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

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HEP Seminar

October 11, 2023

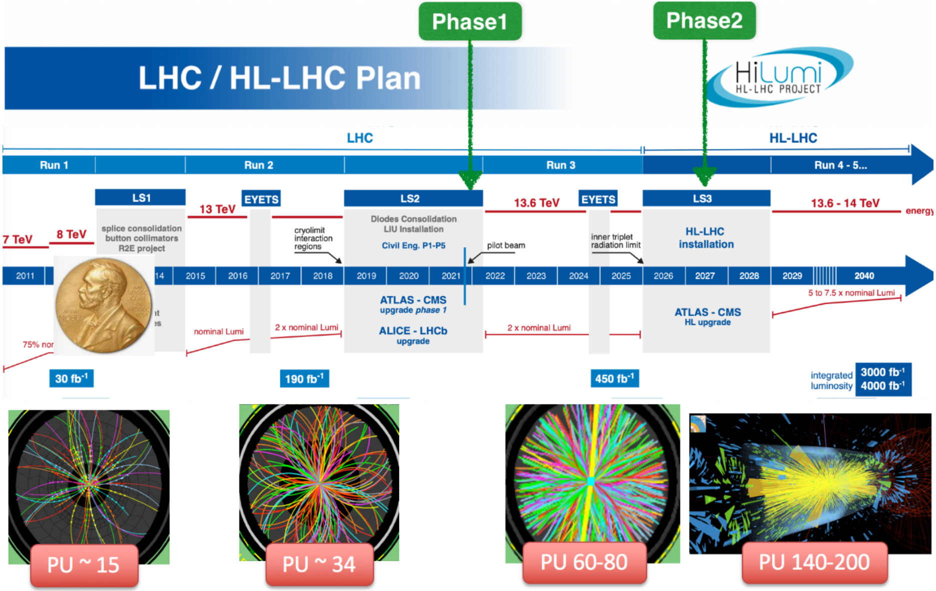
Outline

- Physics motivation
- HL-LHC Challenges
- CMS HL Phase-II updates
- HGCal Layout
  - Silicon sensors
  - Scintillator with SiPM
- Fireworks : CMS in 2029
- Motivation of Muon Tomography in geometry
- Implementation in CMS software
- Validation of HGCAL Geometry
- Status, summary and outlook

Physics Motivation : Collecting a larger statistics

- Precision study of known SM processes
  - top quark property measurements
  - second generation Higgs couplings
- Study of reactions initiated by VBF processes
- Narrow boosted jets from τ
- Merged jets from hadronic decays of W, Z

Challenges of HL-LHC



CMS during HL-LHC

Technical proposal CERN-LHCC-2015-010 https://cds.cern.ch/record/2020886
Scope Document CERN-LHCC-2015-019 https://cds.cern.ch/record/2055167/files/LHCC-G-165.pdf

Complete replacement**

L1-Trigger/HLT/DAQ**
https://cds.cern.ch/record/2283192
https://cds.cern.ch/record/2283193

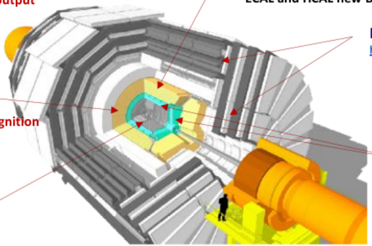
- Tracks in L1-Trigger at 40 MHz
- PFlow-like selection 750 kHz output
- HLT output 7.5 kHz

Calorimeter Endcap**
https://cds.cern.ch/record/2293646

- 3D showers imaging for pattern recognition
- Precision timing for PU mitigation
- Si, Scint+SiPM in Pb/W-SS

Tracker**
https://cds.cern.ch/record/2272264

- P_T module design for tracking in L1-Trigger
- Extended coverage to $\eta \simeq 3.8$
- Much reduced material budget
- Si-Strip and Pixels increased granularity



Major Electronics Upgrade/ Consolidation *

Barrel Calorimeters*
https://cds.cern.ch/record/2283187

- ECAL crystal granularity readout at 40 MHz
- Precision timing for e/γ at 30 GeV, for vertex localization ($H \rightarrow \gamma\gamma$)
- ECAL and HCAL new Back-End boards

Muon systems* ***
https://cds.cern.ch/record/2283189

- Extended GEM coverage to $\eta \simeq 3$
- DT & CSC new FE/BE readout
- RPC back-end electronics
- New GEM/RPC $1.6 < \eta < 2.4$

New Detector System***

MIP Timing Detector***
https://cds.cern.ch/record/2296612

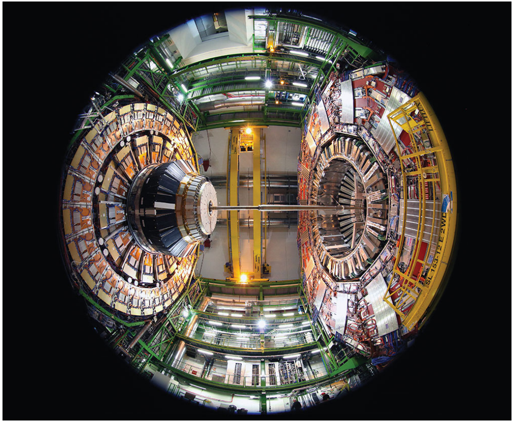
- Precision timing for PU mitigation
- Barrel layer: Crystals + SiPMs
- Endcap layer: Low Gain Avalanche Diodes

Beam Radiation Instr. and Luminosity
Common Systems and Infrastructure
https://cds.cern.ch/record/2020886

New paradigms for a HEP experiment to meet the unprecedented challenges and fully exploit the HL-LHC luminosity and physics potential

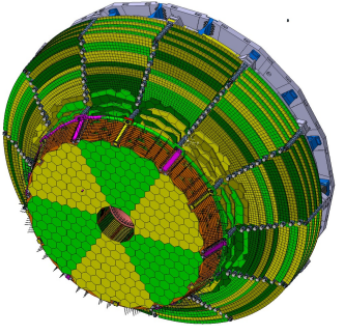
CMS High Granularity Calorimeter (HGCAL)

- 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/



HGCAL Detector Layout

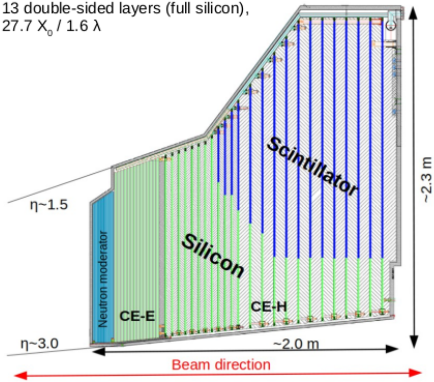
Calorimeter endcaps:
- Coverage 1.5< | η | <3.0
- radiation tolerant
- high granularity
- precise hit/cluster timing
- Enhanced capability for particle flow reconstruction
- Operation at -30°C



