Noble Liquid Calorimetry for FCC-ee

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- Introduction: LAr Calorimetry at LHC
- Calorimetry of the FCC-hh Reference Detector
- Requirements for FCC-ee Calorimetry – Would Noble Liquid Calorimetry Work?
- Conclusions & Outlook

Based on Material from the FCC CDR Summary Volumes (https://fcc-cdr.web.cern.ch/)
and Studies by the FCC-hh Calorimetry Group (https://indico.cern.ch/category/8922/)

Introduction – LAr Calorimetry at LHC

ATLAS LAr EM Calorimeter

Sampling calorimeter

– with Pb absorbers and active LAr gaps (2mm in barrel, 1.2 – 2.7mm in endcap)

Advantages of **liquid argon (LAr) as active material**

– linear behavior

– stability of the response over time

  - ideal to understand systematic effects using large statistics of e.g. Z→ee events and develop corrections

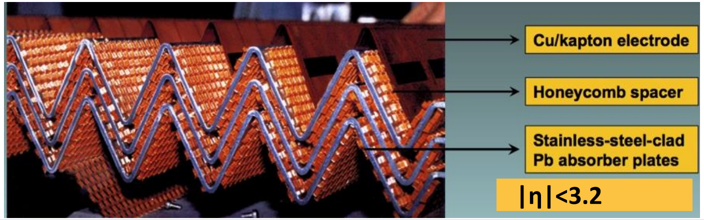
– radiation tolerance

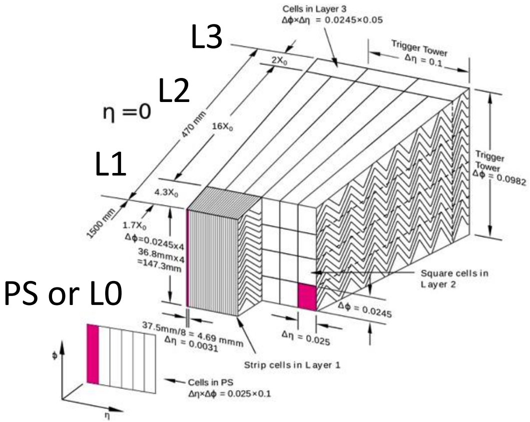
Advantages of **accordion geometry**

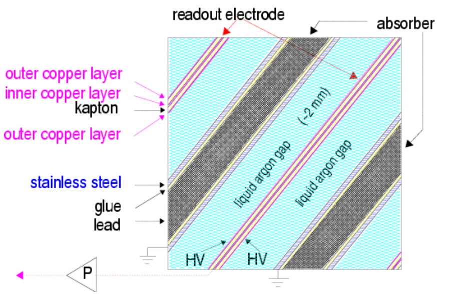
– it allows **a very high η-ϕ granularity** and **longitudinal segmentation** (PS, L1, L2, L3)

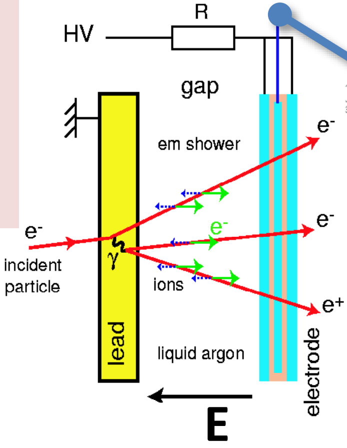
– it allows for very **good hermeticity** since HV and signal cables run only at front and back faces of the detector

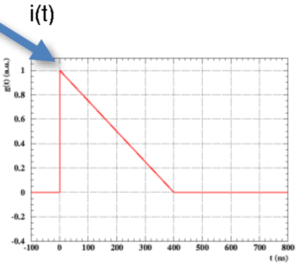
– it allows for **a very high uniformity** in ϕ











$t_{drift} \approx 450$ ns

Incident electrons create **EM showers** in Pb (X_0=0.56cm) and LAr gaps (X_0=14.2cm)

secondary e^+ and e^- create e^-–ion pairs in LAr (W=23.3eV)

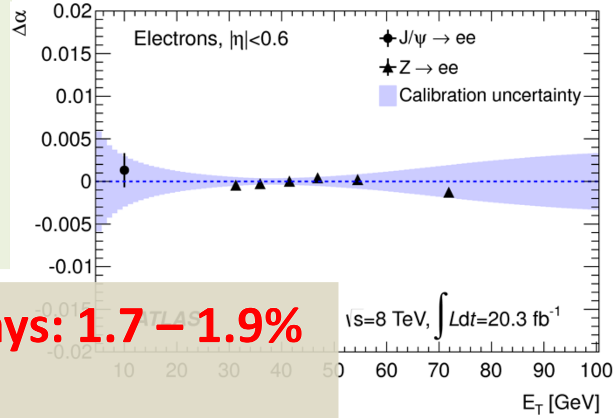
Ionized electrons and ions drift in electric field (2kV for 2mm gaps in barrel) and **induce triangular signal** (≈450ns e^- drift time)

Design resolution:

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

Achieved Resolution and Linearity (e.g. Run1)

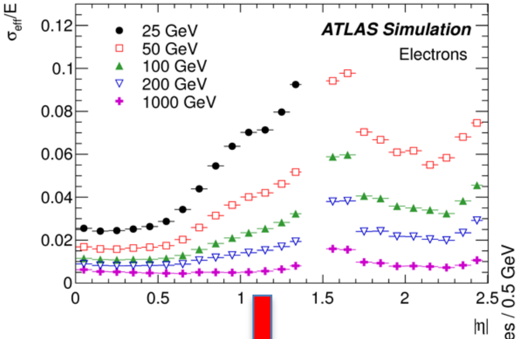
- **Resolution measurement**:
  - Assuming correct sampling term *a* of 10% GeV$^{1/2}$ (validated with J/ψ width)
  - Noise term *b* ≈ 200 – 300 MeV per cluster (+ pile-up noise)
  - Template fit of constant term *c* using m_{ee} invariant mass (Z-peak)
- **Linearity measurement** with J/Ψ, Z-peak (and E/p)

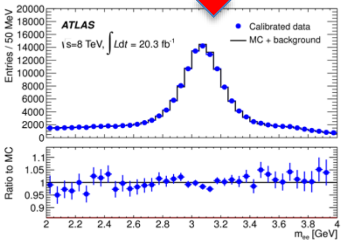


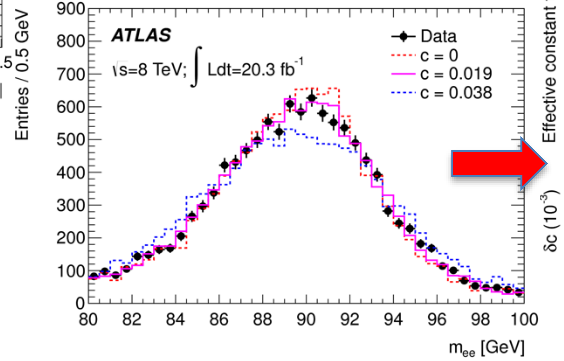
$$\frac{\sigma_E}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c$$

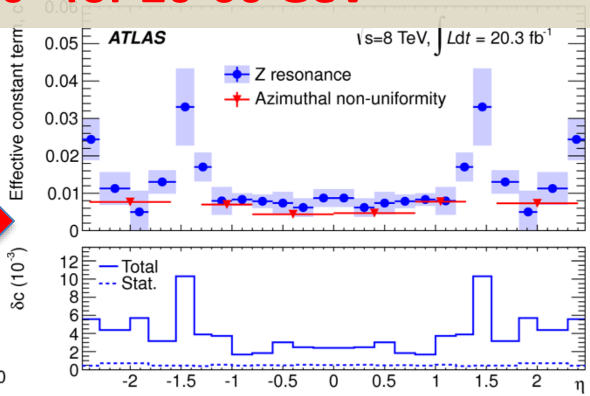
→ σ_E/E for $e^{\pm}$ from Z-decays: 1.7 – 1.9% for central barrel

