Future Noble Liquid Calorimetry

ECFA Detector R&D roadmap

Task Force 6 – Calorimetry

May 7th, 2021

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Based on material from the 'Input from future facilities' sessions

Gratefully acknowledging input from Martin Aleksa, Ronic Chiche, Mogens Dam, Jana Faltova, Daniel Fournier, Maria Soledad Molina Gonzalez, Clément Helsens, Maria Asuncion Barba Higueras, Max Klein, Peter Kostka, Christos Leonidopoulos, Julia Marsh, Nicolas Morange, Alessandro Polini, John Rutherfoord, Juraj Smiesko, Valentin Volkl, Katinka Wandall-Christensen

This talks reflects my own understanding, all mistakes/inaccuracies are mine

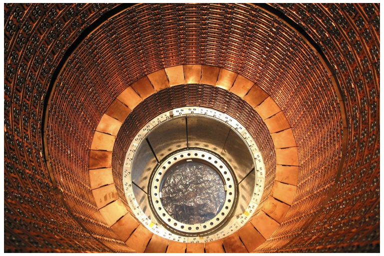
ECFA
European Committee for Future Accelerators

Outline

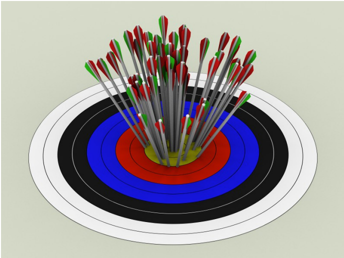
- State of the art
  - ATLAS LAr calorimeters
- Current R&D status
  - Feedthroughs, electrode design, light cryostat, …
- Further R&D needed
  - Full readout chain, mechanical aspects, detector optimization, timing, …
- Detector optimization

Introduction

- Noble Liquid calorimetry is a well proven technology
  - Successfully operated/operating in D0, H1, NA48/62, ATLAS, …



- Key features
  - Radiation hardness, long term stability
  - Linear response, uniformity, high control over systematics
  - Good energy/timing resolution



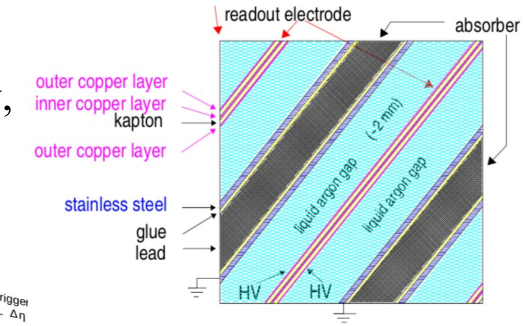
- Very promising candidate to meet future experiment's requirements
  - Proposed as the **baseline for FCC-hh ECAL + Hadronic Endcap/Forward and LHeC ECAL**
  - **Adapted to an e^+e^- experiment** (FCC-ee), leading to a **very interesting option**
- R&D directions
  - Optimization for particle flow reconstruction on top of conventional calorimetry
    - **Higher granularity (noise minimization)**
  - Further improve performances

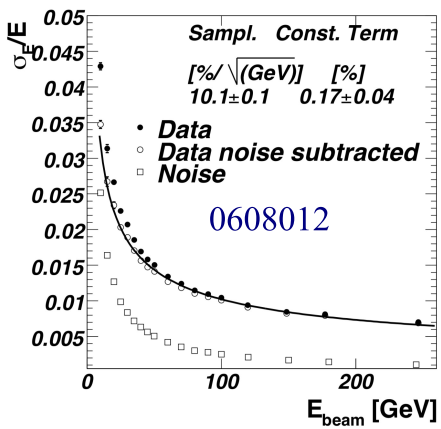
Focus here on the ECAL

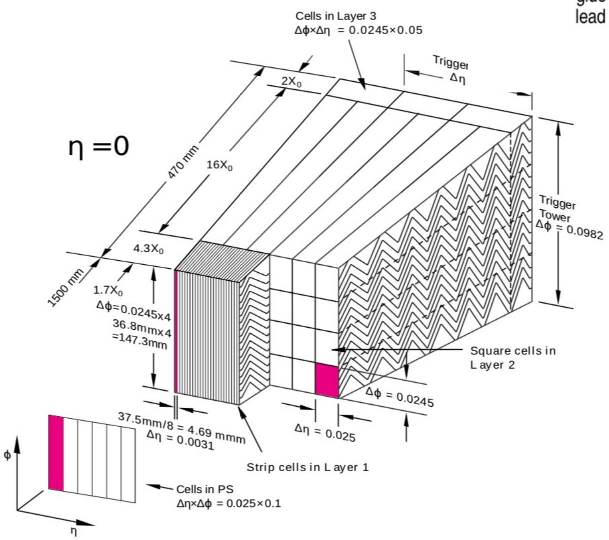
State of the Art

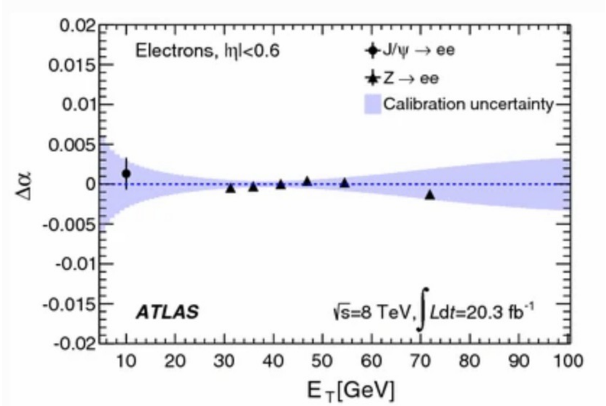
- ATLAS LAr sampling calorimeter: lead absorbers, LAr active gaps, Kapton electrodes with accordion geometry, everything inside a cryostat bath
- Met the designed energy resolution

$$\frac{\sigma(E)}{E} = \frac{10\%}{\sqrt{E}} \oplus \frac{0.2}{E} \oplus 0.2\%$$









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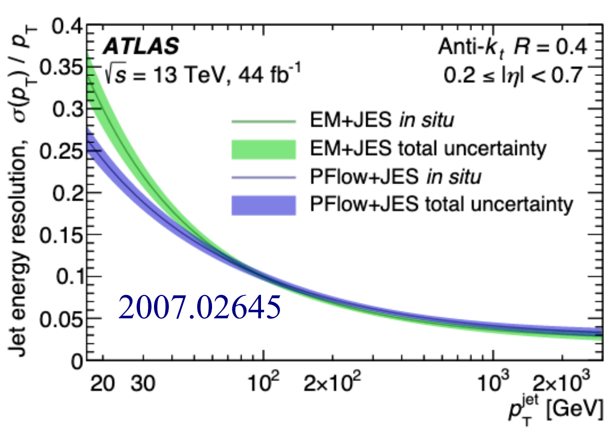
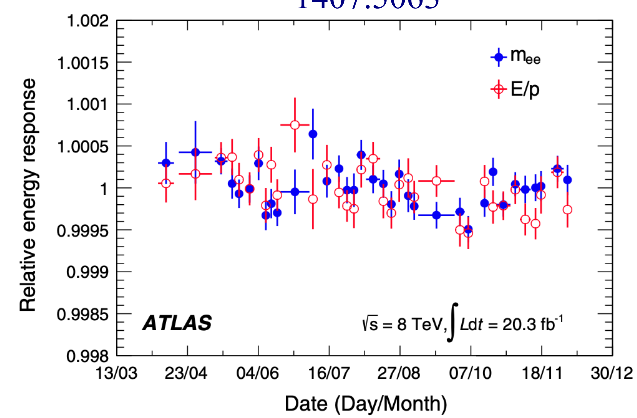
- Linearity: energy scale variation within ~10^{-3} over large E_T range
- Energy response stable at ~10^{-4} level over a year
- Particle flow performances limited due to coarse granularity

