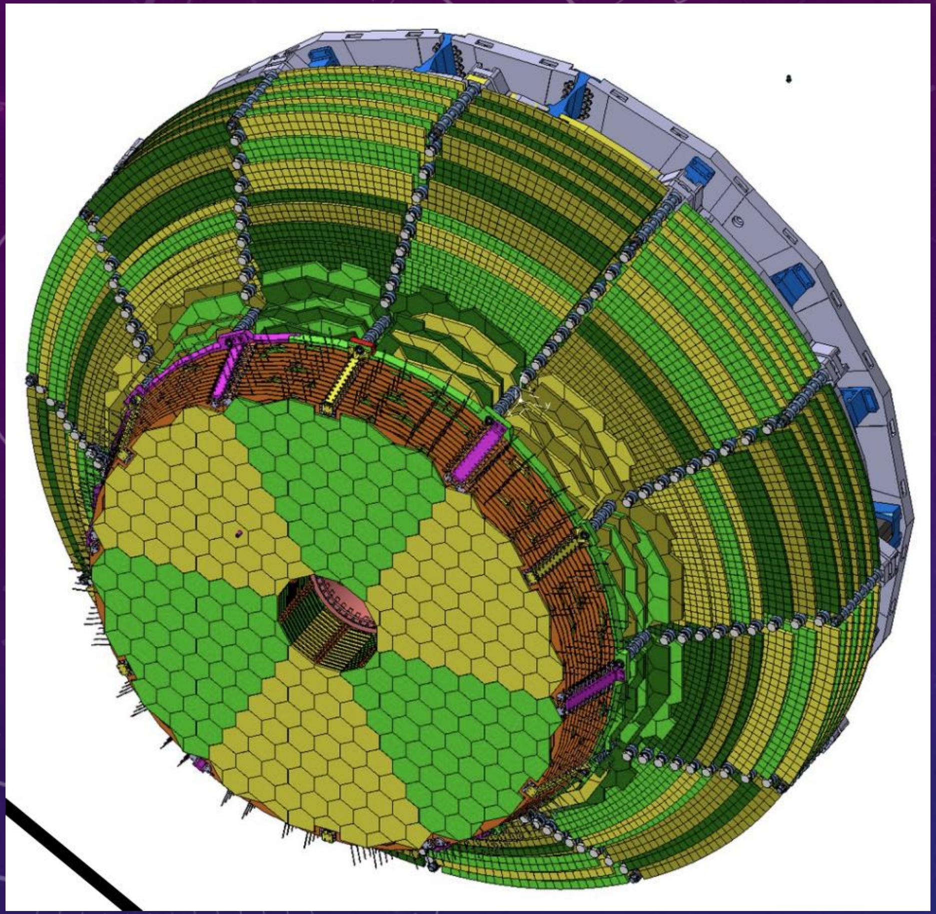


THE CMS HGAL UPGRADE PROJECT: SELECTED HIGHLIGHTS

MARCELLO MANNELLI

LHC DAYS IN SPLIT 2022

July 14 2022: 10'th Anniversary of the Higgs Boson Discovery

It was a long time coming, then happened faster than expected…

It completes the Standard Model, and confronts us with **The Big Questions**

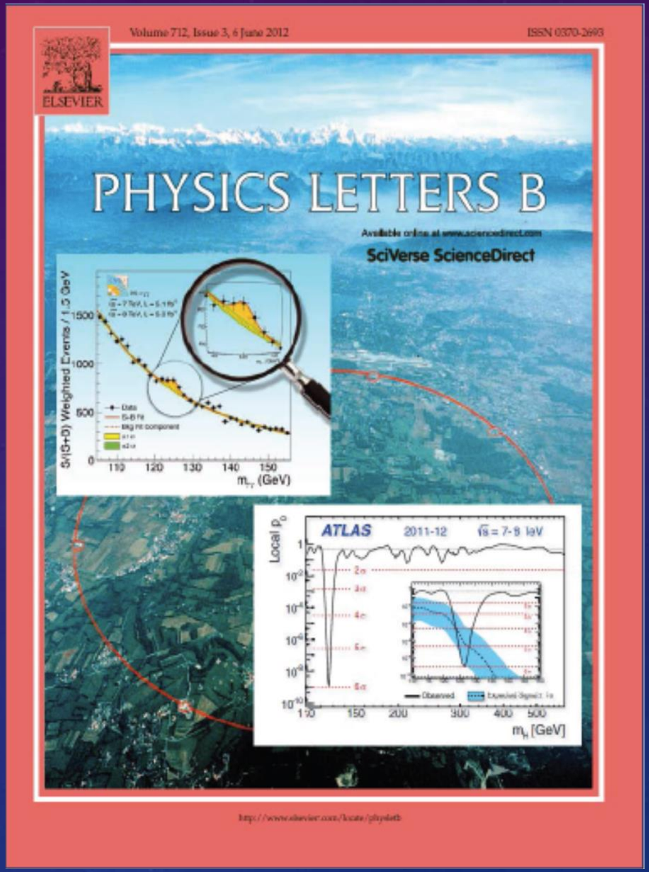
Is the Higgs what we think it is?

What is Dark Matter made of?

What is the nature of Dark Energy?

Is the Universe Natural or Anthropic?

➤ **What, really, lies Beyond the Standard Model?**



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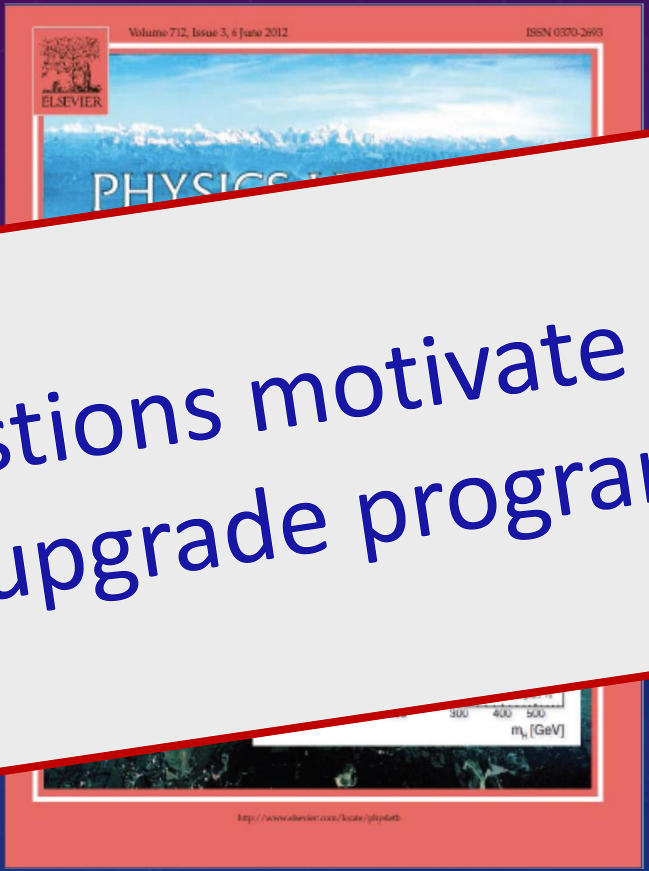

These questions motivate the HL-LHC upgrade program

The CMS HL-LHC Upgrade: Scope

- Aim to enable full program of Precision Measurements and Direct Searches for Rare Processes, Subtle and/or Exotic Signatures, in the search for BSM Physics, allowing for the challenging HL-LHC environment

- The High Radiation Environment necessitates
  - The complete replacement of the Tracker and End-Cap Calorimeter systems
  - Cold operation of the Barrel ECAL (APD Noise Mitigation)
  - Major electronics overhaul and consolidation of the Barrel Calorimeters and Muon systems

- The High Pile Up motivates
  - Improved granularity wherever possible
  - Novel approaches to in-time Pile Up mitigation: Precision Timing detectors (30ps)

- The High Luminosity requires
  - Substantially improved L1 Trigger primitives for better selectiveness, despite the high PU
  - A complete overhaul of the Trigger and DAQ systems

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These challenges define the scope of the CMS HL-LHC upgrade program

The CMS HGCAL: Overview

The CMS HGCAL uses silicon sensors for the electromagnetic section of the calorimeter, as well as for those parts of the hadronic section that are exposed to the highest radiation levels. Plastic scintillator tiles with direct (on-tile) SiPM readout are used for those sections of the hadronic calorimeter that will be exposed to less than ~5×10^{13} n/cm^2 after 3'000fb^{-1}.

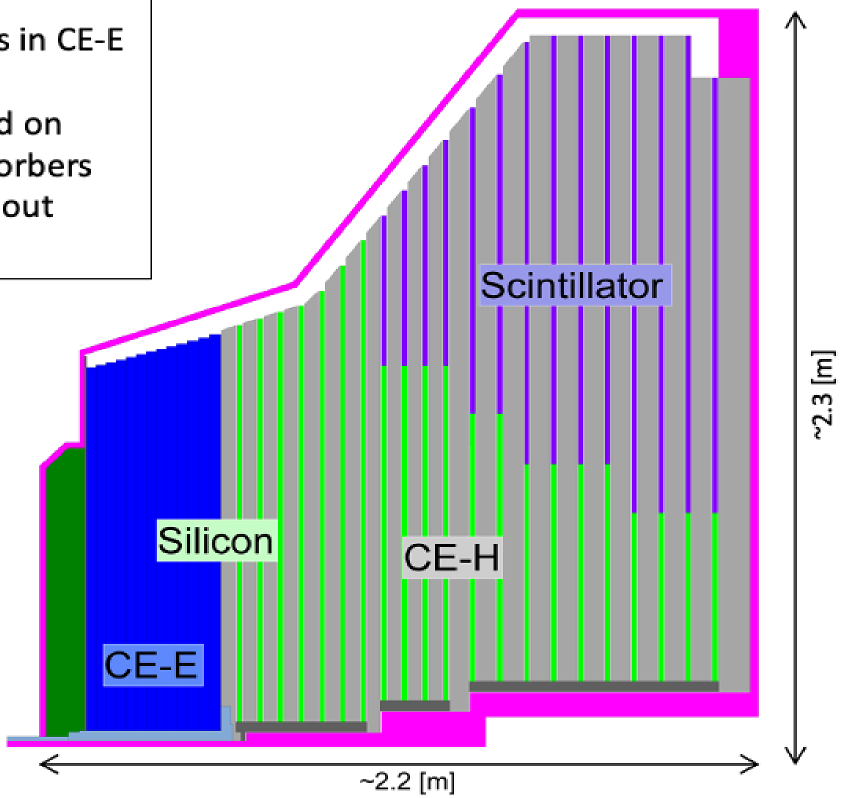
All told the CMS HGCAL employs ~600m2 of silicon sensors with ~6M readout channels, and close to 370m^2 of plastic scintillator with about 240'000 readout channels.