Philippe Bloch, On-detector integration, 2022

CE-E (Electro-magnetic)
Active: Silicon
Passive: Cu, CuW, Pb absorbers
13 double-sided layers (full silicon),
27.7 X_0 / 1.6 λ

CE-H (Hadronic)
Active: Silicon + Scintillator / Silicon-photomultiplier
Passive: Steel absorbers
7 all-Si layers
21 layers, 9.4 λ (total)



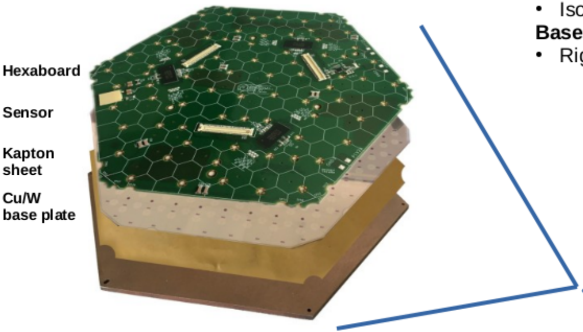
Values for both endcaps:

Silicon
- 620m² of silicon
- 6M channels
- 30k modules
- 0.5 – 1.1cm² per cell

Scintillator + SiPM
- 400m² of scintillator
- 240k tiles + SiPM
- 4000 boards
- 4 - 30cm² per tile

HGCAL design inspired by CALICE studies, e.g. C Adloff et al 2013 JINST 8 P09001

HGCAL Detector Layout : Silicon modules

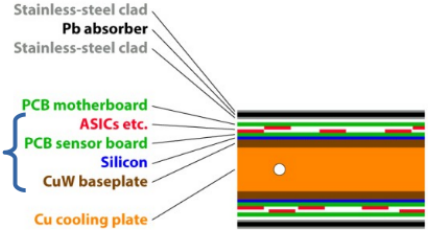


Sensor-PCB (‘Hexaboard’)
- Read-out (HGCROC) of sensor cells + bias supply
- Connects to motherboard for data transfer

Silicon sensor

Kapton sheet
- Isolation to baseplate + bias supply to sensor back side

Baseplate
- Rigidity, contributes to absorber material

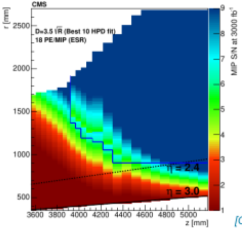


HGCAL Detector Layout : Scintillator + SiPM

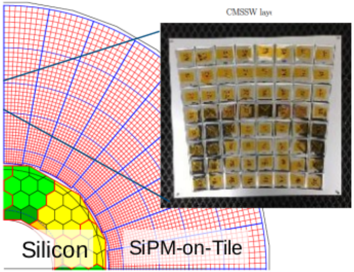
Scintillator tiles with SiPM readout used in low radiation regions (η>2.4)

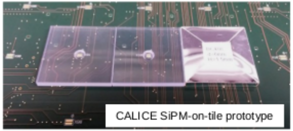
- Require good MIP Signal/Noise after $3000 fb^{-1}$
- Tile size depends on radial-position ($4 cm^2$ to $32 cm^2$)
- Signal strength depends on tile and SiPM geometry → smaller tiles at lower radii

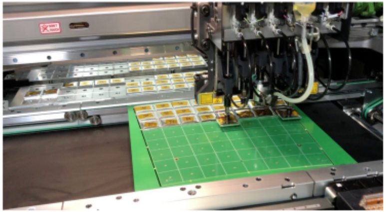
Projected signal-to-noise ratio after $3000 fb^{-1}$

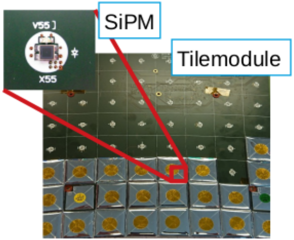


[CMS HGCAL TDR]

