FCC-hh calorimetry in FCC-ee

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FCC-hh detector

H-Cal barrel, extended barrel
$\Delta\eta = 0.025$, $\Delta\phi = 0.025$, ~10/8 layers
Goal $\sigma E/E = 50\text{-}60\%/\sqrt{E} \oplus 3\%$

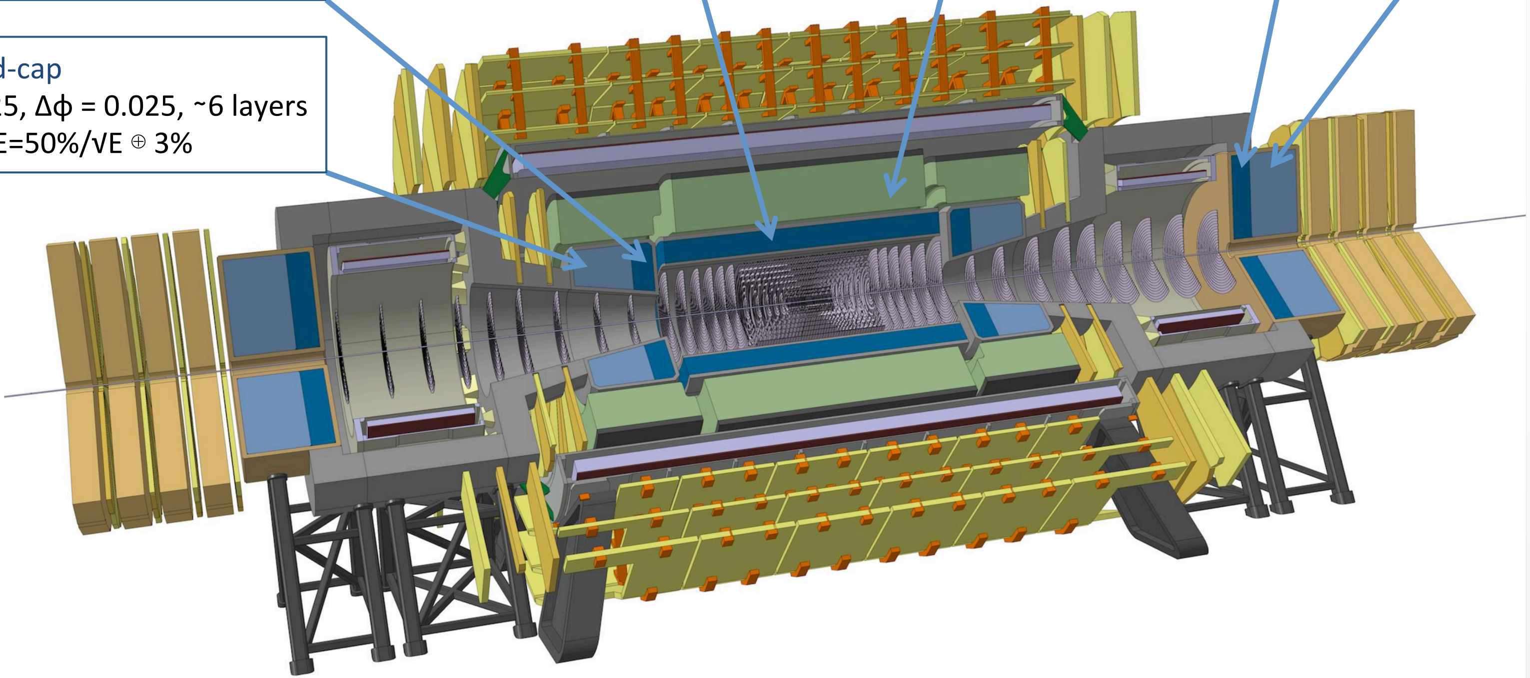
H-Cal forward
$\Delta\eta = 0.05$, $\Delta\phi = 0.05$, ~6 layers
Goal $\sigma E/E = 100\%/\sqrt{E} \oplus 10\%$

E-Cal forward
$\Delta\eta = 0.05$, $\Delta\phi = 0.05$, ~6 layers
Goal $\sigma E/E = 30\%/\sqrt{E} \oplus 1\%$

E-Cal barrel
$\Delta\eta = 0.01$, $\Delta\phi = 0.009$, ~6 layers
Goal $\sigma E/E = 10\%/\sqrt{E} \oplus 0.7\%$

E-Cal end-cap
$\Delta\eta = 0.01$, $\Delta\phi = 0.01$, ~6 layers
Goal $\sigma E/E = 10\%/\sqrt{E} \oplus 0.7\%$

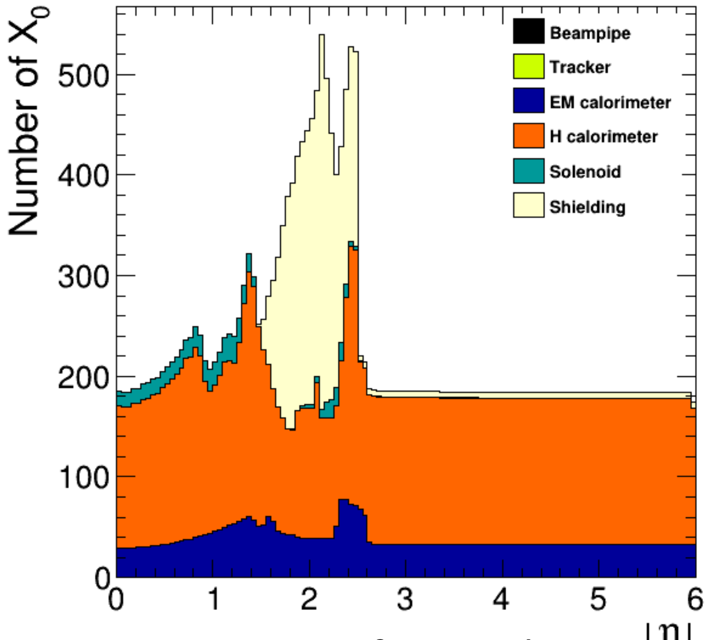
H-Cal end-cap
$\Delta\eta = 0.025$, $\Delta\phi = 0.025$, ~6 layers
Goal $\sigma E/E = 50\%/\sqrt{E} \oplus 3\%$