Active Elements:

- Hexagonal modules based on Si sensors in CE-E and high-radiation regions of CE-H
- "Cassettes": multiple modules mounted on cooling plates with electronics and absorbers
- Scintillating tiles with on-tile SiPM readout in low-radiation regions of CE-H

Key Parameters:

Coverage: 1.5 < |η| < 3.0
~215 tonnes per endcap
Full system maintained at -35°C
~620m^2 Si sensors in ~30000 modules
~6M Si channels, 0.5 or 1cm^2 cell size
~400m^2 of scintillators in ~4000 boards
~240k scint. channels, 4-30cm^2 cell size
Power at end of HL-LHC:
~125 kW per endcap



Electromagnetic calorimeter (**CE-E**): **Si**, Cu & CuW & Pb absorbers, 26 layers, 25 X_0 & ~1.3λ
Hadronic calorimeter (**CE-H**): **Si** & **scintillator**, steel absorbers, 21 layers, ~8.5λ

The CMS HGCAL: Overview

Choice of HGCAL was motivated by the demonstration that **simple planar silicon sensors (single-sided, DC-coupled, n-on-p) can tolerate the required levels of radiation**, while retaining adequate signal charge collection efficiency even after exposure to fluences of $1.5 \times 10^{16} n/cm^2$. **It was made possible by the commitment of key industrial partners towards silicon sensor production on 8” lines, enabling cost effective sensor production** on the very large scale required for the CMS HGCAL, **without undue interference with the silicon sensor production for the Phase II ATLAS and CMS Trackers** on well-established 6” production lines.

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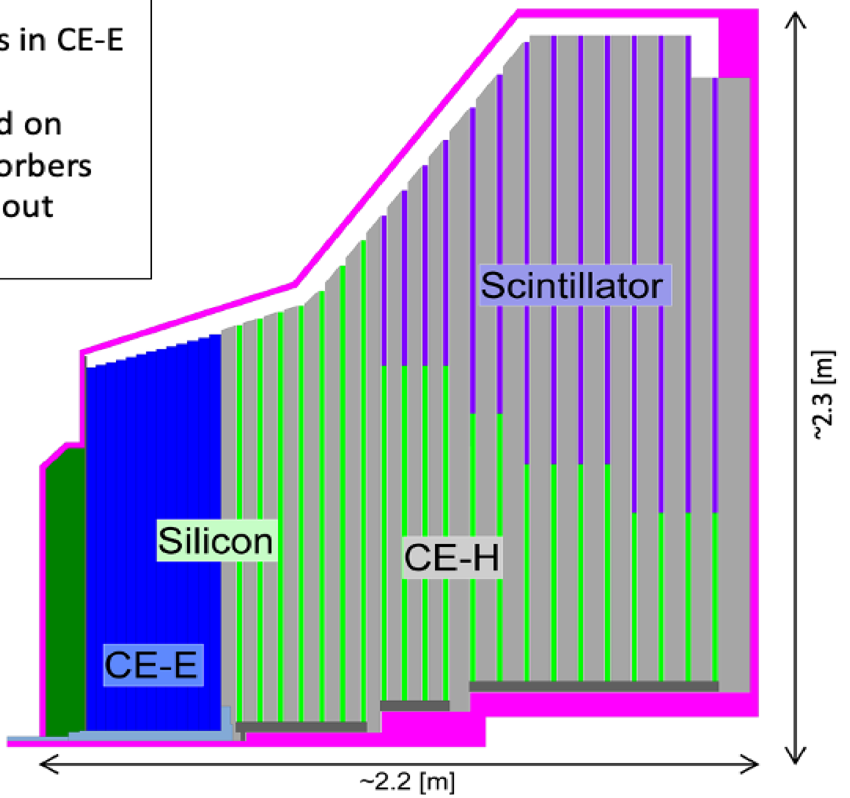

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The CMS HGCAL: Overview

In addition to each cell providing an energy measurement, individual silicon sensor pads with more than a few MIPs equivalent enrgy deposit will also provide precise timing information, down to ~20ps

⇒ **HGCAL will be the first large scale 5D calorimetric imaging detector**

High granularity and precise timing will allow to resolve individual showers, characterise jet (sub-)structure, and mitigate the effects of the 140~200 pile-up collisision within single bunchcrossing

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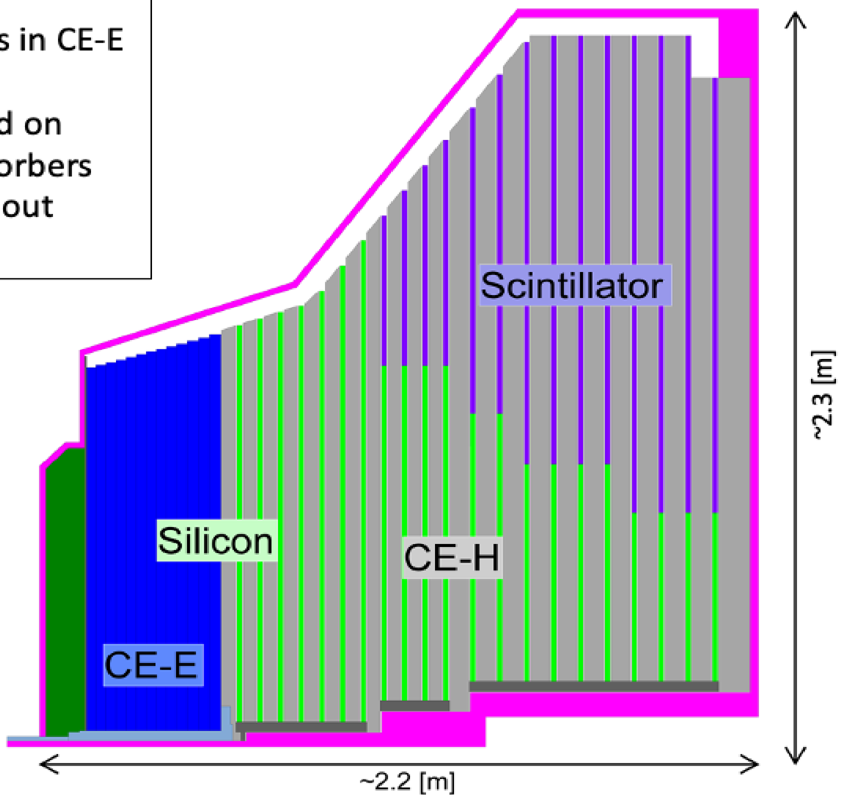

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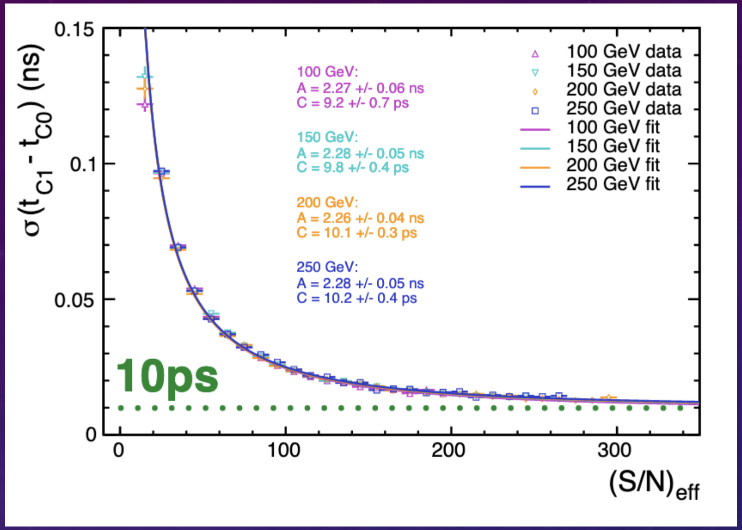
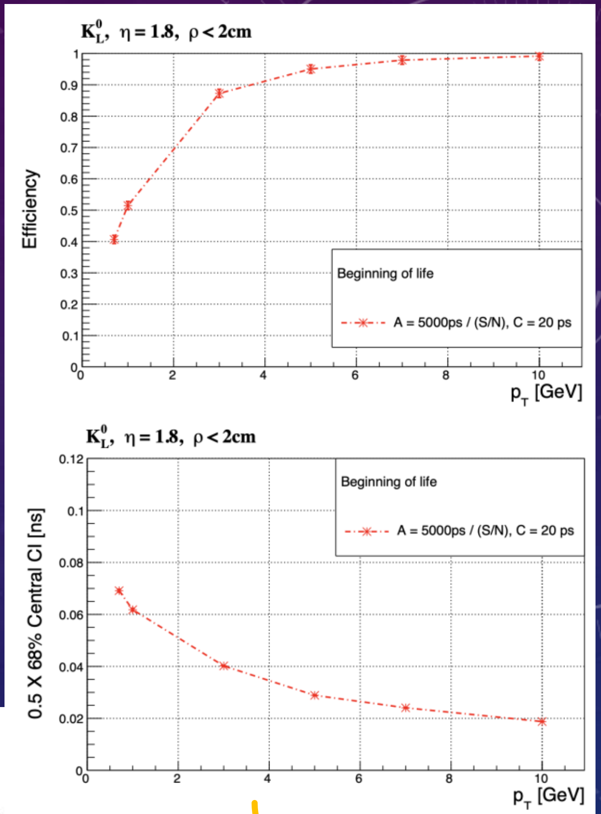
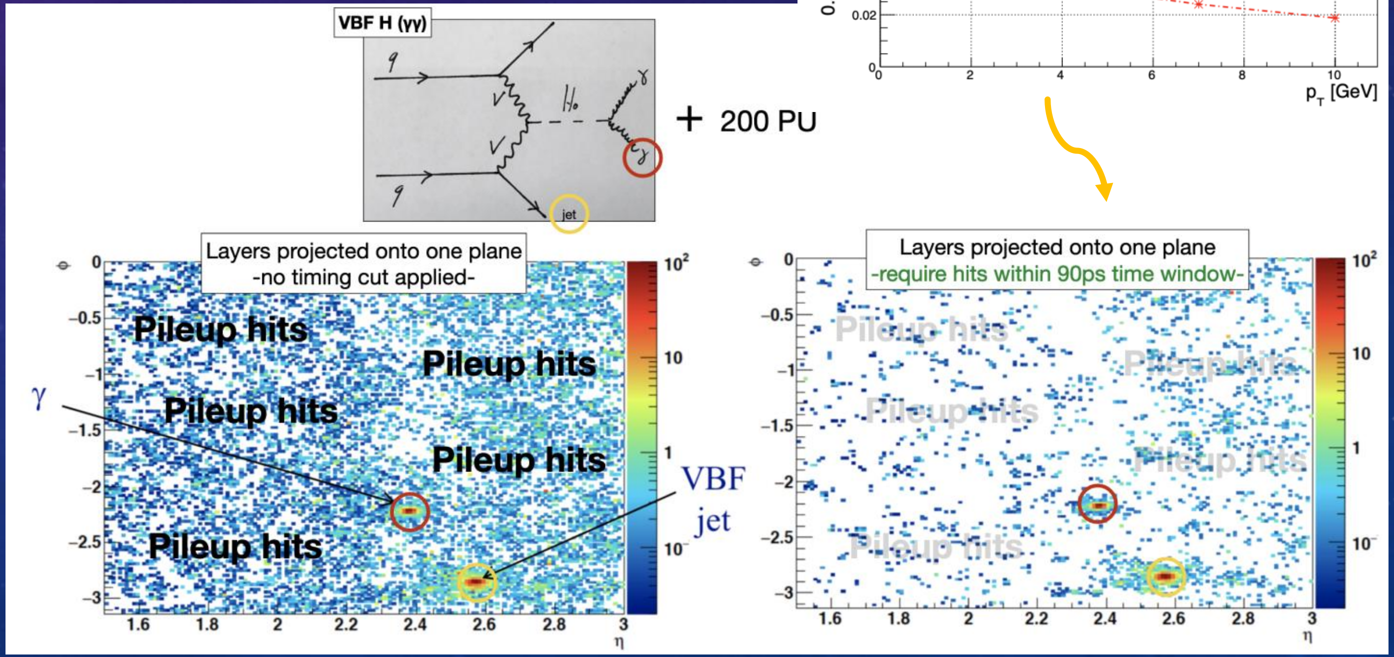
Si sensor timing vs S/N 2016 beam tests [JINST13 (2018) P10023]





