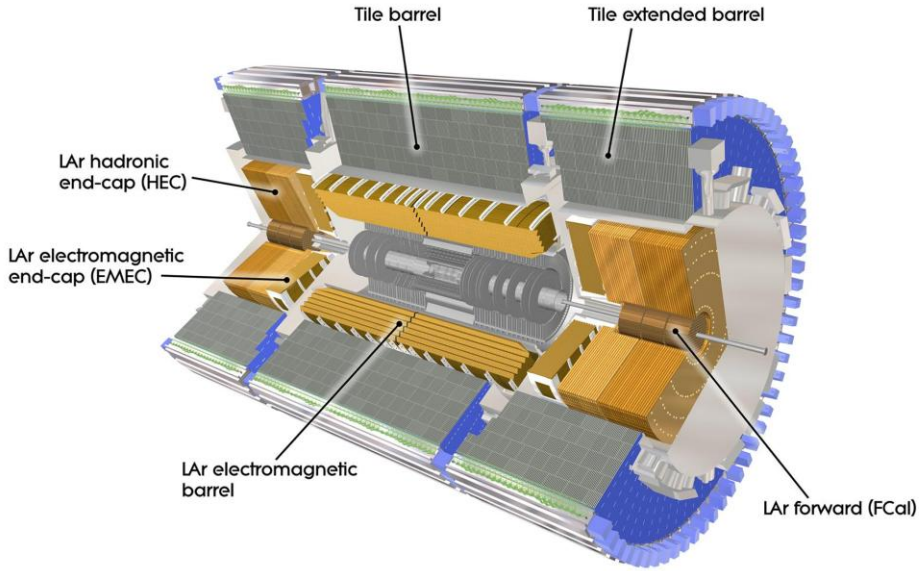
- Absorbers initiate electromagnetic showers
- Ionisation charge develops in noble liquid
- Electrons drift under high voltage to readout electrodes
- Induced current → reconstructed deposited energy

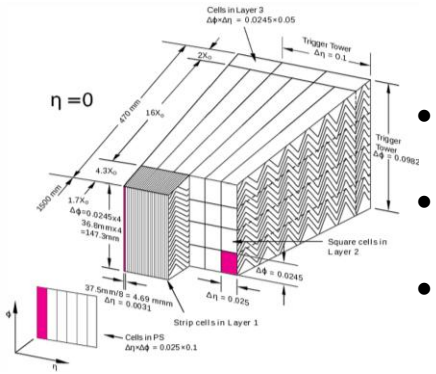
Advantages:

- Good energy resolution
- Linearity, uniformity
- Stability
- Radiation hardness
- Mature technology verified in many HEP experiments
  e.g. D0, H1, NA48/62, ATLAS



Design Evolution toward the FCC-ee ECAL





- Proven LAr technology
- Excellent energy resolution
- Limited granularity is not optimal for Particle Flow

FCC-ee Calorimetry needs:

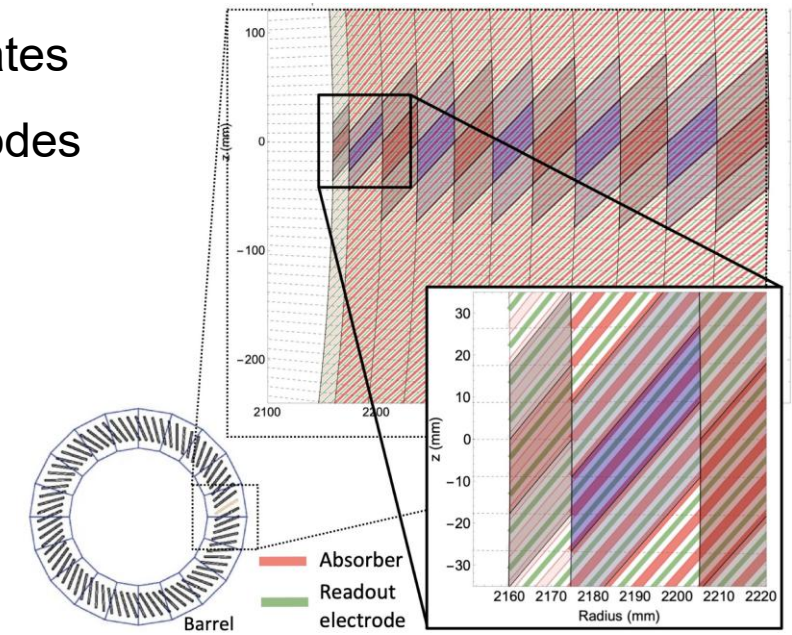
- Jet resolutions ~30%/√E
- γ/π⁰ separation
- Particle-flow