→ linearity 10^{-3} for 20-60 GeV





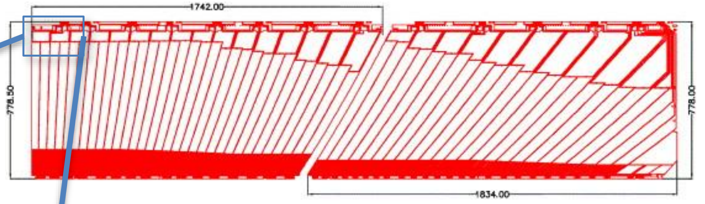


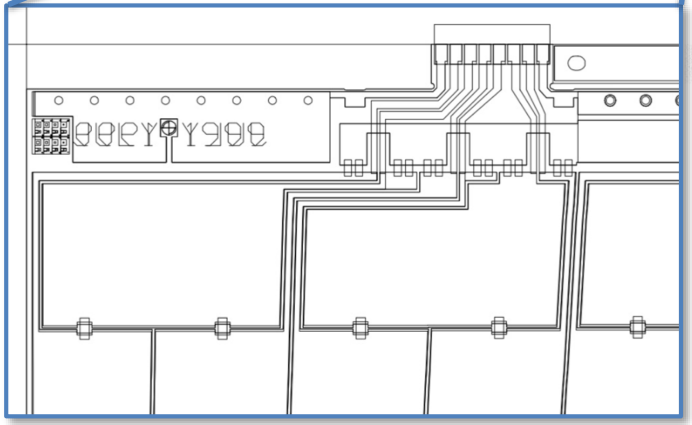


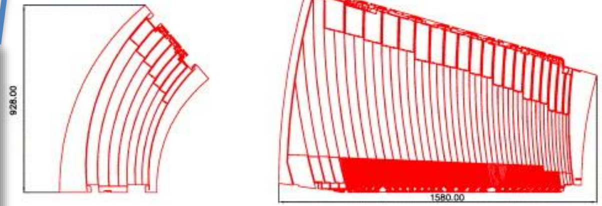
Measured constant term ***c*** **≈ 0.7%** in the central barrel, extracted value in agreement with ϕ non-uniformity

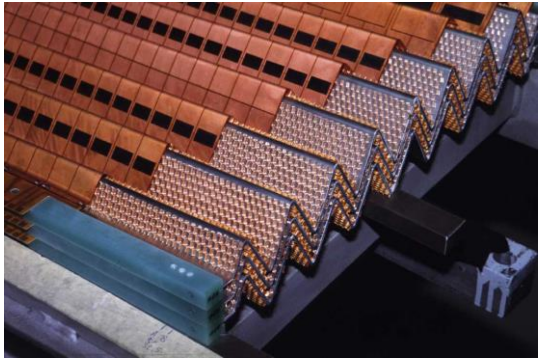
What Limits Granularity in ATLAS LAr?

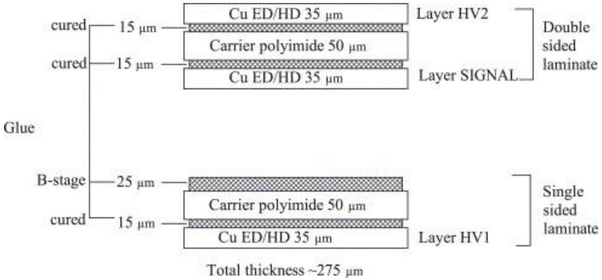
- **In the ATLAS LAr calorimeter** electrodes have 3 layers that are glued together (~275µm thick)
  - 2 HV layers on the outside
  - 1 signal layer in the middle
- → **All cells** have to be connected **with fine signal traces** (2-3mm) to the edges of the electrodes
  - Front layer read at inner radius
  - Middle and back layer read at outer radius
- → **limits lateral and longitudinal granularity**
- → maximum 3 long. layers





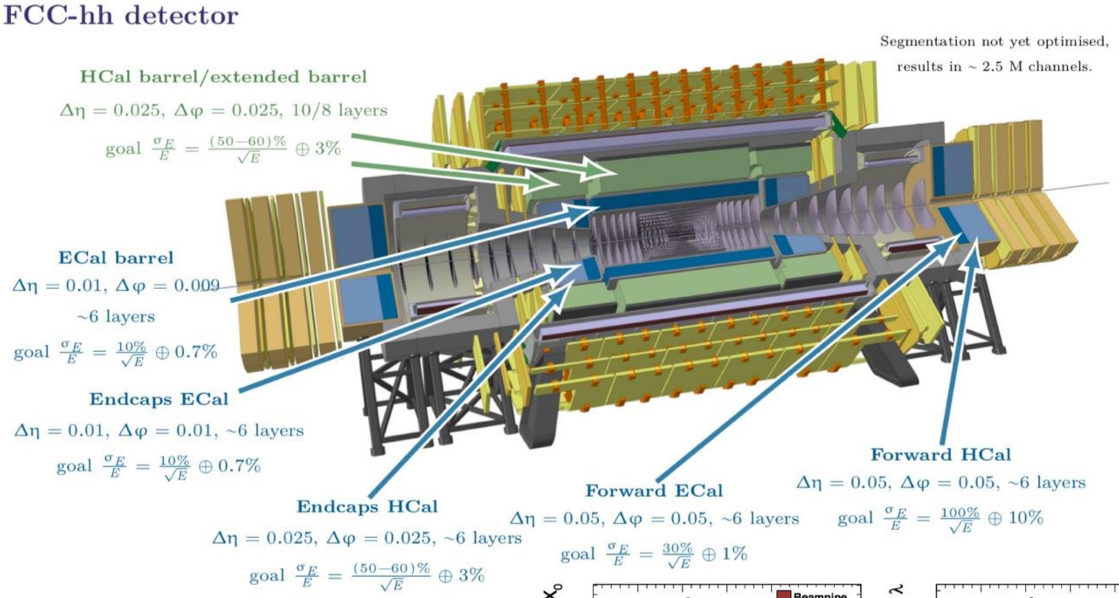




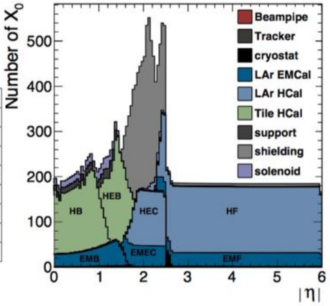


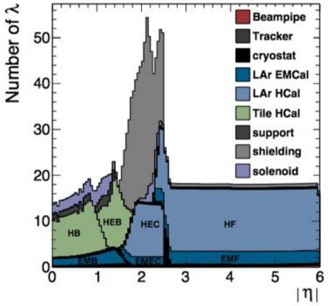
FCC-hh Detector – Calorimetry

FCC-hh Calorimetry



	R_{min}	R_{max}	z coverage	η coverage	Dose	1 MeV n_{eq} fluence
Unit	m	m	m		MGy	$\times 10^{15}$ cm^{-2}
EMB	1.75	2.75	$\lvert z\rvert < 5$	$\lvert\eta\rvert < 1.67$	0.1	5
EMEC	0.82	0.96	$5.3 < \lvert z\rvert < 6.05$	$1.48 < \lvert\eta\rvert < 2.50$	1	30
EMF	0.062	0.065	$16.5 < \lvert z\rvert < 17.15$	$2.26 < \lvert\eta\rvert < 6.0$	5000	5000
HB	2.85	4.89	$\lvert z\rvert < 4.6$	$\lvert\eta\rvert < 1.26$	0.006	0.3
HEB	3.5	5	$4.5 < \lvert z\rvert < 8.3$	$0.94 < \lvert\eta\rvert < 1.81$	0.008	0.3
HEC	0.96	1.32	$6.05 < \lvert z\rvert < 8.3$	$1.59 < \lvert\eta\rvert < 2.50$	1	20
HF	0.065	0.077	$17.15 < \lvert z\rvert < 18.5$	$2.29 < \lvert\eta\rvert < 6.0$	5000	5000





