FCChh Hadronic Calorimeter and performance

Martin Aleksa, Jana Faltova, Clement Helsens, Ana Henriques,
Coralie Neubüser, Michele Selvaggi, Anna Zaborowska

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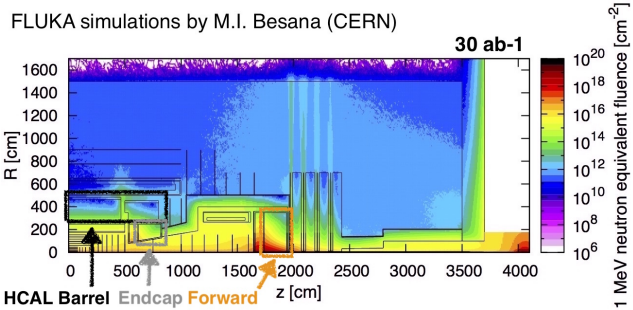
Contents

Challenges for Hadronic Calorimetry at FCC-hh

1. High radiation levels
2. Containment of multi-TeV hadron showers
3. Large number of pile-up

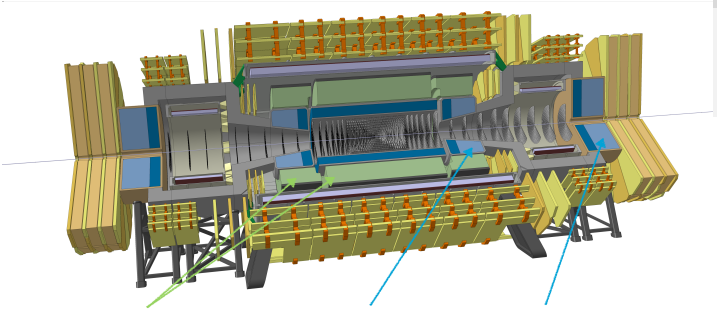
→ η dependent requirements
→ meet performance goals



	1 MeV neq [cm^{-2}]	dose
Barrel	$\leq 3 \times 10^{14}$	≤ 6 kGy
Endcap	$\leq 2 \times 10^{16}$	≤ 1 MGy
Forward	$\leq 5 \times 10^{18}$	≤ 5 GGy

FCC-hh detector

total length ∼47 m, height ∼18 m



Forward Calo up to η=6

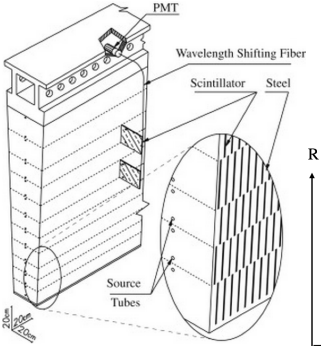
HCAL Barrel / Ext. Barrel $\lvert\eta\rvert < 1.5$	HCAL Endcap $\lvert\eta\rvert = 1.54 - 2.5$	HCAL Forward $\lvert\eta\rvert = 2.5 - 6.0$
Sci-Pb-Steel (1:1.3:3.3)	LAr-Cu (1:5)	LAr-Cu (1:200)
$\Delta\eta < 0.025$, $\Delta\phi = 0.025$	$\Delta\eta = 0.025$, $\Delta\phi = 0.025$	$\Delta\eta = 0.05$, $\Delta\phi = 0.05$
10/8 layers	82 (21 eff.) layers	52 layers
$\sigma_E/E \sim 50\%/\sqrt{E} \oplus 3\%$	$\sigma_E/E \sim 50\%/\sqrt{E} \oplus 3\%$	$\sigma_E/E \sim 100\%/\sqrt{E} \oplus 5\%$

Radiation levels

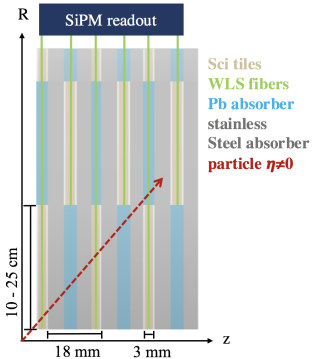
Barrel
ATLAS like Sci tile Calorimeter

- readout at outer radius ($\sim 10^{11}$ neq cm^{-2})
  $\rightarrow$ replace photomultiplier tubes by SiPMs
  $\rightarrow$ single channel readout, timing
- current ongoing R&D on scintillator material and SiPM technology fulfil requirements (6 kGy)