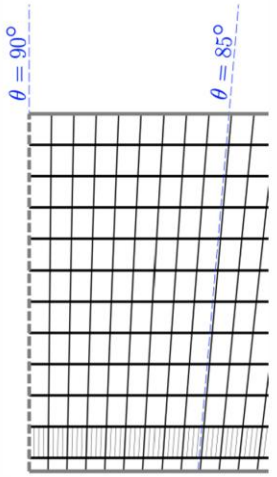
× 10 finer readout granularity than ATLAS ECAL

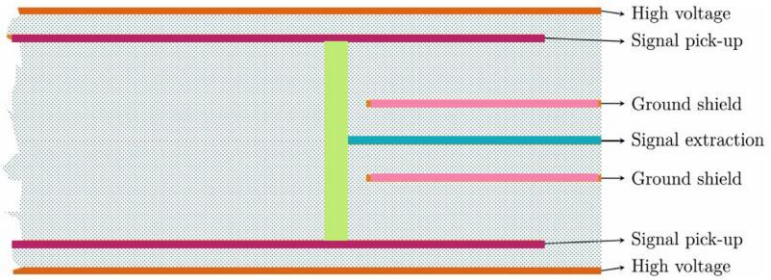
A **L**epton **L**epton collider **E**xperiment with **G**ranular **R**ead-**O**ut

ALLEGRO ECAL Barrel

- 1536 straight inclined(50°) 1.8 mm absorber plates
- Segmented multi-layer PCBs as readout electrodes
- 1.2-2.4 mm noble liquid gaps
- 40cm deep(22 X0)
- Segmentation:
  - $\Delta\theta = 10(2.5)$ mrad in regular(strip) layer
  - $\Delta\phi = 8$ mrad
  - 11 longitudinal layers
- Material choices:
  - Baseline : LAr, Pb absorbers
  - LKr and W absorbers under investigation