Reference Detector

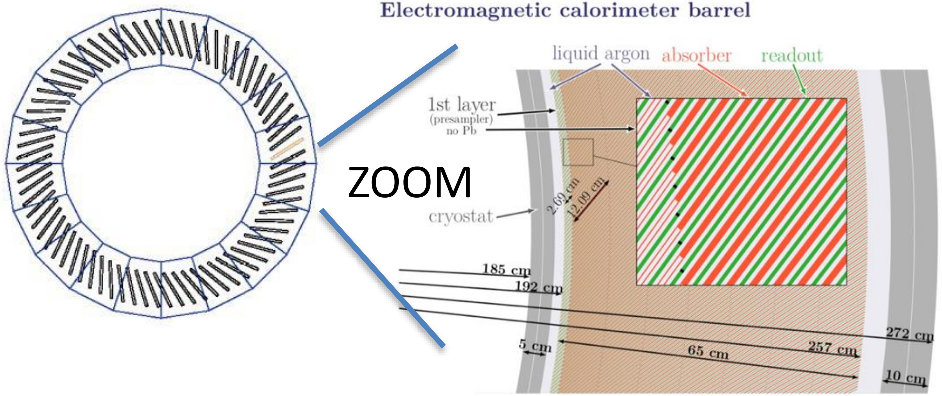
Inspired by ATLAS calorimetry:

- Excellent conventional calorimetry
- In addition high granularity to optimize for Particle Flow techniques, pile-up rejection, boosted objects….
- → **ECAL, Hadronic EndCap and Forward Calo (≥30X_0):**
  LAr / Pb (Cu)
- → **HCAL Barrel and Extended Barrel (≥10λ):**
  Scintillating tiles / Fe(+Pb) with SiPM

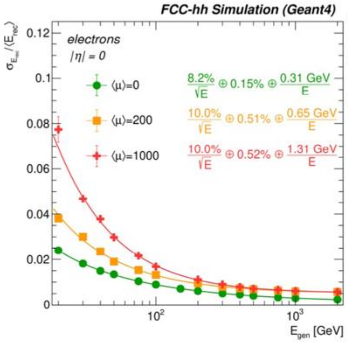
Other options considered for ECAL (see CDR)

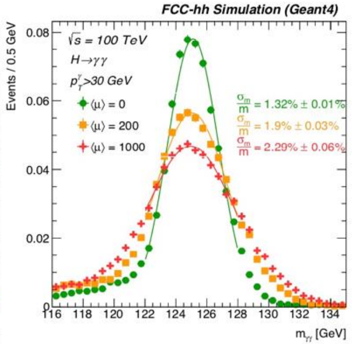
- Digital Si/W
- Analog Si/W

FCC-hh Electromagnetic Calorimeter (ECAL)

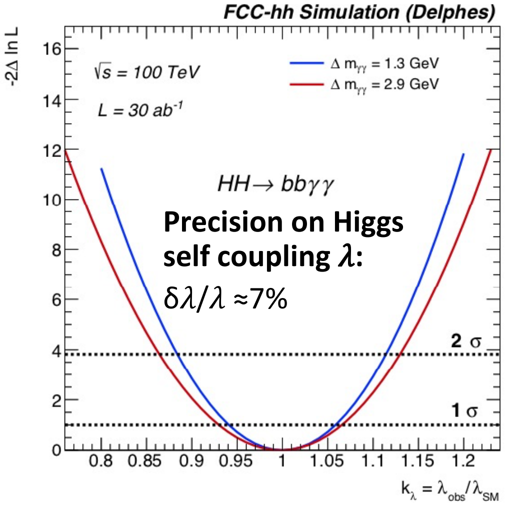


- 2 mm absorber plates inclined by 50° angle;
- LAr gap increases with radius: 1.15 mm–3.09 mm;
- 8 longitudinal layers (first one without lead as a presampler);
- $\Delta\eta = 0.01$ (0.0025 in 2nd layer);
- $\Delta\varphi = 0.009$;





- Compared to ATLAS, **FCC-hh Calo** needs **finer longitudinal and lateral granularity**
  - **Optimized for particle flow**
  - **8 longitudinal compartments**, fine lateral granularity
  - **Granularity:** $\Delta\eta \times \Delta\phi \approx 0.01 \times 0.01$; first layer $\Delta\eta \times \Delta\phi \approx 0.0025 \times 0.02$ → ~2.5M channels
- **Possible only with straight multilayer electrodes (no accordion)**
  - Active material LAr
  - Straight absorbers (Pb + stainless steel sheets), 50° inclined with respect to radial direction
  - Readout and HV on straight multilayer electrodes (PCBs, 7 layers, 1.2mm thick)
  - → Sampling fraction changes with depth $f_{sampl} \approx 1/7$ to $1/4$ (LAr gap 2 x 1.15mm to 2 x 3.09mm)
- **Required energy resolution achieved**
  - Sampling term ≤ 10%/√E, only ≈300 MeV electronics noise despite multilayer electrodes
  - Impact of in-time pile-up at <μ> = 1000 of ≈ 1.3GeV pile-up noise
  - →Efficient in-time pile-up suppression will be crucial (using the tracker)

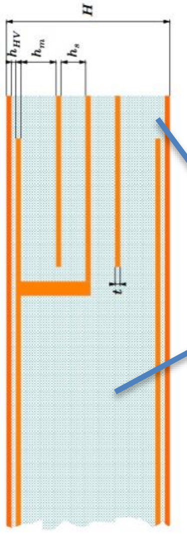


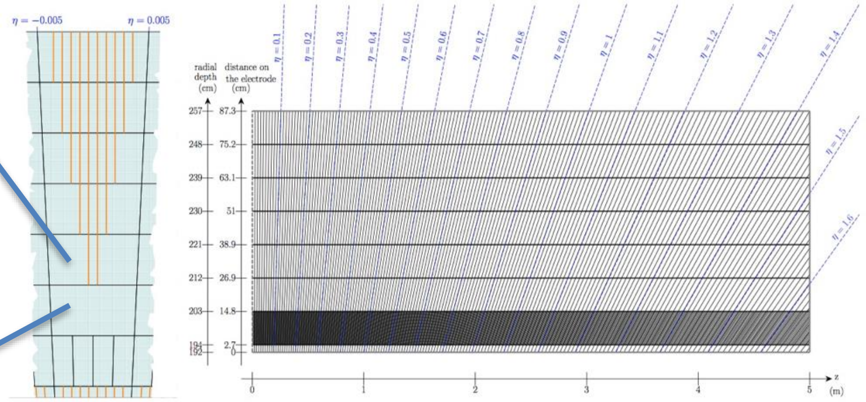
Plots A. Zaborowska, C. Helsens, M. Selvaggi

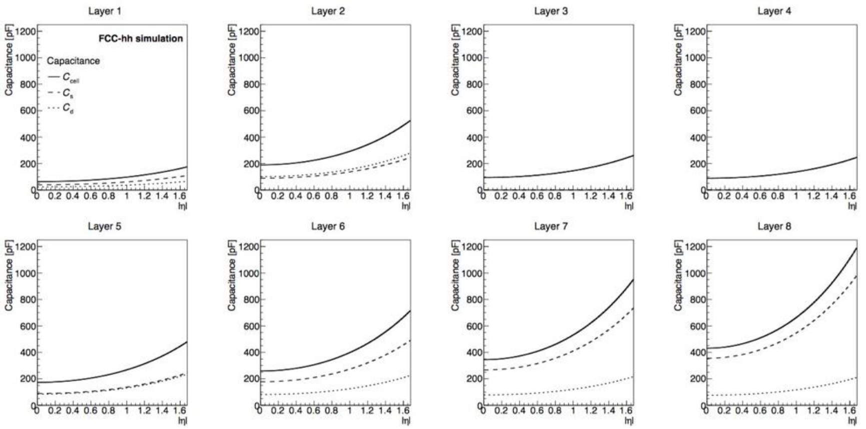
How to Achieve High Granularity?

