System Validation of the SiPM-on-Tile Section of the CMS High Granularity Calorimeter

DPG – Calorimeters Session

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05.02.2024

Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

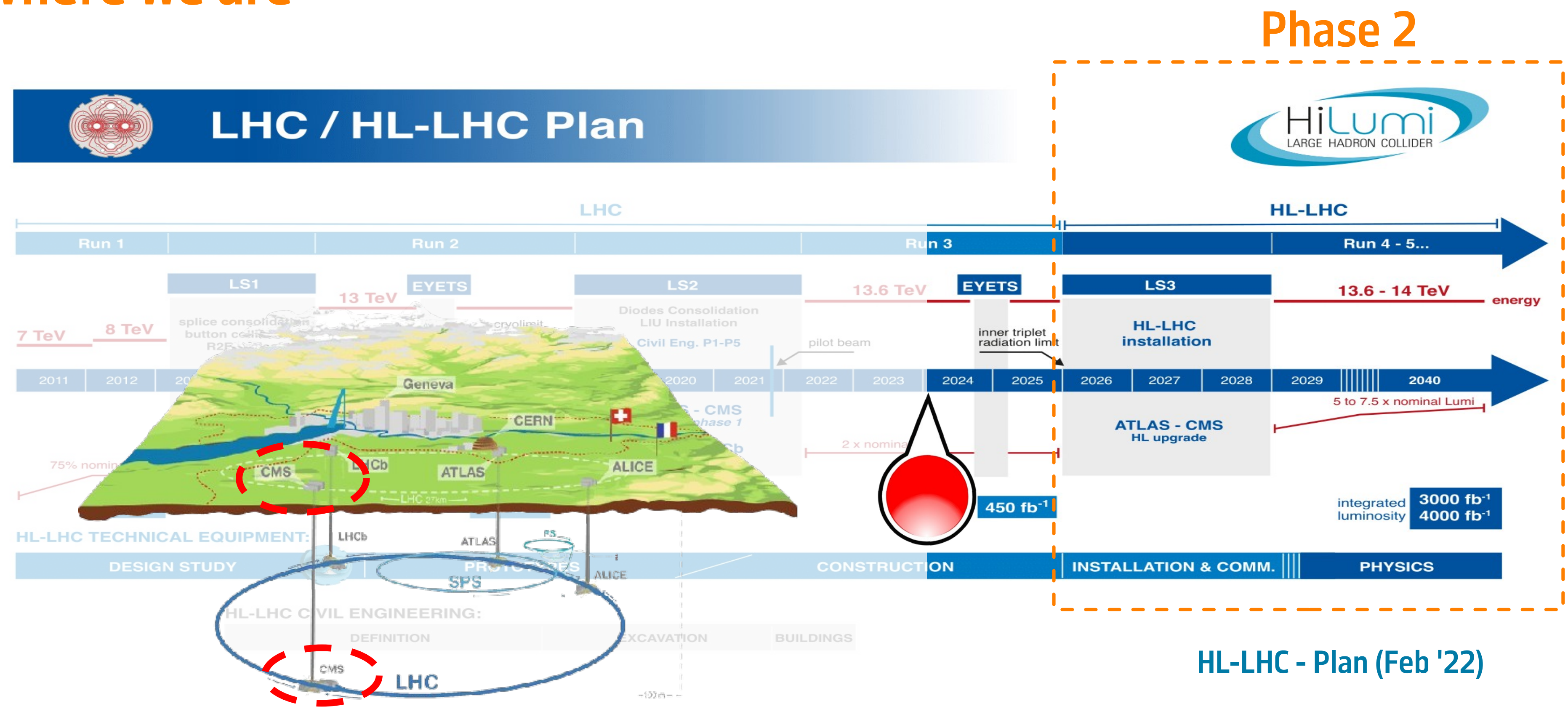
DESY.

DESY HGCAL
CMS High-Granularity Calorimeter

CMS

Future at CERN: HL-LHC

Where we are



HL-LHC - Plan (Feb '22)

Future at CERN: HL-LHC

A "bright" future

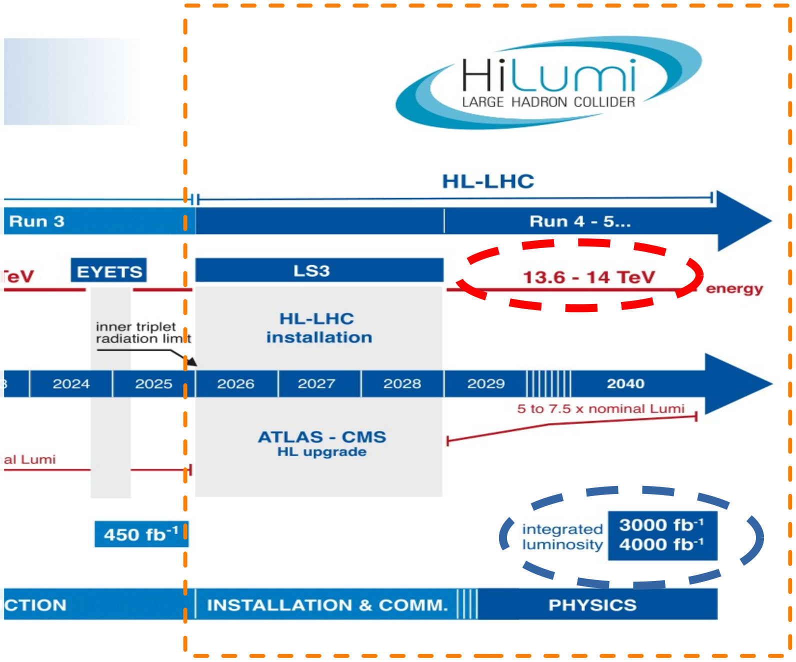
Phase 2 → Pushing LHC to the limit…

- Up to 4000 fb^{-1} of integrated luminosity over 10 years
- 14 TeV centre-of-mass energy

…which comes with

- Pile-up of 140 to 200/BX
- High radiation environment

Major CMS detector upgrades needed



HL-LHC - Plan (Feb '22)

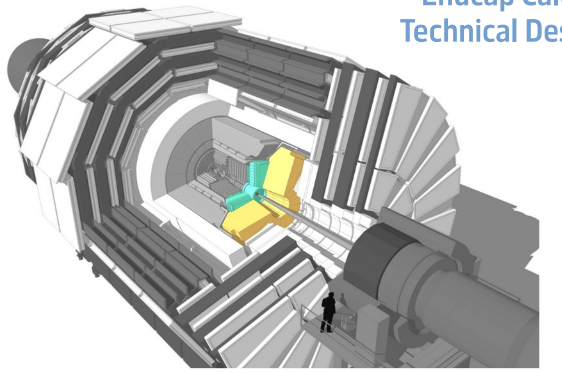
CMS during HL-LHC

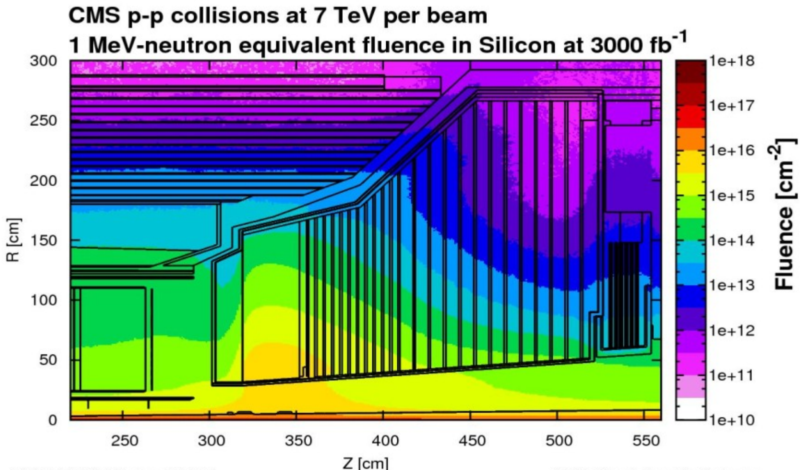
The challenges in the forward regions

- Radiation levels **equivalent** as in the region of the inner pixel trackers
  → Highest fluence of 10^{16} n_{eq}/cm^2 (2 MGy) after 3000 fb^{-1}
- Significant **engineering demands**
  - Dense calorimeter in tight space constraints
  - Fine lateral and longitudinal granularity
- **Unprecedented** number of trigger and data information
  - Online pileup mitigation needed
  - Dedicated offline reconstruction algorithm

→ Existing endcap calorimeter to be replaced by the **High Granularity Calorimeter**

