ELECTROMAGNETIC CALORIMETRY BASED ON LIQUID ARGON FOR THE FCC-HH EXPERIMENTS

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Centre-of-mass collision energy

$\sqrt{s} = 100$ TeV

Consequences

- more particles produced
- higher average and maximum p_T

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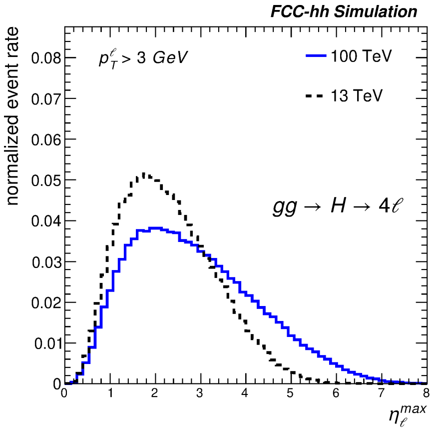


Requirements for EM calorimetry

- depth $\geq 30\ X_0$
- precision tracking and calorimetry for $|\eta| < 4$

Centre-of-mass collision energy

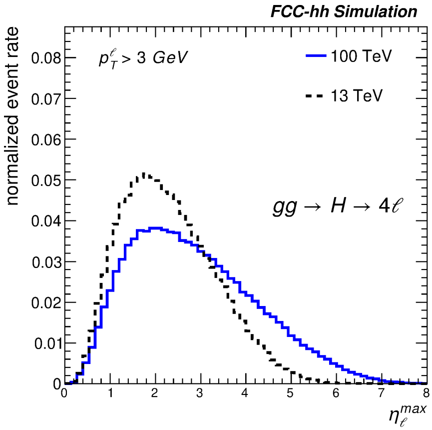
$\sqrt{s} = 100$ TeV

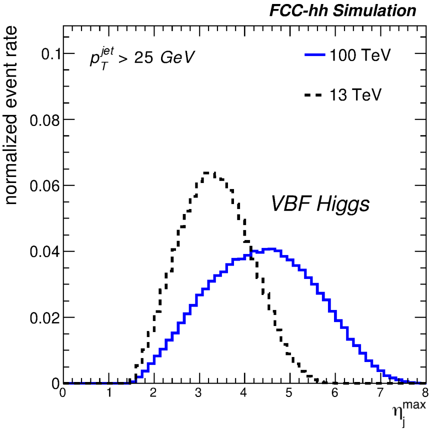
Consequences

- more particles produced
- higher average and maximum p_T
- particles into forward region
- Vector Boson Fusion jets into very forward region

Requirements for EM calorimetry

- depth $\geq 30\ X_0$
- precision tracking and calorimetry for $|\eta| < 4$
- efficient jet tagging for $|\eta| < 6$





Luminosity

peak: $\mathbf{30 \times 10^{34}\ cm^{-2}s^{-1}}$
integrated: $\mathbf{20\ ab^{-1}}$ for 25 y.

Consequences

- huge pile-up
  ($\langle\mu\rangle \approx 1000$ in ultimate scenario)

Requirements for EM calorimetry

- high granularity for pile-up rejection
- use of timing information
- combination with tracker information
  (particle flow technique)

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integrated: $\mathbf{20\ ab^{-1}}$ for 25 y.

Consequences

- huge pile-up
  ($\langle\mu\rangle \approx 1000$ in ultimate scenario)
- strong requirements on radiation hardness

	1 MeV neutron equivalent fluence ($n_{eq}cm^{-2}$)	Dose (MGy)
barrel	4×10^{15}	$\mathcal{O}(0.1)$
endcap	3×10^{16}	$\mathcal{O}(1)$
forward	5×10^{18}	5×10^{3}

Requirements for EM calorimetry

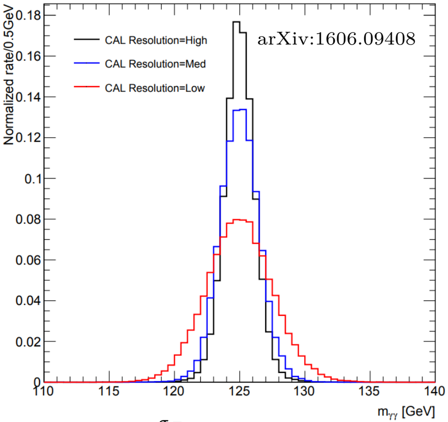
- high granularity for pile-up rejection
- use of timing information
- combination with tracker information
  (particle flow technique)
- choice of radiation hard materials, especially for high-η regions