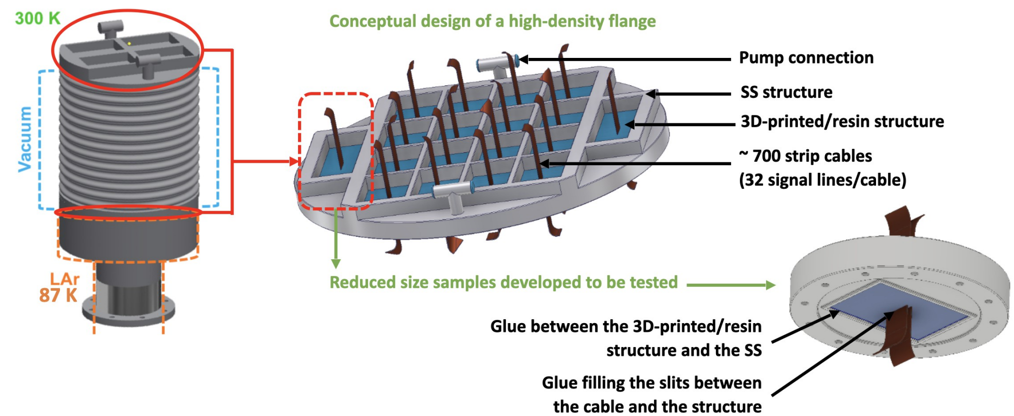


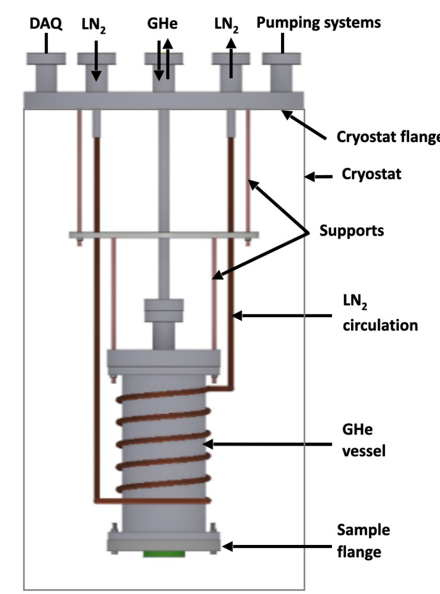


Current R&D status

High density feedthroughs

- **Increase** Noble Liquid calorimeters **granularity (factor 10-15** compared to ATLAS)
- If the electronics sits outside of the cryostat (warm electronics), one needs **high density feedthroughs**
- Ongoing CERN R&D
  - Higher area dedicated to signal extraction
  - High density flange (5x more signals/cm^2)
  - 20 000 wires per feedthrough
  - Reduced size samples development
    - Testing different 3D-printed epoxy resins as structures with slits allowing the passage of cables – glued to the flange
    - Leak and pressure tests at 300 and 77 K
- **Next steps: construction of an entire feedthrough + test under operating conditions**

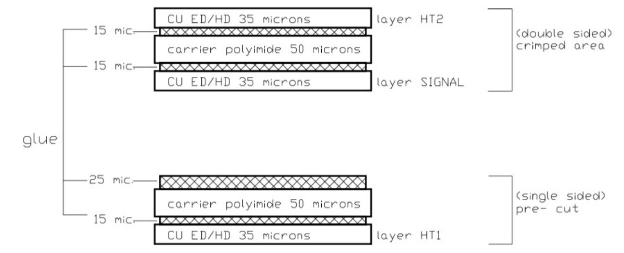


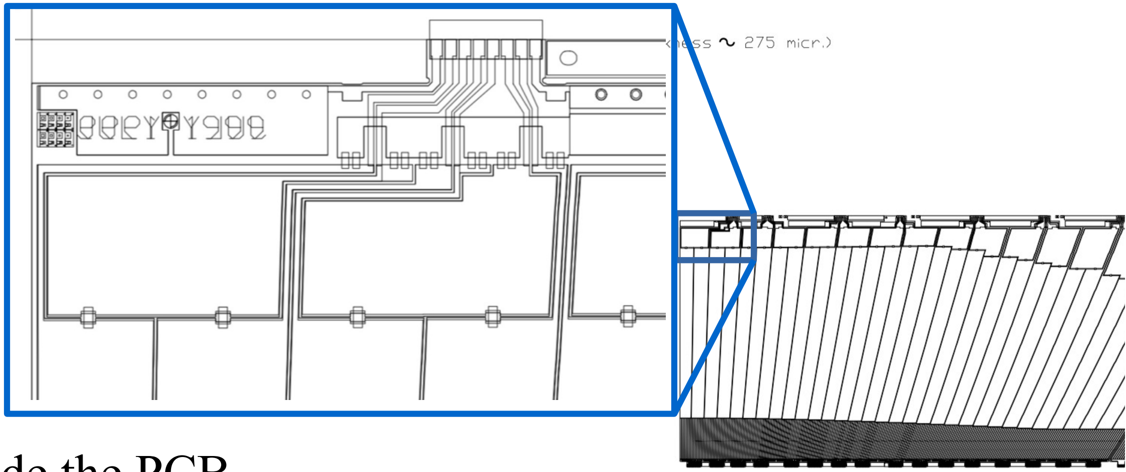


Experimental setup

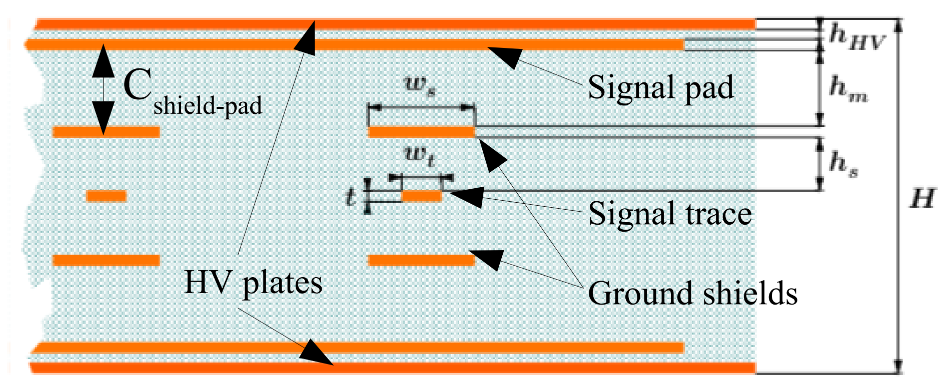
High granularity electrodes

- 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 routed via traces in the same layer as the pad, alongside other cells
    - Longitudinal granularity limited by trace density/cross-talk



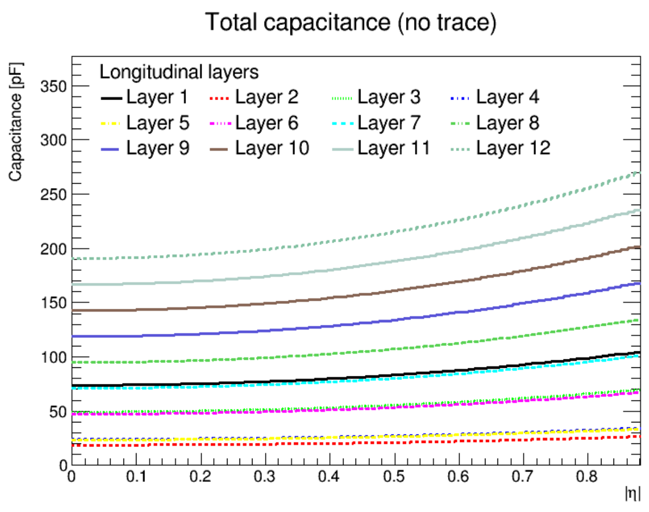


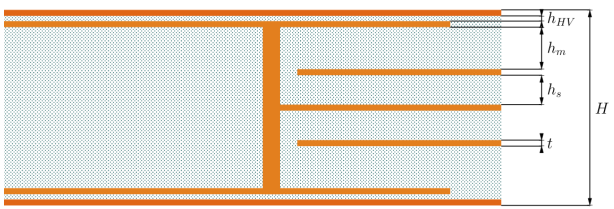
- **Higher granularity can be achieved thanks to multilayer PCB electrode**
  - Traces can run beneath other cells, inside the PCB
  - Prevent cross talk with ground shields
  - Ground shields increase the capacitance → noise
    - $C_{cell} = C_{shield\text{-}pad} + C_{detector}$
    - $C_{detector}$: signal pad – absorber ground
    - Careful optimization