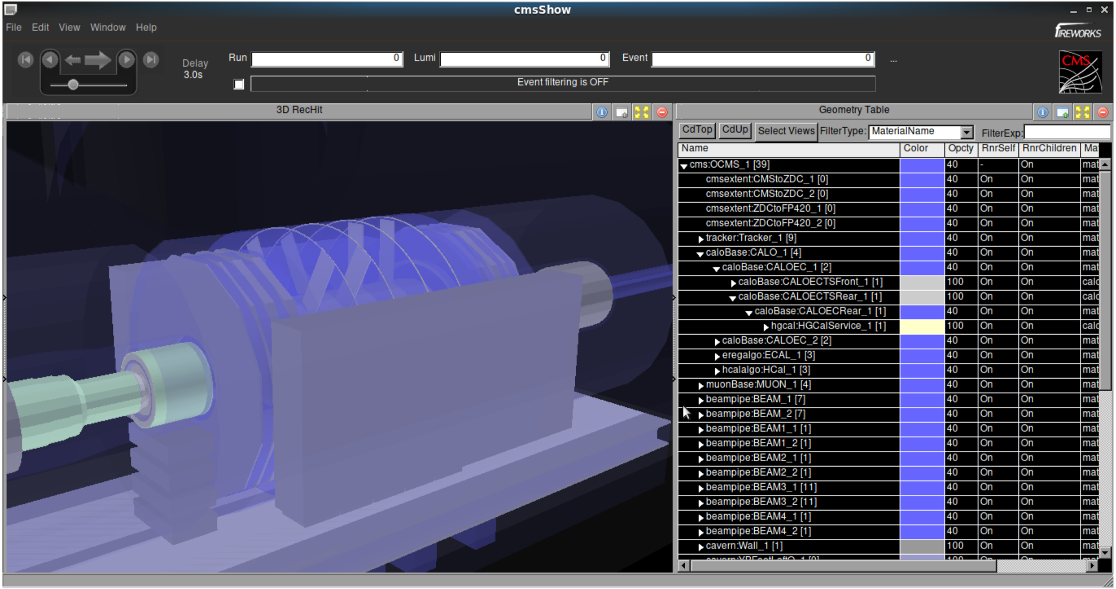




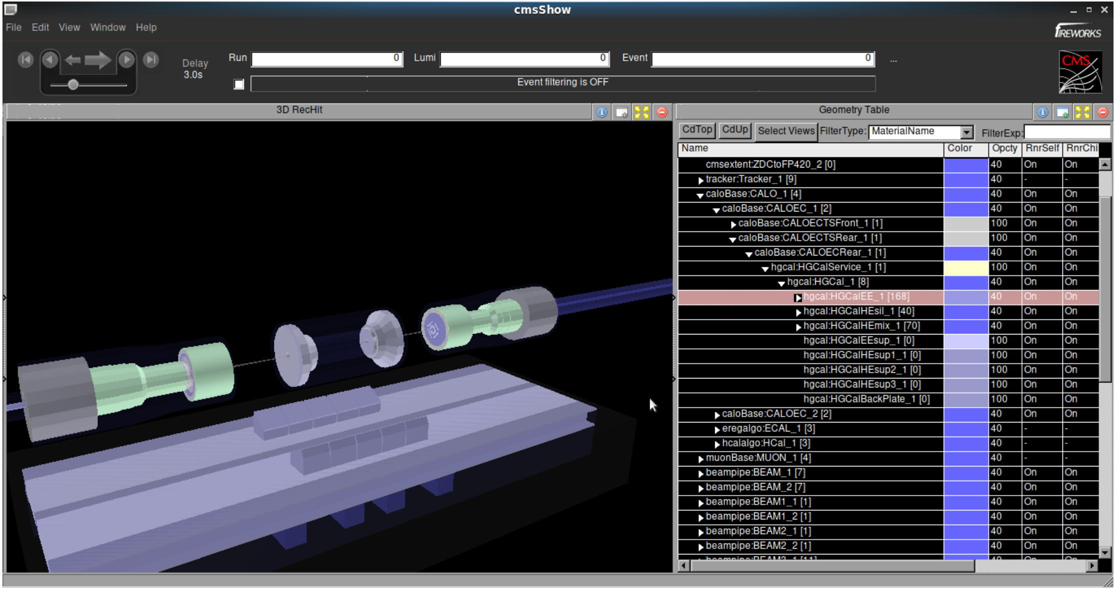




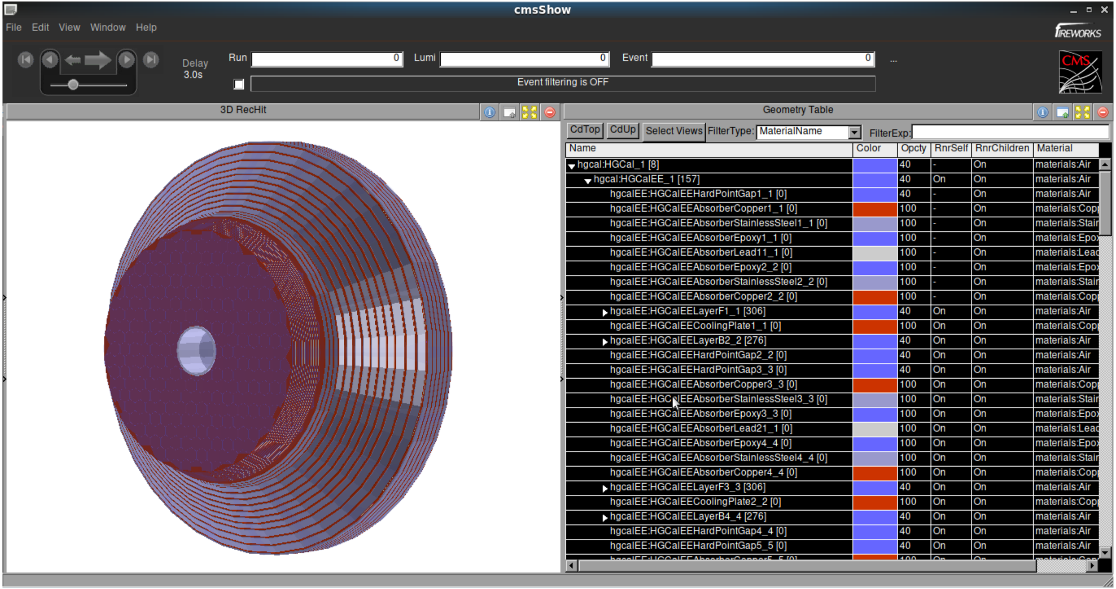
How will CMS look in 2029 ?