"The Phase-2 Upgrade of the CMS Endcap Calorimeter" Technical Design Report



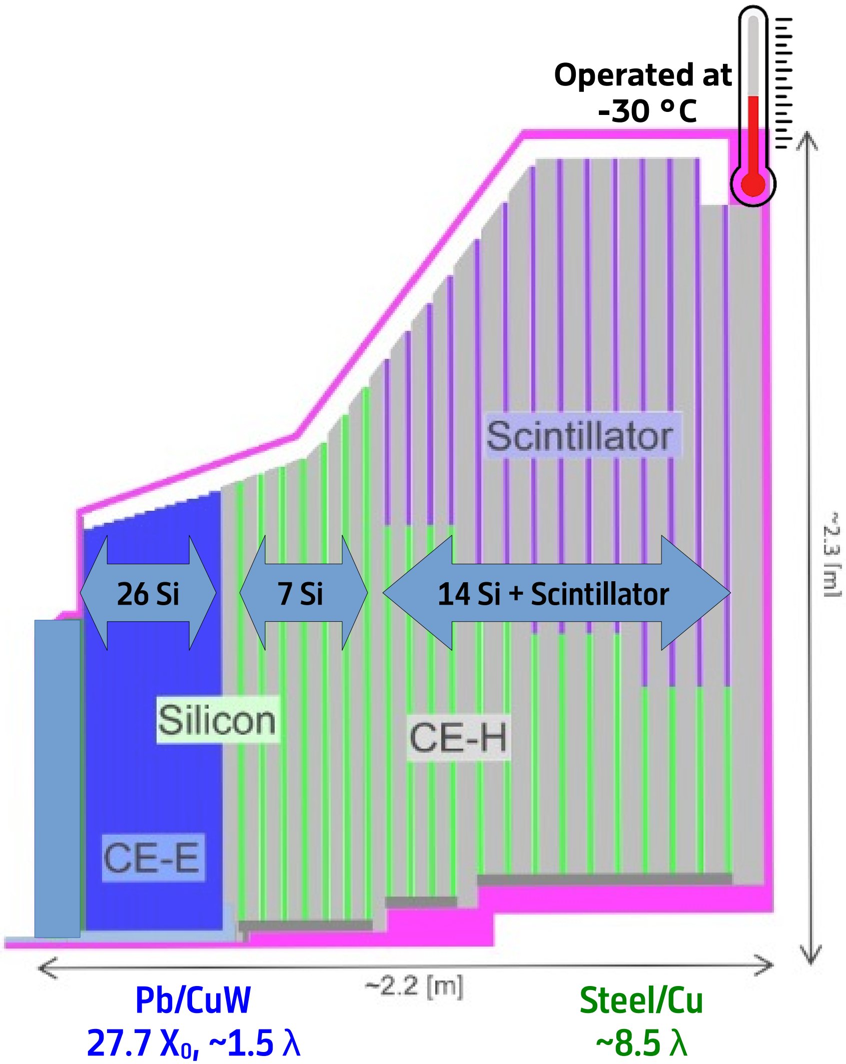


The HGCAL Project

5D Imaging Calorimeter

- High Granularity Sampling Calorimeter
  - 5D imaging calorimeter:
    3D spatial granularity, energy, timing information
  - Two separated sections in one single detector

- **Active Materials**
  - Silicon Sensors (CE-E and CE-H)
    - Hexagonal 8" wafers
    - **6M pads** (~620 m^2)
  - Plastic Scintillators with SiPM readout (CE-H)
    - **240k** scintillator tiles (~370 m^2)



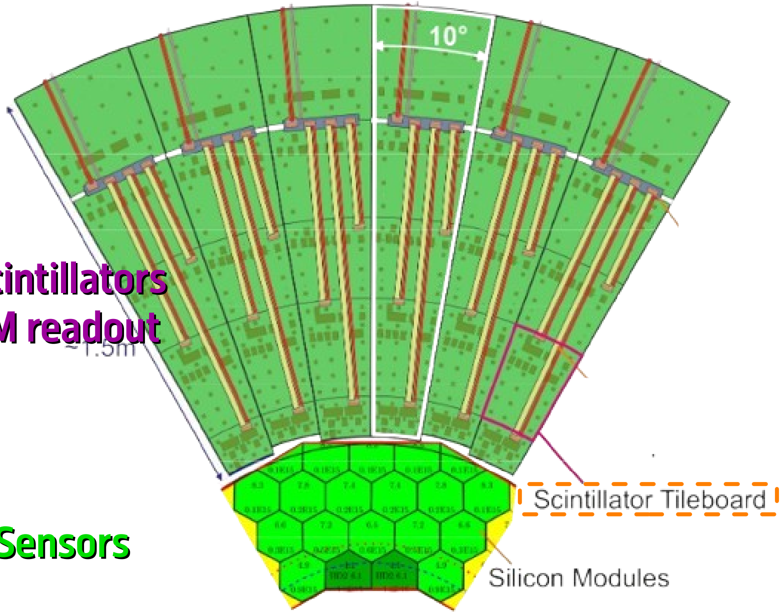
The CE-H Section

Mixed Design

Transverse View

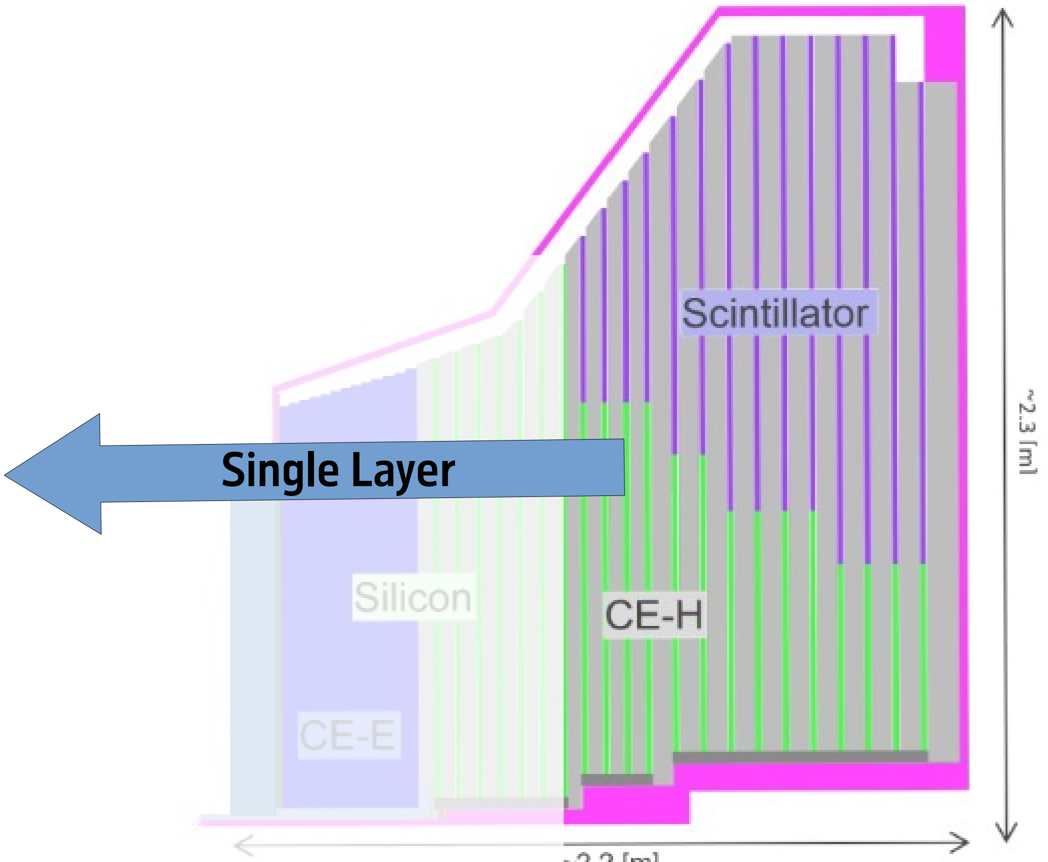
Plastic Scintillators with SiPM readout

Silicon Sensors



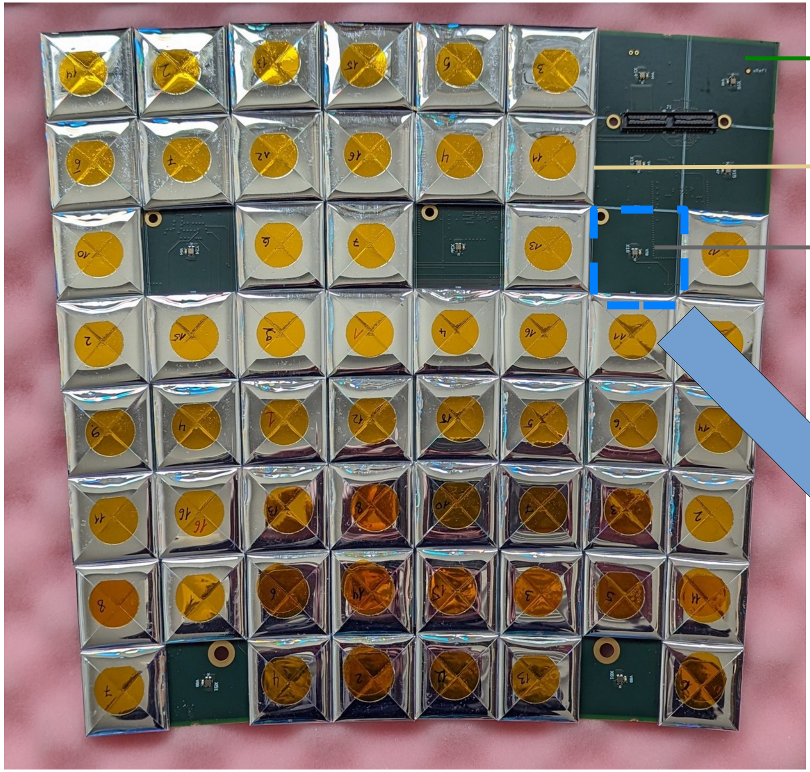
60° Mixed Design "Cassette"