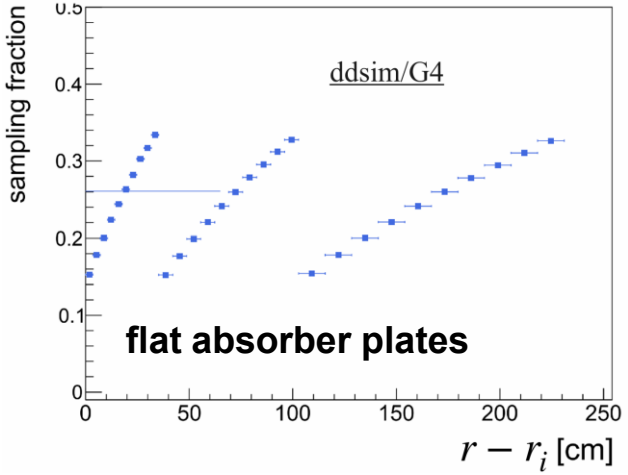


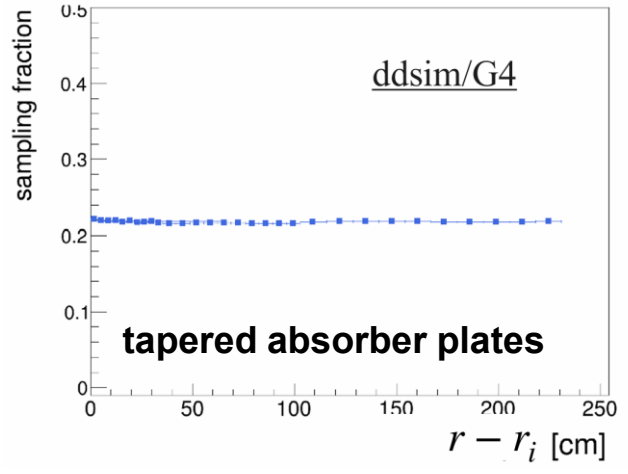


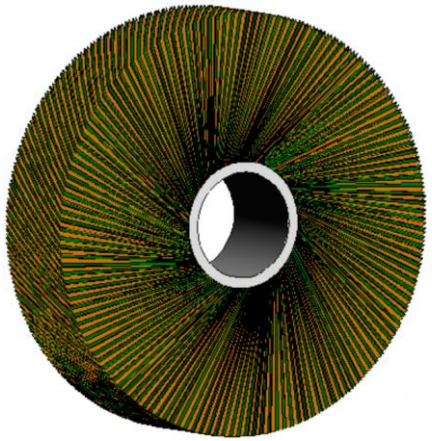


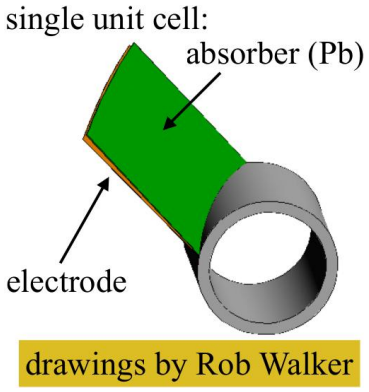
ECAL Endcap

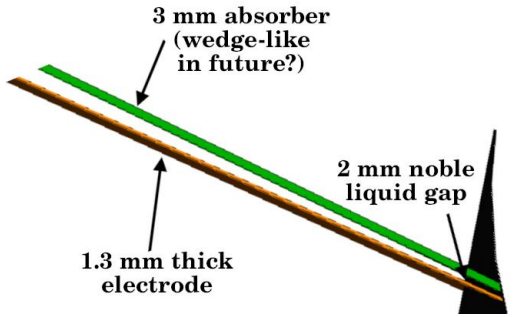
- Similar concept to the barrel
- Turbine-like structure with azimuthally repeated absorber plates
- 420 mm < R < 2750 mm
- 3 nested wheels to mitigate the variation of gaps with radius
- Flat absorber plates / tapered (variable thickness) absorbers(being investigated)







