R&D on Noble Liquid Calorimetry for FCC

FCC Physics and Experiments workshop

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Noble Liquid Calorimetry Group
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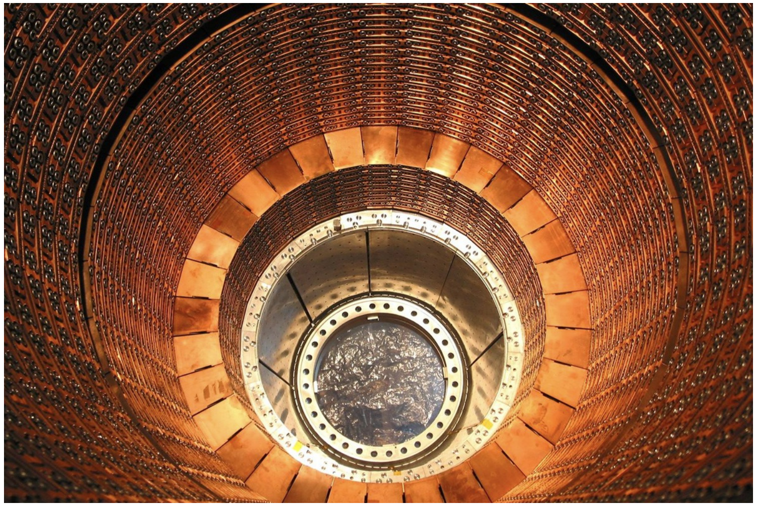
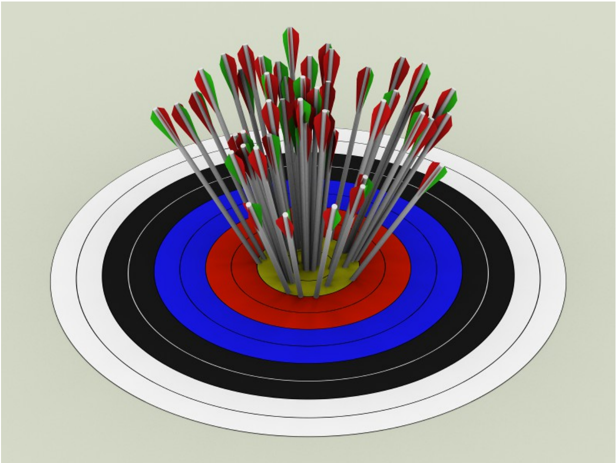
Nov 11th, 2020

Noble liquid calorimeters

- Why Noble Liquids calorimeters?
  - Well proven technology
    - ATLAS LAr calorimeter operating very successfully since the start of the LHC
  - High energy/timing resolution
  - Radiation hardness
  - Control of systematics
    - Linear response w.r.t. incoming energy
    - Stability over time
- CERN EP R&D work package "3.1 Liquid-Argon Calorimetry"
  - Mandated to bring this technology towards future experiment requirements





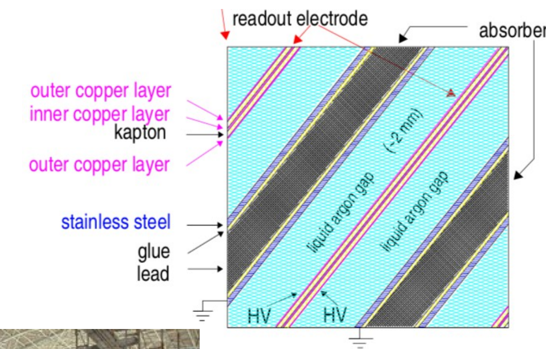
Outline

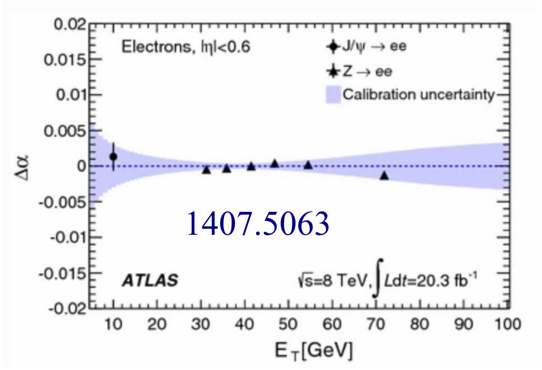
- Existing Noble Liquid calorimeter
  - ATLAS
- FCC-hh
  - Reference detector
  - Electrode design
    - Noise estimation
- FCC-ee
  - Requirements
  - Updated design
  - FCCSW

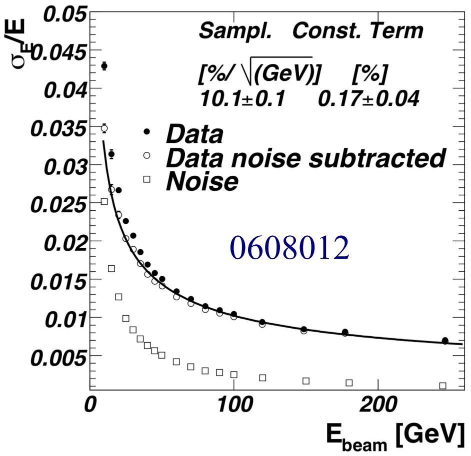
Focus on the Barrel ECAL

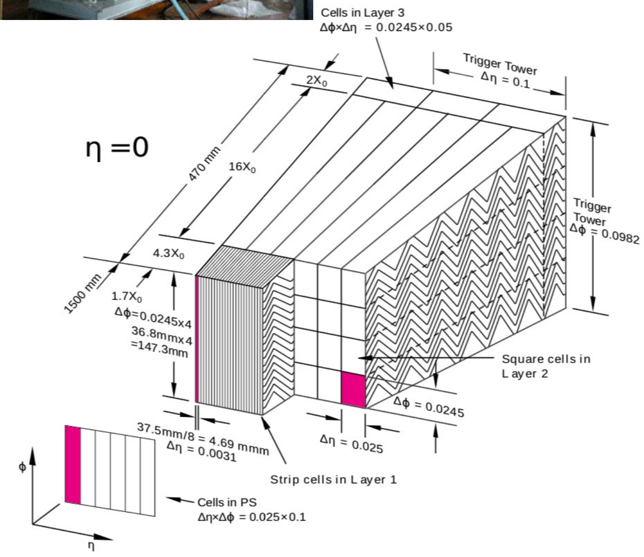
ATLAS LAr calorimeter

- ATLAS LAr calorimeter
  - Sampling calorimeter
  - Lead absorbers, LAr active gaps, Kapton electrodes with accordion geometry, everything inside a cryostat bath
- Longitudinal segmentation
  - Pre-sampler for upstream material correction, layer 1 with higher granularity (strip layer) for π^0 rejection, thick layer 2 for the shower bulk, thin layer 3 to estimate shower leakage
- Design energy resolution $\frac{\sigma(E)}{E} = \frac{10\%}{\sqrt{E}} \oplus \frac{0.2}{E} \oplus 0.2\%$
- Linearity: energy scale variation within ~10^{-3} over large E_T range









What/how do we want to improve?

