

Design and performance studies of the calorimeter system for a FCC-hh experiment

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on behalf of the FCC-hh Detector group

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The Future Circular Collider project



International FCC collaboration (124 institutes, 32 countries)

- ▶ 100 TeV p-p collider (**FCC-hh**): main emphasis, defining infrastructure requirements
- ▶ 90-400 GeV e^+e^- collider (**FCC-ee**): as potential first step
- ▶ ~100 km tunnel infrastructure in Geneva area, site specific
- ▶ p-e (**FCC-he**) option studied

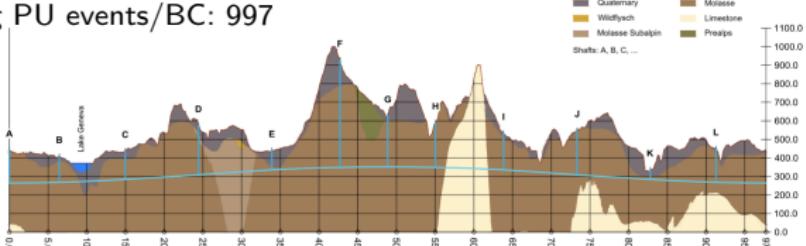
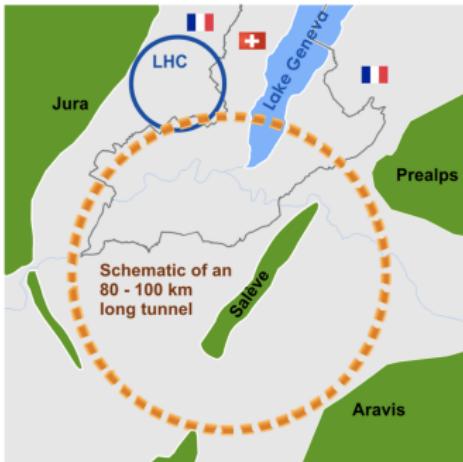
FCC-hh luminosity:

baseline: $5 \times 10^{34} \text{ cm}^{-2} \text{s}^{-1}$

ultimate: $30 \times 10^{34} \text{ cm}^{-2} \text{s}^{-1}$

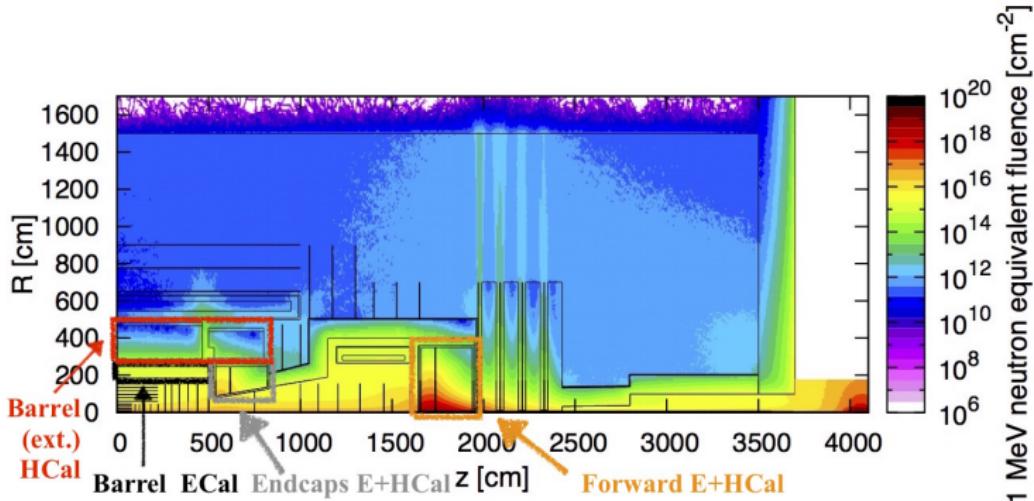
$O(30 \text{ ab}^{-1}) \approx 25 \text{ years of operation}$

-> peak avg PU events/BC: 997



Talk on FCC-hh machine by D. Schulte [Link](#)

Requirements on radiation hardness



	$1 \text{ MeV neq } [\text{cm}^{-2}]$	dose	
ECal Barrel	$\leq 5 \times 10^{15}$	$\leq 100 \text{ kGy}$	► Liquid argon technology extreme radiation hard
HCal Barrel	$\leq 3 \times 10^{14}$	$\leq 8 \text{ kGy}$	► Barrel HCAL tolerances met for scintillator and Silicon Photomultipliers (SiPMs)
Endcap	$\leq 3 \times 10^{16}$	$\leq 1 \text{ MGy}$	$\rightarrow \eta$ dependent requirements
Forward	$\leq 5 \times 10^{18}$	$\leq 5 \text{ GGy}$	\rightarrow meet performance goals

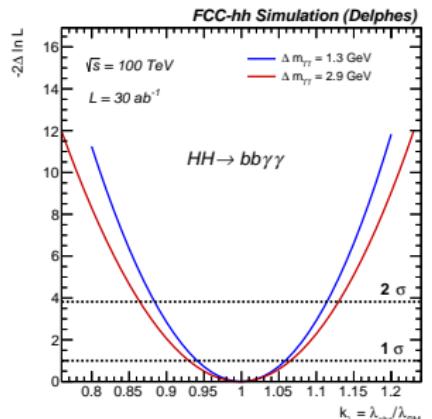
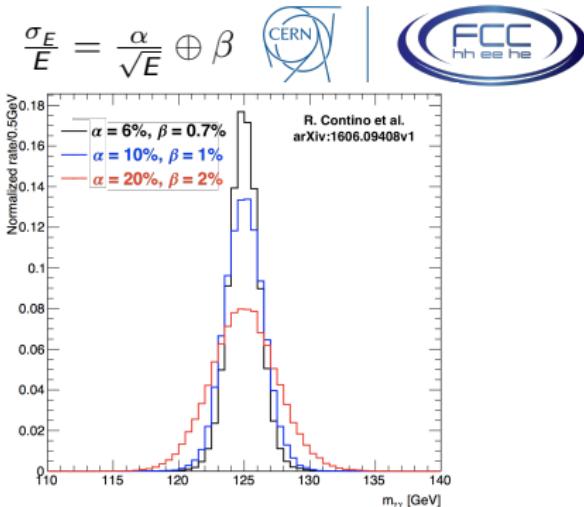
FCC-hh EM calorimeter

