Development of Muon Tomography for the validation of the HGCAL simulation geometry of CMS

Pruthvi Suryadevara
(on behalf of CMS Collaboration)

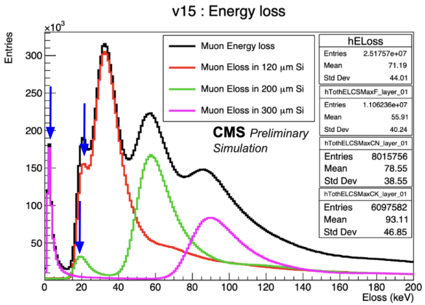
Tata Institute of Fundamental Research, Mumbai

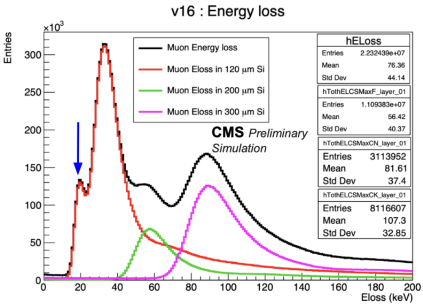
DAE-BRNS High Energy Physics Symposium 2022
December 12^{th} to 16^{th}

Motivation of Muon Tomography

- The default HGCAL simulation workflow (link) uses Close-By-Photon generator.
- 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 μm, 200 μm, 300 μm).
  2. Obtaining the image of each layer using muon hits overalyed 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 if found to arrive the cell between (0-25) ns [in-bunch hits].
- The energy loss distribution obtained for the cell with maximum deposited energy in a given layer is used for the present study.

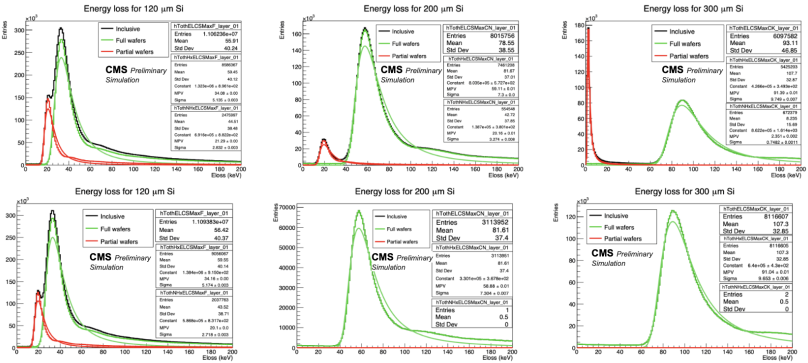
Muon Energy loss





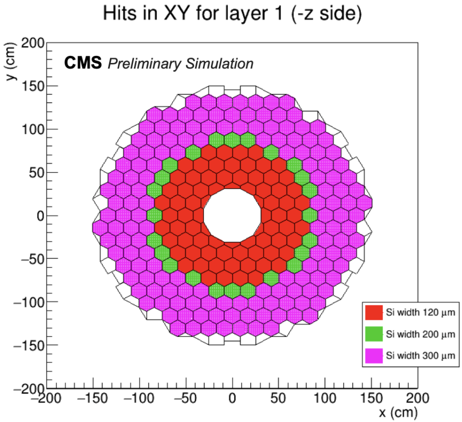
- The energy loss of muons in Si wafers are shown in black color for HGCAL geometry version v15(left) and v16(right).
- The energy loss histograms for different depletion depths, 120 μm, 200 μm and 300 μm are shown in red, green and magenta color, respectively.
- In addition to the expected energy loss peaks as per thickness of the depletion depth, 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.

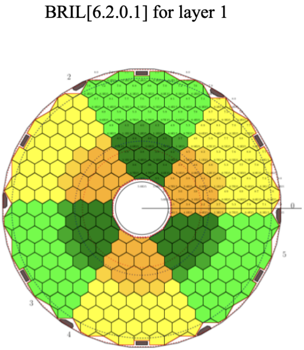
Energy loss for different depletion depths



- 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 μm in case of v16.
- The energy loss peaks ∼34 keV, ∼60 keV and ∼90 keV are observed to be in proportion with different depletion depths (120 μm, 200 μm, 300 μm).
- The anomalous low energy peak with Si wafers of 120 and 200 μm depletion depth is ∼20 keV and it is close to 2 keV for Si wafers of 300 μm depletion depth.