Realize read-out electrodes as multi-layer PCBs (1.2mm thick)

- Signal traces (width w_t) in dedicated signal layer connected with vias to the signal pads
- Traces shielded by ground-shields (width w_s) forming 25Ω – 50Ω transmission lines
- → capacitance between shields and signal pads C_s will add to the detector capacitance C_d
- → $C_{cell} = C_s + C_d \approx 100 - 1000$pF
- The higher the granularity the more shields are necessary → C_{cell} increases

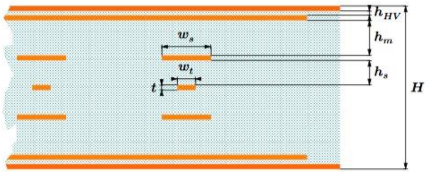






→ Serial noise contribution proportional to capacitance C_{cell}

→ 4 – 40MeV noise per read-out channel assuming ATLAS-like electronics



Hadronic showers: Energy sums over O(500-10000) cells

Plots A. Zaborowska, J. Faltova

FCC-hh Hadronic Calorimeter Barrel (HCAL)

Barrel HCAL:

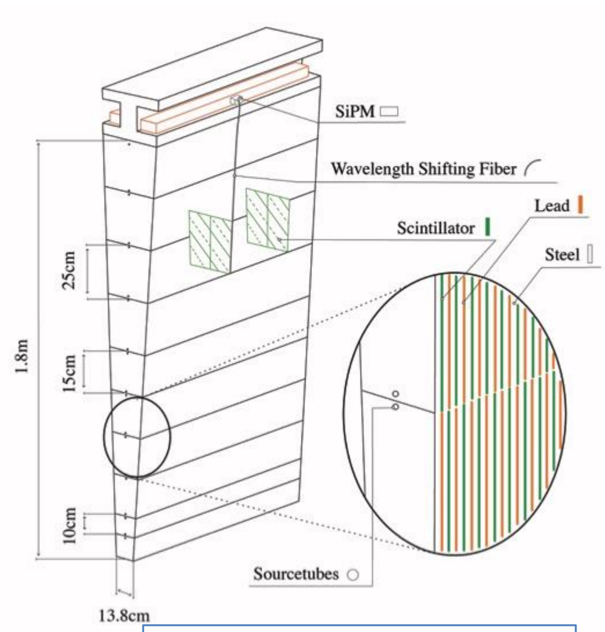
- ATLAS type
  - Scintillator tiles – steel
- **Higher granularity** than ATLAS
  - $\Delta\eta \times \Delta\phi = 0.025 \times 0.025$
  - 10 instead of 3 longitudinal layers
  - Steel –> stainless Steel absorber (Calorimeters inside magnetic field)
- SiPM readout → faster, less noise, less space
- Total of 0.3M channels

Combined pion resolution (w/o tracker!):

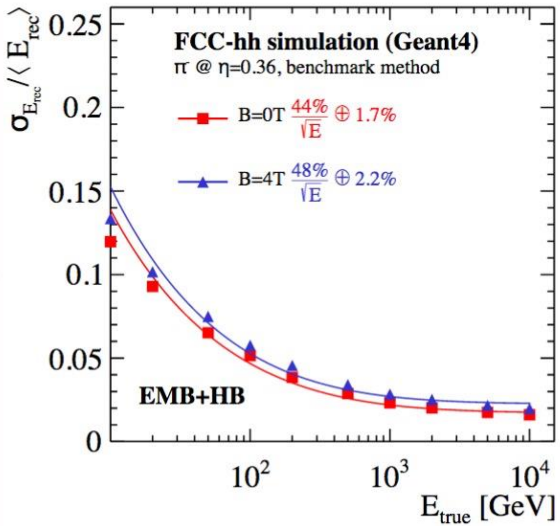
- Simple calibration: $44\%/\sqrt{\bar{E}}$ to $48\%/\sqrt{\bar{E}}$

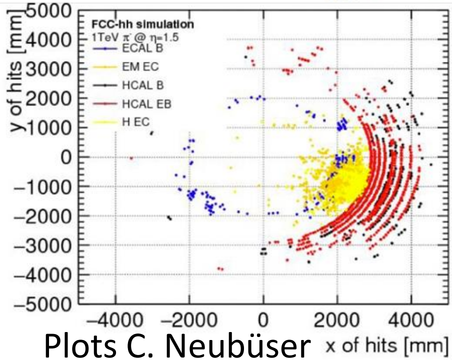
Jet resolution:

- Jet reconstruction impossible without the tracker @ 4T → particle flow.



e/h ratio very close to 1 → achieved using steel absorbers and lead spacers (high Z material)

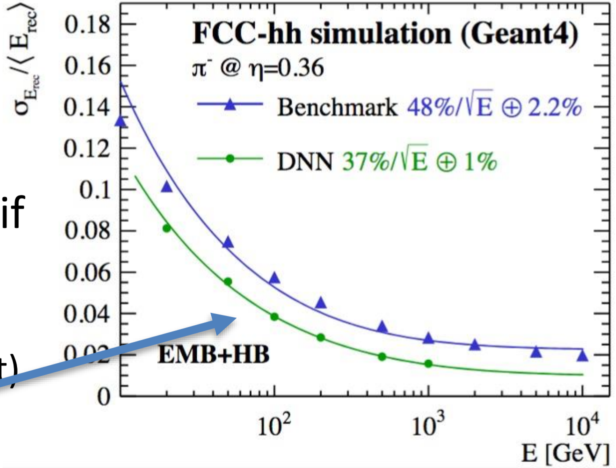


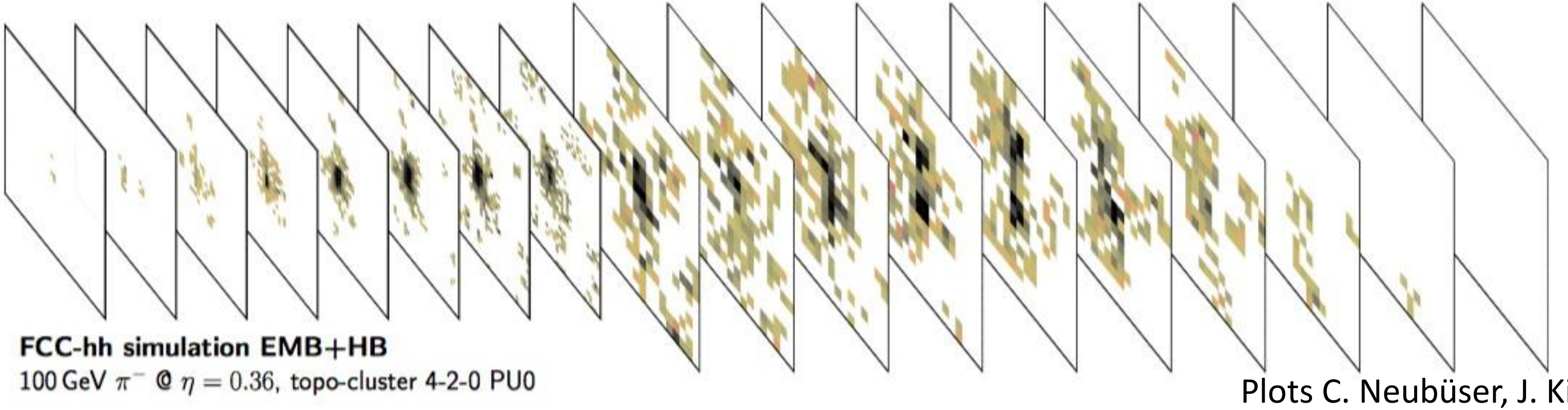


Plots C. Neubüser

Combined Performance for Hadrons

- **FCC-hh calorimetry: High granularity of EM and HCal**
- → Ideal for particle flow techniques (but not yet implemented in SW)
- → Which resolution can be achieved with calorimetry only, if using the full shower-imaging information?
- **First results** obtained using a **convolutional neural network**
  - Training with 8M events (without electronics noise for the moment)
  - Excellent results obtained → **Sampling term of 37%/√Ē (!!!)**





