CMS High Granularity Calorimeter (HGCAL)

From Prototype to Production

2025 International Workshop on the High Energy Circular Electron Positron Collider

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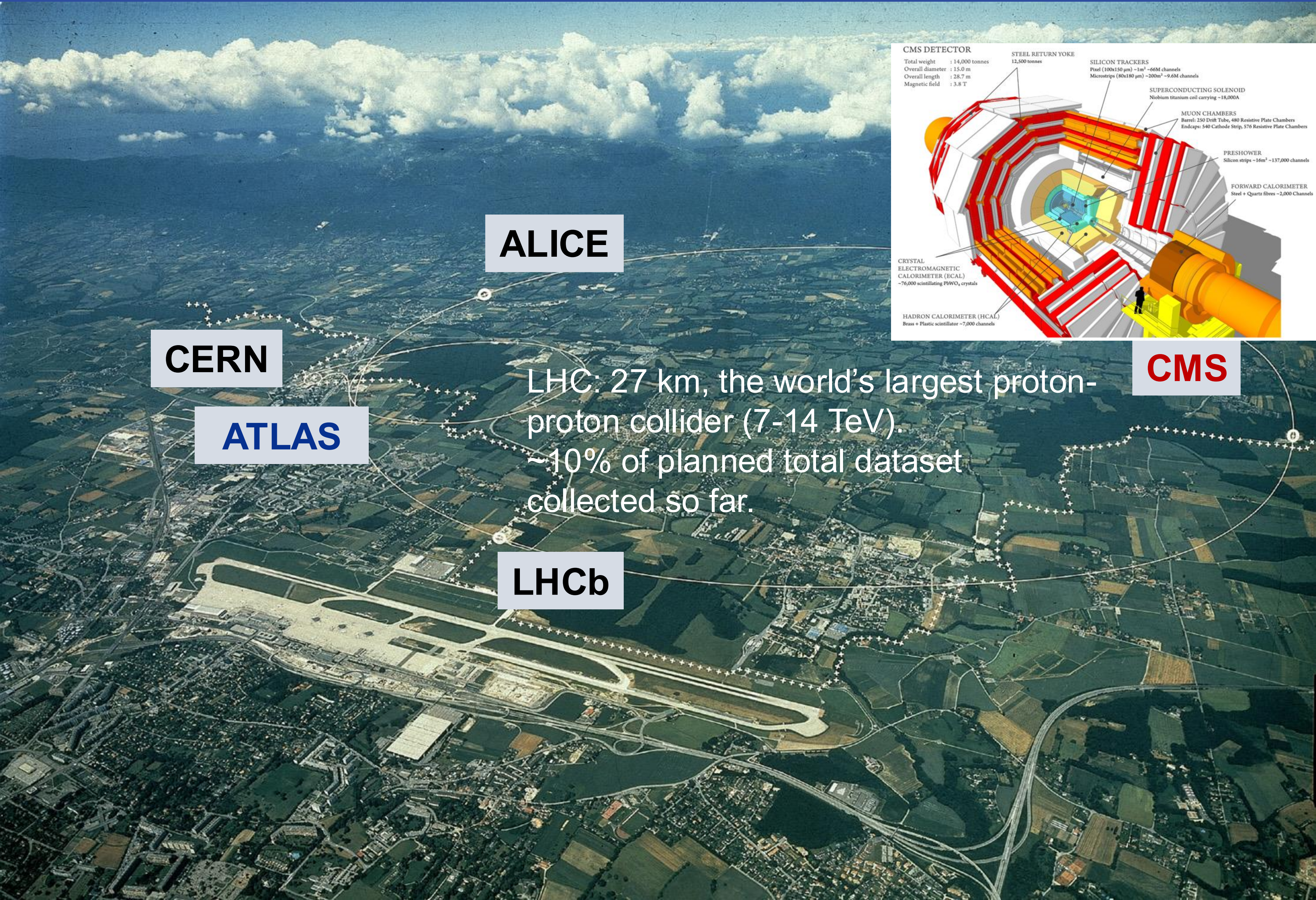
On behalf of the CMS collaboration

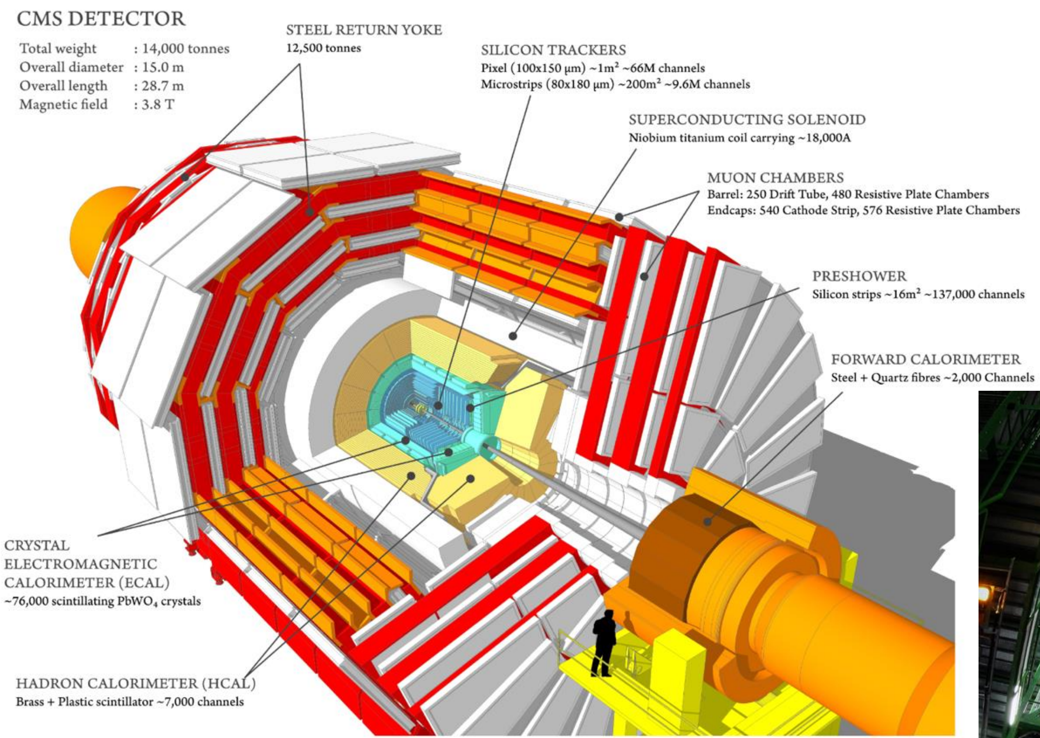
Guangzhou, Guangdong
2025-11-8

LHC and CMS

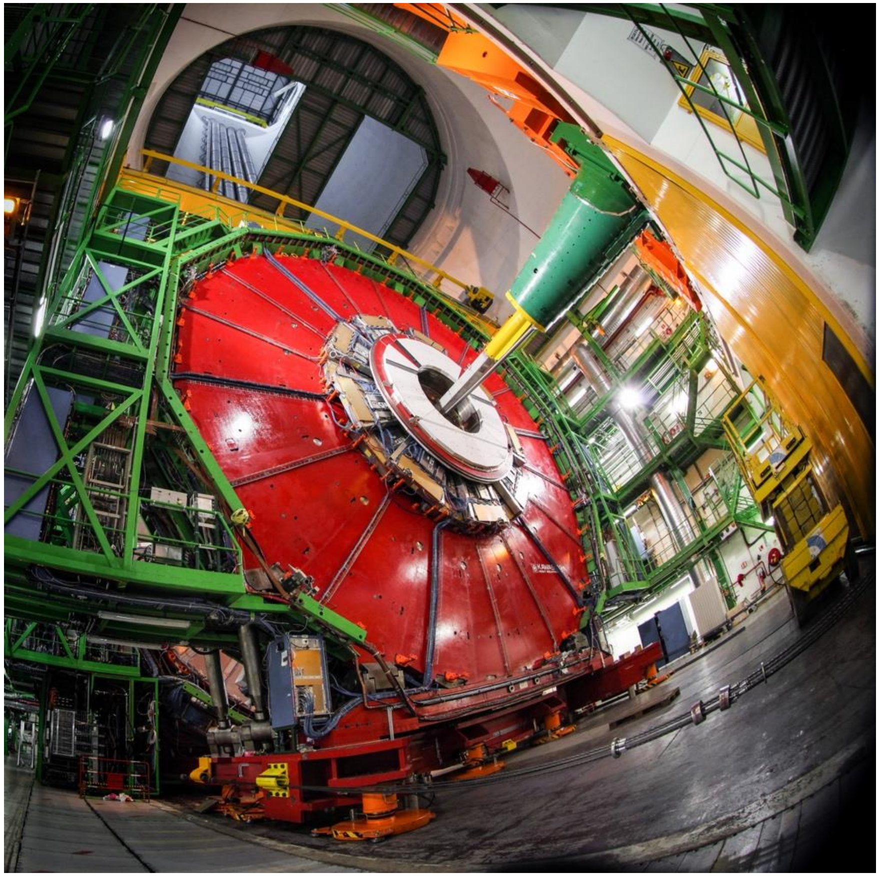


LHC: 27 km, the world's largest proton-proton collider (7-14 TeV).
~10% of planned total dataset collected so far.