- Future experiment design has to make sure one can optimally exploits every sub-detector complementarity with **particle flow** algorithms
  - **Particle Identification**
    - High transverse and longitudinal granularity (shower imaging)
      - π^0/γ separation
      - Good cluster/track association (position and direction resolution)
      - Avoid shower merging from close-by particles

- The figure of merit used to optimize the detectors have to be aware of the 'global event description'
  - E.g. energy resolution
    - Electrons: dominated by tracker
    - Muons: tracker + muon chambers
    - **Photon: ECAL**
    - Jets: dominated by neutral hadron energy resolution (HCAL)

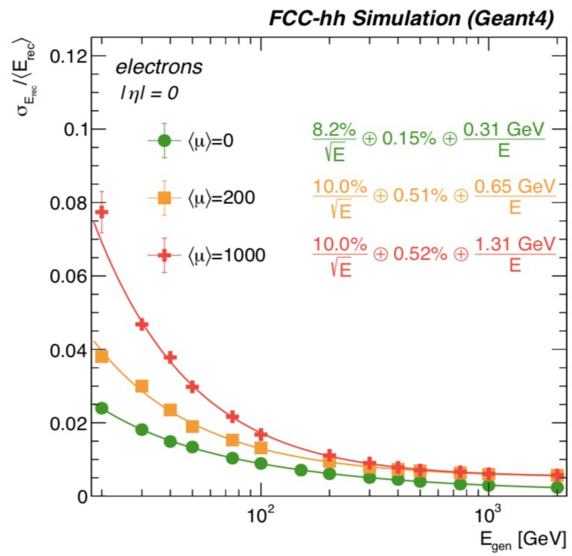
Component	Detector	Energy Fract.	Energy Res.	Jet Energy Res.
Charged Particles ($X^{\pm}$)	Tracker	$\sim 0.6\,E_j$	$10^{-4}\,E_{X^{\pm}}^2$	$< 3.6 \times 10^{-5}\,E_j^2$
Photons (γ)	ECAL	$\sim 0.3\,E_j$	$0.15\,\sqrt{E_\gamma}$	$0.08\,\sqrt{E_j}$
Neutral Hadrons (h^0)	HCAL	$\sim 0.1\,E_j$	$0.55\,\sqrt{E_{h^0}}$	$0.17\,\sqrt{E_j}$

0907.3577

FCC-hh

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



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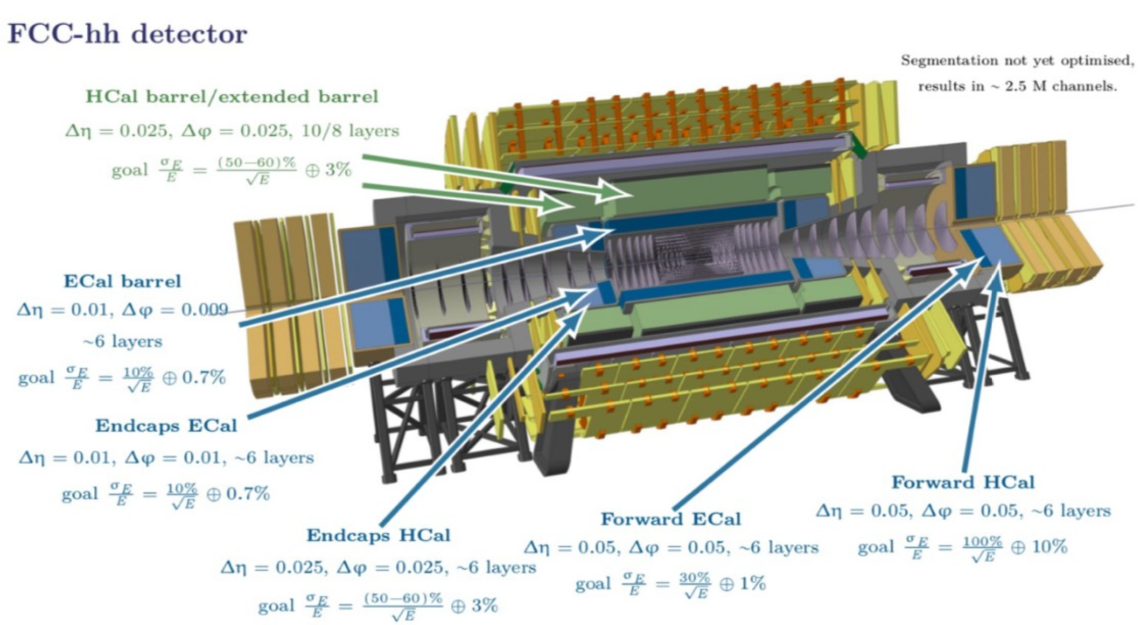
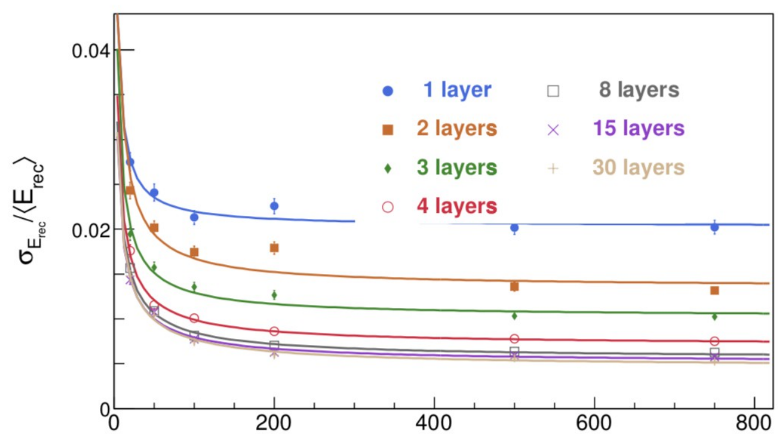
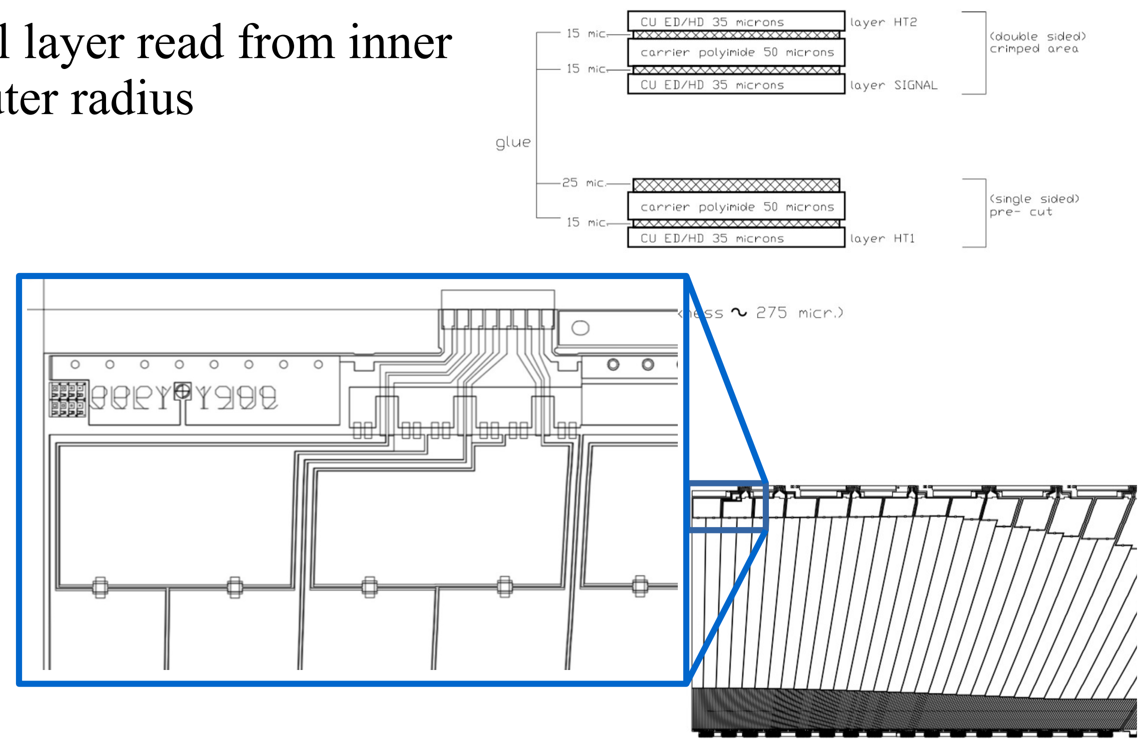


