Design & Tests of Tilemodules for the CMS HGCAL

Detector R&D retreat

Malinda Da Silva, Fabian Hummer, Katja Krueger, Antoine Laudrain, Jia-Hao Li, **Gabriele Milella**, Matthias Komm, Mathias Reinecke, Daria Selivanova

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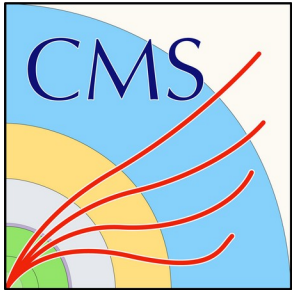
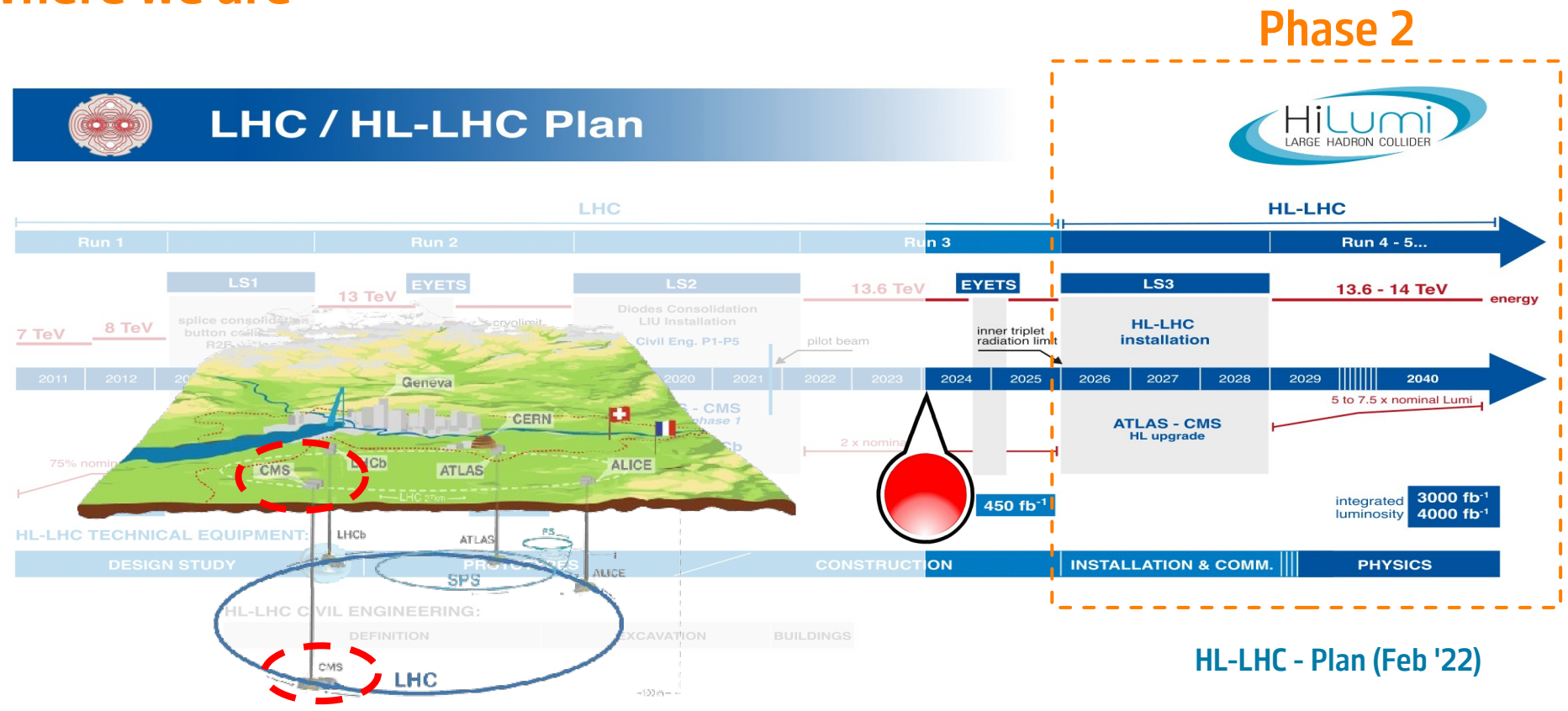


Future at CERN: HL-LHC

Where we are



HL-LHC - Plan (Feb '22)

Future at CERN: HL-LHC

A "bright" future

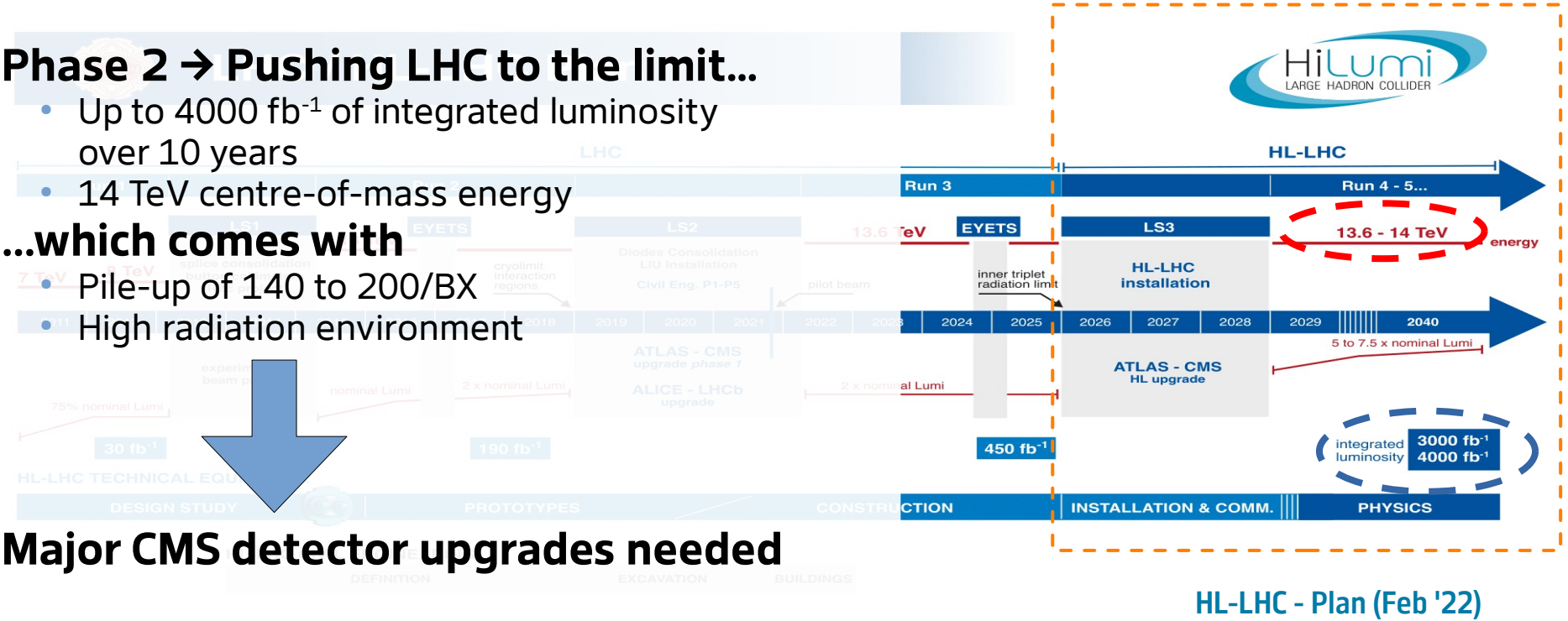
Phase 2 → Pushing LHC to the limit…

- 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)