CMS: Compact Muon Solenoid



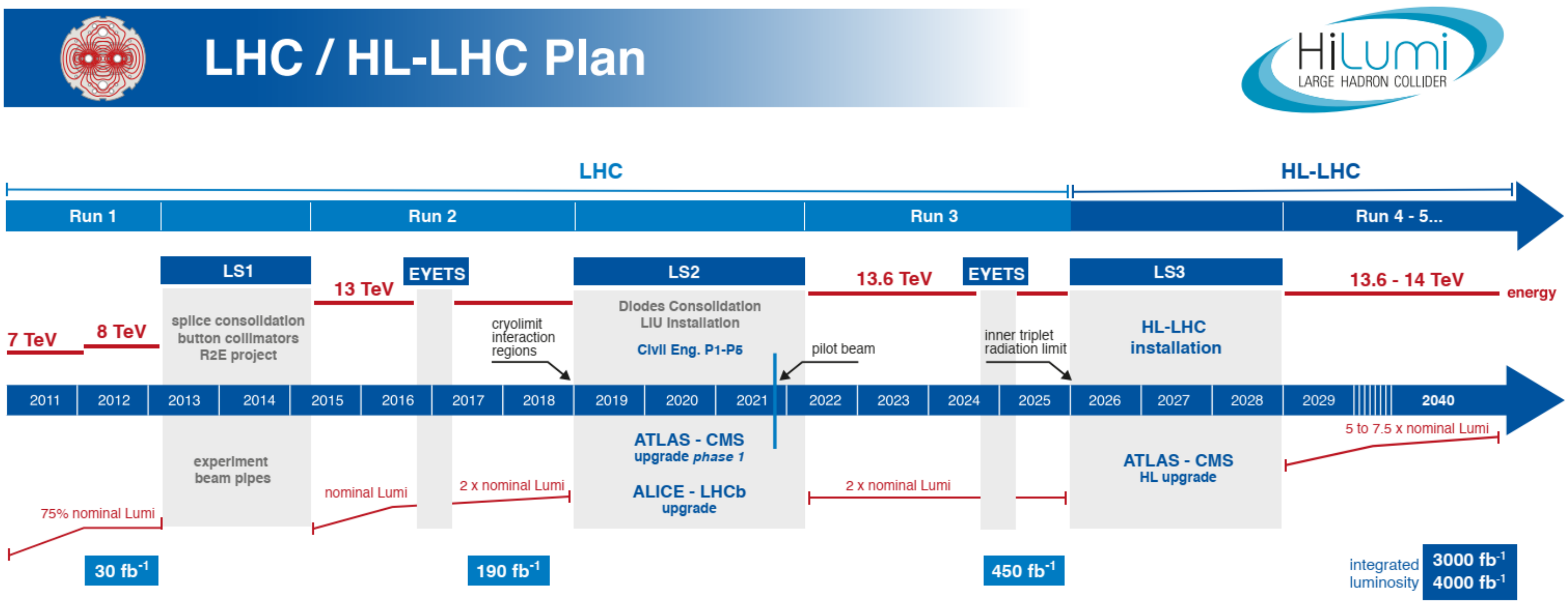
Multi-purpose experiment: Higgs sector physics, SM precision measurements, BSM searches…



Several sub-detectors nested around the LHC collision interaction point

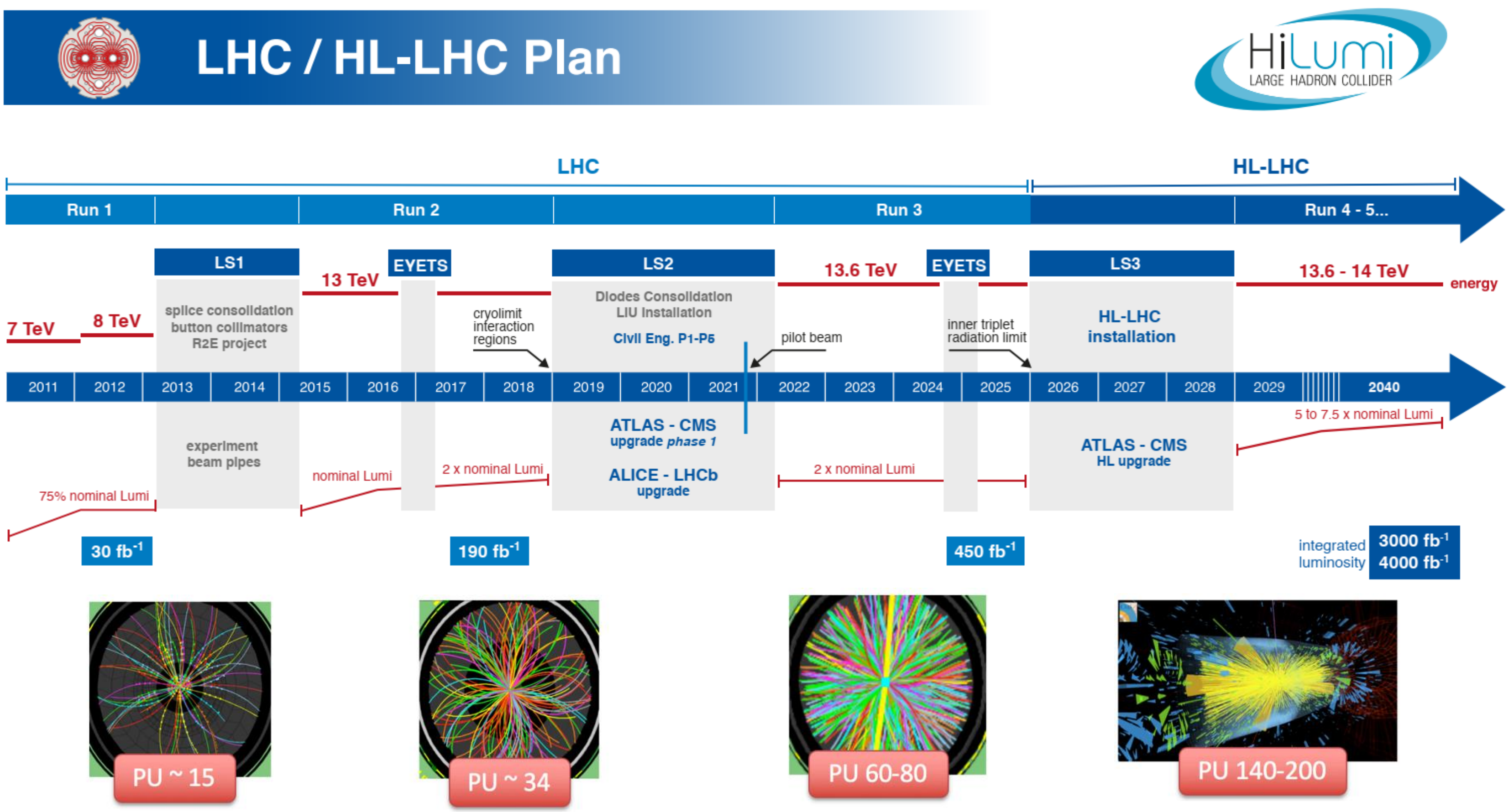
The LHC roadmap

- So far, the LHC has delivered **only around 10%** of its ultimate dataset.
  - HL-LHC physics programme will Integrate 10x more luminosity (3000 fb^{-1}), offering abundant opportunities for **high-precision measurements** and **explorations of new physics**.

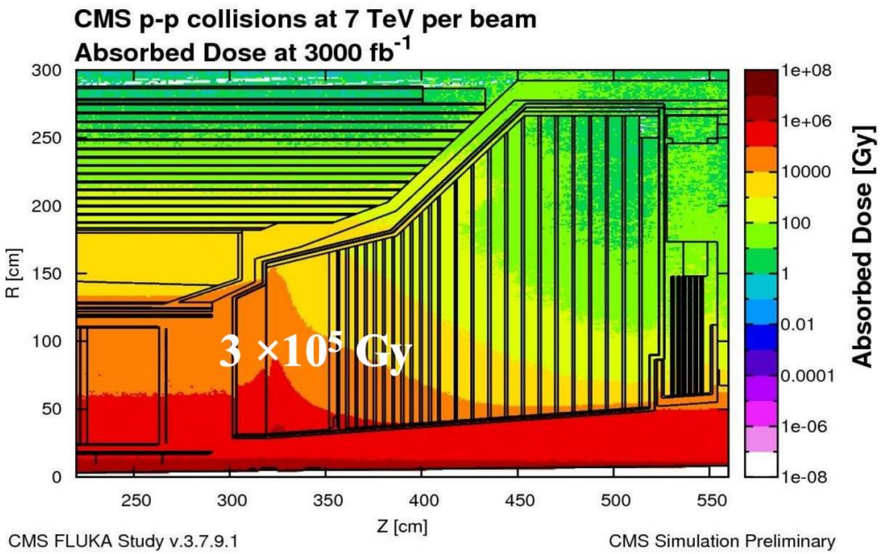


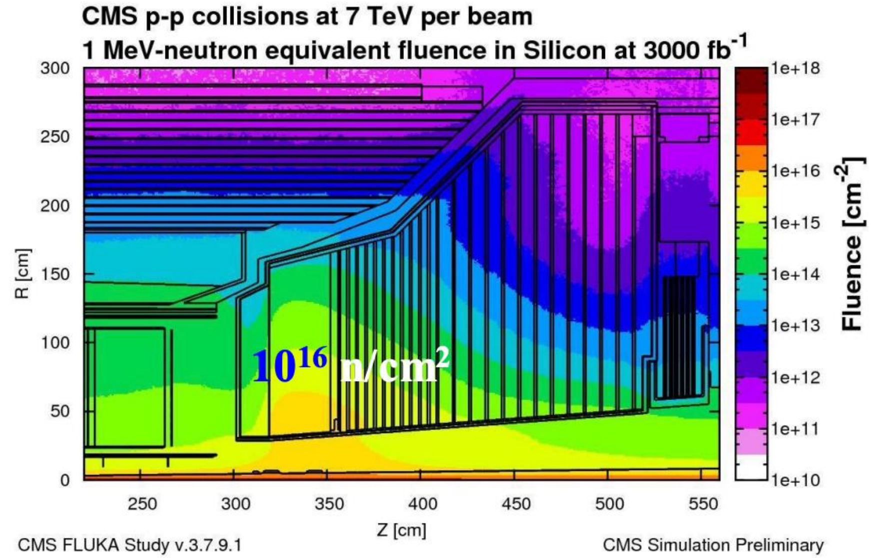
The HL-LHC

- The HL-LHC will provide PU up to 200 and higher luminosity.
  - The **present electromagnetic calorimeter ($PbWO_4$-based)** and the **hadron calorimeter (plastic-scintillator)** were designed for a total integrated luminosity of only 500 fb^{-1}. Their performance would degrade under HL-LHC conditions.



Radiation challenge

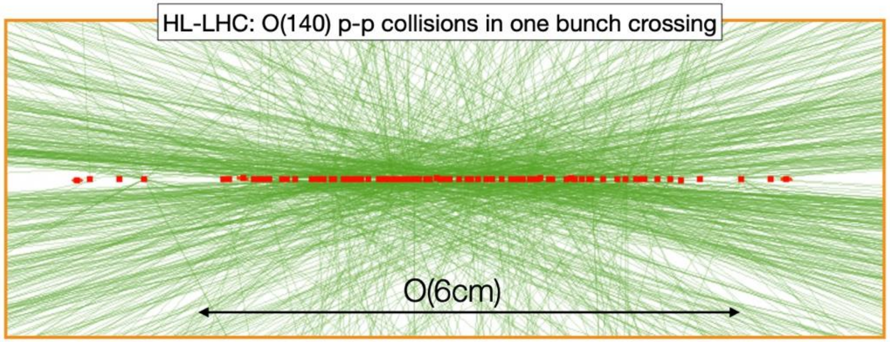


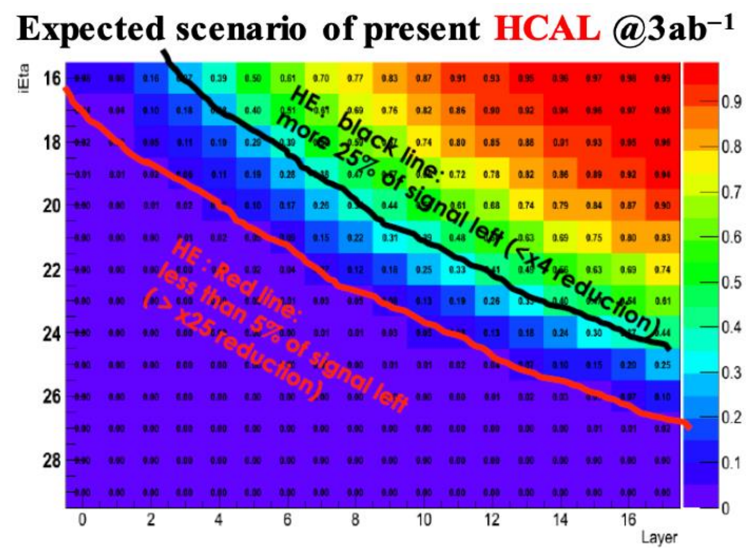


- The upgraded HL-LHC will expose the forward calorimeters to **very high radiation** and **pile-up**.
  - Fluence up to ~ 10^{16} n_{eq}/cm^2
  - Absorbed dose up to 2 MGy
  - We need ultra-radiation-hard sensors and electronics, and the design should be adapted to each detector's exact location.