– requirements

- ▶ heavy resonances:
 $Z' \rightarrow e^+ e^-$, $W' \rightarrow e\nu$, $X \rightarrow \gamma\gamma$, $X \rightarrow jj$
- ▶ precision physics:
 $HH \rightarrow bb\gamma\gamma$

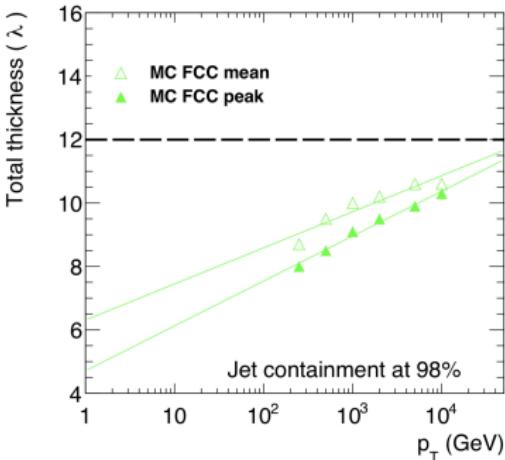
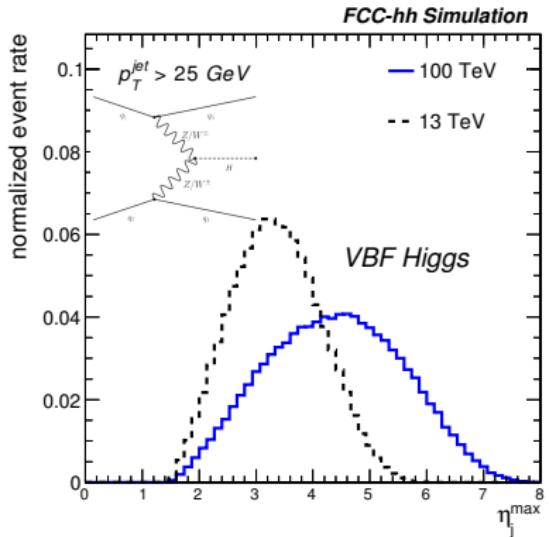
1. Significance of mass peaks
 - ▶ high energy resolution
 - ▶ high angular resolution
2. Measurement of invariant masses
 - ▶ good Linearity of calorimeter response
3. Pileup rejection & π^0 identification
 - ▶ high granularity

→ constant term <1% essential!: excellent resolution on the Higgs trilinear self-coupling, strong dependence on $\Delta m_{\gamma\gamma}$



FCC-hh hadron calorimeter

– requirements



- ▶ Jet rapidity of VBF $\rightarrow \eta$ coverage up to 6
- ▶ High p_T jets at $\eta = 0 \rightarrow$ containment $\geq 11 \lambda$
- ▶ Highly collimated final states (boosted decay products of heavy objects)
 \rightarrow High granularity to resolve jet sub-structure and background rejection
(e.g. pile-up jets)

FCC-hh detector



total length ~ 47 m, height ~ 18 m, segmentation not optimised, 2.5 M channel

ECAL Barrel

LAr-Pb (1:3), 6-8 layers

$\Delta\eta = 0.01, \Delta\phi = 0.009$

$\sigma_E/E \sim 10\%/\sqrt{E} \oplus 0.7\%$

ECAL Endcap

LAr-Cu (1:3), 6-8 layers

$\Delta\eta = 0.01, \Delta\phi = 0.01$

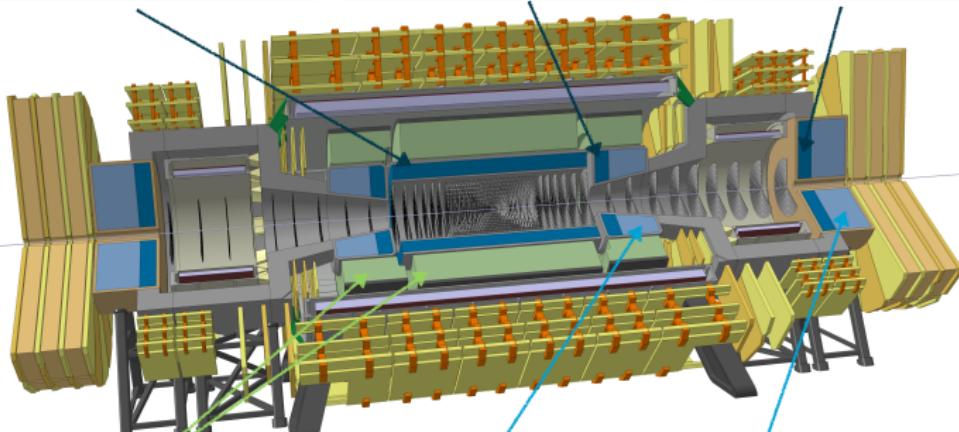
$\sigma_E/E \sim 10\%/\sqrt{E} \oplus 0.7\%$