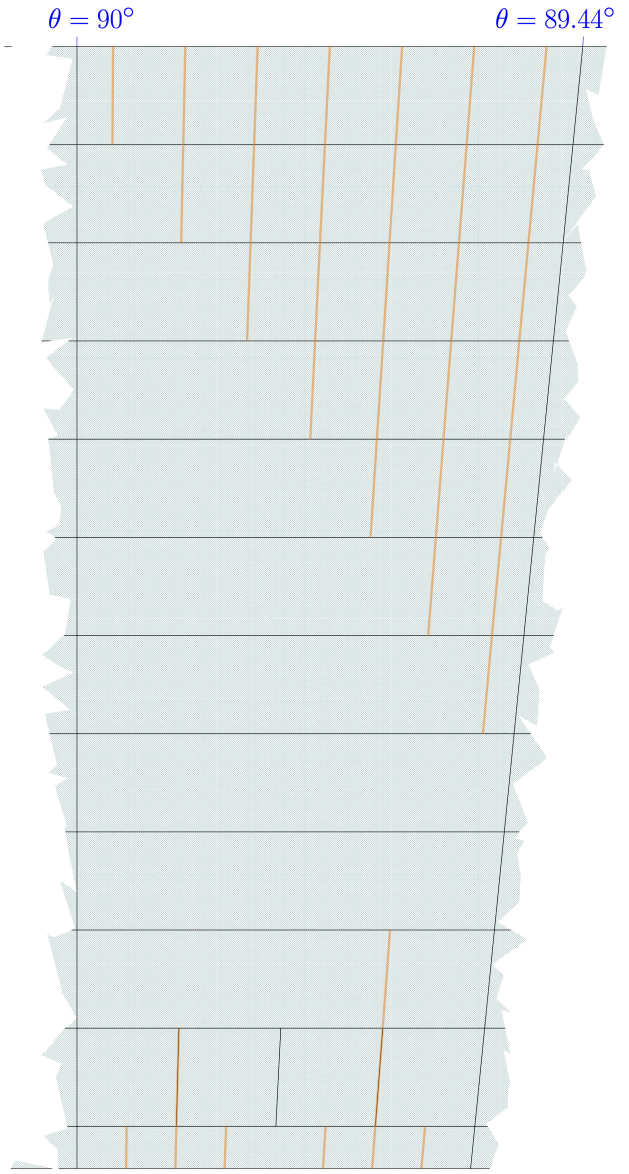


High granularity electrodes (II)

- Status of the FCC-ee electrode implementation (simulation)
  - Lower the number of signal traces/ground shields by reading two signal pads with one trace
  - Keep the number of traces extracted from front low
    - Noise term dominate for low energy particles which deposit their energy mostly in early longitudinal layers
  - Derived cell capacitance from Finite Element Method tools
    - 25 – 250 pF depending on the cell (does not include transmission line capacitance)
  - MIP can easily be seen using cold electronics, investigating whether this also holds for warm electronics (more details later)

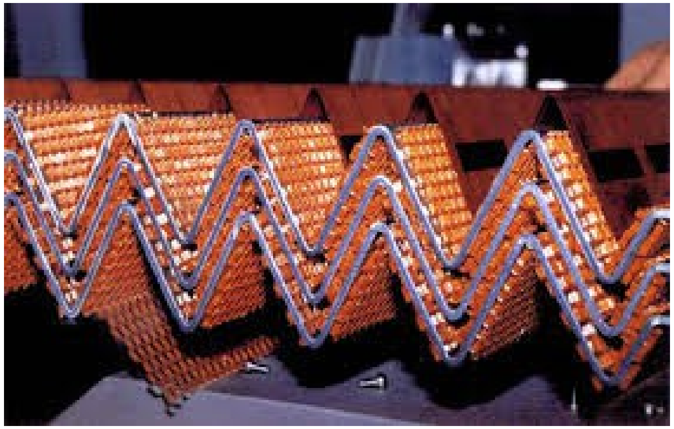


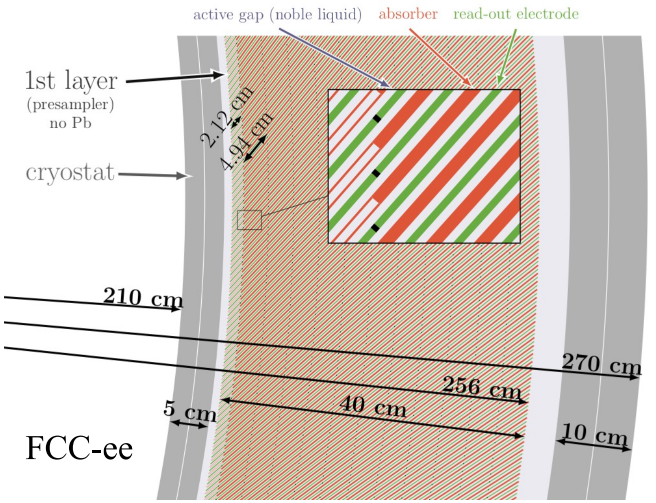




Horizontal axis expanded by a factor 10

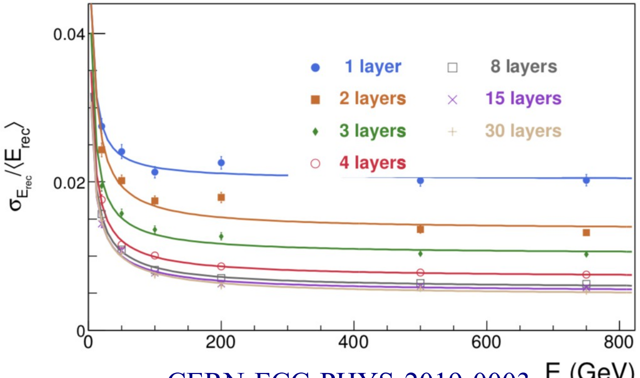
Detector Geometry





- Accordion geometry is impossible to implement with rigid PCB's → propose a new geometry with **straight inclined plates**
  - Simpler geometry
    - Should be **beneficial** for **detector non-uniformities**
  - Sensitive gap widening towards high radius → non-constant sampling fraction within a cell
    - Mitigated in ATLAS by evolving kink angle
    - Mitigated here by the high longitudinal segmentation (per layer sampling fraction)

FCC-hh LAr energy resolution for different longitudinal segmentations



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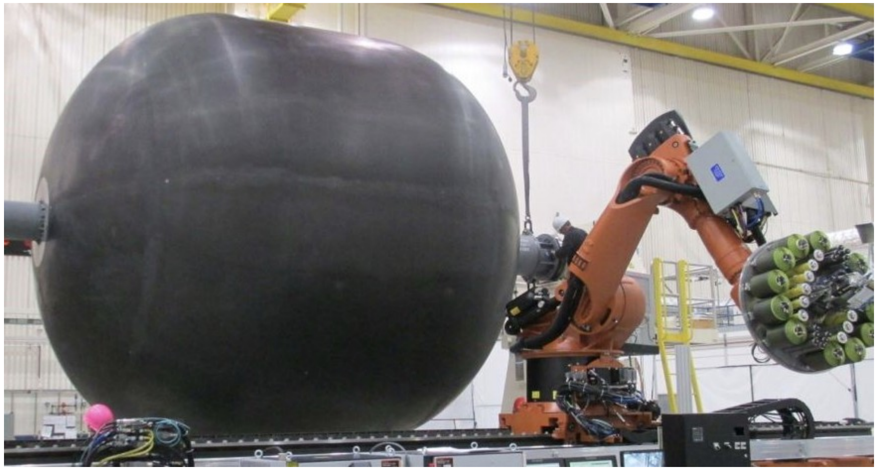
Minimizing material budget

- Trying to **minimize the dead material introduced by the cryostat**
  - Important for the lepton collider low energy particle measurements
  - Ongoing CERN R&D on Carbon Fiber Reinforced Polymer cryostat vessels (more details in this talk)
    - Microcrack resistance, sealing method for flanges, leak and pressure tests
  - State of the art in aerospace
- The solenoid and calorimeter can share the same vacuum vessel (while operating at different temperature)
  - Less dead material and lower radial extent
  - Some additional manufacturing/operation constraints
    - Chosen solution for the ATLAS barrel



NASA's lineless cryotank

High rate mitigation

- HiLum/FCalPulse R&D project
  - Understand/quantify space charge effects under high rate: targets ATLAS HL-LHC but is interesting for any high rate experiment (e.g. FCC-hh)
    - Anode screening (HV drop), recombination
  - Impact on current pulse (degradation, distortion)
    - Affected regions: FCal1, FCal2, EMEC at high η
  - Planning a test beam to measure LAr drift and recombination parameters
  - At fixed high ionization rate, is the pulse height still linearly proportional to the energy deposit?
  - Develop software corrections to recover energy response
- Other handles: reduced sensitive gap thickness, adapted HV distribution