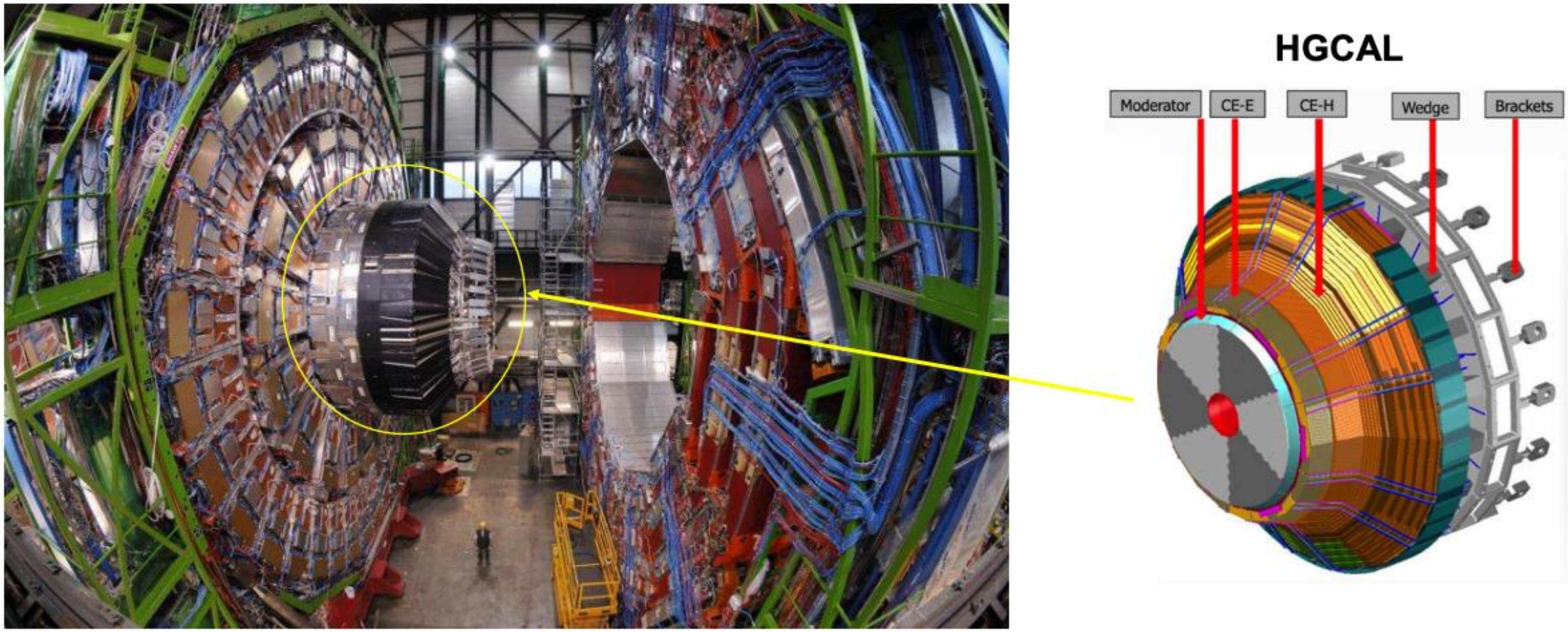
Technical requirements

- **Radiation tolerance**
  - Preserve energy resolution and calibration till 3 ab^{-1}
- **Fine lateral granularity**
  - separate showers, identify narrow jets, reduce pile-up, aid calibration.
- **Fine longitudinal granularity**
  - improve EM resolution, pattern recognition, and pile-up suppression.
- **Precision measurement of time (~30ps)**
  - Pile-up suppression and primary vertex identification
- **40MHz read-out**
  - provide trigger information for every bunch crossing.





HGCAL is the choice



As part of the CMS phase-II upgrade, **the High-Granularity Calorimeter (HGCAL) fulfils all of those requirements** and will replace the current CMS endcap in the HL-LHC era.

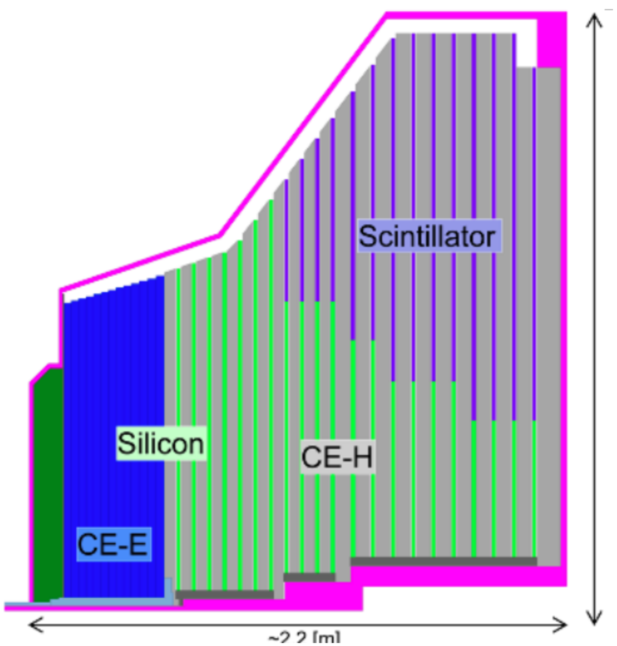
CMS internal nomenclature: Calorimeter Endcap (CE), divided into CE-E and CE-H

Key specifications

- **Silicon section (using silicon sensors):** electromagnetic calorimeter (CE-E) and part of the Hadronic calorimeter (CE-H).
- **Scintillator section (using SiPM-on-tile technology):** CE-H where the expected end-of-life neutron fluence is less than $5x10^{13}$ n/cm^2.
- **TDR:** https://cds.cern.ch/record/2293646

Both endcaps	Silicon	Scintillators
Area	~620 m^2	370 m^2
Channel size	0.5 - 1 cm^2	4 - 30 cm^2
#Modules	~31000	4000
#Channels	6.1 M	240 k
Op. temp.	-30 °C	-30 °C

Per endcap	CE-E	CE-H (Si)	CE-H (Si+Scint)
Absorber	Pb, CuW, Cu	Stainless steel, Cu	
Depth size	25.5 X_0, 1.7 λ	9.5 λ	
Layers	28	8	14
Weight	23 t	205 t	



Physics potential

HGCAL can **mitigate the effects of PU** and **provide high geometric acceptance on forward physics：** The 1st 5D calorimeter (energy, X, Y, Z, t)

Energy reconstruction

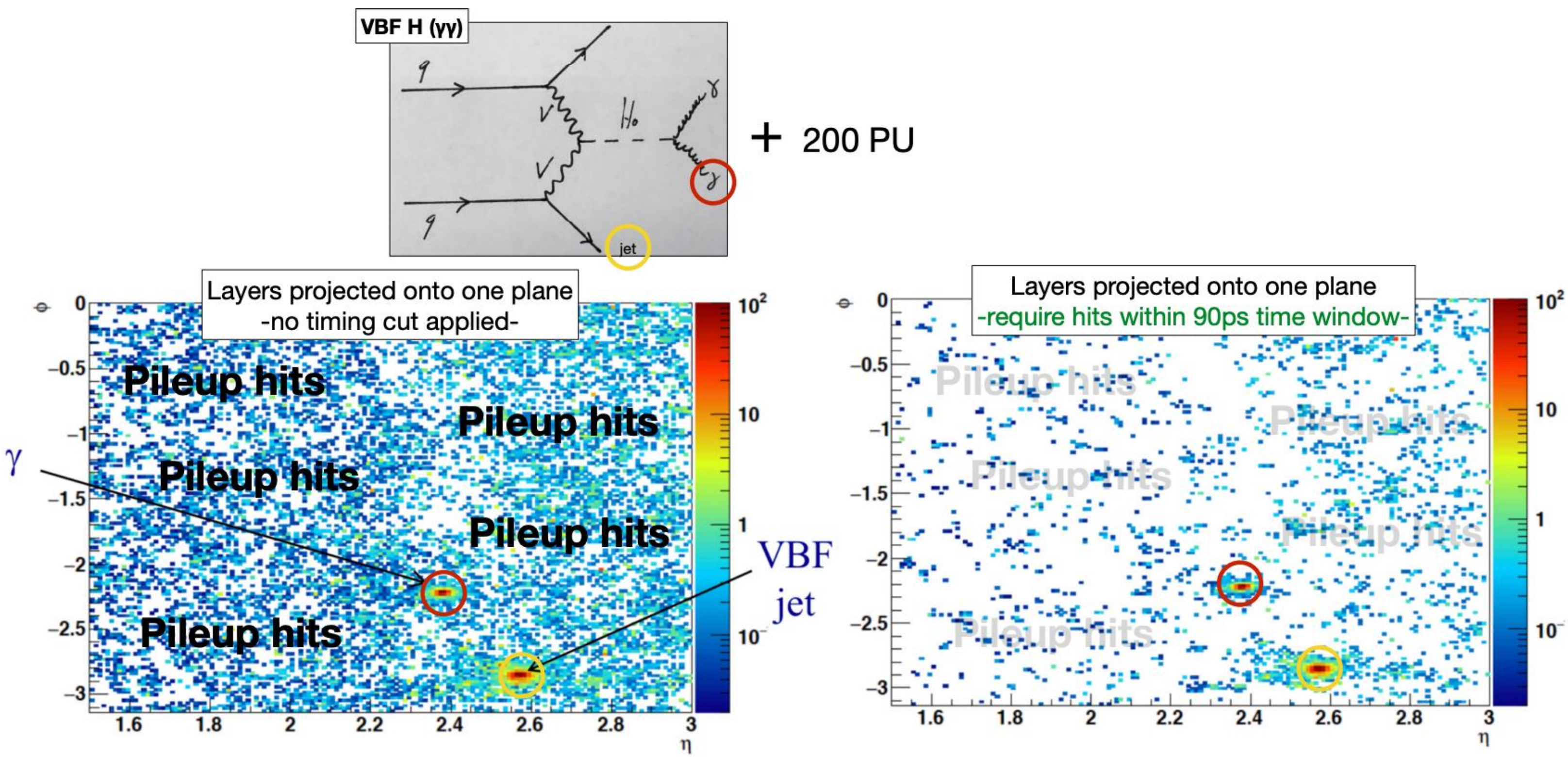
- Dynamic range: 0.2 fC - 10 pC
- Calibrate on single MIP
- Measure energetic jets O(10k) MIP