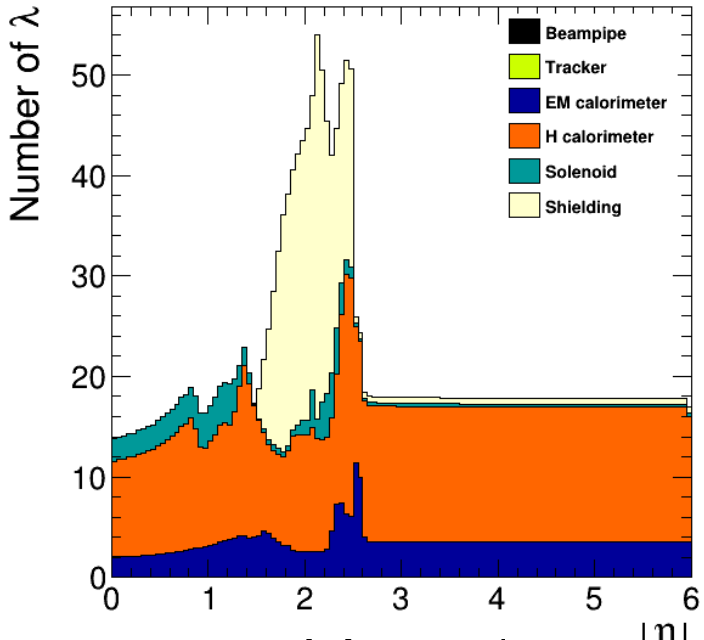
Calorimeter choices

- E-Cal: Liquid Argon used for barrel, end-cap and forward
- H-Cal: scintillator in the barrel, liquid argon in end-cap and forward

} Radiation hardness



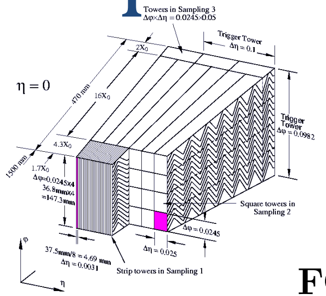
$>30x_0$ for E-Cal



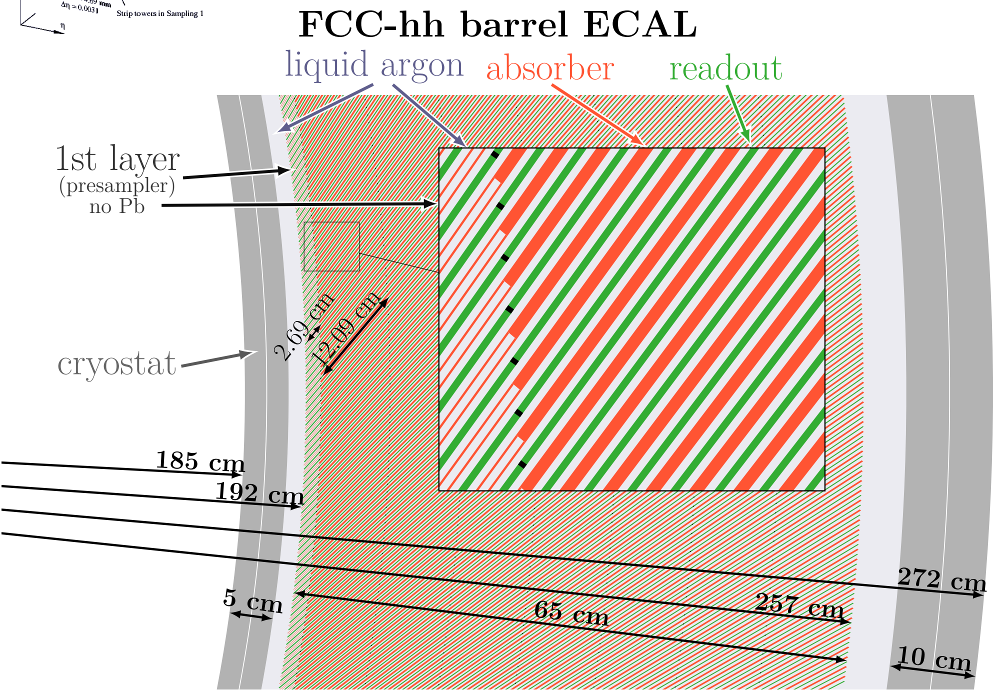
>11λ for H-Cal

Liquid Argon Calorimeters

Liquid argon calorimeter (barrel)

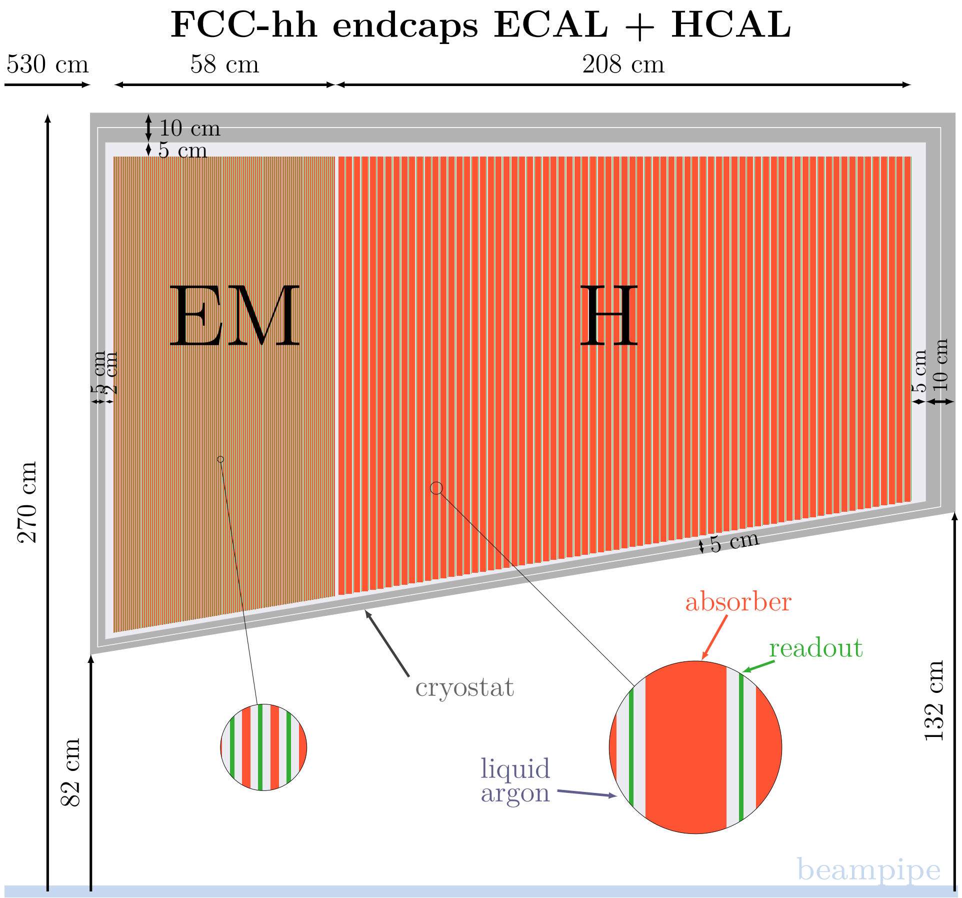


- Much more granular than ATLAS calorimeter (×10)
- High long. and lat. segmentation possible with straight multilayer electrodes
  - + Easier construction (inaccuracies enlarge the constant term)
  - − Sampling fraction changes with calorimeter depth