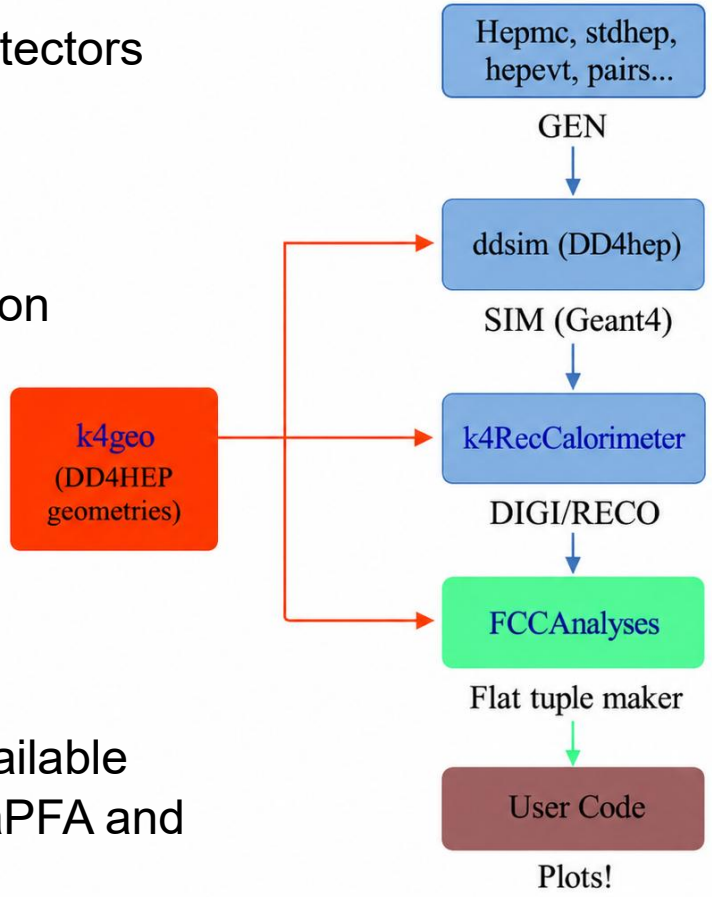




Simulation Tools

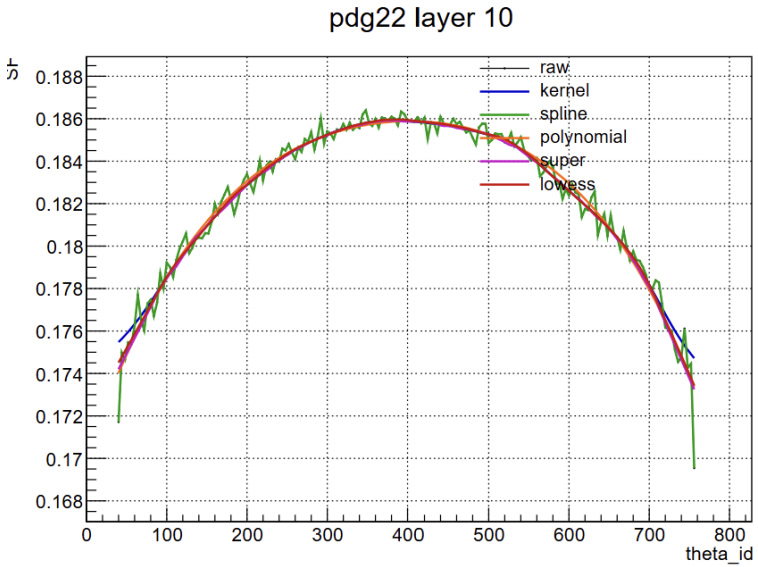
- ALLEGRO simulation is fully integrated in the Key4hep framework
  - Modular approach, ability to simulate with other sub-detectors
- Geometry described with DD4hep / k4geo
  - Detector structure defined in C++
  - Configurable parameters read from XML files
  - Convenient for geometry scans and detector optimization
- Digitization:
  - Electronic noise and cross-talk effects
  - Developments of detailed digitization ongoing
- Reconstruction includes:
  - Sliding window, topological clustering
  - π^0/γ separation
  - MVA-based energy calibration and theta correction available
  - Particle-flow object (PFO) reconstruction with PandoraPFA and ML-PFlow is under development

Simulation and reconstruction chain



Sampling Fraction of ECAL barrel

- Sampling fraction calibrates the active noble-liquid signal to the total energy deposited in the ECAL.
- Layer-dependent SF introduced to account for the depth-dependent sampling structure.
- For e/γ showers, a residual θ-dependent response observed after layer SF calibration.
- EM shower development and the θ-dependent non-uniformity of the projective barrel geometry induces θ dependence.
- Therefore, the layer SF is extended to a layer–θ SF for EM shower calibration.