High Spatial granularity

- 6M channels in ~40 m^3
- Cell sizes: 0.5 - 30 cm^2

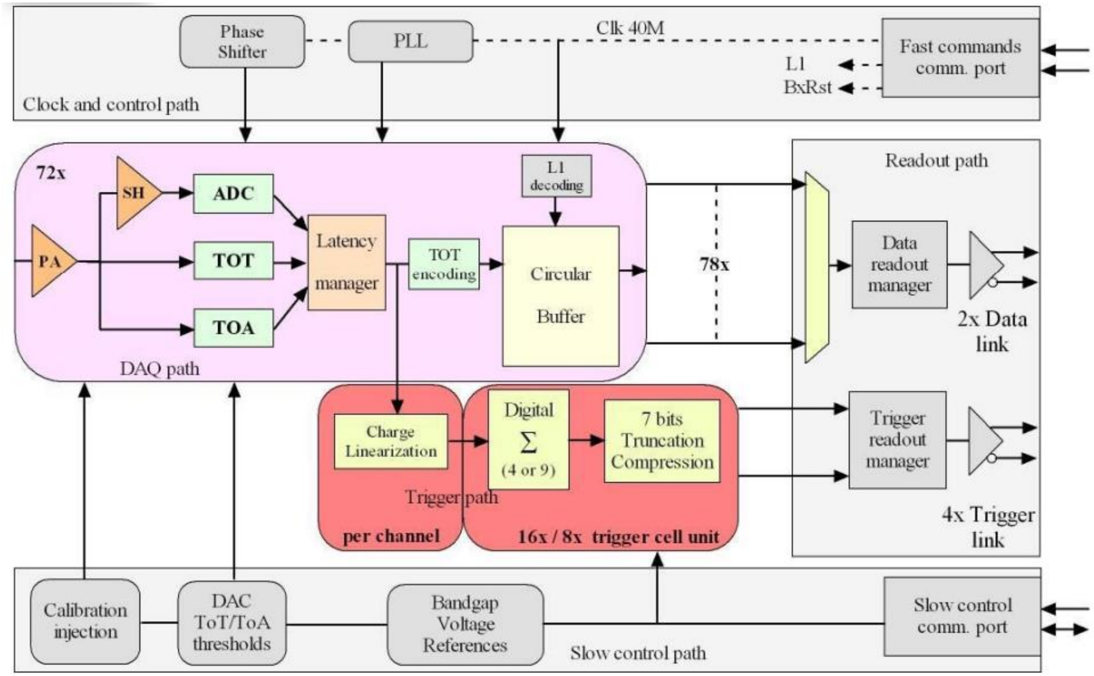
Precise Timing

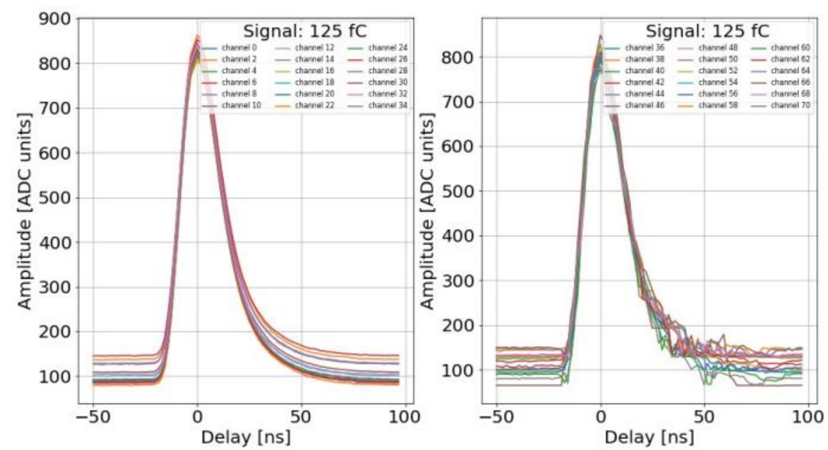
- O(25 ps) per channel energy above O(10) MIPs
- Essential to mitigate pileup at HL-LHC



HGCROCV3: Final FE chip for HGCal

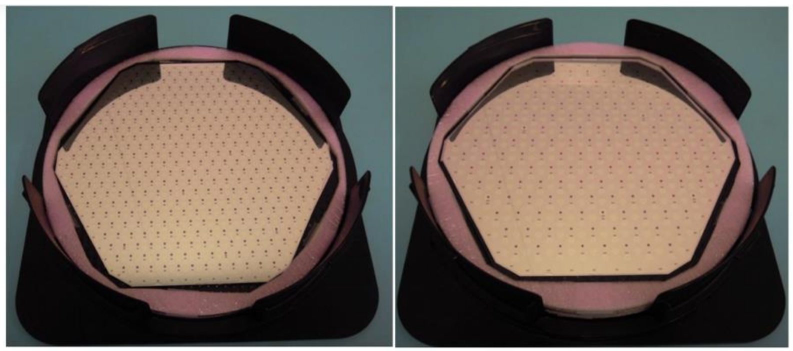
- **Two versions:** Silicon and SiPM
- **Radiation Hardness:** (200 Mrad, 1.10^{16} neq/cm2)
  - Tested to 310 Mrad
- **Low noise:** < 2500 e (0.4fC) and ~1800e （0.3fC）
- **Charge measurement range** (0.2 fC to 10 pC)
  - Linearity < 1% for ADC/TDC
- **Fast shaping** (peak <25 ns)
- **Precise timing capability** (25 ps)
  - Jitter: TOA < 25 ps





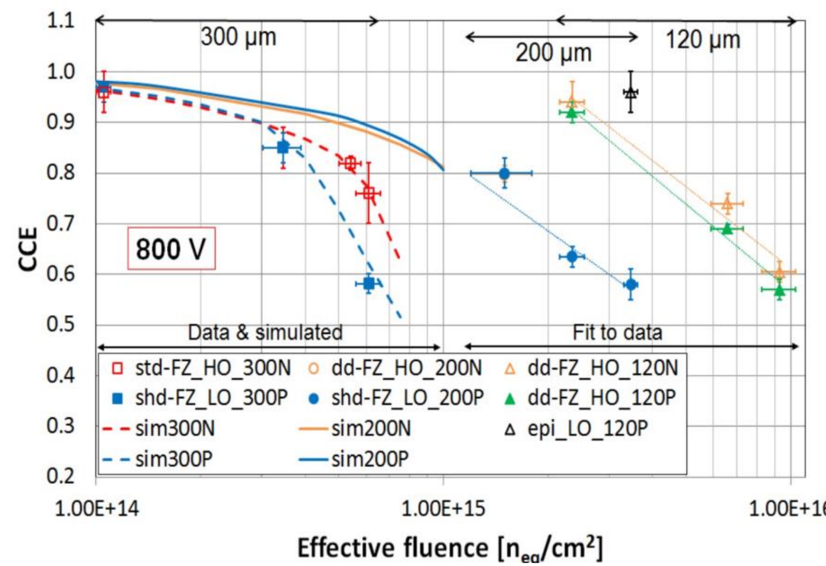
310 M rad (in 5 days) and 2 days annealing

Silicon sensor



8” High-Density sensor
432 cells with ~0.5cm2 size
120μm active thickness

8” Low-Density sensor
192 cells with ~1.1cm2 size
200/300μm active thickness

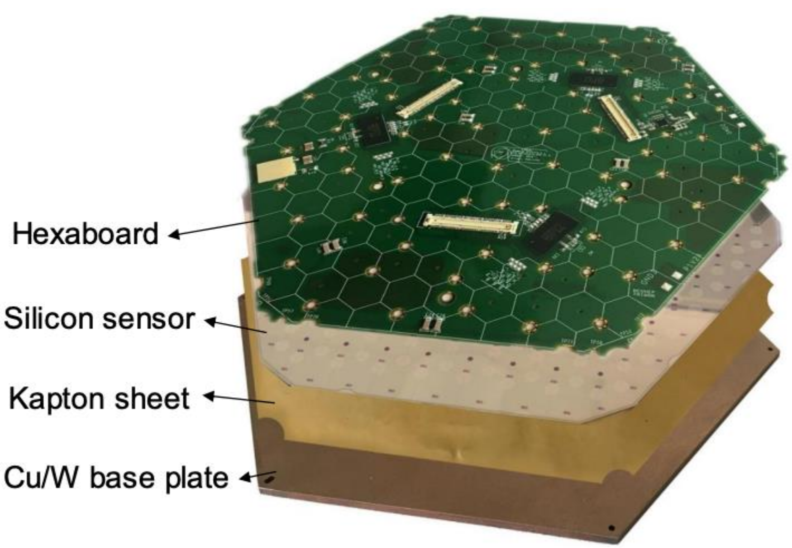


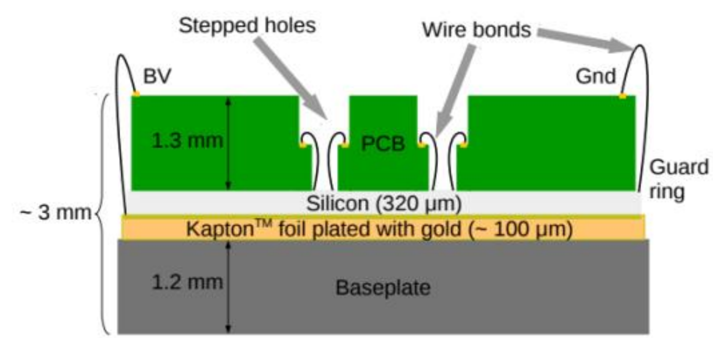
- **Planar p-type, DC-coupled pads**
  - easier to make; p-type silicon resists radiation better than n-type.
- **Hexagonal cells**
  - need ~30 % fewer sensors than square cells.
- **Three thicknesses (300 μm, 200 μm, 120 μm)**
  - match sensor thickness to the local radiation level.
- **Simple, rugged modules with automated assembly**
  - allow fast, repeatable high-volume production.
- **Neutron-irradiation tests (8-inch sensors, 10^{16} n/cm²)**
  - confirmed the best production process and proved the sensors’ radiation hardness.