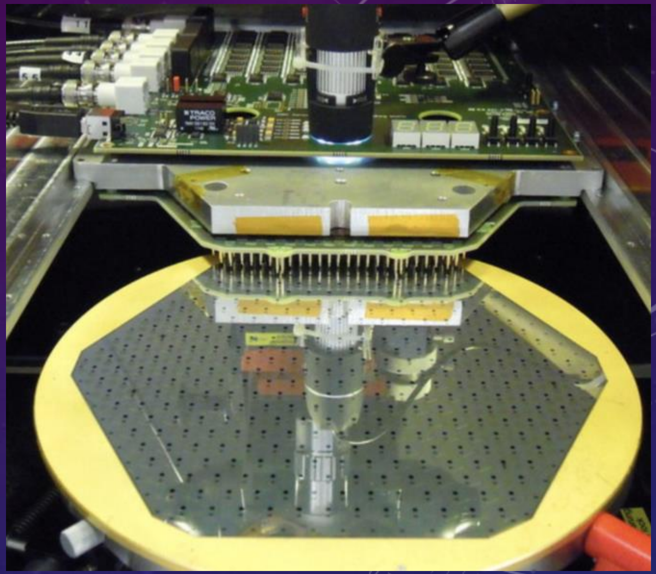


The Silicon Sensors of the CMS HGCAL

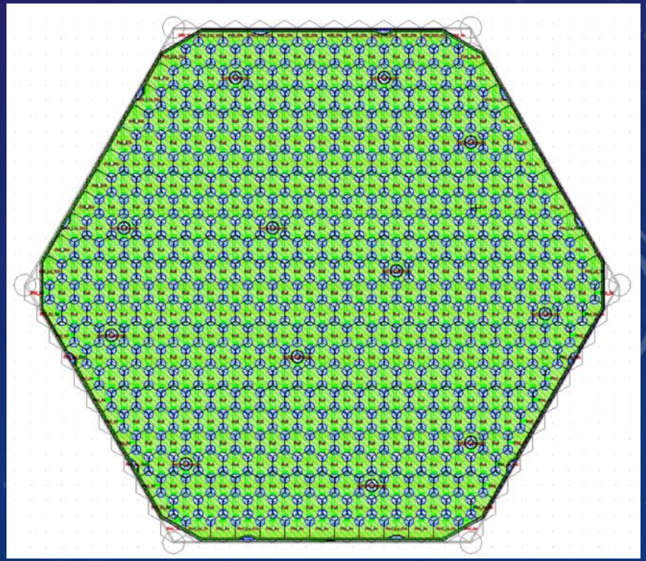
The silicon sensors are of hexagonal shape, the largest tile-able polygon, which allows the most efficient use of the sensor wafer: **in combination with the use of 8" wafers this minimizes the number of modules** to be assembled and integrated into the system, **reducing it by well over a factor two** compared to the more usual square sensors produced on 6" wafer sensors.

There are three different sensor thickness: 300um, 200um and 120um to optimize performance as function of radiation, which varies from $5x10^{13}n/cm^2$ at the Silicon-Scintillator interface up to close to $1x10^{16}n/cm^2$ towards the inner radius of the CEE.

There are two different pad sizes: ~1cm^2 for the 300um and (most of) the 200um sensors (LD), and ~0.5cm^2 for the 120um sensors (HD), in order to limit the pad capacitance and leakage current, so as **to ensure sufficient S/N for MIP calibration** over the full HL-LHC operation of the HGCAL.



LD 192 x 1.18cm^2 sensor cells*



HD 432 x 0.52cm^2 sensor cells*

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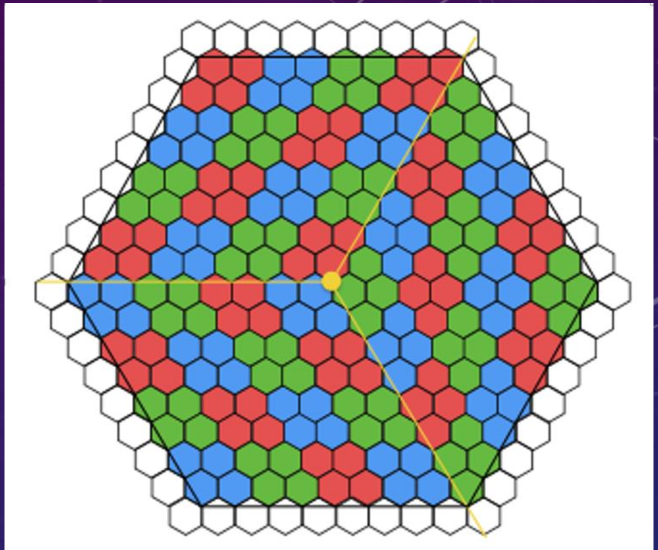
Adjacent sets of silicon **sensor pads are summed in groups of 2x2 (LD) or 3x3 (HD) trigger supercells, of approximately 4cm^2 surface**, and sent off detector at 40MHz for use in the L1 Trigger primitive generation



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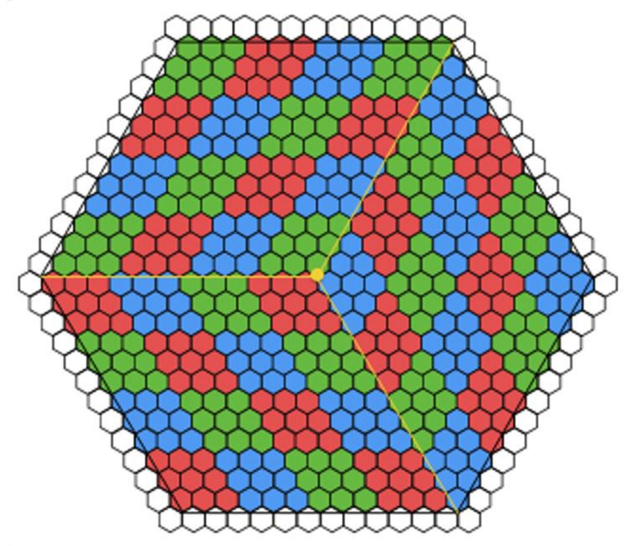
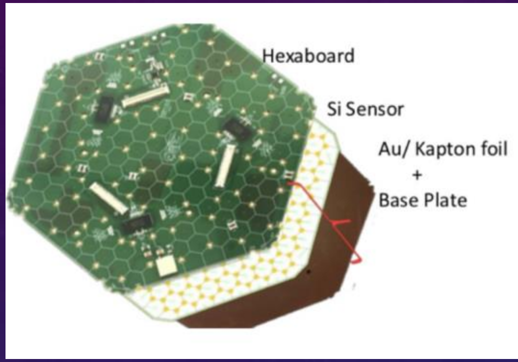
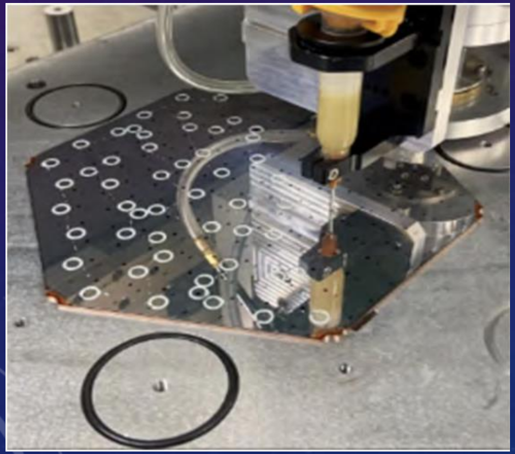


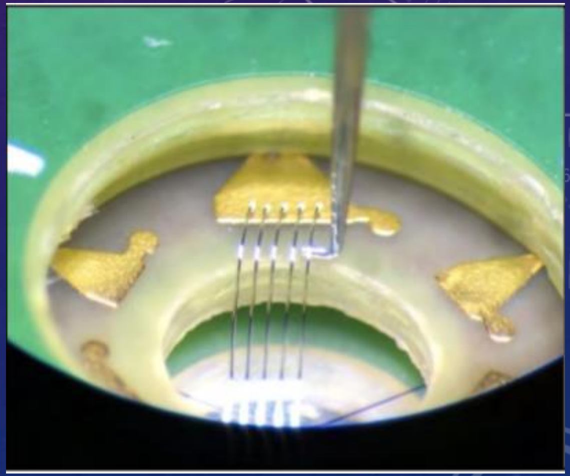
HD 432 x 0.52cm^2 sensor cells*

The Silicon Sensor Modules of the CMS HGCAL

With approximately 26’000 silicon modules, **there is a strong emphasis on a simple, mechanically robust module design well adapted to automated robotic assembly and ease of handling**.



