# High Granularity Calorimeter : GEANT4 Geometry


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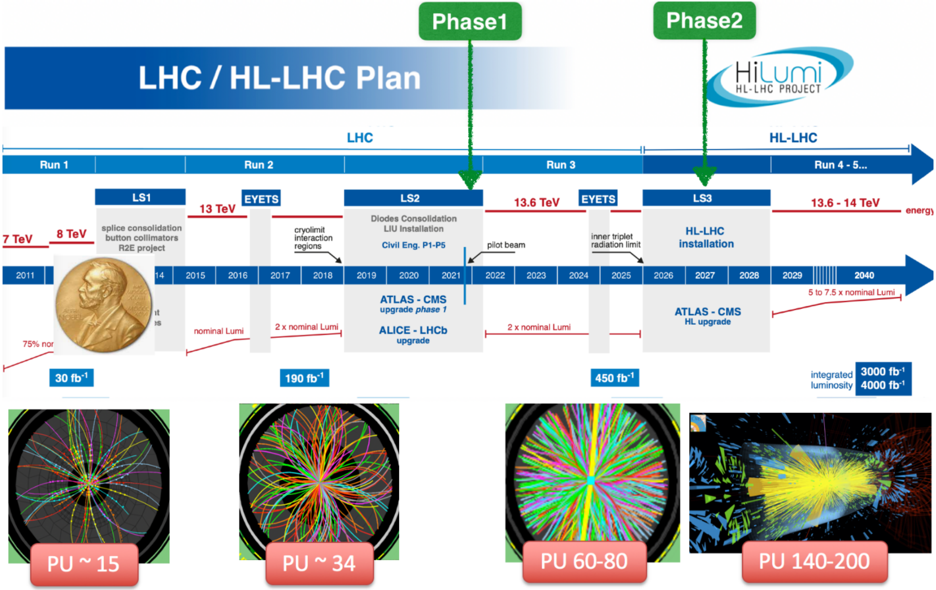
# Outline

- Physics motivation
- HL-LHC Challenges
- CMS HL Phase-II updates
- HGCal Layout
  - Silicon sensors
  - Scintillator with SiPM
- Fireworks : CMS in 2028
- Shower development in Calorimeter
- HGCal GEANT4 studies
- HGCal validation : Muon Tomography
- Introduction to HGCal tutorial
- 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 $\tau$
- Merged jets from hadronic decays of $W, Z$

# Challenges of HL-LHC




- [source : Status and Overview of the CMS HGCal, by Zoltan Gecse in CALOR 2022 (link) ]

# CMS during HL-LHC

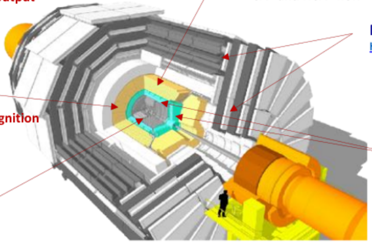
Technical proposal CERN-LHCC-2015-010 https://cds.cern.ch/record/2020886
Scope Document CERN-LHCC-2015-019 https://cds.cern.ch/record/2055167/files/LHCC-G-165.pdf

**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 $1.6 < \eta < 2.4$

**MIP Timing Detector*****
https://cds.cern.ch/record/2296612
- Precision timing for PU mitigation
- Barrel layer: Crystals + SiPMs
- Endcap layer: Low Gain Avalanche Diodes

**New Detector System*****

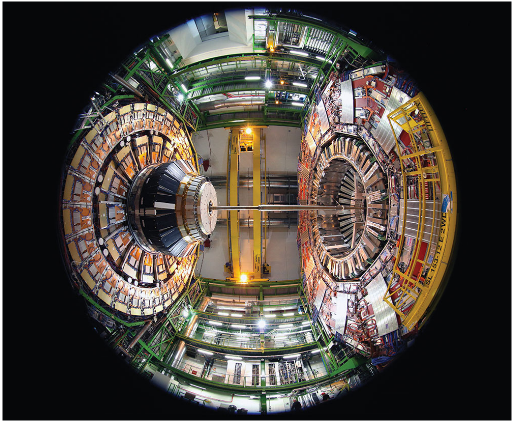
Beam Radiation Instr. and Luminosity
Common Systems and Infrastructure
https://cds.cern.ch/record/2020886

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

- [source : CMS HL-LHC Upgrade: Selected Highlights, by Marcello Mannelli in LHCP 2020 (link) ]

# CMS High Granularity Calorimeter (HGCal)

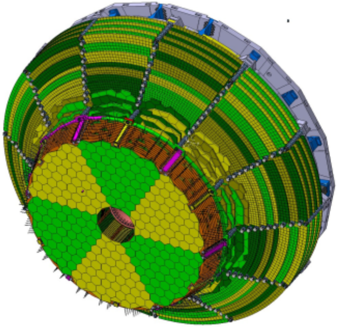
- Luminosity : LHC aims to operate at 5 times the nominal luminosity during HL-LHC.
- Detector Plan : HGCal, a sampling calorimeter, is planned to be installed between 2026-28 replacing the current ECal and HCal in the Endcaps region.
- Physics prospects : Vector Boson Fusion, boosted topologies, narrow 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