Silicon module

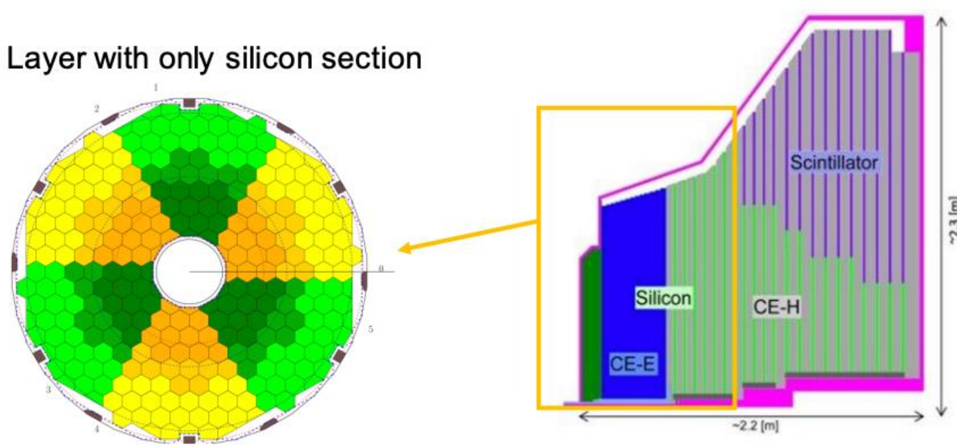
The fundamental unit of the HGCAL silicon section is the **silicon module**.

- **High-precision sandwich structure** glued by gantry
- Connect sensor to FE-PCB(Hexaboard) with bonder and encapsulated



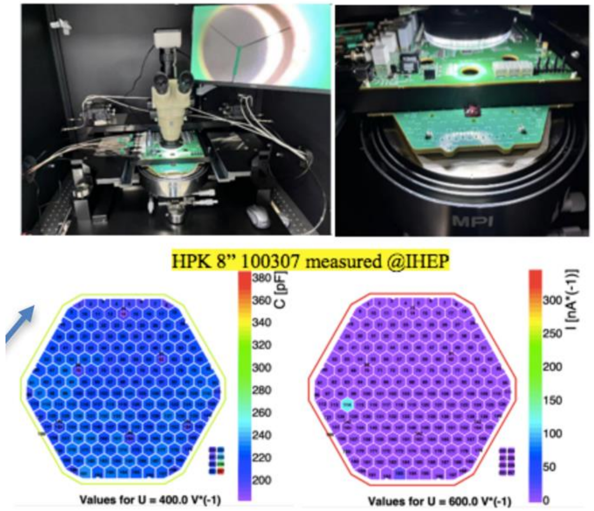


Layer with only silicon section

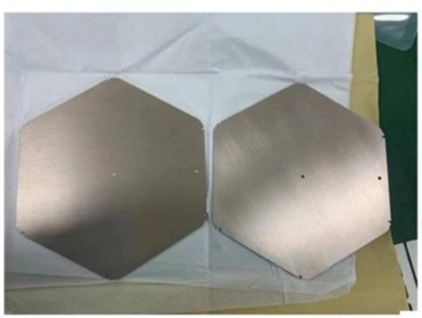


China HGCal activities on silicon modules

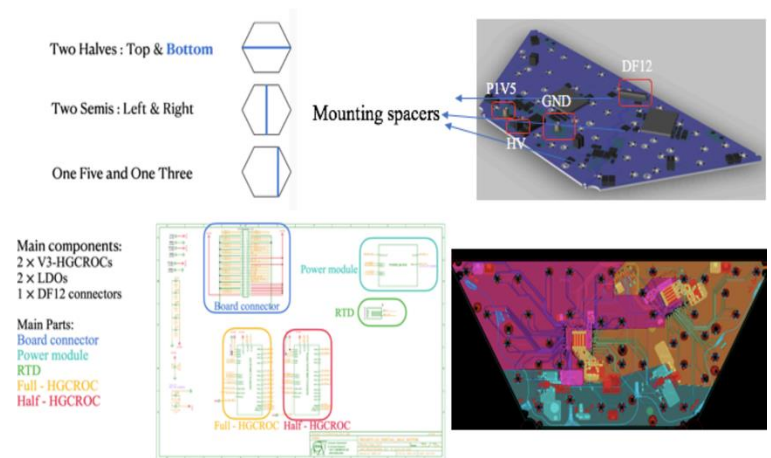
- Manufacture ~5000 low-density (LD) full-Si modules, **covering ≈ 100 m² (~ 1/5 of the total)** at IHEP.



- Sensor Quality Control (SQC) inspections



- **~90%** of the Cu-W baseplates production



- Contribute to the **Partial hexaboard design**

Module Assembly Center at IHEP

- There are currently **6 module assembly centres (MAC)** sharing the silicon module production tasks.
  - 3 in US (CMU, TTU, UCSB)，3 in Asia (IHEP, NTU, TIFR)

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COMPACT MUON SOLENOID COLLABORATION
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December 15, 2021

Subject: Certification of qualification the HGCAL Module Assembly Centre at IHEP, Beijing

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To whom it may concern,

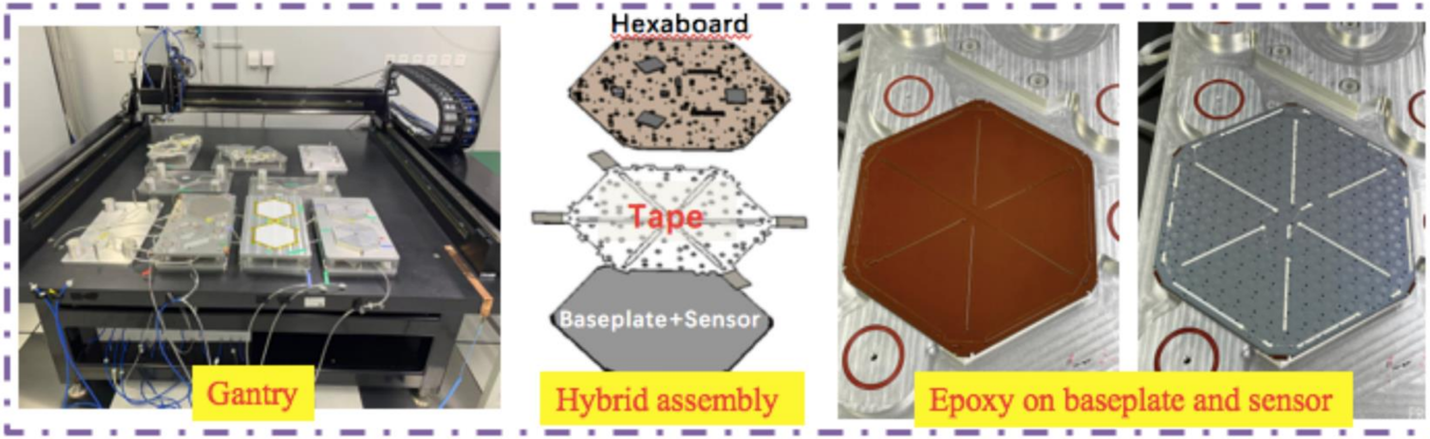
I am writing as Project Manager for the CMS endcap calorimeter upgrade project (HGCAL) to certify that the silicon module assembly center (MAC) at IHEP Beijing, led by Prof. Huaqiao Zhang, has been qualified for the HGCAL project as ready to move into the Pre-Series phase of construction.

HGCAL will replace several of the present CMS sub-detectors: the silicon/lead endcap pre-shower detector, the lead-tungstate crystal electromagnetic endcap calorimeter, and the plastic/brass endcap hadron calorimeter. HGCAL is a novel sampling calorimeter, based on a large-scale deployment of silicon modules (a grand total of approximately 26000 installed, plus 5% spares), positioned between dense layers of absorber. The silicon modules will be complemented with plastic scintillator tiles instrumented by silicon photomultipliers (SiPMs) in regions of the detector where particles arrive with lower intensity.

The qualification of the IHEP Beijing MAC has been completed on time to meet the corresponding project milestone. The MAC is set up in a Class 1000 clean room that is dedicated to this facility and all of the equipment for mass production of silicon modules for HGCAL has been installed in the clean room and commissioned. This equipment includes a gantry machine for automated module assembly, a wire-bonding machine, an optical inspection and coordination measurement machine, and a silicon module test-stand. The IHEP Beijing team has been trained in how to use the MAC equipment, and they have practiced extensively on dummy module components before moving onto using live components.

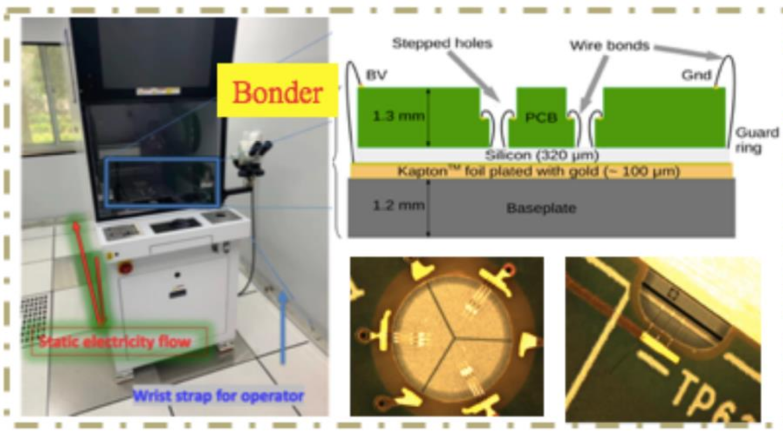
- IHEP MAC was certified officially in 2021
- Produce the first 8-inch real HGCal Si-module for CMS（2021）
- Massive module production using the final V3C hexaboard started in September 2025.