Operated at -30 °C



Scintillator Tileboard

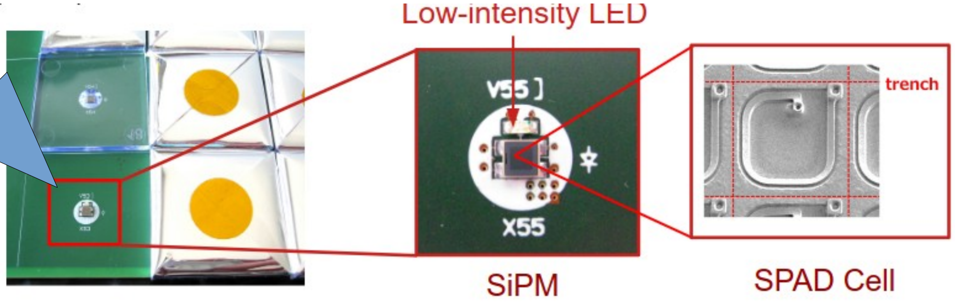
SiPM-on-tile



Tileboard (TB) PCB
Hosting the readout chip

Wrapped Scintillating tile
Reflective foil

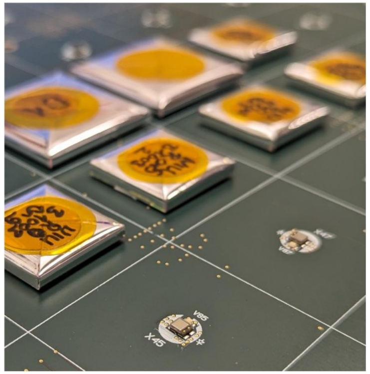
Silicon PhotoMultiplier (SiPM)
Calibration with LED

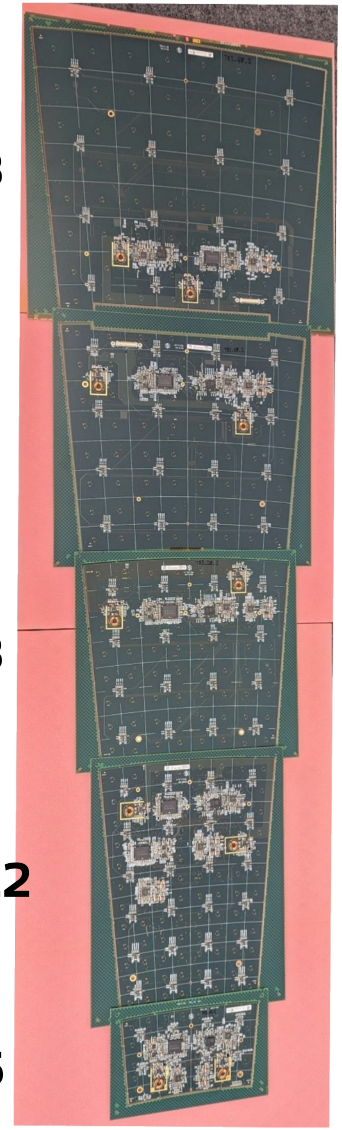


Production at DESY

Workflow

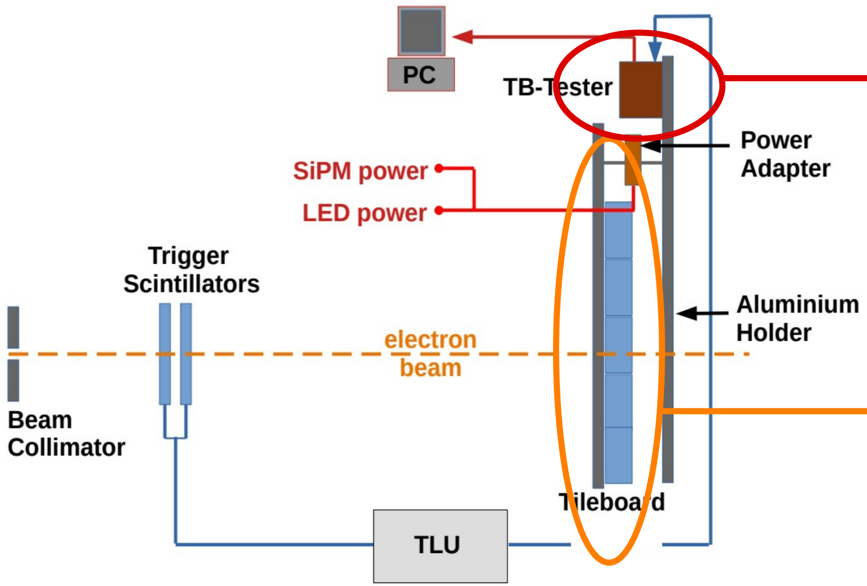
- DESY is Tilemodule Assembly Center (**TAC**)
  - Tilemodule production
  - QC from small components to full-stack
    - Different board designs
    - Different tile materials and sizes
    - Different SiPMs sizes
  - Test in laboratory and test beam

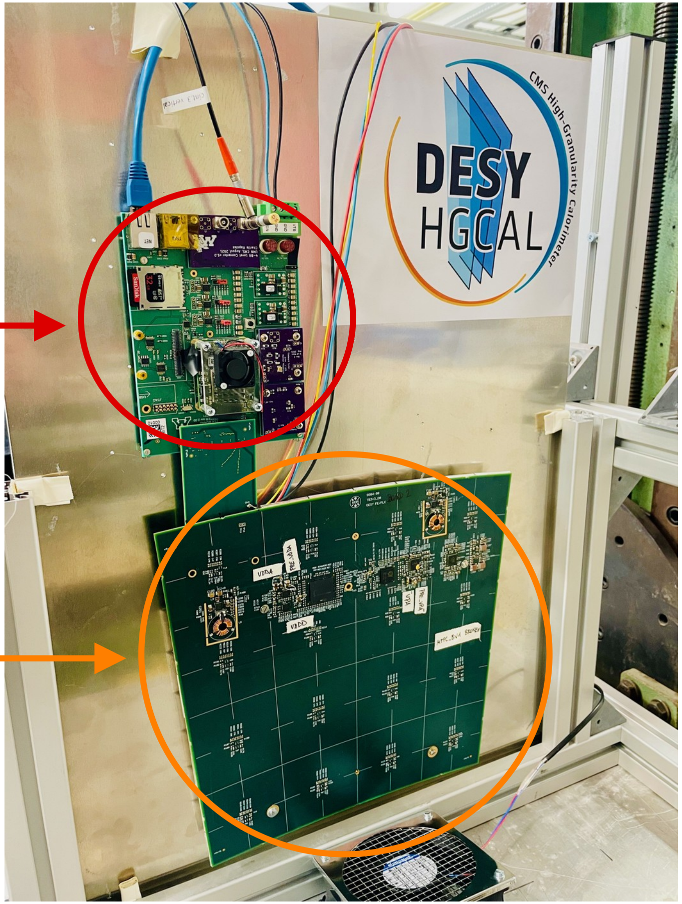




Test Beam Campaigns

Setup





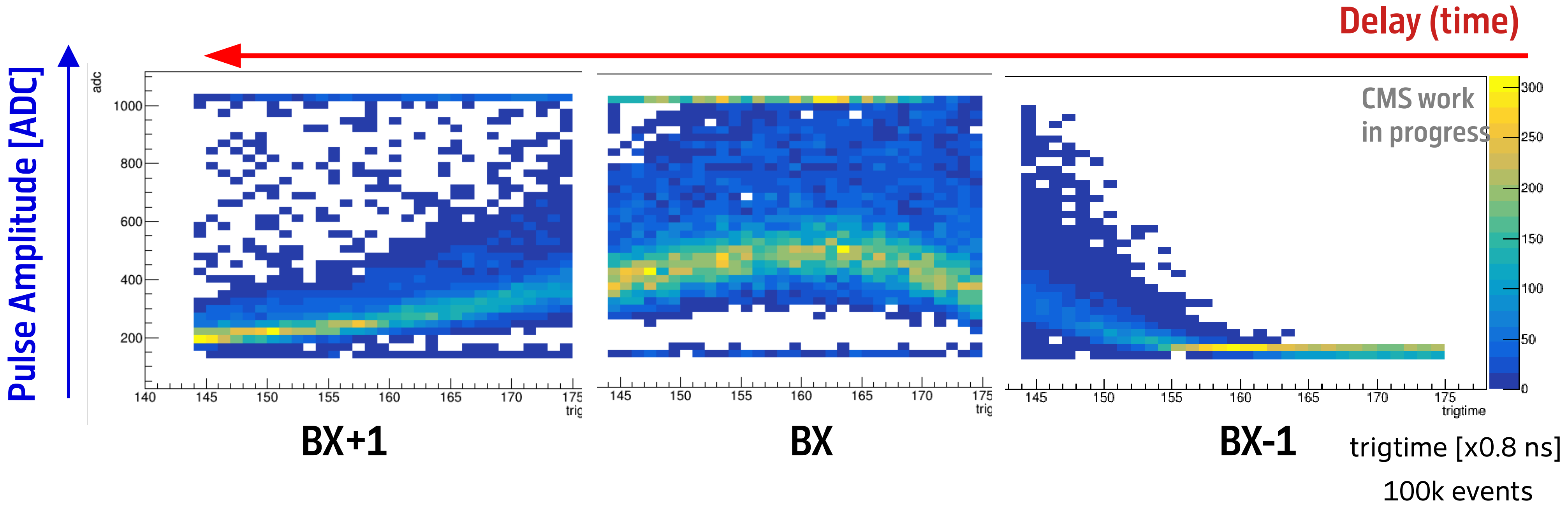
Tiles on the other sides!

