FCC-ee TileCal simulation and reconstruction

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on behalf of the FCC-ee TileCal team

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Overview

- Present ongoing work on hadronic calorimeter design for FCC-ee based on ATLAS TileCal

- ATLAS TileCal in a nutshell:
  - Steel plates and plastic scintillators (the tiles) coupled to wavelength shifting fibres
  - About 5000 pseudo-projective cells, each cell readout by 2 photomultiplier tubes (10000 PMTs in total)
  - Dynamic range 10 MeV to 2 TeV per cell
  - $\frac{\sigma_E}{E} = \frac{50\%}{\sqrt{E[\mathrm{GeV}]}} \oplus 3\%$

- Previously, TileCal-like HCal was included in the detector design for FCC-hh - our starting point
  - TileCal-like geometry implemented in FCCDetectors
  - Algorithms for signal digitization and reconstruction implemented in k4RecCalorimeter

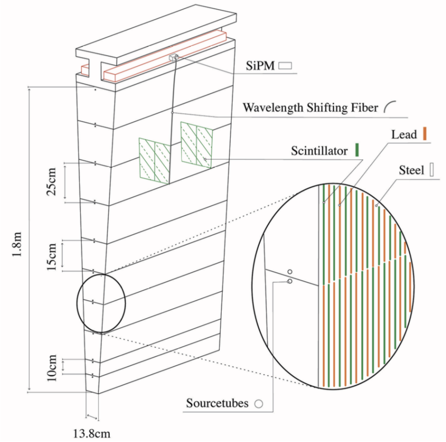
- Goal is the full detector simulation within the Noble Liquid ECal based detector concept

A design for FCC-hh central calorimeter system

Specs:

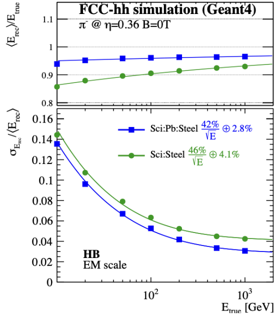
- 5mm steel absorber plates, alternating with 3mm Scint. and 4mm Pb tiles
- 128 modules in ϕ, 2 tile/module
- 10 radial layers
- $\Delta\eta = 0.025$ (grouping 3-4 tiles), $\Delta\phi = 0.025$

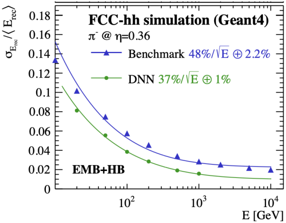
- 4 times the tile density of ATLAS, 1 tile 1 channel
- SiPM readout at outer radius
- Ongoing R&D on scintillator material and SiPMs
- Mechanical structure feasible
- Tested Sci tile + WLS fibre + SiPM readout



Standalone FCC-hh Tile and combined LAr+Tile performance

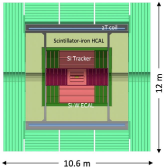
- Optimised absorbers for hadronic performance
  - decreasing non-compensation by suppression of EM response
    Pb: X0 =0.6cm/Fe: X0 =1.8cm
  - improves stochastic and constant term, and e/h from 1.24 to 1.1
- 8 layer LAr + 10 layer TileCal achieves desired performance
  - high granularity allows for machine learning technique: Deep Neural Nets (DNNs)
  - granularity achieved in the HCal barrel through SiPM readout
- Work documented in a note CERN-FCC-PHYS-2019-003 by Aleksa et. al.





A design for FCC-ee central calorimeter system

CLD

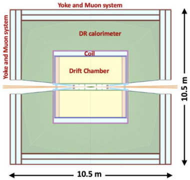


- Full Silicon vertex detector + tracker;
- Very high granularity, CALICE-like calorimetry;
- Muon system
- Large coil outside calorimeter system;

- Possible optimization for
  - Improved momentum and energy resolutions
  - PID capabilities

CDR

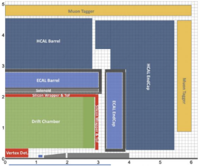
IDEA



- Si vertex detector;
- Ultra light drift chamber w. powerfull PID;
- Monolitic dual readout calorimeter;
- Muon system;
- Compact, light coil inside calorimeter;

- Possibly augmented by crystal ECAL in front of coil;

Noble Liquid ECAL based



new

- High granularity Noble Liquid ECAL as core;
  - PB+LAr (or denser W+LCr)
- Drift chamber (or Si) tracking;
- CALICE-like HCAL;
- Muon system;
- Coil inside same cryostat as LAr, possibly outside ECAL.