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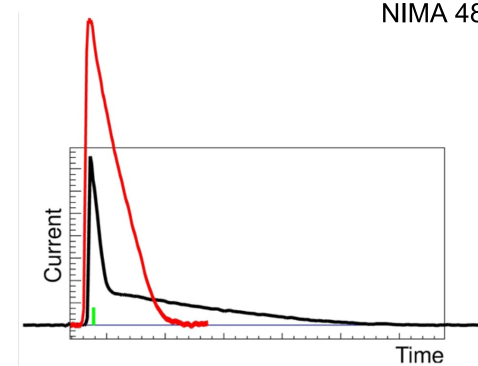
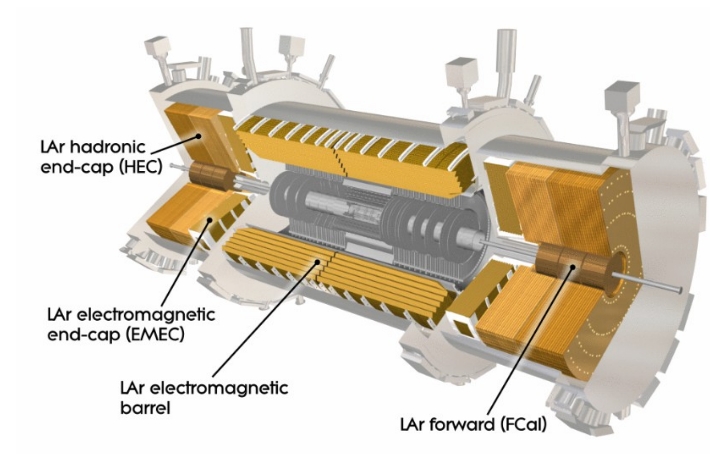
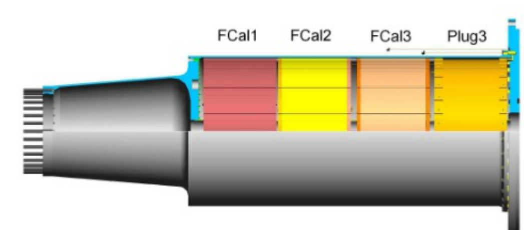


HiLum R&D project: EMEC normal pulse (red) and degraded pulse (black)



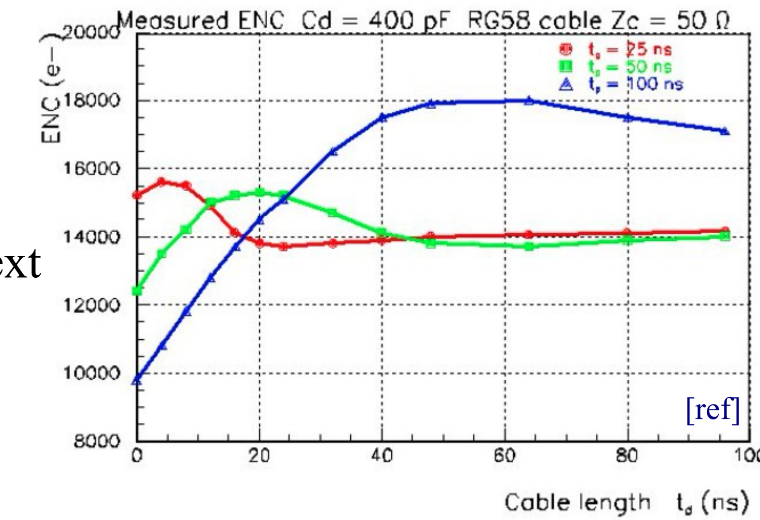


Further R&D needed

Further electronics R&D needed

- **A detailed and complete readout chain study has to be conducted**
  - Keep cross-talk at the % level
    - Ground shield width, distance between PCB layers (impacts the cell capacitance)
  - Produce a first PCB prototype to validate the simulated design
  - Understand the interplay between detector capacitance, transmission line length/impedance and the shaper time constant to minimize the noise
  - Investigate both the warm and cold electronics options (next slide)
  - Investigate both charge and current pre-amplifiers
  - Dynamic range: 14-16 bits estimated for FCC-ee/hh

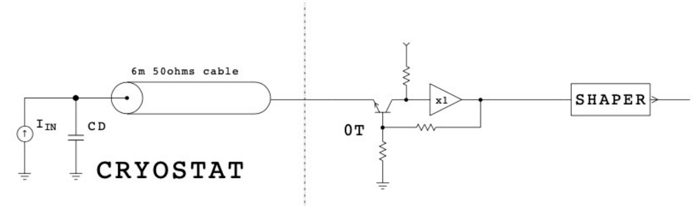
ATLAS electronics noise vs cable length for different shaping time



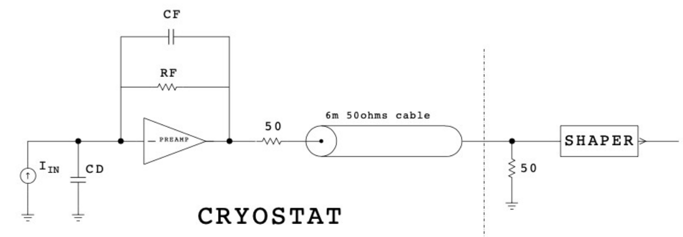
- **The ability to extract the signal from such new granular Noble Liquid Calorimeters is the corner stone of the project success**

Warm or Cold Electronics?

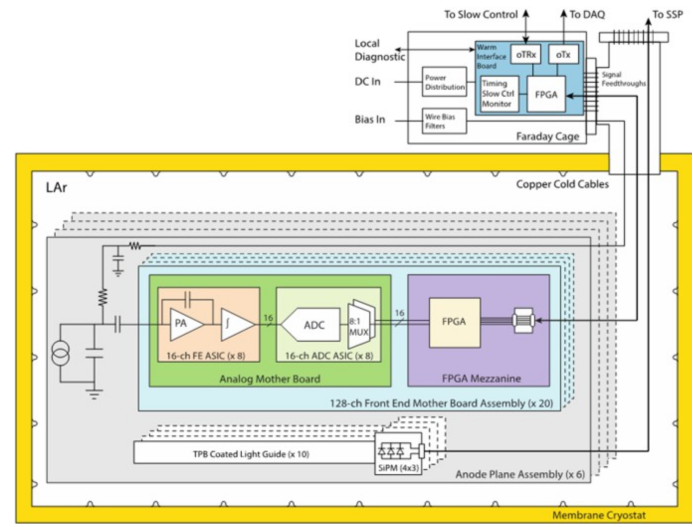
- **Advantages** of placing the front-end inside the cryostat (**cold electronics,** choice for Dune experiment)
  - **Lower noise:** electronics at lower temperature, PA directly connected to the sensor wire (no cable), longer shaping time envisaged
    - Can **easily achieve MIP S/N > 5 per cell**
  - **Eases** the **feedthrough design** (possibility to use optical fibers)
- **Drawbacks**/technical challenges
  - Very **difficult maintenance or upgrade** (cryostat opening) → robust electronics + redundancy
  - Minimize **heat dissipation** inside Noble Liquid (low power electronics)
    - Avoid bubbles (electrical breakdown, local change of sampling fraction)
- **Amount of dead material to be evaluated** (link to LAr/LKr choice, signal extraction scheme)
- Need a **full readout chain study in both scenarios** to evaluate the noise performances and make an informed decision
- **Cold electronics is a very interesting option for lepton colliders**
  - Lower radiation, electronic noise is more critical, shorter operation time compared to hadron colliders