ECAL Forward

LAr-Cu (1:100), 6-8 layers

$\Delta\eta = 0.05, \Delta\phi = 0.05$

$\sigma_E/E \sim 100\%/\sqrt{E} \oplus 10\%$



HCAL Barrel / Ext. Barrel

Sci-Pb-Steel (1:1.3:3.3), 10/8 layers

$\Delta\eta < 0.025, \Delta\phi = 0.025$

$\sigma_E/E \sim 50\%/\sqrt{E} \oplus 3\%$

HCAL Endcap

LAr-Cu (1:5), 6-8 layers

$\Delta\eta = 0.025, \Delta\phi = 0.025$

$\sigma_E/E \sim 50\%/\sqrt{E} \oplus 3\%$

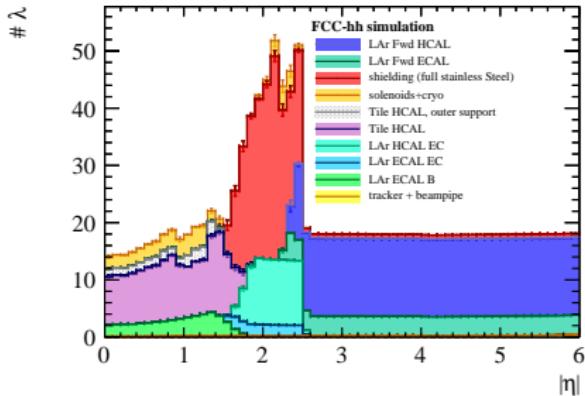
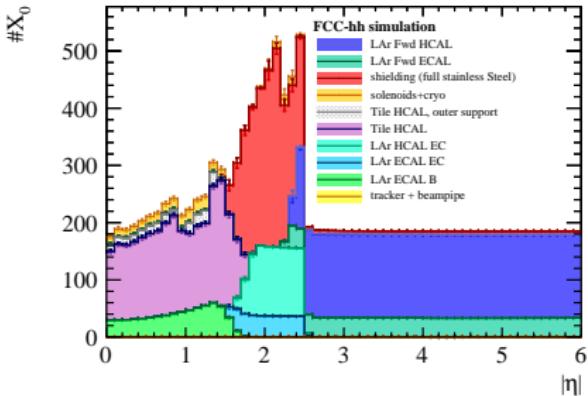
HCAL Forward

LAr-Cu (1:200), 6-8 layers

$\Delta\eta = 0.05, \Delta\phi = 0.05$

$\sigma_E/E \sim 100\%/\sqrt{E} \oplus 5\%$

Calorimeter choices



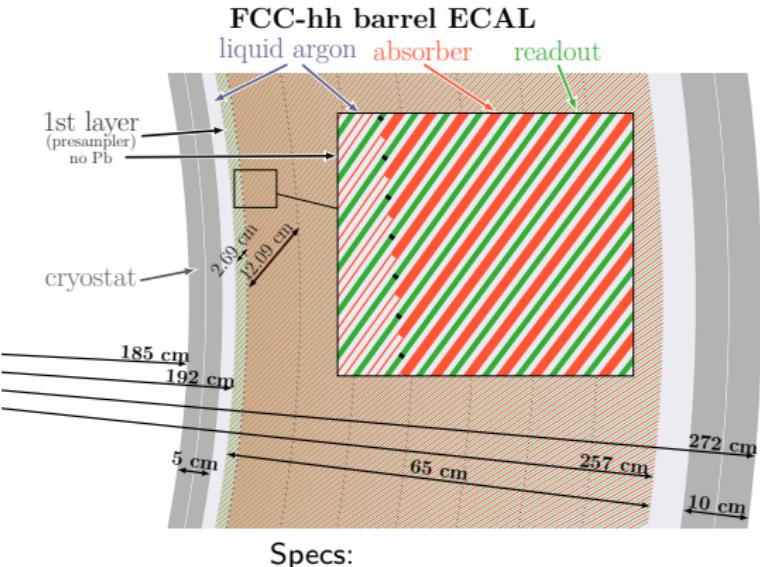
	ECAL	HCAL
electrons/photons	$> 30 X_0$	-
hadrons	$> 2 \lambda$	$> 8.5 \lambda$
muons	$> 30 X_0$	$> (120 + 10) X_0$

→ performance studies concentrated on Barrel

FCC-hh Barrel ECal – LAr/Pb



- ▶ 10× granularity of ATLAS ECal
- ▶ improved precision due to simpler layout compared to ATLAS accordion (slightly increased noise)
- ▶ electronics noise study of multilayer read-out electrodes done
 - note: alternative ECal design in Si(Monolithic Active Pixel Sensors)/W technology under study



Specs:

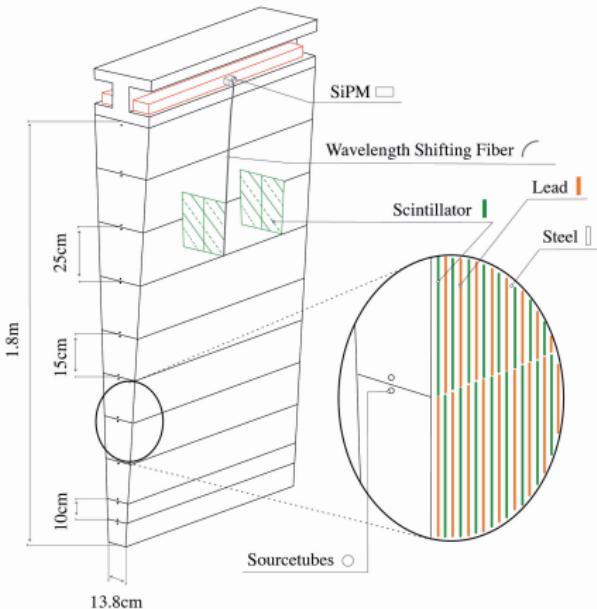
2 mm Pb/steel plates inclined by 50°
LAr gap increases with radius:
1.15 mm-3.09 mm
8 longitudinal layers
 $\Delta\eta = 0.01$ $\Delta\phi = 0.009$