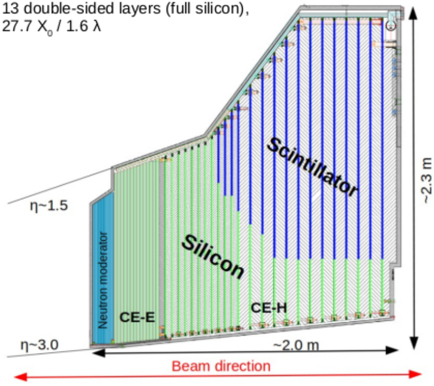
**Calorimeter endcaps:**
- Coverage 1.5< | η | <3.0
- radiation tolerant
- high granularity
- precise hit/cluster timing
- Enhanced capability for particle flow reconstruction
- Operation at -30°C



*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*

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

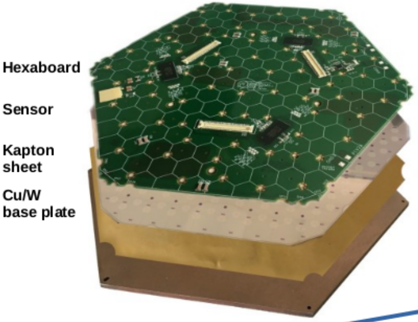
# HGCal Detector Layout : Silicon modules

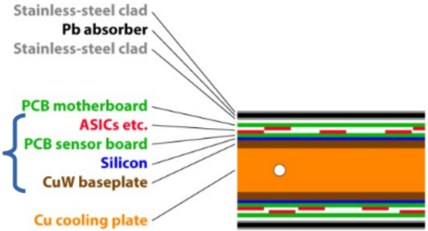

**Sensor-PCB ('Hexaboard')**
- Read-out (HGCROC) of sensor cells + bias supply
- Connects to motherboard for data transfer

**Silicon sensor**

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

**Baseplate**
- Rigidity, contributes to absorber material



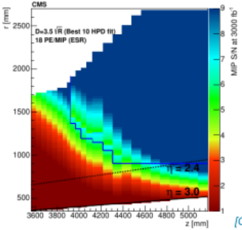

- [source : The CMS High Granularity Calorimeter for the High Luminosity LHC by Moritz Wiehe in VCI 2022 (link) ]

# HGCal Detector Layout : Scintillator + SiPM

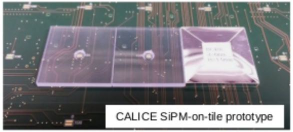
**Scintillator tiles with SiPM readout used in low radiation regions** (η>2.4)

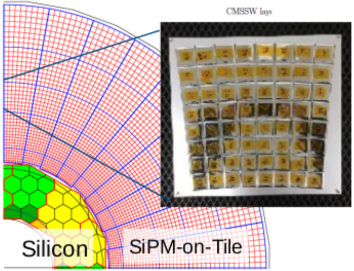
- Require good MIP Signal/Noise after 3000fb$^{-1}$
- Tile size depends on radial-position (4cm$^2$ to 32cm$^2$)
- Signal strength depends on tile and SiPM geometry → smaller tiles at lower radii

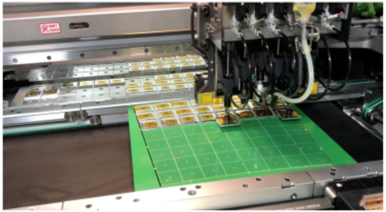
**Projected signal-to-noise ratio after 3000fb$^{-1}$**

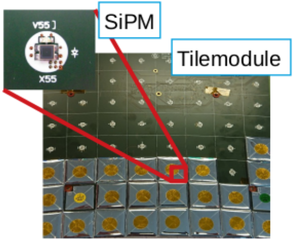



[CMS HGCAL TDR]