ATLAS ECAL



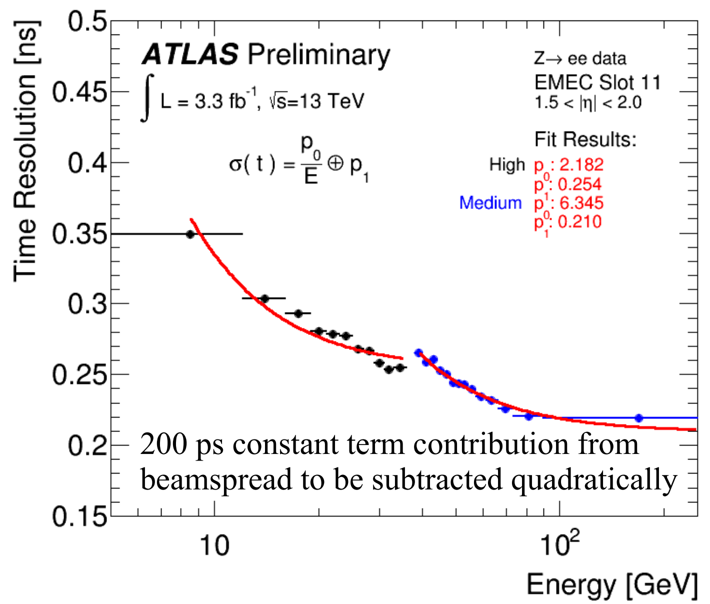
ATLAS Hadronic End Cap



ProtoDUNE

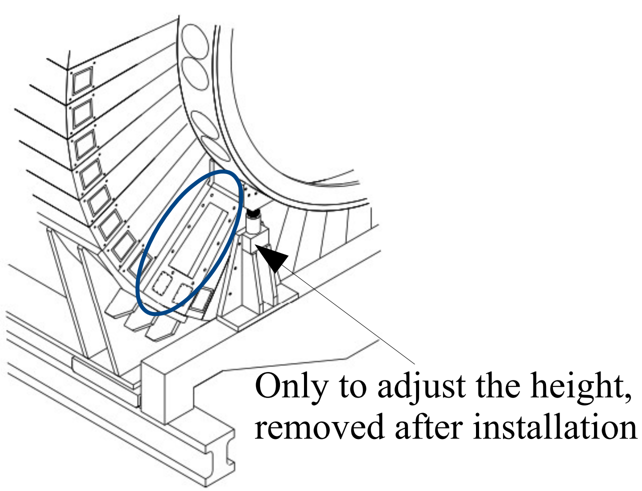
Timing

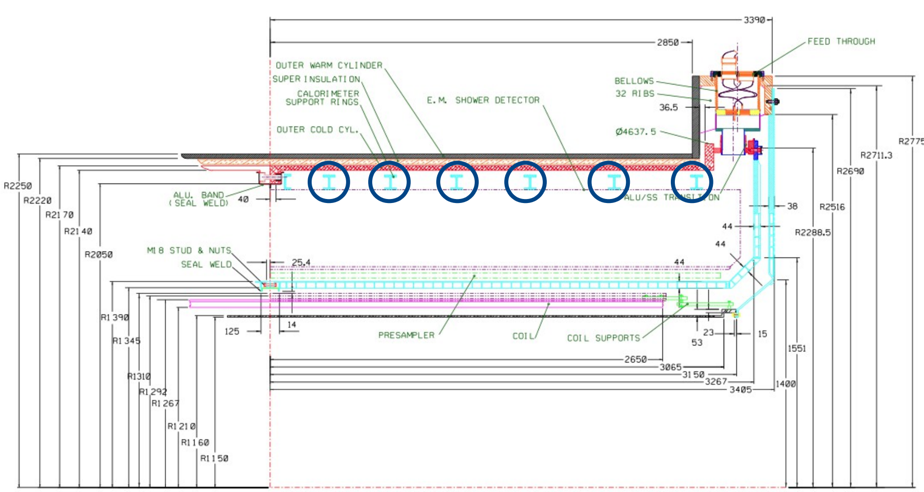
- Timing will play an important role in future colliders (PU removal, particle identification, heavy stable charged particles, …)
- Time resolution achieved by ATLAS
  - ~260 ps for EM showers ≥ 20 GeV, ~130 ps for EM showers ≥ 100 GeV
- **Time resolution needs to be evaluated and optimized with the new designs (and full readout chain)**
  - Depends on the shaping time
    - Which will mainly be driven by noise considerations for lepton colliders
  - Limitations: time-walk, stochastic ionization, cell inter-calibration
  - To be considered with the big (detector) picture in mind
    - Jitter from external sources
    - Do we have dedicated timing layers or not?
    - Do we have dE/dx or dN/dx for particle ID?



Mechanical Considerations

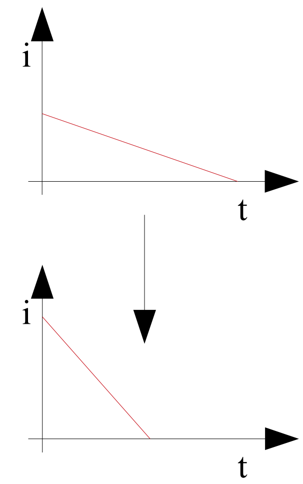
- Mechanical considerations
  - Calorimeters are heavy objects (100's of tons)
    - **High precision large-scale structures capable of supporting such masses**
      - Without jeopardizing hermeticity
        - Was done in the past: ATLAS barrel cryostat lies on the tile calorimeter
      - Unprecedented acceptance knowledge requirements for lepton colliders
      - Challenge for the light weight cryostat (heavy loads on thin rails)
  - Gap thickness uniformity (constant term < 1% for ECAL's in FCC-hh)
  - “Carpenter-like (roof-top) scales and cabinet-maker type tolerance”





Further interesting R&D

- **Doping the Noble Liquid to improve S/N**
  - Enhance the drift velocity and hence the signal yield (current pre-amplifiers and fast shaping)
  - Was already studied in the past [ref] but not implemented
    - Unknown behavior of the dopants under high radiation, impurities
  - Given the time ahead of us, might be interesting to re-consider this option with a more thorough radiation hardness study

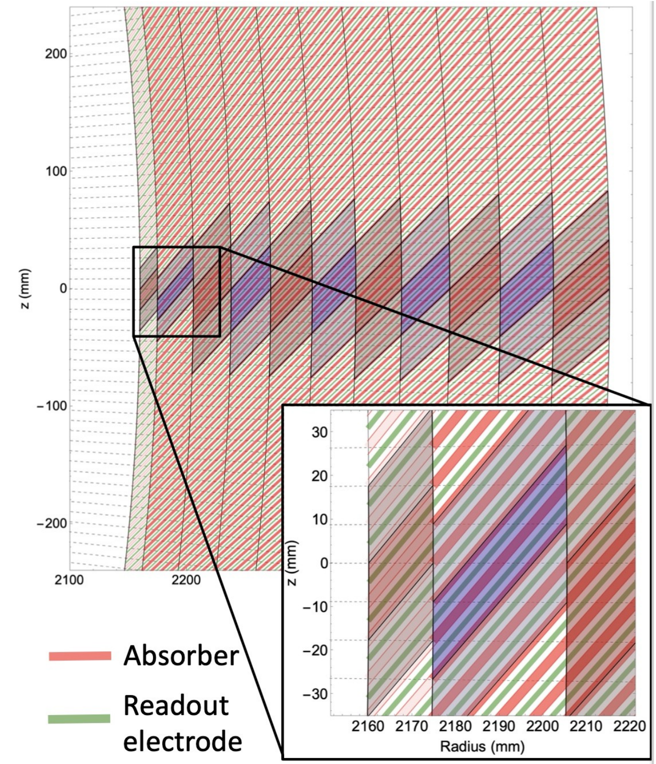


- **Noble Liquid Scintillation**
  - Used in Neutrino and Dark Matter TPC's Triggers
    - Huge sensitive volume → signal from charge is much-delayed compared to scintillation signal
  - Very thin sensitive gaps in accelerator detectors (~instantaneous signal coming from charge drift)
  - Could potentially provide an **independent measurement of the energy** deposit but brings quite a lot of **challenges**
    - Transparent honeycomb spacers, light collection system inside the calorimeter (spacial constraints, hermeticity, heat dissipation), Noble Liquid purity, light reflection by the absorber and PCB coating
- **Warm Liquids:** material with Noble's properties but high boiling point
  - Also studied in the past by the WALIC program (see e.g. here)
  - No double-wall cryostat: less X_0 in front of ECAL, reduced radial size

Strong connection with TF2 'Liquid Detectors'

Detector optimization (I)

- **All the 'free' parameters of the detector have to be optimized**
  - Absorber material (considering Pb and W), Noble Liquid (LAr, LKr, LXe)
    - Energy resolution, radial compactness/Moliere radius, signal over noise, dead material, cost and availability
  - Absorber and sensitive gap thickness
    - Machining capability, energy resolution, compactness
    - Absorber with increasing thickness towards large radius
      - Reduce the radial thickness, approach a constant sampling fraction
      - More complex manufacturing → may introduce more non-uniformities
  - Plate inclination, layer depths, cell merging…