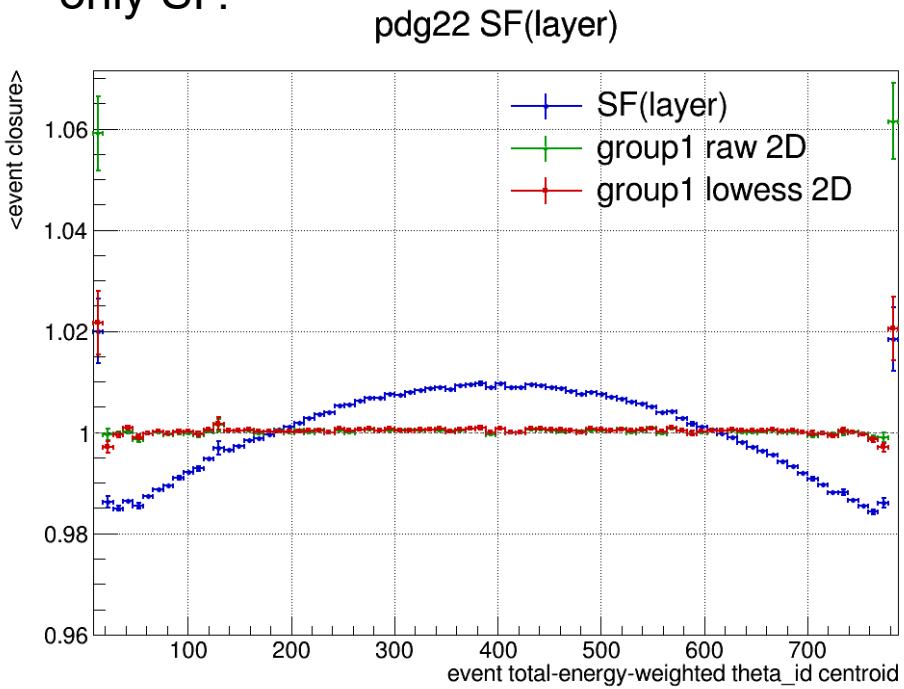


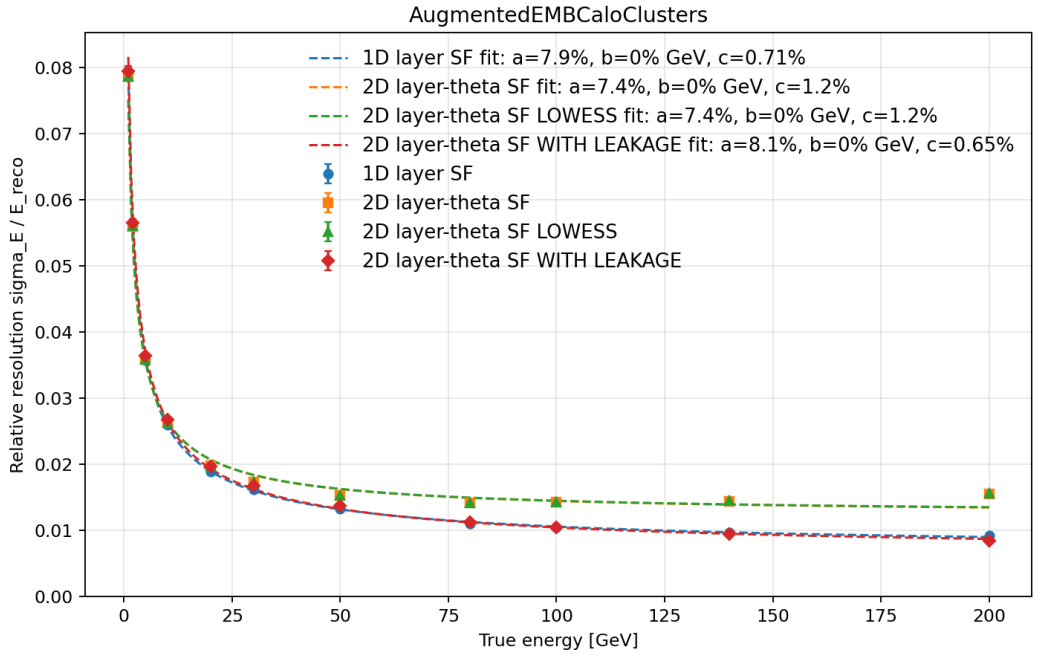
$$\mathrm{SF}(\mathrm{layer_i}) = \text{Gaussian mean of} \frac{\mathrm{E^i_{acitve}}}{\mathrm{E^i_{total}}}$$

$$\mathrm{SF}(\mathrm{layer_i}, \theta_\mathrm{j}) = \frac{< \mathrm{E^{i,j}_{acitve}} >}{< \mathrm{E^{i,j}_{total}} >}$$

Validation of Sampling Fraction

- A layer–θ sampling fraction improves closure to the total energy deposited inside the ECAL.
- To recover the incident particle energy, θ-dependent leakage must also be considered; with this correction, a small improvement in energy resolution is observed compared with layer-only SF.





Energy Resolution of Single Particle

Sampling term(a):

- Depends on absorber thickness, active gap size, material
- Barrel: 8% with baseline option (Pb + LAr), ~5-6% achievable with Pb/W + LKr

Noise term(b):

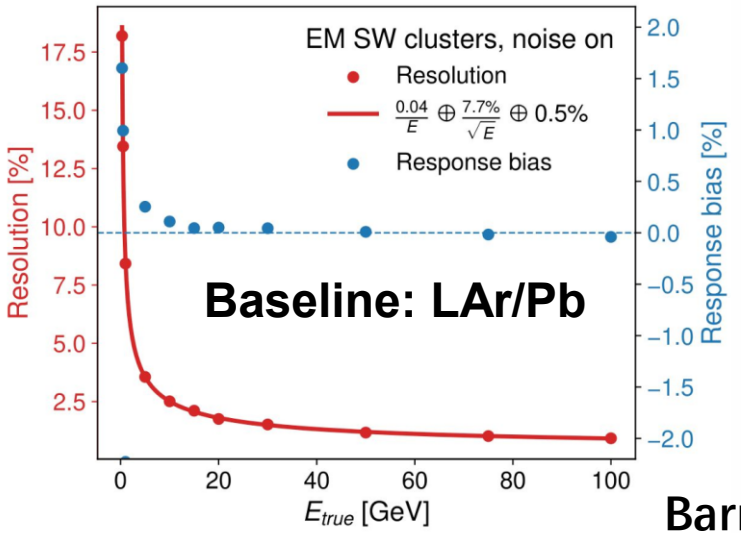
- Dominates the energy resolution at low energies(down to 200 MeV)
- Dominated by readout electronics and detector conditions, including capacitance (C_d), temperature (T), and peaking time (τ_p).