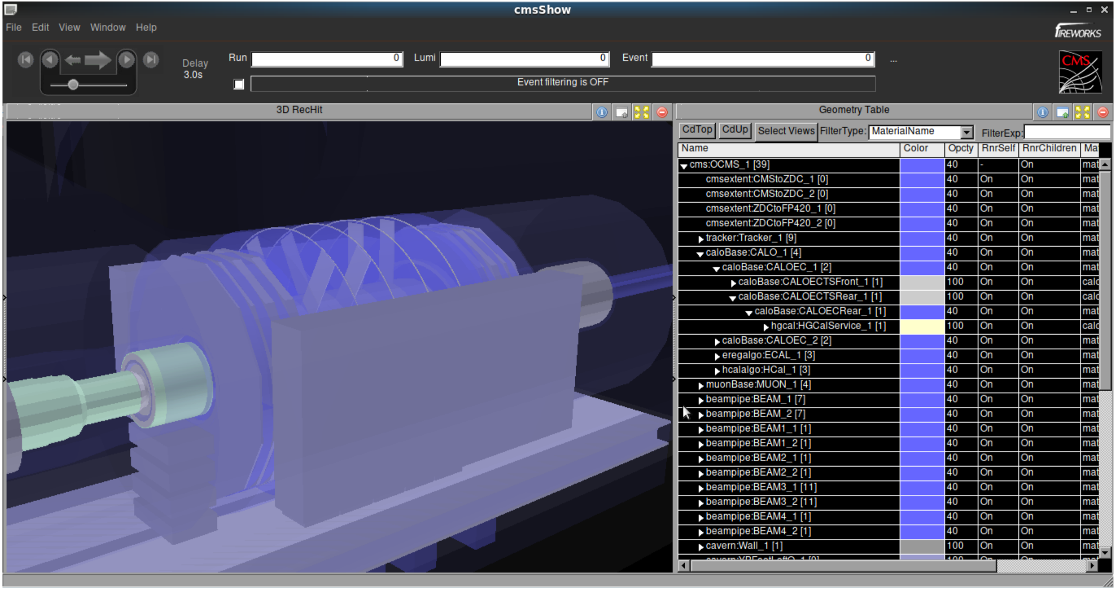



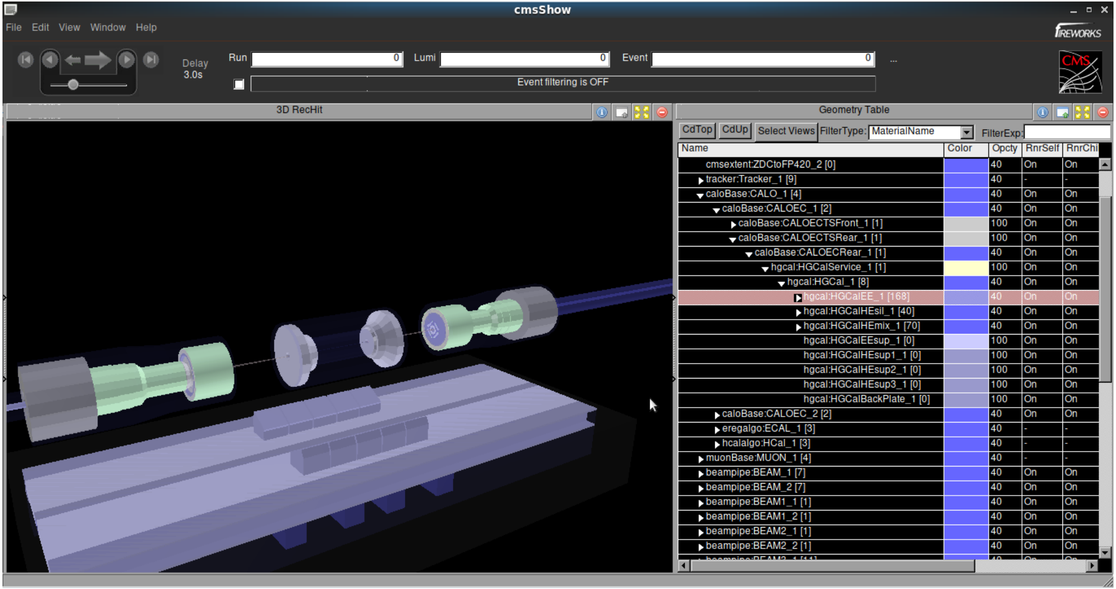



- [source : The CMS High Granularity Calorimeter for the High Luminosity LHC by Moritz Wiehe in VCI 2022 (link) ]

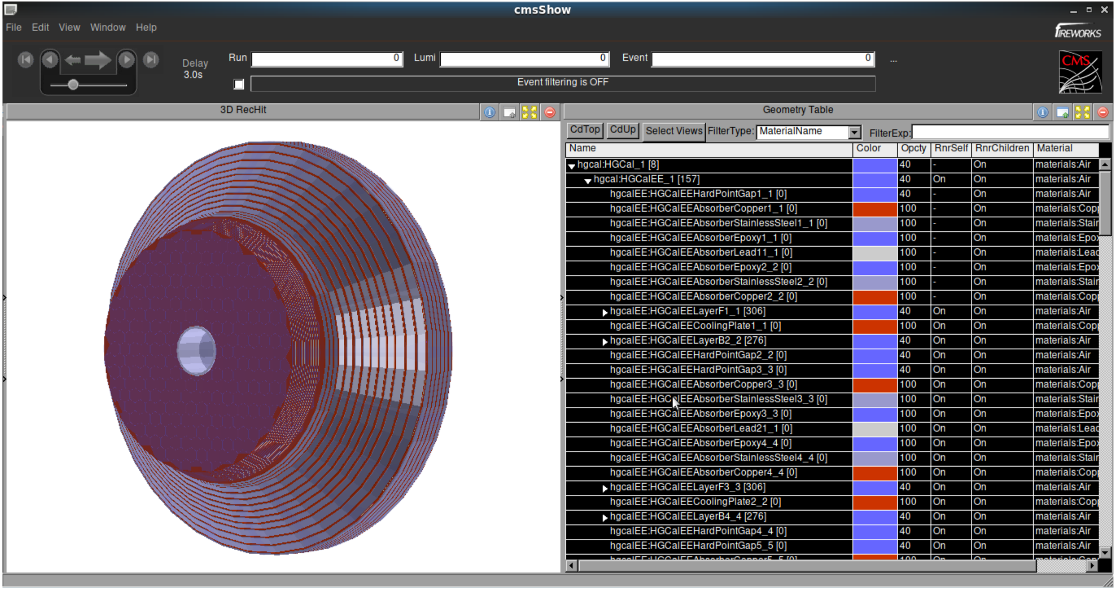
# How will CMS look in 2028 ?