- Characteristics
  - 2 mm absorbers inclined by 50° angle
  - LAr gap increases with radius:
    - 1.15 mm–3.09 mm
  - 8 longitudinal layers
    - first one without lead as a pre-sampler
  - $\Delta\eta = 0.01$ (0.0025 in 2nd layer)
  - $\Delta\phi = 0.009$

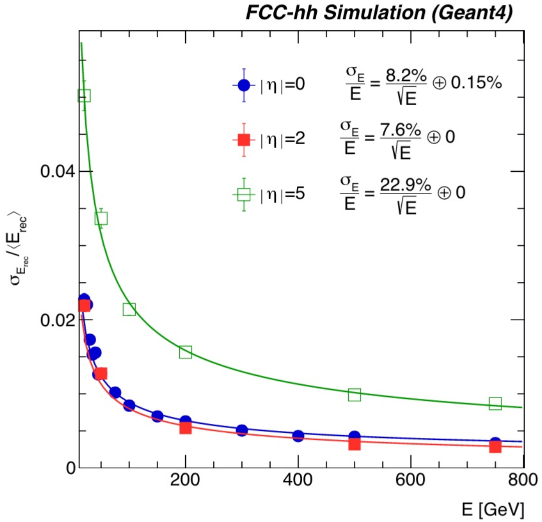
Liquid argon calorimeter (end-caps)



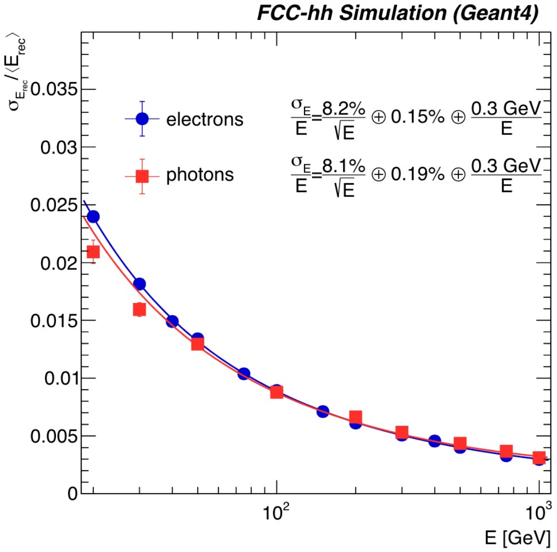
- Both E-Cal and H-Cal within same cryostat
- E-Cal:
  - 1.5 mm lead discs
  - 0.5 mm LAr gap
- H-Cal:
  - 2 cm copper discs
  - 2 mm LAr gap
- First layer serves as a pre-sampler
- Forward-Cal simulated with same layout
  - 0.1 mm LAr gap
  - 1 cm copper discs in E-Cal
  - 4 cm copper discs in H-Cal

Single electron/photon performance

- Simulation of single electrons
- No noise in detector
- Reconstruction
  - sliding window algorithm
- Very good performances over the acceptance range



- Simulation of single electrons and photons
- Electronic noise in detector
- Reconstruction
  - sliding window algorithm
- Very similar performances electrons/ photons



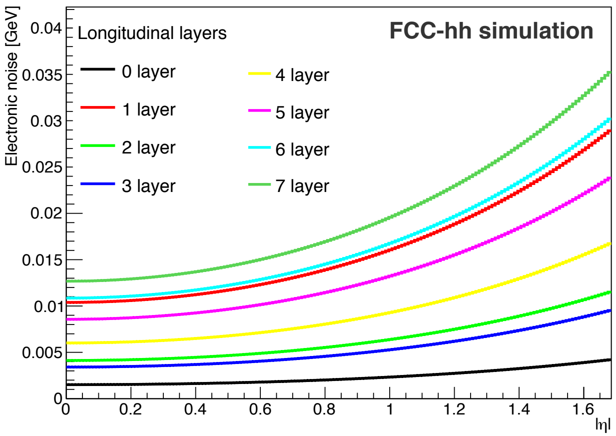
FCC-hh calorimetry

07/03/19

Noise (in cluster ΔηxΔΦ=0.07x0.17)

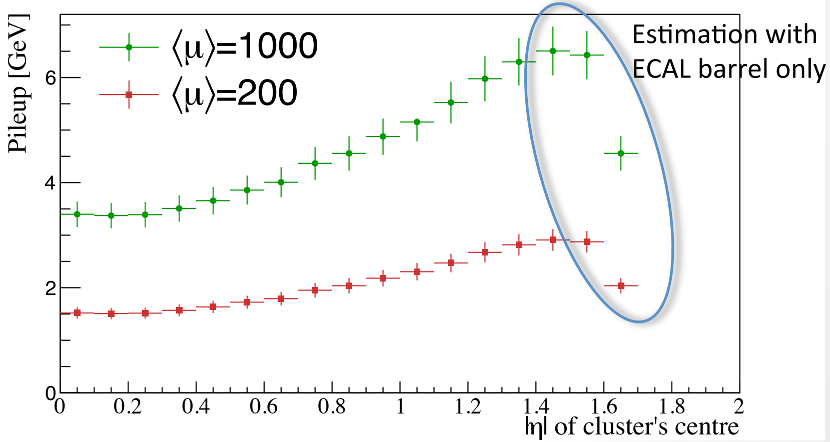
- Electronic noise
  - estimated for PCB readout (additional capacitance)
  - Noise in cluster ~ 300 MeV