Specs:

5 mm steel absorber plates,
alternate w/ 3 mm Si and 4 mm Pb tiles
10 longitudinal layers
 $\Delta\eta(> 0.006) = 0.025$ $\Delta\phi = 0.025$

- ▶ 4× granularity of ATLAS HCal
- ▶ SiPM readout at outer radius ($\sim 10^{11}$ neq)
→ single channel readout, timing
- ▶ current ongoing R&D on scintillator material and SiPM technology fulfil requirements (8 kGy)

→ mechanical structure feasible, assembly study done
→ first test of Sci tiles in FCC size started

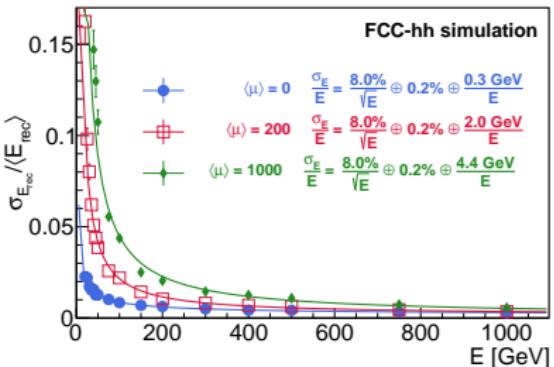


Calorimeter performance

Electron/photon reconstruction



Energy resolution, $\eta=0$



reco with sliding window algorithm:

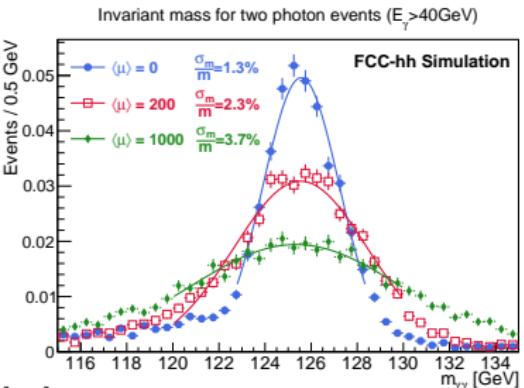
- ▶ building towers in $\Delta\eta = 0.01$, $\Delta\phi = 0.009$
- ▶ window size: 0.07×0.17

pile-up scenarios tested on single electron resolution and di-photon invariant mass $m_{\gamma\gamma}$:

→ need pile-up rejection strategies, algorithm (window size) not optimised

→ resolution goals achieved

→ noise rejection strategies needed



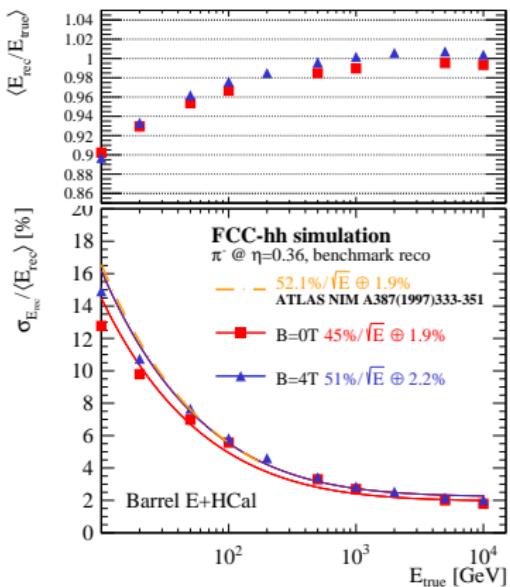
Single π^- reconstruction



combine E+HCal signals with benchmark reconstruction method on cell level:

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

- recovers lost energy in LAr cryostat



	stochastic term	constant term
HCal only	42%	2.8%
Ecal + HCal benchmark	45%	1.9%
B=4T	51 %	2.2 %

- > magnetic field effects lower energies
- > resolution goals achieved, without noise

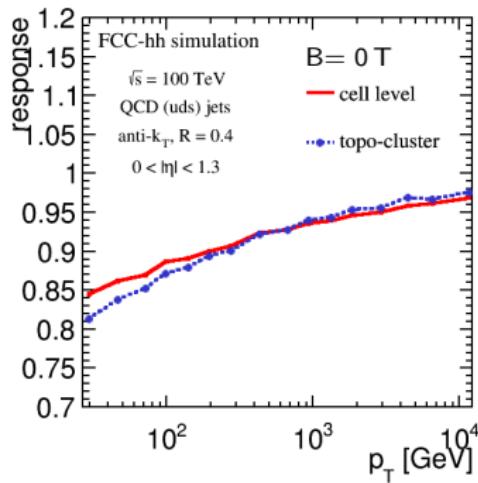
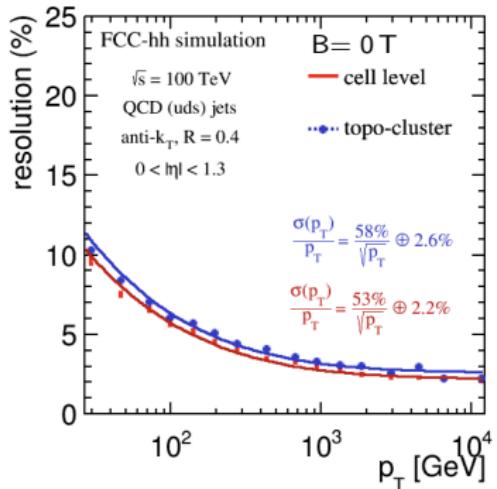
Jet energy resolution



reconstruction of jets with anti- k_T algorithm
input can be

1. calo cells

2. topo-cluster: collection of cells based on significance $\xi_{\text{cell}} = \frac{E_{\text{cell}}}{\sigma_{\text{noise}}} - \frac{\sigma_{\text{cell}}}{\sigma_{\text{noise}}}$