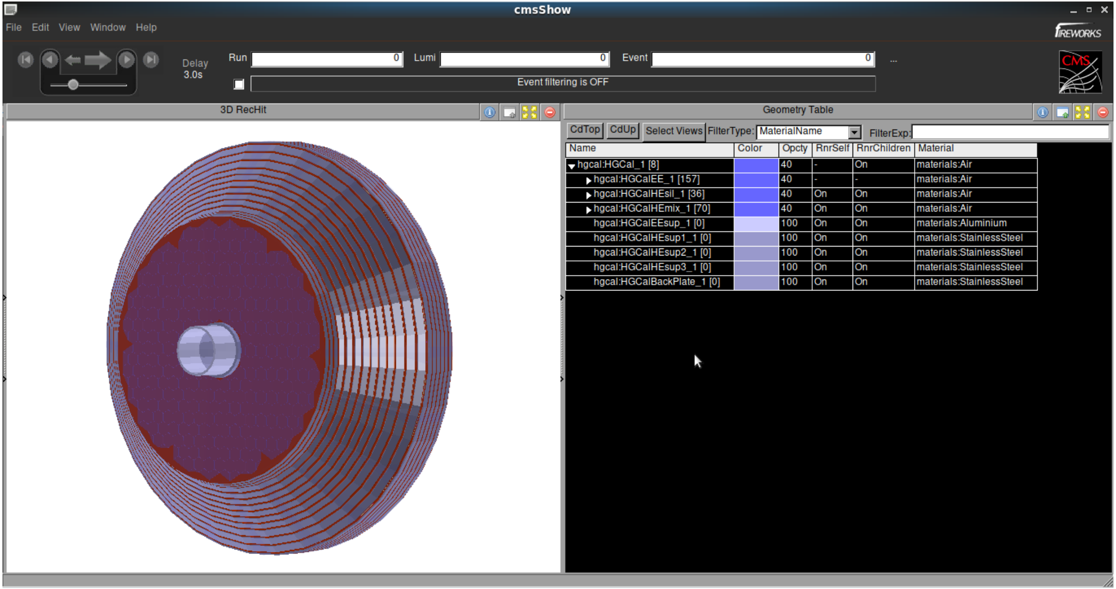
# Visualization of HGCAL



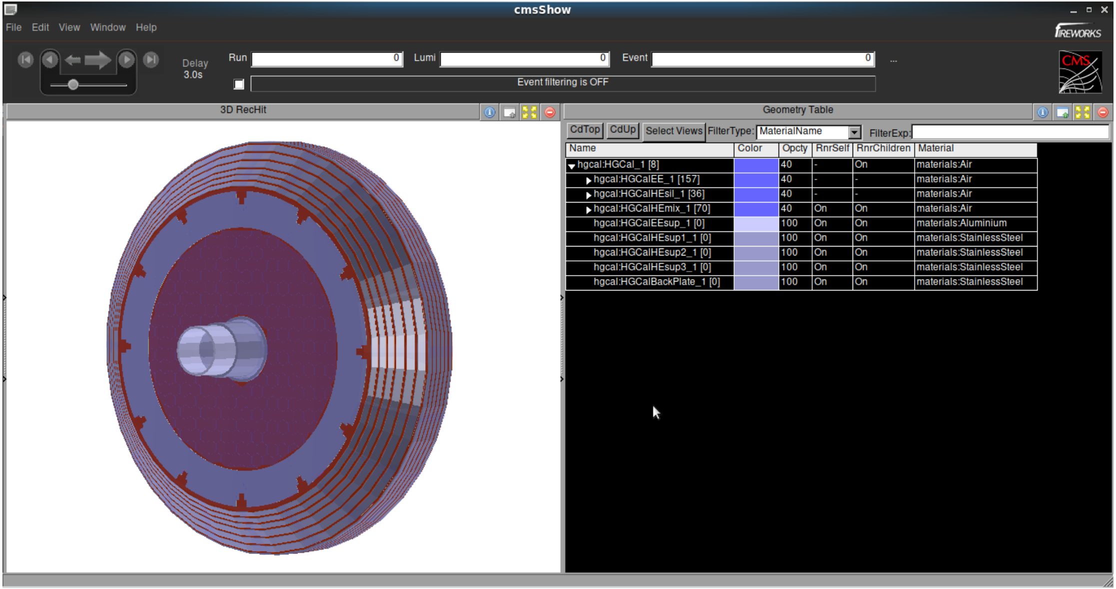
# The first layer of HGCAL CEE



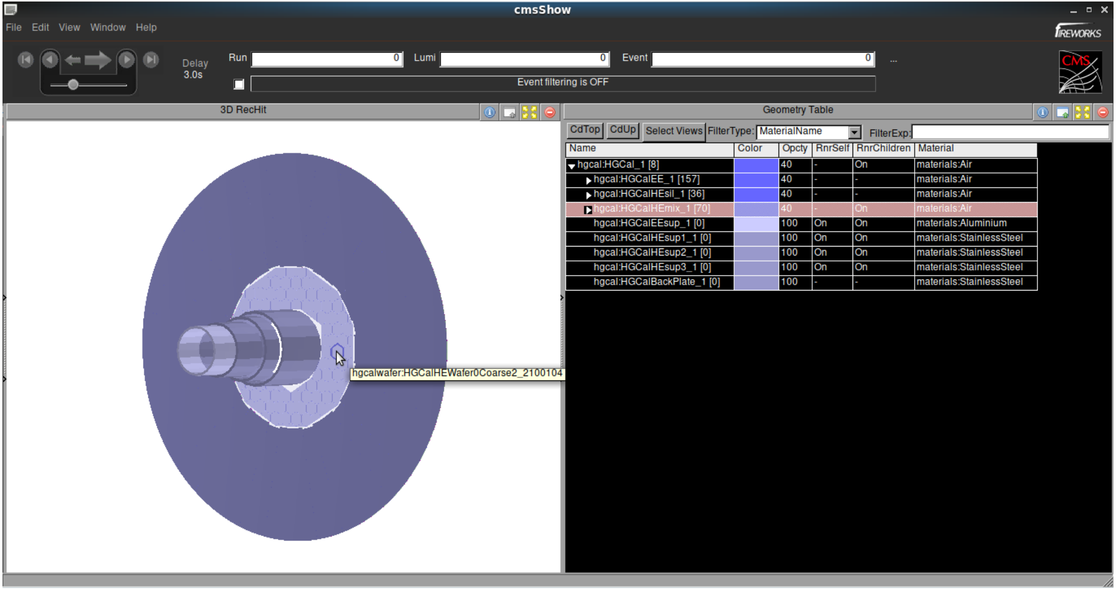
# The first layer of HGCAL CEH Front



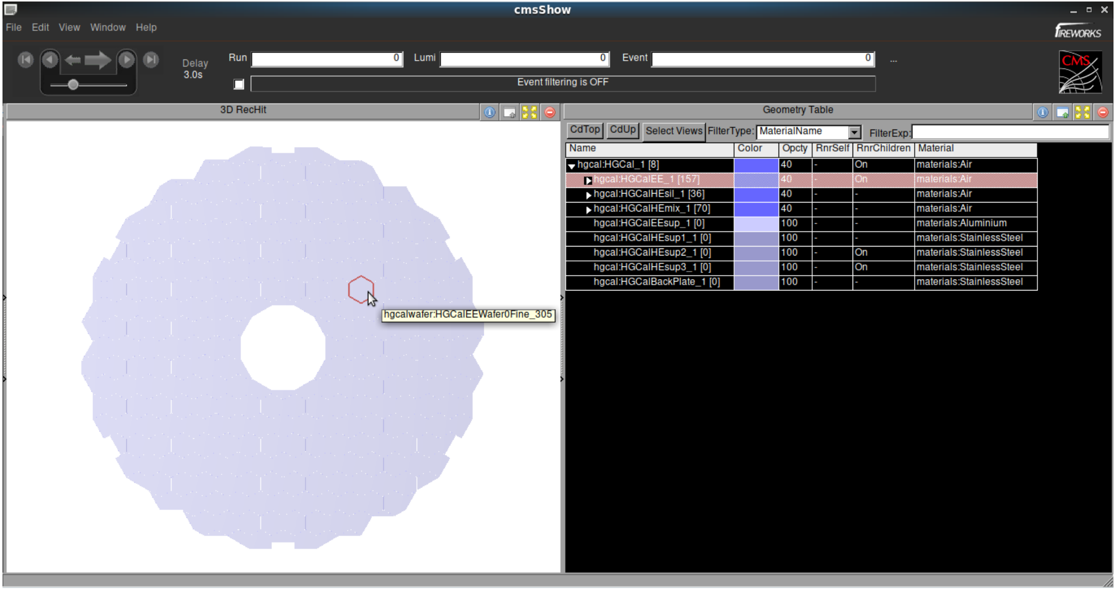
# The first layer of HGCAL CEH Back



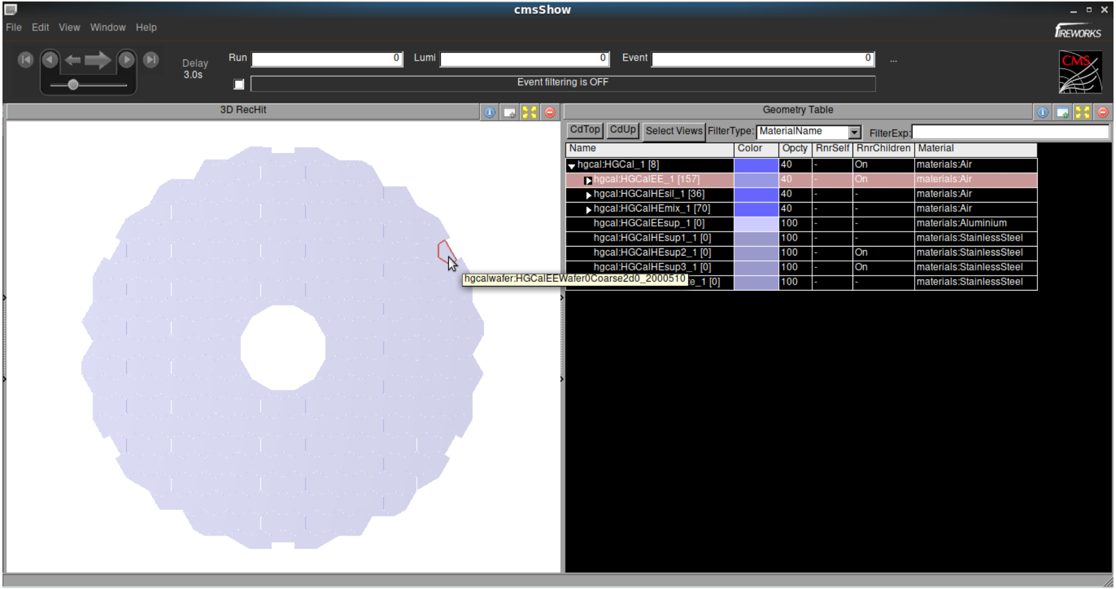
# The last layer of HGCAL



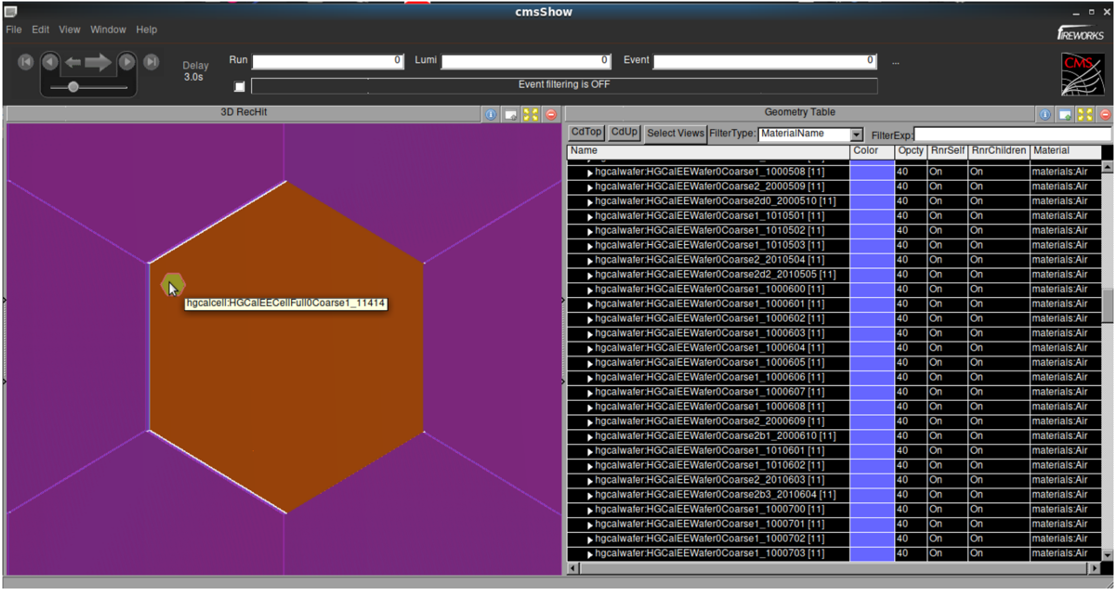
# Visualization of Si full wafer



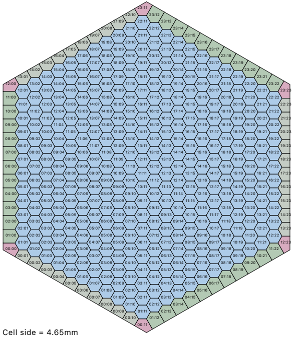
# Visualization of Si partial wafer



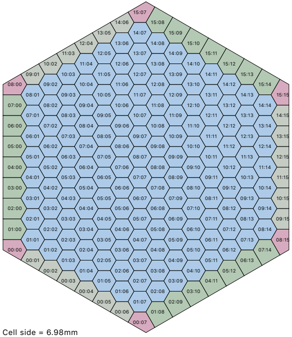
# Visualization of Si cell inside full wafer



# HGCal : The cells in wafers



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

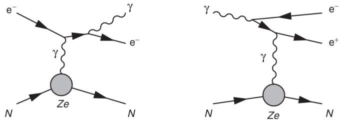