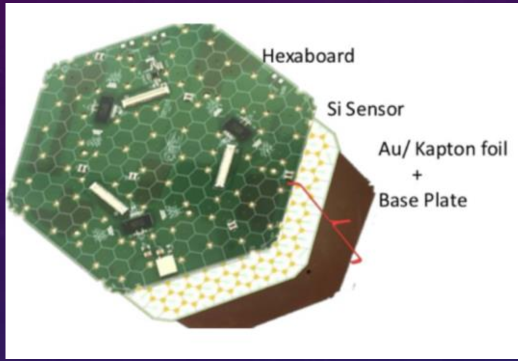


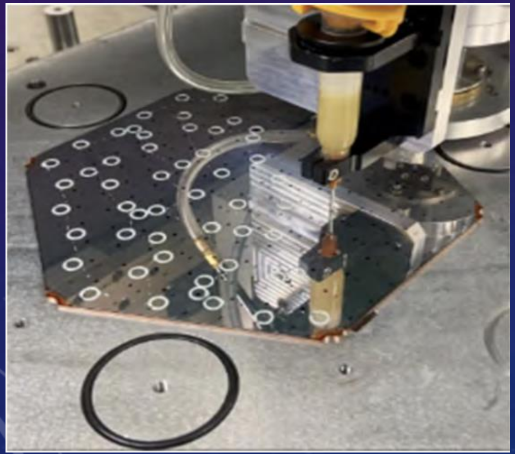


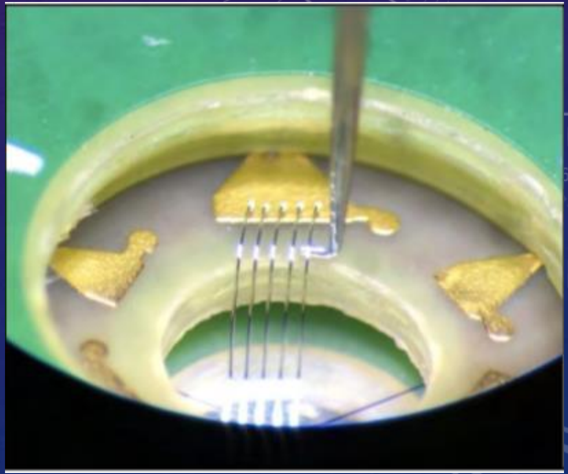
8” Silicon Sensor Modules

The Silicon Sensor Modules of the CMS HGCAL

The HGCAL silicon modules include **a base plate onto which the sensor is glued**. A front-end read out PCB **“Hexaboard” is then glued on top of the silicon, which covers the full area of the sensor**. The Hexaboard is connected to the sensor by wire bonds via through holes in the PCB. The base plate is made of Cu/W for the Electromagnetic section of the calorimeter, where it forms part of the absorber, and a simple PCB for the hadronic part. A Kapton foil is laminated onto the baseplate to provide both bias (high) voltage DC protection as well as AC de-coupling of the silicon sensor backside.



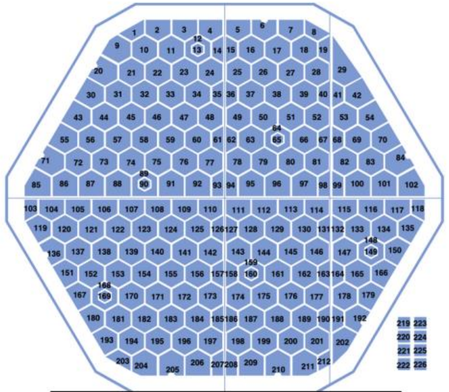




8” Silicon Sensor Modules

The Silicon Sensor Modules of the CMS HGCAL

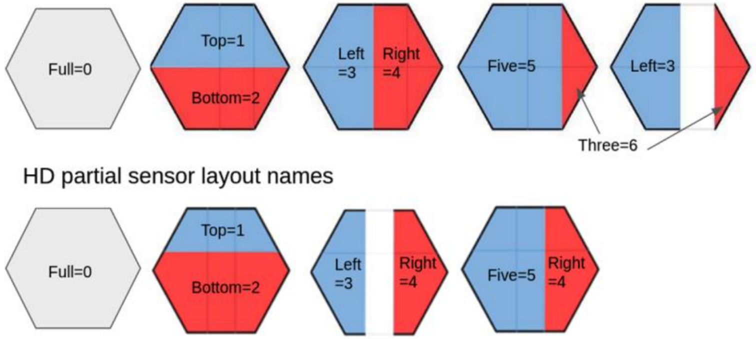
- Multi-geometry wafers (MGW) produced to tile inner and outer edges of HGCAL's sensitive layers.



LD MGW sensor layout

LD partial sensor layout names

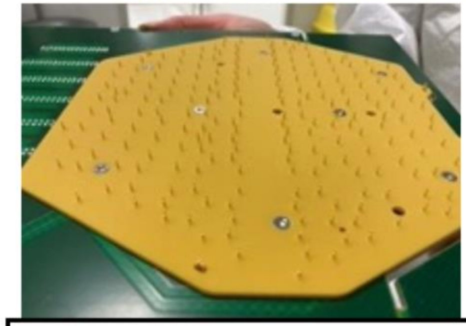
HD partial sensor layout names



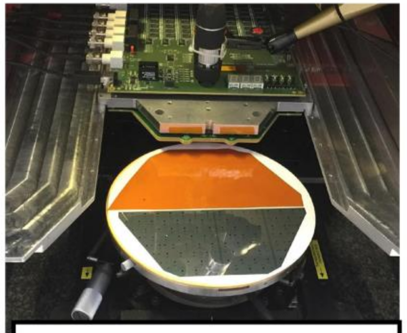
3-4 dicing types

2x20 LD and 2x12 HD partials arrived in February 22

- Qualification of testing procedure completed at CERN. Distribution of equipment and procedures to CMS institutes soon.



New LD MGW probe cards.
Pins for HD card were delayed by three months.



Cover missing Si area with Kapton foil during tests

Established workflow for all partial types, e.g. new xy-alignment concept

Eva Sicking | P2UG May 2022, 11 May 2022

8

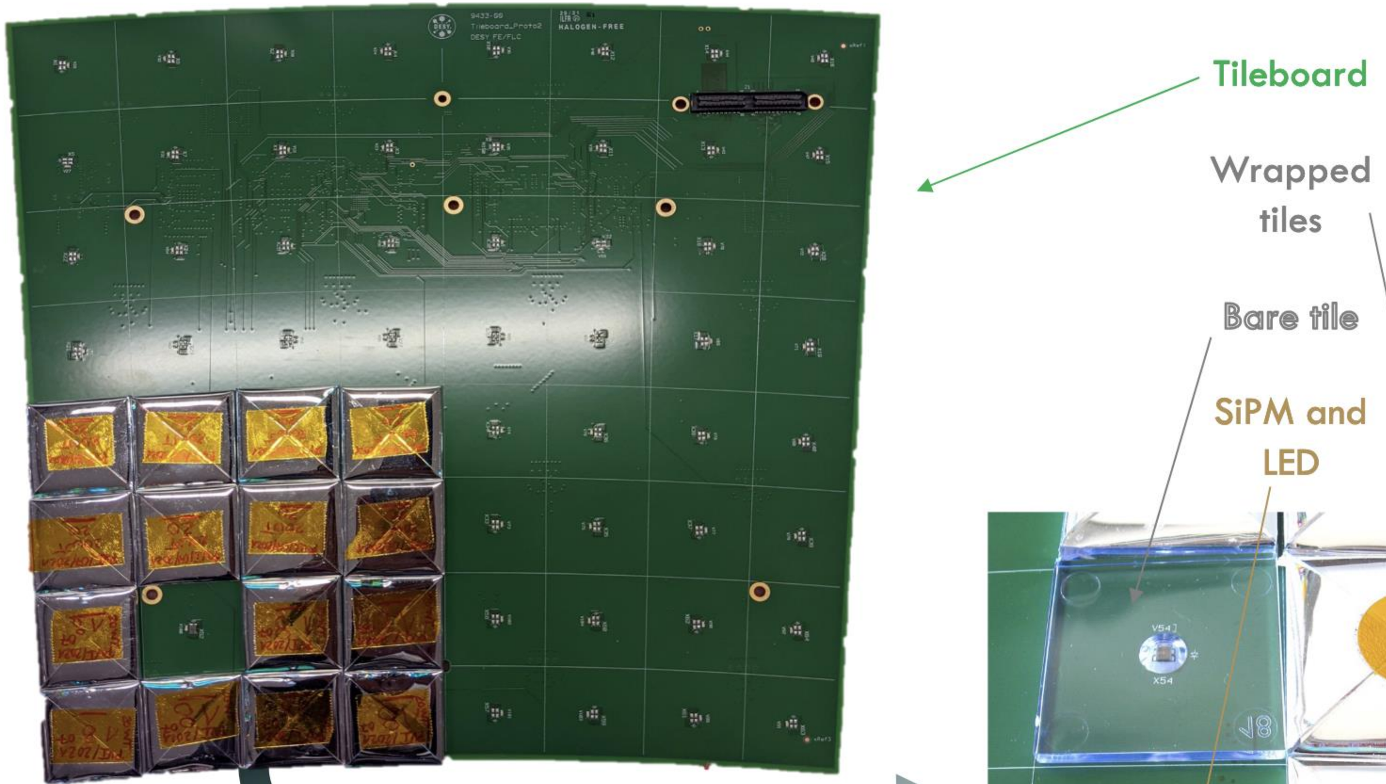
The SiPM on tile Modules of the CMS HGCAL

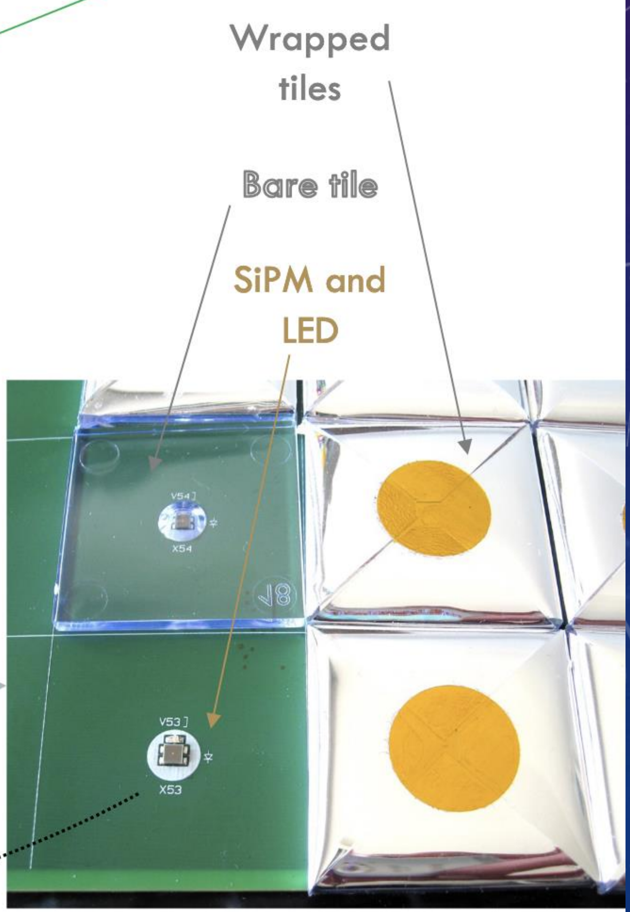
"Tile board" PCB

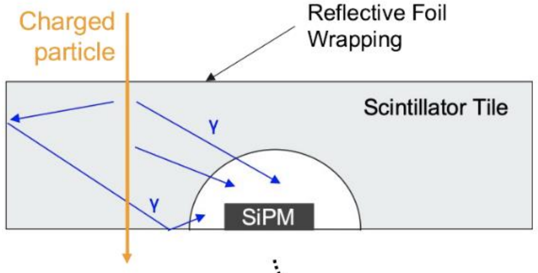
- Connects Silicon photo multipliers (SiPM) to HGCROC ASIC.
- Connects to motherboard for control and data transfer.

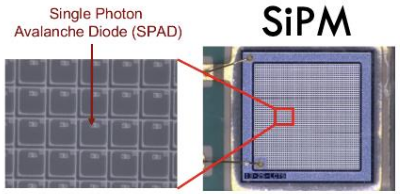
Wrapped scintillating tiles

- Reflective foil wrapping.
- Light collected by SiPM.
- Light injection LED.