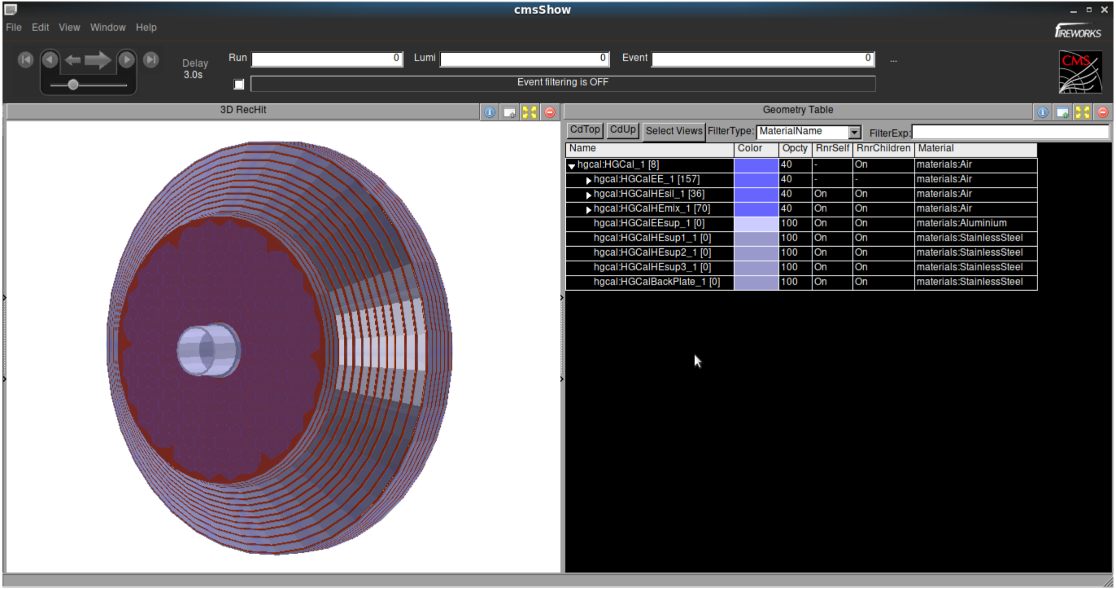
Visualization of HGCAL



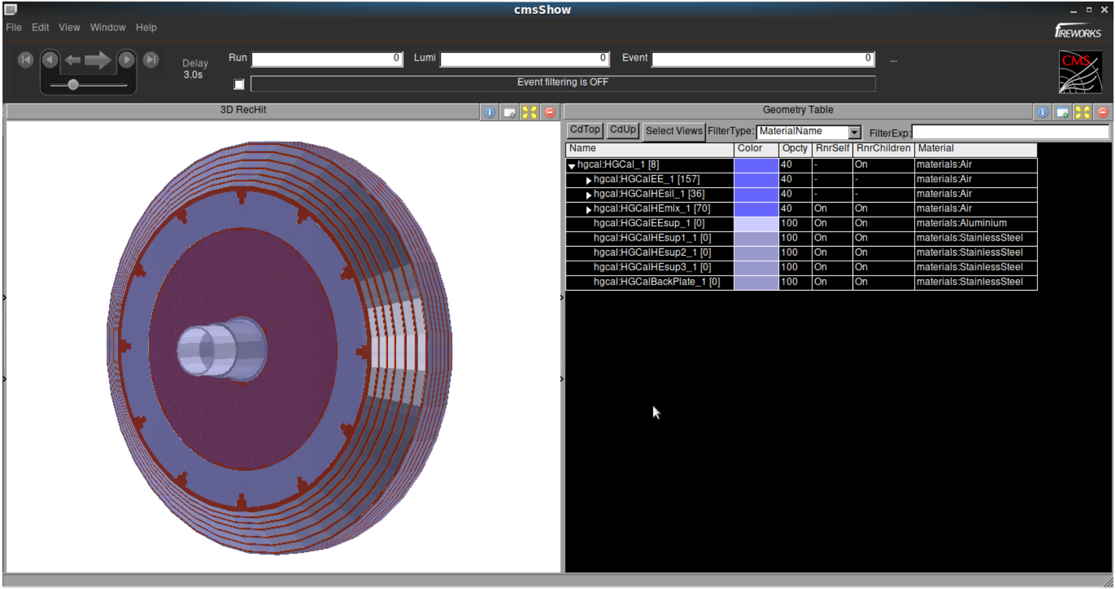
The first layer of HGCAL CEE



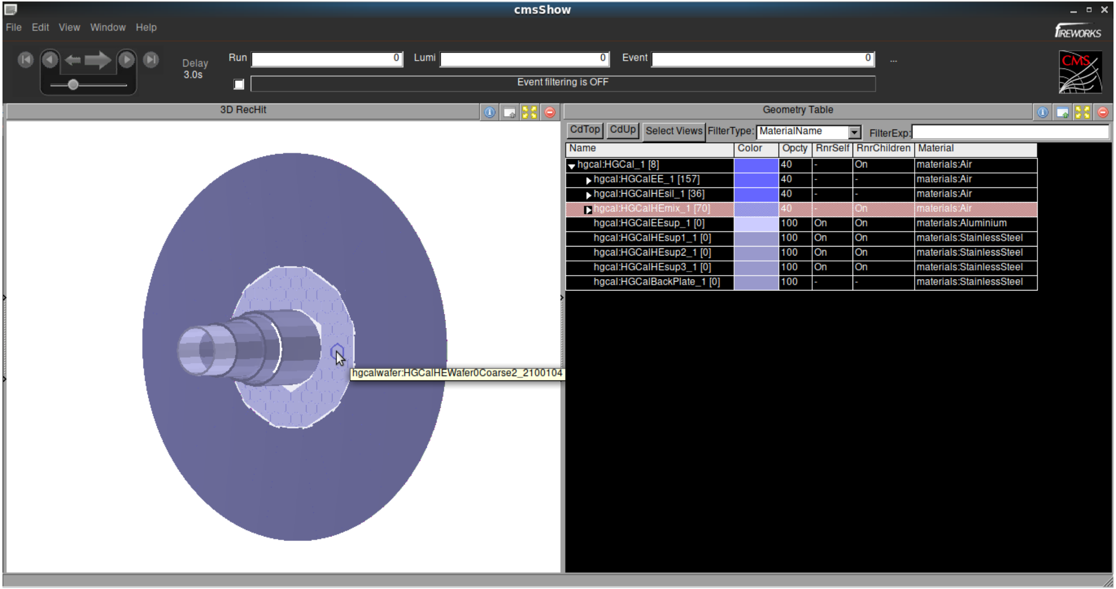
The first layer of HGCAL CEH Front



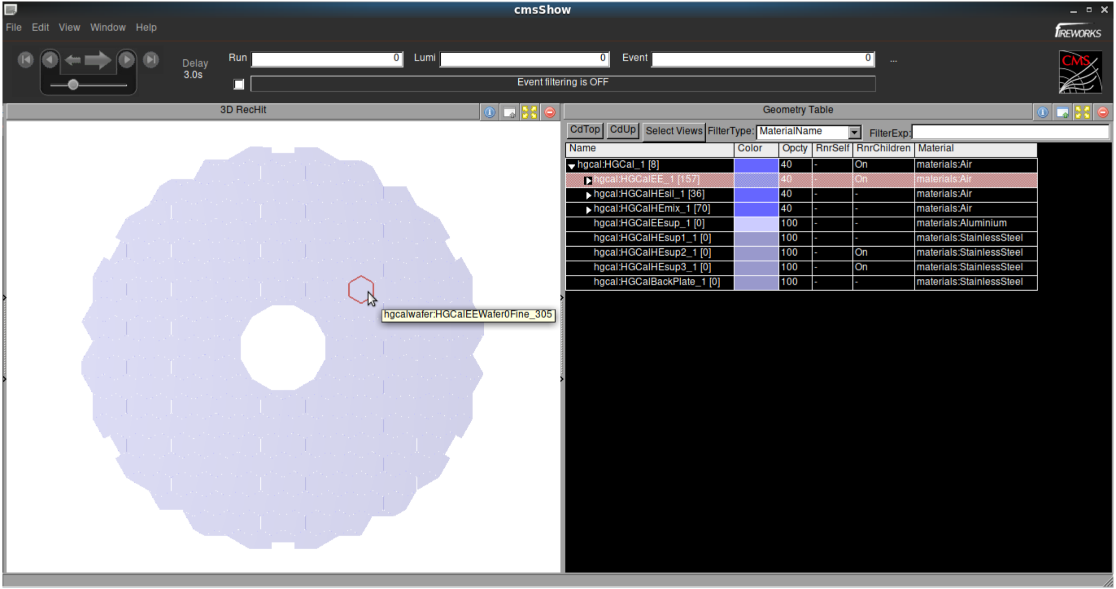
The first layer of HGCAL CEH Back



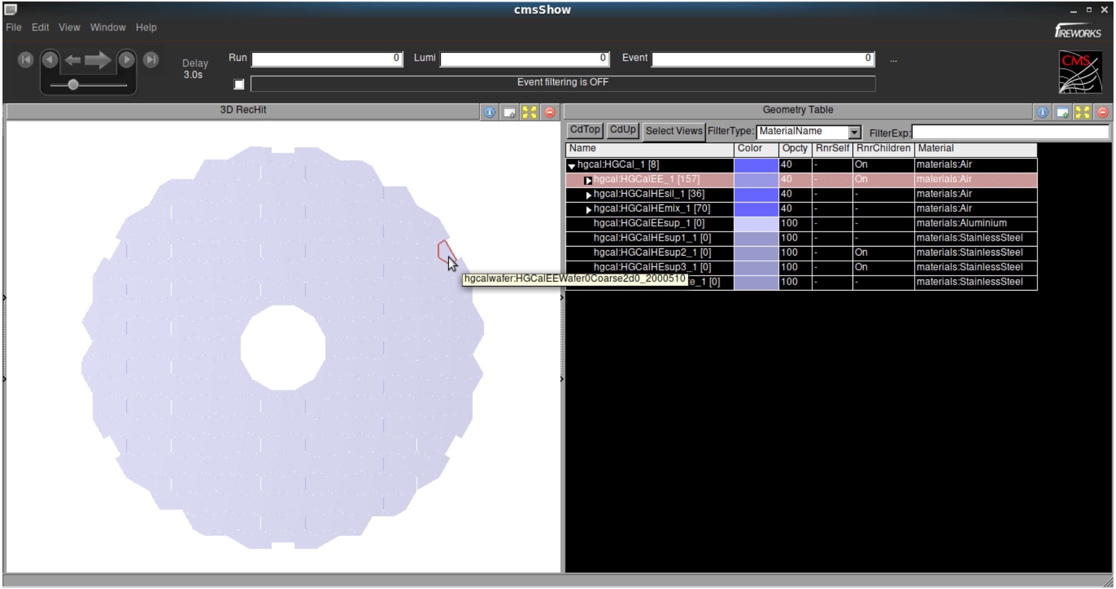
The last layer of HGCAL



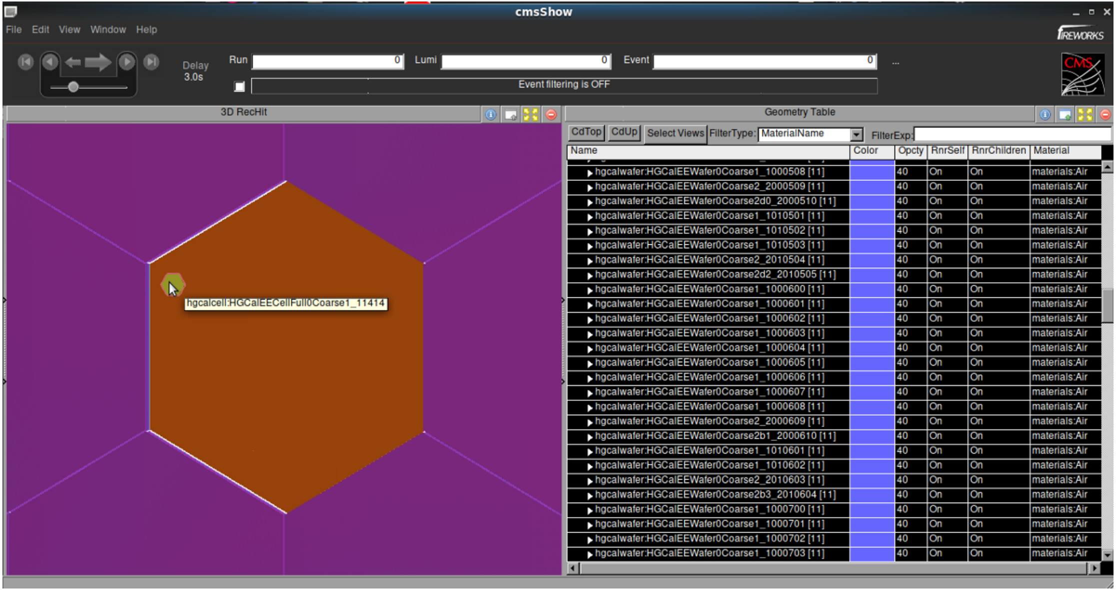
Visualization of Si full wafer



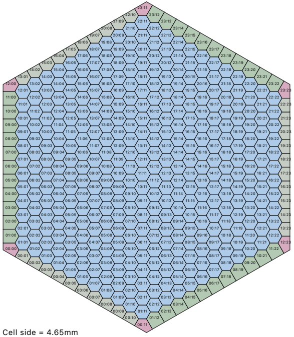
Visualization of Si partial wafer



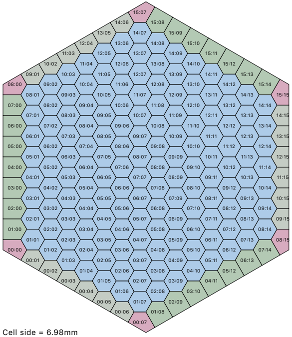
Visualization of Si cell inside full wafer



HGCal : The cells in wafers



Cell side = 4.65mm
Cell flat-to-flat = 8.06mm



Cell side = 6.98mm
Cell flat-to-flat = 12.08mm

- The Fine type (high density) wafer is shown at the left hand size [source : (link)].
  - The flat-to-flat cell size is 8.06 mm and contains 432 cells.