- DESY II test beam facility (>10 campaigns since 2020)
  - 3 GeV electron beam → Minimum Ionizing Particle (MIP)

Test Beam Results

Pulse Shape Reconstruction of 3 GeV electron

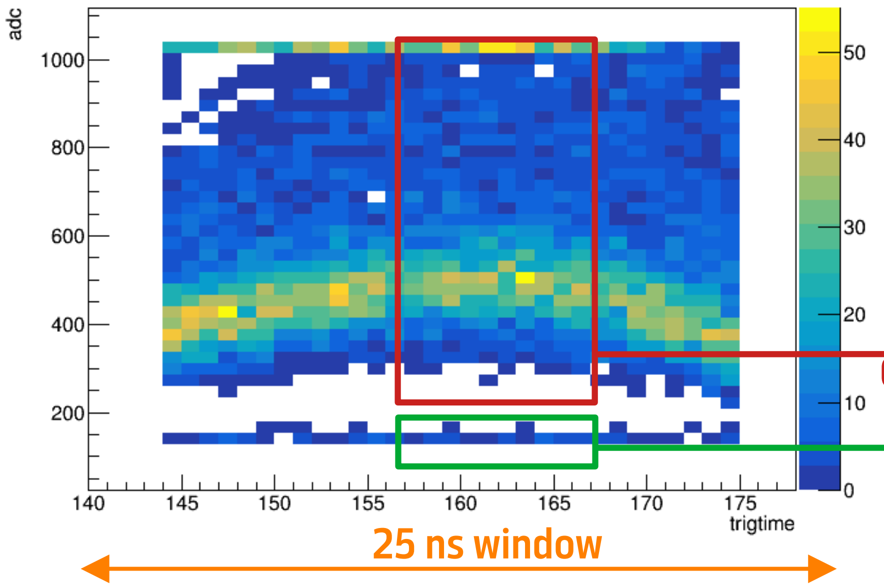
- Timestamps of triggered events used to reconstruct the signal pulse
- 1 Bunch crossing (BX) = 25 ns (LHC)



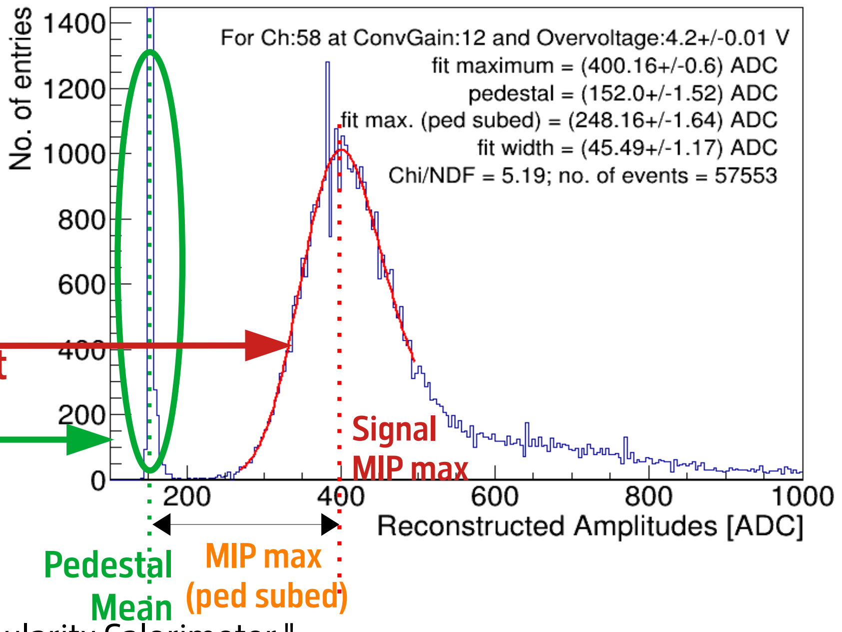
Test Beam Results

MIP Analysis

- Time selection for in-time MIP signal in one BX
- Reconstruction of the MIP spectra → Landau-Gaussian shape
- Extraction of the MIP maximum → **Signal MIP max** – **Pedestal mean**



convoluted Landau-Gaussian fit

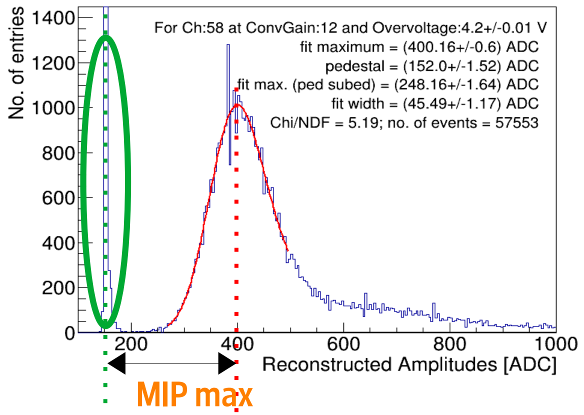


Test Beam Results

Quantifying SiPM-on-Tile performance

- Measurements of the scintillation **Light Yield**:

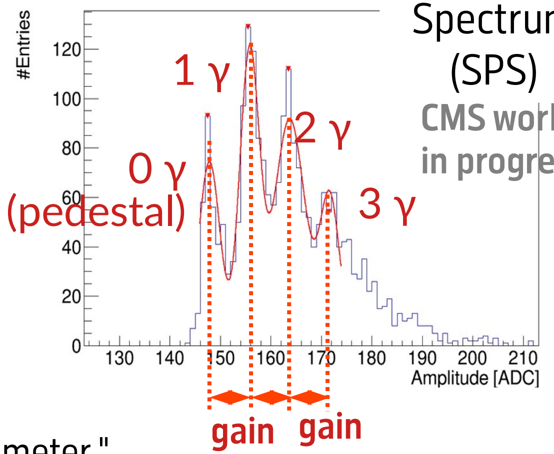
$$Light\ Yield[p.e.] = \frac{MIP\ maximum[ADC]}{SiPM\ Gain[ADC/p.e.]}$$



- MIP extraction from beam data
- SiPM gain extraction using low intensity LED:
  - Single Photon Spectrum reconstruction
  - Distance between photoelectrons peaks

Single Photon Spectrum (SPS)

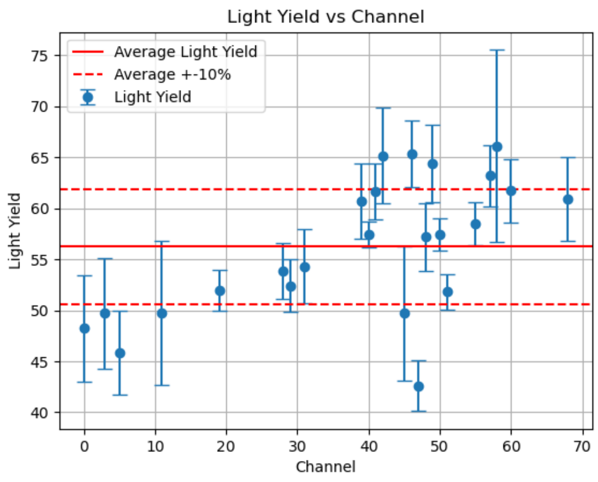
CMS work in progress

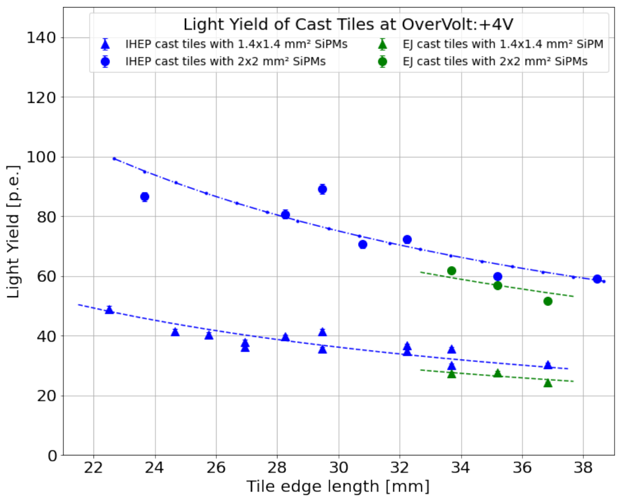


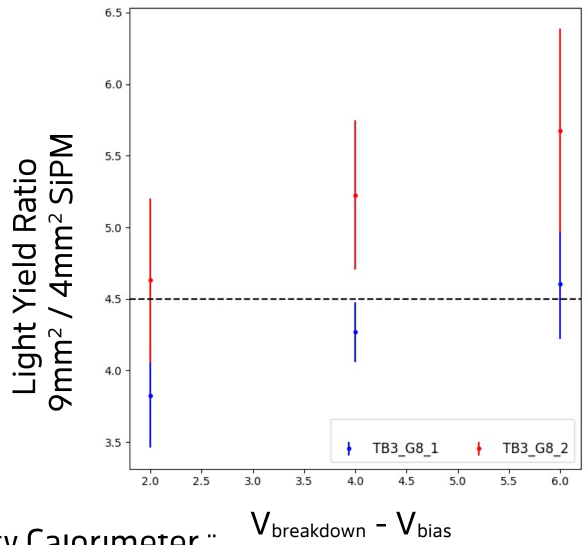
Test Beam Results

Quantifying SiPM-on-Tile performance

- System validation: measuring Light Yield
- Requirements:
  - Uniformity over a single tileboard
  - Light Yield inverse proportionality with tiles area
  - Performance of SiPM of different area