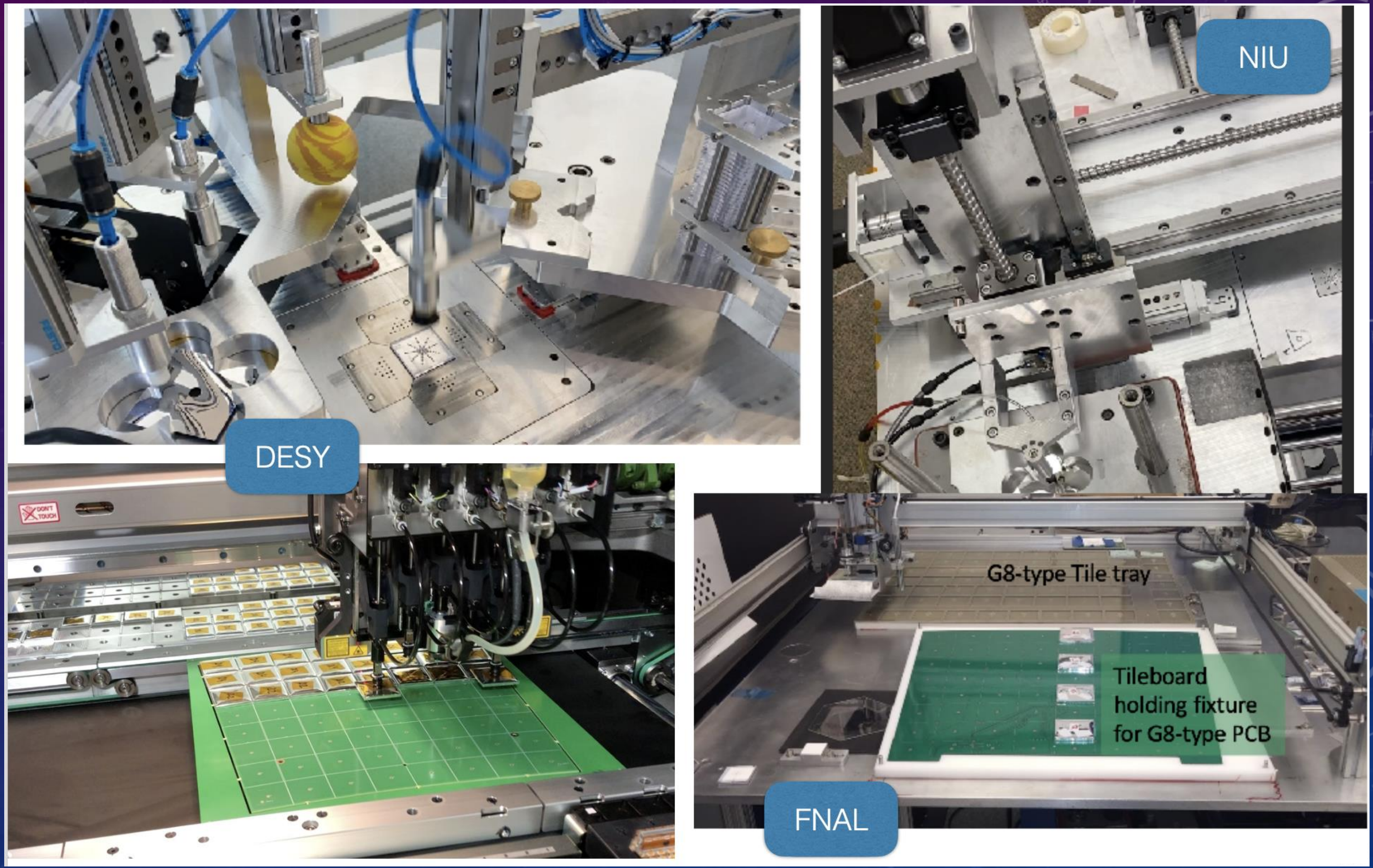


@ichep2022 - HGCAL performance

@DRANDREDAVID @CERN

The SiPM on tile Modules of the CMS HGCAL

Automatic tile wrapping and pick-and-place machines developed **to ensure high reproducibility and tight tolerances for the ~240'000 tiles of the CMS HGCAL.**



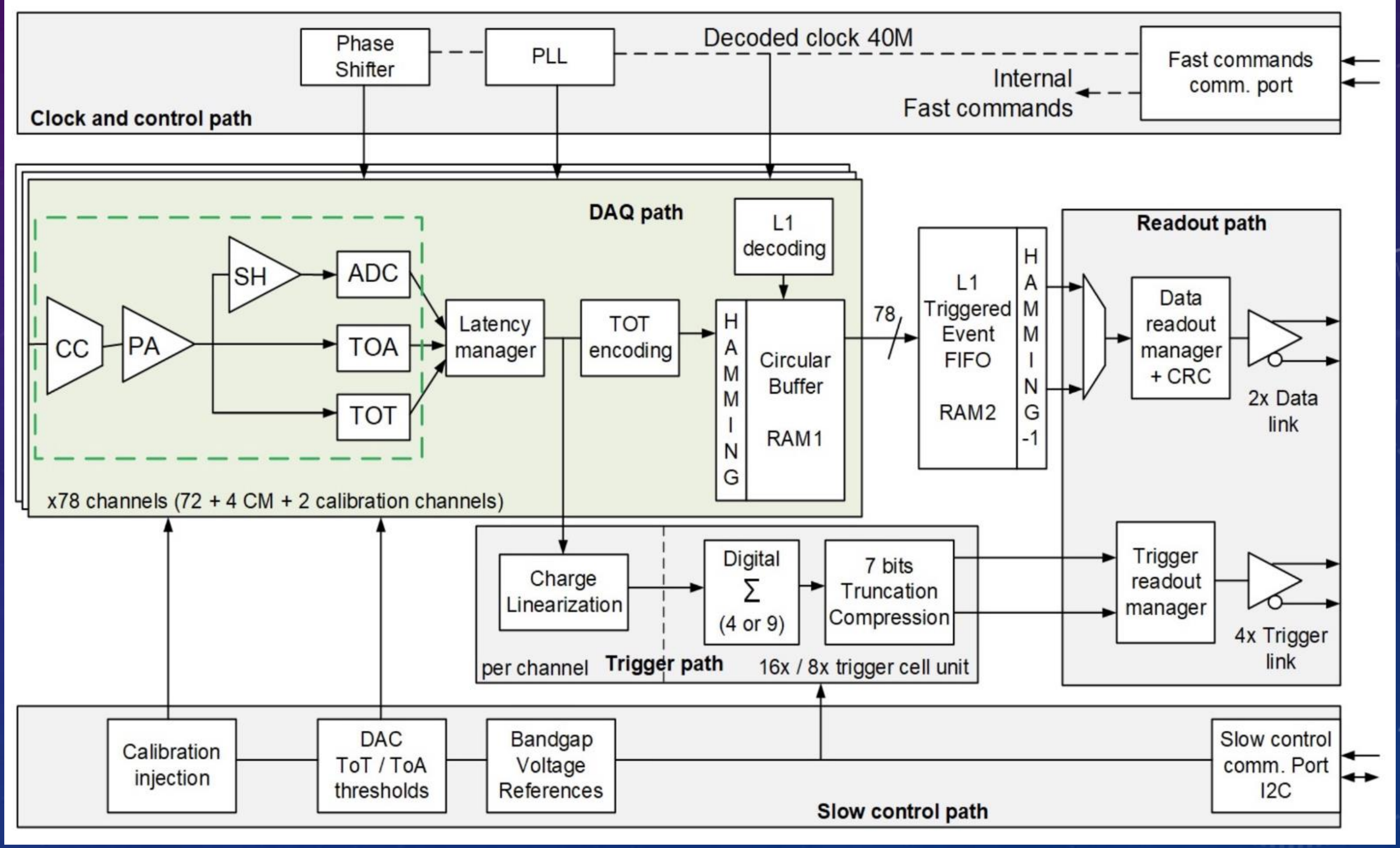
The Front End ASICs of the CMS HGCAL

HGCROC:
- Covers full dynamic range of HGCAL, for both silicon and SiPM-on-tile with small adaptations

Analogue architecture:
- Programmable pre-amplifier gain
- ADC for small values: 10-bit 40 MHz SAR
- TOT TDC after preamplifier saturates: 12-bit, 50ps LSB
- Timing: TOA TDC 10-bit and 25ps LSB

Outputs 1.28 Gb/s:
- Trigger primitive data: Sum of 4 (9) channels, linearization, compression to 7-bit floating point
- DAQ event data: 12.5 µs latency buffer (500-deep) for ADC/TOT/TOA.
- 32-event de-randomizer buffer (750 kHz av. trigger rate).

Control:
- Synchronous fast control: 320 MHz (8 bit @ 40 MHz)
- Asynchronous slow control: I2C