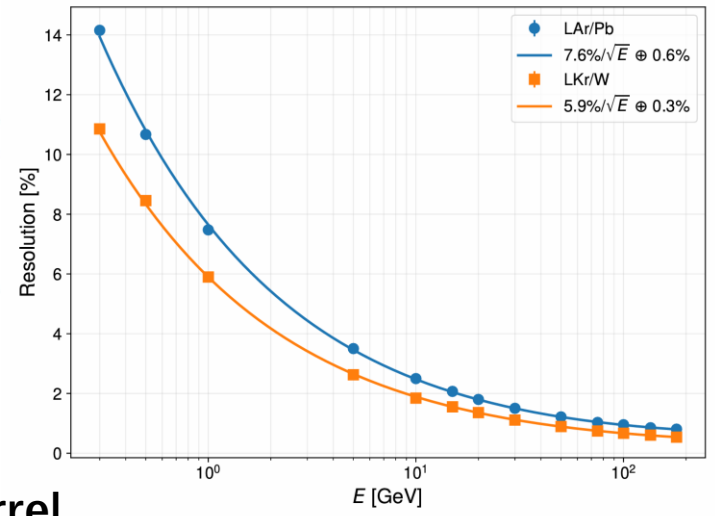
Constant term(c) :

- Upstream material,
- Longitudinal leakage
- non-uniformity

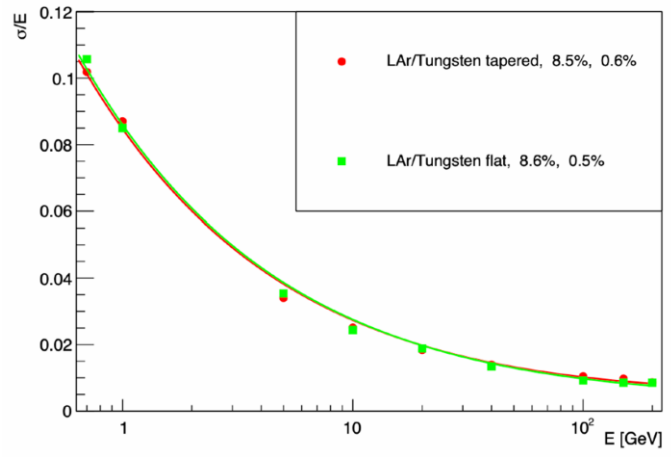
$$\frac{\sigma_E}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c$$

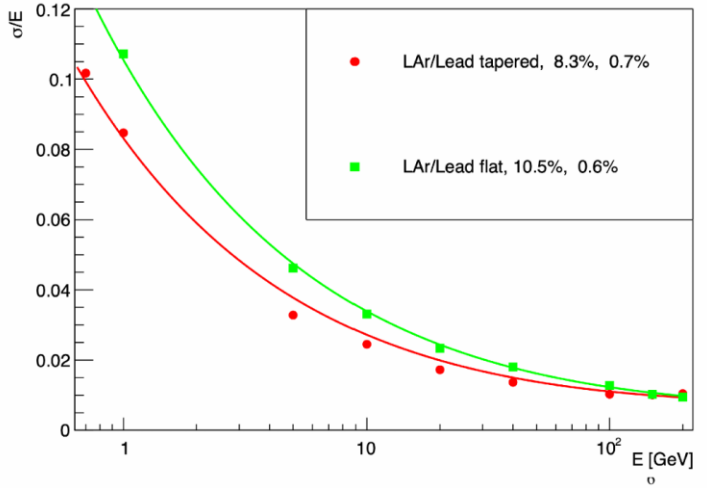
$$Noise \sim C_d \sqrt{\frac{4kT}{g_m \tau_p}}$$