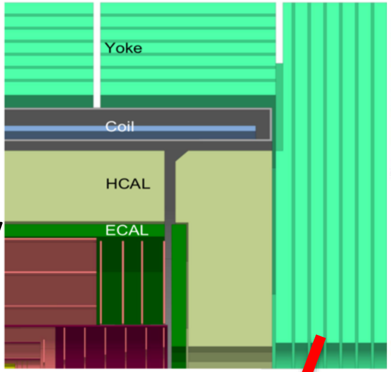
Plots C. Neubüser, J. Kieseler

Requirements for FCC-ee Calorimetry

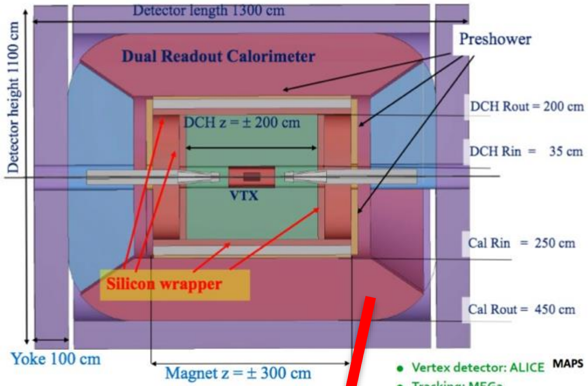
FCC-ee

- **Calorimetry requirements**:
  - ***Excellent jet energy resolution*** (~30%/√Ē)
  - ***Particle ID***
- **→ High granularity calorimetry based on particle flow**
  - **Same technologies as for CLIC/ILC under study**
    - e.g. Si/W ECAL and Scintillator/Iron HCAL
  - **On top of that fibre-sampling dual-readout calorimetry** could be a very interesting option for future leptonic colliders
    - Fine transverse granularity
    - Need longitudinal segmentation to separate e/γ from $\pi^{\pm}$! → Idea with fibres of different length
    - Excellent hadronic resolution (simulation ~35%/√Ē)
  - **Noble liquid based calorimetry**
    - Calo only: Simulation with DNN calib. for LAr ECAL + TileCal HCAL: ~37%/√Ē
    - Fine granularity → particle flow reco with ID

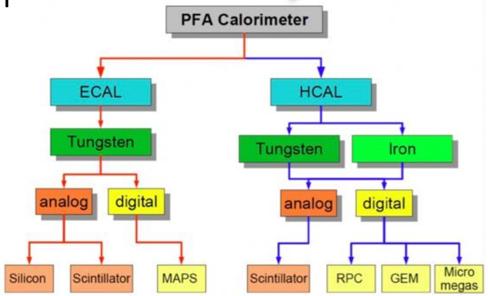
"CLIC-detector revisited - CLD"

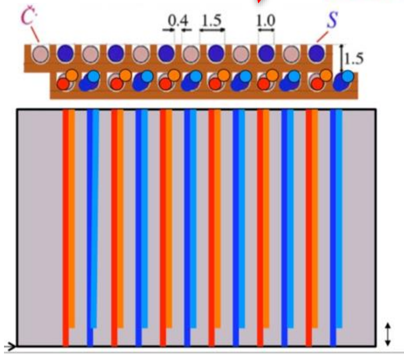


"IDEA"



- Vertex detector: ALICE MAPS
- Tracking: MEG2
- Si Preshower
- Ultra-thin solenoid (2T)
- Calorimeter: DREAM
- Equipped return yoke





Inspired from CMS HF Calo [Only Č fibres]

Requirements for FCC-ee Calorimetry

- **Energy range of particles:**
  - All particles ≤ 182.5 GeV
    - → $22X_0$ and 5-7λ sufficient
  - Measure particles down to 300 MeV (e.g. photons)
    - → Little material in front of the calorimeter
    - → Low noise (noise term dominant at small energies, $b \ll 300$ MeV)!
- **EM resolution as good as possible** (≤ 15%/√Ē)
  - e.g. for CLFV τ decays $\tau \rightarrow \mu\gamma$
- **Jet resolution must be excellent** (~ 30%/√Ē) to separate W and Z decays
- **Position resolution of photons:** $\sigma_x = \sigma_y = (6\ \mathrm{GeV}/E \oplus 2)$ mm **Particle ID:**
  - $e^{\pm}/\pi^{\pm}$ separation,
  - τ decays with collimated final states, separate different decay modes with minimal overlap (e.g. π_0 close to $\pi^{\pm}$)

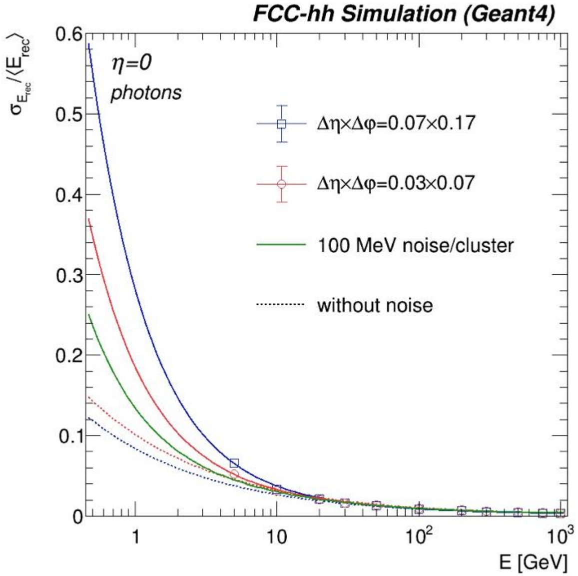
Dimensions: Example CLD

Table 1.1: Comparison of key parameters of CLD and CLICdet detector models. The inner radius of the calorimeters is given by the smallest distance of the calorimeter (dodecagon) to the main detector axis.

Concept	CLICdet	CLD
Vertex inner radius [mm]	31	17
Tracker technology	Silicon	Silicon
Tracker half length [m]	2.2	2.2
Tracker outer radius [m]	1.5	2.1
Inner tracker support cylinder radius [m]	0.575	0.675
ECAL absorber	W	W
ECAL X_0	22	22
ECAL barrel r_{min} [m]	1.5	2.15
ECAL barrel Δr [mm]	202	202
ECAL endcap z_{min} [m]	2.31	2.31
ECAL endcap Δz [mm]	202	202
HCAL absorber	Fe	Fe
HCAL λ_{I}	7.5	5.5
HCAL barrel r_{min} [m]	1.74	2.40
HCAL barrel Δr [mm]	1590	1166
HCAL endcap z_{min} [m]	2.4	2.4
HCAL endcap Δz [mm]	1590	1166
Solenoid field [T]	4	2
Solenoid bore radius [m]	3.5	3.7
Solenoid length [m]	8.3	7.4
Overall height [m]	12.9	12.0
Overall length [m]	11.4	10.6

Could Noble Liquid Calorimetry Work? (1/2)

- **Dimensions:**
  - ECAL: $22X_0$: → ~60 cm radial space for FCC-hh type LAr/Pb calorimeter (including 15cm cryostat thickness)
    - Could be further reduced to ~45cm by using W instead of Pb
  - ECAL+HCAL: 5-7λ: → ~1.2 m radial dimension for TileCal (FCC-hh style)
  - → Calorimetry within Δr = 1.65m (W ECAL + TileCal) to Δr = 1.8m (Pb ECAL + TileCal).
  - → Only slightly bigger than CLD (Δr_{CLD} = 1.4m)
- **EM resolution:**
  - **Sampling term** of ≈ $10\%/\sqrt{\bar{E}}$ quite easily achievable
  - Resolution at low energies dominated by **noise term**
    - Noise term ≈ 300MeV achieved with FCC-hh calorimeter
    - Noise term of ≤ 100 MeV seems possible for low energy deposits (optimized cluster size, see back-up)
    - In addition for large cell capacitances: Could probably gain factor 1.5 when going to slower shaping times τ ≥ 100 ns (FCC-hh τ = 45ns)
  - To measure down to 300 MeV need to **minimize material in front of the calorimeter** → "thin" Al cryostat or carbon fibre cryostat (R&D program at CERN has been launched, see next slide)