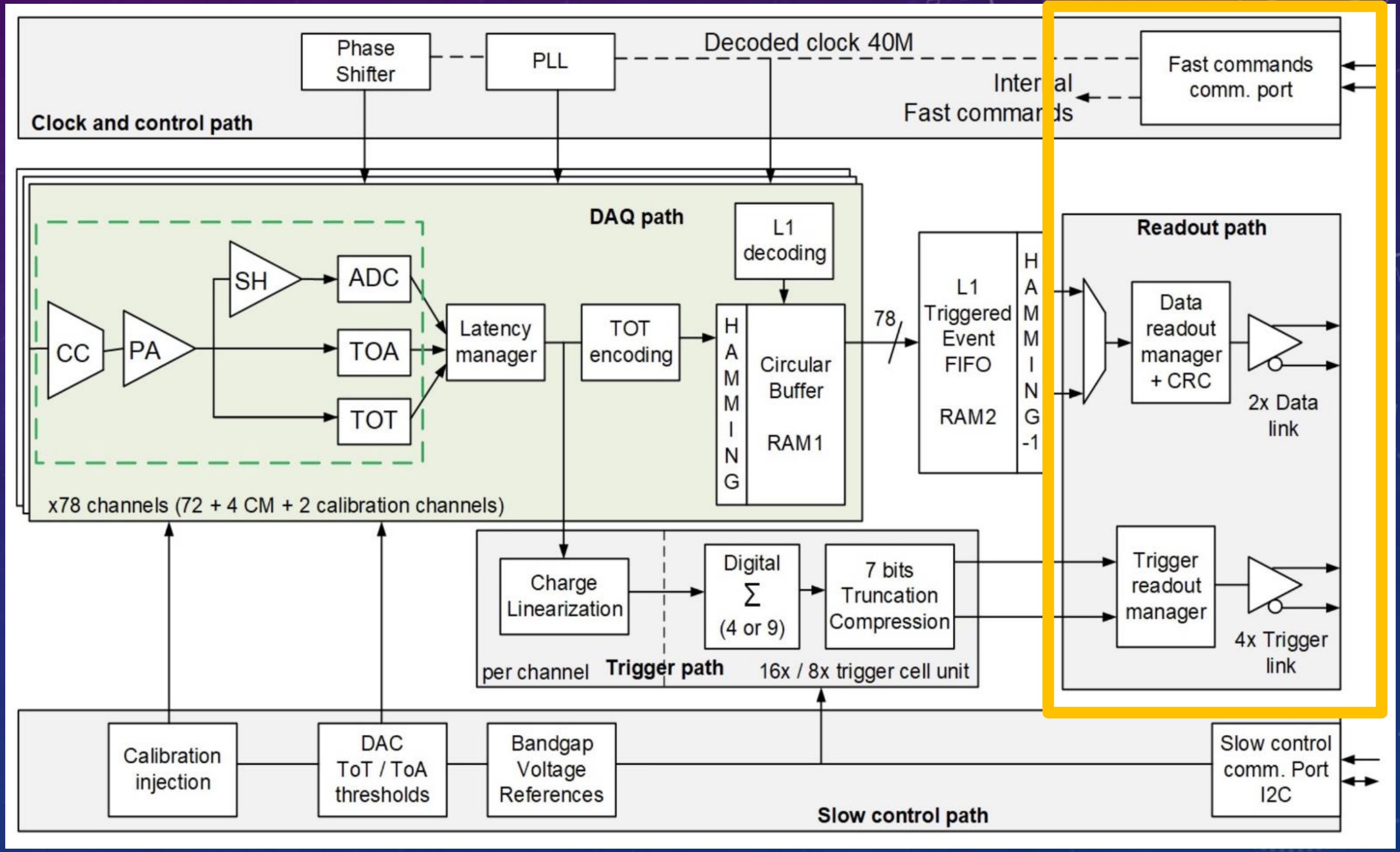
The Front End ASICs of the CMS HGCAL

ECON-T: FRONTEND CONCENTRATOR CHIP FOR TRIGGER PATH, CONCENTRATES TRIGGER DATA VIA ONE OF 4 TRIGGER ALGORITHMS

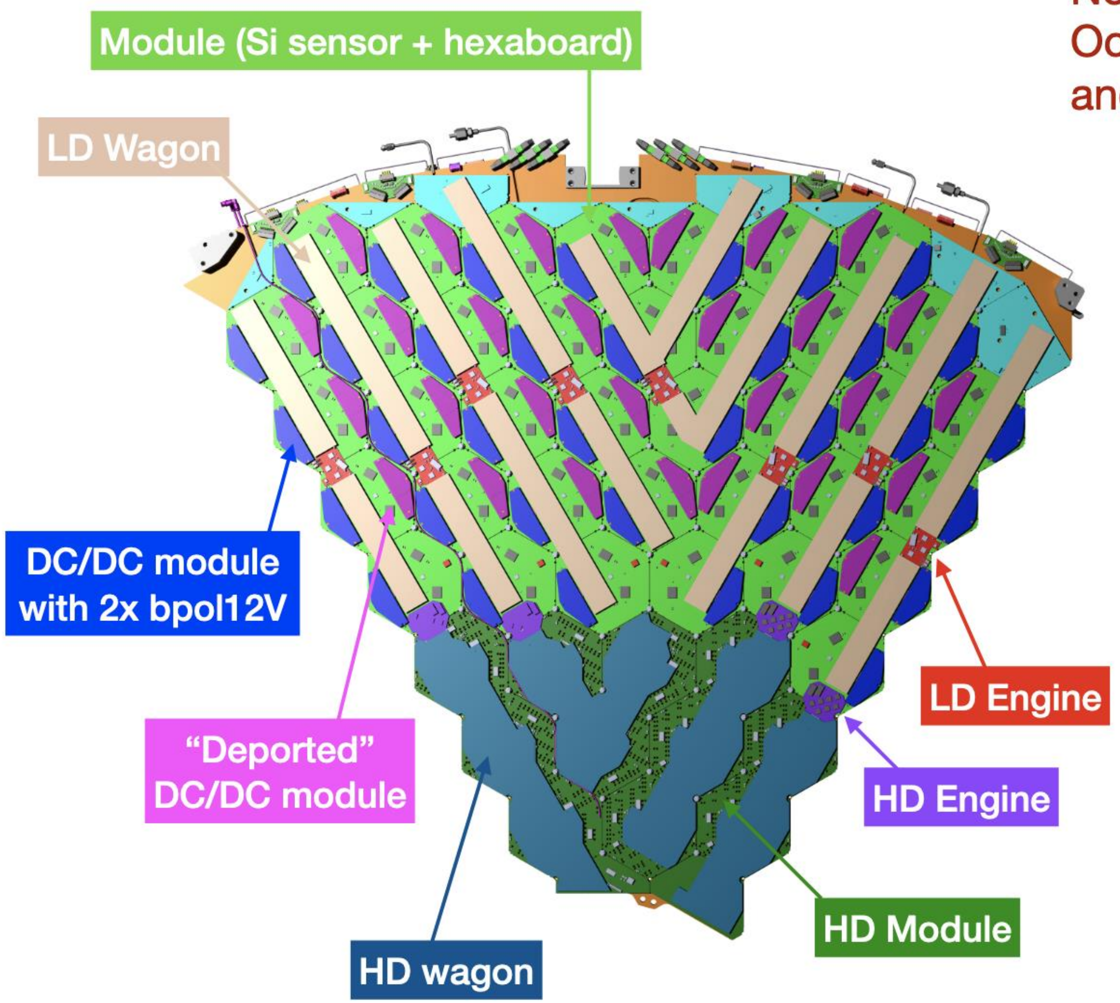
ECON-D: FRONTEND CONCENTRATOR CHIP FOR DAQ PATH, PERFORMS CHANNEL ALIGNMENT AND ZERO SUPPRESSION AFTER L1 ACCEPT

RAFAEL: CLOCK AND FAST CONTROL FANOUT

LPGBT: FOR SENDING/RECEIVING DATA/CLK/CONTROL SIGNALS VIA OPTICAL LINK (AND VTRX+)



The Front End Electronics system integration of the CMS HGCAL



Note: each layer is different! Occupancies vary greatly within and between layers

Low density region
- Si sensor 200 or 300 µm thickness
- 192 channels (3 HGCROC) per 8" hexagonal module

High density region
- Si sensor 120 µm active thickness
- 432 channels (6 HGCROC) per 8" hexagonal module

The Front End Electronics system integration of the CMS HGCAL

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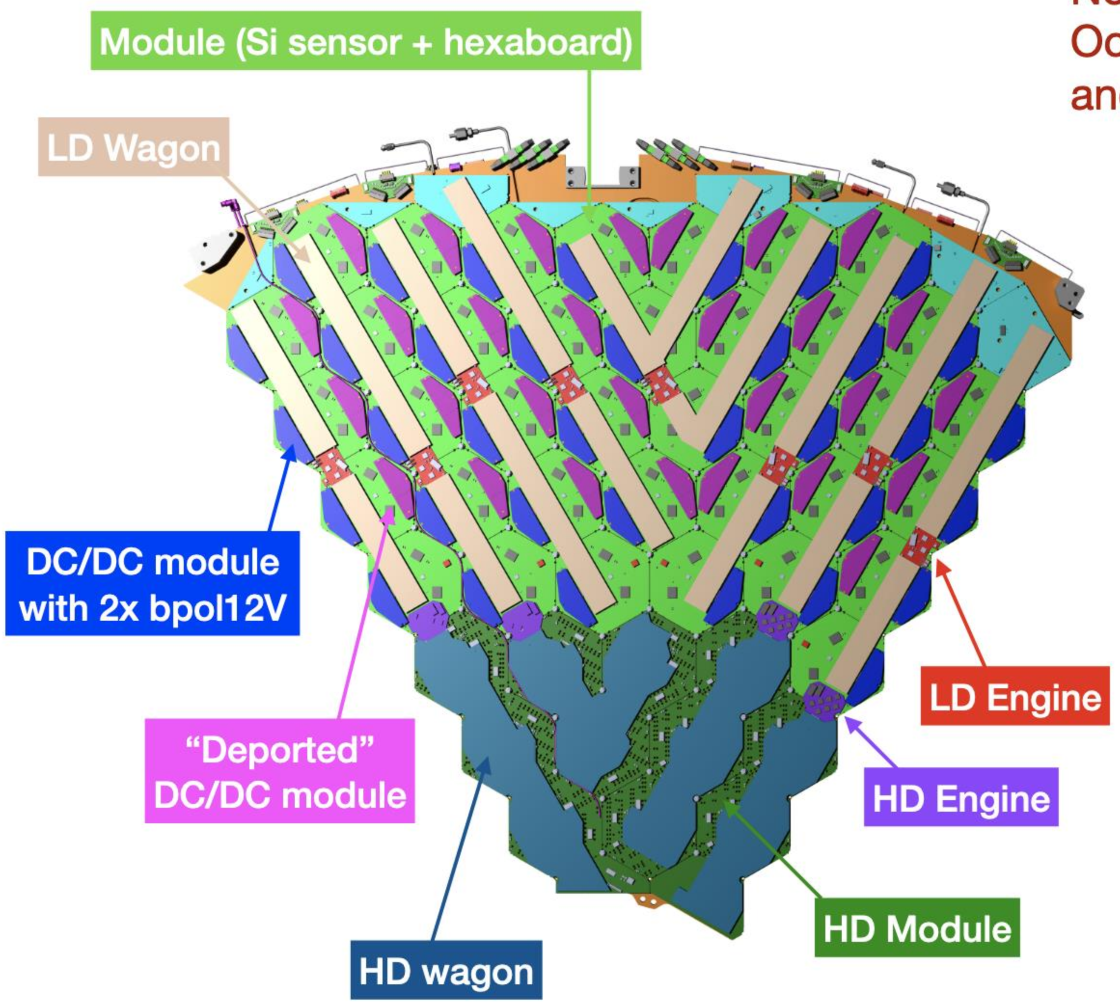
Occupancies vary greatly within and between layers