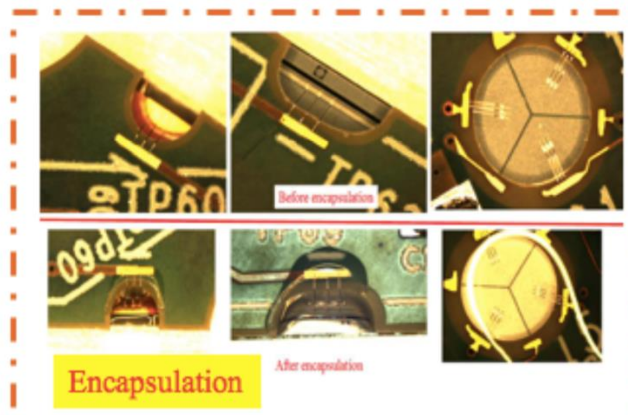
Module Assembly - Workflow



Hybrid assembly (epoxy + transfer tape) method for improving the production rate

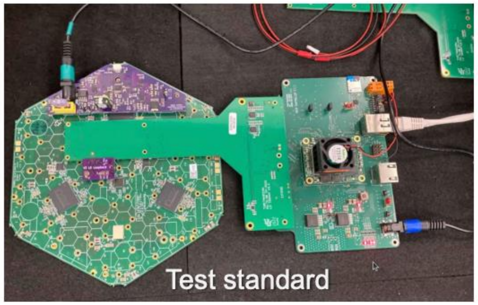
- In November, IHEP MAC will ramp-up to 8 modules per day
- The final production rate will be **16 modules per day.**

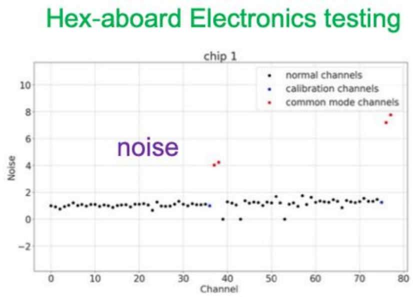




Programmatic **bonding** (30 mins per module)
Automatic **encapsulation** (15 mins per module)

Module Assembly - Workflow

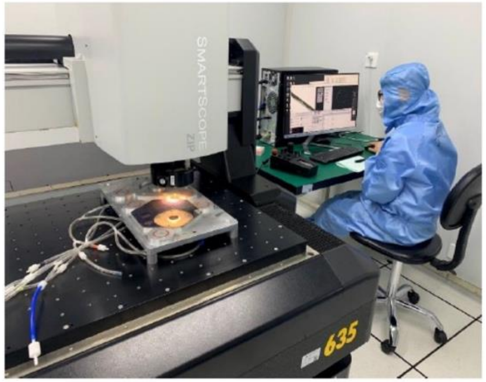


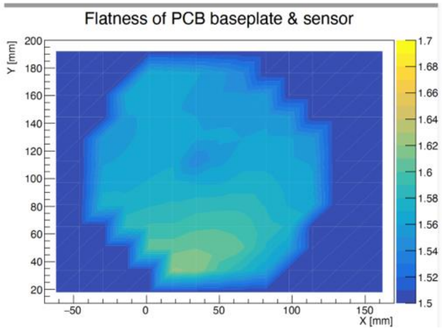


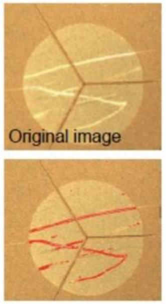
Module status	Number	IV(@500V)<10 0uA	Noise + Dead + Unbonded channels < 4	Grade A Modules
Waiting for test	4			
Completely Bonded	20	20	20	20
Completely Encapsulated	4	4	4	4
Total	28	24	24	24

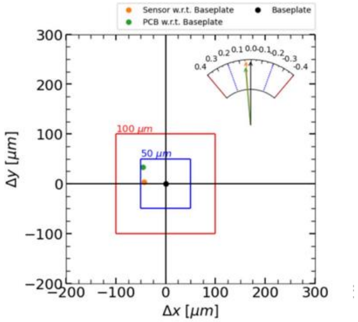
Electronic test performed before/after module assembling

- Switching to Multi Module Test System in November (3 modules per run)





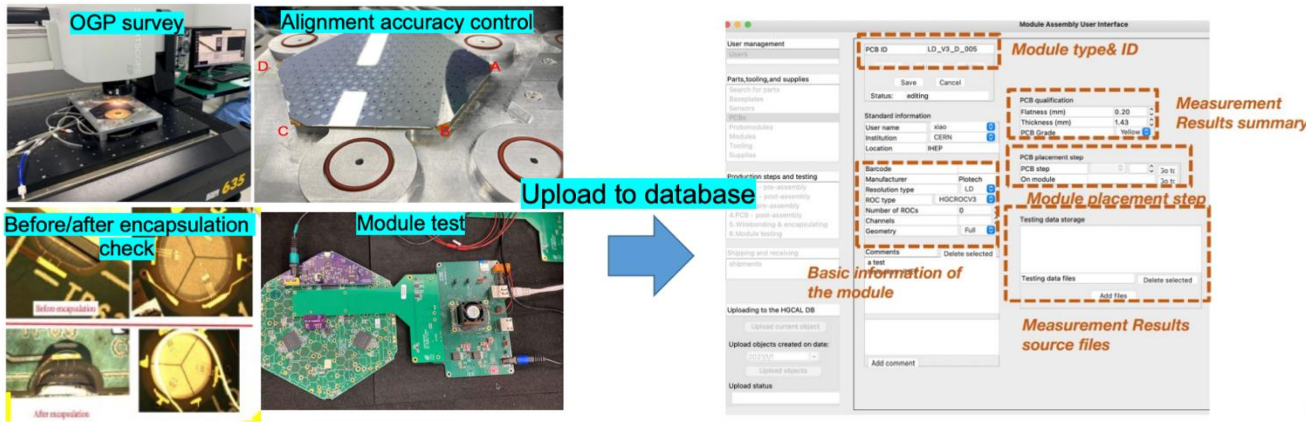




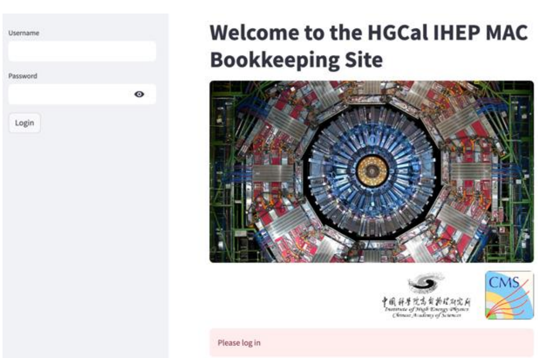
Test Hexa-board, sensor, baseplate and module on **Optical gauging product** (OGP)

- No-touch measurement with resolution of ~1μm.

Module Assembly – QA/QC & web-UI-tracking



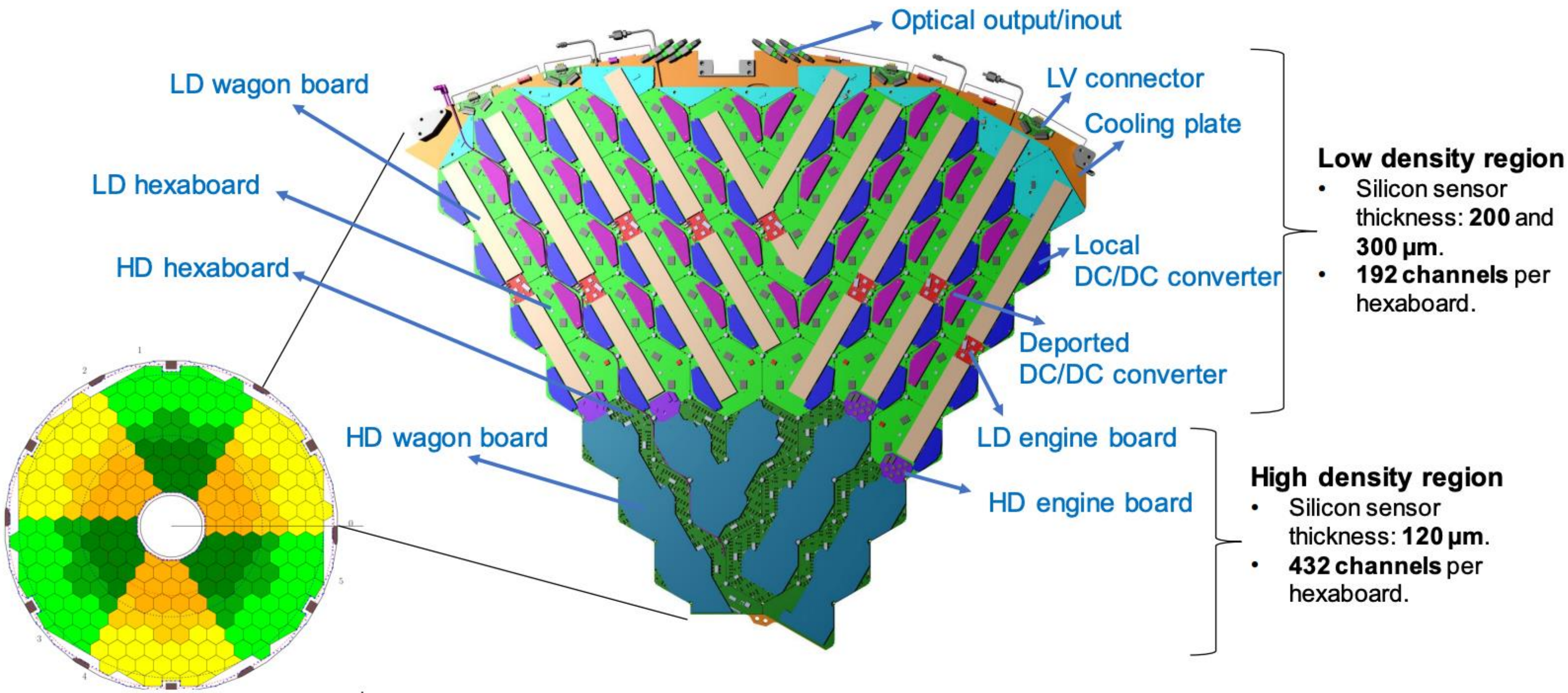
- QA/QC procedures are followed in whole module assembly process
- All QA/QC testing results synchronised to the central database

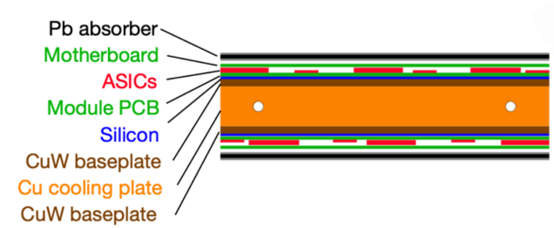


China-HGCal team develop a **HGCAL Module Production Web-UI Tracking System**

- The system offers powerful, user-friendly tools for real-time production logging, automated notifications, and comprehensive data visualisation.
- Deployed on the CERN cloud service and used in IHEP and TTU

A cassette in the silicon section



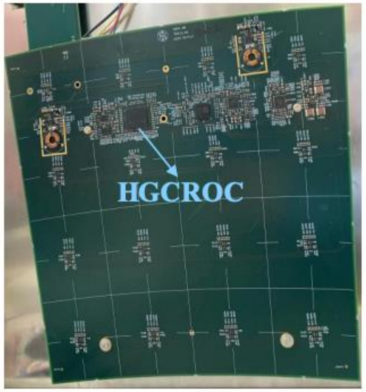


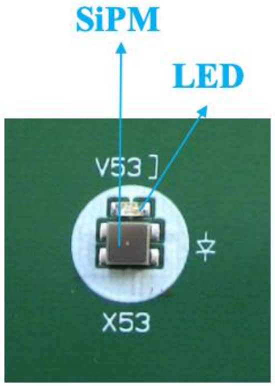
Integration of modules and auxiliary components

- Self-supporting sandwich structures (with absorbers).
- Modules placed on both sides of Cu cooling plate and closed with Pb plates.