M. Aleksa et. al.

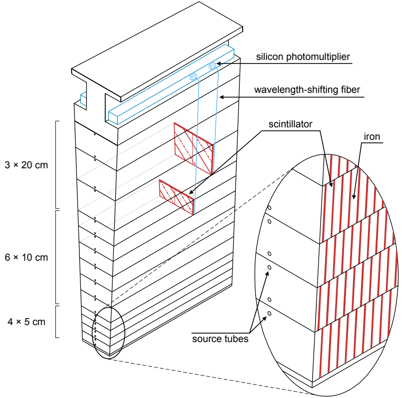
- Implemented TileCal-like barrel calorimeter in the 3rd detector concept, geometry optimization and performance studies ongoing

A design for FCC-ee central calorimeter system

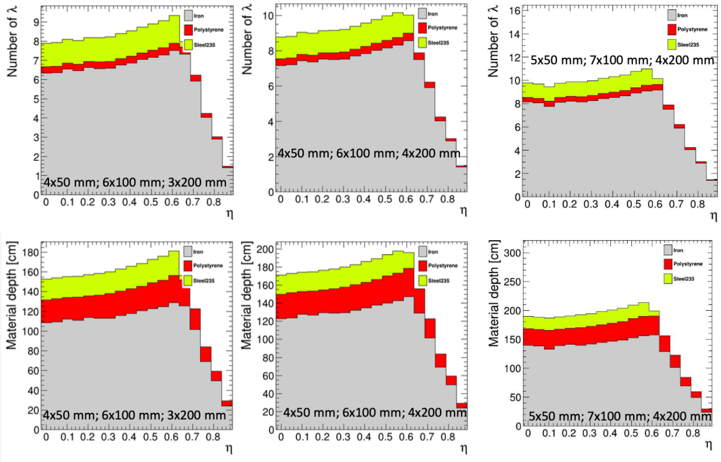
Specs:

- 5mm steel absorber plates alternating with 3mm Scint.
- 128 modules in ϕ, 2 tile/module
- 13 radial layers
- $\Delta\eta = 0.025$ (grouping 3-4 tiles), $\Delta\phi = 0.025$

- Removed the Pb plates compared to FCC-hh design (HCAL acts as return yoke for the central solenoid)
- 13 layers in depth (smaller cells)
- FCC-ee TileCal geometry is available in FCCDetectors
- Work on optimisation of segmentation and reconstruction is in full swing
- Started testing Sci tile + WLS fibre + SiPM readout

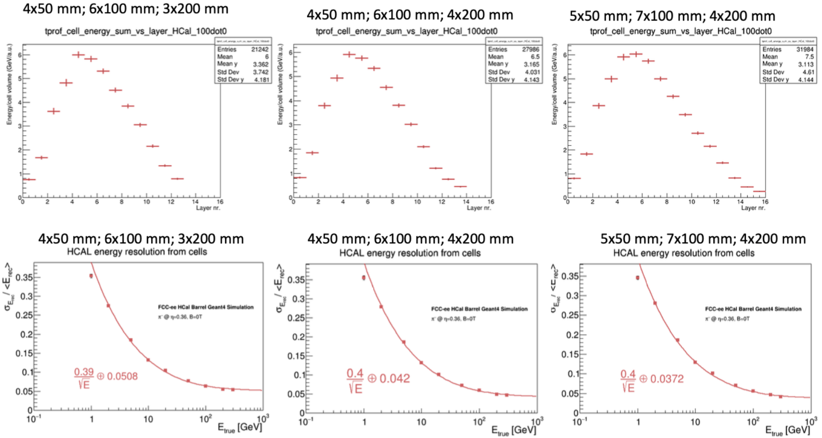


Standalone FCC-ee TileCal geometry studies



- Varying the number of radial layers and depth of the HCal
- From $\sim 8\lambda \;\rightarrow\; \sim 8.75\lambda \;\rightarrow\; \sim 9.5\lambda$

Standalone FCC-ee TileCal performance studies



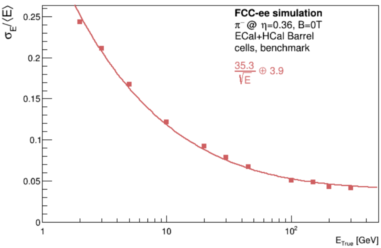
- With 13 layers (default) still have quite a lot of energy deposited in the last radial layer (100 GeV $\pi^{\pm}$)
    - Extending HCal dimension in R reduces the energy in the last layer and the constant term decreases
- Energy resolution for single $\pi^{\pm}$ at $\eta = 0.36$ for 3 different HCal geometries (work by B. Pereira (LIP))

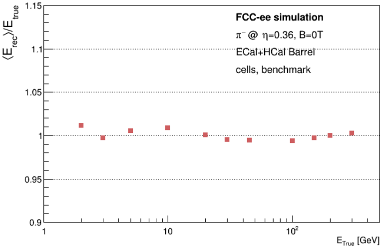
Combined LAr+Tile performance (cells)