Requirements for EM calorimeter performance

- good energy resolution $\frac{\sigma_E}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c$

  design goal: $a = 10\%$, $c = 1\%$

- vertex identification
  - tracker for e^-, e^+
  - good pointing resolution for γ
- linearity of calorimeter response
- large detector acceptance
- fine granularity
  - combination with tracker information
  - 3D imaging
  - pileup mitigation
  - π^0 rejection
  - separation of boosted particles



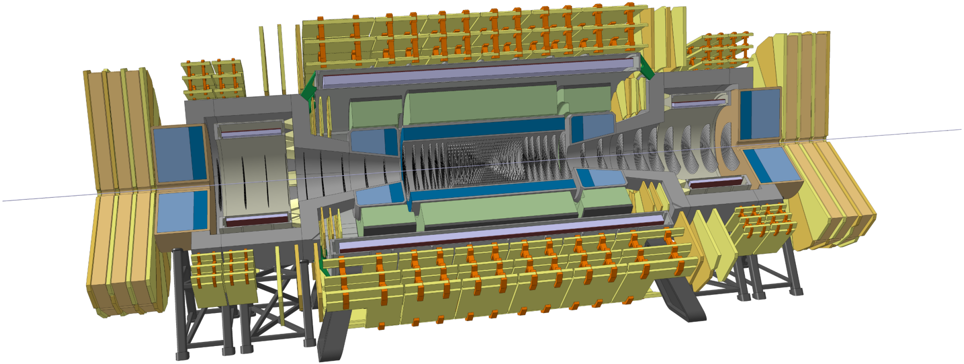
$$\frac{\sigma_E}{E} = \frac{a}{\sqrt{E}} \oplus c$$

a=6%, c=0.7%

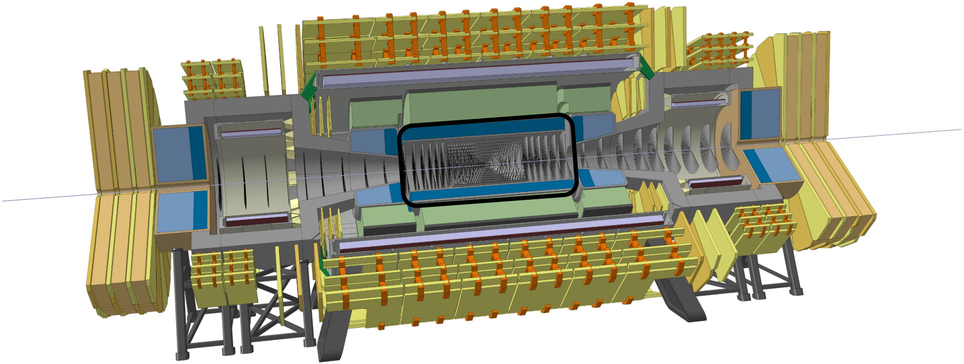
a=10%, c=1%

a=20%, c=2%

FCC-hh detector



FCC-hh detector

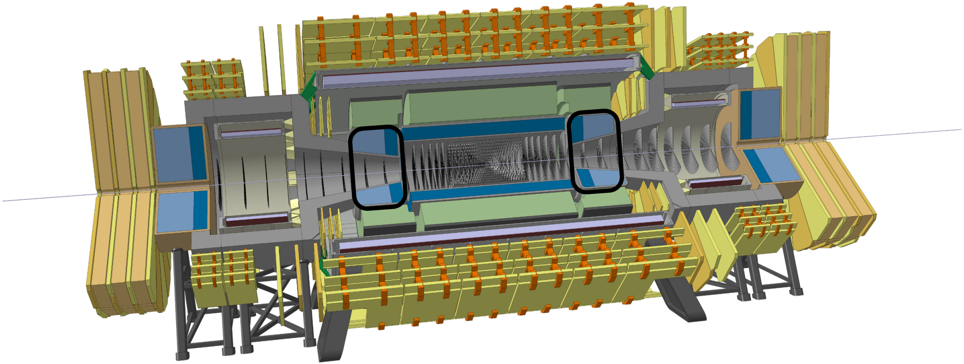


Electromagnetic calorimeter

Barrel:

- $|\eta| < 1.5$

FCC-hh detector



Electromagnetic calorimeter

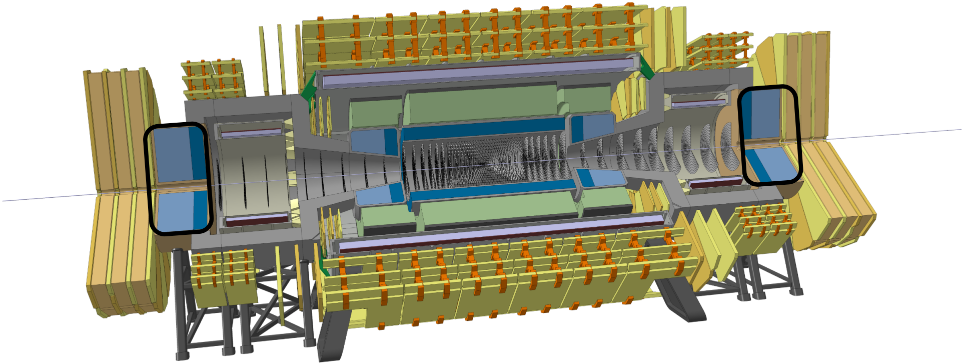
Barrel:

- $|\eta| < 1.5$

Endcap:

- $1.4 < |\eta| < 2.5$

FCC-hh detector



Electromagnetic calorimeter

Barrel:

- $|\eta| < 1.5$

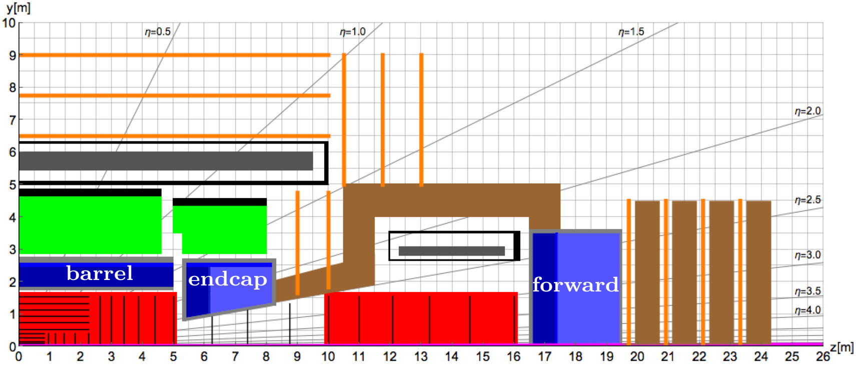
Endcap:

- $1.4 < |\eta| < 2.5$

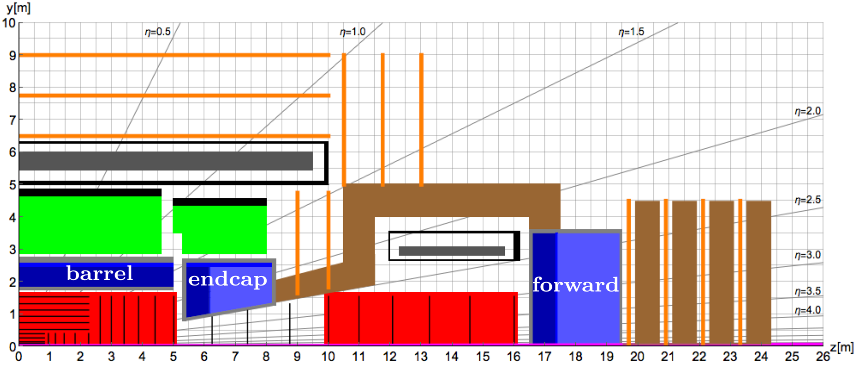
Forward:

- $2.3 < |\eta| < 6$

Electromagnetic calorimeter



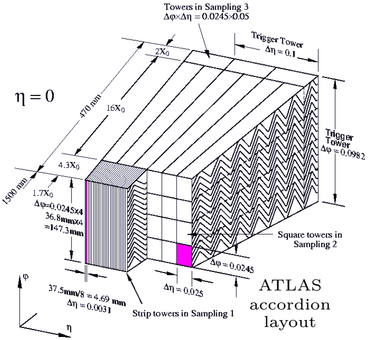
Electromagnetic calorimeter



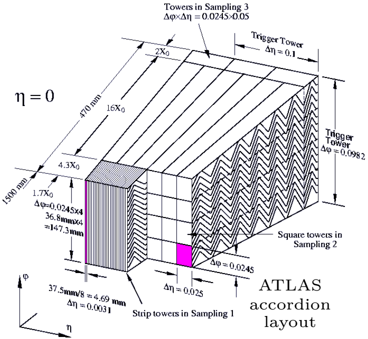
“Reference” detector: based on liquid argon