HGCAL geometry v16





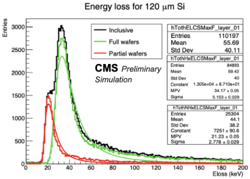
- The GEANT hit distribution in the XY plane for v16(left) is compared with the BRIL[6.2.0.1](right).
- Comparing the Si wafer pattern (with the help of overlay) shows the missing hits in partial wafers in the outer region, namely the 300 μm partial Si wafers.

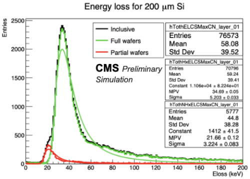
Effect of change of active Si (depleted) depth

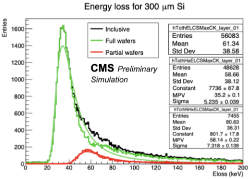
- Three separate simulation sets are produced with 10K events using v15.
  - Active Si (depleted) depth all wafers changed to 120 μm.
  - Active Si (depleted) depth all wafers changed to 200 μm.
  - Active Si (depleted) depth all wafers changed to 300 μm.

Peak position of energy loss distribution (in keV)						
Active Si depth	Full wafers			Partial wafers		
	Fine	CoarseThin	CoarseThick	Fine	CoarseThin	CoarseThick
All wafers 120 μm	34.17 $\pm$ 0.05	34.69 $\pm$ 0.05	35.2 $\pm$ 0.1	21.23 $\pm$ 0.05	21.66 $\pm$ 0.12	58.14 $\pm$ 0.22
All wafers 200 μm	58.16 $\pm$ 0.06	59.24 $\pm$ 0.07	60.14 $\pm$ 0.09	19.87 $\pm$ 0.05	20.09 $\pm$ 0.11	32.49 $\pm$ 0.13
All wafers 300 μm	88.27 $\pm$ 0.08	90.13 $\pm$ 0.09	91.41 $\pm$ 0.11	2.21 $\pm$ 0.01	2.19 $\pm$ 0.02	2.33 $\pm$ 0.02

- The energy loss distributions when the active Si (depleted) depth for of wafers are changed to 120 μm for v15.



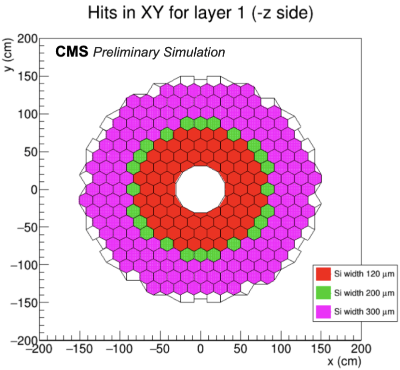


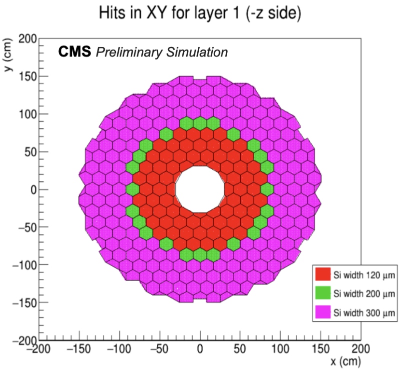


Origin of the issues

- The total width of Si wafer was defined as 310 μm for all wafer types (120 μm, 200 μm, 300 μm) in v15.
- The total width of Si wafer for different wafer types were properly set in v16.
  - 300 μm width for 120 and 300 μm type wafers and 200 μm for 200 μm.
- The GEANT simhits corresponding to the inactive regions are stored for partial wafers.
  - v15 : An additional factor applied for partial wafers to account the energy loss corresponding to the active Si (depleted) depth.
  - v15 : Energy loss corresponding to $\rightarrow$ 190 μm, 110 μm and 10 μm for 120, 200 μm for 300 μm wafer types respectively.
  - v16 : Energy loss corresponding to $\rightarrow$ 180 μm, 0 μm and 0 μm for 120, 200 μm for 300 μm wafer types respectively.

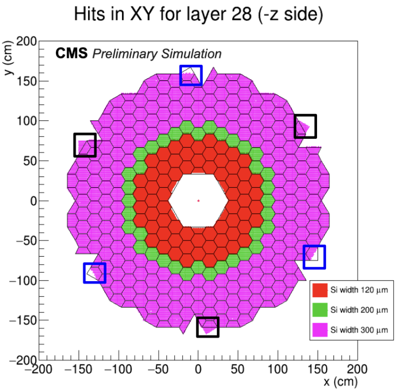
Validation of the solution of the issue (v16)





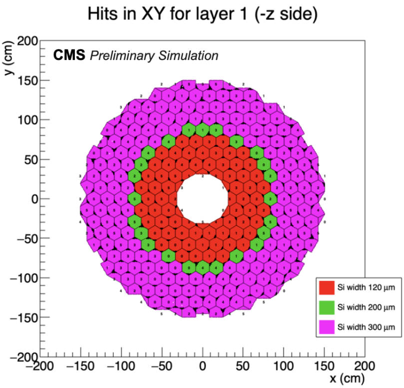
- The GEANT simhit distribution in the xy-plane of layer 1 of HGCAL before(left) and after(right) the fix.