- 12 layer LAr + 13 layer TileCal
- Benchmark method
  - Was developed for ATLAS test-beam measurements
  - To be used for hadron simulation when combining ECal and HCal
  - Applies a correction for the energy lost between ECal barrel (EB) and HCal barrel (HB) and calibrates the energy deposits to the hadronic scale
  - Derived using the energy deposited in cells
  - The total energy:

$$E_{\mathrm{rec}}^{\mathrm{bench}} = p_0 \cdot E_{\mathrm{EB}}^{\mathrm{EM}} + p_1 \cdot E_{\mathrm{HB}}^{\mathrm{HAD}} + p_2 \sqrt{|p_0 \cdot E_{\mathrm{EB}}^{\text{last layer}} \cdot E_{\mathrm{HB}}^{\text{first layer}}|} + p_3 (p_0 \cdot E_{\mathrm{EB}}^{\mathrm{EM}})^2 + p_4 \cdot E_{\mathrm{EB}}^{\text{first layer}}$$

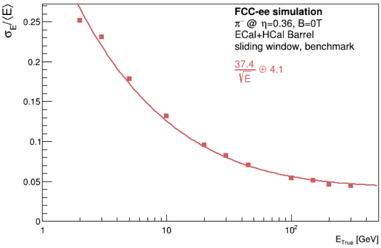
  - Newly added upstream material (e.g. ECal cryostat) correction p_4
  - Benchmark method calibration now available in the k4RecCalorimeter

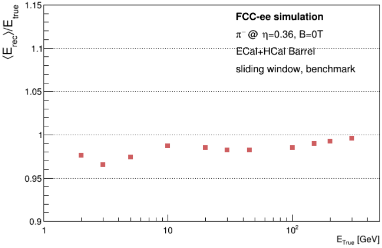




Combined LAr+Tile performance (clusters)

- Cluster reconstruction done with the sliding window algorithm
- Benchmark method applied to correct clusters energy





- Stochastic term $\sim 37-38\%$, constant term $\sim 4\%$
- Linearity of response for $\pi^{\pm}$ with energies > 10 GeV is within 2%, for energies below 10 GeV the linearity is within 4%

Outlook

- Presented work on TileCal-like hadronic calorimeter for FCC-ee
- TileCal-like hadronic calorimeter was implemented in the 3rd detector concept with Noble liquid ECal
- Ongoing performance studies and geometry optimization for standalone HCal and combined ECal+HCal simulation
- Endcaps implemented in FCCDetectors for both ECal and HCal, geometry optimization ongoing
- Cluster reconstruction in the barrel region done with the sliding window algorithm, next step is to move to topoclustering
- In parallel, starting an effort to train a Neural Net for the ECal+HCal energy reconstruction

Standalone FCC-ee TileCal performance studies

<table>
<tr><th></th><th>λ</th><th>Geometry</th><th>Layers</th><th>Δη</th><th>Energy Resolution (%)</th><th>Scintillator number in 1 module</th></tr>
<tr><td rowspan="3">FCCee</td><td>~8</td><td>4x50 mm; 6x100 mm; 3x200 mm</td><td>13</td><td>0.025</td><td>$\frac{38.70}{\sqrt{E}} \oplus 5.09$</td><td>4030</td></tr>
<tr><td>~8.75</td><td>4x50 mm; 6x100 mm; 3x200 mm</td><td>14</td><td>0.025</td><td>$\frac{39.81}{\sqrt{E}} \oplus 4.07$</td><td>4340</td></tr>
<tr><td>~9</td><td>5x50 mm; 7x100 mm; 4x200 mm</td><td>16</td><td>0.025</td><td>$\frac{39.88}{\sqrt{E}} \oplus 3.58$</td><td>4960</td></tr>
<tr><td rowspan="2">FCChh</td><td>Pb and Steel</td><td rowspan="2">2x100; 4x150; 4x200</td><td rowspan="2">10</td><td rowspan="2">0.025</td><td>$\frac{42}{\sqrt{E}} \oplus 2.8$</td><td></td></tr>
<tr><td>Steel</td><td>$\frac{46}{\sqrt{E}} \oplus 4.1$</td><td></td></tr>
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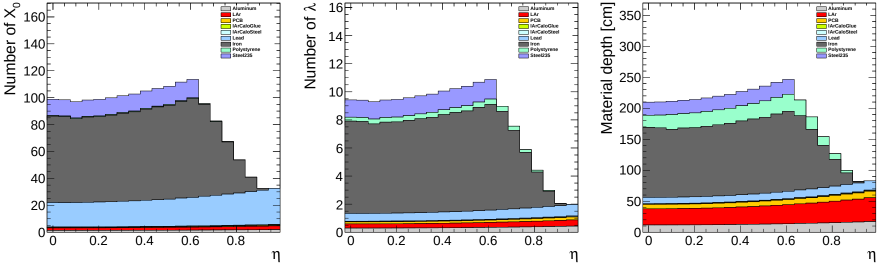
Material budget LAr+Tile



- $\sim 100\ X_0$ and $\sim 9.5\lambda$