Cell side = 6.98mm
Cell flat-to-flat = 12.08mm

- 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 $\mu$m.
- 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 $\mu$m (CoarseThin) and 300 $\mu$m (CoarseThick).

# Shower development in calorimeter - I

- In Calorimetry, we aim to fully contain the shower.
  - Homogeneous : comprised solely with active material.
  - Sampling : alternate layers of active and passive material.
- HGCal, a calorimeter of the second type, measures both EM and Hadronic showers.
- In case of EM shower from high energy $e^{\pm}$,
  - Shower develops due to $\gamma$ radiated via Bremsstrahlung process.
  - Bremsstrahlung process creates further $e^+e^-$ pairs.
  - A cascade of $\gamma$s, $e^-$s and $e^+$s is produced.
  - Till the critical energy is reached $\epsilon_c = \frac{610}{Z+1.24}$ MeV
  - Ionization process dominates below this threshold.
  - $X_0 = 7/9 \cdot$ mean free path of pair production
- In case of EM shower from high energy $\gamma$,
  - Pair-production process creates $e^+e^-$ pairs for $E_\gamma > 10$ MeV.
  - Compton scattering $\gamma e^- \rightarrow \gamma e^-$ continues until $E_\gamma \sim 1$ MeV
  - Photoelectric effect dominates in the low energy regime.
  - The angular distribution of Photoelectric and Compton are isotropic, however Bremsstrahlung is directional.
  - The cross section for pair production gradually increases until reaches an asymptotic value near $\sim 1$ GeV.




