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The CMS HGCAL detector for the HL-LHC upgrade

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The High Luminosity LHC (HL-LHC) will integrate 10 times more luminosity than the LHC, posing significant challenges for radiation tolerance and event pileup on detectors, especially for forward calorimetry, and hallmarks the issue for future colliders. As part of its HL-LHC upgrade program, the CMS collaboration is designing a High Granularity Calorimeter to replace the existing endcap calorimeters. It features unprecedented transverse and longitudinal segmentation for both electromagnetic (ECAL) and hadronic (HCAL) compartments. This will facilitate particle-flow calorimetry, where the fine structure of showers can be measured and used to enhance pileup rejection and particle identification, whilst still achieving good energy resolution. The ECAL and a large fraction of HCAL will be based on hexagonal silicon sensors of 0.5 - 1 cm^2 cell size, with the remainder of the HCAL based on highly-segmented scintillators with SiPM readout. The intrinsic high-precision timing capabilities of the silicon sensors will add an extra dimension to event reconstruction, especially in terms of pileup rejection. An overview of the HGCAL project will be presented, covering motivation, engineering design, readout and trigger concepts, and performance (simulated and from beam tests).

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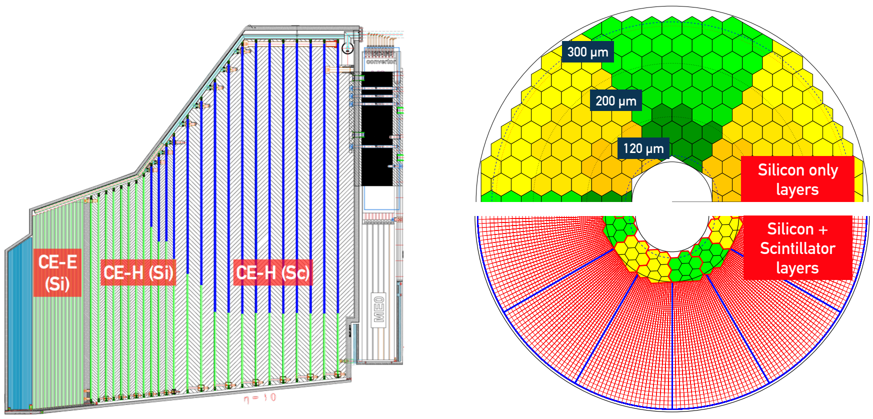

Figure 1: *Left*: Transverse illustration of the HGCAL highlighting the silicon and scintillator compartments in green and blue, respectively. *Right*: layout of a silicon-only (top) and mixed silicon-scintillator (bottom, not to scale) layer indicating the different silicon wafer thickness regions.

The Large Hadron Collider (LHC) is currently the largest and most powerful collider worldwide. In the light of the excellent physics results already obtained at the LHC, an increase of the integrated luminosity by an order of magnitude will help measure important Standard Model parameters with higher precision and possibly uncover new phenomena. Therefore, an upgrade of the accelerator complex called High Luminosity LHC (HL-LHC) is foreseen in the years 2024-2026 and will allow for a three to four times higher instantaneous luminosity with respect to the current LHC operation, providing 3000 fb^{-1} of integrated luminosity by about 2035.

The increased intensity will also result in higher particle fluxes, radiation levels and simultaneous interactions (pileup) occurring at the LHC experiments. In order to cope with the more challenging environment and mitigate effects of radiation damage, the CMS collaboration [1] is planning an upgrade of its detector systems and infrastructure.

Among these upgrades is the replacement of the current calorimeter endcaps, which will not survive the radiation levels anticipated at the HL-LHC, with the high granularity calorimeter (HGCAL) [2] comprising a total of 52 longitudinal layers of finely segmented silicon sensors and scintillators (figure 1). Silicon is placed in areas of higher particle flux and radiation, whereas scintillators are used in lower radiation areas. In many aspects, this project profits from previous developments within the CALICE Collaboration for the SiW-ECAL and AHCAL [3, 4].

The HGCAL silicon part is tiled with hexagonal sensors of different active thickness (120, 200 or 300 μm). The cell size also differs (0.5 cm^2 for the thinnest ones, 1 cm^2 for the others), resulting in 192 to 432 channels per 8" sensor respectively. In order to mitigate the effects of radiation damage in silicon sensors, the full endcaps are cooled down to -30°C, and the thinner and more granular wafers are placed at higher pseudorapidity regions. The scintillator part comprises single tiles of constant azimuthal angle decreasing in size with increasing pseudorapidity from 32 cm^2 to 4 cm^2. The readout of each individual scintillator tile is performed with on-tile-silicon photomultipliers (SiPMs). A total of 6 million silicon cells and 400 000 scintillator tiles cover an area of ∼600 and ∼500 m^2, respectively. Single silicon wafers and arrays of scintillator tiles are assembled into individual modules, of which there are a total of 27000 and 4000, respectively.