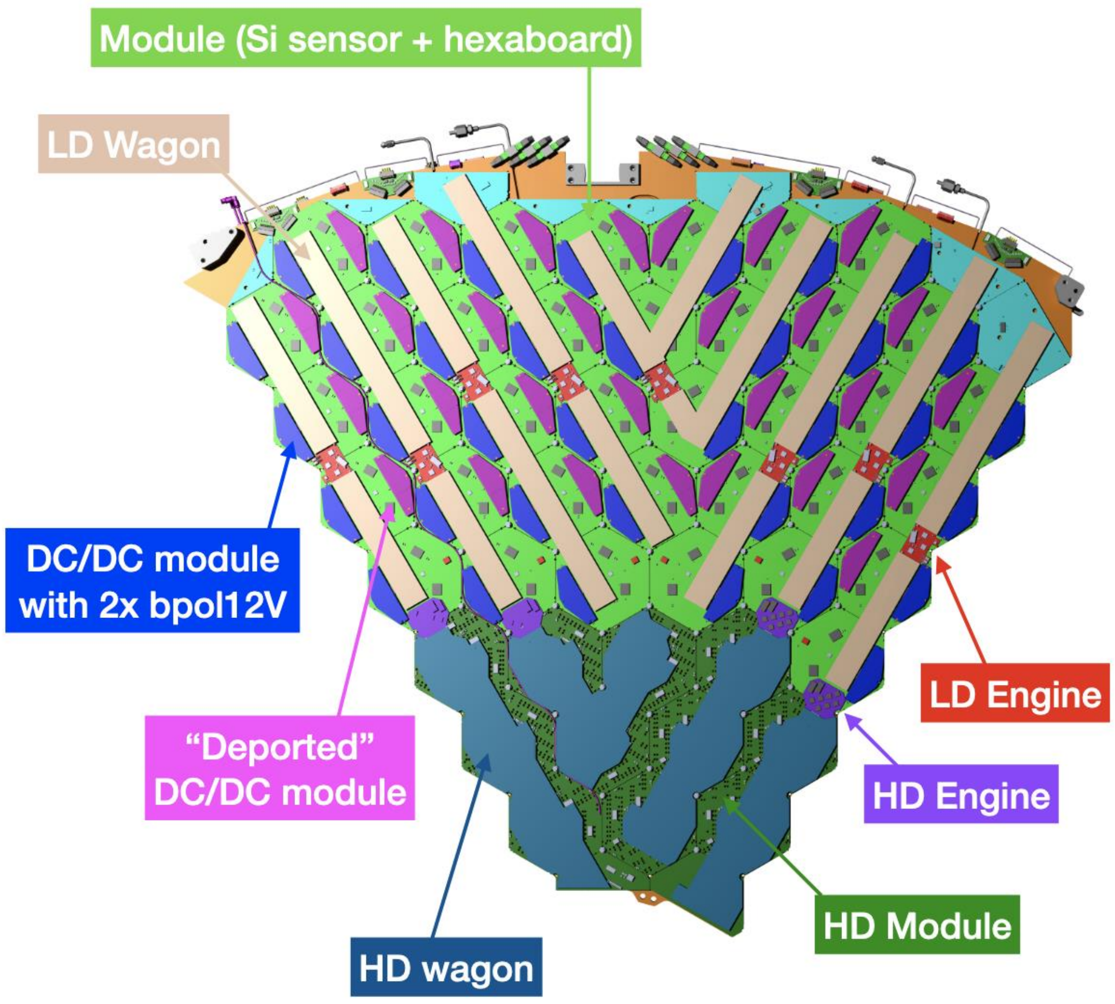
Readout train = engine + wagon(s)

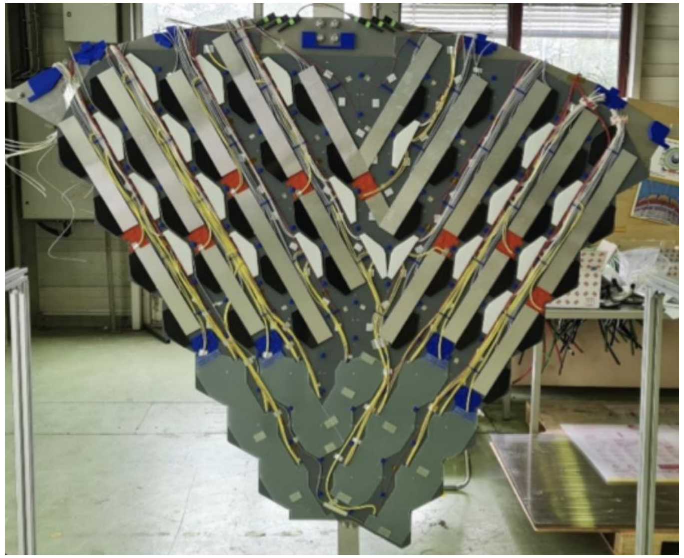
Engine:
- complex components
- few varieties

Wagons:
- "rigid wires" absorb the geometrical complexities
- many varieties

Additional design constraints from need to route services

The Front End Electronics system integration of the CMS HGCAL

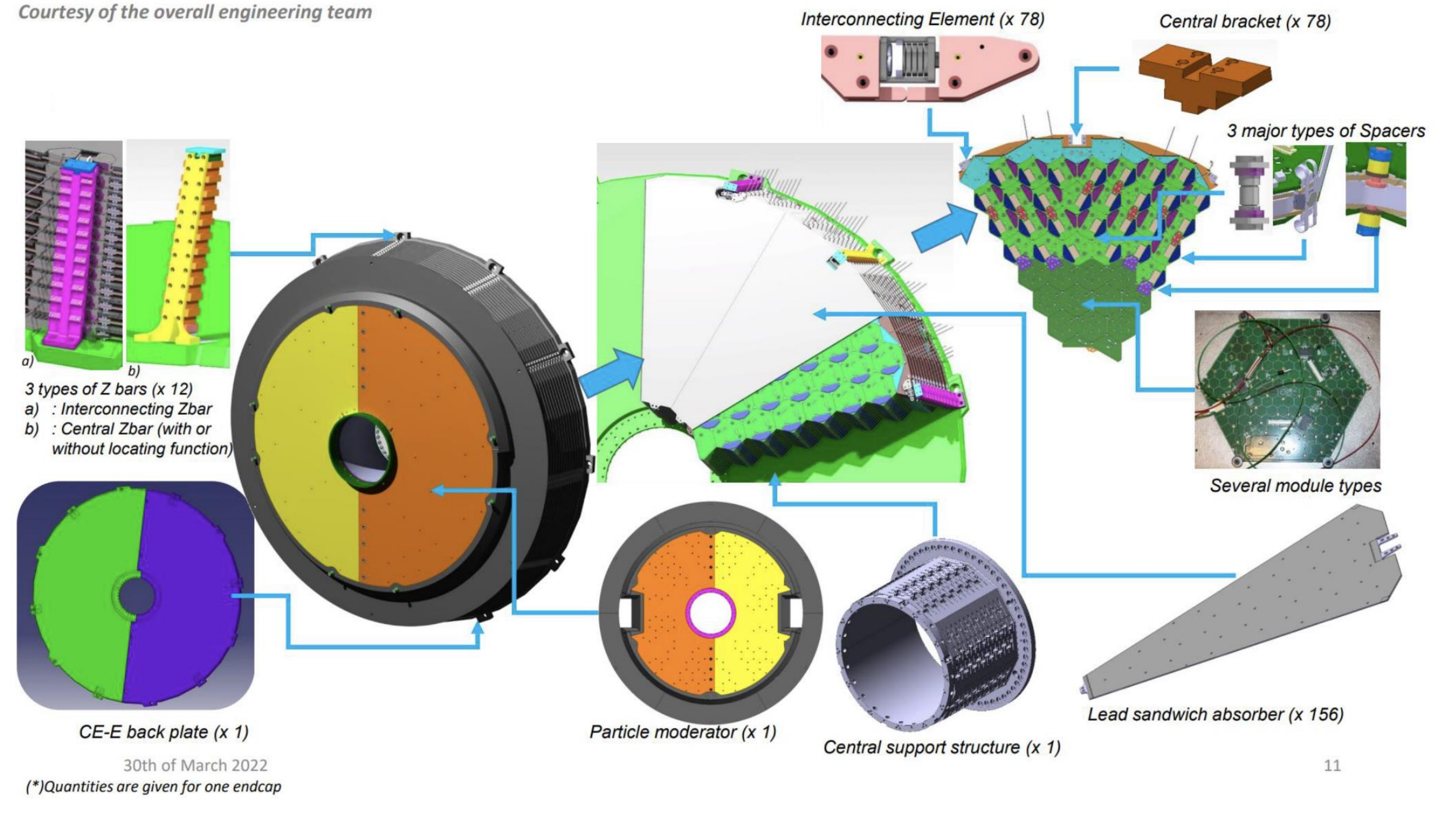




The Mechanics of the CMS HGCAL

- High precision
- High density
- High mass
- Warm-cold transition
- Services integration

ElecroMagnetic section



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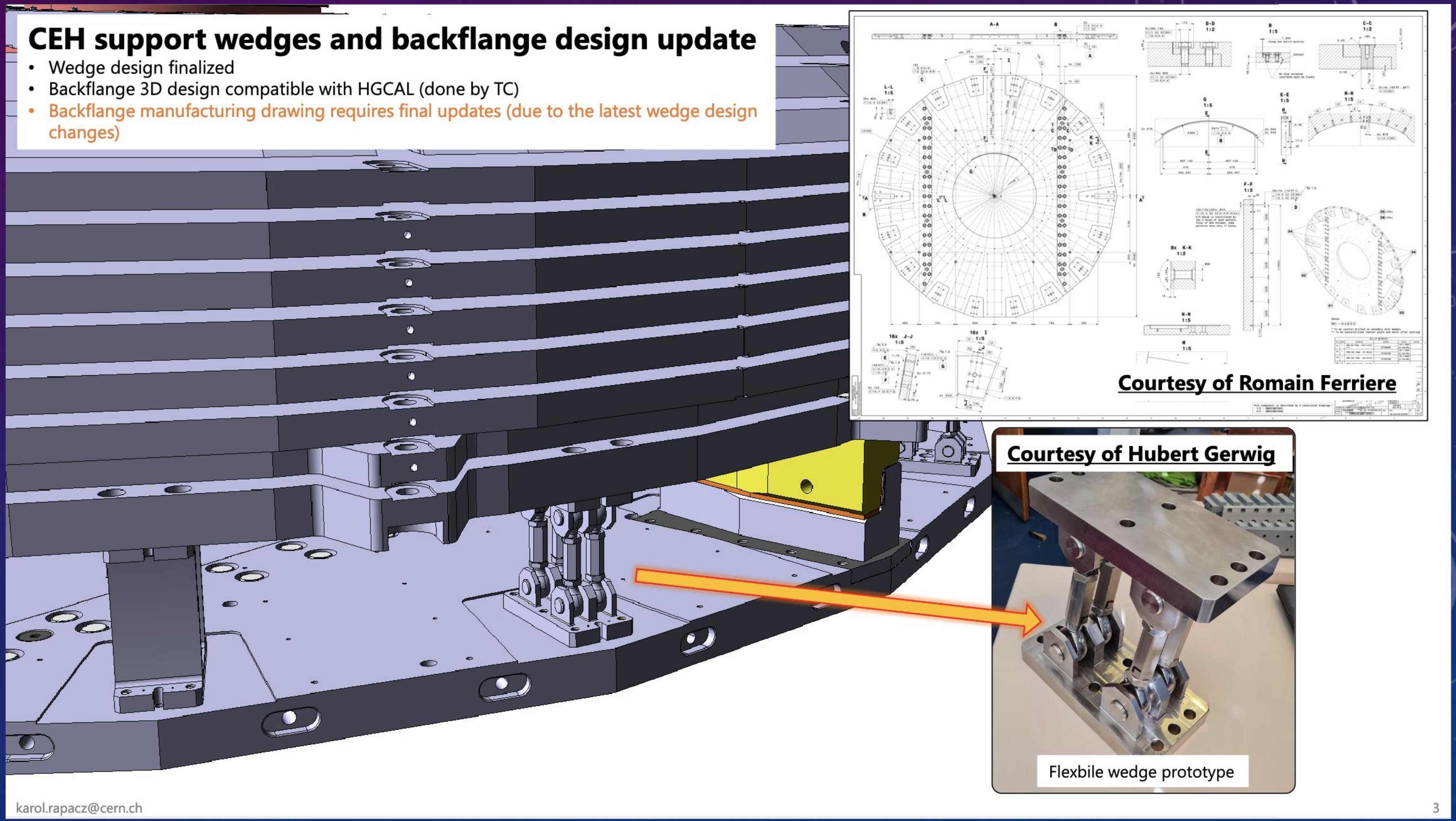
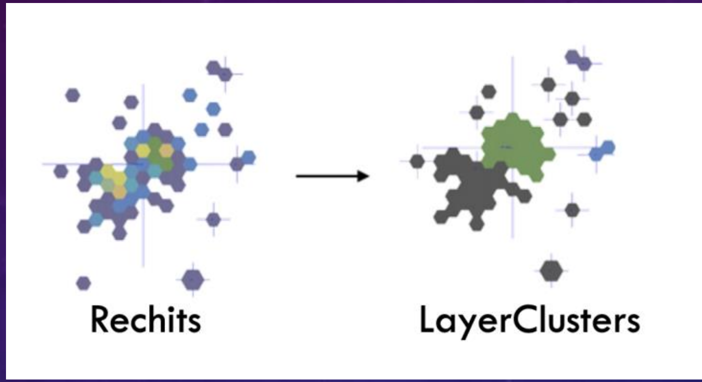