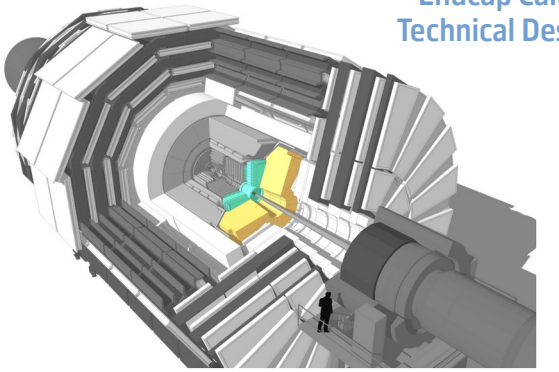
CMS during HL-LHC

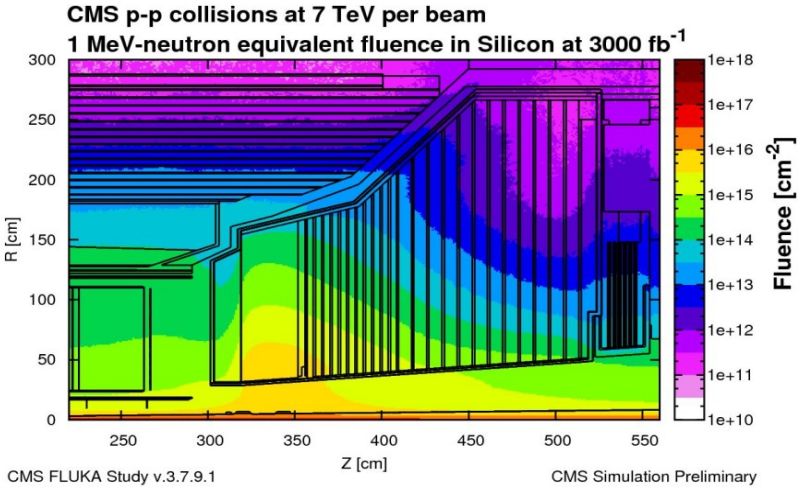
The challenges in the forward regions

- 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



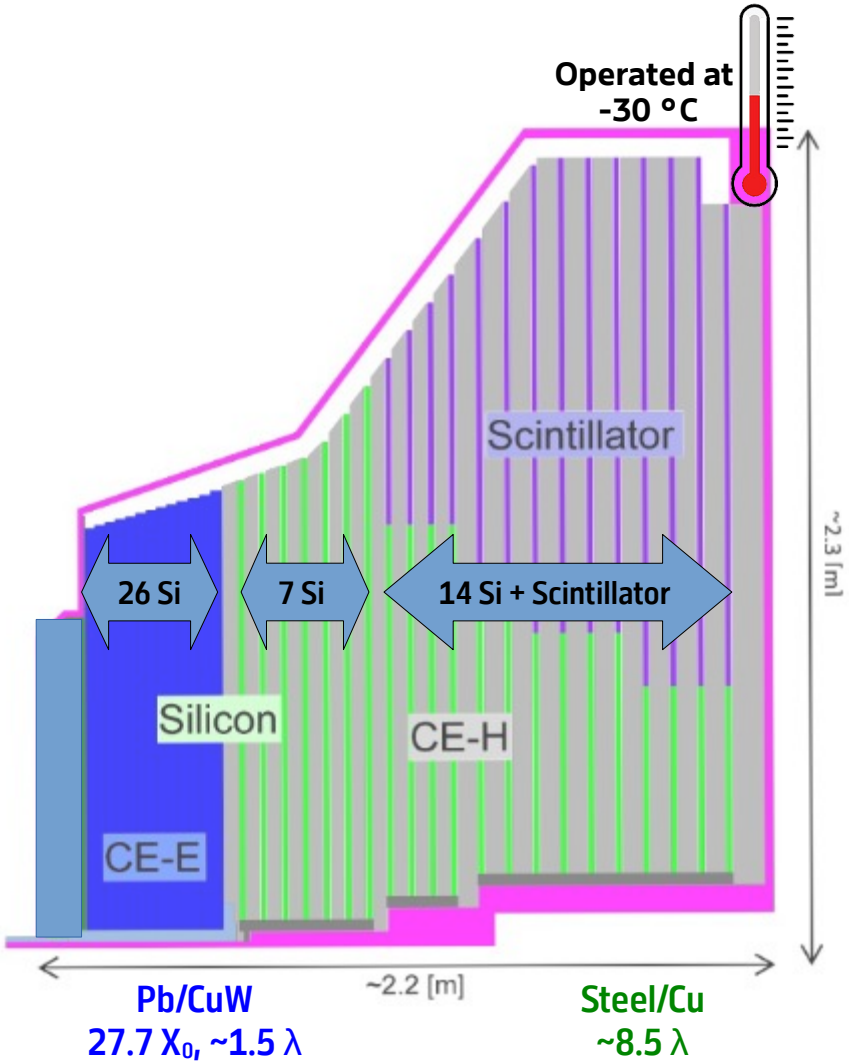


The HGCAL Project

5D Imaging Calorimeter

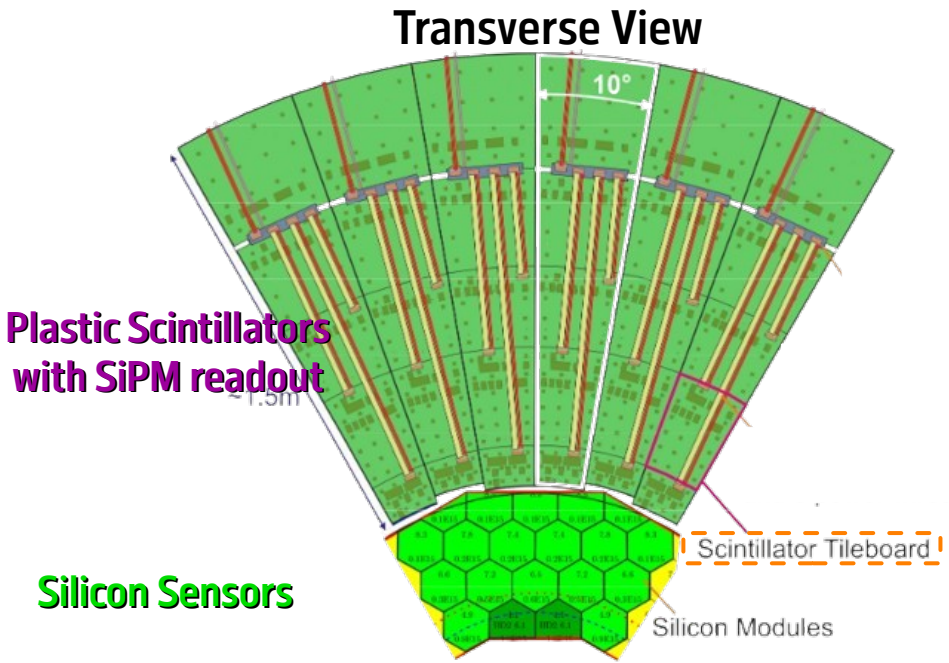
- High Granularity Sampling Calorimeter
  - 5D imaging calorimeter:
    3D spatial granularity, energy, timing information
  - Two separated sections in one single detector