ATLAS TileCal



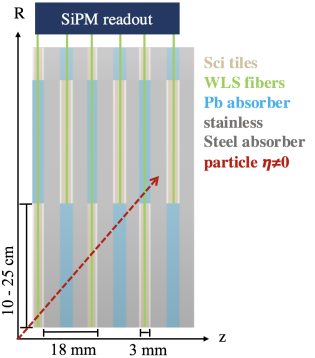
FCChh TileCal

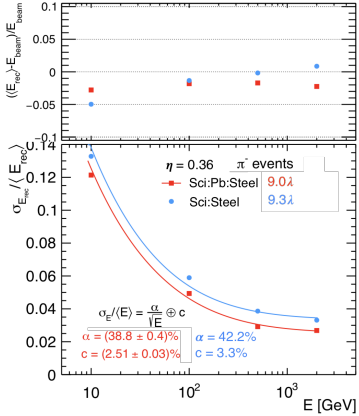


$\rightarrow$ mechanical structure feasible, assembly study done at JINR (N. Topiline)
$\rightarrow$ first test of Sci tiles in FCC size started at LIPP institute, Lisbon (R. Goncalo)

Optimisations of Barrel Tile HCal

- included Pb absorbers
  $\rightarrow$ Scintillator/Pb/Steel (1:1.3:3.3)
- decreasing non-compensation by suppression of EM response
  Pb: $X_0 = 0.6\,\text{cm}$, $\lambda_n = 17.6\,\text{cm}$
  (Fe: $X_0 = 1.8\,\text{cm}$, $\lambda_n = 16.8\,\text{cm}$)
- reduces total depth $[\lambda_n]$ from 8.9 (full Steel) to 8.5





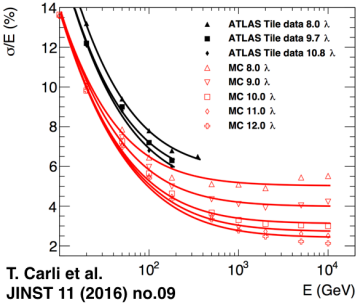
	stochastic term	constant term	e/h
Sci:Steel (1:4.7)	42.2% GeV$^{1/2}$	3.3%	1.23
Sci:Pb:Steel (1:1.3:3.3)	38.8% GeV$^{1/2}$	2.5%	1.1

Containment and calorimeter depth

- multi TeV hadron showers penetrate up to $12\lambda_n$
- avoid leakage to preserve small constant term

$$\sigma_E/E = \frac{\alpha}{E} \oplus c \qquad (1)$$

depth $[\lambda_n]$	stoch. term [% GeV$^{1/2}$]	const. term [%]
8	41	5
9	43	4
10	43	3.1
11	43	2.7
12	43	2.4



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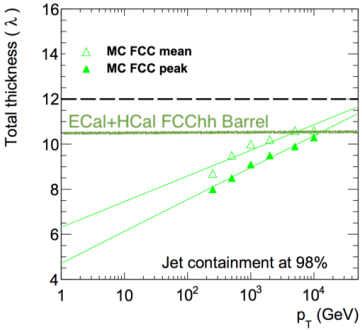
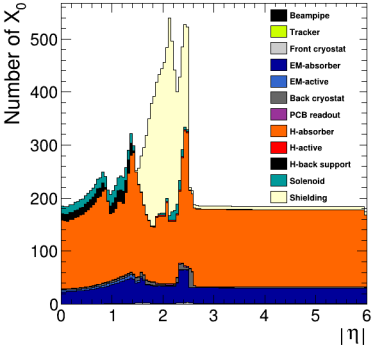
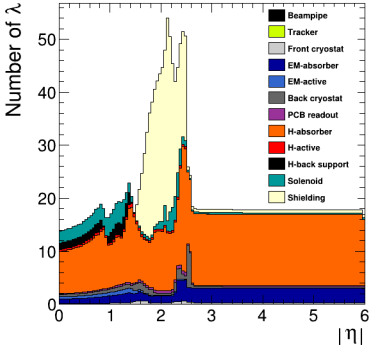