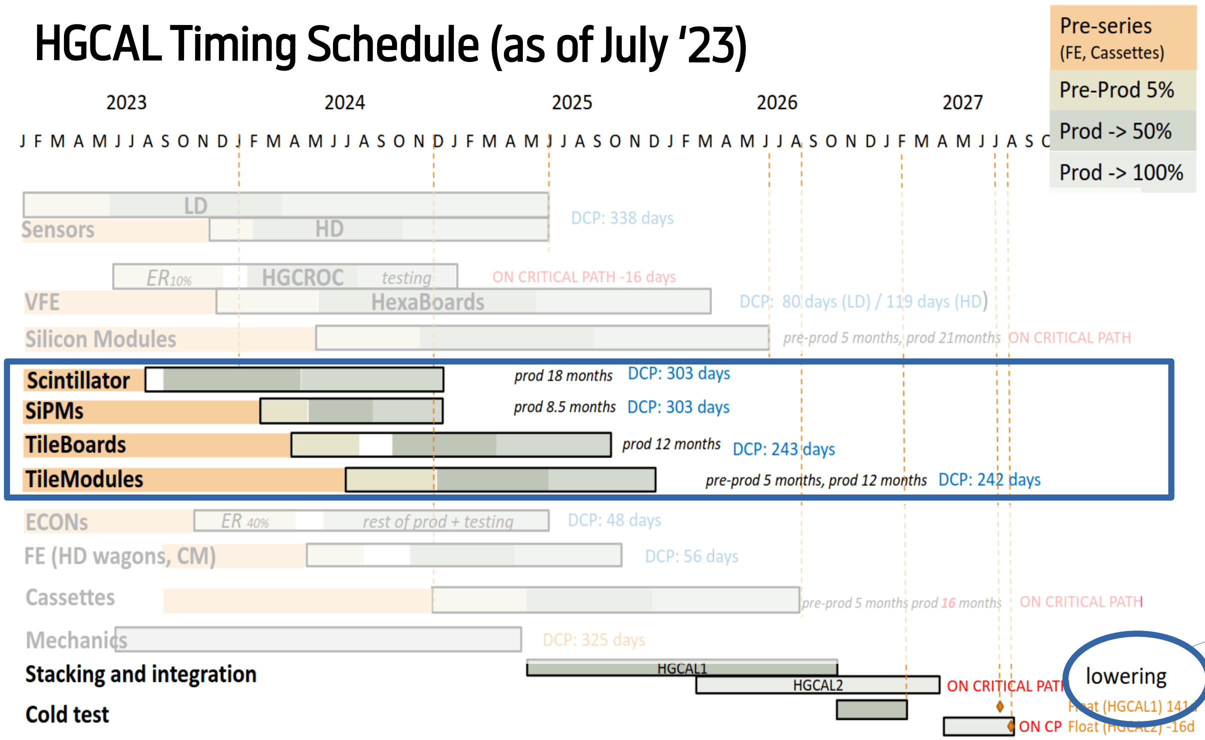






Status of the Project

Preparation of mass production



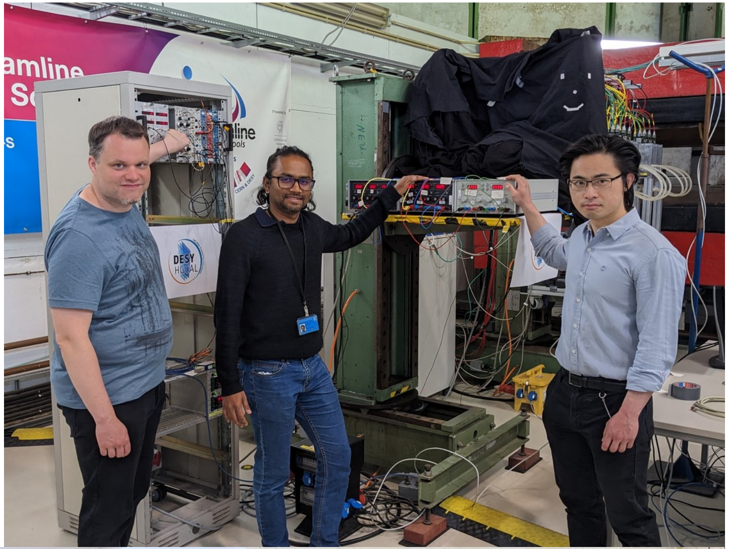
- **Pre-series components**
  - Finalizing the design
  - Qualifying manufacturer or process
  - Not included in the installation
  - Preparation for pre-production
- **Pre-production (2024)**
  - 5% of the total production
  - Intended for the installation

In time for the scheduled lowering in 2027

Outlook

Journey to the CMS HGCAL

- **CMS preparing for High Luminosity**
  - New endcap calorimeter → **HGCAL**
- **Key role of DESY for the scintillator section**
  - Assembly and test center
- **Important progress and ongoing developments**
  - System performance in testbeams and lab tests



BACKUP

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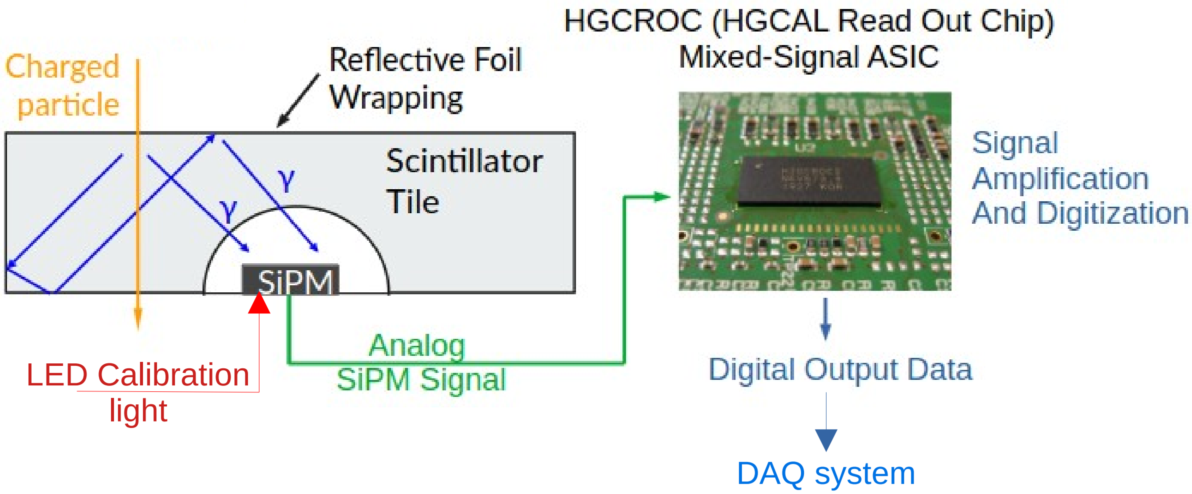
Scintillator Tileboard

Detection Principle



SiPM

- Thousands of single photon avalanche diodes (**SPAD**) working in Geiger-Mode
- Each individual SiPM-on-tile is equipped with a low intensity LED used for calibration

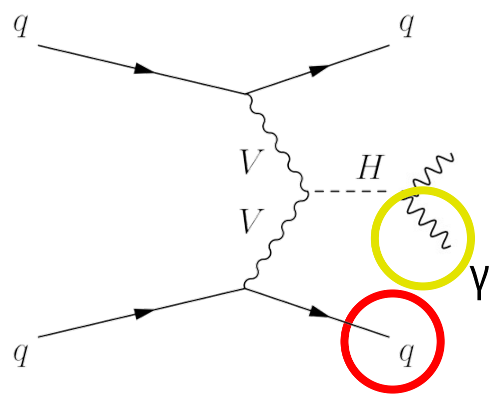
HGCROC

- Front-end ASIC components
- Read up to 72 channells
- Charge and time measurements