The bremsstrahlung and $e^+e^-$ pair-production processes. $N$ is a nucleus of charge $+Ze$.

- [source : Modern Particle Physics by Mark Thomson]

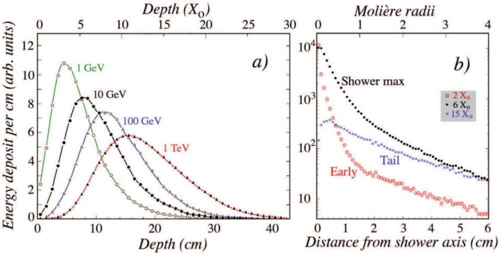



**Fig. 2:** The energy deposited as a function of depth for 1, 10, 100 and 100 GeV electron showers developing in a block of copper. In order to compare the shower profiles, the integrals of these curves have been normalized to the same value ($a$). The radial distributions of the energy deposited by 10 GeV electron showers in copper, at various depths ($b$).

- [source : Calorimetry by Richard Wigmans in Scientifica Acta 2, No. 1, 18-55 (2008)]

# Shower development in calorimeter - II

- Longitudinal development of EM shower,
  - The number of particles in an EM shower approximately doubles after every $X_0$
  - Average energy of the particles after $x$ radiation lengths is $\langle E \rangle \sim E/2^x$
  - The shower continues to develop until $\epsilon_c$, beyond this limit ionization is responsible for falling tail.
  - The maximum is reached at $x_{\max} \sim \frac{\ln(E/\epsilon_c)}{\ln 2}$
- The lateral EM shower development,
  - $e^-$s and $e^+$s moving away from shower axis due to Multiple Coulomb Scattering.
  - Photons produced isotropically in the Compton and Photoelectric effect.
  - Moliere radius which contains 90% of shower energy is $R_M = 0.0265 \cdot X_0(Z + 1.2)$.
  - $R_M \propto A/Z$ is less material dependent than $X_0 \propto A/Z^2$.
- Study of hadronic shower development is challenging,
  - Charged particles (mostly pions and protons) loose energy continuously by ionization.
  - Undergoes, strong interaction with the nucleus, producing secondaries
  - Hadron energy spent to overcome nuclear binding energy in order to release $n$, $p$s is known as invisible energy, since this energy can not be measured by hadron calorimeter.
  - Almost 90% of total charged particles are pions.
  - The $\pi^0$ are produced about 1/3 of total pions which decays to two $\gamma$s giving rise to EM shower.

# Shower development in calorimeter - III

- Hadron shower (in Pb) deposits energy
  - 56% by ionizing particles
  - 10% neutrons
  - invisible energy 34%
- The calorimeter signal for hadrons are smaller than EM at same energy due to invisible energy.
- The EM component of Hadron shower due to $\pi^0$ increases with energy as more $\pi^0$s are produced from detector material due to strong interaction.
- Due to the energy dependance of the EM part of hadronic shower the hadronic measurements are further non-linear.
- Nuclear interaction length $\lambda \propto (A)^{1/3}$
- The longitudinal profile of hadronic shower is similar to EM shower except the leakage effects due $\pi^0$s.
- Laterally, it takes less material to contain a shower with high energy than low energy one (also due to $\pi^0$s).

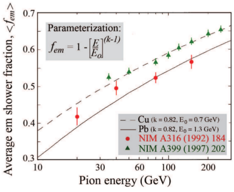



**Fig. 6:** Comparison between the experimental results on the em fraction of pion-induced showers in copper-based and lead-based calorimeters [3, 4].

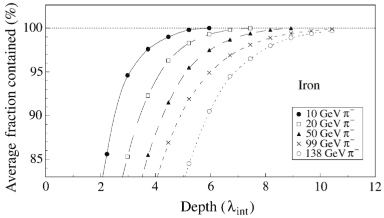
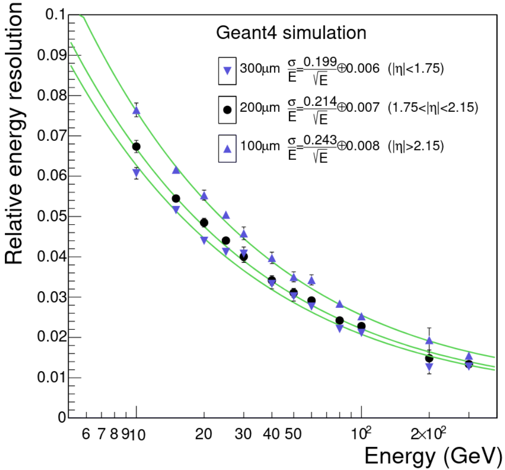



**Fig. 8:** Average energy fraction contained in a block of matter with infinite transverse dimensions, as a function of the thickness of the absorber [6].