- used for barrel, endcap and forward detector (radiation hard)
- endcap and forward detector ($1.4 < |\eta| < 6$) of hadronic calorimeter also based on liquid argon

EM calorimeter barrel



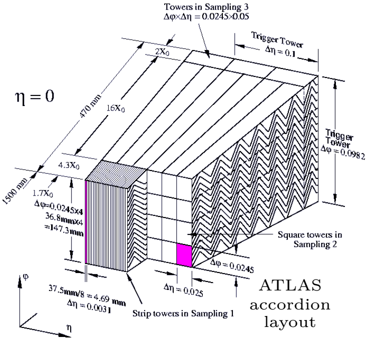
EM calorimeter barrel



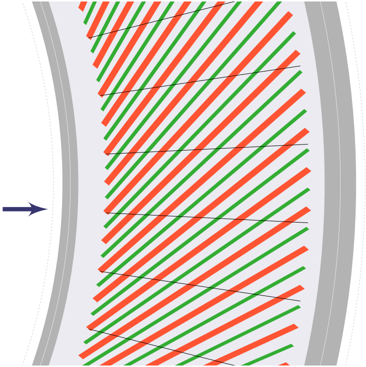
→

- much more granular than ATLAS calorimeter ($\times 10$)
- high longitudinal and lateral segmentation possible with straight, multilayer electrodes

EM calorimeter barrel



ATLAS accordion layout

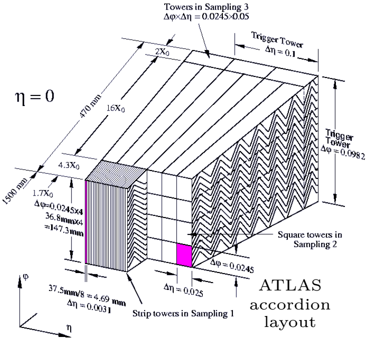


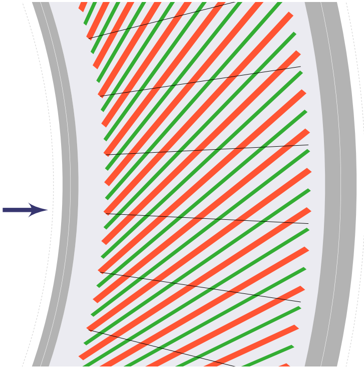
zoom ×8

- proposed layout:
  - liquid argon
  - plates inclined in transverse plane
  - absorber (lead, glue and steal)
  - printed circuit board (PCB)

- much more granular than ATLAS calorimeter (×10)
- high longitudinal and lateral segmentation possible with straight, multilayer electrodes

EM calorimeter barrel

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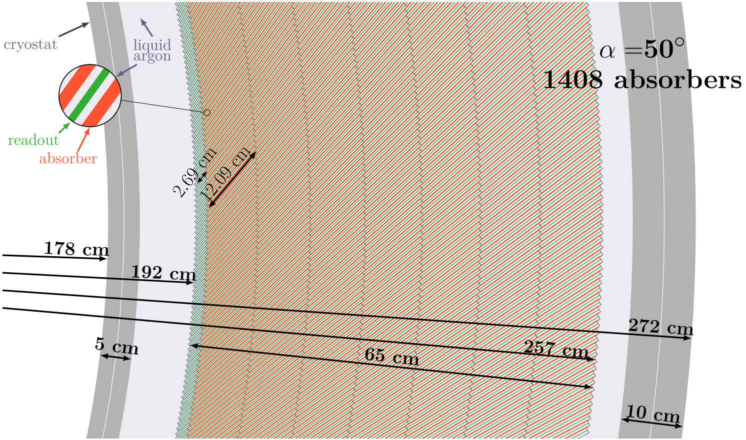
- much more granular than ATLAS calorimeter (×10)
- high longitudinal and lateral segmentation possible with straight, multilayer electrodes