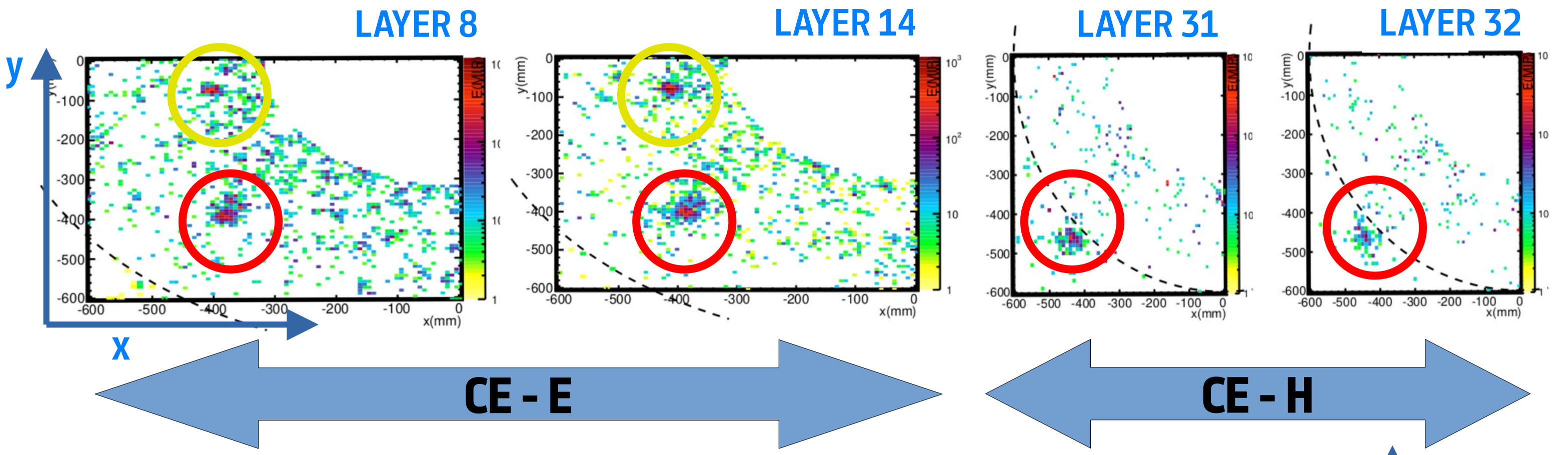
HGCAL: 5D Imaging Calorimeter

Forward jet signatures from VBF

VBF H → γγ + 200 PU



"The Phase-2 Upgrade of the CMS Endcap Calorimeter"
Technical Design Report

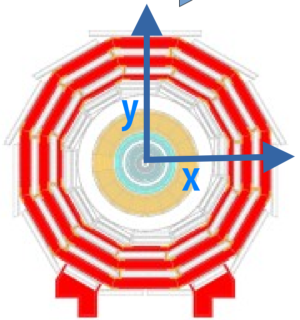


Spatial 3D Granularity

- High lateral and longitudinal granularity
- Two showers can be clearly separated

Energy Measurements

- Large dynamic range per cells → 10^5
- From MIP calibration to showers



HGCAL: 5D Imaging Calorimeter

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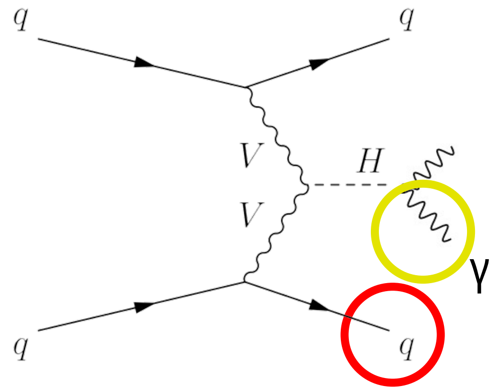
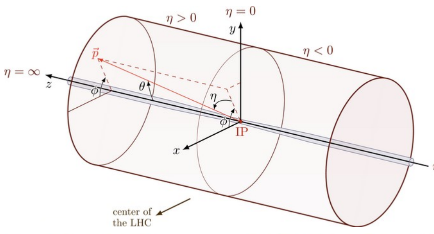
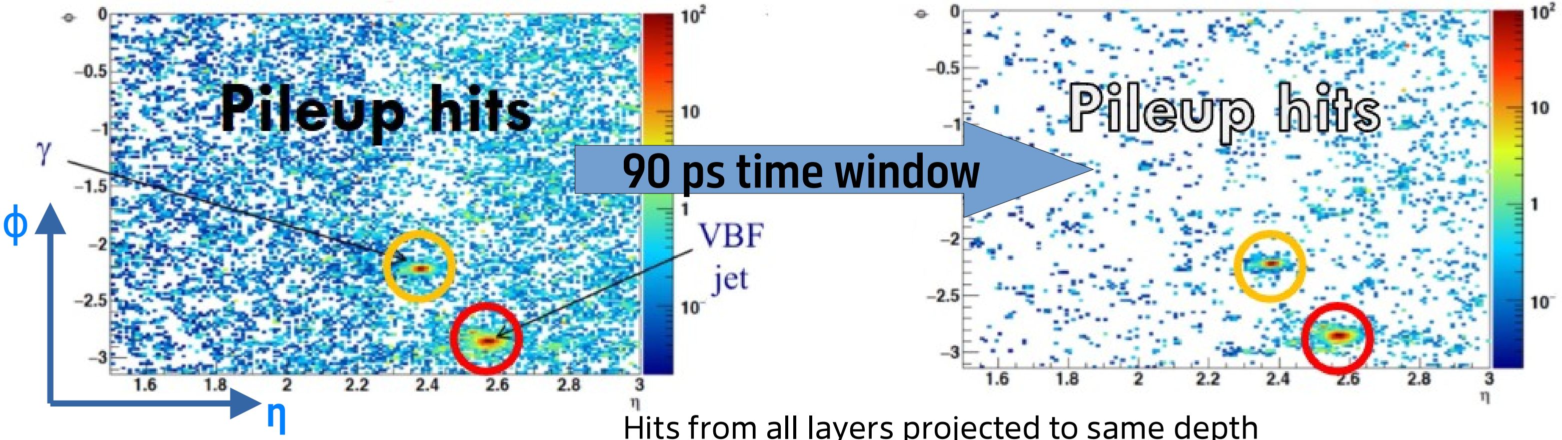


"The Phase-2 Upgrade of the CMS Endcap Calorimeter"
Technical Design Report

Timing Information & Resolution

- Ability to contribute to the level-1 CMS trigger (L1)
  → Pileup mitigation
- 20 ps per channel of targeted resolution
  - 100% time-tagging efficiency for photon with pT~5 GeV
  - Independent from detector ageing

