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
  • \( \frac{\sigma_E}{E} = \frac{50\%}{\sqrt{E\,[\text{GeV}]}} \oplus 3\% \)

• 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 $\phi$, 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: $X_0 = 0.6\text{cm}$/Fe: $X_0 = 1.8\text{cm}$
  - 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

A design for FCC-ee central calorimeter system

- 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

- Si vertex detector;
- Ultra light drift chamber w. powerfull PID;
- Monolithic dual readout calorimeter;
- Muon system;
- Compact, light coil inside calorimeter;
- Possibly augmented by crystal ECAL in front of coil;

- 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 $\phi$, 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

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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 π⁺⁻)
  - Extending HCal dimension in R reduces the energy in the last layer and the constant term decreases
- Energy resolution for single π⁺⁻ at η = 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:
    \[
    E_{\text{rec}}^{\text{bench}} = p_0 \cdot E^{\text{EM}}_{\text{EB}} + p_1 \cdot E_{\text{HB}}^{\text{HAD}} + p_2 \sqrt{|p_0 \cdot E_{\text{EB}}^{\text{EM}}| \cdot E_{\text{EB}}^{\text{EM}} + p_3 (p_0 \cdot E_{\text{EB}}^{\text{EM}})^2 + p_4 \cdot E_{\text{EB}}^{\text{first layer}}}
    \]
  - 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>
<thead>
<tr>
<th>l</th>
<th>Geometry</th>
<th>Layers</th>
<th>Δη</th>
<th>Energy Resolution (%)</th>
<th>Scintillator number in 1 module</th>
</tr>
</thead>
<tbody>
<tr>
<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>Pb and Steel</td>
<td>2x100; 4x150; 4x200</td>
<td>10</td>
<td>0.025</td>
<td>$\frac{42}{\sqrt{E}} \oplus 2.8$</td>
<td></td>
</tr>
<tr>
<td>Steel</td>
<td></td>
<td></td>
<td></td>
<td>$\frac{46}{\sqrt{E}} \oplus 4.1$</td>
<td></td>
</tr>
</tbody>
</table>
• $\sim 100 \ X_0$ and $\sim 9.5 \ \lambda$