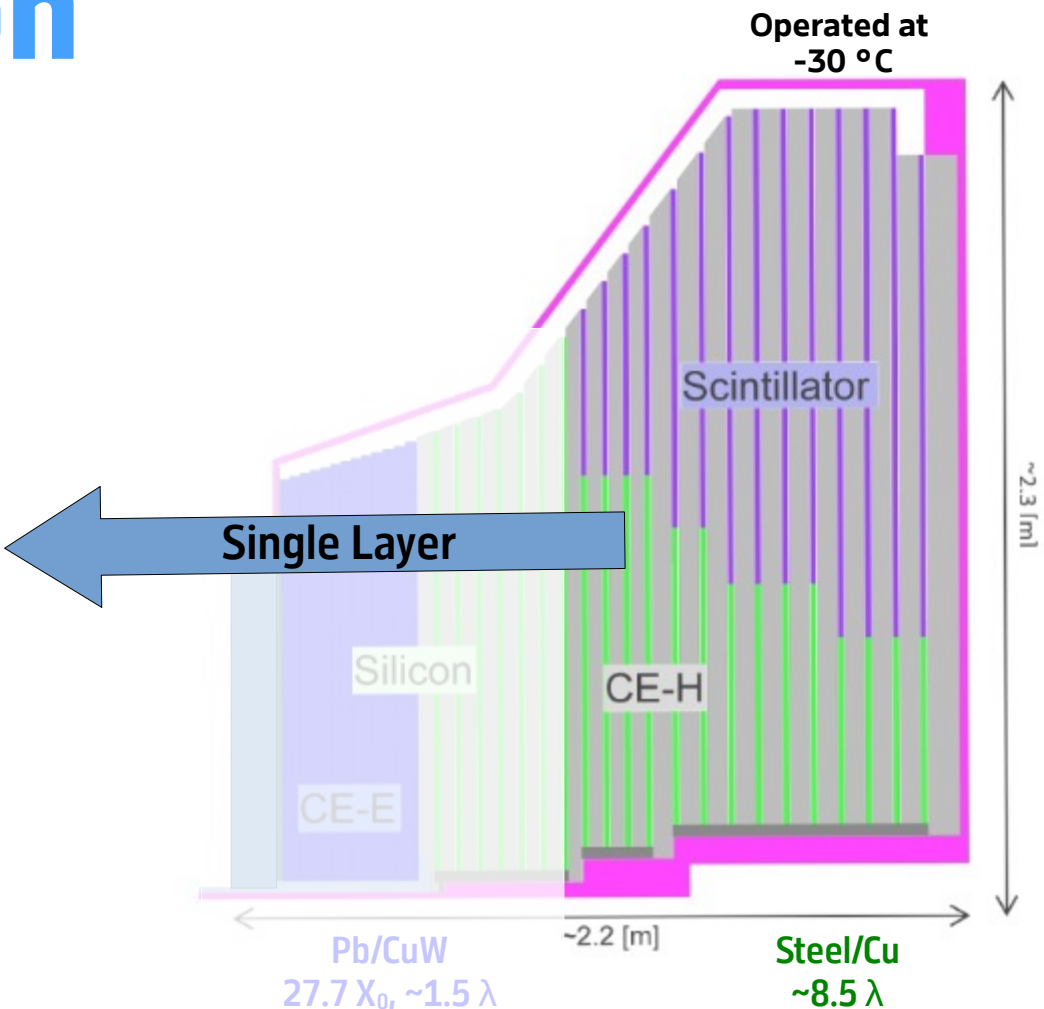
- **Active Materials**
  - **Silicon Sensors (CE-E and CE-H)**
    - Hexagonal 8″ wafers
    - **6M pads** (~620 m^2)
  - **Plastic Scintillators with SiPM readout (CE-H)**
    - **240k** scintillator tiles (~370 m^2)



The CE-H Section

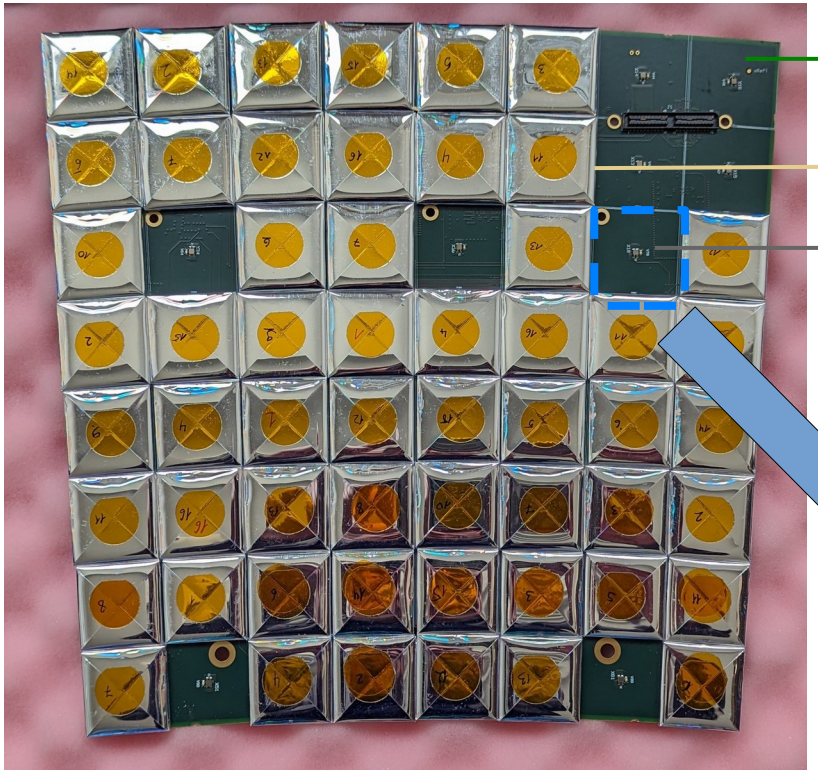
Mixed Design





Scintillator Tileboard

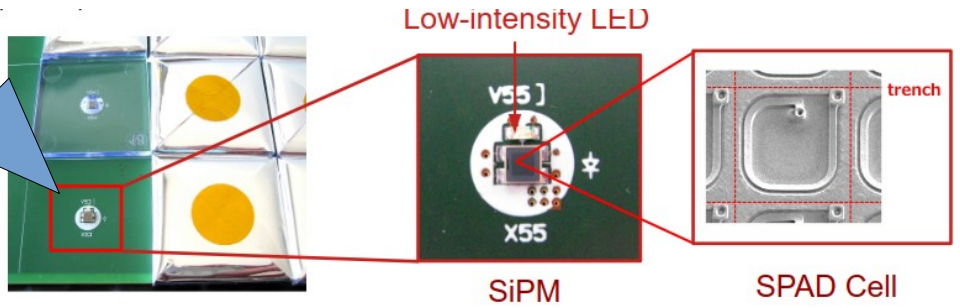
SiPM-on-tile



Tileboard (TB) PCB
Hosting the readout chip

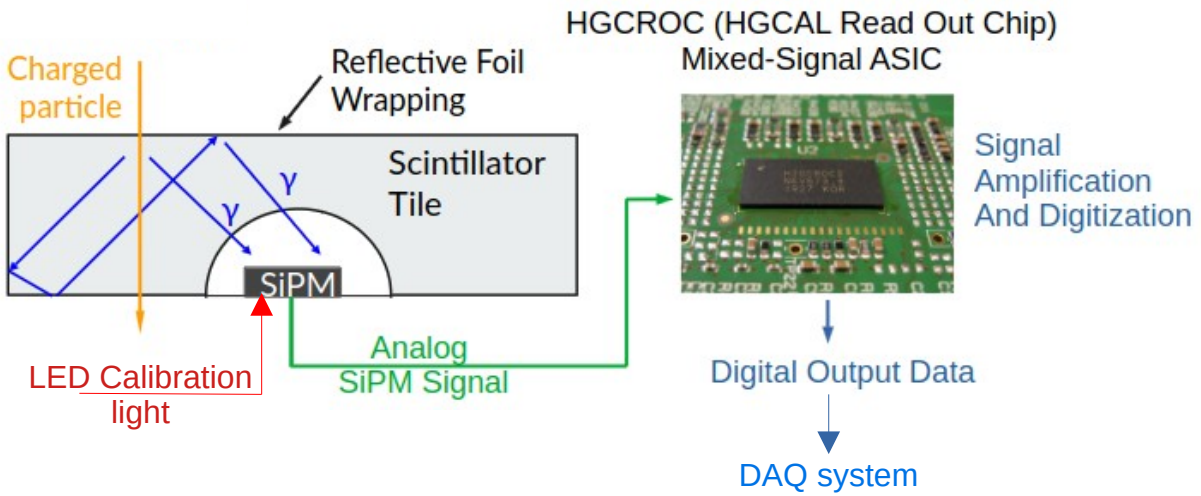
Wrapped Scintillating tile
Reflective foil