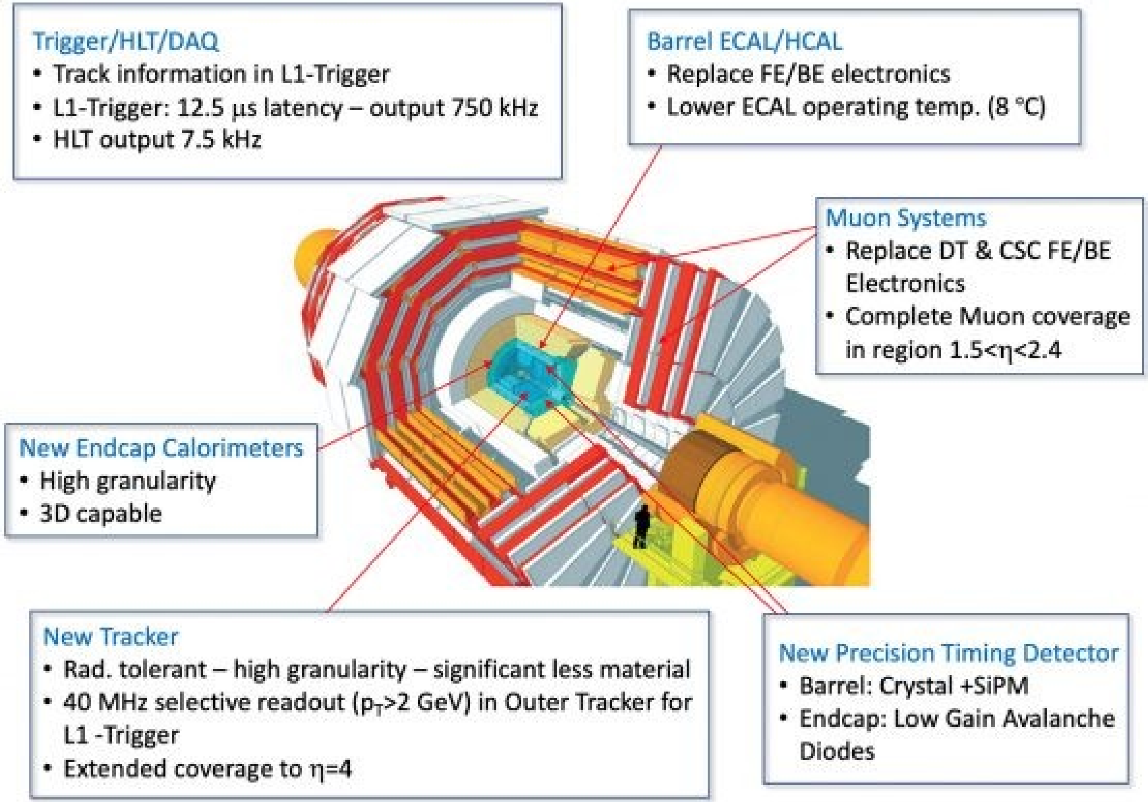




Hits from all layers projected to same depth

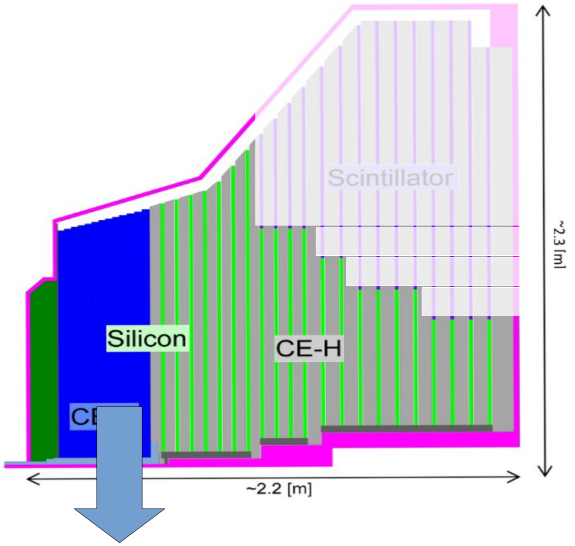
CMS during HL-LHC

Upgrades overview



Active Material - Silicon

Silicon Module



Radiation levels similar to pixel tracker

Hexaboard PCB

→ Hosting the readout chip

Silicon Sensor

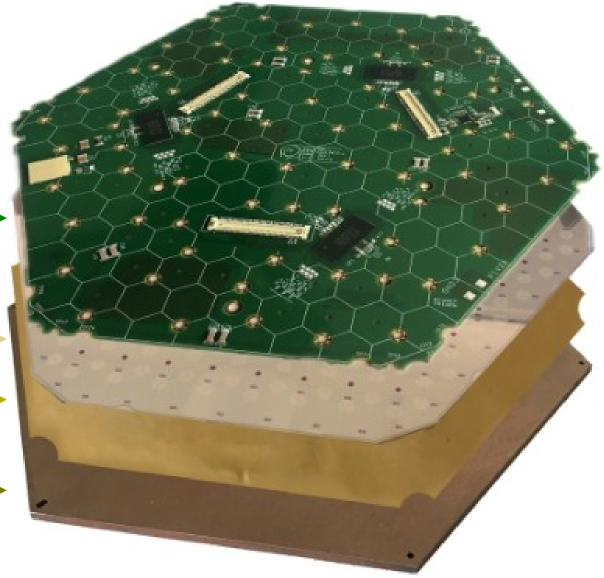
Metalized Kapton Sheet

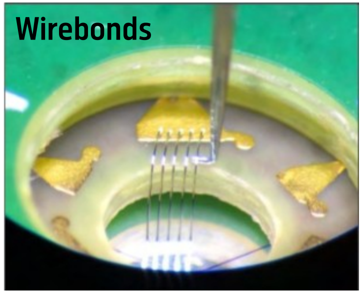
→ Bias supply to sensor back side

CuW BasePlate*

→ Rigidity, contributes to the absorber material

*PCB baseplate in the hadronic sector

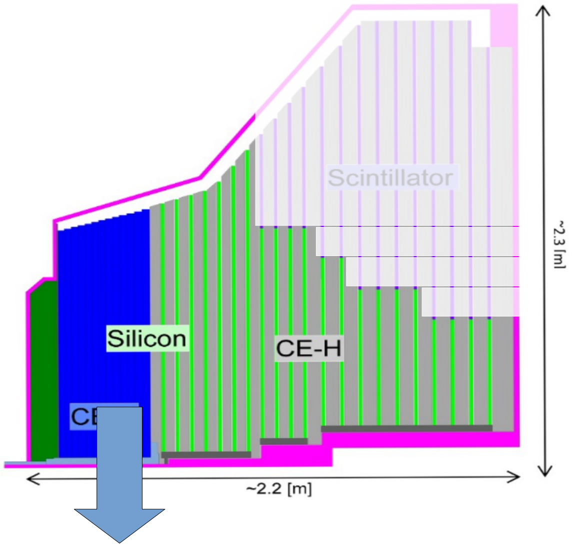




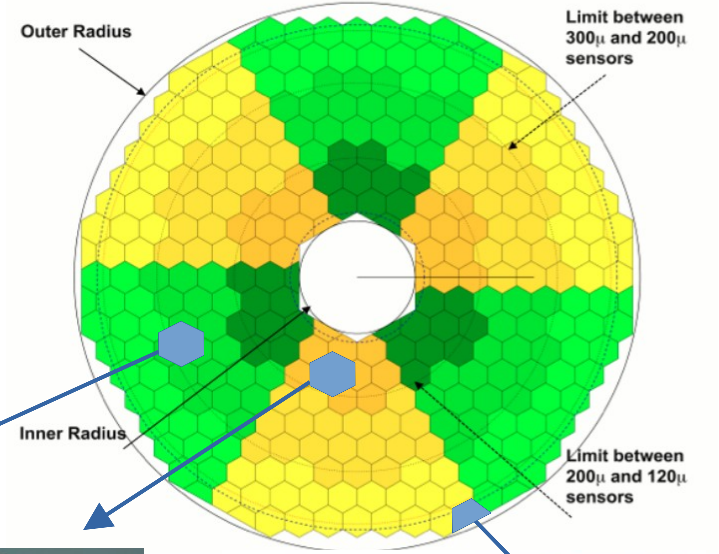
Active Material - Silicon

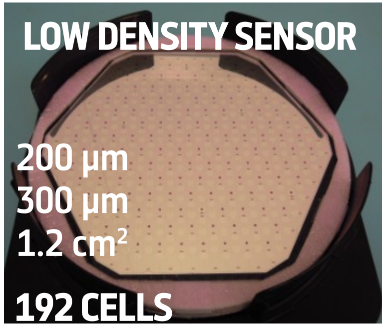
Silicon Sensors

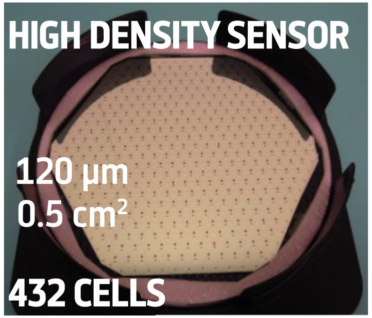
- **8" hexagonal wafers**
- Different cells sizes
  - Different e.m./hadronic lateral shower development
  - Same cell capacitance
- Partials design
  - Circular endcap from hexagons



Radiation levels similar to pixel tracker







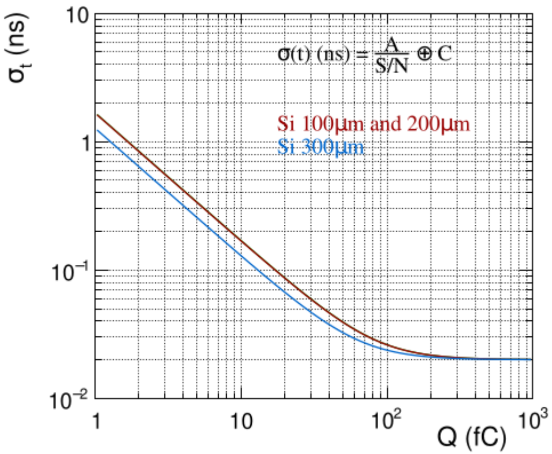
"Measurement of silicon-sensor prototypes for the CMS High-Granularity Calorimeter" ICHEP 2022

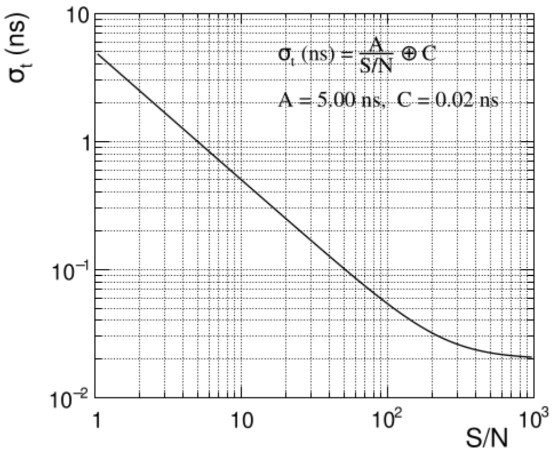
Timing Resolution

Specifications

- $\boldsymbol{\sigma_t = \sigma_{jitter} \oplus \sigma_{floor}}$
  - $\sigma_{jitter} = A / (S/N)$, $\sigma_{floor} \sim 20$ ps
  - 20 ps → targeted resolution

- Timing resolution **not** varying significantly with sensor thickness or radiation when the resolution is measured as a function of S/N