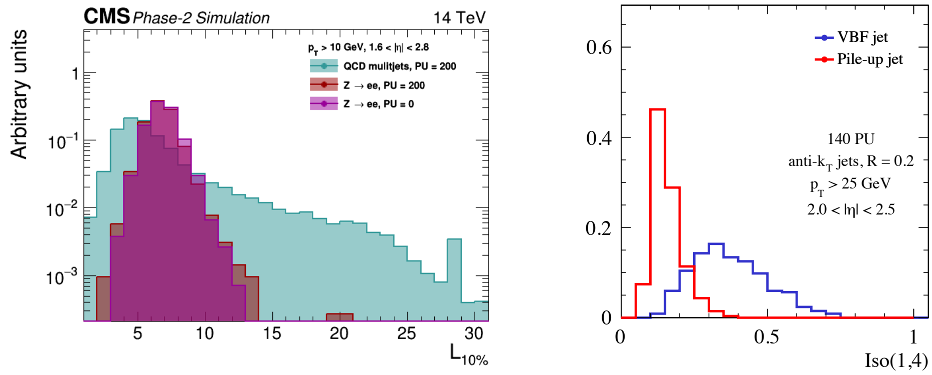

Figure 2: *Left*: distributions of the layer number at which the cumulative longitudinal energy exceeds 10% of the total energy in a cluster for true electron clusters with and without pileup to clusters from QCD multijet showers. *Right:* comparison of the relative isolation for pileup jets and jets from VBF production.

Physics performance One of the key aspects of the HGCAL detector is the possibility of performing highly granular imaging of particle showers in a five-dimensional space: the magnitude and timing of energy deposits are measured with three cartesian coordinates.

This granularity plays a key role for the event reconstruction in the challenging environment of the HL-LHC, especially in the high occupancy forward region of $1.54 < |\eta| < 3$ where the calorimeter will be located. For example, the Molière radius of electromagnetic shower containment in the dense ECAL part is of the order of 3 cm, whereas the cell size does not exceed 1.3 cm. The large number of longitudinal sampling layers facilitates the exploitation of the differences in the longitudinal shower development for various physics objects, such as electrons or photons and jets originating from vector boson fusion (VBF) or pileup processes (figure 2).

Together with the other CMS detectors such as the tracker and muon systems, the HGCAL will enable Particle Flow reconstruction to be performed with unprecedented flexibility[5]. The reconstruction with this detector offers a great opportunity for novel tracking, clustering and imaging techniques using algorithmic and machine learning approaches.

Beam tests Several beam tests have been performed over the last three years in order to explore the feasibility of the novel detector design of HGCAL as well as to evaluate the physics performance in prototypes [6]. These beam tests also serve to verify and optimize the physics models used for Monte Carlo simulations of this kind of sampling calorimeter with silicon and scintillator active layers. Such simulations are a key ingredient to fine-tuning the detector design in terms of mechanics, readout and trigger electronics. In addition, beam tests enable the technological prototyping of the silicon detector modules as well as the validation of fundamental architecture choices of the front-end chip: the time-over-threshold and time-of-arrival measurements [7].

Two test beam campaigns were performed in 2018. The first took place in March at the DESY beam facility and served to study the response of single silicon modules to low energy electrons using precise tracking with a beam telescope providing up to 10 μm precision on the impact position. In June, a major setup comprising 28 single-module layers of the ECAL part was tested at the CERN SPS beam facility. The modules were arranged in double-sided cassettes with active cooling similar to the foreseen detector design. Data were taken with beams of muons, electrons

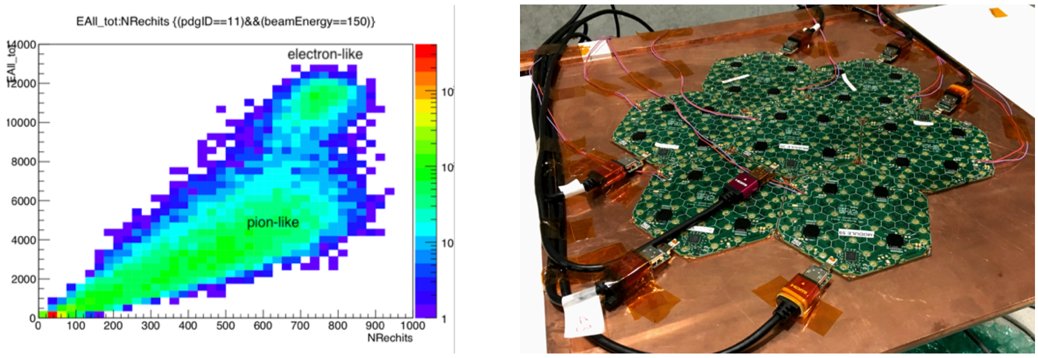

Figure 3: *Left*: total deposited energy plotted against the total number of hits in the prototype for a run with 150 GeV electrons and a strong pion contamination corresponding to the lower population. *Right*: seven 6" silicon sensor modules mounted on a copper support & cooling plane during the 2017 beam test campaign.

and pions in a wide energy range from 10 to 150 GeV. Preliminary results such as the separation of electrons and pions based on calorimetric shower variables look promising, see figure 3 (left).

A large-scale beam test with about 100 silicon modules is scheduled for October 2018. This will populate up to 12 layers of 7-module planes in the hadronic compartment (figure 3, right) in addition to the 28-layer electromagnetic compartment. The setup will be complemented with a 39-layer AHCAL prototype in order to mimic the scintillator and SiPM-on-tile part of the HGCAL. This beam test will allow the exploration of a complete HGCAL-like calorimeter system in terms of physics performance, including the timing of hadronic showers with sub-nanosecond precision.

The design of the HGCAL is ongoing, with assembly due to start in 2021 and installation during the LHC Long Shutdown 3 in 2024/2025

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