Electronic Noise for one cell Δη×Δϕ=0.01×0.009

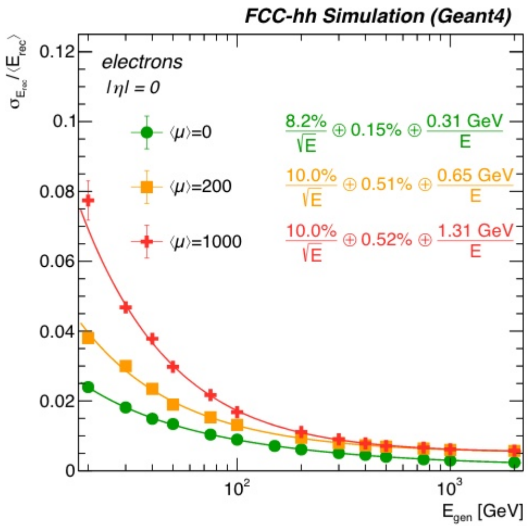


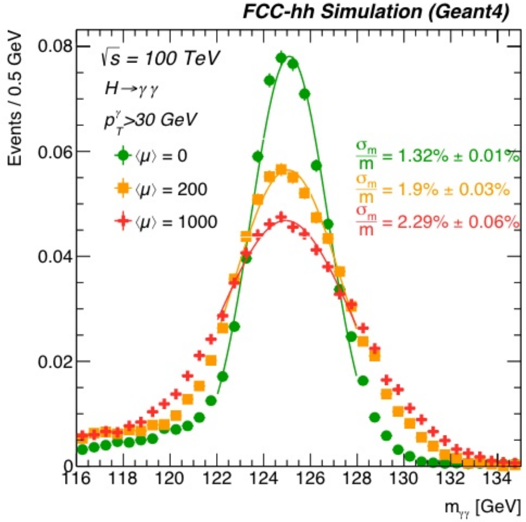
- Pile-up noise
  - From Min-Bias simulation
  - In-time pile-up suppression
    - rejecting energy deposits from pile-up vertices tagged by the inner tracker (to be studied)
  - Out-of-time pile-up as correction factor (~ 1.5)
    - Not included
    - HL-LHC suppress it to a large extent

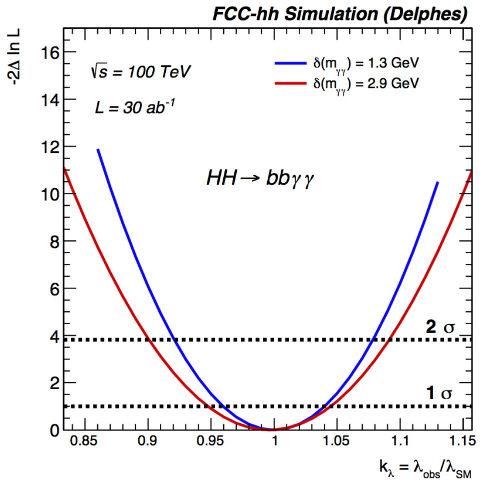
Pileup noise in cluster Δη×Δφ = 0.07×0.17



Photon resolution





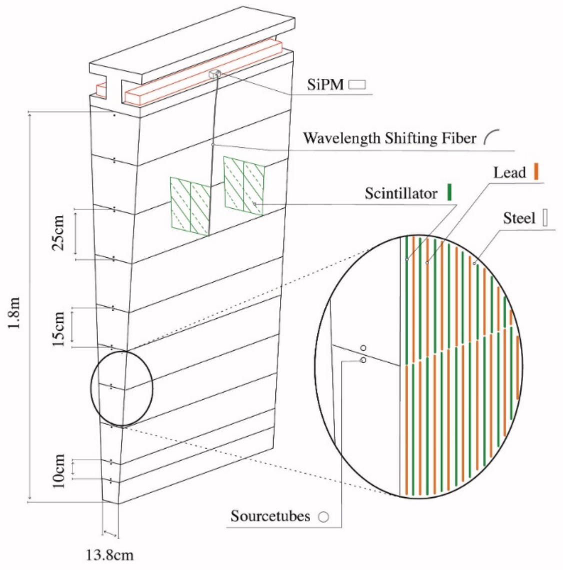


- Large impact of in time PU on the noise term
  - Out of the box with no sophisticated technics for removal!!
  - Severely degrades $m_{\gamma\gamma}$ resolution
  - Improving clustering, not sliding windows may help
  - Impacts Higgs self-coupling precision by $\delta\kappa_{\lambda} \approx 1\%$
  - Some thought needed (tracking, timing information can help?)

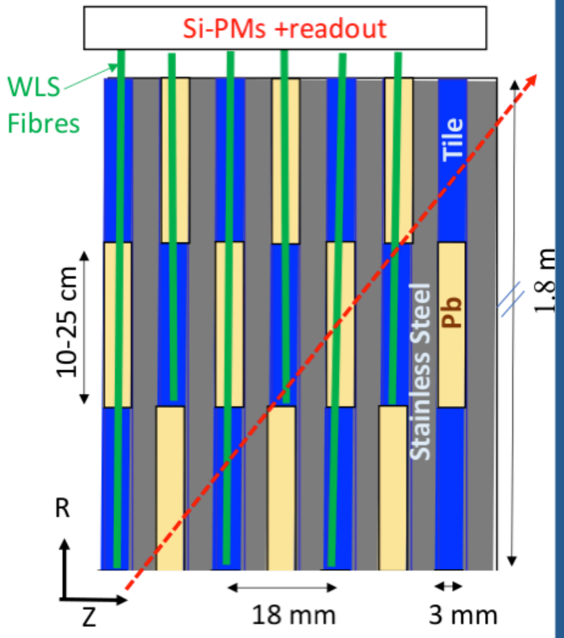
Tile Calorimeters

Tile calorimeter

- Granularity
  - Much more granular than ATLAS (×10)
  - $\Delta\eta = 0.025$, $\Delta\phi = 0.025$
  - 10 longitudinal layers



FCC-hh

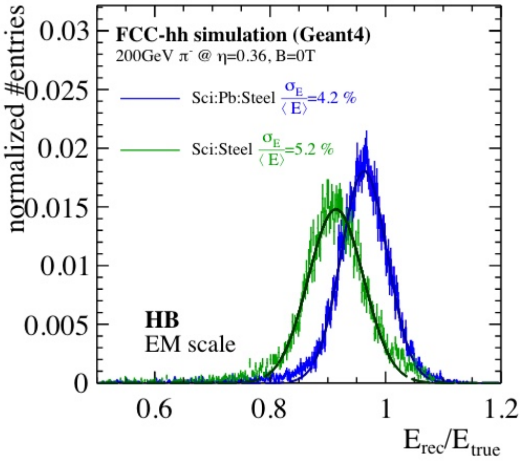


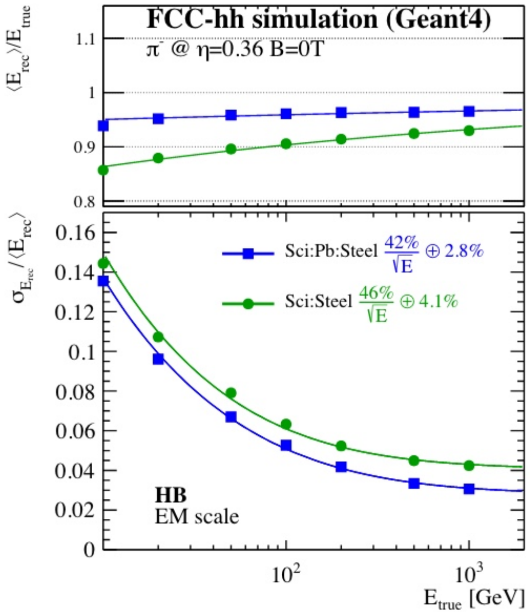
- High longitudinal and lateral segmentation possible with SiPMs
- Mechanical structure feasible, assembly study done
- First test of scintillator tiles started