  - The depletion width of the cells for Fine type wafer is 120 μm.
- The Coarse type (low density) wafer is shown at the right hand side.
  - The flat-to-flat cell size is 12.08 mm and contains 192 cells.
  - The depletion widths of the cells for Coarse type wafer can be 200 μm (CoarseThin) and 300 μm (CoarseThick).

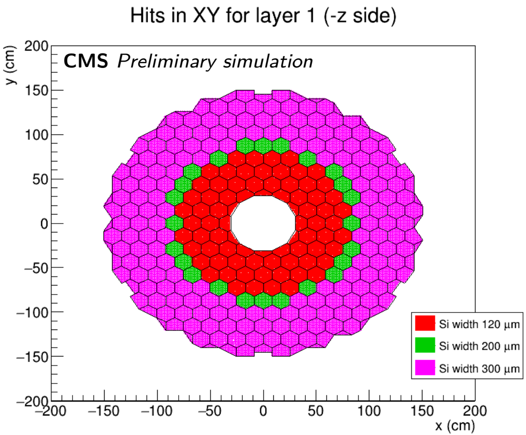
Motivation of Muon Tomography in geometry

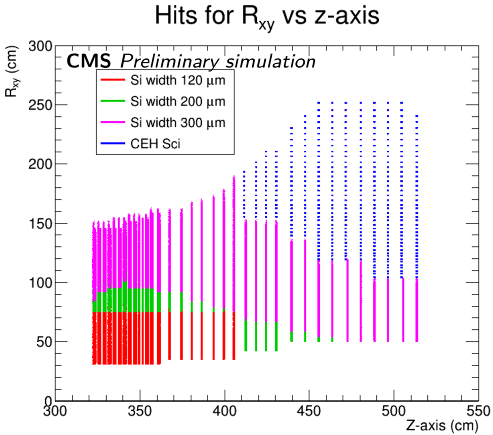
- Muon Tomography with cosmic muons is a popular tool
  - Scientific research (Detector alignments and other validations)
  - Archaeological explorations (hidden chambers in pyramid)
  - Mineral search (different angle of bending for different soil/rock composition)
  - Security scans (illegal transport 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

- 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 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.