Barrel

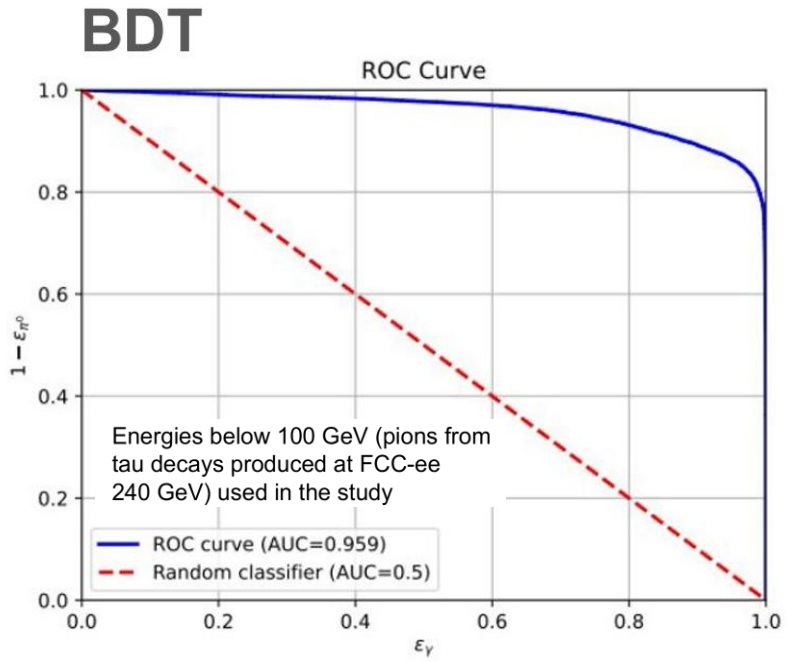


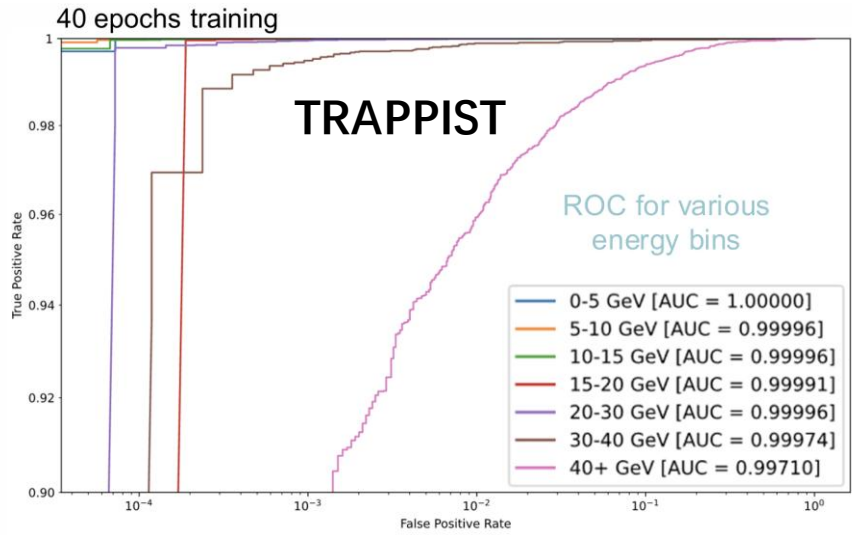


Endcap

γ/π^0 Separation

- **Critical for**
  - Background rejection
  - Tau hadronic decay mode identification (Z → tau tau, H → tau tau)
  - Axion-Like Particles searches
- **BDT baseline**
  - Uses reconstructed cluster energy and shower-shape variables.
  - Targets unresolved π⁰ showers after resolved π⁰ reconstruction with invariant-mass-based cluster pairing.
  - Reference performance: AUC ≈ 0.959
  - Performance is excellent for single-π⁰ identification, while multi-π⁰ decay modes remain challenging because of merged showers and clustering ambiguities.
- **Transformer-based model TRAPPIST**
  - Uses calorimeter hit position and energy inside selected clusters.
  - Geometric Algebra Transformer: hits treated as graph nodes and encoded as geometric objects.
  - Photon ID eff. >99.5% with <1% mis-identification of π^0
- **Studies used for the optimization of the position of the strip layer**