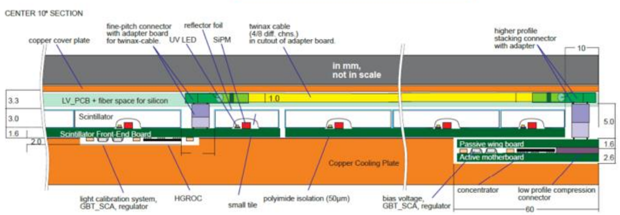
Scintillator section

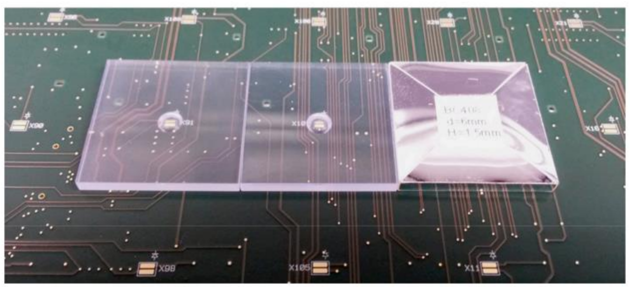
A **Tile module** is the basic unit in the scintillator section of the HGCAL.



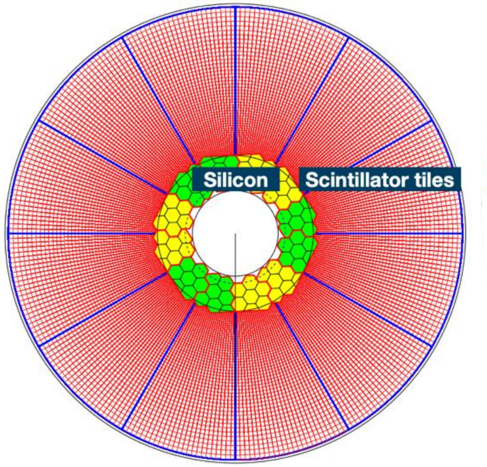


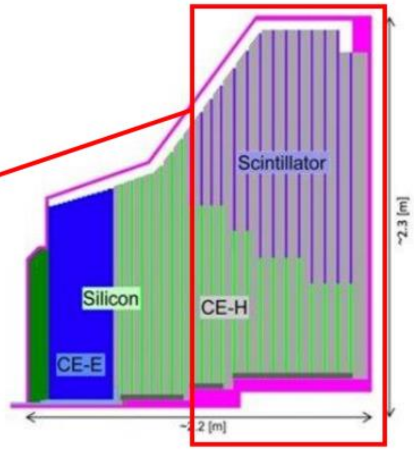
Scintillator + SiPM





Design ("SiPM-on-Tile") for CALICE-AHCAL prototype adopted as the **baseline** for CMS-HGC scintillator part





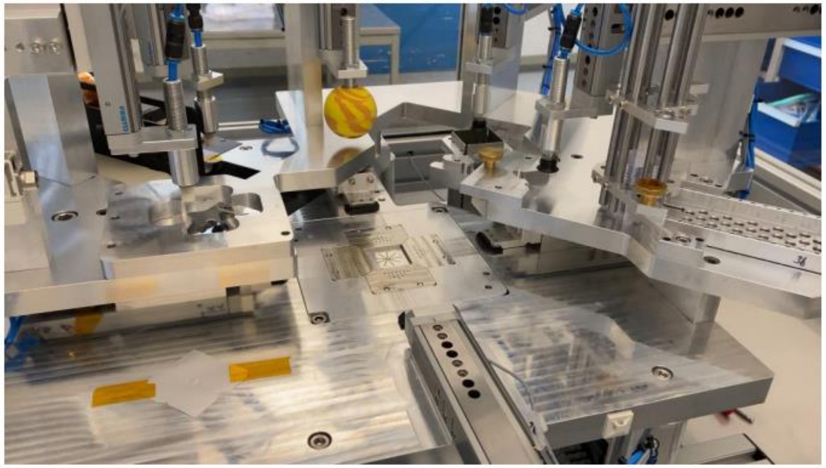
Each Tilemodule comprises:

- Wrapped scintillator tiles (4 – 30 cm²)
- SiPMs (4 mm² or 9 mm²)
- HGCROC ASIC (reads out 72 channels per module)
- LED-based calibration system and supporting electronics

Scintillator assembly

There are currently two Tile module assembly centres. One of them is in DESY and the other is in Fermilab (FNAL).

Tile wrapping machine

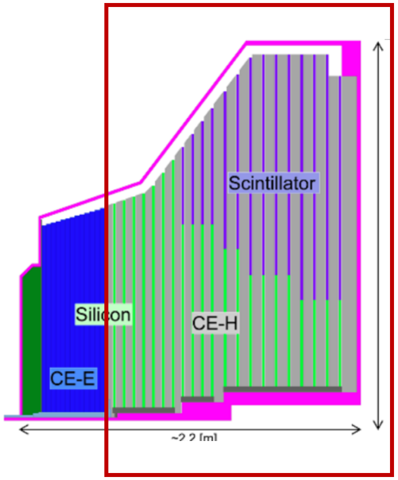


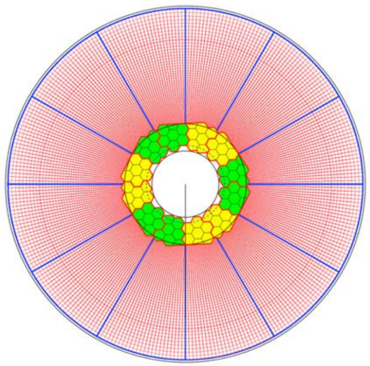
Pick-and-place machine

As of Oct. 2025

- Melded tiles made at FNAL (>70k, 70%)
- Cast tiles machined at NIU (>90k, 47 %)
- Tile wrapping at DESY and NIU

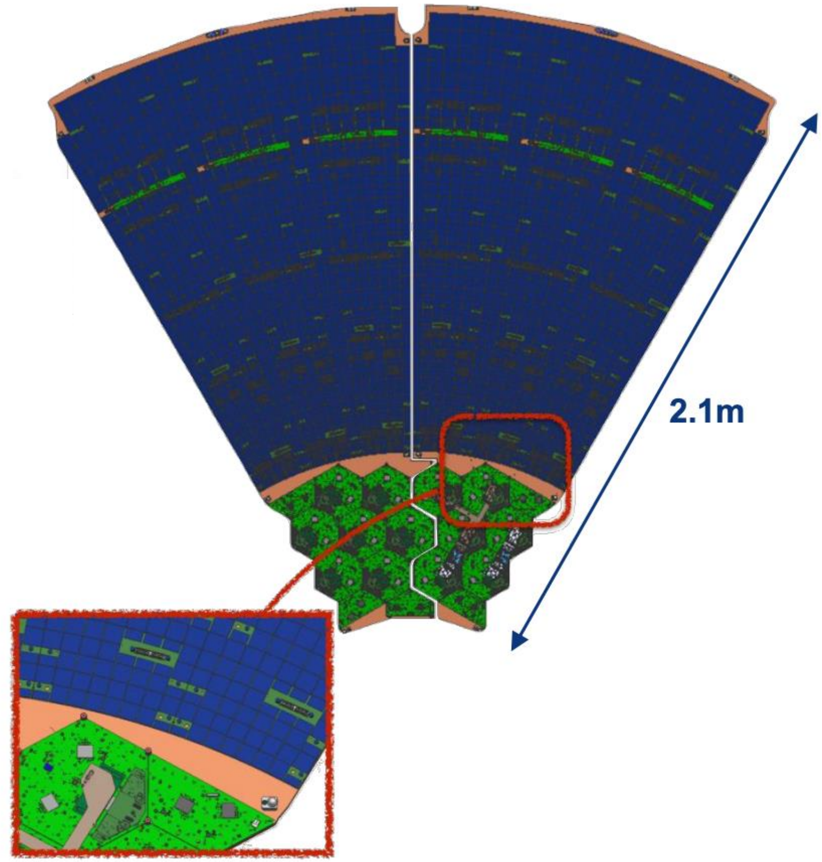
A cassette in the CE-H mixed section



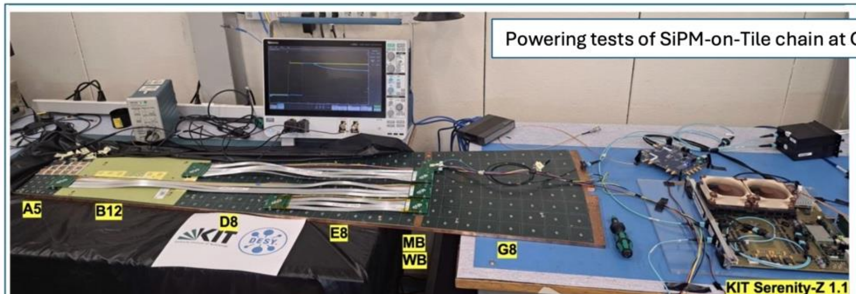


Mixed layer (in CE-H) with silicon at high η and scintillator+SiPM at low η.

CE-H mixed cassette (Fermilab)



Powering tests of SiPM-on-Tile chain at CERN

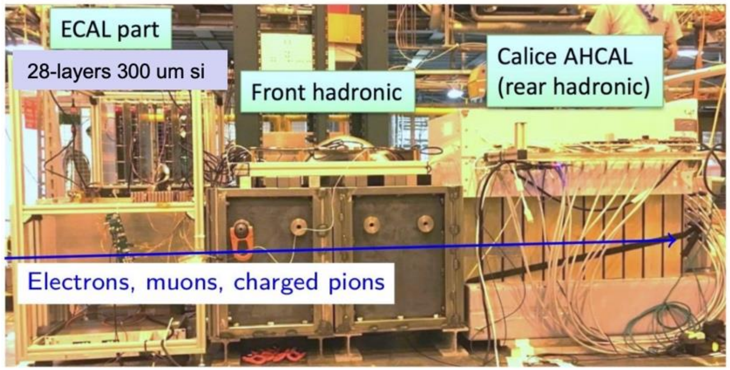


- Copper plate + 5 tileboards + ECON-D motherboard

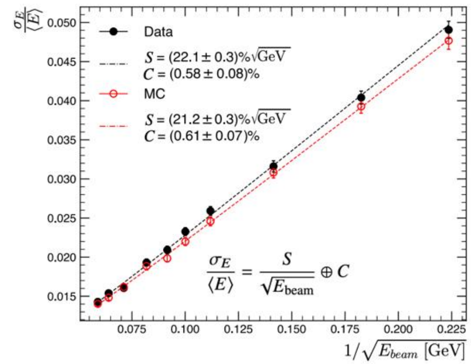
CE-H cassettes are single-sided and exist in both all-silicon and mixed (scintillator and silicon sensor) types.