Containment and calorimeter depth

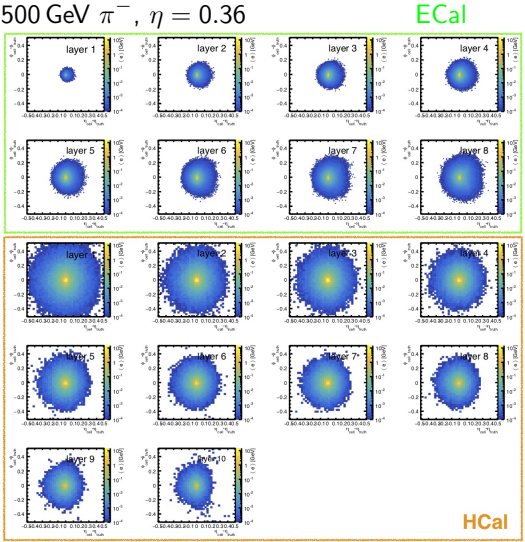




Barrel $|\eta| < 1.5$: 1.8 m thick HCal ($\eta = 0$) $\rightarrow$ 8.5 λ HCal only
$\rightarrow$ 10.5 λ incl. ECal $\rightarrow$ 12 λ (incl. supports) punch throughs seen in muon chambers
Endcap & Forward $|\eta| = 1.4 - 6.0$: cover min. 12 λ

High pile-up environment

- High transverse and longitudinal granularity
  Barrel max. granularity:
  $\rightarrow$ 10 longitudinal layers (0.5 to 1.25) λ_n
  $\rightarrow$ $\Delta\eta \leq 0.006$, $\Delta\phi = 0.025$
  $\rightarrow$ 1,305,600 channels
- timing
  $\rightarrow$ Sci + SiPMs already possible $\sim$ 30 ps (CMS timing layer)

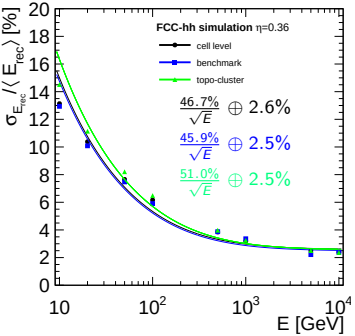


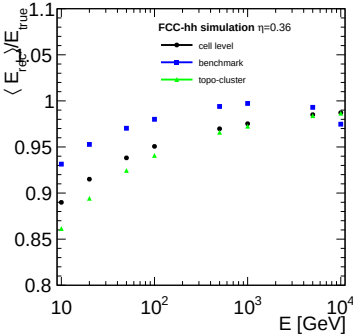
Combined calorimeter performance

Single π^- reconstruction

Reconstruction methods:

1. cell level:
   $E_{rec} = E^{em} + E^{\pi}_{had}$
2. benchmark:
   $E_{rec} = E_{em} \cdot a + E^{\pi}_{had} + b \cdot \sqrt{|E_{em,lastL} \cdot a \cdot E_{had,firstL}|} + c \cdot (E_{em} \cdot a)^2$
3. topo-cluster: clustered Calo cells





- benchmark reconstruction recovers the lost energy up to 5%
- expected decrease in response after topo-clustering ← thresholds
- next step include benchmark on cluster level

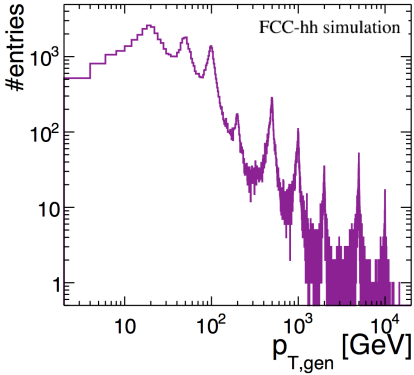
	stochastic term	constant term
HCal only	38.8%	2.5%
ECal + HCal benchmark	45.9%	2.5%
ECal + HCal topo-cluster	51.0%	2.5%