R&D on Low Mass Composite Cryostats

See WG4 contribution at EP R&D WS
https://indico.cern.ch/event/743661/contributions/3154180/attachments/1721546/2781799/20180925_WG4_Detector_Mechanics.pdf

ACTIVITY N.1 TASK N.2

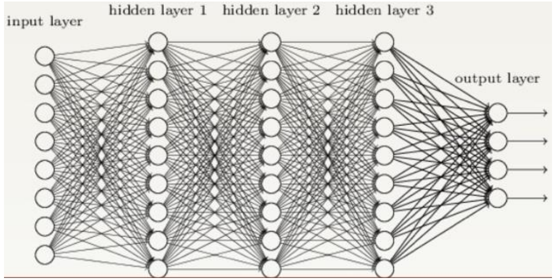
LOW MASS COMPOSITE : CALORIMETERS AND DETECTOR MAGNETS

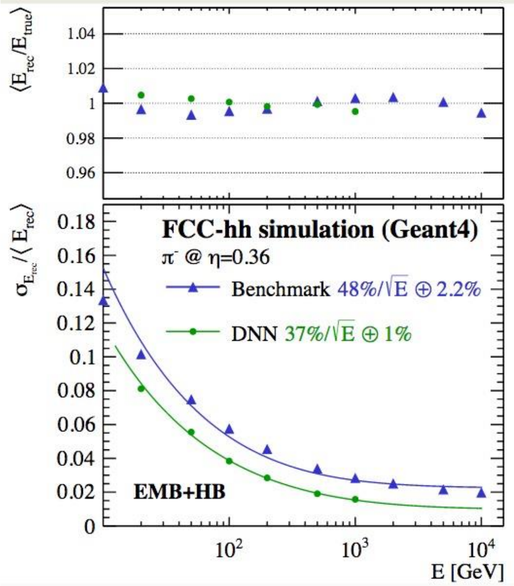
✓ Cryostat in HEP detector should profit from similar development in aerospace cryotank: CHATT, CCTD, SpaceX Programs

✓ Investigate how to tailor these new processes and materials for HEP cryostat: thermal insulation, feed through, rad loads 15

Could Noble Liquid Calorimetry Work? (2/2)

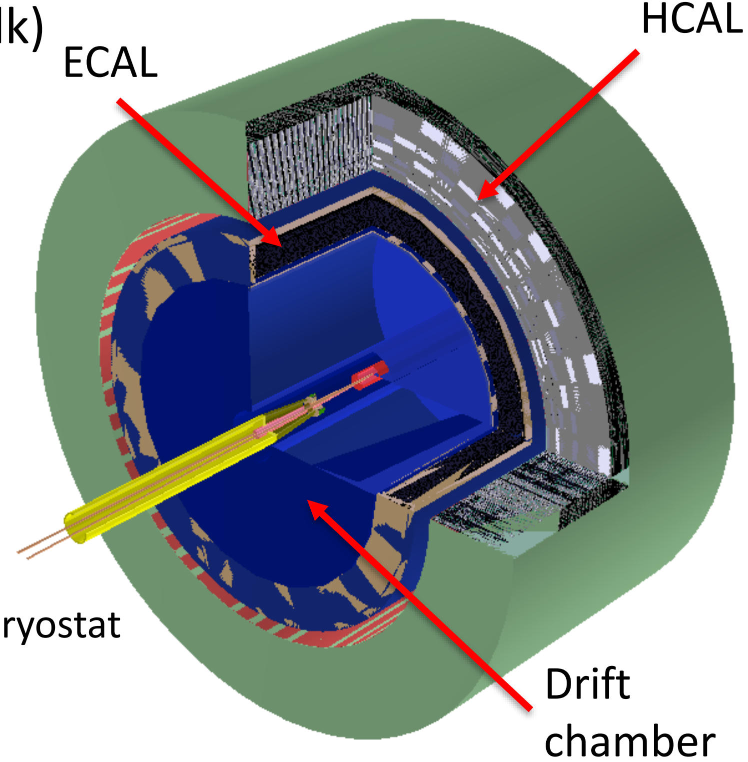
- **Jet resolution**
  - **Requirement:** (~ 30%/√Ē) to separate W and Z decays
  - **Calo only:** hadron resolution (π^-) achieved in FCC-hh (LAr ECAL + TileCal HCAL):
    - Benchmark reconstruction: ~48%/√Ē
    - Simulation with DNN calibration ~37%/√Ē
    - → Already close to the required 30%/√Ē
  - **Particle flow** will further reduce the jet resolution (not simulated yet)
  - **Future jet energy reconstruction** will probably use machine learning to combine **tracker information and full 3D imaging** information
- **Particle ID:**
  - Fine granularity in η, ϕ, depth can be adjusted according to needs (PCB)
  - E.g. FCC-hh first calorimeter layer 5mm x 20mm cells (x 9cm depth)
  - Similar segmentation of read-out electrode would lead to cell sizes of 2.5mrad x 2.5mrad for FCC-ee
- **Position resolution:**
  - For FCC-hh achieved $\sigma_\eta \approx 2\text{x}10^{-3}/\sqrt{\bar{E}}$
  - → ≈ 4.4mm/√Ē → ~1mm for 20GeV (2mm for 5GeV) → sufficient
- **Timing:**
  - ATLAS LAr: Timing resolution of 150ps achieved for EM showers ≥30GeV, 65ps for EM showers ≥100GeV
  - Possibility to further improve this resolution – studies needed and planned





Towards an FCC-ee Experiment

- **FCC-hh style calorimeter has been implemented into FCC-ee Experiment in FCC SW** (see next talk)
- **First implementation:**
  - Inner Tracker: DREAM-like drift chamber
  - ECAL: FCC-hh style LAr/Pb calorimeter
  - HCAL: FCC-hh style Tile calorimeter (Fe absorbers)
  - Solenoid coil outside the calorimetry
- **Options which will be studied**
  - Inner tracker: Si tracker
  - ECAL: W absorbers, LKr as active material
  - HCAL: CLD-like HCAL
  - Solenoid coil in front of the ECAL, integrated into LAr cryostat (need thin coil and low-material cryostat)
- **H2020 EoI has been submitted to study PCB electrode design**



Conclusions and Outlook

- **Noble liquid calorimetry** has been **successfully used for LHC experiments** (ATLAS LAr Calorimeter)
  - Strengths: Stability, pointing resolution, particle ID, radiation hardness
- **Noble liquid calorimetry** is **proposed for the reference detector of FCC-hh**
  - Simulations show that such a calorimeter would fulfil physics requirements for FCC-hh
- **Noble liquid calorimetry** is also an **interesting option for a FCC-ee experiment!**
  - Preliminary considerations: such a calorimeter could be feasible and would fulfil physics requirements for FCC-ee
  - Potentially cheaper than other options!
  - High stability of response will give us handles to keep systematic errors down (and develop corrections)
  - Layout has been adapted to an FCC-ee experiment
    - Noble liquid calorimeter has been implemented into FCC-ee experiment in FCC SW
    - → Start full-sim studies and optimization (see next talk by V. Volkl)!
- **Please join us if you are interested in this promising option!**

Thank You for Your Attention!

Back-Up

LHC EM Calorimeters Requirements

→ **LHC Calorimeters were designed for benchmark channels**: SM precision measurements, Higgs discovery and measurements, discovery of heavy resonances.