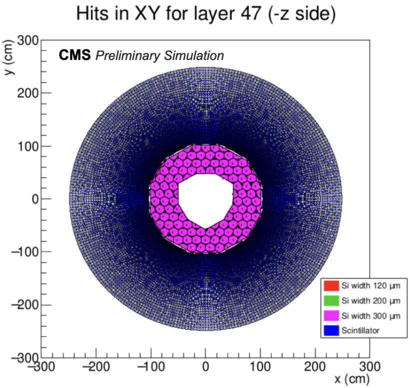
HGCAL rotated layers



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

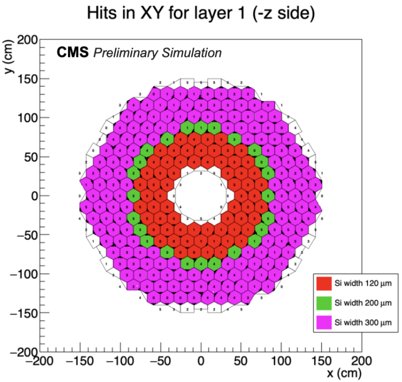
Muon Tomography upgrade for v17





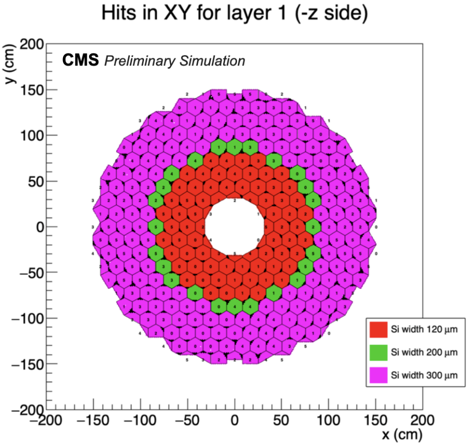
- v17 version of the HGCAL introduced the concept of rotated full wafers and new convention for numbering the cell within them.
- The overlay was upgraded to represent the orientation and with black mark pointing towards the channel #1 of the Si wafers and an index at the center to indicate the orientation from sensor layout file (left).
- Muon Tomography tool was also upgraded to include the scintillator regions (right).
- v17 version of the HGCAL also introduced the feature to shift cassettes and the overlay is upgraded to reflect the same (shown in later slides).

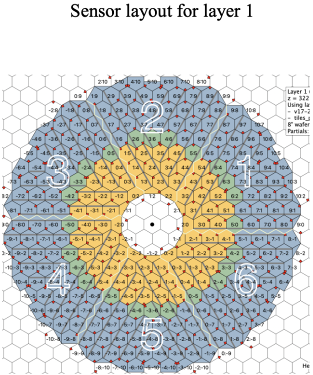
HGCAL geometry v17



- With the help of GEANT simhit distribution, the issue of missing hits in partial wafers was found in v17 (left).
- The issue was narrowed down to the bug in the validity check of partial wafers.
- After the correction GEANT simhit distribution showed that there was an issue with the orientation of the partial wafers (right).

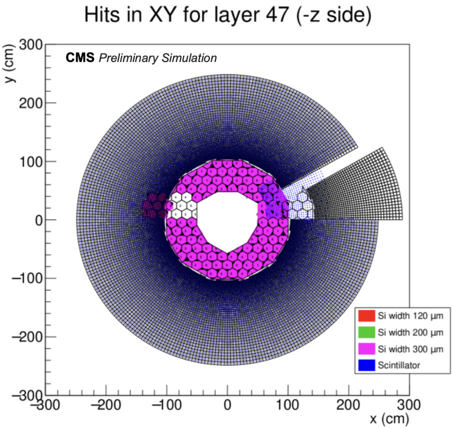
Validation of the solution of the issue (v17)





- The GEANT simhit distribution in the xy-plane of HGCAL after the fix (left) compared with the sensor layout (right) for layer 1.

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.