Silicon PhotoMultiplier (SiPM)
Calibration with LED



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

Production at DESY

Workflow

Tilemodules Assembly Center (TAC)

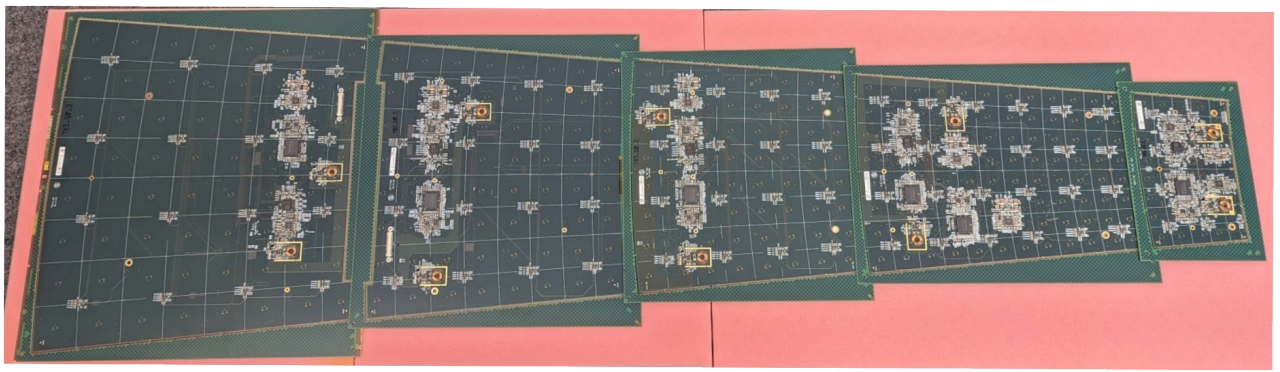
- **Shipment to DESY**
  - Naked tiles
  - SiPMs
  - PCB modules

See Jia-Hao's talk for the QC

- **Tile Wrapping**
  - Wrapping station
- **Tilemodules assembly**
  - Pick-and-place machine

Check the videos!

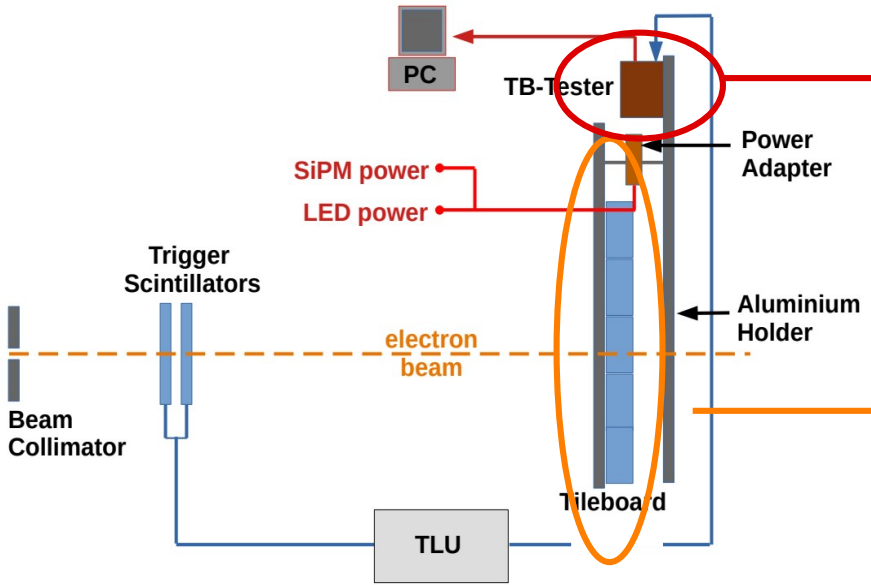
- **Test of the modules**
  - **Tests in lab**
    - Electronics test
    - Climate chamber test
  - **Test beam campaign**