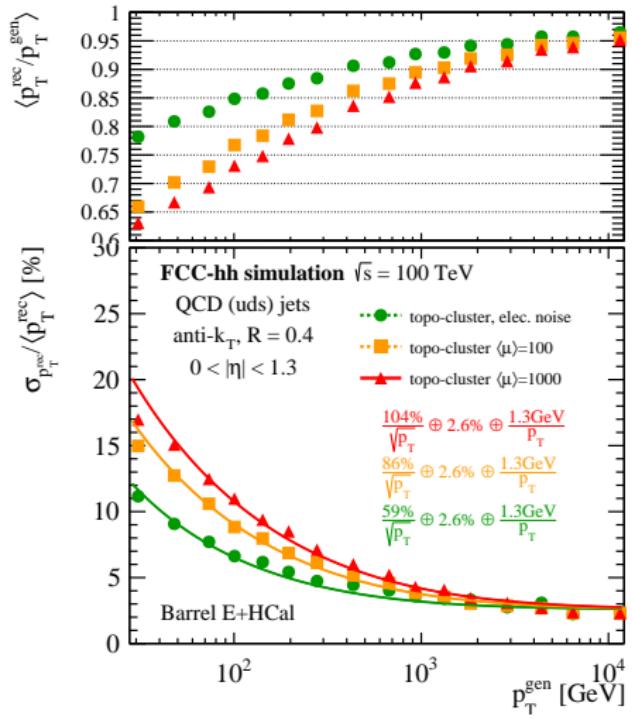
- ▶ in case of $B = 0 \text{ T}$, constant term smaller than 3 %
- ▶ validated the topo-clustering

Jet energy resolution in $\langle \mu \rangle = 200, 1000$



tests of calorimeter performance with pile-up, without B field

- ▶ large impact of pile-up on low p_T
- ▶ topo-cluster algorithm successfully reduces the impact of noise, but due to higher thresholds increase in sampling term
- ▶ need strategy for PU rejection.

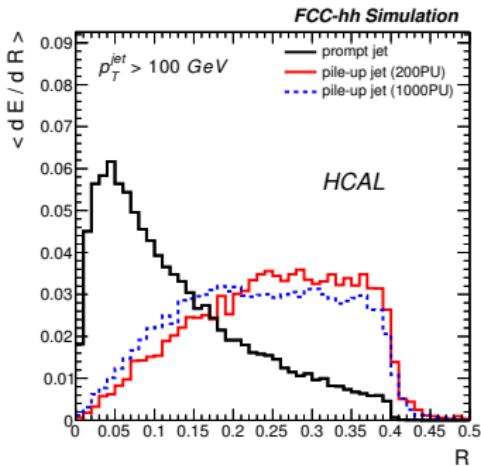
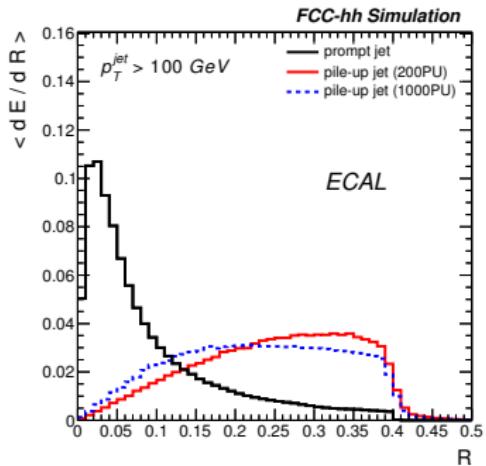


Pileup rejection strategies



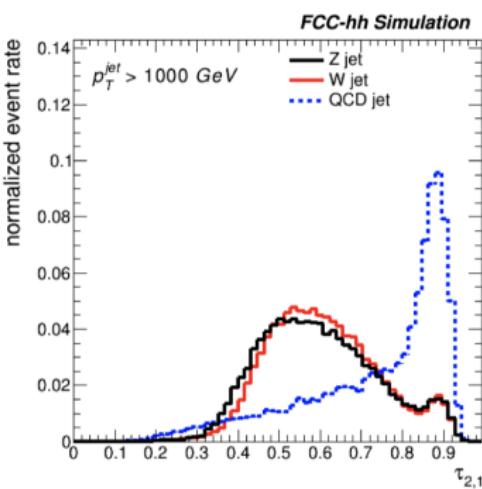
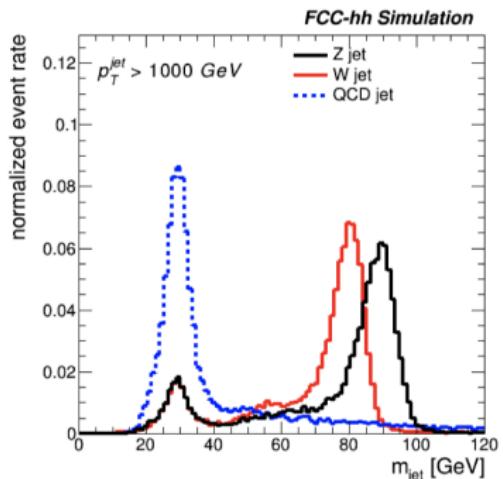
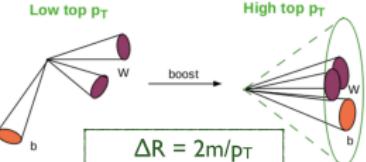
- ▶ exploit the longitudinal/lateral segmentation for PU identification:

$$\text{radial profile in } R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$$