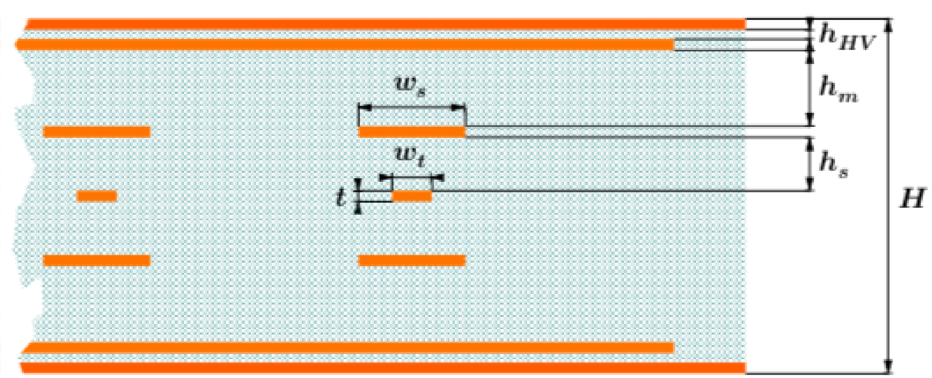


A. Zaborowska

High granularity electrodes

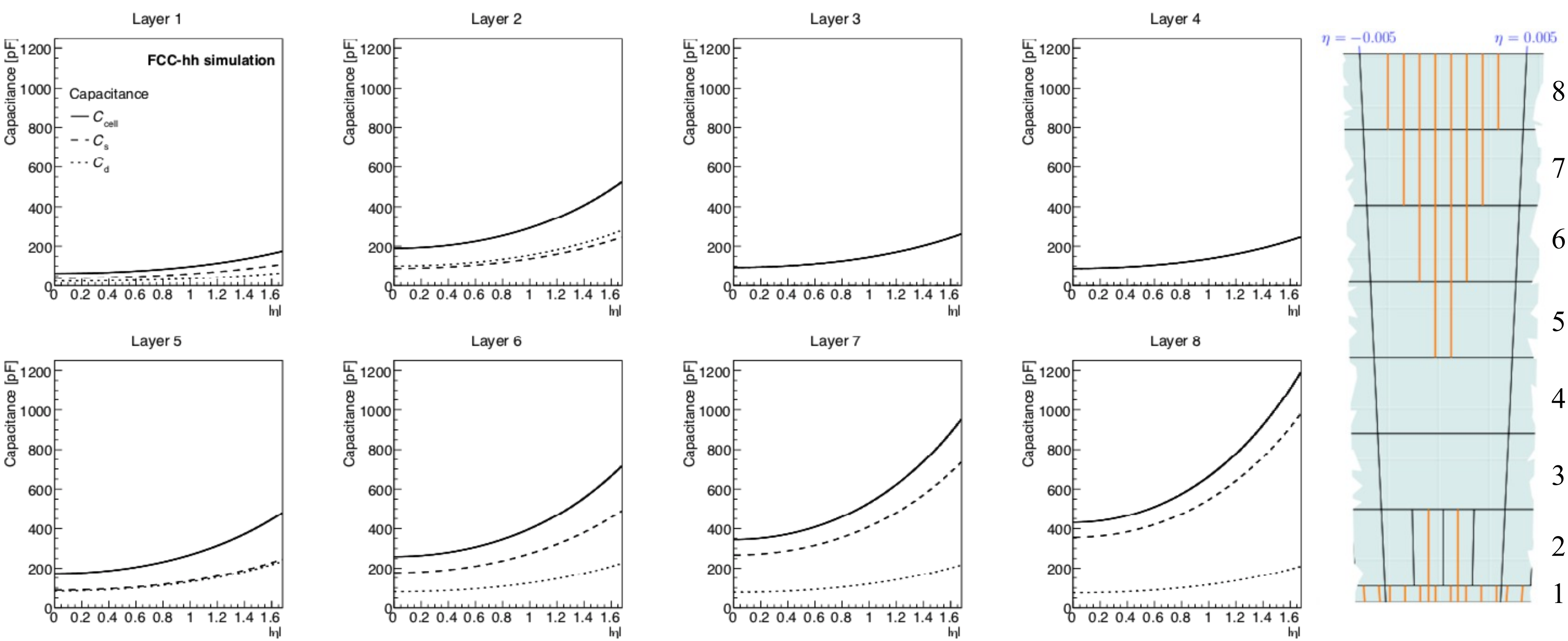
- ATLAS signal extraction: first longitudinal layer read from inner radius, middle and back layer read from outer radius
  - Kapton electrode implementation
    - 3 layers glued together
    - 2 HV layers + 1 signal layer
    - Signal traces must be routed via the edge of the cells to avoid cross talk with the next layer
    - Longitudinal granularity limited by trace density
- Higher granularity can be achieved thanks to multi-layer PCB electrode
  - Prevent cross talk when a trace runs beneath other signal pads with ground shields
  - Increases the capacitance
    - $C_{cell} = C_{shield\text{-}pad} + C_{detector}$
- Higher granularity means also more signal traces to extract from the cryostat
  - See Maria's talk about high density feedthrough!





Electronic noise

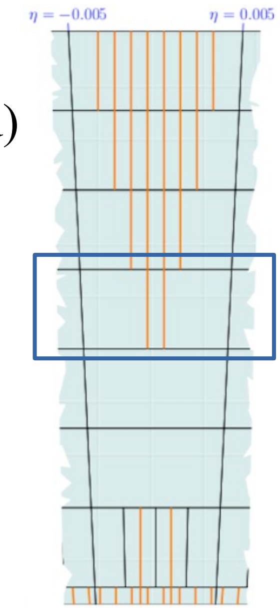
- Electronic noise estimation
  - Noise-capacitance relationship derived from present ATLAS calorimeter
  - Capacitance derived from analytical formulas: 100 – 1000 pF
  - 4 - 40 MeV noise per read-out channel assuming ATLAS like electronics