\+ easier construction (inaccuracies enlarge the constant term)

– sampling fraction changes with calorimeter depth

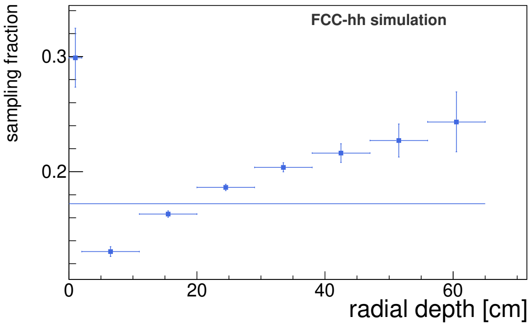
EM calorimeter barrel



- 2 mm absorber plates inclined by 50° angle
- LAr gap increases with radius 1.15 mm–3.09 mm
- 8 longitudinal layers
- $\Delta\eta = 0.01$ (0.0025 in 2nd layer), $\Delta\varphi = 0.009$

Calibration to EM scale

- sampling fraction changes with calorimeter radius
- calibration to EM scale done per layer



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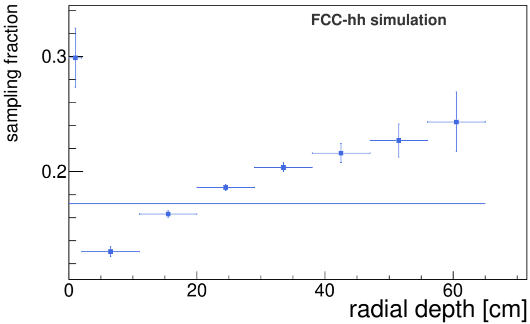
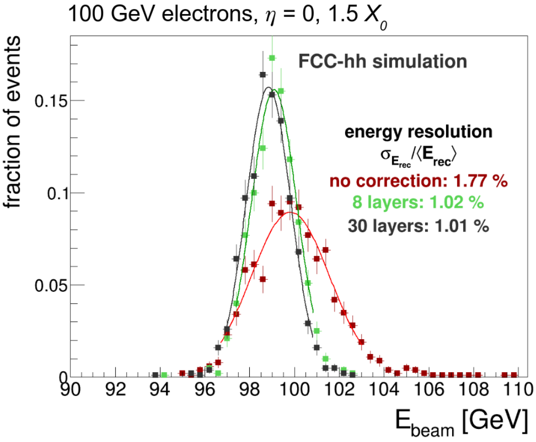
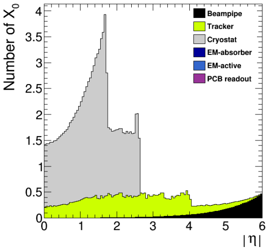




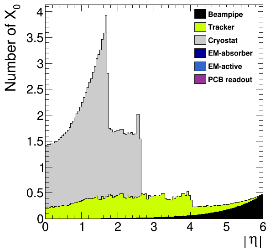
- significant improvement for 8 layers

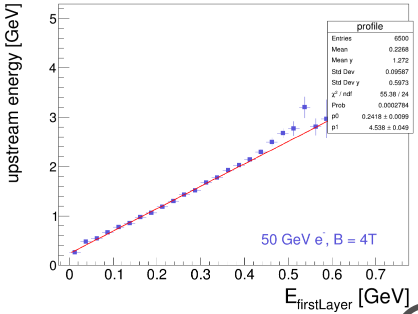
Correction for material upstream



Correction for material upstream

- linear correlation between energy deposited upstream and in the first layer





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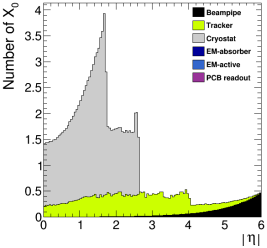