Jet reconstruction

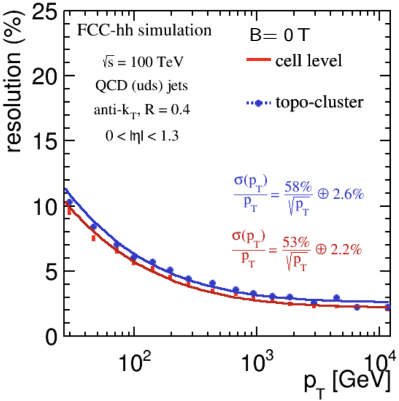
Simulations : 100 TeV pp collisions,
p_t range of di-jets from 20 GeV to 10 TeV

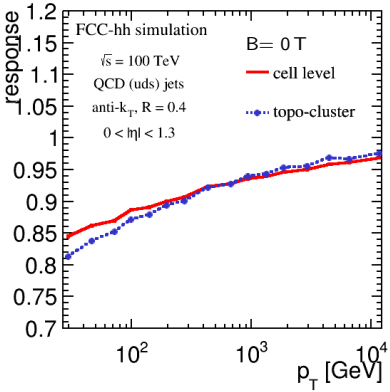
Reco with FastJet :
anti-k_t jet algorithm based on $d_{i,j} = min\left(1/p_{ti}^2, 1/p_{tj}^2\right)\frac{\Delta R_{ij}^2}{R^2}$
with $\Delta R_{ij}^2 = \left(\eta_i - \eta_j\right)^2 + \left(\phi_i - \phi_j\right)^2$, $\Delta R < 0.4$
matching of reco and gen jets within $\Delta R < 0.3$

1. cell level
2. topo-cluster
   - seed thr. ECal: 7.5 MeV
   - seed thr. HCal: 11.5MeV
   - every neighbour is collected
3. topo-cluster w/ noise
   - seed thr. 4σ of cell noise level
   - neighbour thr: 2σ of cell noise level
   - in last step all neighbours are collected



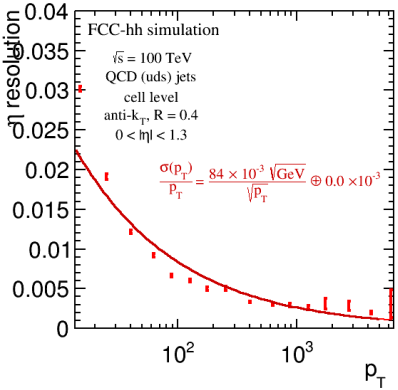
Jet energy resolution

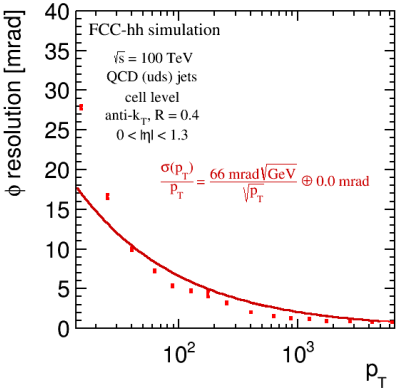




- in case of B= 0 T, constant term smaller than 3 %
- validated the topo-clustering

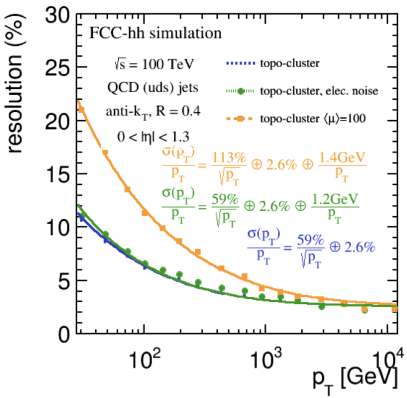
Jet angular resolutions

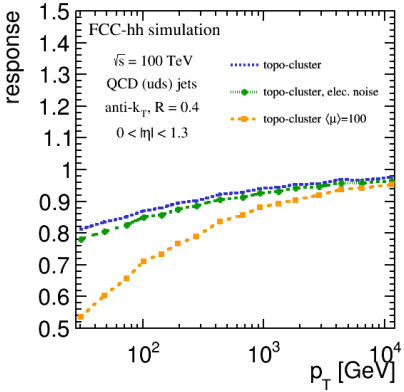




- η resolution reaches the average HCal granularity of 0.005
- ϕ resolution better than max HCal granularity of 25 mrad