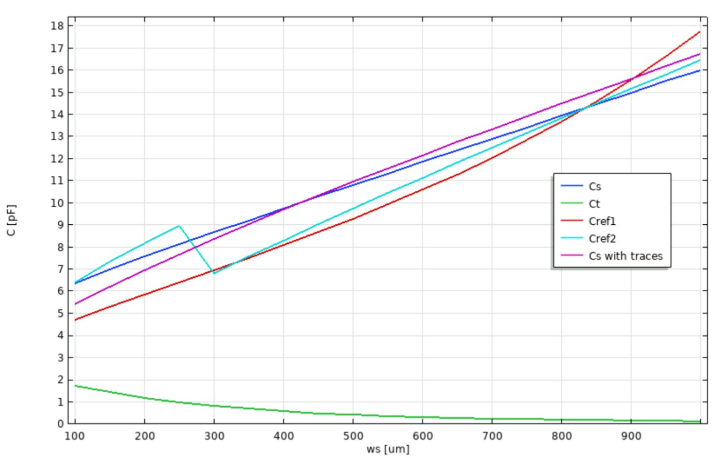


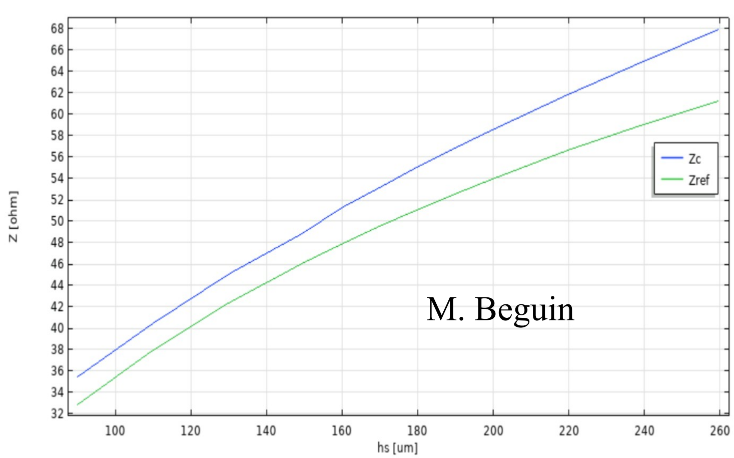
A. Zaborowska, J. Faltova

Electrode in-depth study

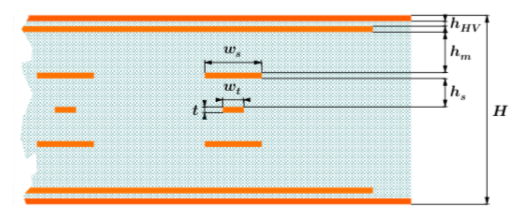
- Validation of the capacitance estimation and further studies
  - Implemented layer 5 of the electrodes in COMSOL® (finite element method)
  - Shield-pad capacitance as a function of the shield width
    - Values found in good agreement with the analytical formulas
  - Trace-shield transmission line impedance as a function of h_s
    - Also in reasonable agreement with analytical formulas used so far
    - Target 25-50 Ω
  - Will also use this model to extract cross-talk
  - Initiating also an alternative approach with CERN PCB Lab

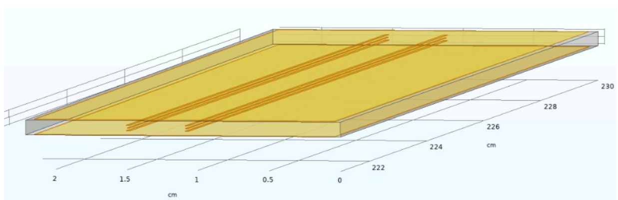






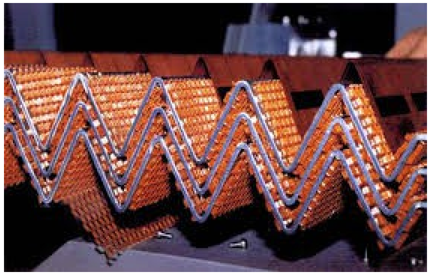
M. Beguin



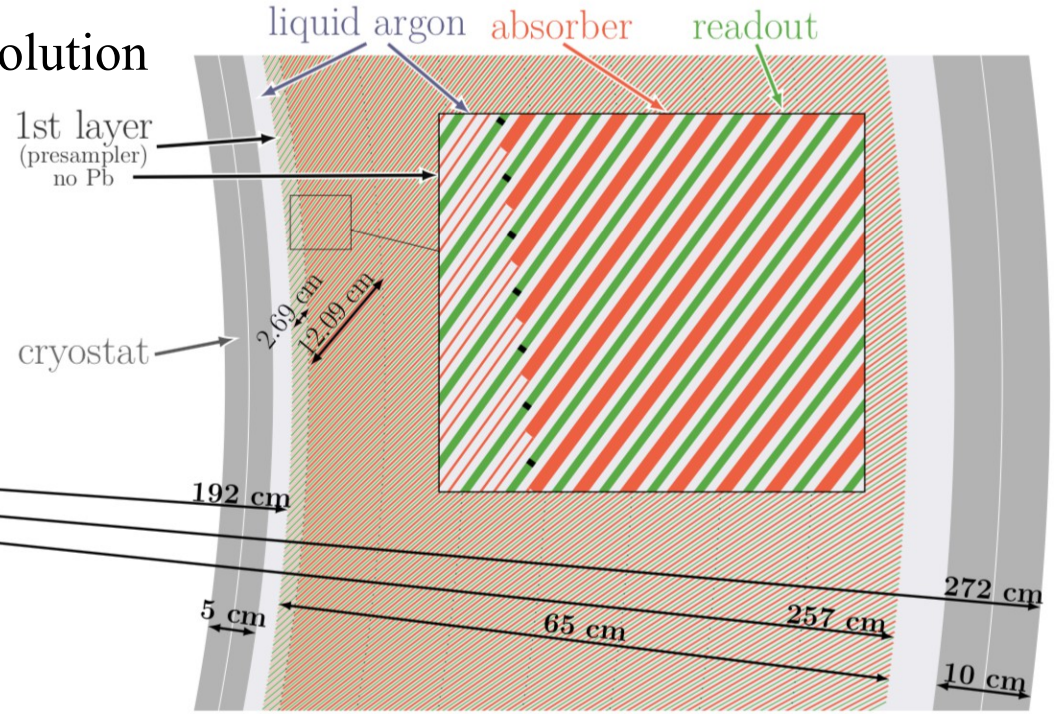


Geometry design

- Accordion geometry (ATLAS)
  - Not suited for PCB mechanical rigidity (ATLAS uses Kapton)
  - Mechanical complexity induces detector non-uniformities degrading energy resolution



- Solution: plates inclined w.r.t. the radial direction
- Inclination choice based on energy resolution
  - Small angle
    - Low sampling frequency
    - Phi non-uniformity
  - Large angle
    - Longer trace → signal attenuation, noise
  - Chosen trade off: 50°



A. Zaborowska

FCC-ee

Noble Liquid Calorimeter for FCC-ee

FCC-ee requirements

- Very small statistical errors call for high control over systematics
  - Noble liquid calorimeters nicely suited for that
  - Stability over time and linearity
    - Huge statistics to derive calibration parameters
    - Mitigate energy and time dependance of the calibration

Table 1: The observed impact of the different uncertainties on the measurement of m_{H}

Source	Contribution (GeV)
Electron energy scale and resolution corrections	0.10
Residual p_{T} dependence of the photon energy scale	0.11
Modelling of the material budget	0.03
Nonuniformity of the light collection	0.11
Total systematic uncertainty	0.18
Statistical uncertainty	0.18
Total uncertainty	0.26

CMS crystals
2002.06398

- EM resolution
  - 10-15%/√E deemed sufficient for many studies, easily achievable
  - Will still try to improve it as much as possible (5%/√E could be needed for rare processes, B physics, $Z \rightarrow \nu_e\nu_e$, …)

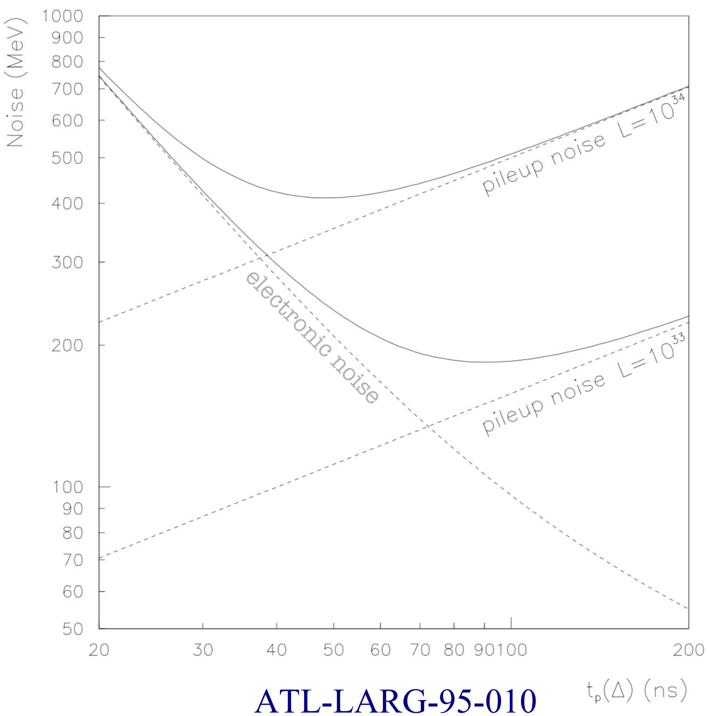
Roy Aleksan

- Excellent jet energy resolution (30%/√E) 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)