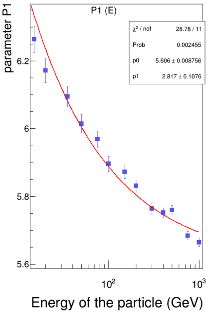

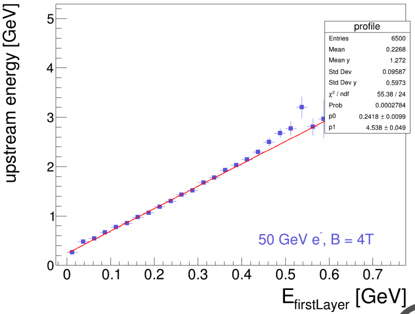

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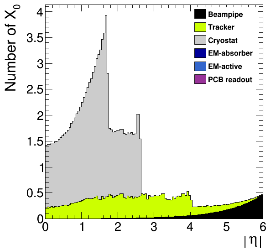
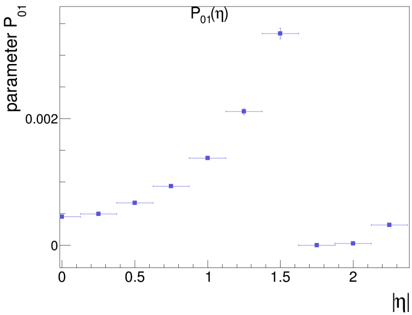
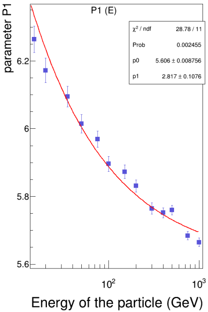
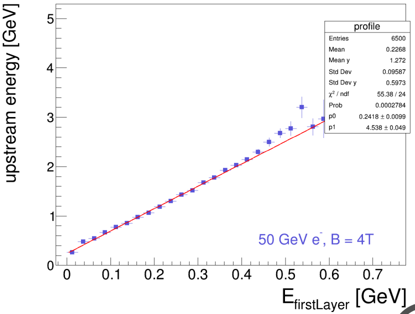






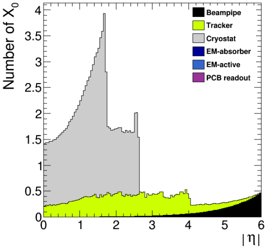


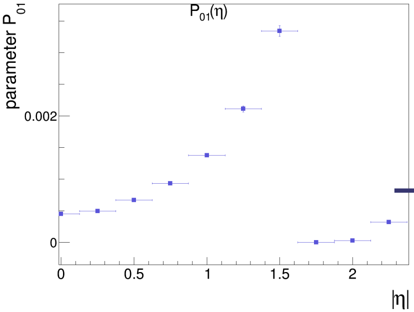
Correction for material upstream

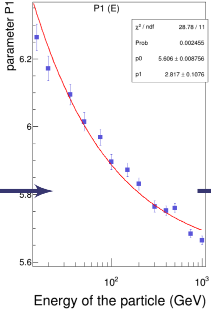
- linear correlation between energy deposited upstream and in the first layer

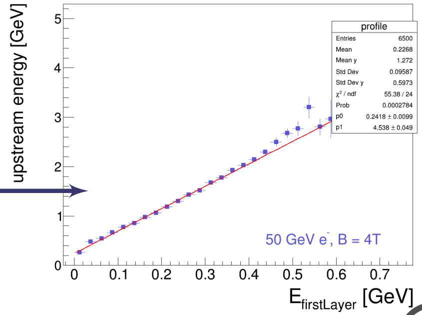
$$E_{\rm clu}^{\rm corr} = \sum_{cells} f_{\rm sampl}^{\rm layer} E_{\rm deposit} + E_{\rm upstream}$$

$$E_{\rm upstream} = P_{00} + P_{01} \cdot E_{\rm clu} + (P_{01} + \frac{P_{11}}{\sqrt{E_{\rm clu}}}) \cdot E_{\rm 1stLayer}$$