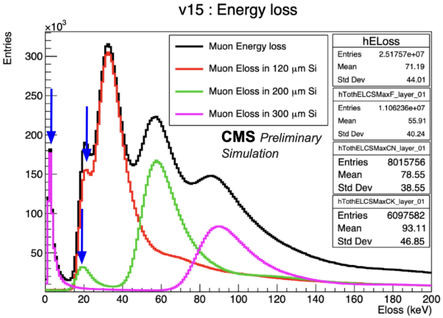
Muon Tomography

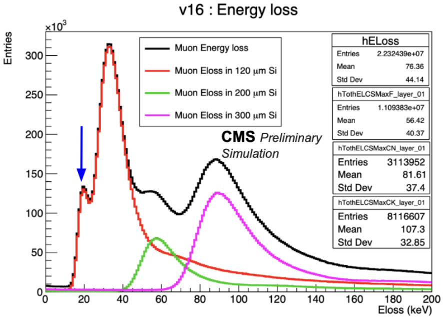




- Left: the front of HGCal layer1, Right: the side view of HGCal layers.
- The muon hit distributions showing different types active elements.
  - The Si wafers with depletion width of 120 μm, 200 μm, 300 μm are shown in red, green and magenta, respectively.
  - The Scintillator tiles are shown in blue.

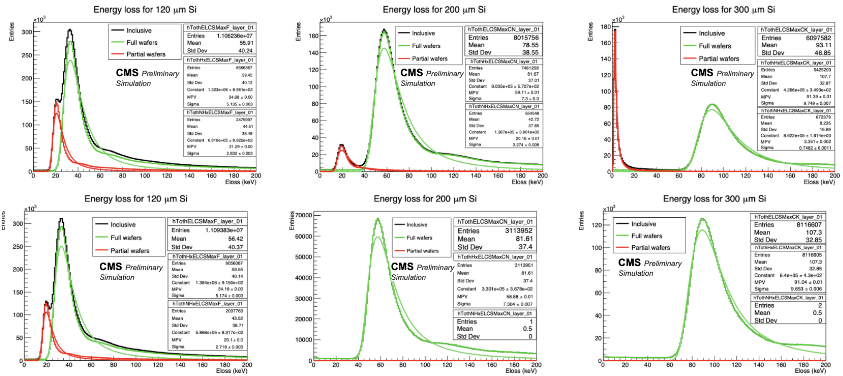
Validation : A case study of muon energy loss





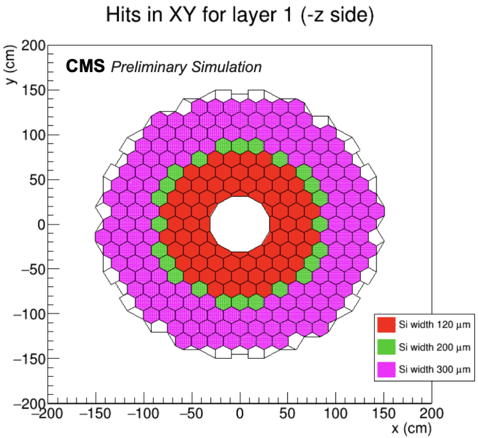
- Muon energy loss studies have been carried out for two geometry versions, namely v15 and v16.
- The energy loss in Si wafers are shown in black color for v15(left) and v16(right).
- The energy loss histograms for different depths of sensitive material, 120 μm, 200 μm and 300 μm are shown in red, green and magenta color, respectively.
- In addition to the expected energy loss peaks as per thickness of the 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.

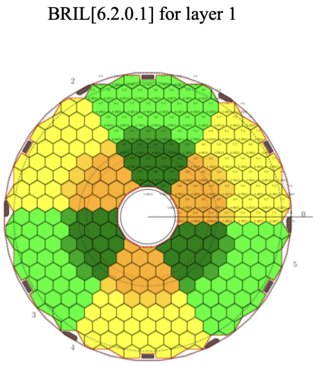
Validation : muon energy loss (contd.)



- 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 μm 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 μm, 200 μm, 300 μm).
- The anomalous low energy peak with Si wafers of 120 and 200 μm thickness is $\sim$20 keV and it is close to 2 keV for Si wafers of 300 μm thickness.

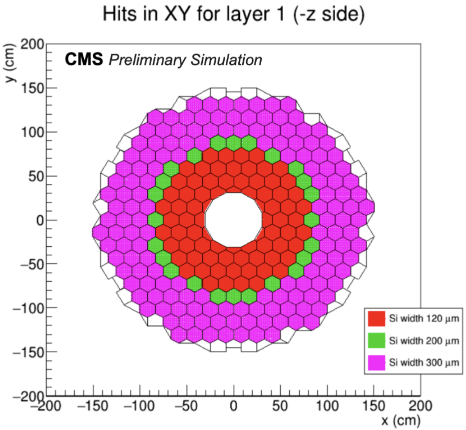
Validation : muon energy loss (contd.)

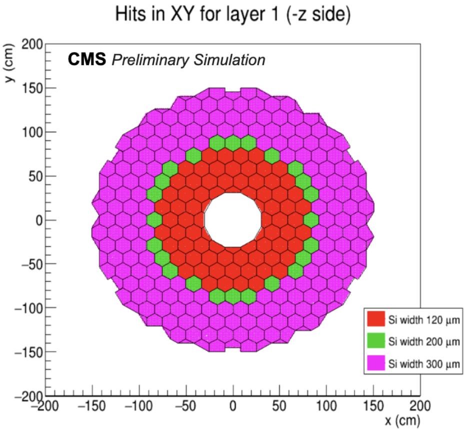




- The GEANT hit distribution in the XY plane for v16(left) is compared with the Technical drawing (right).
- Comparing the Si wafer pattern (with the help of overlay) shows the missing hits in partial wafers in the outer region, namely the 300 μm partial Si wafers.

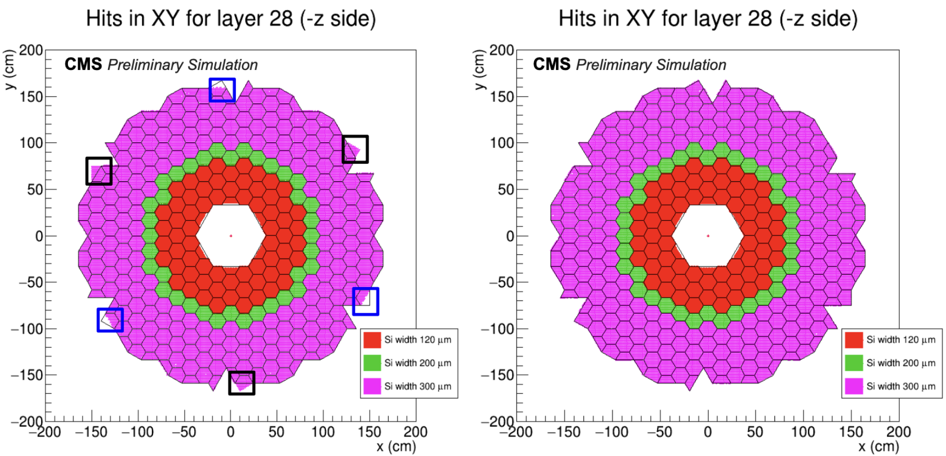
Validation : muon energy loss (contd.)