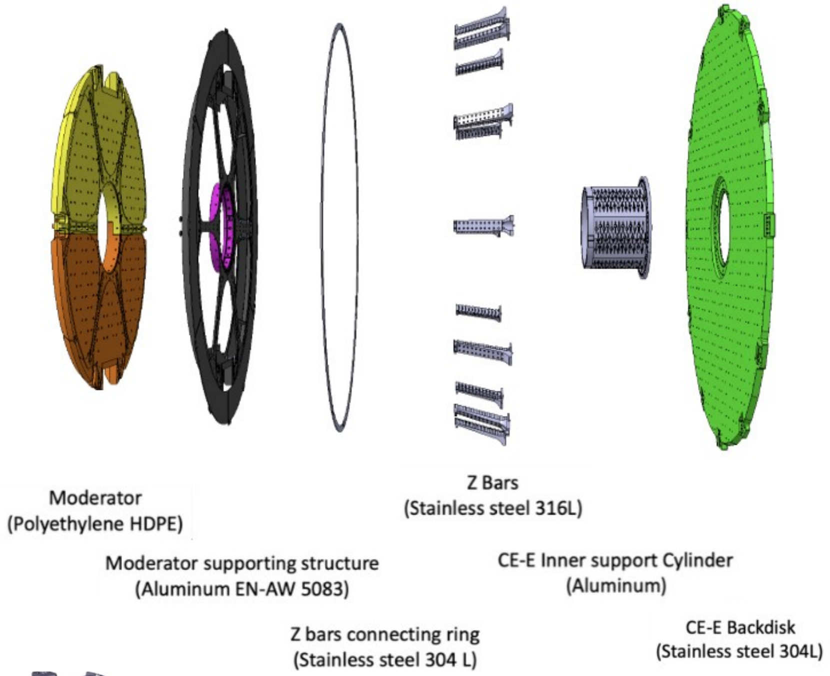




HGCAL Mechanics

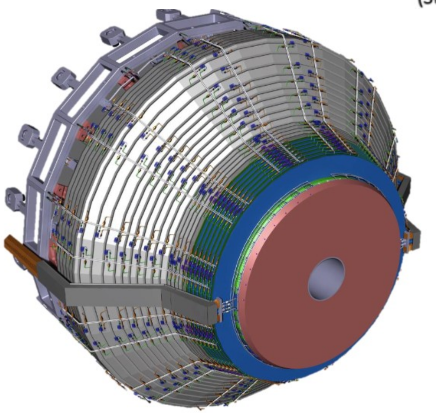
CE-E Mechanics:

- Dense layering of cassettes, lead sheets, stacked on a stainless steel back-plate
- Mechanics in advanced design stage
  - To be made by CERN and industrial partners



CE-H Mechanics:

- Layered stainless steel structure
- All raw steel plates and cylinders have been manufactured
  - Pre-production started in March 2023



HGCAL Readout Chip

HGCROC

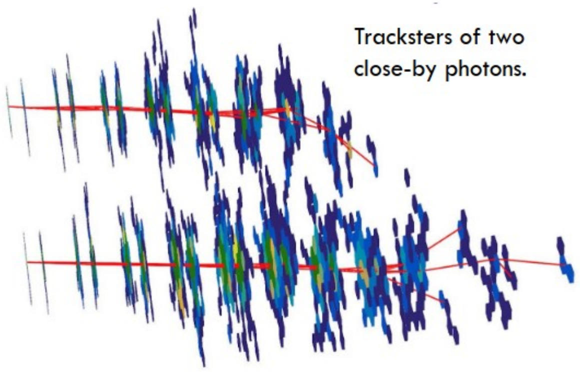
"The Phase-2 Upgrade of the CMS endcap calorimeter"
Technical Design Report

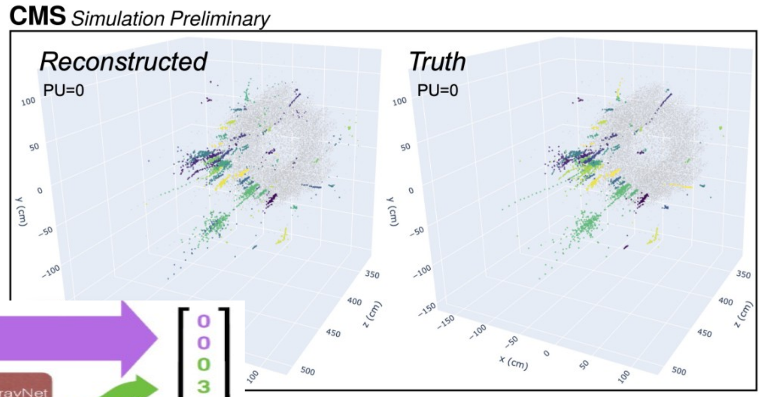
- Front-end ASIC component
- Same design for Si and Scintillator with adaptation
  → conveyor gain used as pre-ampflier
- Two halves chip with 78 channels
- Low noise, large dynamic range
  → from MIP to showers
- Accommodating 12 μs of latency
  → L1 requirement
- High speed readout links
  → 1.28 Gb/s
- Radiation tolerance
- Low power consumption: ~20 mW
  → 125 kW per endcap

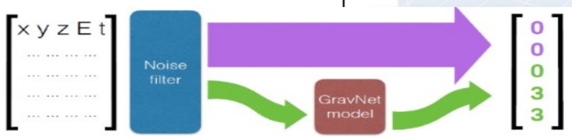
Simulation and Reconstruction

Offline reconstruction

- Detector simulation
  - Geometry close to the final design
  - Sensor/Electronics provide full end-to-end simulation
  - Reconstruction with realistic end-of-life conditions
- Raw data unpacking
  - Full unpacking in ~40ms
  - First-level calibration exploiting GPU-compliant module
- Reconstruction with TICL and CLUE-3D
  - Iterative clustering
  - RecHits → LayerClusters → Tracksters
- End-to-end Machine Learning
  - Noise filter
  - GravNet graph neural network performs clustering on cleaned data

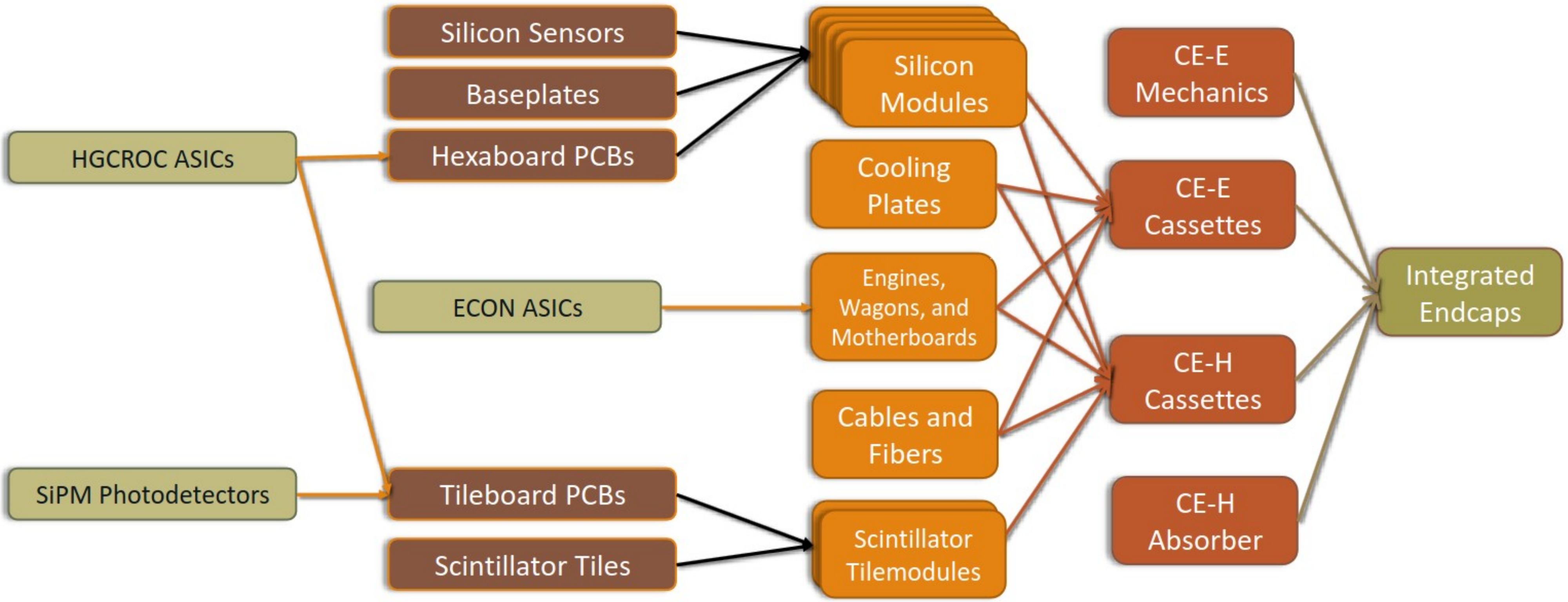






Status of the Project

Summary of the principal components and Workflow



SiPM Gain Analysis

Single Photon Spectrum

- The LED system on-board the tileboard pulses the low intensity LEDs.
- The photons produced by the LEDs are detected by the SiPMs
  - Pulses from SiPM are sampled at the pulse amplitude
  - Resulting histogram shows the pedestal peak and peaks corresponding to the number of SiPM cells discharged due to photon detection
    - Often referred to as a **Single Photon Spectrum (SPS)**