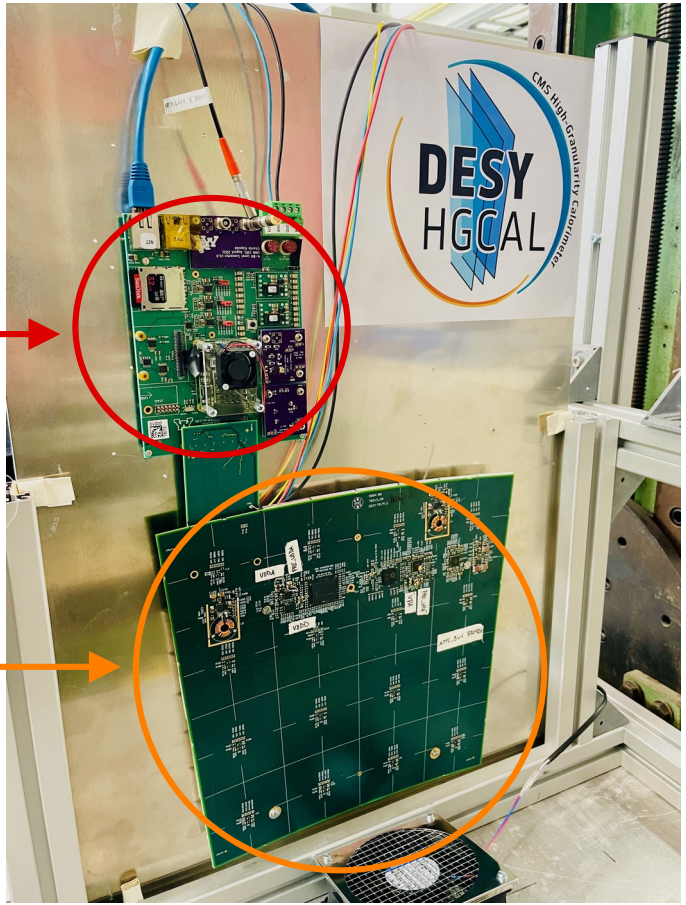


Different modules designs for the 10° slab of one layer

Test at DESY

Test beam campaign





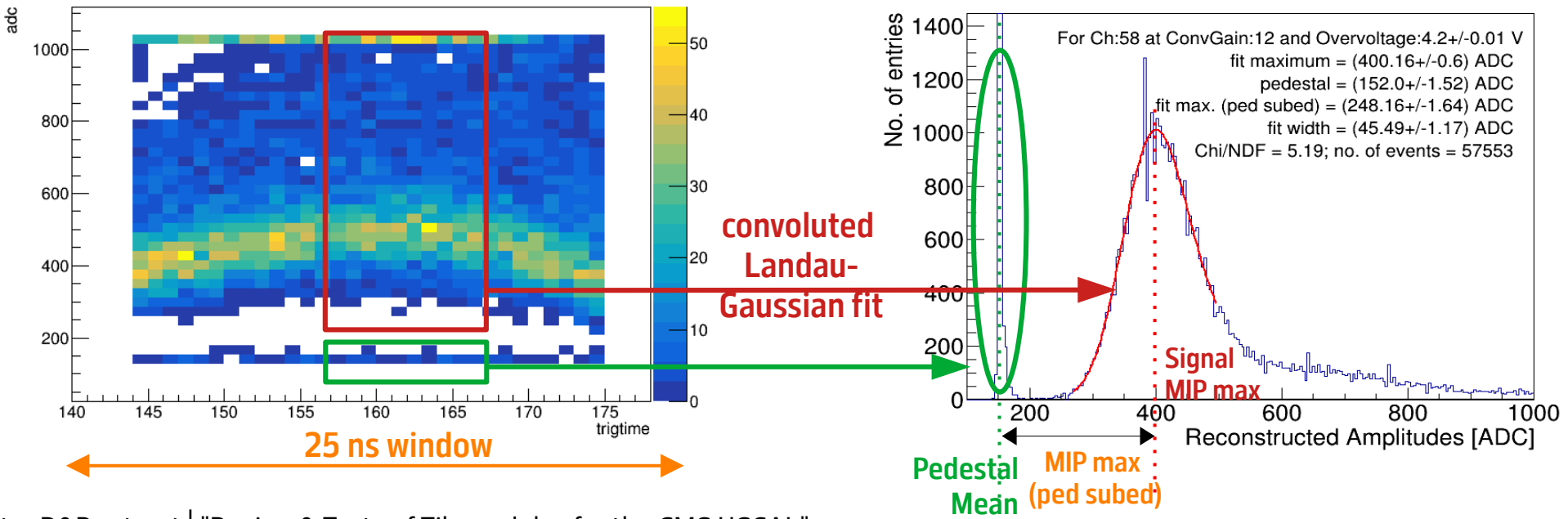
- DESY II test beam facility (>10 campaigns since 2020)
  - 3 GeV electron beam → Minimum Ionizing Particle (MIP)

Tiles on the other sides!

Test at DESY

Test beam campaign

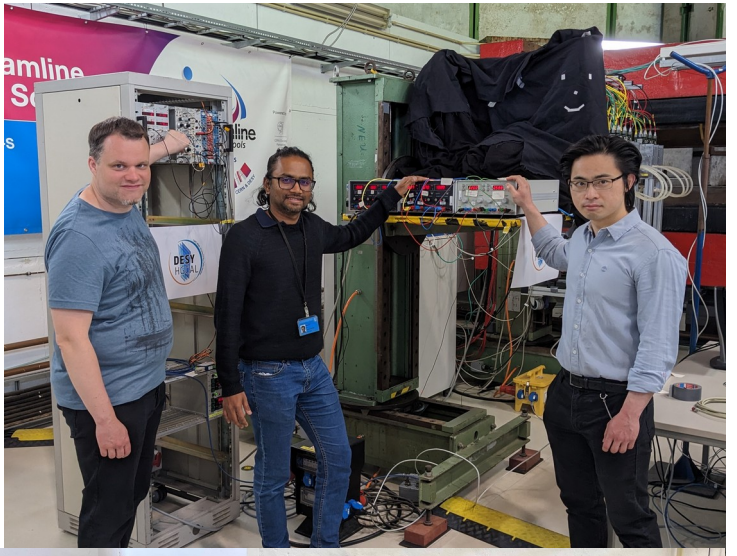
- Stamp of the DAQ trigger every 25 ns (LHC Bunch-crossing)
- Possibility to reconstruct the electron (MIP) pulse amplitude



Outlook

Journey to the CMS HGCAL

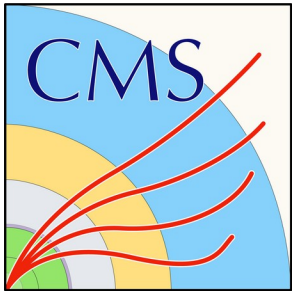
- **CMS preparing for High Luminosity**
  - New endcap calorimeter → **HGCAL**
- **Key role of DESY for the scintillator section**
  - Assembly and test center
- **Important progress and ongoing developments**
  - System performance in testbeams and lab tests
  - Development of software for calibration and mapping (*see Lovisa's talk!*)