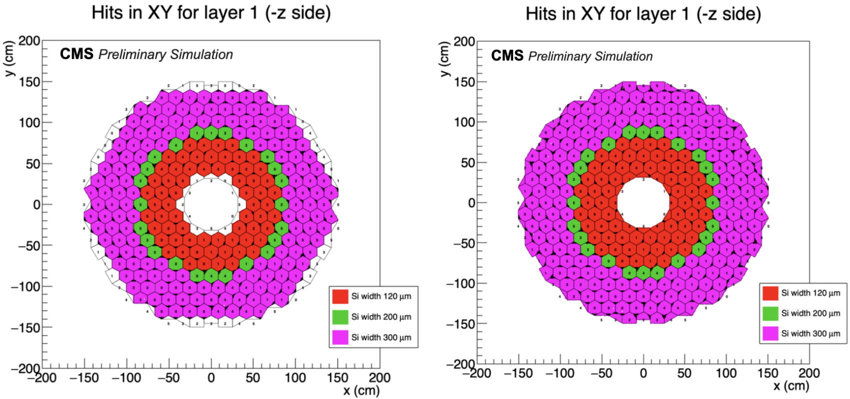
- The origin of the issues have been found to be a scale down factor applied for the partial wafers in v15 and an incorrect definition of active width of the silicon in v16.
- The GEANT simhit distribution in the xy-plane of layer 1 of HGCAL before(left) and after(right) the fix.

Validation : HGCAL layer rotation



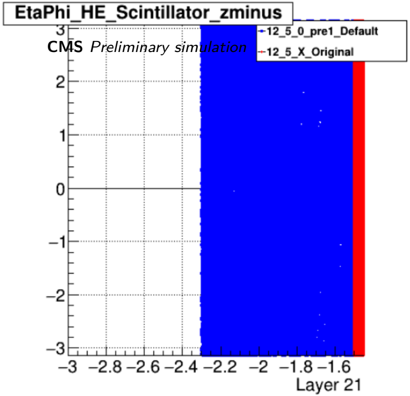
- The layers 28, 30, 32 of the HGCAL are rotated by 30° along the z-axis to reduce the dead area of the detector.
- The GEANT hit distribution in the XY plane for layer 28 (left), shows discrepancy.
- It was observed that the overlay was perfectly matching with the hits if it was rotated by -30° instead of 30° and appropriated correction was made (right).

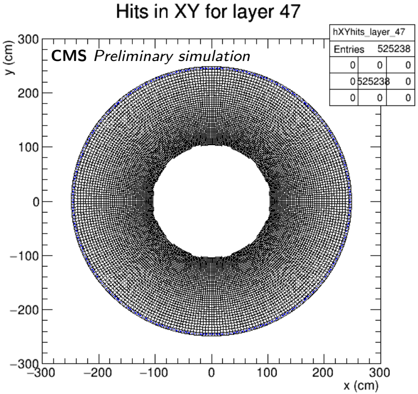
Validation : HGCAL module rotation



- 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).

Validation : Hit occupancies in SiPM-on-tile

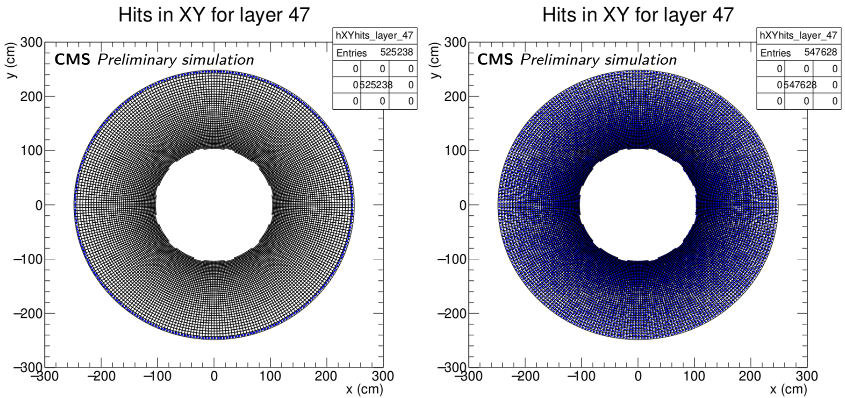




Left : The $\eta - \phi$ distribution of hits for layer 47 (26+21) as obtained via DQM(from You-Ying).

Right : The hit distribution of layer number 47 shows the hits are only present in the outermost ring as obtained via Muon Tomography.

Validation : Hit occupancies in SiPM-on-tile

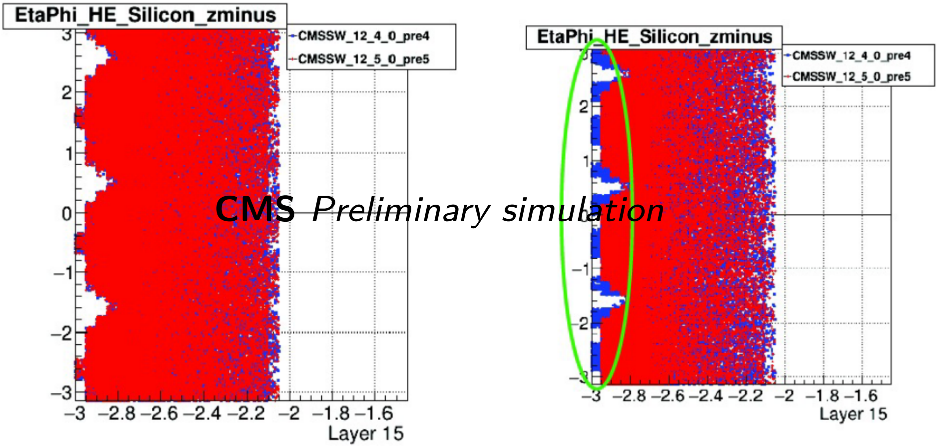


- Following a finding by the data quality monitoring (DQM) team of HGCAL, hit occupancies are studied for SiPM-on-tiles.
- Missing hits are observed in the inner rings.
- The issue was an incorrect scale conversion mm→cm in geometry definition.
- After the correction GEANT simhit distribution showed no issues for SiPM-on-tile modules (right).