- **Complicated exercise** given the number of figure of merits, the number of free parameters and their interdependence
  - High dimensional manifold with many local minima's and forbidden regions

Detector optimization (II)

- An ideal optimization can only be done within a **holistic approach**
  - Interplay between sub-systems
    - Track to cluster association has to enter the figure of merits
    - The muon chambers design will tell which flux they can sustain
      - Impacts calorimeter thickness/shielding
    - Realistic MET definition needs all the sub-systems
    - Solenoid position impacts the optimization strategy (compactness)
    - …
- **Need a full detector software implementation together with a global event description**
  - Even though a 'frozen' detector configuration only comes late, having a flexible software framework integrating as many aspects/detectors as possible will considerably ease and provide flexibility to the optimization process
  - Key4Hep version of FCCSW including particle flow!
- It is convenient to choose a specific component for 'early' R&D designs (e.g. ECAL barrel), one should move soon enough to the whole system description (e.g. including endcaps, HCAL) because the optimization will be different

Main players

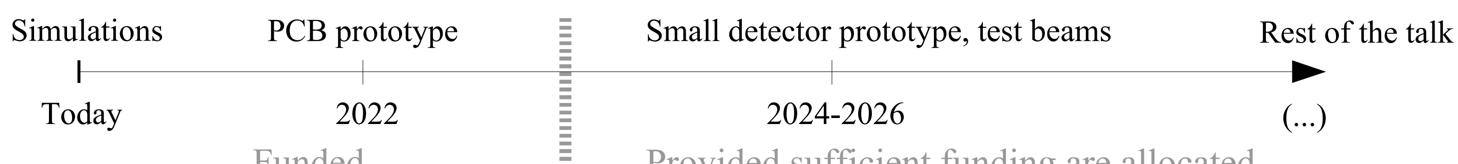
- CERN
- Charles University, CZ
- IJCLAB – Université Paris-Saclay, FR
- University of Copenhagen, DK
- University of Edinburgh, GB
- AIDAInnova
- ATLAS LAr collaboration
  - Major readout electronics upgrade being prepared for ATLAS-LAr at HL-LHC

A very active group started to work on detector simulation and design

New players are more than welcome!

Conclusion

- Noble Liquid calorimetry is a reliable technology with proven excellent performances and stability
  - It may represent the only choice for FCC-hh ECAL (radiation hardness)
  - Very promising option for lepton collider physics programs (high control over systematics) and for all type of future collider experiments in general (LHeC, FCC-eh, muon colliders)
- R&D has started to optimize Noble Liquid calorimetry for particle flow and lepton collider requirements
- The biggest challenge is to increase the granularity while keeping a good S/N and a low cross-talk
- Having this technology ready for the next experiment generation is realistic, provided sufficient fundings are allocated
  - Short timeline

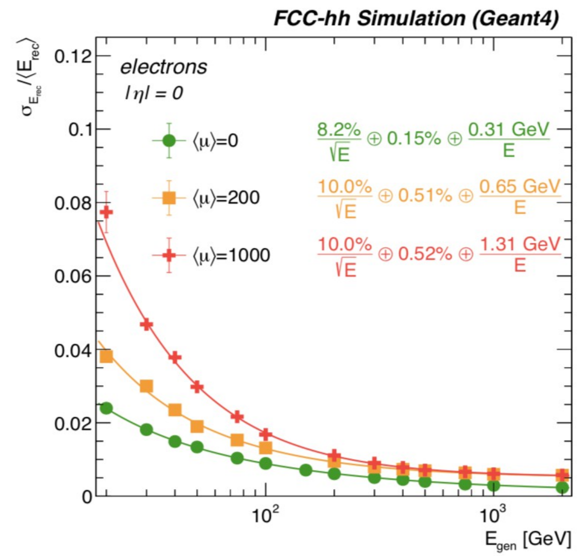


We are ready to proceed to a more involved R&D program!
(detector on paper → real life)

Additional material

FCC-hh Calorimeter Performance

- FCC-hh reference calorimeter inspired by ATLAS Calo and CMS HGCal
  - ECAL, Hadronic Endcap and Forward Calo: LAr/Pb (Cu)
    - 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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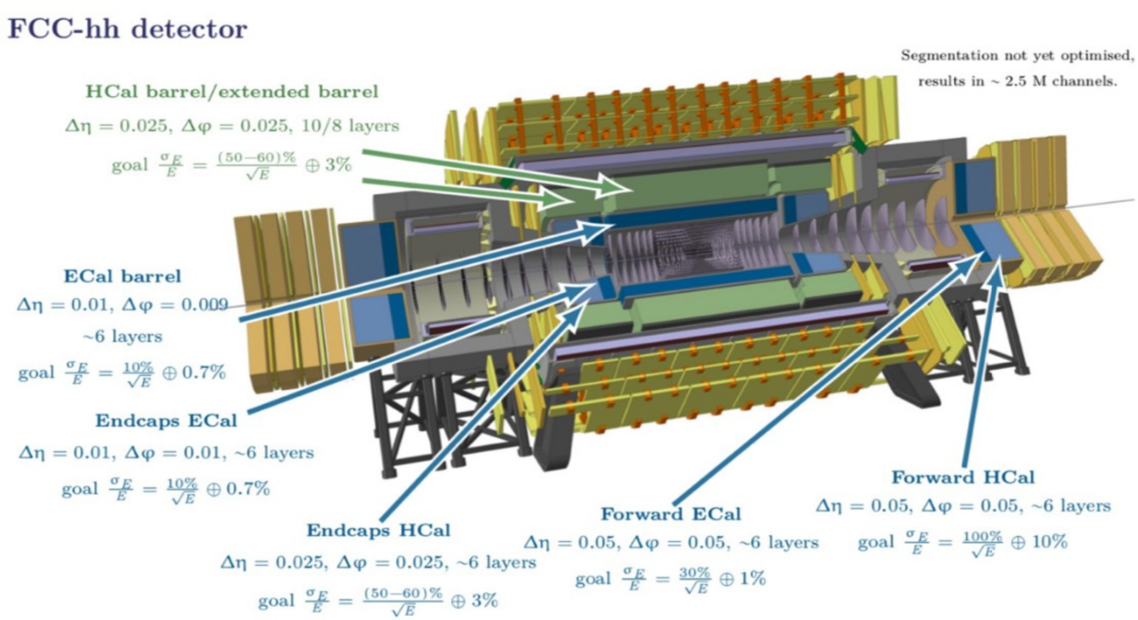
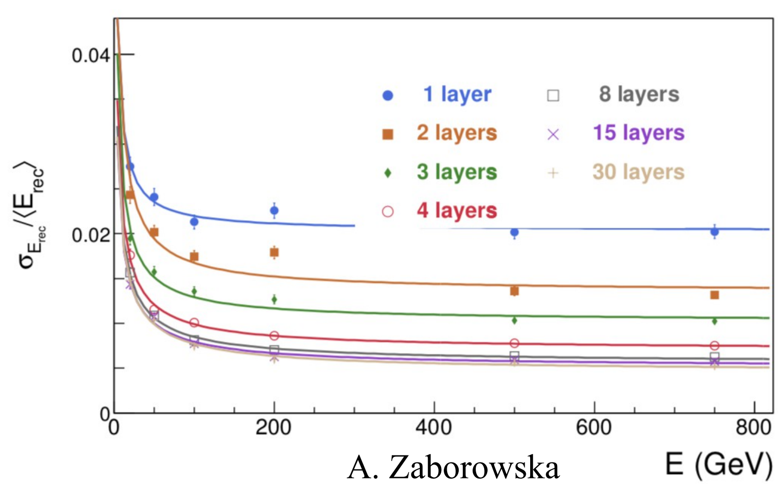
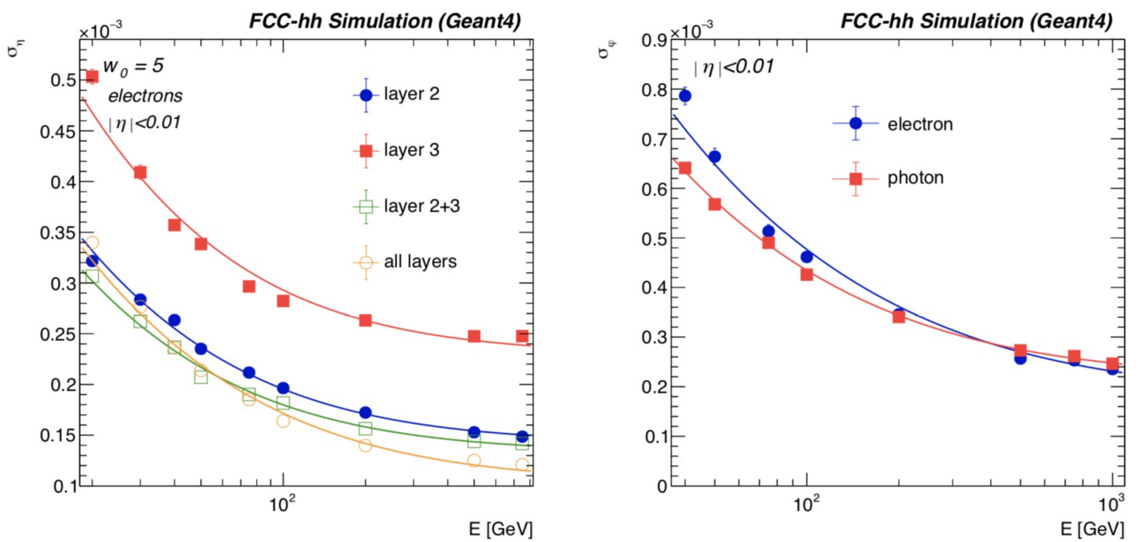