BACKUP

Universität Hamburg

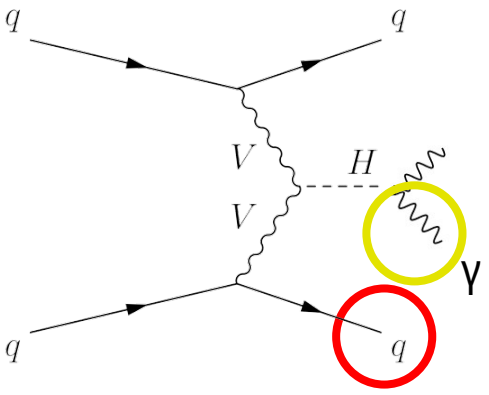
DER FORSCHUNG | DER LEHRE | DER BILDUNG



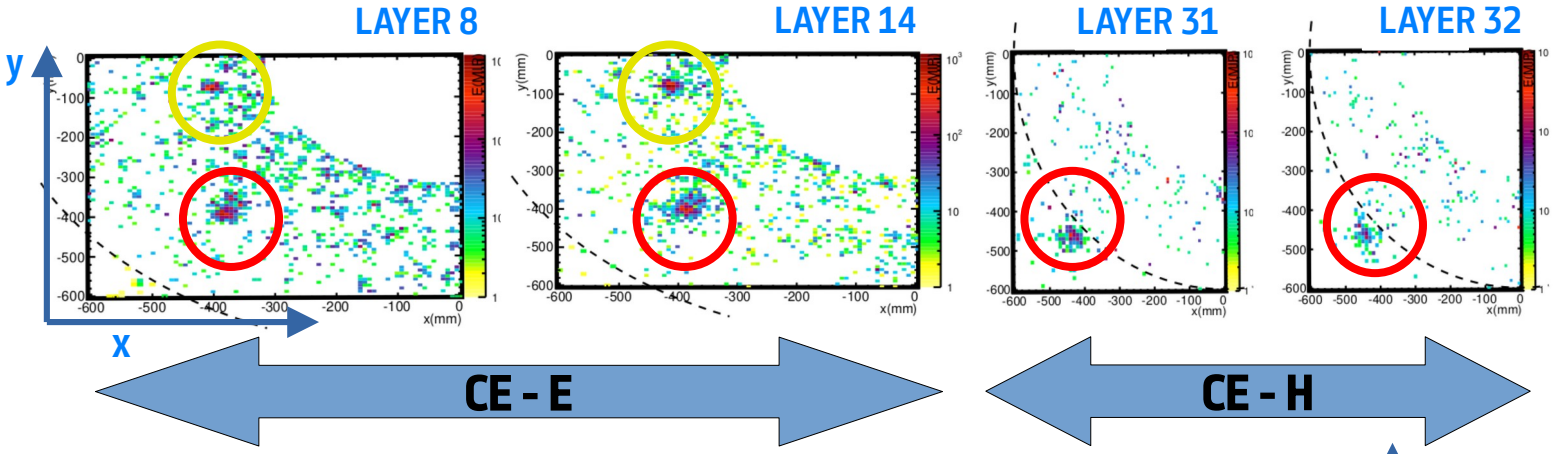
HGCAL: 5D Imaging Calorimeter

Forward jet signatures from VBF

VBF H → γγ + 200 PU



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

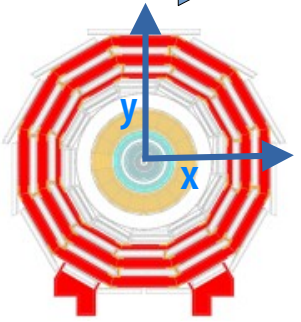


Spatial 3D Granularity

- 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



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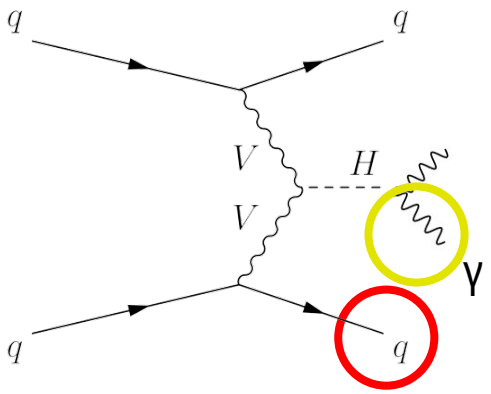
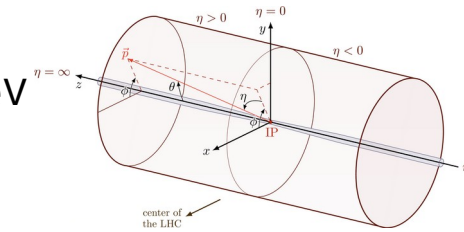
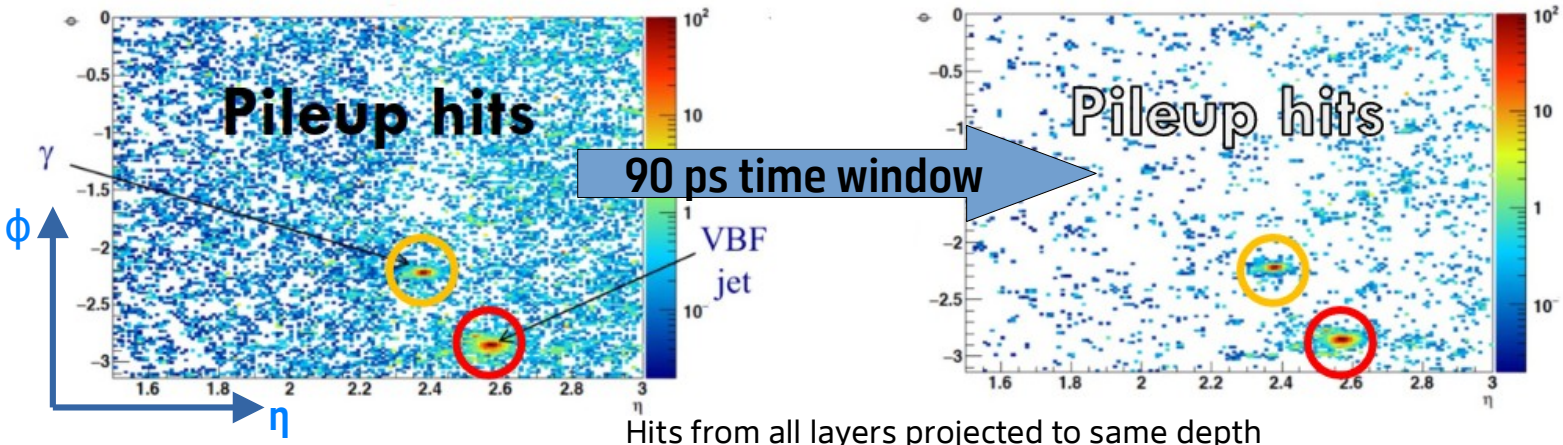