- ▶ threshold optimisation of topo-clustering
- ▶ machine learning (Deep Neural Nets) study on-going

Jet sub-structure



Performance good up to 1 TeV, with Calorimeter standalone, and without B field!
Far from having explored everything possible:

- ▶ Particle-Flow tracks and B field (decrease local occupancy) will improve
- ▶ Machine Learning techniques will help a lot (train on 3D shower image)

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

	stochastic term	constant term
electrons	8.0%	0.2%
hadrons	51.0%	2.2%

- ▶ multiple pile-up rejection techniques possible, especially due to the high granularity (first promising results of DNN)
- ▶ numerous additions possible: cluster calibration (on-going), tracking (on-going within FCCSW) -> particle flow, timing
- ▶ comprehensive summary of FCC project is in preparation
-> delivery of Conceptual Design Report until end of year



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Optimisations of Barrel Tile HCal

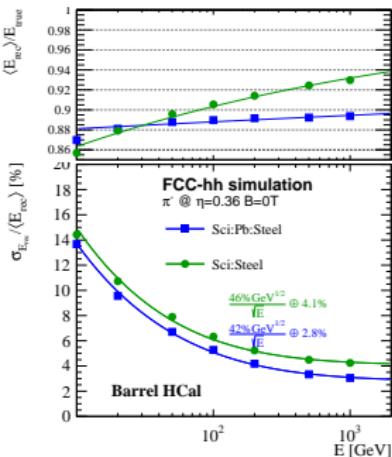
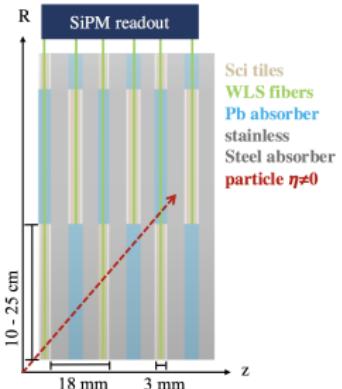


- included Pb absorbers
→ Scintillator/Pb/Steel
(1:1.3:3.3)

- decreasing
non-compensation by
suppression of EM
response

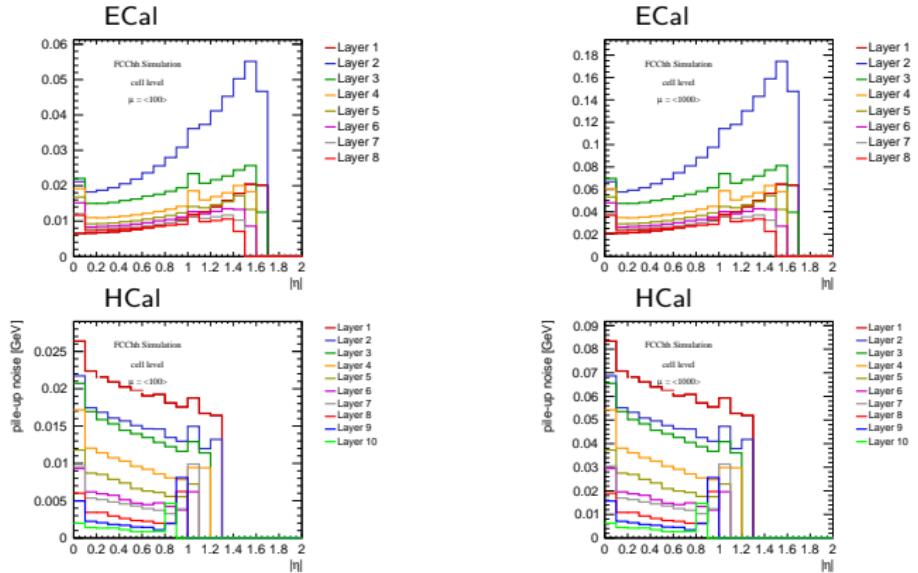
Pb: $X_0 = 0.6 \text{ cm}$,
 $\lambda_n = 17.6 \text{ cm}$ (Fe:
 $X_0 = 1.8 \text{ cm}$,
 $\lambda_n = 16.8 \text{ cm}$)

- reduces total depth [λ_n]
from 8.9 (full Steel) to
8.5



	stochastic term	constant term	e/h
Sci:Steel (1:4.7)	46% $\text{GeV}^{1/2}$	4.1%	1.24
Sci:Pb:Steel (1:1.3:3.3)	42% $\text{GeV}^{1/2}$	2.8%	1.1