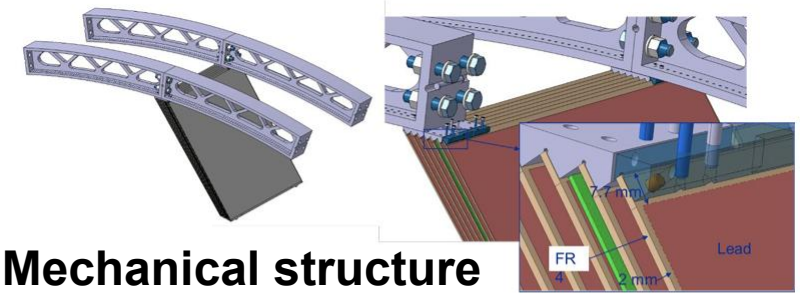
Summary

- Noble-liquid calorimetry is a mature and robust technology for future high-precision lepton-collider experiments.
- The ALLEGRO ECAL design combines proven LAr calorimeter performance with much finer granularity for FCC-ee physics requirements.
- The current simulation framework enables detailed studies of geometry, calibration and reconstruction performance.
- Single-particle energy resolution, γ/π^0 separation and particle-flow reconstruction provide key benchmarks for the ECAL design.
- Calibration studies, such as fine sampling-fraction and leakage corrections, are part of the ongoing effort to validate and optimize the detector response.

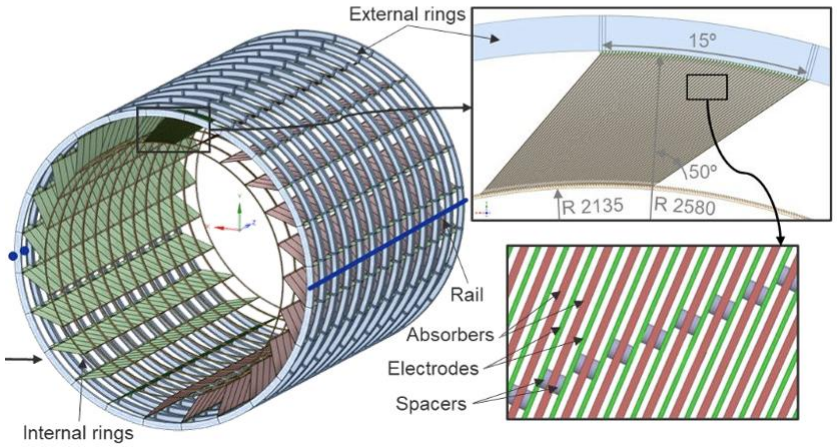
backup

Hardware R&D

Not a complete overview!

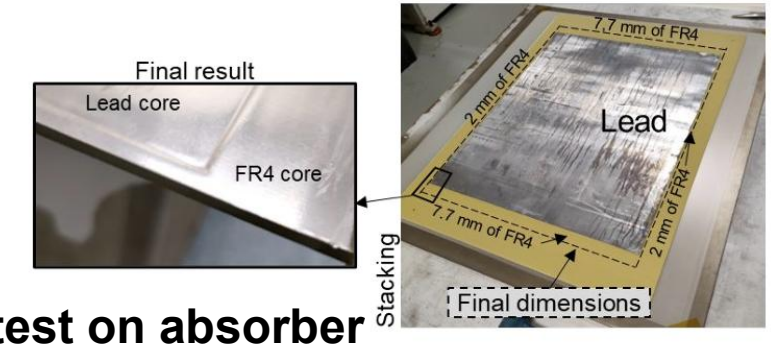


Mechanical structure

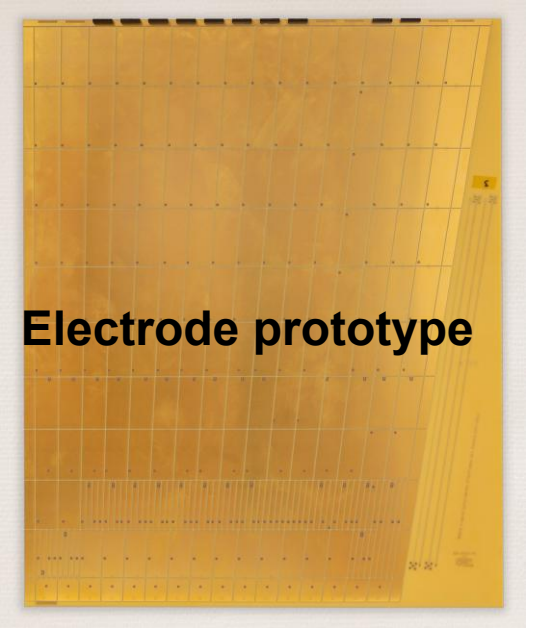


Lightweight cryostat

Electrical bench test



Cold test on absorber



Electrode prototype