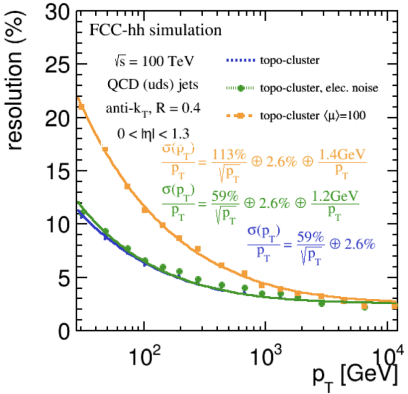
Jet energy resolution in $\langle\mu\rangle = 100$ – PRELIMINARY

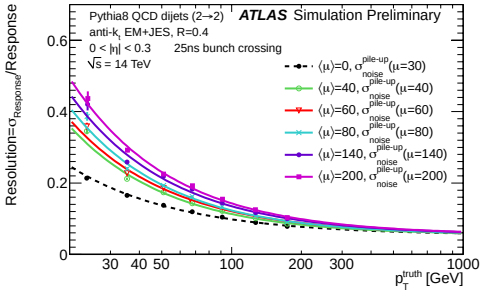




- topo-cluster algorithm successfully reduces the impact of electr. noise to minimum
- first look at impact of pile-up shows need for strategy for PU rejection (e.g. optimise topo-cluster threshold)

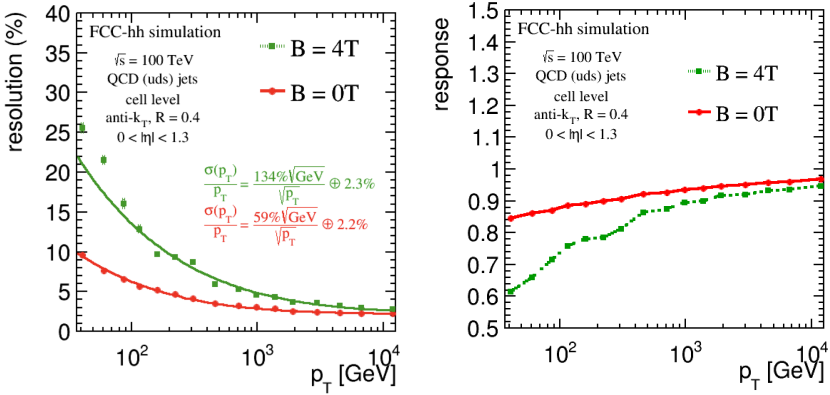
Jet energy resolution in $\langle\mu\rangle = 100$ – PRELIMINARY





- no pile-up rejection technique applied, except for topo-cluster threshold
- compared to ATLAS simulations, that include additional pile-up rejection

Jet energy resolution in B= 4 T – PRELIMINARY



- large effect of B field, loose large fraction of the jets' energy for $p_T < 500$ GeV (low energetic charged particles do not reach calorimeters)
- need tracker → PFA

Summary & Outlook

- full simulation and reconstruction chain in FCCSW established for single hadrons and jets
- the hadronic and EM calorimeter of the Barrel region shows promising energy resolutions :

	stochastic term	constant term
single particle	51.0%	2.5%
jets	58.0%	2.6%

$\rightarrow$ numerous additions possible (cluster calibration incl. benchmark correction, particle flow, timing)

Next steps towards CDR:

- estimations of ultimate pileup scenario
- performances of Endcap/Forward

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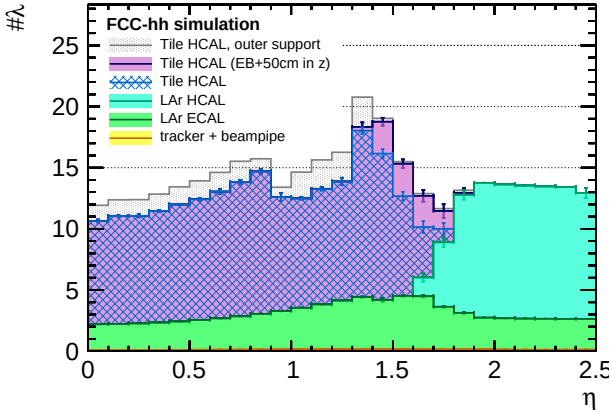
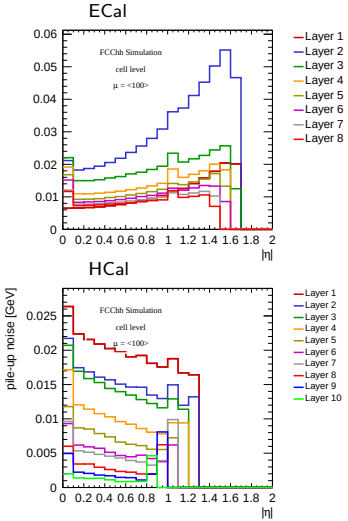
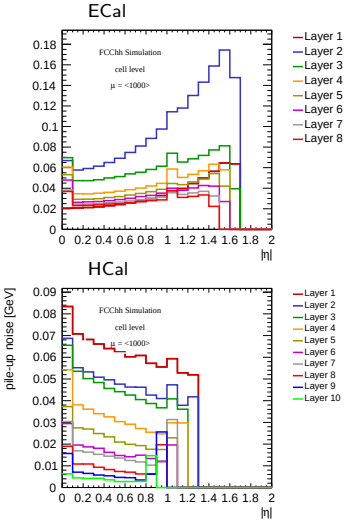
Material budget

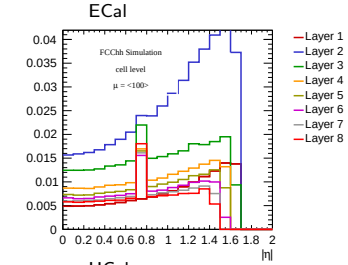


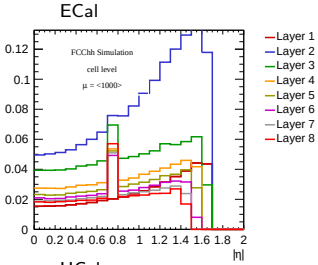
Pileup noise per cell no B field

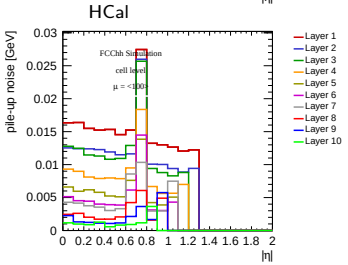


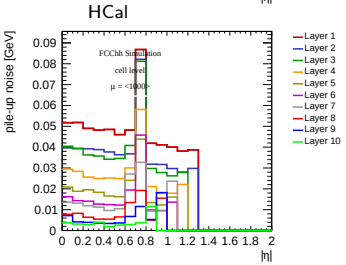


Pileup noise per cell in 4T field



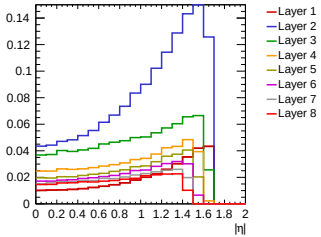






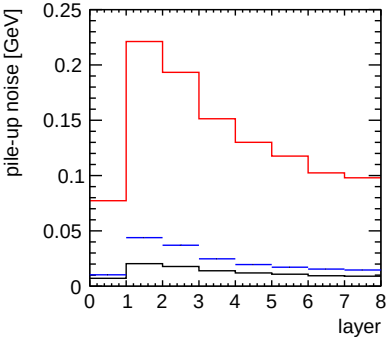
Pileup noise estimate topo-clusters – ECal no B field