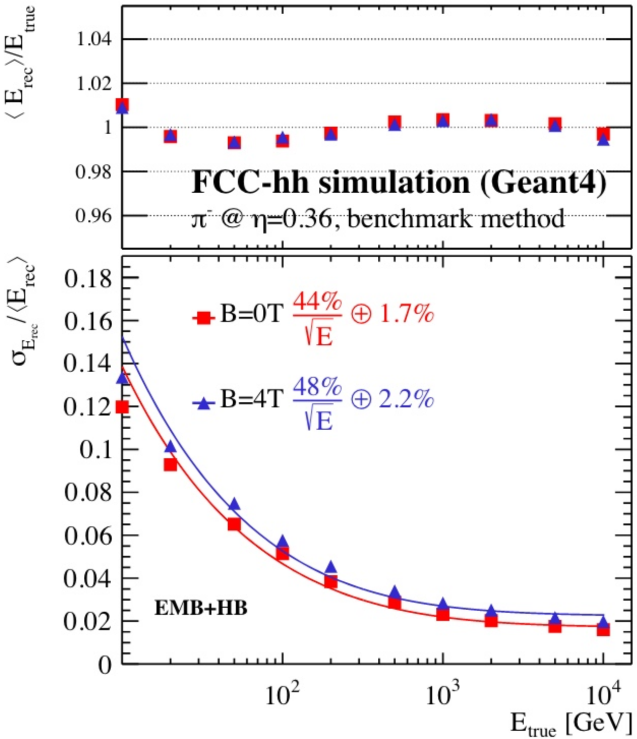
H-Cal barrel optimisation

- Steel absorbers partially substituted with lead
  - Decreasing non-compensation by suppression of EM response
  - Reduction of depth by 0.4 λ (at η = 0)

- Simulation of single pions
  - No noise in detector
  - Achieved goal resolution for combined E-Cal H-Cal

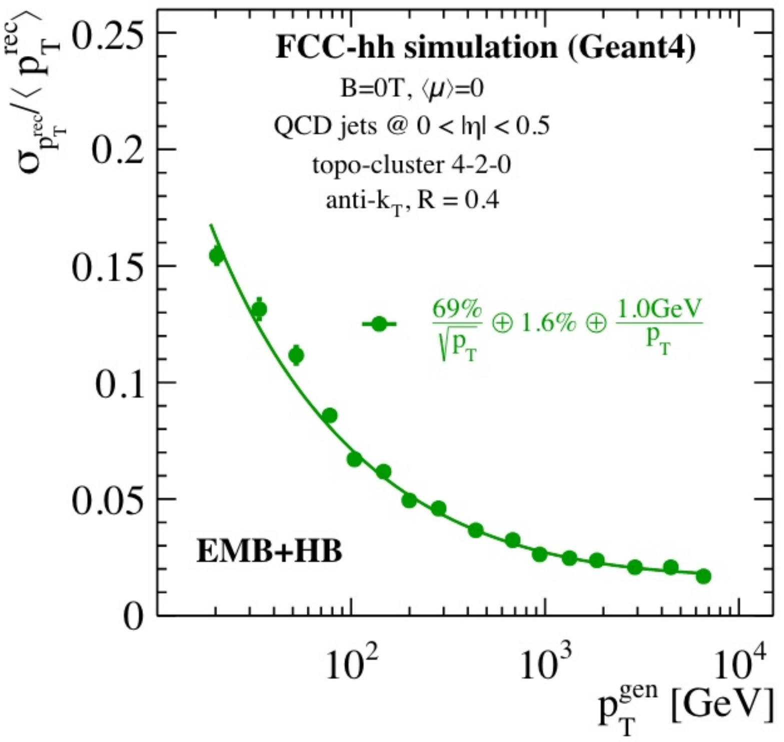






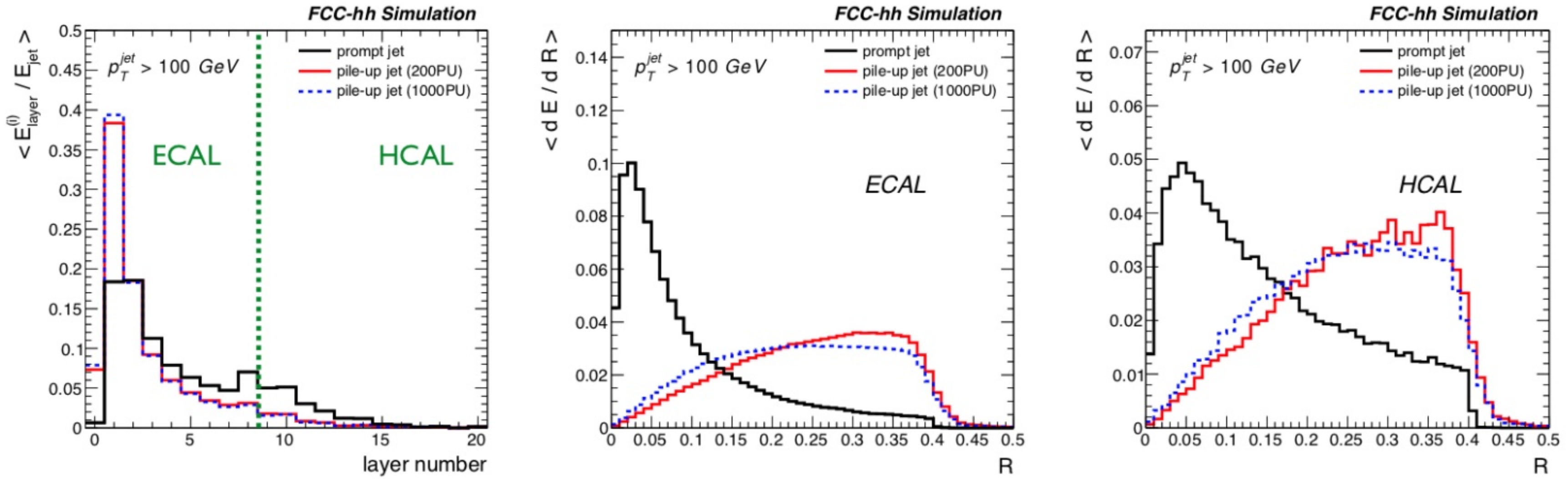
Jet performance

- Excellent resolution up to p_T =10 TeV
- Large impact of PU at low p_T (as exp.)
  - Crucial for low mass di-jet resonances
  - Again, such as HH→bbγγ
- Further motivation for Particle-flow
  - Charged PU contribution can be "easily" subtracted (Charged Hadron Subtraction)

