Development of Muon Tomography for the Geometry Validation of the CMS High Granularity Calorimeter

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1/19

Outline



- High Granularity Calorimeter (HGCAL)
- Motivation of Muon Tomography in geometry
- Implementation in CMS software
- Validation of HGCAL Geometry
- Summary and Outlook

London CMS High Granularity Calorimeter (HGCAL)



- Particle flux : LHC aims to operate with an higher particle flux than the designed value (higher statistics but challenging detector design and operation).
- Detector Plan : HGCAL, a sampling calorimeter, is planned to be installed between 2026-28 replacing the current ECal and HCal in the Endcaps region.
- Physics prospects : Vector Boson Fusion, boosted topologies, narrow and merged jets.
- Challenges : High pileup (${\sim}200)$ and high radiation dose (${\sim}2$ MGy) [CMS-TDR-019].
- Parameters :
 - 1.5 < $|\eta|$ < 3.0
 - CEE : 26 layers (R \sim 1.5 m) with hexagonal Si wafers.
 - CEH : 21 layers ($R \lesssim$ 2.5 m) with Si wafers and Scintillator tiles with SiPM.
 - 5 dimensional measurements in (x, y, z, t, E)
- Source : CMS-TDR-019 and https://hgcaldocs.web.cern.ch/



• [source : CERN courier (link)]

HGCAL Detector Layout

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• [source : The CMS High Granularity Calorimeter for the High Luminosity LHC by Moritz Wiehe in VCI 2022 (link)]

HGCAL Detector Layout : Silicon modules





• [source : The CMS High Granularity Calorimeter for the High Luminosity LHC by Moritz Wiehe in VCI 2022 (link)]

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Imperial College London HGCAL Detector Layout : Scintillator + SiPM

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Projected signal-to-noise ratio after 3000fb⁻¹

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Scintillator tiles with SiPM readout used in low radiation regions (η >2.4)

- Require good MIP Signal/Noise after 3000fb⁻¹
- Tile size depends on radial-position (4cm² to 32cm²)
- Signal strength depends on tile and SiPM geometry → smaller tiles at lower radii



• [source : The CMS High Granularity Calorimeter for the High Luminosity LHC by Moritz Wiehe in VCI 2022 (link)]

London Motivation of Muon Tomography in geometry

- Muon Tomography with cosmic muons is a popular tool
 - Scientific research (Detector alignments and other validations)
 - Archaeological explorations (hidden chambers in pyramid)
 - Mineral search (different angle of bending for different soil/rock composition)
 - Security scans (illegal transport of high Z materials)
- Muons interact mostly through ionization with the materials and thus traverse the detector providing a consistent trace which identified by a Landau distribution.
- · Validation of detector geometry requires,
 - energy and hit information,
 - access to every corner of all the detector layers,
 - repetitive studies for debugging,
 - faster processing,
 - low volume files.
- Muon satisfies all above criteria compared to shower producing particles.



Implementation in CMS software



8/19

- To study the response of HGCAL to muons, which are Minimum Ionizing Particles (MIPs) and deposit roughly the same energy for a broad range of energies:
 - 1. Study of energy loss dependence as function of thickness of depletion depth (120 μ m, 200 μ m, 300 μ m).
 - 2. Obtaining the image of each layer using muon hits overlayed with the pattern from sensor layout files.
- 1M events with two muons ($\mu^+ + \mu^-$) at constant p_T (100 GeV/c) towards HGCAL (1.3 < $|\eta|$ < 3.1) in +ve and -ve z directions are simulated.
- The energy loss stored in simhit array for a given cell are added for the in-bunch cell hits.
- The energy loss distribution obtained for the cell with maximum deposited energy in a given layer is used for the present study.



Eloss (keV) Muon energy loss studies have been carried out for two geometry versions, namely v15 and v16.

The energy loss in Si wafers are shown in black color for v15(left) and v16(right).

The energy loss histograms for different depths of sensitive material, 120 μ m, 200 μ m and 300 μ m are shown in red, • green and magenta color, respectively.

- In addition to the expected energy loss peaks as per thickness of the sensitive material, several anomalous peaks (shown with blue arrow) for each of v15 and v16 geometries are noted.
- Number of anomalous peaks for v15 and v16 are not the same.

 Eloss (keV)

Validation : muon energy loss (contd.)





- The energy loss of muons is shown for v15(top) and v16(bottom).
- Surprisingly, we do not find any hits in the partial wafers corresponding to 200 and 300 μ m in case of v16.
- The energy loss peaks \sim 34 keV, \sim 60 keV and \sim 90 keV are observed to be in proportion with different thicknesses (120 μ m, 200 μ m, 300 μ m).
- The anomalous low energy peak with Si wafers of 120 and 200 μ m thickness is ~20 keV and it is close to 2 keV for Si wafers of 300 μ m thickness.



- The GEANT hit distribution in the XY plane for v16(left) is compared with the Technical drawing (right).
- Comparing the Si wafer pattern (with the help of overlay) shows the missing hits in partial wafers in the outer region, namely the 300 μ m partial Si wafers.

Validation : muon energy loss (contd.)

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- The origin of the issues have been found to be a scale down factor applied for the partial wafers in v15 and an incorrect definition of active width of the silicon in v16.
- The GEANT simhit distribution in the xy-plane of layer 1 of HGCAL before(left) and after(right) the fix.

Validation : HGCAL layer rotation





- The layers 28, 30, 32 of the HGCAL are rotated by 30° along the z-axis to reduce the dead area of the detector.
- The GEANT hit distribution in the XY plane for layer 28 (left), shows discrepancy.

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It was observed that the overlay was perfectly matching with the hits if it was rotated by -30° instead of 30° and appropriated correction was made (right).

Validation : HGCAL module rotation





- A module rotation of silicon wafers are applied in v17 for the proper implementation of technical design.
- Missing hits in partial wafers are observed.
- The issue was narrowed down to the bug in the validity check and the orientation of partial wafers.
- After the correction GEANT simhit distribution showed that there was an issue with the orientation of the partial wafers (right).

Imperial College Validation : Hit occupancies in SiPM-on-tile





- · Following a finding by the data quality monitoring (DQM) team of HGCAL, hit occupancies are studied for SiPM-on-tiles.
- Missing hits are observed in the inner rings.

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- The issue was an incorrect scale conversion $mm \rightarrow cm$ in geometry definition. •
- After the correction GEANT simhit distribution showed no issues for SiPM-on-tile modules (right).

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Validation : Unexpected detector hits





- HGCAL DQM has reported a mismatch of the $\eta \phi$ distribution of detector hits in simulation and reconstruction result.
- An high resolution muon tomography study found the origin of discrepancy is due to the unexpected detector hits.
- The unexpected hits are shown in brown and black color points for failed detector IDs.

Validation : Cassette shift





• The GEANT simhit distribution in the xy-plane of HGCAL with 40 cm shift to cassette #1 along x-axis in layer 47.

- The black overlay represents the expected while the blue and pink dots showing the actual displacement.





- We have demonstrated that muon tomography is an useful validation tool for complex detector geometry.
 - Incorrect definition of active thickness.
 - Missing hits in partial wafers.
 - Rotation of layers in opposite direction.
 - Issues with module rotation.
 - Scale conversion for SiPM-on-tile hits.
 - Unexpected detector hits.
 - Wrong cassette shifts.
- The tool is now an integral part of CMS software framework used for validation of geometry.
- In future colliders, where complex detector system is envisaged, muon tomography could play crucial role in geometry debugging.

Thank You

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