Noble Liquid Calorimeter for FCC-ee (II)

FCC-ee requirements

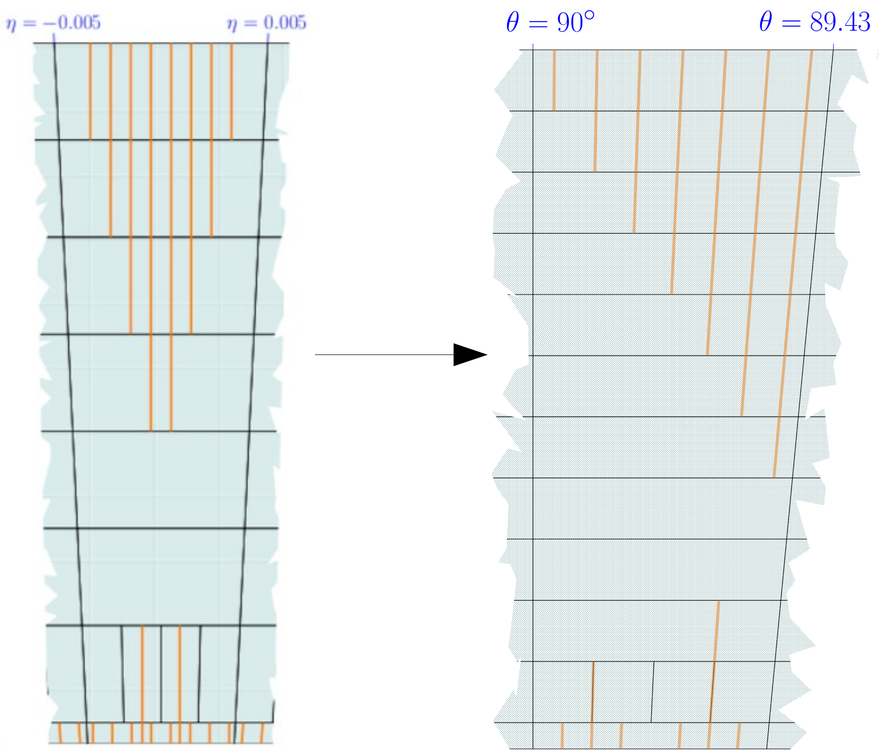
- Measure particles down to 300 MeV
  - Little material in front of the calorimeter
    - WG 4.4 “Ultra-light cryostat studies”: Maria's talk
  - Keep noise term low (b << 300MeV)
    - Can probably afford longer shaping time to reduce elec. noise (no PU)
    - Detailed electrode and readout chain study
- Time resolution
  - ATLAS LAr: 150 ps achieved for EM showers ≥ 30 GeV, 65 ps for EM showers ≥ 100 GeV
  - No in-time PU to remove
  - Heavy stable charged particles (slow moving) probably do not need such a resolution
  - Study to be done



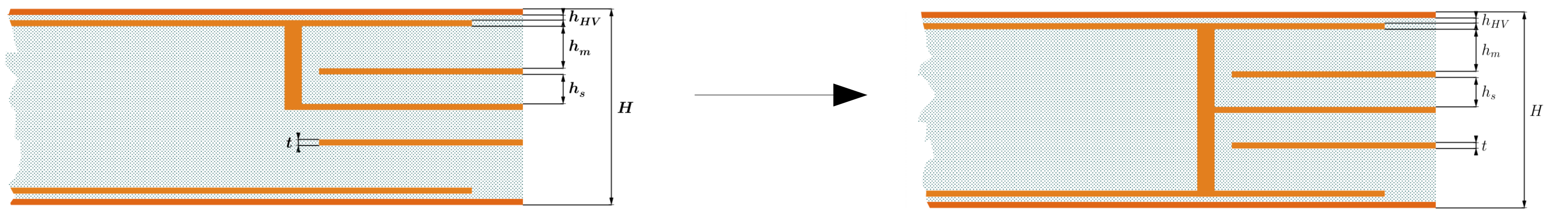
ATL-LARG-95-010

FCC-ee Electrode Design

- Updated electrode design (barrel ECAL)
  - Investigating an even higher longitudinal granularity compared to the reference FCC-hh design
    - Mitigate the impact on the number of signal traces by reading two signal pads with one trace
    - Lower the number of traces extracted from front
      - Noise term dominate for low energy particles which deposit their energy mostly in the early layers
  - Will derive electronic noise and cross-talk with the simulation tools mentioned earlier

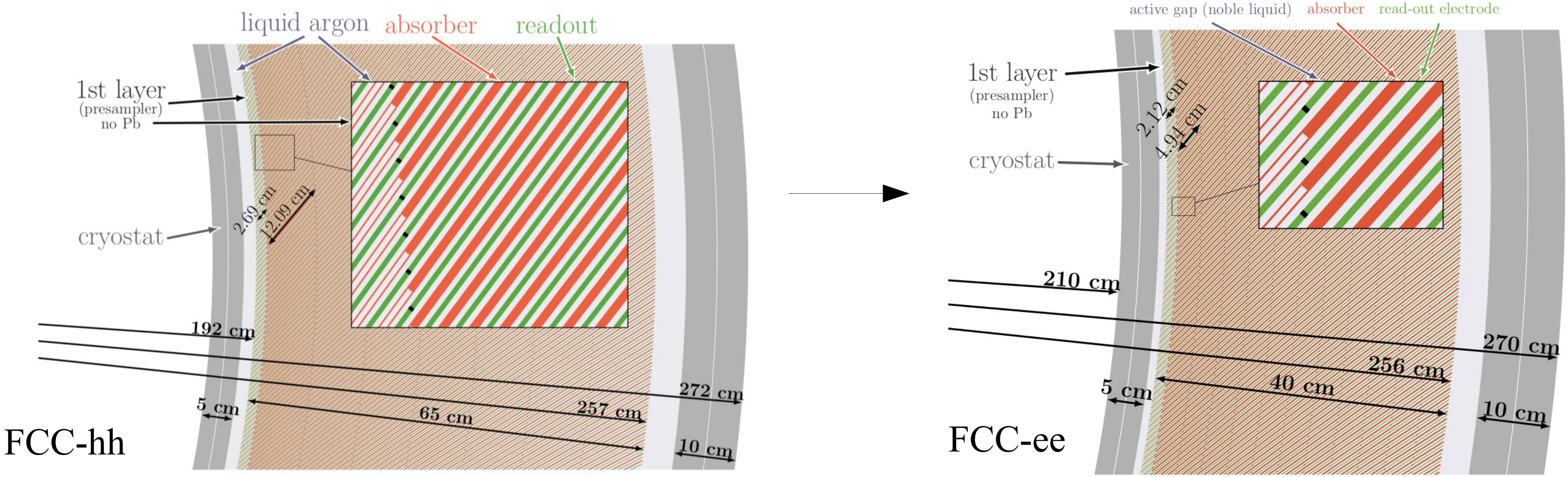


Horizontal axis dilated by a factor 10



FCC-ee Barrel ECAL Geometry

- Main changes w.r.t. FCC-hh geometry design
  - Low energy particles (≤ 182.5 GeV)
    - 22 X_0, 7 λ sufficient
  - Bigger tracker → inner ECAL radius pushed further (185 cm → 210 cm)
  - 1536 cells (2 mm Pb absorber, 1.2 mm readout, 1.24 mm gap x 2), 22 X_0 reached after ~40 cm radial depth and ~50 cells crossed by a straight trajectory at θ=90°
    - Δθ ~ 9.8 mrad, ΔΦ ~ 8 mrad if one reads two cells per channel
    - Will perform the optimization with FCCSW Full Sim: granularity, sampling frequency, sampling fraction, active material (Krypton, …), absorber material
      - E.g. using W instead of Pb → radial depth decreases by ~13 cm