Energy distributions of clusters, cells in layer 2:

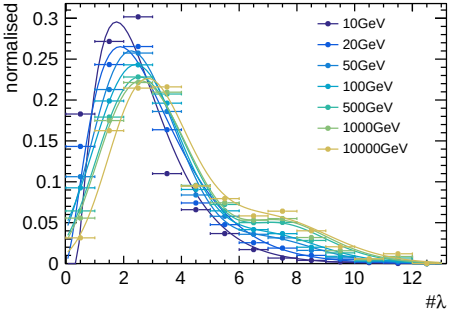


- $\sum E_{cell}$
- $\sqrt{\sum E_{cell}^2}$
- RMS of $E_{cluster}$

cluster size: $\Delta\eta \times 7$, $\Delta\phi \times 17$, at $|\eta| < 0.1$



BARREL – Longitudinal profiles $\eta = 0.36$

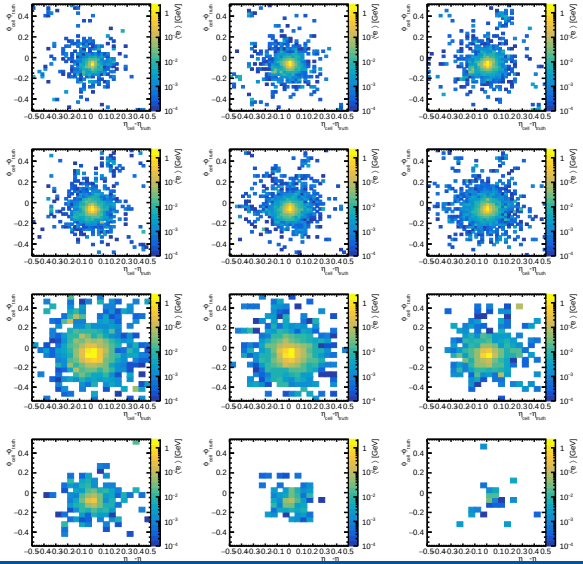


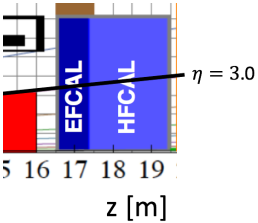
$$\lambda_{eff}^{ECAL} = \frac{\lambda_{eff,0}^{ECAL}}{\cos(\eta_{truth})} + d_{cell}^{ECAL}/\lambda_{ECAL} \qquad (2)$$

$$\lambda_{eff}^{HCAL} = \frac{\lambda_{eff,0}^{HCAL}}{\cos(\eta_{truth})} + d_{cell}^{HCAL}/\lambda_{HCAL} \qquad (3)$$

with depth of cell $d_{particle}$, along shower axis, within active Calorimeter
$\lambda_{eff,0}^{ECAL}(\eta = 0) = .3$, $\lambda_{eff,0}^{HCAL}(\eta = 0) = 2.2$
$\lambda_{ECAL} = 29.4\,\text{cm}$, $\lambda_{HCAL} = 20.1\,\text{cm}$

Shower images 100 GeV π^- at $\eta = 3$.

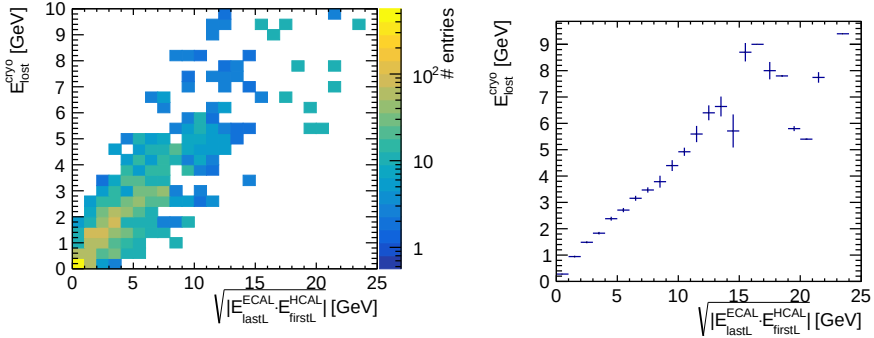




Benchmark reconstruction

correction for lost energy between E and HCAl (in cryostat)

$$E_{benchmark} = E_{em} \cdot a + E_{had}^{\pi} + b \cdot \sqrt{|E_{em,lastL} \cdot a \cdot E_{had,firstL}|} + c \cdot (E_{em} \cdot a)^2 \quad (4)$$