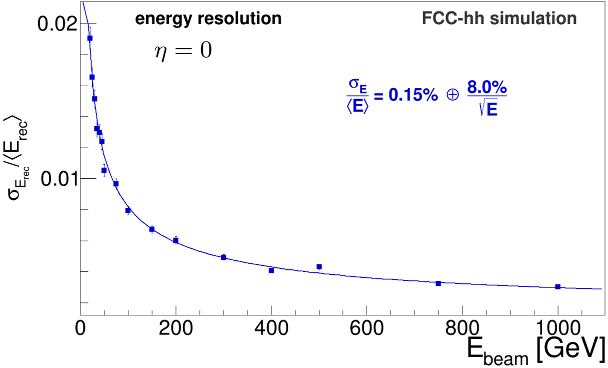






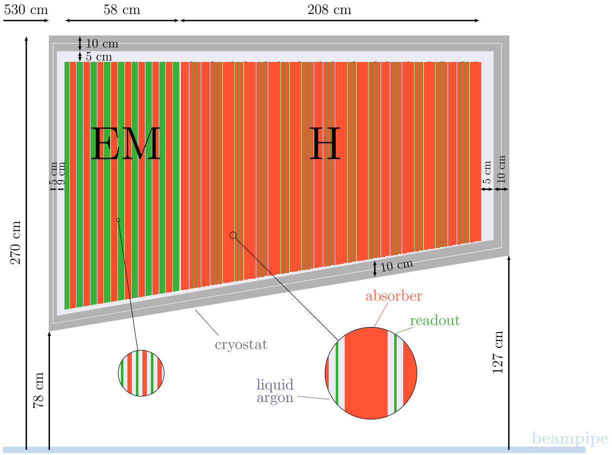
Performance for single particles

- simulation of single electrons
- no electronic or pile-up noise in detector
- reconstruction with sliding window algorithm $\Delta\eta \times \Delta\varphi = 0.07 \times 0.17$



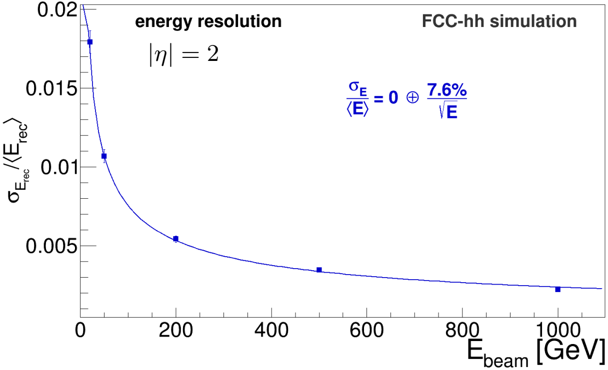
Endcaps layout

- both electromagnetic and hadronic calorimeters within same cryostat
- electromagnetic calorimeter
  - 1.5 mm lead discs
  - 0.5 mm LAr gap
- hadronic calorimeter
  - 2 cm copper discs in H
  - 2 mm LAr gap
- forward calorimeter simulated with same layout
  - 0.1 mm LAr gap
  - 1 cm copper discs in EM
  - 4 cm copper discs in H



Performance for single particles

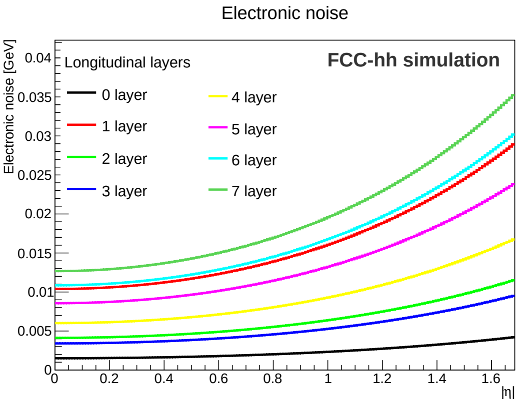
- simulation of single electrons
- no electronic or pile-up noise in detector
- reconstruction with sliding window algorithm $\Delta\eta \times \Delta\varphi = 0.07 \times 0.17$
- no constant term due to constant and ideal ratio LAr/absorber



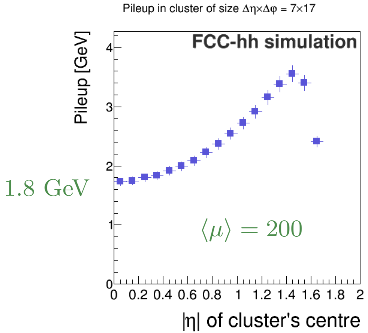
Electronic noise

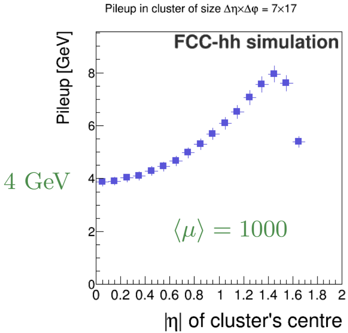
Preliminary estimations

- extrapolation from ATLAS electronics
- electronic noise estimated for PCB readout (additional capacitance)
- plot presents noise per one cell $\Delta\eta\times\Delta\varphi$=0.01×0.009 for each detector layer
- noise in cluster of size $\Delta\eta \times \Delta\varphi = 0.07 \times 0.17$ approx. 300 MeV