A. Zaborowska

FCC-hh Calorimeter Performance

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

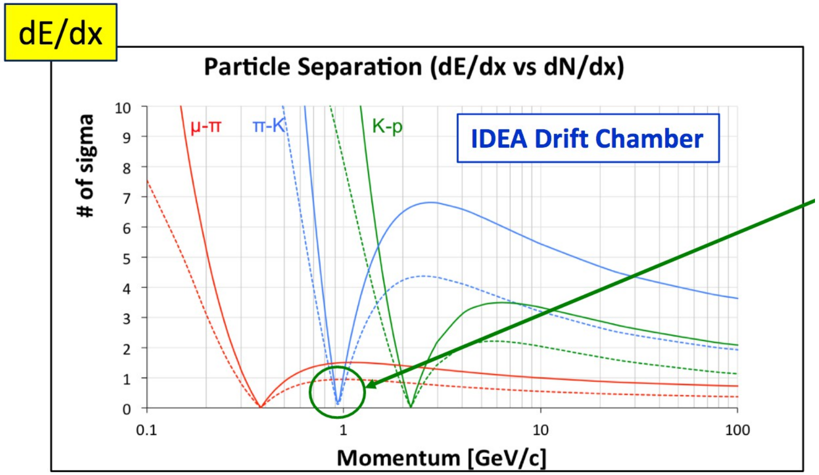


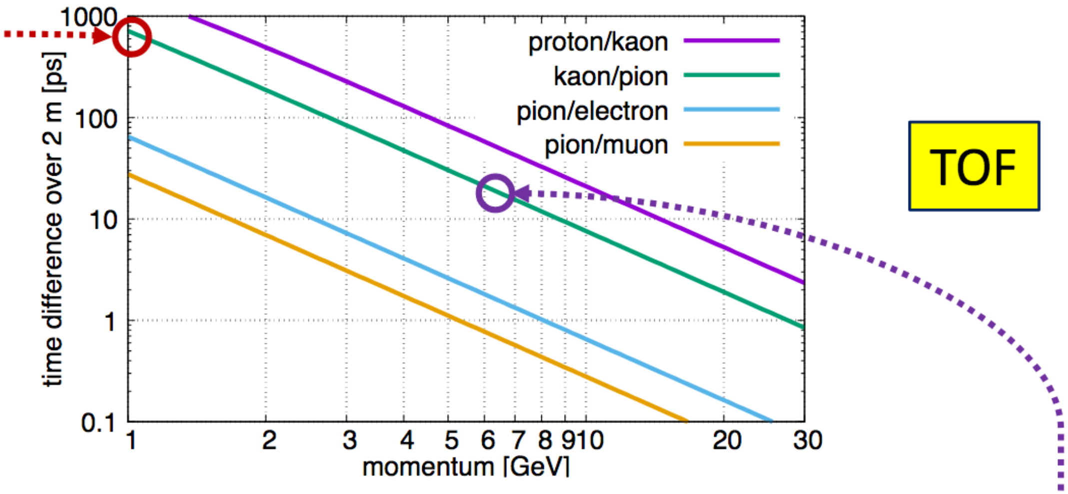
(a) (b)

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

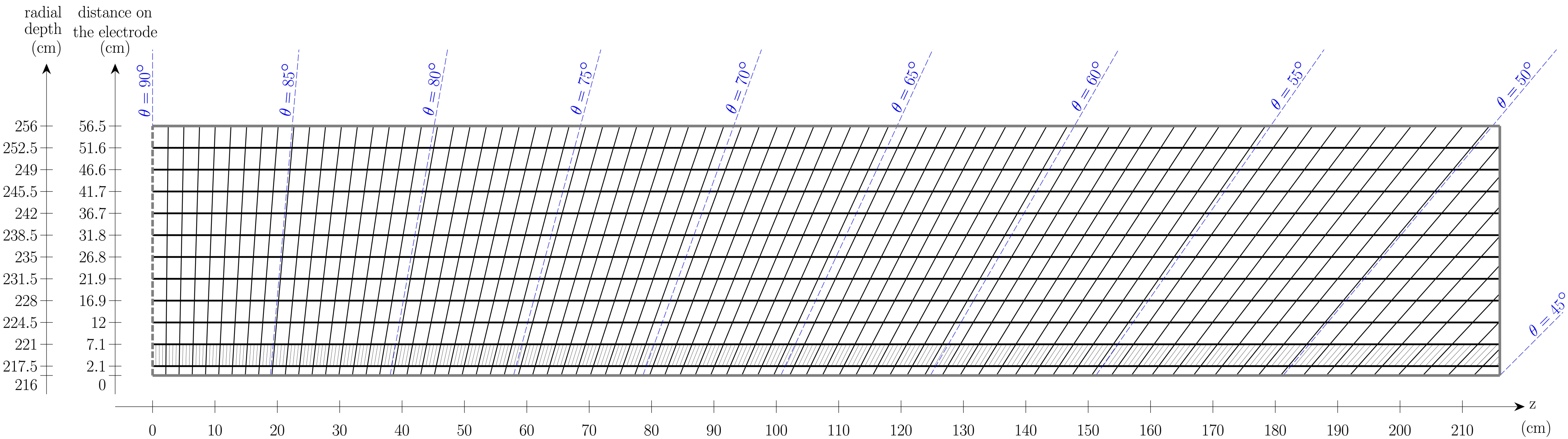
- dE/dx or dN/dx performs very well for particle ID, except in a few points where timing could help (low energy)





Granularity

- Increased granularity
  - ATLAS: Δη=0.025 (0.0031 strip layer), ΔΦ=0.024, 3 longitudinal layers (pre-sampler separated)
  - FCC proposal: Δη=0.01 (0.0025 strip layer), ΔΦ=0.008, 8-12 longitudinal layers