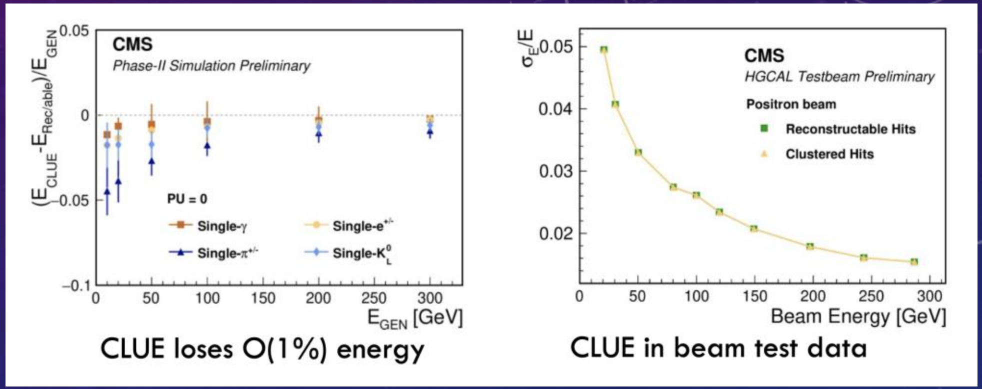
Looking ahead: the Performance Potential of the CMS HGCAL

Clustering based Reconstruction

CLUE – algorithm for energy Clustering within singe layers

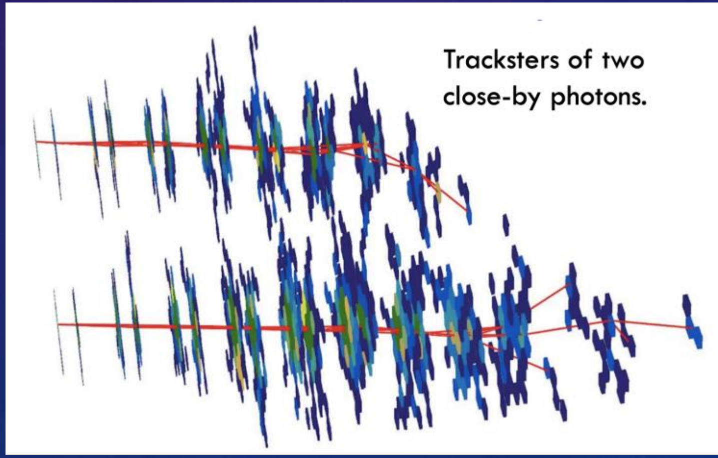
- **Rechits -> 2D Layer Clusters**
- Combinatorics reduced ~10x
- Parallelized, runs on GPUs.
- Tested with test-beam data.

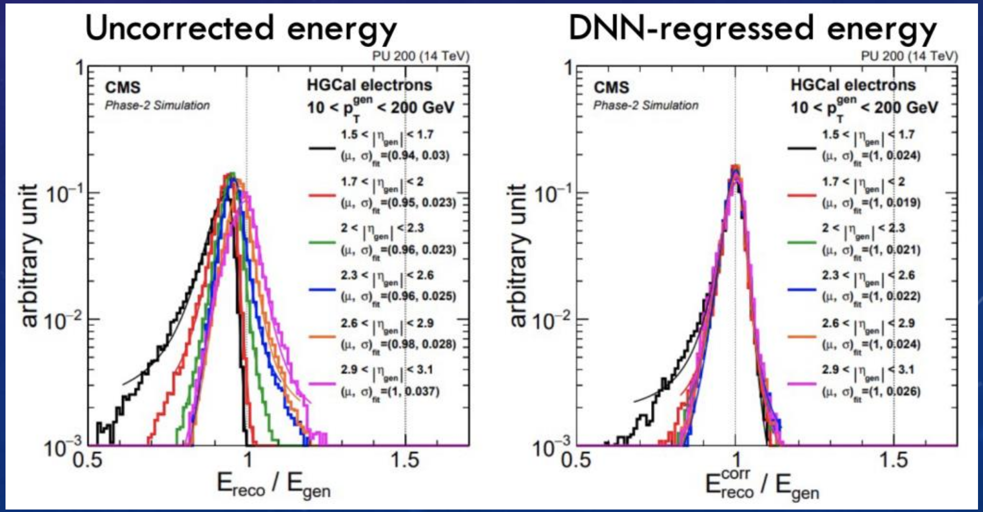




TICL – The Iterative Clustering

- **2D Layer Clusters -> 3D Tracksters** (showers/particles)
- Trackster information regressed with ML techniques.



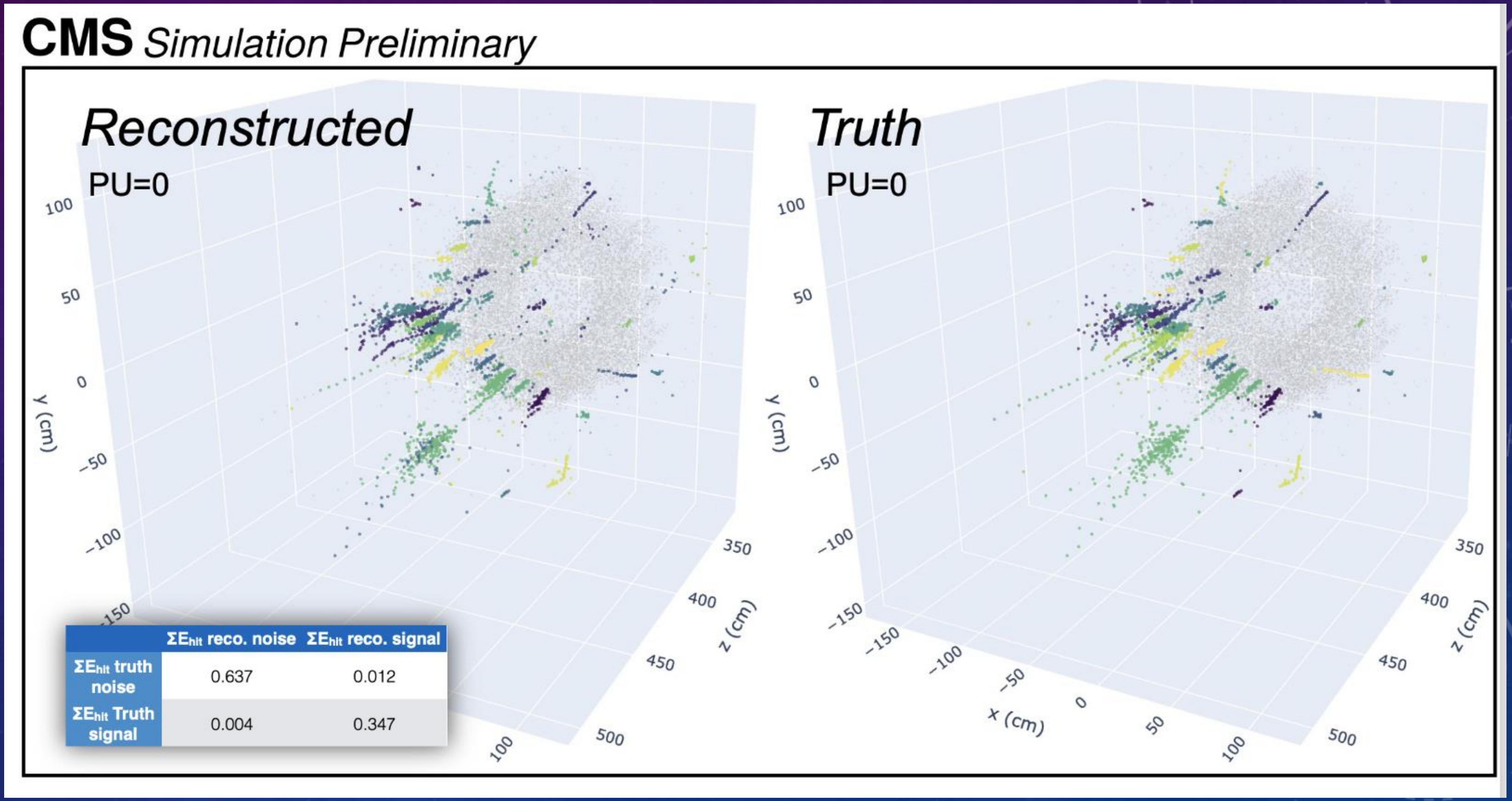


Looking ahead: the Performance Potential of the CMS HGCAL

END-TO-END MACHINE LEARNING RECONSTRUCTION

Rechits -> 3D Showers/Particles

- Two-stage model with:
- Noise filter to identify bulk of (uninteresting) hits.
- GravNet graph neural network performs clustering on cleaned data.
- Promising performance
- Studying physics performance on single particles



	ΣE$_{hit}$ reco. noise	ΣE$_{hit}$ reco. signal
ΣE$_{hit}$ truth noise	0.637	0.012
ΣE$_{hit}$ Truth signal	0.004	0.347

Two tau leptons, each decaying hadronically to $\pi^{\pm}\pi^{0}$ - Zero Pile up

The CMS HGCAL: Outlook

- The technology choices and ky design parameters of the CMS HGAL were driven by the HL-LHC environment and physics goals: the result is a calorimeter with unprecedented characteristics, aimed at enabling CMS to make best use of the HL-LHC physics potential

- The HGCAL leverages longstanding experience with large scale silicon detectors, together with extensive R&D and large scale prototyping for SiPM-on-tile technology (CALICE)
- And relies crucially on state-of-art ASICs design know within the HEP community
- It is nevertheless a substantial step up in both scale and complexity compared to any other existing semi-conductor based detector

- Very good progress continues to be made, and the project is transitioning from large scale prototyping to system validation and qualification, and the start of production of key components: but much work still lies ahead