Large dynamic range: 10 MeV – 3TeV (noise level up to highest energy deposits per cell)

→ **≈16bit dynamic range (several gains necessary)**

Large dynamic range: 10 MeV – 3TeV (noise level up to highest energy deposits per cell)

→ **≈16bit dynamic range (several gains necessary)**

Energy resol. ($e^{\pm}$,γ): $\sigma_E/E \approx 10\%/\sqrt{E} \oplus 0.7\%$ (for $H \rightarrow \gamma\gamma$ mass with 1% resolution @ 120GeV)

→ **precise mechanics & electronics calibration**

Linearity: 0.1 %, 10^{-4} around the Z-peak (for W-mass measurement!)

→ **pre-sampler (correction for dead material), layer weighting, electronics calibration**

Fast shaping to optimize signal/noise ratio:

→ **40 MHz sampling rate (LHC bunch crossing)**

→ **Digital filtering for signal reconstruction**

Minimal coherent pickup noise (<5% of incoherent noise)

Minimal dead time at Level 1 (L1) 75 – 100 kHz trigger rate and storing of signals during the **latency** of the L1 trigger of up to 2.5μs (100 bunch crossings)

→ **realized with switch capacitor array of 144 bunch crossings**

EM Calorimeter: ATLAS – CMS Comparison

ATLAS

- Sampling calorimeter (LAr-Pb), 3 longitudinal layers + presampler, 173000 channels), E range MIP – TeV
- High lateral granularity
  - $\Delta\eta=0.0031$, $\Delta\phi=0.025$
- Presampler + 3 longitudinal layers
- Radiation resistance
- Good energy resolution
- Very stable response in time
  - rms in time $\approx 3\text{x}10^{-4}$
  - → ideal to understand systematic effects using large statistics of e.g. Z→ee events and develop corrections!
- Outside solenoid field (behind the coil) → 3 – 6 X_0 in front of calorimeter
- Main correction: dead material correction using presampler
- Strength: background rejection (e.g. π^0), stability, photon vertex measurement (pointing)

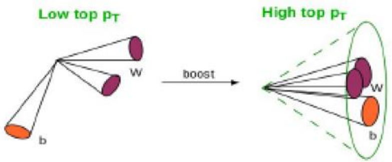
CMS

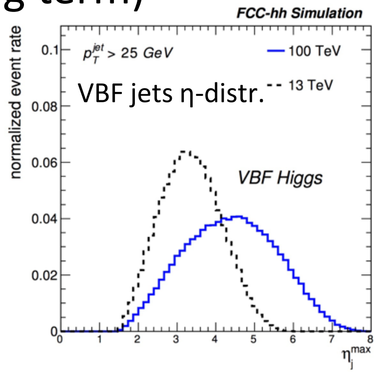
- Homogeneous calorimeter (75000 $PbWO_4$ crystals + PS in forward direction), E range MIP – TeV
- High lateral granularity
  - $\Delta\eta=\Delta\phi=0.0175$
- No longitudinal segmentation
- Radiation resistance
- Excellent energy resolution
- Response impacted by radiation
  - after laser correction rms $\approx 2\text{x}10^{-3}$
- Inside strong solenoid field → only 0.4 – 1.9 X_0 in front of calorimeter
- Main correction: Laser correction to compensate impact of radiation
- Strength: little material in front, energy resolution

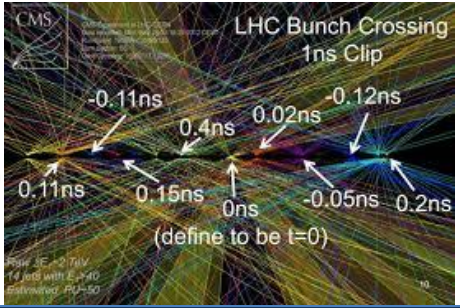
Requirements for FCC-hh Detector

Used in Delphes physics simulations

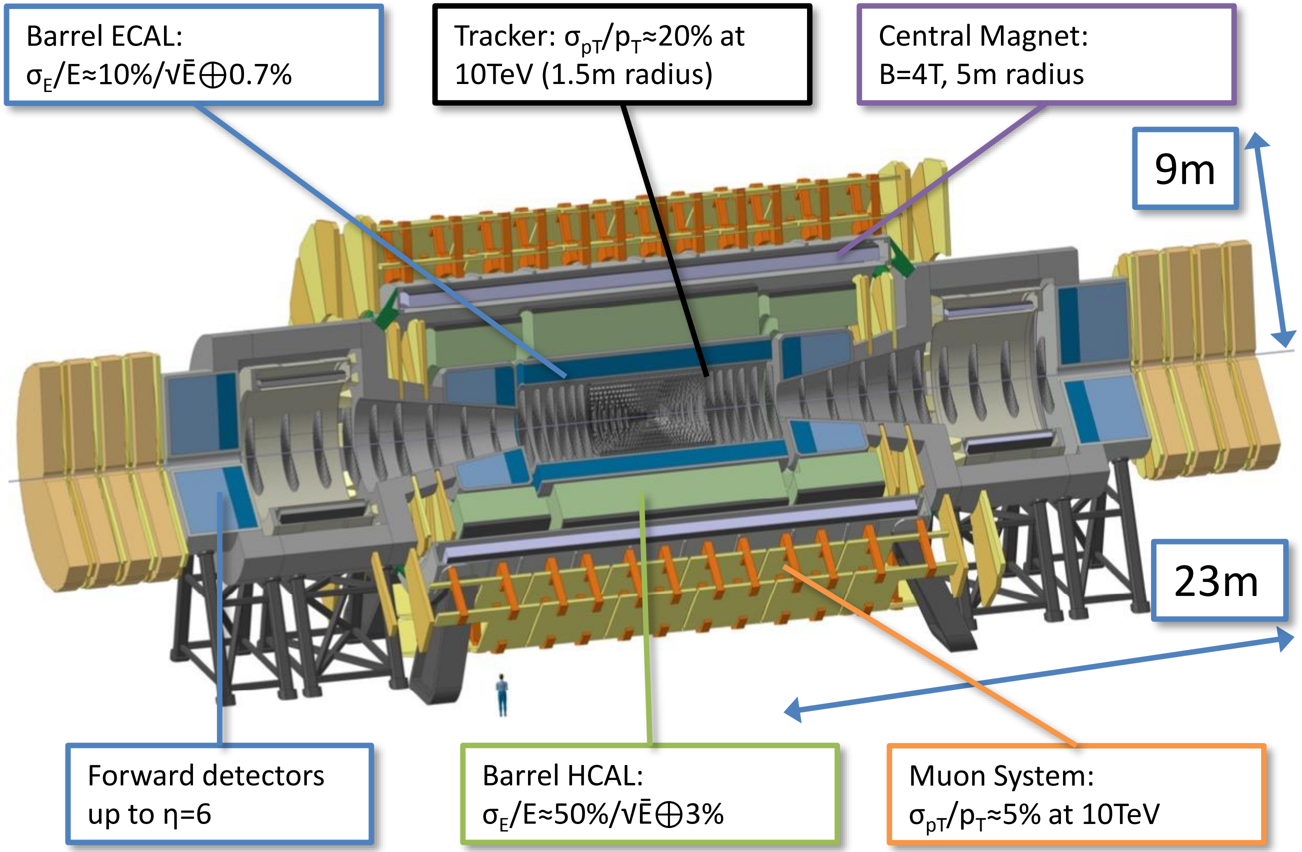
- **ID Tracking target**: achieve σ_{pT} / p_T = 10-20% @ 10 TeV
- **Muons target**: σ_{pT} / p_T = 5% @ 10 TeV
- Keep **calorimeter constant** term as small as possible (and good sampling term)
  - Constant term of <1% for the EM calorimeter and <2-3% for the HCAL
- **High efficiency b-tagging, τ-tagging, particle ID**!
- **High granularity** in tracker and calos
- **Pseudorapidity (η) coverage**:
  - Precision muon measurement up to |η|<4
  - Precision calorimetry up to |η|<6
- **→ Achieve all that at a pile-up of 1000! → Granularity & Timing!**
- **On top of that radiation hardness and stability!**