FCC-ee

FCC-ee CDR detector concepts

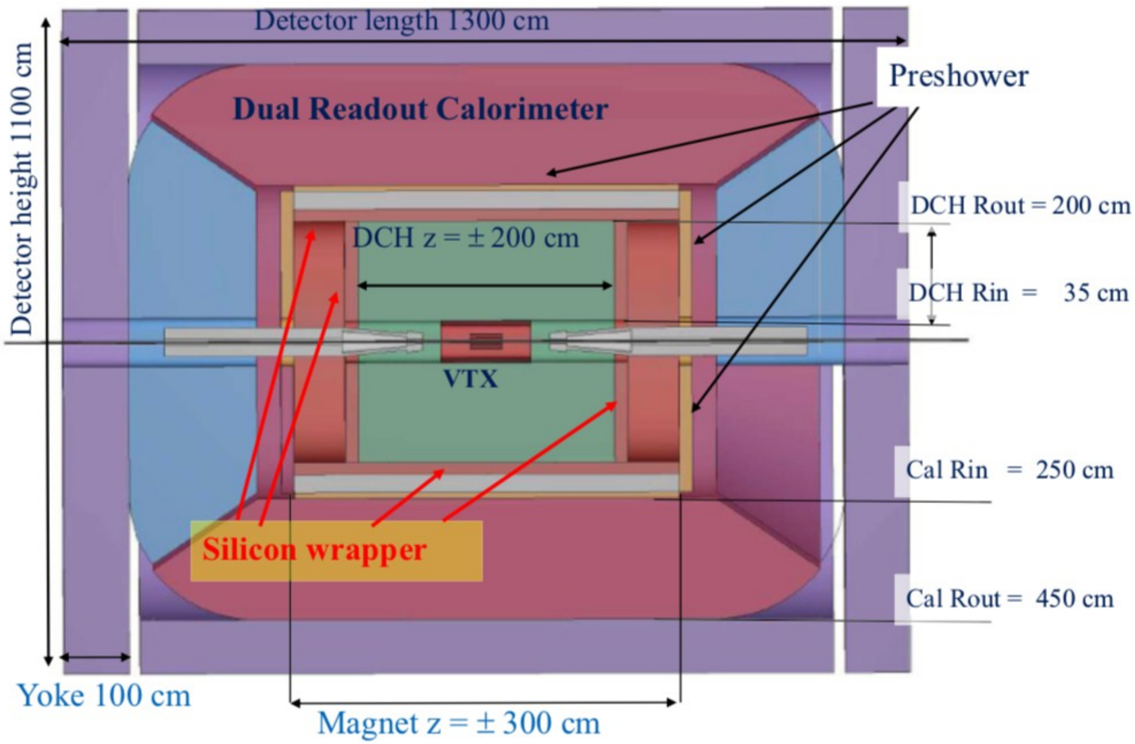
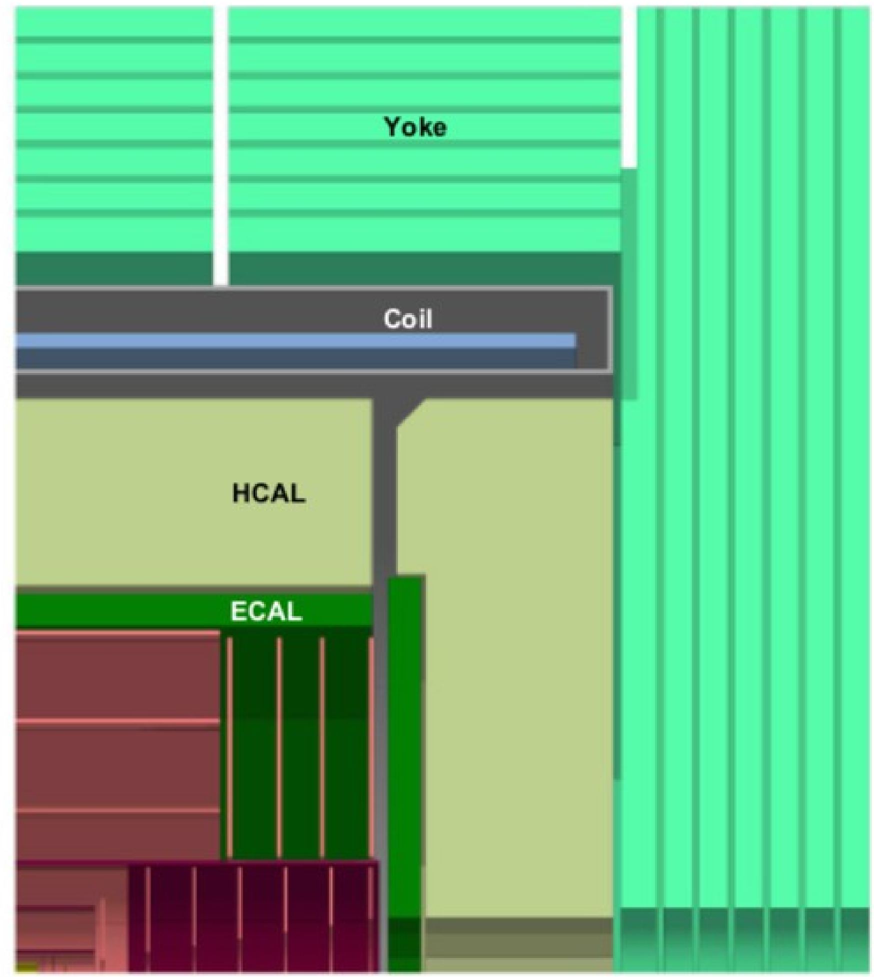


Fig. 7.9. Schematic layout of the IDEA detector.

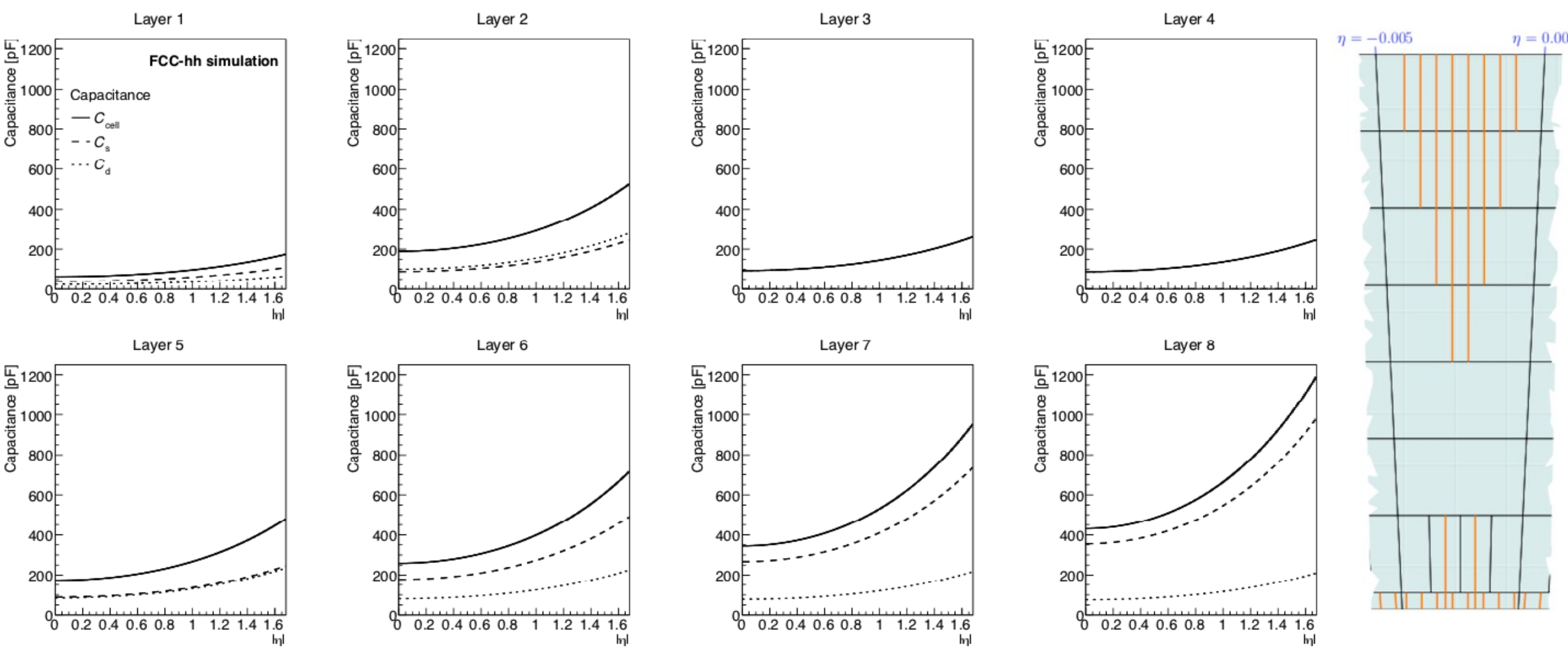
Hadronic resolution of ~ 35%/√E



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

Electronic noise

- Electronic noise estimation in FCC-hh
  - Capacitance derived from analytical formulas: 100 – 1000 pF
  - Capacitance to noise extrapolation derived from present ATLAS calorimeter
  - 4 - 40 MeV noise per read-out channel assuming ATLAS like electronics



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