"The Phase-2 Upgrade of the CMS Endcap Calorimeter" Technical Design Report

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

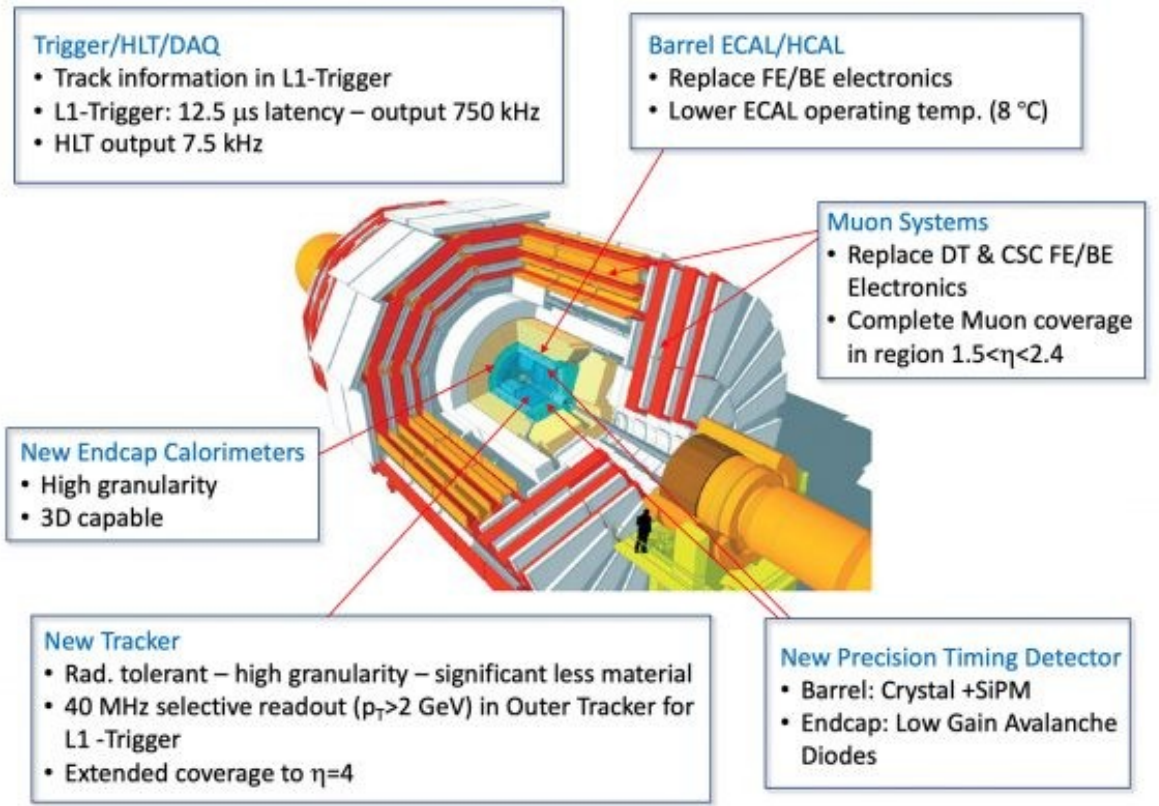




Hits from all layers projected to same depth

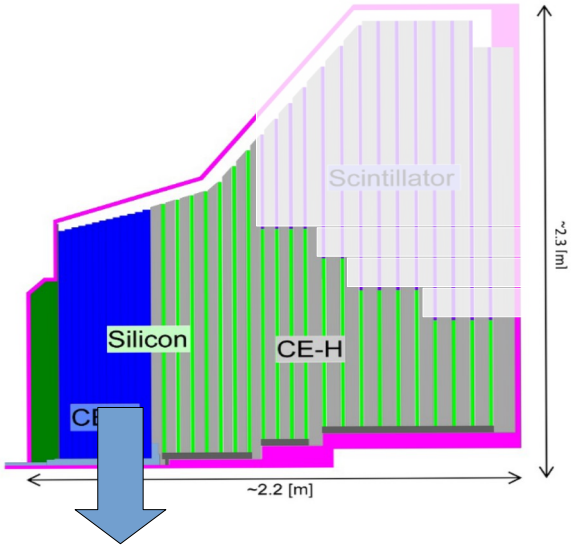
CMS during HL-LHC

Upgrades overview



Active Material - Silicon

Silicon Module



Radiation levels similar to pixel tracker

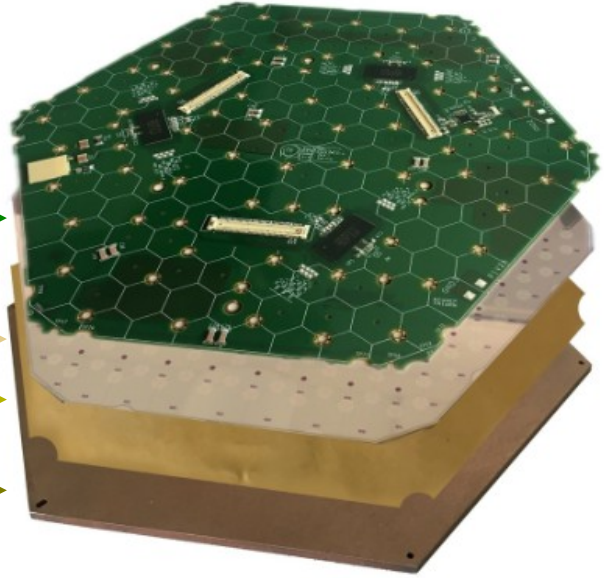
Hexaboard PCB
→ Hosting the readout chip

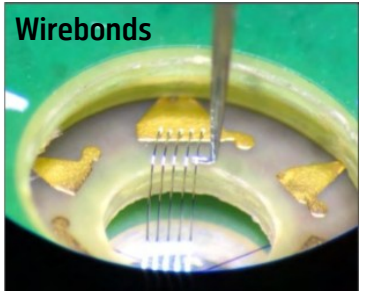
Silicon Sensor

Metalized Kapton Sheet
→ Bias supply to sensor back side

CuW BasePlate*
→ Rigidity, contributes to the absorber material

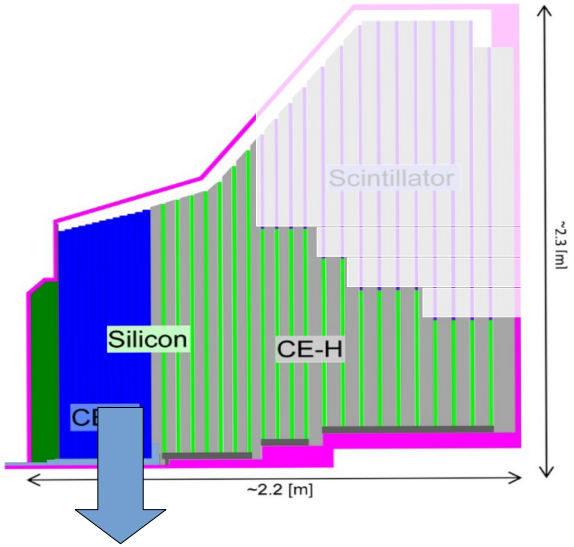
*PCB baseplate in the hadronic sector





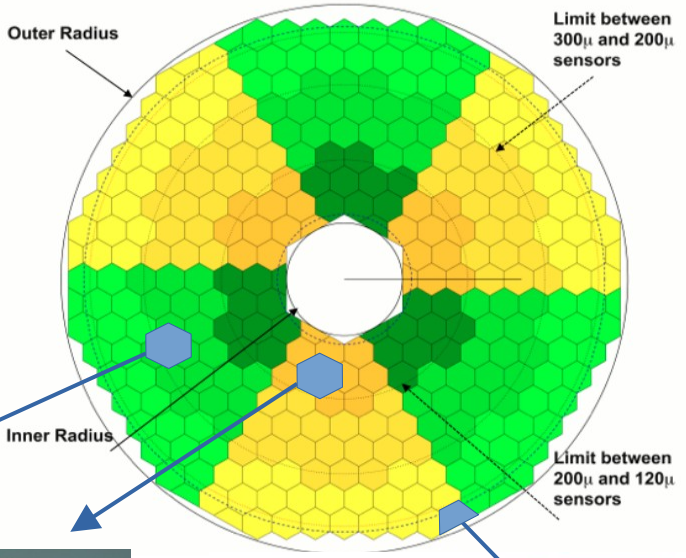
Active Material - Silicon

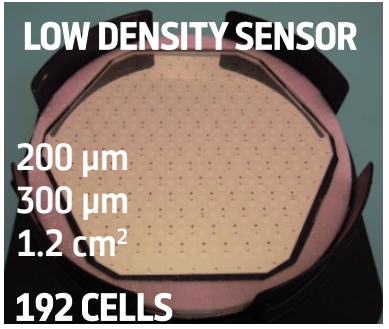
Silicon Sensors

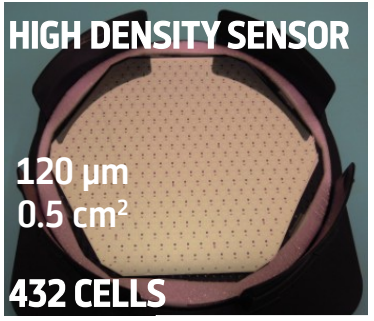


Radiation levels similar to pixel tracker

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





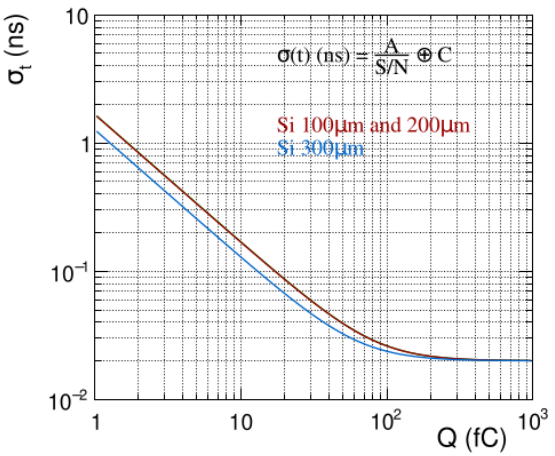


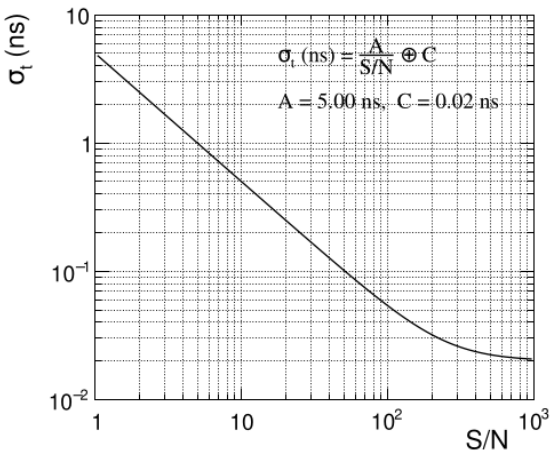
"Measurement of silicon-sensor prototypes for the CMS High-Granularity Calorimeter"
ICHEP 2022