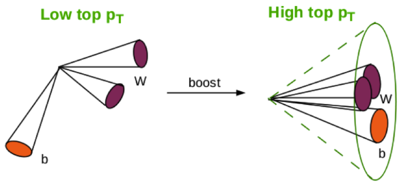


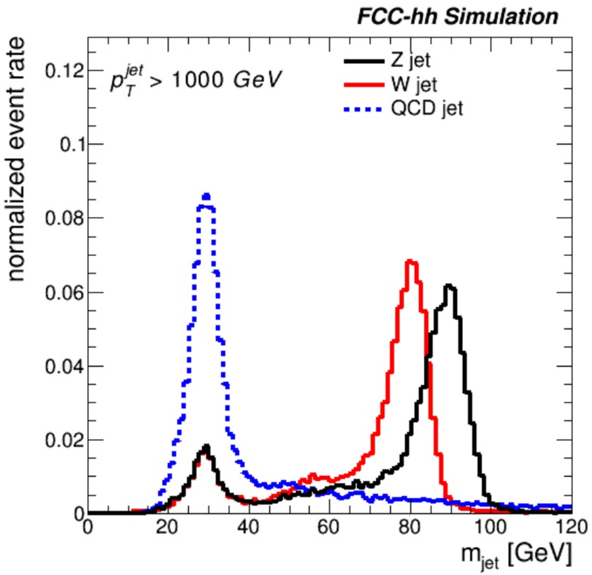
Jet pile-up identification

- With 200-1000PU
  - Will get large amount of fake-jets from PU combinatorics
  - Need both longitudinal/lateral segmentation for PU identification
  - Simplistic observables show possible handles, pessimistic…
  - In reality tracking will help a lot

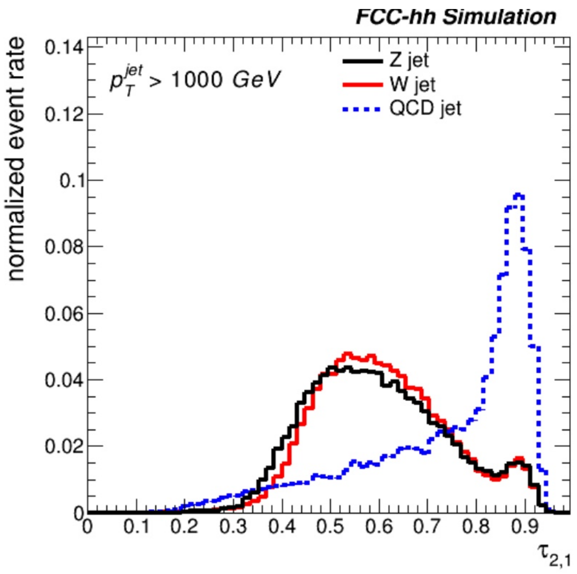


Jet sub-structure





W/Z->qq



- With Calorimeter standalone, and without B field
  - Performance good up to 1 TeV
- Far from having explored all possibilities:
  - Particle-Flow tracks and B field (decrease local occupancy) will improve
  - Machine Learning techniques will help a lot (train on 3D shower image)

FCC-ee

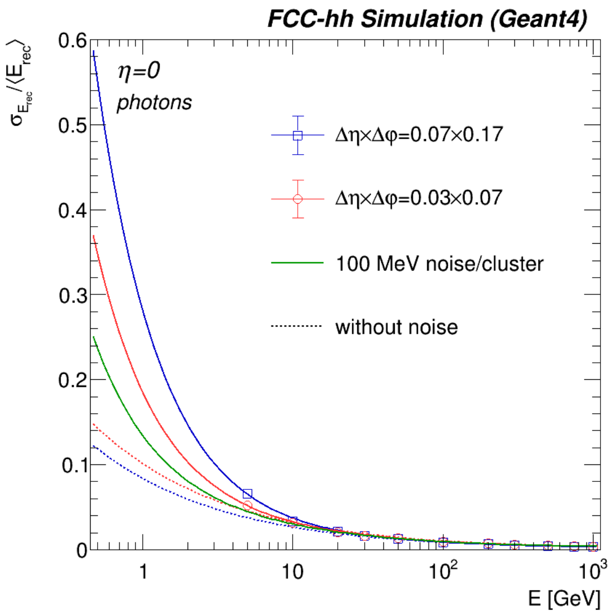
Requirements for FCC-ee Calorimetry

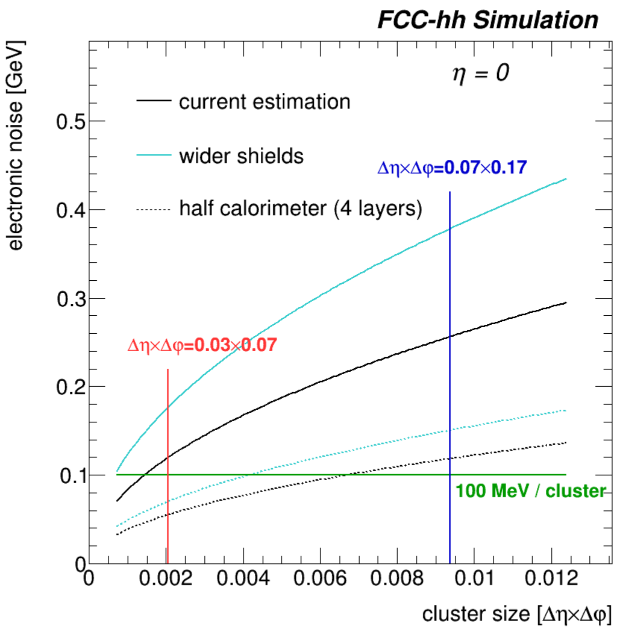
- Energy range of particles:
  - All particles ~ below 100 GeV (from a top decay)
  - 22X0 and 5-7 lambda sufficient
  - Measure particles down to 300 MeV (e.g. photons)
    - Little material in front of the calorimeter
    - Low noise (noise term dominant at small energies, b≪300 MeV)!
- EM resolution as good as possible (a≤ 15%/√Ē)
  - e.g. for CLFV τdecays τ→ μgamma
- jet resolution must be excellent (ajet~ 30%/√Ē) to separate W and Z decays
- Position resolution of photons: σx=σy= (6 GeV/E⊕2) mm Particle ID:
  - e±/π±separation
  - τdecays with collimated final states, separate different decay modes with minimal overlap (e.g. π0close to π±)