DQM spotted an issue (You-Ying) geometry:v16

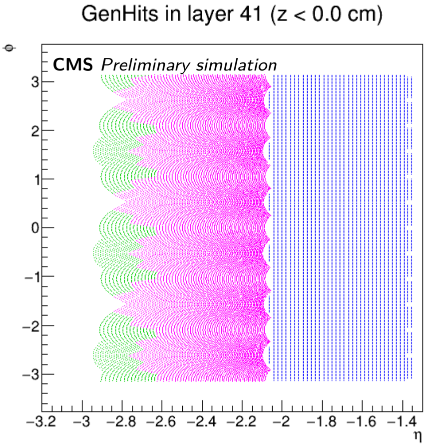
- You-Ying has reported missing silicon hits in the recent version of CMSSW

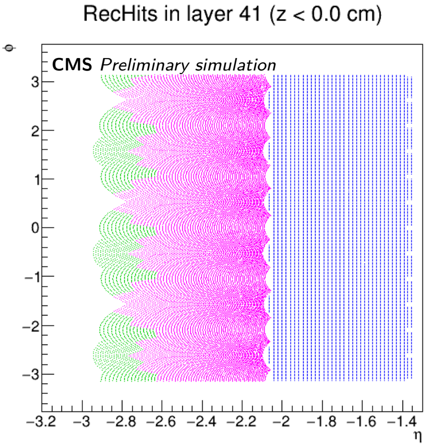
SimHits | RecoHits



- While there is little difference in the SimHit pattern, the RecHit distribution shows missing hits at the highest |η| region

The $\eta - \phi$ plots for v16

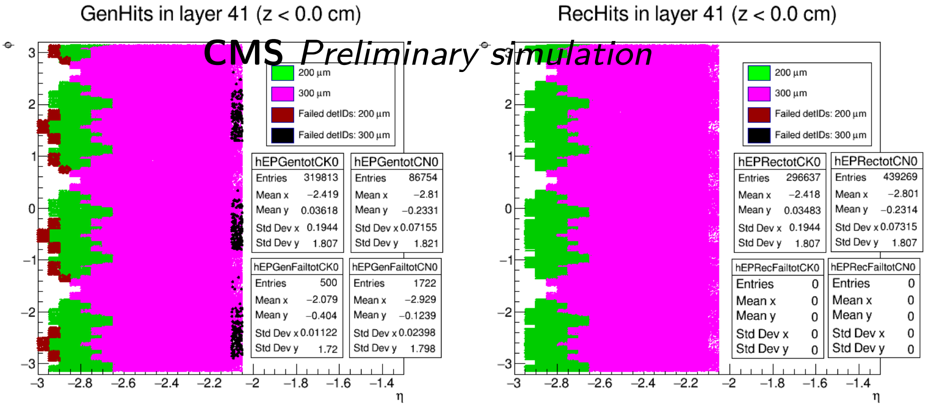




Left : particle-level hits, Right : reconstructed hits.
Layer 41 = 26(EM) + 15(Had)

red: Si 120 μm, green : Si 200 μm, magenta : Si 300 μm, blue : Sci.

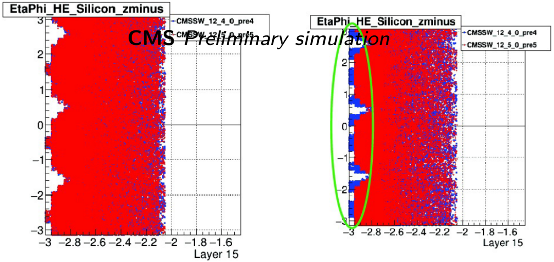
The $\eta - \phi$ plots for v16 (valid+invalid detIds)

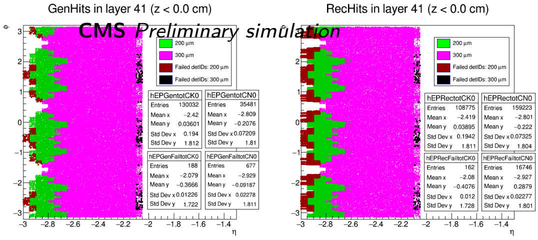


Left : particle-level hits, Right : reconstructed hits.

Swtich off : [!(HGCalGeometry::topology().valid(detId))] + low resolution

The $\eta - \phi$ plots for v16 (CMSSW_12_4_0_pre4)

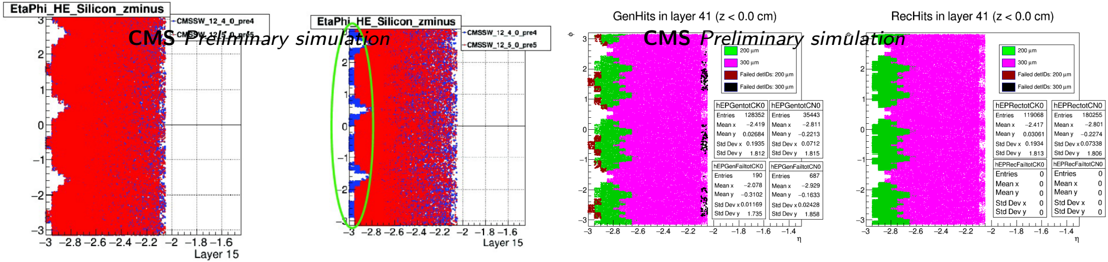




Left pair : DQM plot, Right pair : Muon Tomography.

Muon Tomography is able to reproduce the DQM plot and spot the issue.

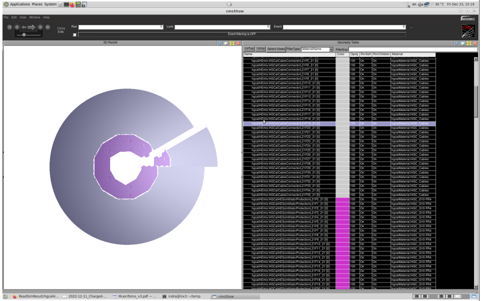
The $\eta - \phi$ plots for v16 (CMSSW_12_5_0_pre5)

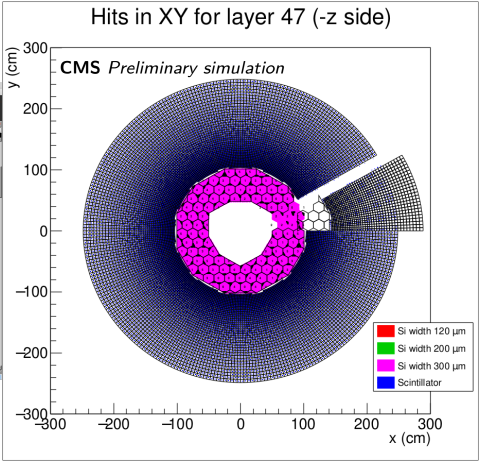


Left pair : DQM plot, Right pair : Muon Tomography.

Muon Tomography is able to reproduce the DQM plot and spot the issue.

Fireworks vs Muon Tomography





A 40 cm shift of cassette 1 of Layer 47.
Left : Fireworks display Left : Muon Tomography

Fireworks shows shift is correct, however the detectors hits are not shifted accordingly.

Summary

- 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.
- In future colliders, where complex detector system is envisaged, muon tomography could play crucial role in geometry debugging.
- To run : https://hgcal.web.cern.ch/Geometry/geometry_validation/.
- The applications are documented in a CMS detector note DN-23-003.
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Thank you