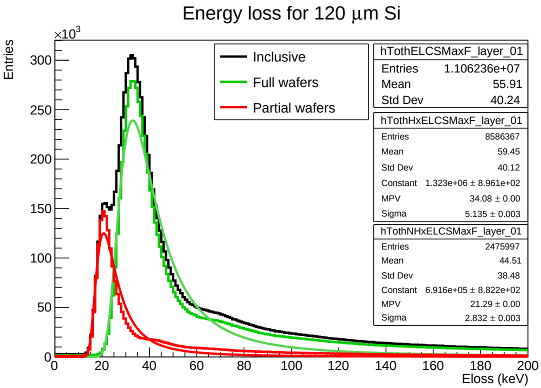
Summary

- The Muon Tomography has successfully been able to pin-point the problems in v15 and v16 detector geometries.
  - Abnormal energy loss distributions for Muons (v15 and v16)
  - Missing hits in partial wafers (v16).
  - Rotation of layers 28, 30, 32 (v16).
- It has been an integral tool for the development and validation of the v17 version of the geometry (Refer to poster 'Geometrical description of HGCAL in CMS software framework').
  - Missing hits in partial wafer.
  - Wrong cassette shifts.
- Further with the inclusion of detid validity check, it has been used to spot the origin of the Sim-vs-Reco problems observed during DQM study.
- The tool is now an integral part of CMS software framework used for validation of geometry.
- Indranil Das was awarded a CMS 2021 award for 'implementing a new concept of muon tomography for HGCAL GEANT geometry simulation and validation'.

Thank You

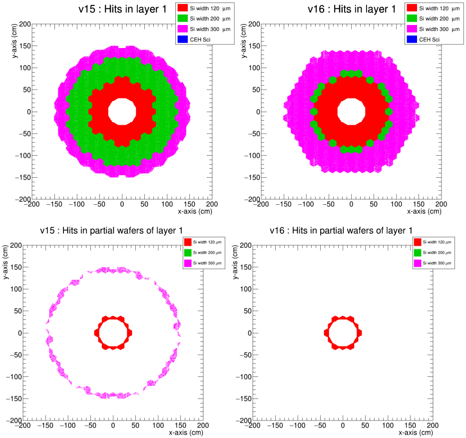
Backup

Energy loss for Fine Wafers (120 μm depletion)



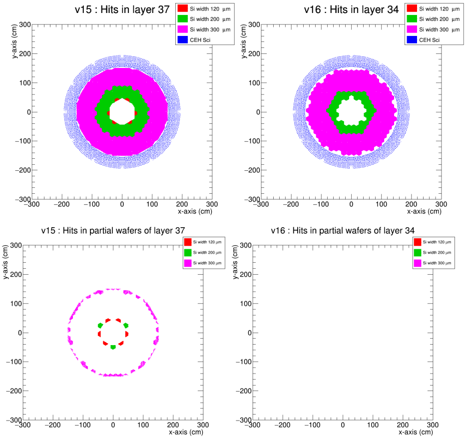
- Energy loss distribution for full wafer is normal without any anomalous peak.
- However, there is NO normal energy loss distribution for partial wafers. The observed energy loss distribution is completely anomalous.
- The energy loss distributions for full as well as partial wafers are observed to follow the Landau distribution.

SimHit distribution for layer 1



- The GEANT simhit distributions in the XY plane are shown for layer 1 of v15(left) and v16(right).
- The GEANT simhit distributions for all wafers(top) and exclusively partial wafers(bottom) are shown for layer 1.
- The partial wafers are missing in the outermost circles of Si wafers in v16 geometry.

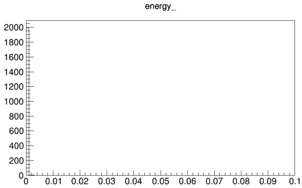
SimHit distribution in CEH for matching layer of v15 and v16

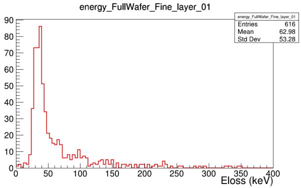


- The partial wafers are missing in innermost and outermost area of v16 geometry.

DQM plots corresponding to Muon Tomography

- The HGCAL DPG conveners encouraged us to propagate the Muon Tomography plots in CMSSW DQM file.
- The main histograms of Muon Tomography is now in CMSSW since PR #36484.





- The energy loss distribution for HGCAL layer 1 and Si wafer of 120 μm for HGCAL layer 1 are shown in the left and right side plots.
- In total six 1D energy loss histograms and six 2D xy simhit distributions are stored for each Silicon layer of HGCAL in the DQM file.
- In addition, one 2D xy simhit distributions are stored for each Scintillator layers of HGCAL DQM in the DQM file.