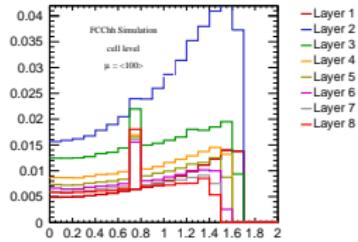
Pileup noise per cell no B field



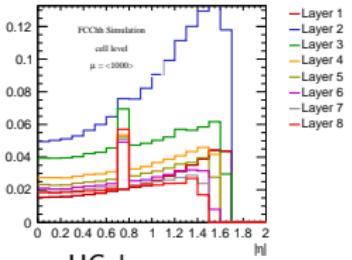
Pileup noise per cell in 4T field



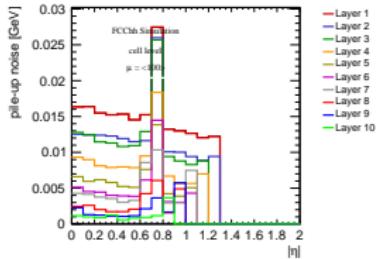
ECal



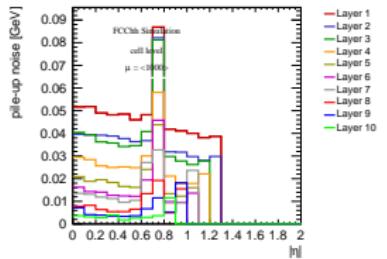
ECal



HCal



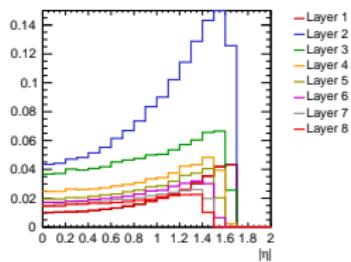
HCal



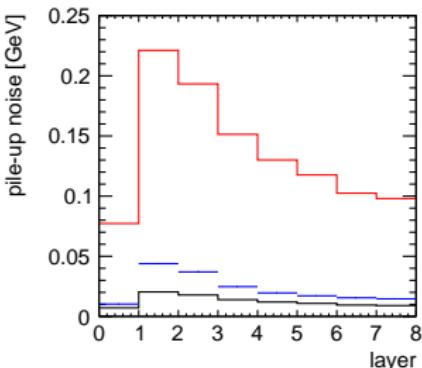
Pileup noise estimate topo-clusters – ECal no B field



Energy distributions of clusters,
cells in layer 2:

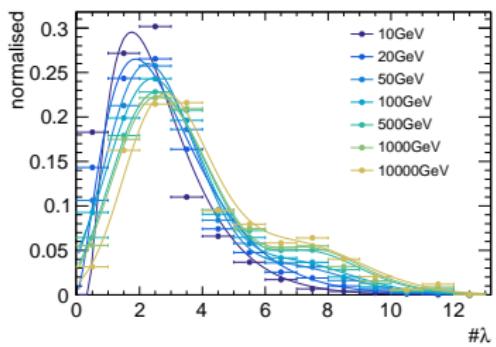


cluster size: $\Delta\eta \times 7$, $\Delta\phi \times 17$,
at $|\eta| < 0.1$



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

BARREL – Longitudinal profiles $\eta = 0.36$



$$\lambda_{\text{eff}}^{\text{ECAL}} = \frac{\lambda_{\text{eff},0}^{\text{ECAL}}}{\cos(\eta_{\text{truth}})} + d_{\text{cell}}^{\text{ECAL}} / \lambda_{\text{ECAL}} \quad (1)$$

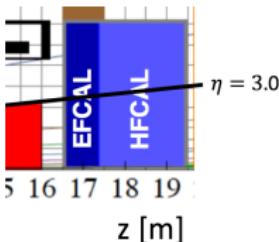
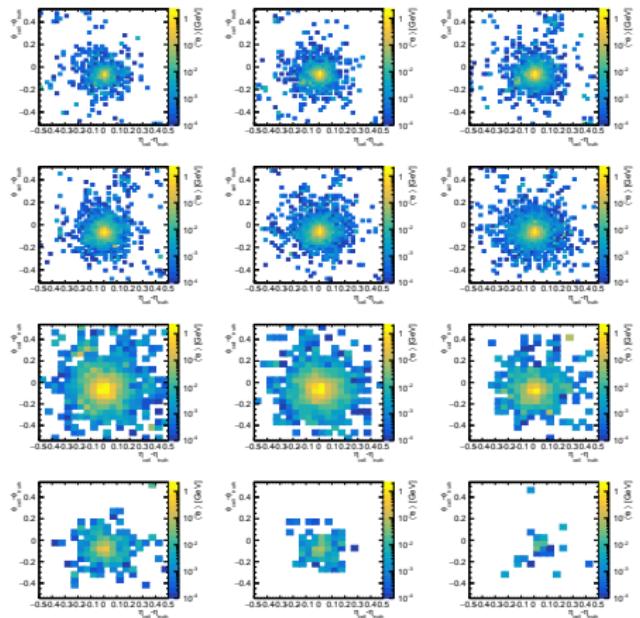
$$\lambda_{\text{eff}}^{\text{HCAL}} = \frac{\lambda_{\text{eff},0}^{\text{HCAL}}}{\cos(\eta_{\text{truth}})} + d_{\text{cell}}^{\text{HCAL}} / \lambda_{\text{HCAL}} \quad (2)$$

with depth of cell d_{particle} , along shower axis, within active Calorimeter

$$\lambda_{\text{eff},0}^{\text{ECAL}}(\eta = 0) = .3, \quad \lambda_{\text{eff},0}^{\text{HCAL}}(\eta = 0) = 2.2$$

$$\lambda_{\text{ECAL}} = 29.4 \text{ cm}, \quad \lambda_{\text{HCAL}} = 20.1 \text{ cm}$$