Example: Optimize Noise for FCC-hh Calo

- 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

Not shown but only 3.5% of the energy in layers 5 to 8 (for 300 MeV photon)



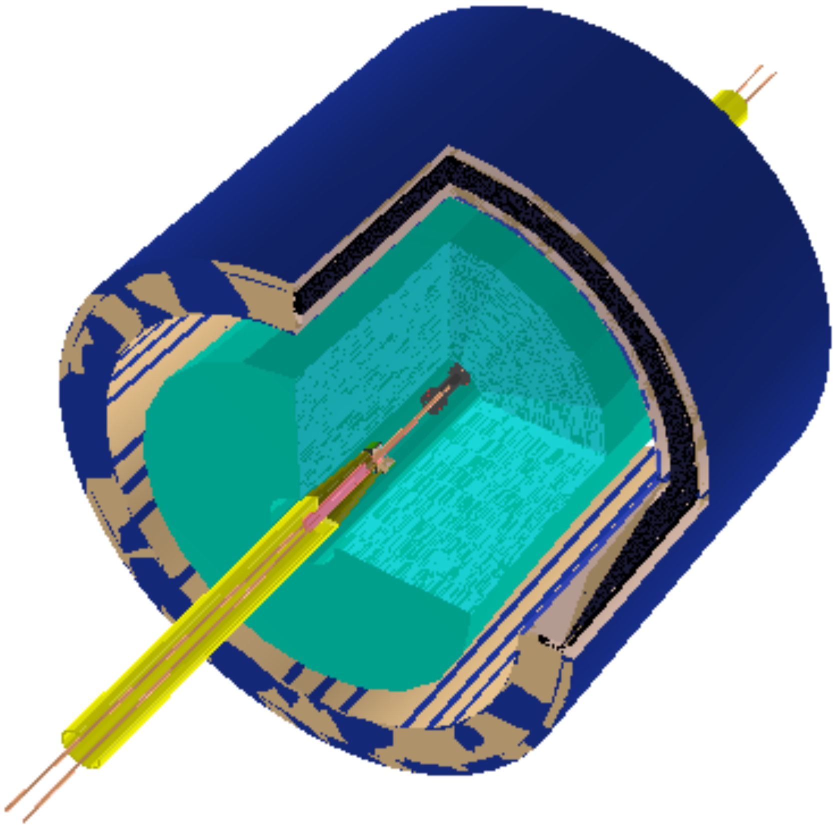


Detector concept

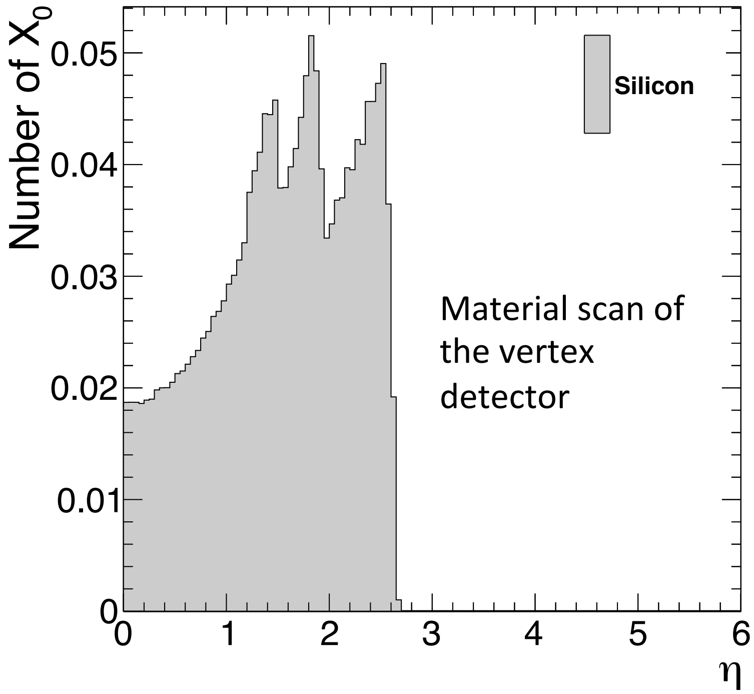
- Can already use the FCC-hh calorimeter concept in FCCSW for FCC-ee studies:
  - Need to finalise the dimensions and slightly adapt the layout
  - As tracker we will use the already existing implementation of IDEA
  - But will also consider a pure silicon tracker
  - We should investigate both options of having the solenoid before and after the calorimeter system
    - If before, would be ATLAS like, thus need to understand how it can be build as light as possible to mechanically support the calorimeters
    - If after, to be cost effective, could consider:
      - Using the CMS magnet (free inner diameter of 5.9m length 13m)
      - Using part of FCC-hh main dipole? (would have 10m in diameter which is roughly the size of IDEA)