- optimised with (10 & 100) GeV, (1 & 10) TeV à 400 events
- $a = 0.978$, $b = 0.479$, $c = -5.4 \times 10^{-6}$ GeV^{-1}

Topo-Clustering within FCCSW

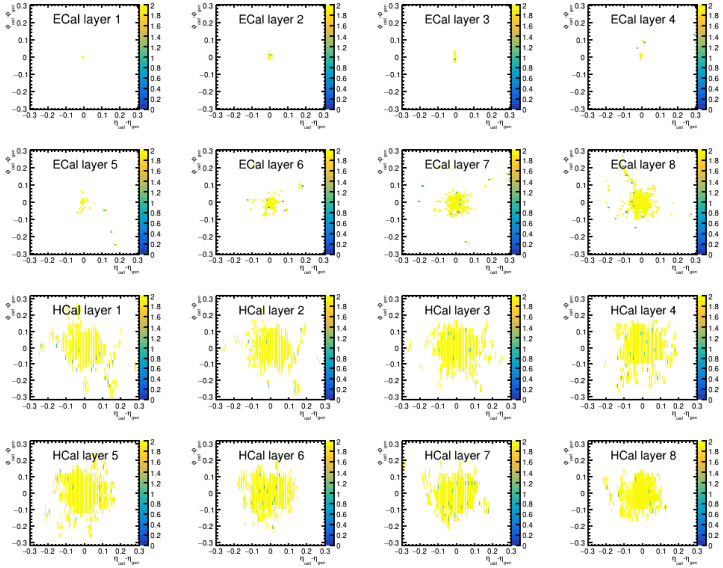
Algorithm to cluster Calorimeter cells
Logic algorithm:

1. Finding seed cells above **1rst threshold** of noise level in cell
2. seeds are sorted by energy
3. building clusters
4. find neighbours of the seed, include to cluster if above **2nd threshold**
5. the found neighbours become new seeds

repetition of 4 and 5, until no more neighbours found

6. add all neighbours for last seed (**3rd threshold**=0)

Topo-clusters – 500GeV π^-, w/B field, w/o noise



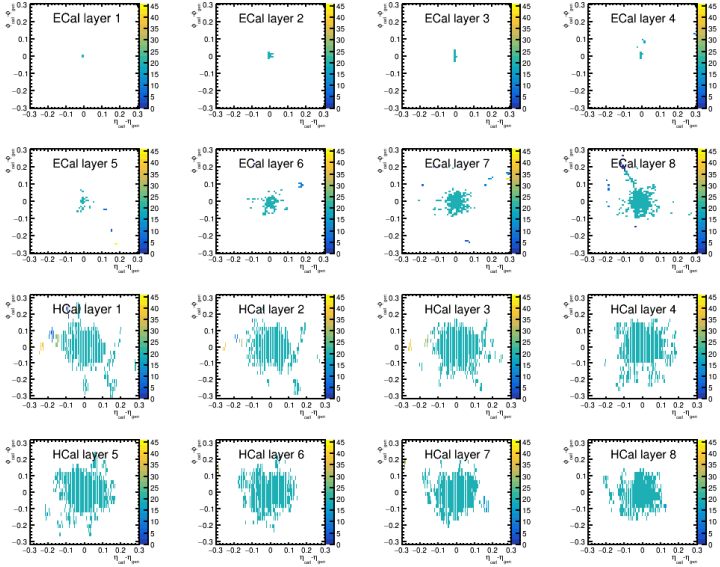
z axis

cell types:

1 = seed cell

2 = neighbour

Topo-clusters – 500GeV π^-, w/B field, w/o noise



HCal granularity not 0.01 in η, decreasing with increasing η

z axis **cluster ID**