FCCSW for FCC-ee ECAL optimization

V. Volkl
J. Faltova

- LAr ECAL barrel already implemented in the FCCSW Full Sim IDEA detector description
  - New FCC-ee geometry is being propagated
  - Can already perform simple studies (e.g. ECAL energy resolution for different geometries)
- Will need further developments before comprehensive optimization can be done
  - Object reconstruction/Particle Flow
  - Investigate new clustering algorithms
  - Optimal detector specs can only be derived within a realistic global event reconstruction
- Currently porting the calorimeter reconstruction to EDM4hep
- Future plans: detector requirements from physics studies
  - Starts with ECAL related key aspects common to several physics analyses (e.g. γ/π^0 separation)
  - Possibly move to a more thorough physics analysis in a second phase
    - $Zh\gamma$ coupling, $\gamma\gamma$ resonances (Axions, …), tau physics, $Z \rightarrow e\mu$,…

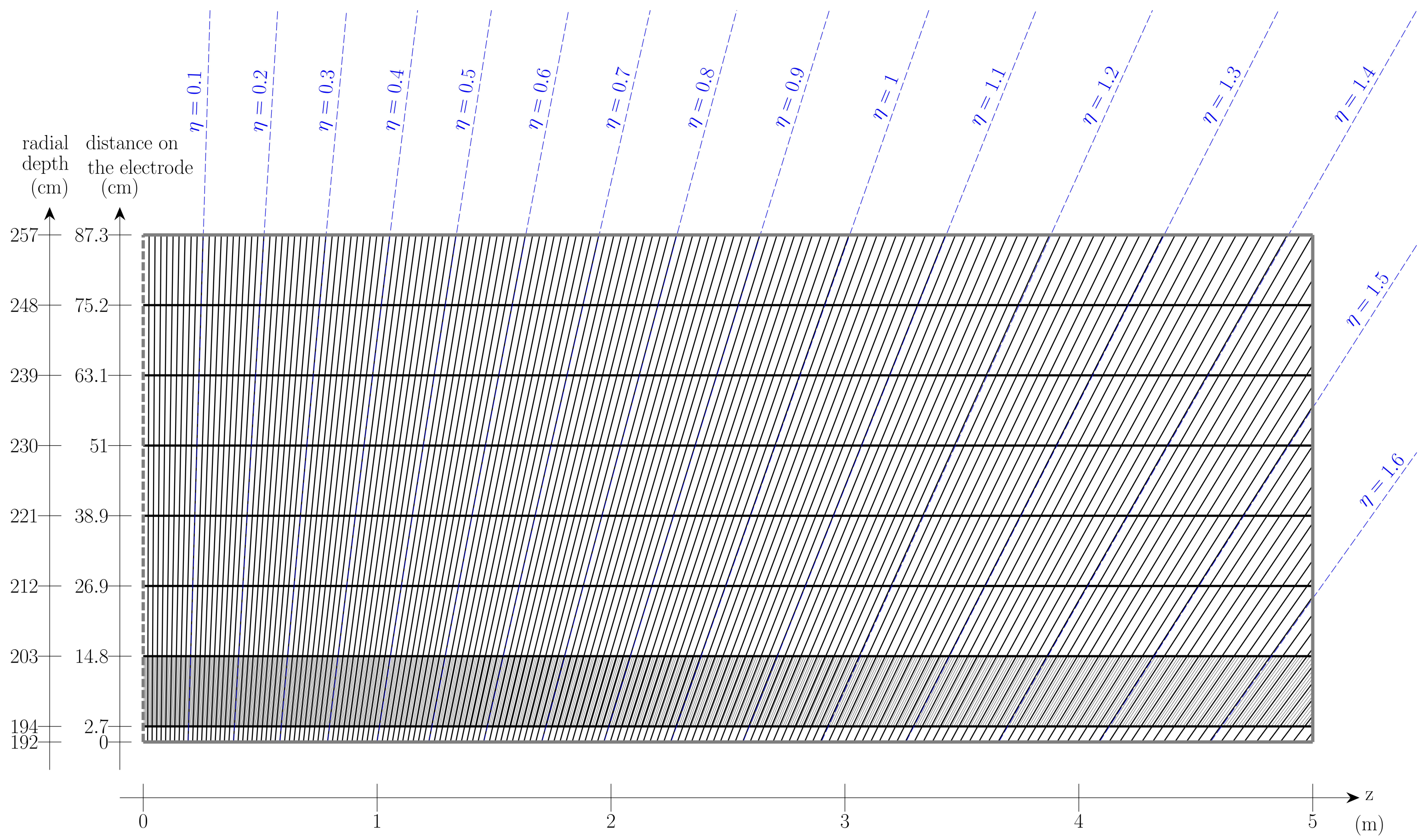
More details in
Clement's talk

Conclusions and Outlooks

- Noble liquid calorimetry is a state of the art technology that has been successfully implemented in a large scale collider experiment (ATLAS)
- New concept for noble liquid calorimeters to merge excellent conventional calorimetry with high-granularity needs of future experiments
- A LAr based calorimeter has shown to meet the FCC-hh requirements and is included in the reference design
- Focus is now on evaluating its strengths and feasibility for FCC-ee
  - Keep systematics under control as much as we can
    - Noble Liquid calorimeter is a nicely suited technology (stability, linearity, …)
  - Measure low energy particles
    - Keep noise term under control → detailed electrode (and readout electronics) modeling
  - Starting optimization campaign with FCCSW Full Sim: granularity, absorber material, active material, sampling fraction and frequency, …