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

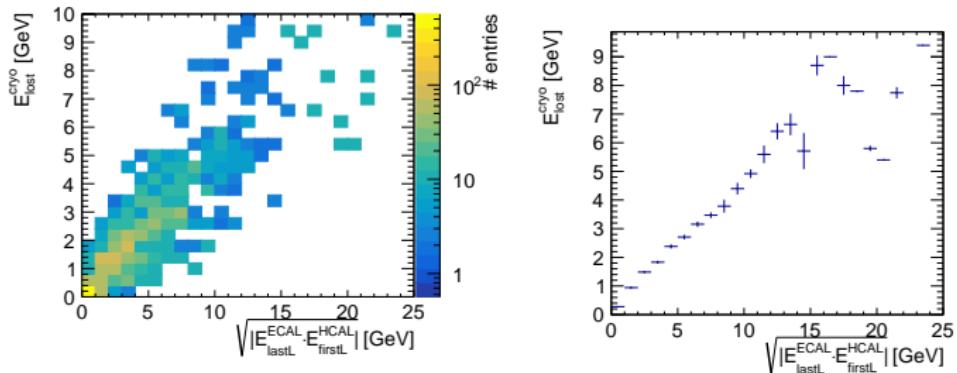


Benchmark reconstruction



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

$$E_{benchmark} = E_{em} \cdot a + E_{had}^{\pi} + b \cdot \sqrt{|E_{em, lastL} \cdot a \cdot E_{had, firstL}|} + c \cdot (E_{em} \cdot a)^2 \quad (3)$$



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

Algorithm to cluster Calorimeter cells

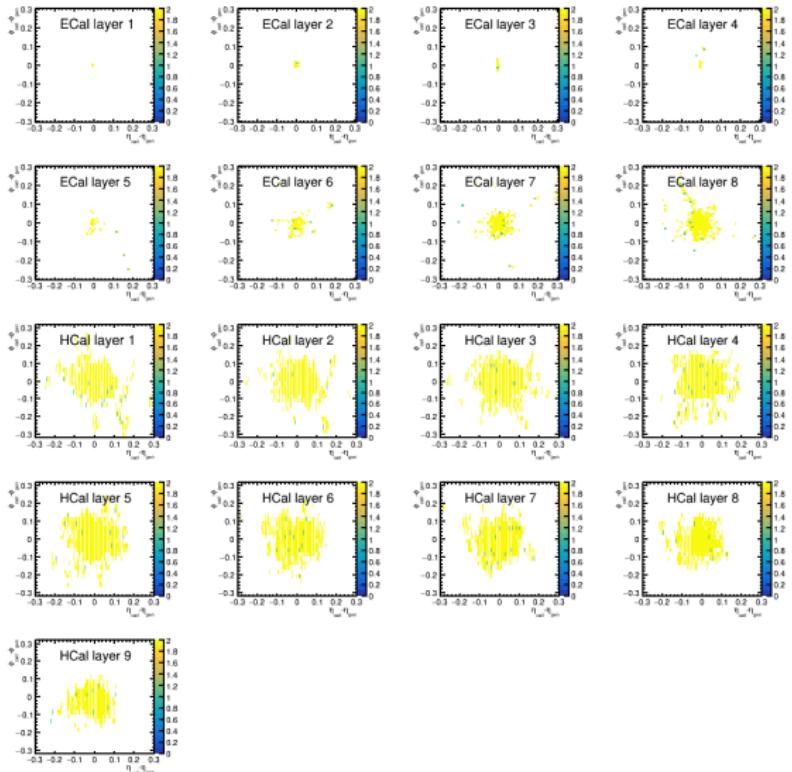
Logic algorithm:

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,



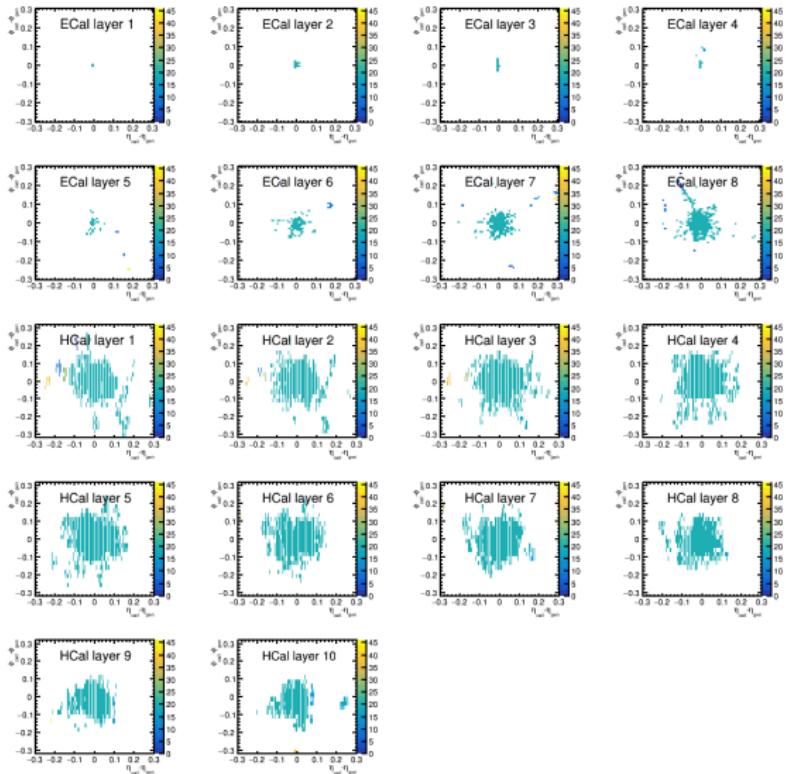
z axis

cell types:

1 = seed cell

2 = neighbour

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



HCal granularity
not 0.01 in η ,
decreasing with
increasing η
z axis
cluster ID

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

$$d_{i,j} = \min \left(1/p_{ti}^2, 1/p_{tj}^2 \right) \frac{\Delta R_{ij}^2}{R^2},$$

$$\text{with } \Delta R_{ij}^2 = (\eta_i - \eta_j)^2 + (\phi_i - \phi_j)^2,$$

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: 11.5 MeV
- ▶ 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