Pileup noise



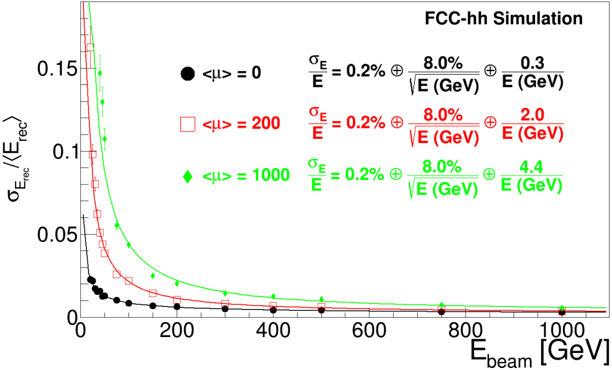


- estimation from minimum bias events' simulation
- noise calculated for clusters
- additional contribution from out-of-time pile-up as correction factor (~ 1.5) - not included in the plots as like for HL-LHC it is planned to suppress the out-of-time pile-up contribution to a large extent.

The (enormous) in-time pile-up will need to be suppressed by rejecting energy deposits from pile-up vertices tagged by the inner tracker (to be studied).

Performance for single particles

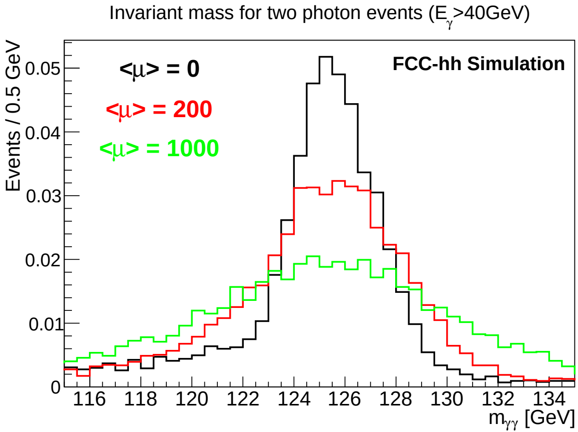
- simulation of single electrons
- electronic and pileup noise included
- reconstruction with sliding window algorithm $\Delta\eta \times \Delta\varphi = 0.07 \times 0.17$



Size of clusters needs still to be optimised to contain a large fraction of the shower and the smaller amount of pile-up (optimised sliding window cluster or topo-cluster).

Di-photon invariant mass

- simulation of $H \to \gamma\gamma$
- pile-up scenarios $\langle\mu\rangle = 0$, $\langle\mu\rangle = 200$ and $\langle\mu\rangle = 1000$
- reconstruction with sliding window algorithm $\Delta\eta \times \Delta\varphi = 0.07 \times 0.17$



It is obvious that efficient in-time pile-up suppression will be crucial.

This pile-up contribution is basically independent of the chosen active material of the EM calorimeter. A small reduction of in-time pile-up is expected for W absorbers.

Summary

- LAr detector studied as a reference for FCC-hh experiments
  - electromagnetic calorimeter in $|\eta| < 6$
  - hadronic calorimeter in $1.4 < |\eta| < 6$
- with optimised layout achieved the goal resolution
  - sampling term $\sim 8\%$
  - constant term $< 0.2\%$
  - noise term highy depends on the pile-up
- pile-up the main challange for any calorimeter
- tackle the pile-up with:
  - readout system (out-of-time)
  - optimised reconstrution algorithms (in-time)
  - tagging pile-up in tracker (in-time)

Backup

Reconstruction

Sliding window algorithm

- Reconstruction of electrons in photons
- Based on https://cds.cern.ch/record/1099735

1. Calorimeter towers with fixed $\Delta\eta \times \Delta\varphi$ size
2. Seeding
   - Scanning the $\Delta\eta \times \Delta\varphi$ tower map with a fixed size window for local maxima
   - If energy inside window is above threshold $\longrightarrow$ mark as pre-cluster
3. Barycentre position calculation
   - Energy-weighted position for each pre-cluster
4. Duplicates removal
   - If two pre-clusters are next to each other, the pre-cluster with lower energy is removed
5. Cluster building
   - Each step (1-4) can use window of different size (centred around the tower seed)