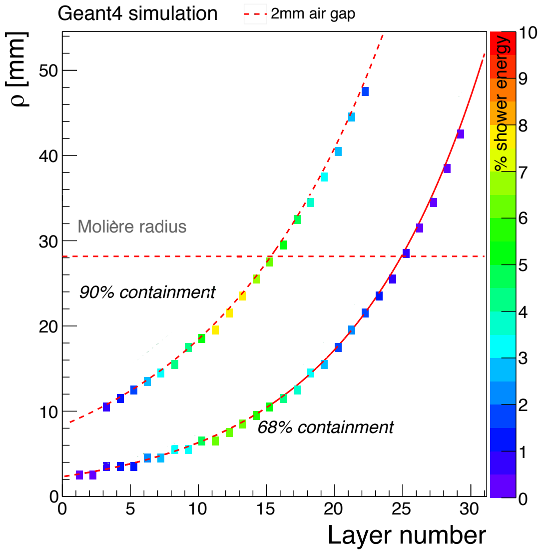
- [source : Calorimetry by Richard Wigmans in Scientifica Acta 2, No. 1, 18-55 (2008)]

# HGCal GEANT4 - Energy resolution



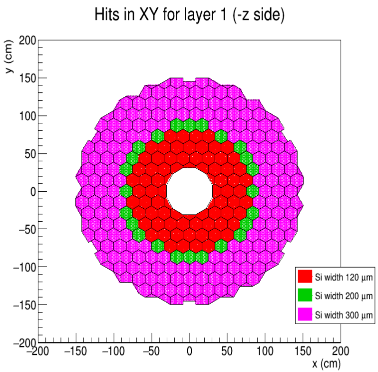

- [source : CMS-TDR-15-02, ISBN 978-92-9083-417-5]
- The result obtained using electron gun on CEE geometry of the detector.
- An improvement in the energy resolution at higher energies compared to that in lower is shown as a function of energy of the incident electron.

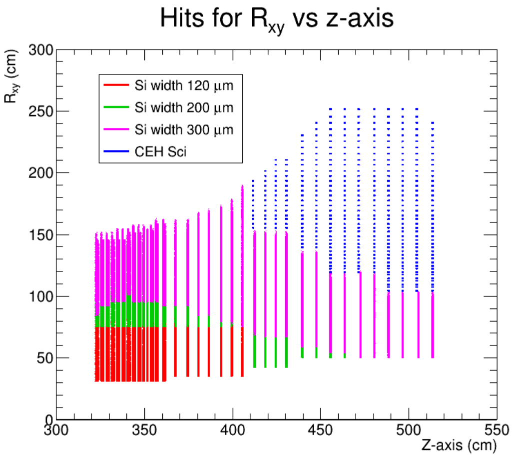
# HGCal GEANT4 - Moliere radii




- [source : CMS-TDR-019, CERN-LHCC-2017-023]
- The result obtained using electron gun on CEE geometry of the detector.

# HGCal Validation : Muon Tomography

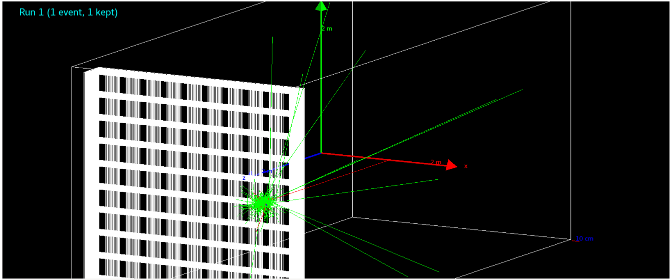



- Left: the front of HGCal layer1, Right: the side view of HGCal layers.
- The muon hit distributions showing different types active elements.
  - The Si wafers with depletion width of 120 $\mu$m, 200 $\mu$m, 300 $\mu$m are shown in red, green and magenta, respectively.
  - The Scintillator tiles are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

# Introduction to HGCal tutorial

- We have constructed a simplified geometry HGCal CEE section.
- There will be 26 cassettes of dimension 302 cm x 302 cm x 3.0345 cm, each will contain consecutive layers of
  1. one 300 cm x 300 cm layer of Si (density : 2.33 g/cm3) with 0.3 mm of thickness
  2. one 300 cm x 300 cm layer of CuW (density : 14.979 g/cm3, W:Cu = 75%:25%) with 1.4 mm thickness
  3. one 300 cm x 300 cm layer of Cu (density : 8.96 g/cm3) with 6.05 mm thickness
  4. Another layer of CuW of same dimension as above
  5. Another layer of Si of same dimension as above
  6. one 300 cm x 300 cm layer of Pb (density : 11.35 g/cm3) with 4.97 mm thickness




- [An electron of 10 GeV momentum hitting the detector]

- Divide the Si sensor in square cells of 30 cm x 30 cm dimension.
- Learn how to perform sensor segmentation on fly.
- Store output in ROOT ntuples.
- Apply multithreading features of GEANT4 to benefit in case of looping over various beam types of various momenta and originating from different locations.

# Status, Summary and Outlook

- The current GEANT4 geometry of HGCAL is interfaced via DD4hep (link).
- An extensive effort has been to made the geometry as per the production specification of materials.
- However, it is never complete even after the data collection (past experience).
- Several validation tools are present
  - code level – Validation codes
  - display – Fireworks
  - simulation and reconstruction – Muon Tomography
  - data quality – Data Quality Monitoring
- It will be interesting to analyze the HGCal data comprising 5 dimensional measurements.
- Interested student/postdoc welcome to collaborate (indranil.das@cern.ch).

Thank you