Timing Resolution

Specifications

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

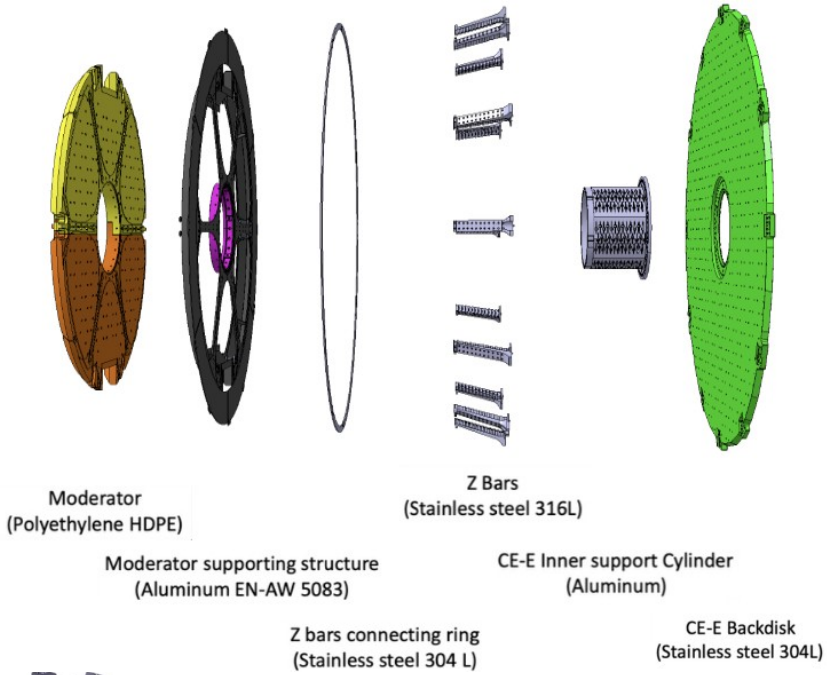




HGCAL Mechanics

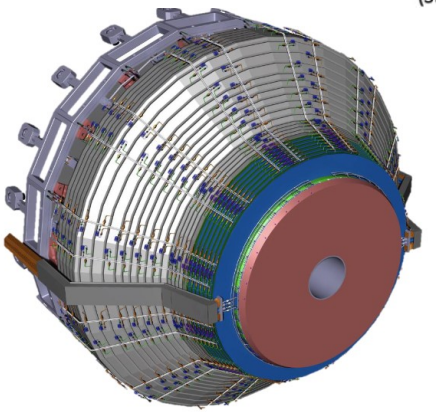
CE-E Mechanics:

- 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

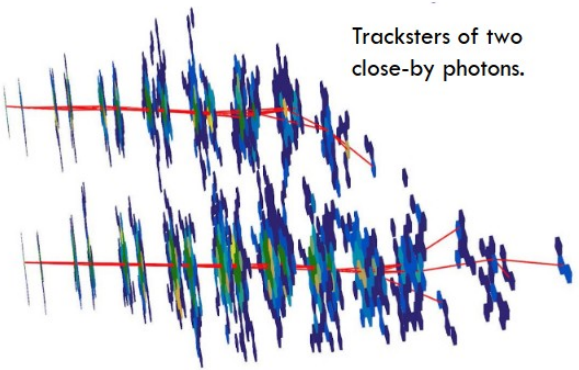
"The Phase-2 Upgrade of the CMS endcap calorimeter"
Technical Design Report

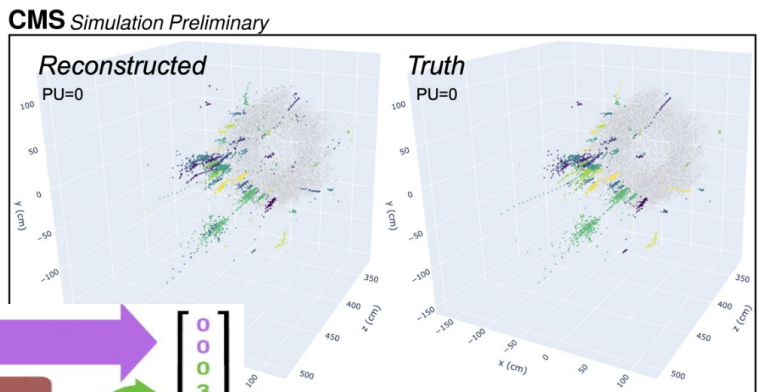
- Front-end ASIC component
- Same design for Si and Scintillator with adaptation
  → conveyor gain used as pre-ampflier
- Two halves chip with 78 channels
- Low noise, large dynamic range
  → from MIP to showers
- Accommodating 12 μs of latency
  → L1 requirement
- High speed readout links
  → 1.28 Gb/s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

Simulation and Reconstruction

Offline reconstruction

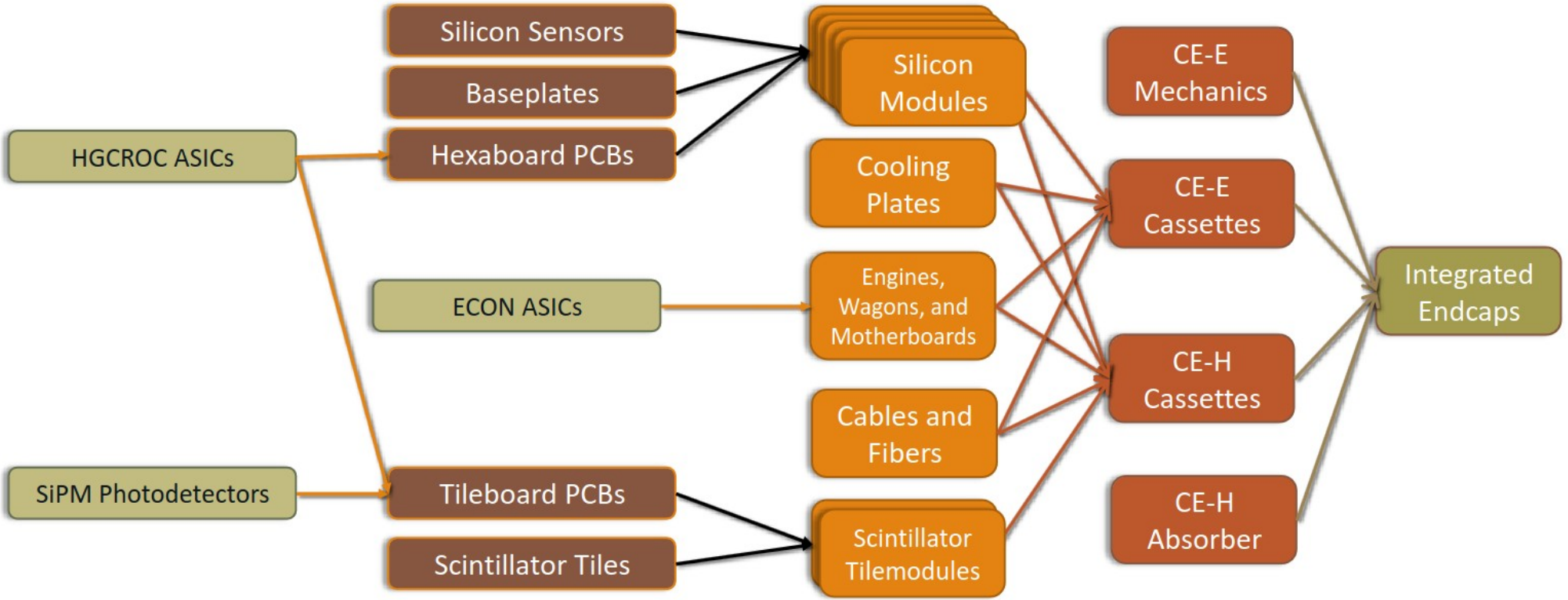
- Detector simulation
  - Geometry close to the final design
  - Sensor/Electronics provide full end-to-end simulation
  - Reconstruction with realistic end-of-life conditions
- Raw data unpacking
  - Full unpacking in ~40ms
  - First-level calibration exploiting GPU-compliant module
- Reconstruction 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)**