A Possible FCC-hh Detector – Reference Design for CDR

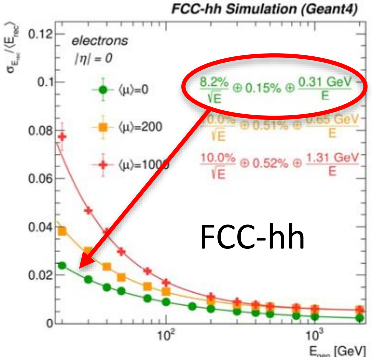


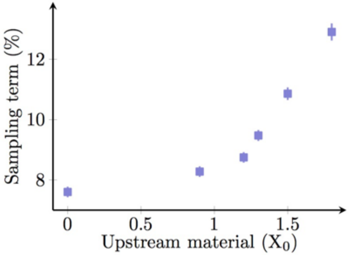
- During last years converged on **reference design for an FCC-hh experiment**
- **Radiation simulations**
- Demonstrate in the CDR document, that an **experiment** exploiting the **full FCC-hh physics potential** is **technically feasible**
- **→ Input for Delphes physics simulations**
- Room for other ideas, other concepts and different technologies
- See **FCC CDR Summary Volumes**
  - https://indico.cern.ch/event/750953/

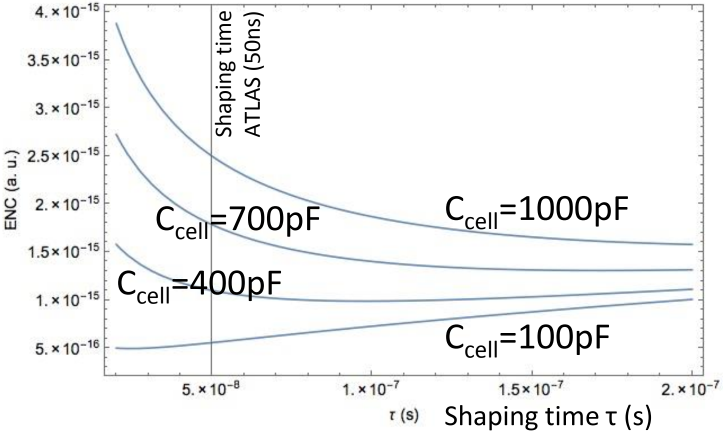
Could Noble Liquid Calorimetry Work?

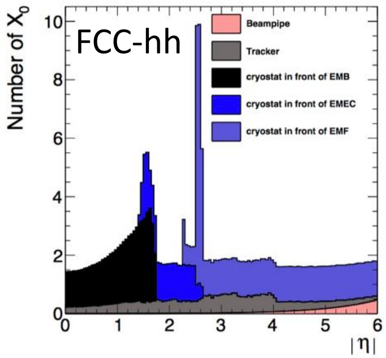
- **Dimensions:**
  - ECAL: $22X_0$: → ~60 cm radial space for FCC-hh type LAr/Pb calorimeter (including 15cm cryostat thickness)
    - Could be further reduced to ~45cm by using W instead of Pb
  - ECAL+HCAL: 5-7λ: → ~1.2 m radial dimension for TileCal (FCC-hh style)
  - → Calorimetry within Δr = 1.65m (W ECAL + TileCal) to Δr = 1.8m (Pb ECAL + TileCal).
  - → Only slightly bigger than CLD (Δr_{CLD} = 1.4m)

- **EM resolution:**
  - **Sampling term** of *a* ≈ 10%/√Ē quite easily achievable
  - Resolution at low energies dominated by **noise term** ***b***
    - Noise term *b* ≈ 300MeV achieved with FCC-hh calorimeter
    - Noise term of *b* ≤ 100 MeV seems possible for low energy deposits (optimized cluster size, see back-up)
    - In addition for large cell capacitances: Could probably gain factor 1.5 when going to slower shaping times τ ≥ 100 ns (FCC-hh τ = 45ns)
  - To measure down to 300 MeV need to **minimize material in front of the calorimeter** → "thin" Al cryostat or carbon fibre cryostat (R&D program at CERN has been launched, see next slides)





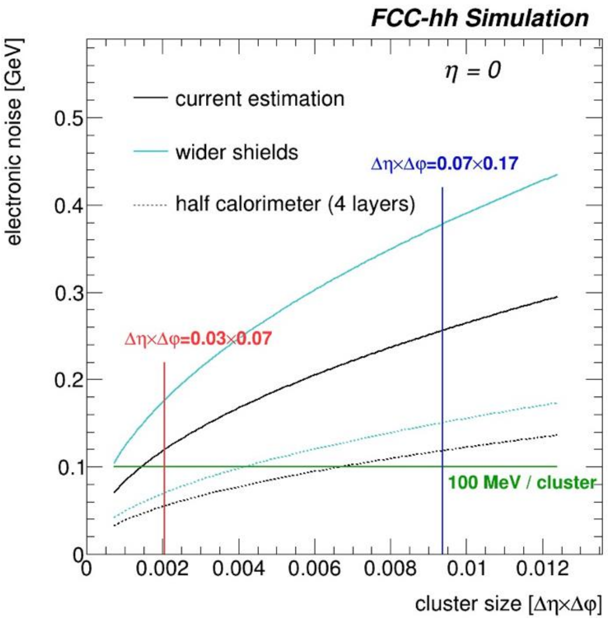


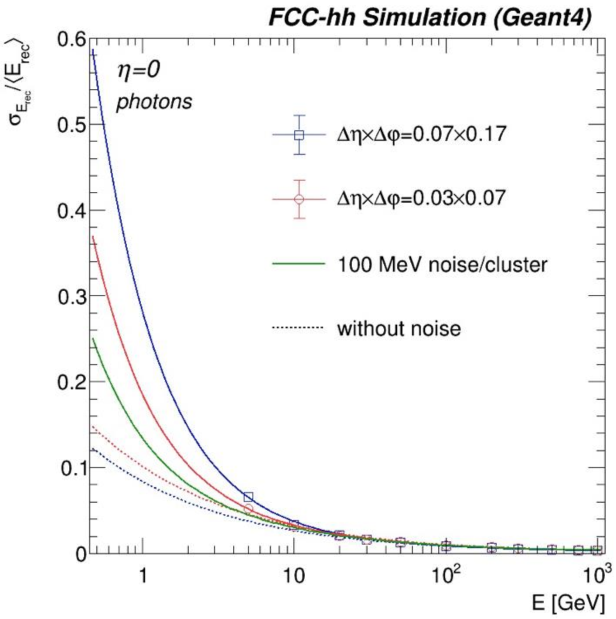


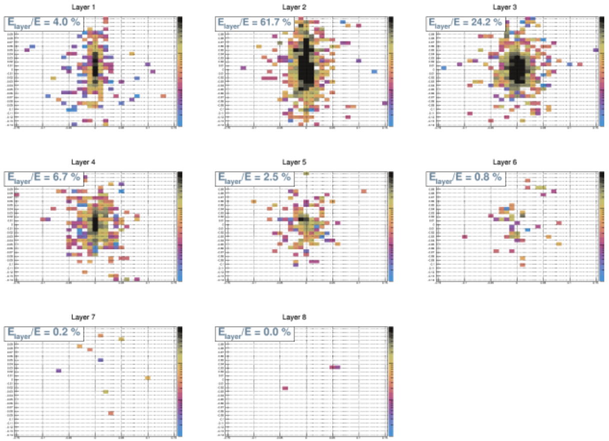
Example: Optimize Noise for FCC-hh Calorimeter

Challenge: Good photon energy resolution down to 300MeV:

- 30% resolution at 300MeV if noise level can be kept below 100MeV
- → Cluster size optimization (only first layers have significant energy deposits) → less cells per cluster → less electronics noise







→ Only 3.5% of the energy in layers 5 to 8 (for 300 MeV photon)

Courtesy A. Zaborowska