Additional material

FCC-hh electrode segmentation



FCC-ee CDR detector concepts

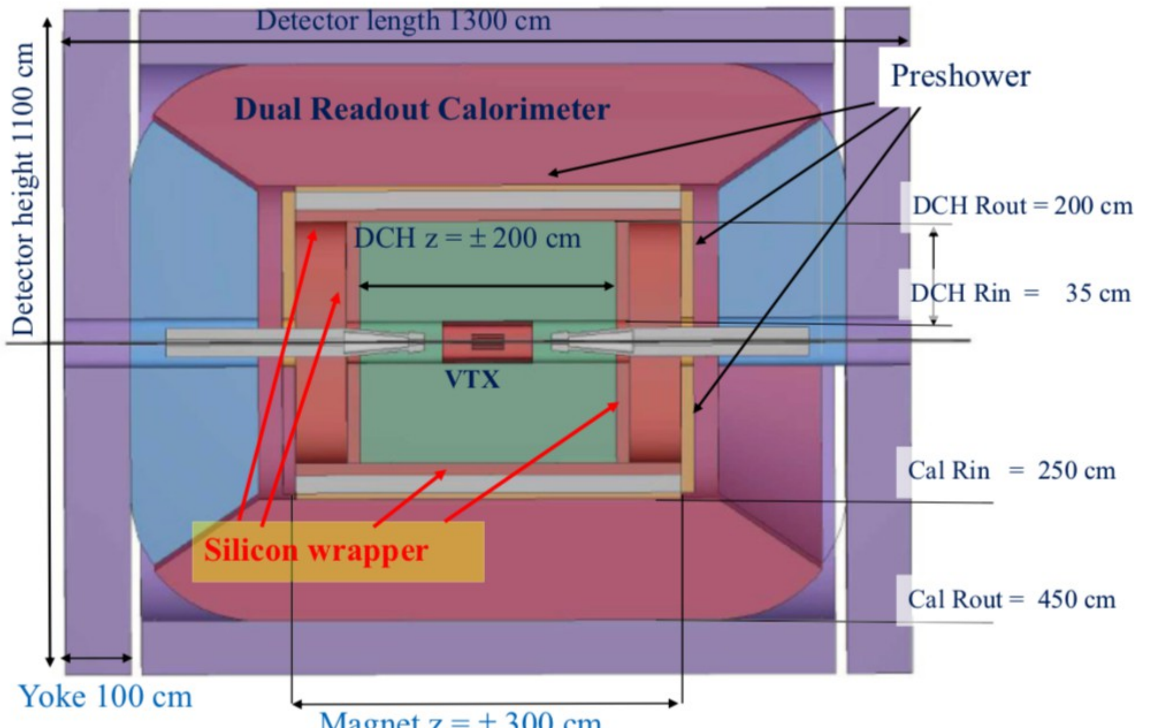
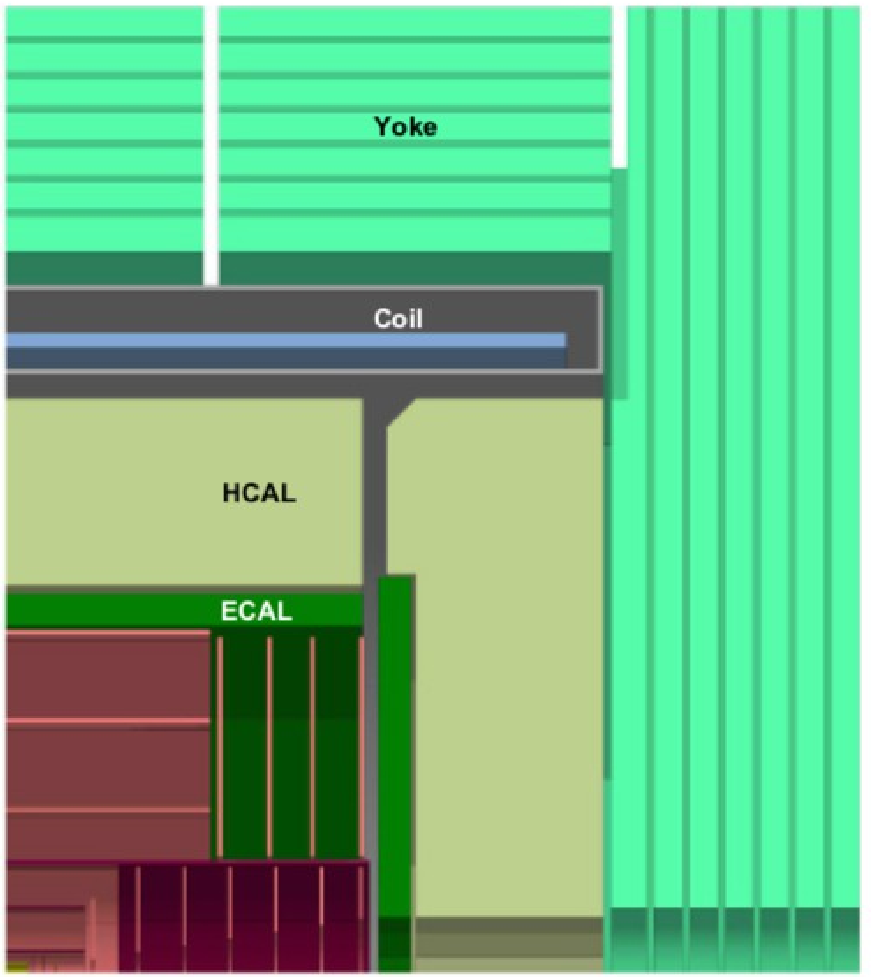


Fig. 7.9. Schematic layout of the IDEA detector.

Hadronic resolution of ~ 35%/√E



CLD (SiW ECAL, Steel scintillaor HCAL)
ECAL 15%√E

FCC-ee CLD calorimeter

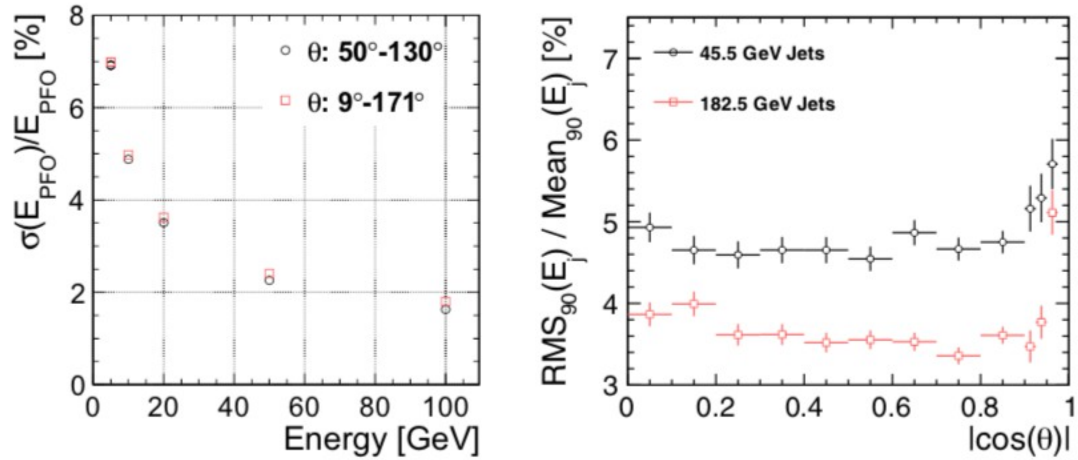


Fig. 7.8. CLD calorimeter performance. Photon energy resolution as a function of energy (left), comparing the barrel region with the full detector acceptance. Jet energy resolution for light quark jets as a function of polar angle (right).