Beam tests

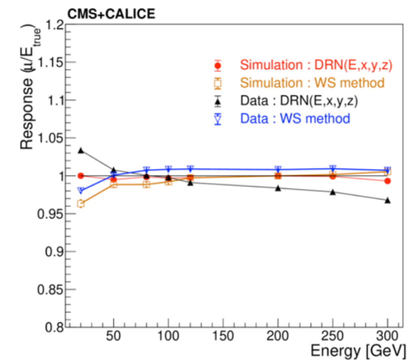
Beam tests in 2016–2018 using 6-inch silicon + SKIROC-cms modules and CALICE Sci. AHCAL



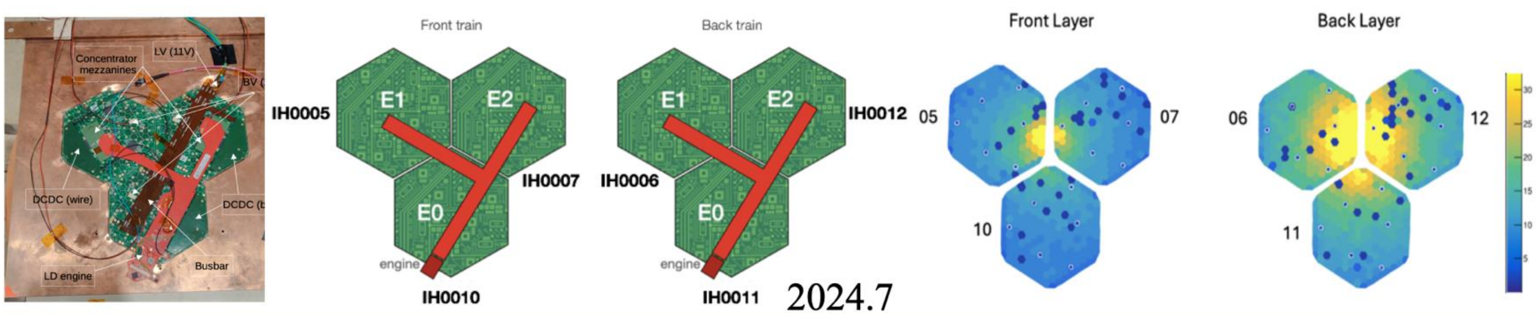
Energy resolution

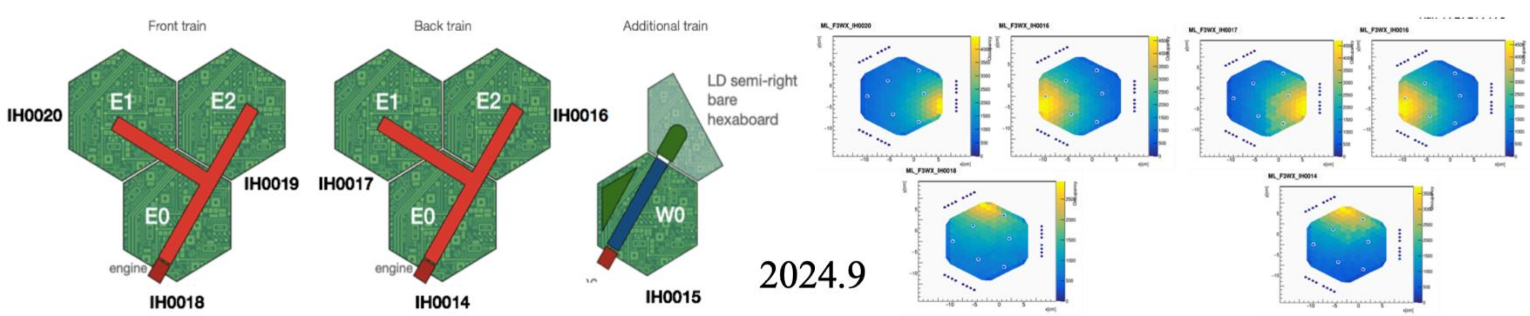


Linearity



Later beam tests on pre-production models confirmed good module performance



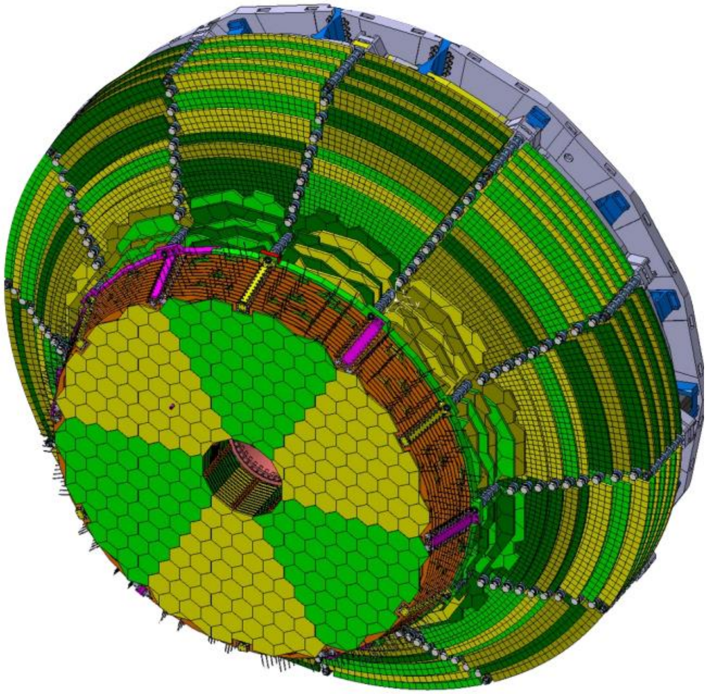


HGCAL - a 5D Imaging Calorimeter

Very heterogeneous system + Ultra-high granularity + precise timing

Handles HL-LHC challenges

- Suppresses extreme pile-up
- Resists very high radiation levels in the forward region



Project timeline

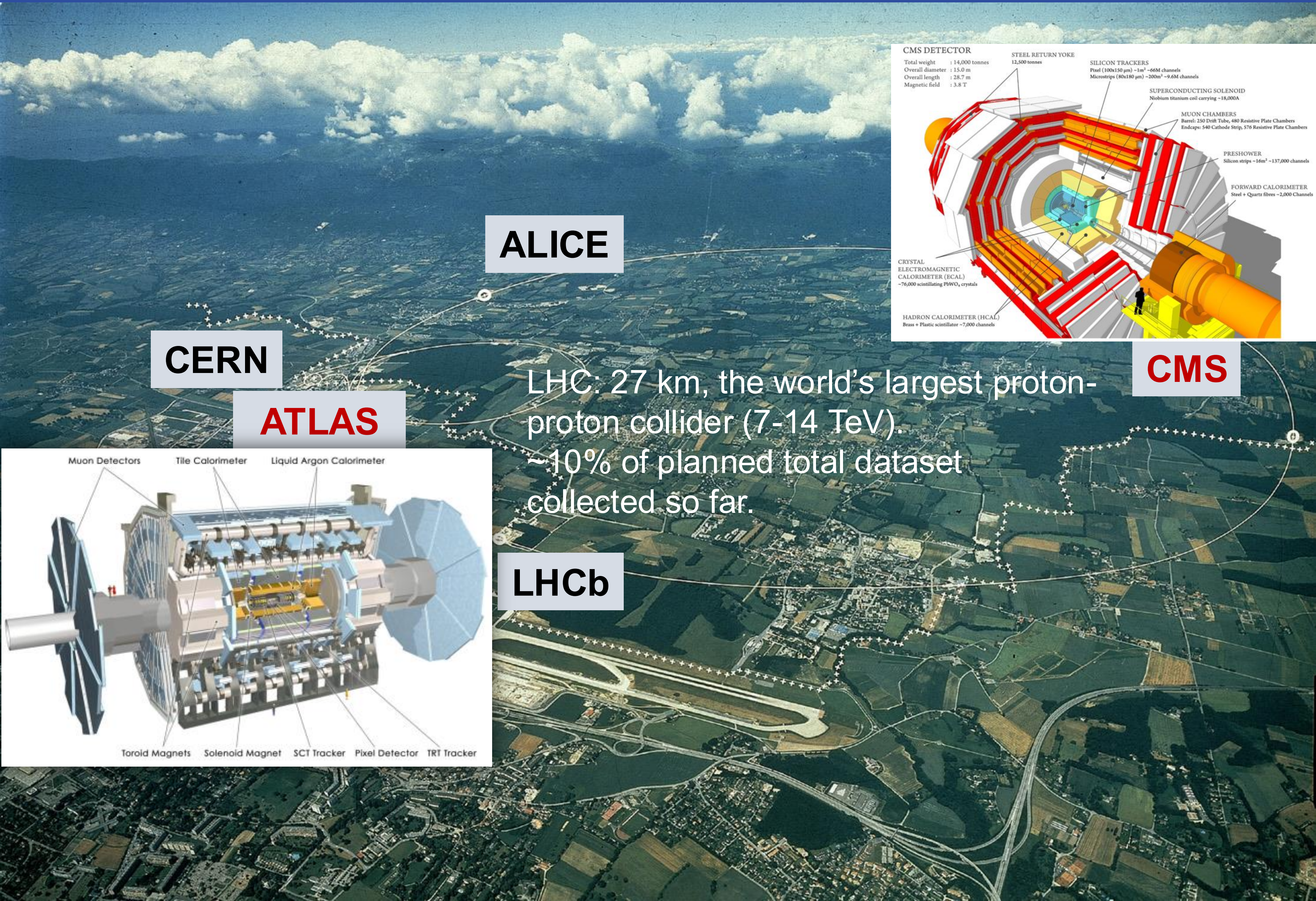
- Design, development, and production on schedule
- Final end-caps to be installed in the CMS cavern by **mid-2027**

Technical opportunities

- Cutting-edge work in electronics, hardware, firmware, and software
- Ideal platform for experimental physicists to tackle frontier R&D challenges

Thanks

LHC



LHC: 27 km, the world's largest proton-proton collider (7-14 TeV).
~10% of planned total dataset collected so far.