IDEA tracker with LAr ECal

- Not necessarily to scale but design optimisation are underway

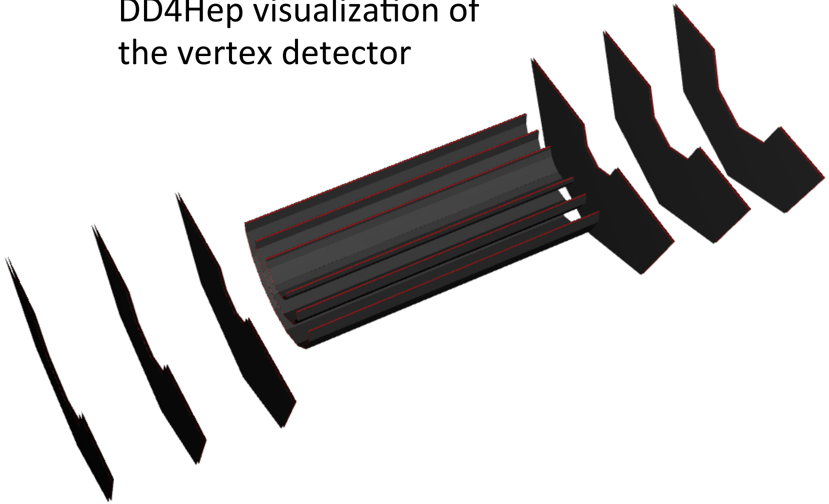


Vertex detector in FCCSW

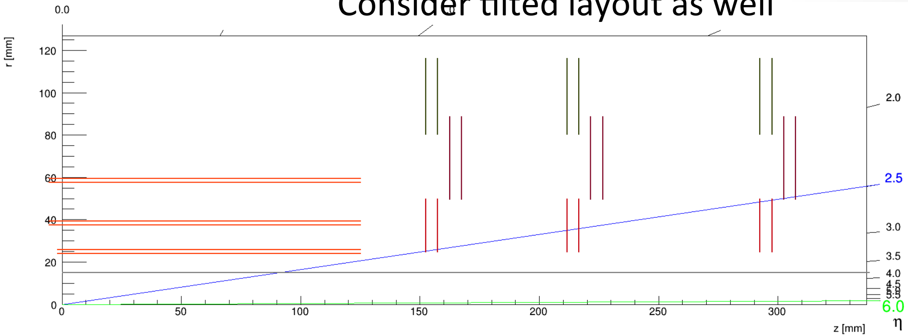


Material scan of the vertex detector

DD4Hep visualization of the vertex detector



TkLayout implementation
Consider tilted layout as well



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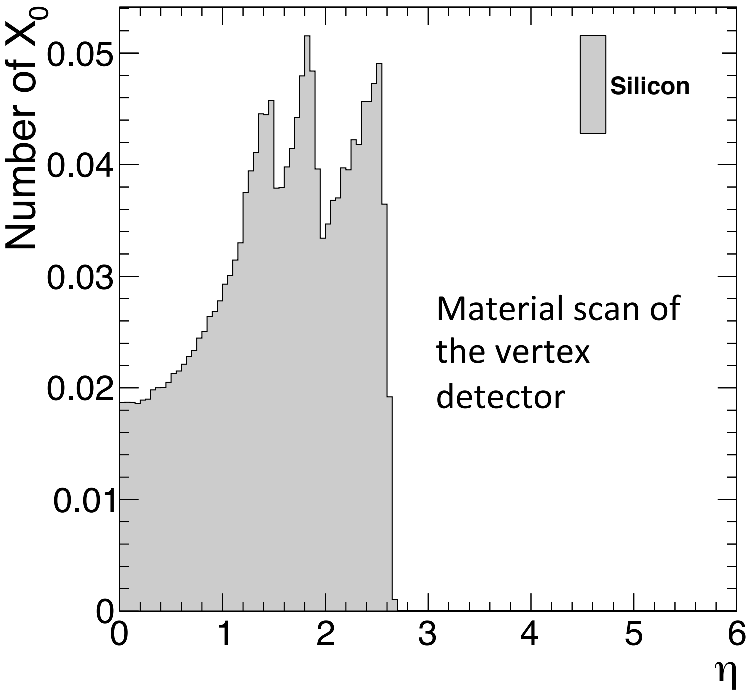

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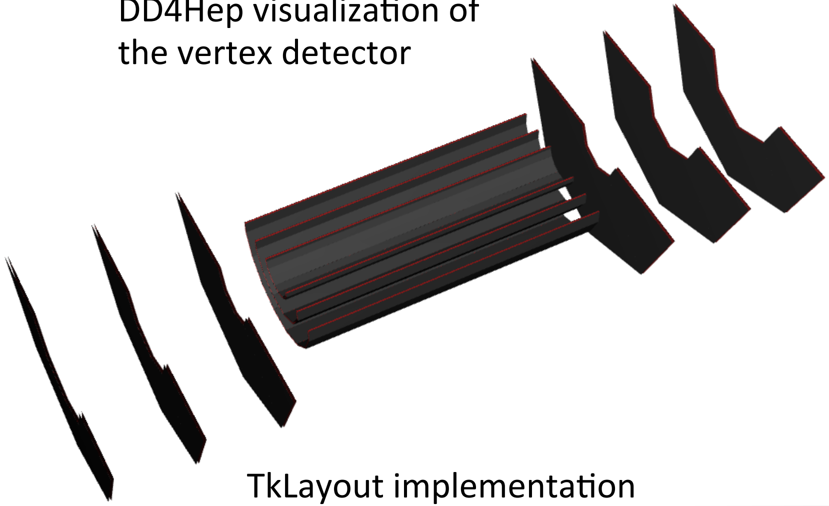

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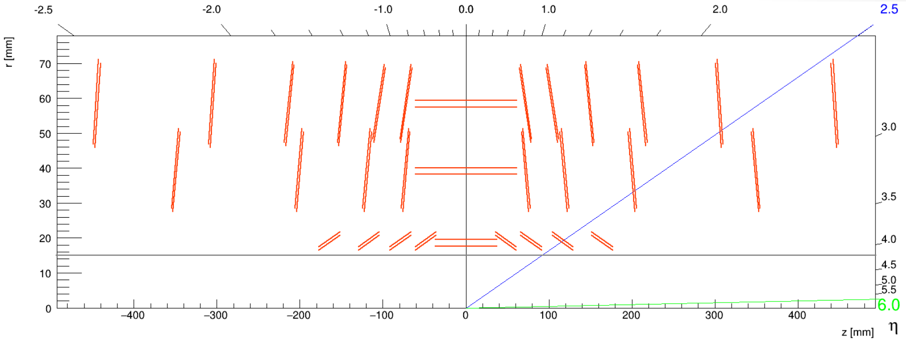

Next steps

- Goal: prove that such calorimeter concept is suitable to meet the performance requirements of FCC-ee
  - Some modifications to the design like
    - trying to collect Cherenkov light in both the ECAL and HCAL by adding SiPMT and in the hadronic-calorimeter by exploring different types of scintillators/crystals are envisaged
    - For HCAl start in simulation for Cherenkov light in scintillating tiles. Possibly add quartz tiles (talk)
  - Progress on our understanding of possible new materials for the cryostat of the ECAL benefiting from the ongoing R&D on Experimental Technologies WG3 will be made.
  - Reconstruction with particle-flow algorithm (PFA) which is responsible for combining tracking and calorimeter measurements, and is a necessary ingredient to achieve the required performance of the calorimeter system in any FCC environment
  - Start by implementing the PFA in the less busy environment of FCC-ee, by considering a realistic tracker design and the full simulation of the calorimeters
    - Start looking at very simple cases like photon electron ID
  - Electron and single pion response to validate the FCC-ee implementation
  - Could consider adding timing information, very relevant for FCC-hh