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

FCC-hh LAr barrel calo angular resolution

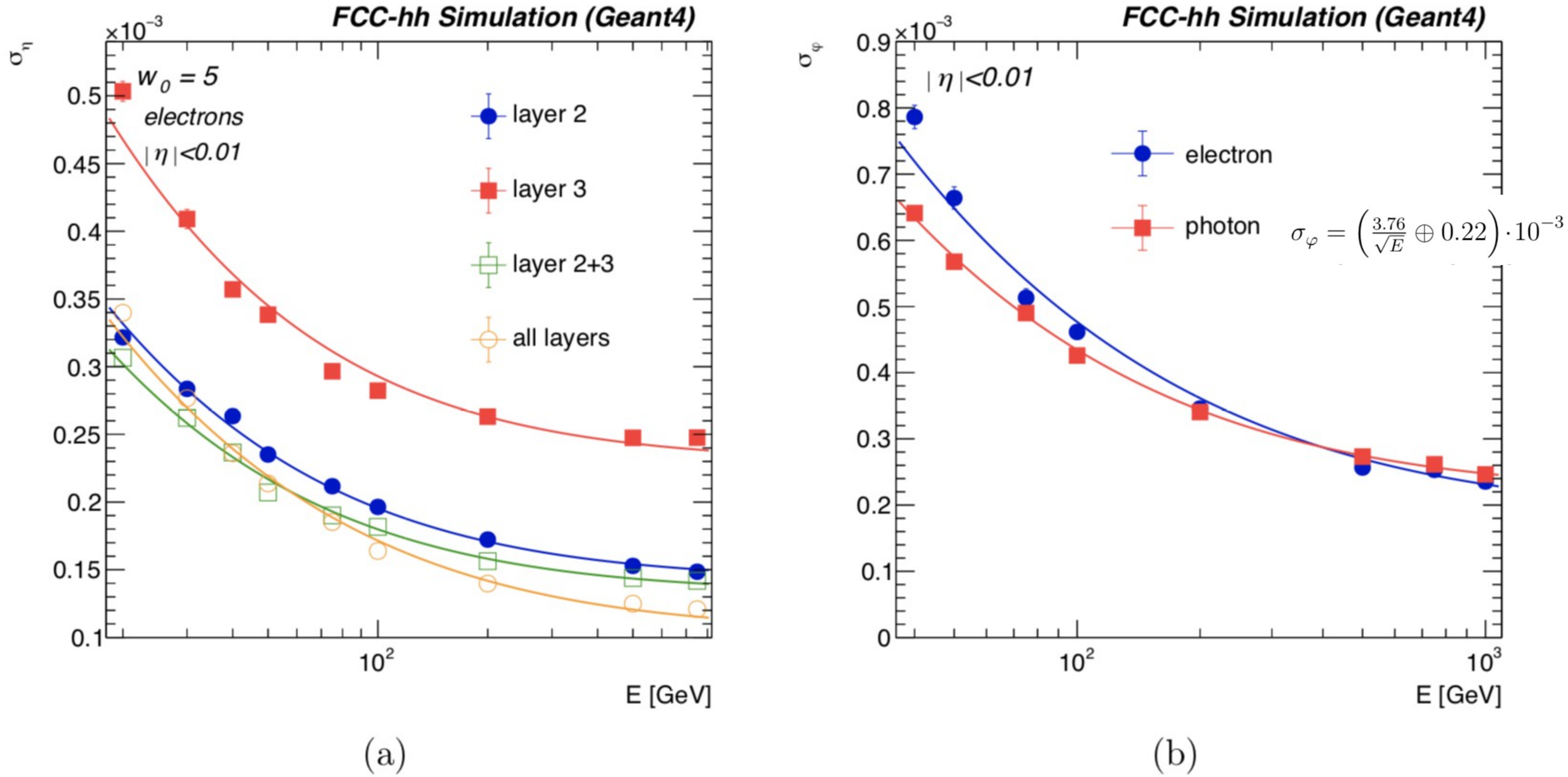
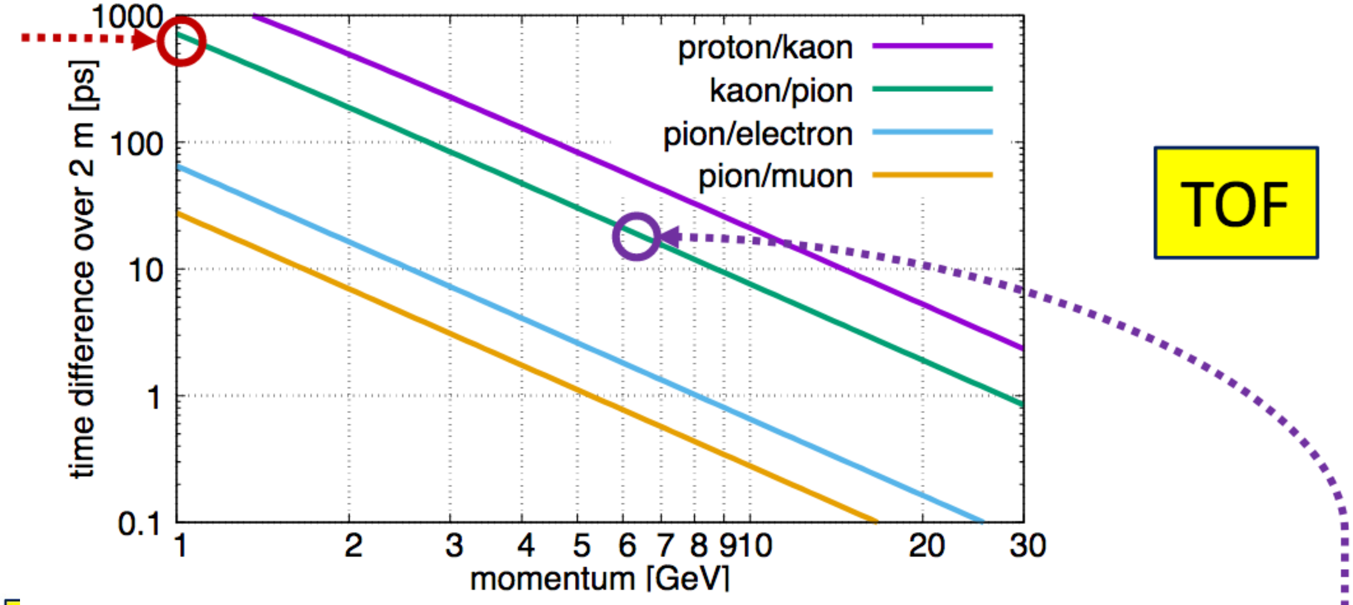
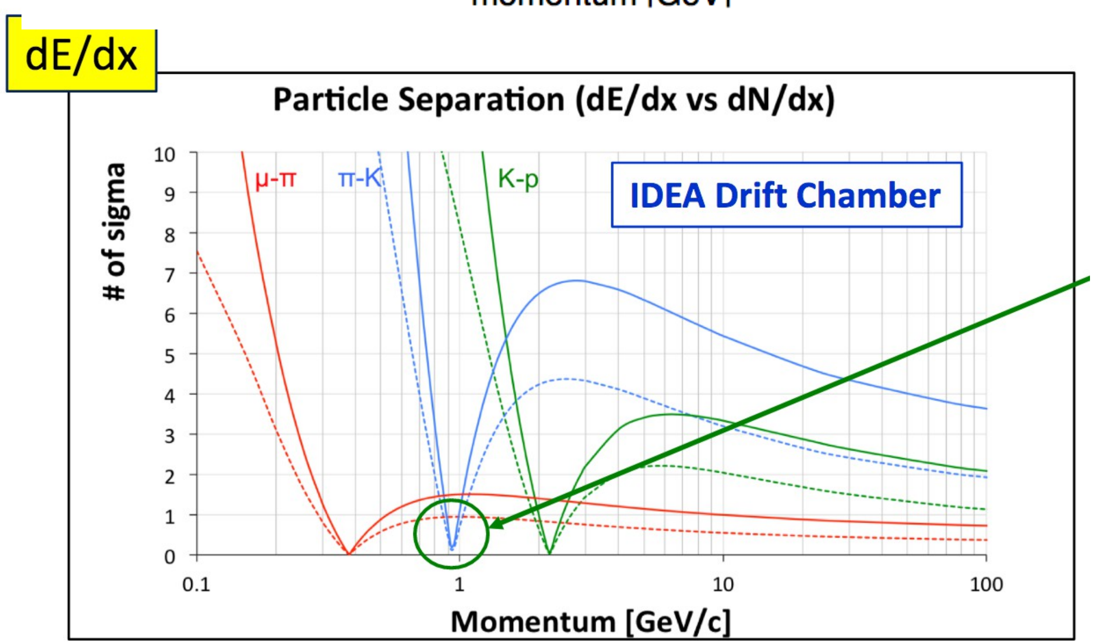


Figure 51: (a) Pseudorapidity resolution for two best calorimeter layers: second (red full circles) and third (blue full squares), as well as combined measurements of those two layers (green hollow squares) and from all EMB layers (yellow hollow circles). (b) Azimuthal angle resolution for electrons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

Particle ID



TOF
proton/kaon
kaon/pion
pion/electron
pion/muon
time difference over 2 m [ps]
momentum [GeV]
1000
100
10
1
0.1
1
2
3
4
5
6
7
8
9
10
20
30



dE/dx
Particle Separation (dE/dx vs dN/dx)
IDEA Drift Chamber
μ-π
π-K
K-p
# of sigma
Momentum [GeV/c]
0
1
2
3
4
5
6
7
8
9
10
0.1
1
10
100