



HGCAL: A Novel Imaging Calorimeter for the CMS Upgrade

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TIFR Mumbai

On behalf of the CMS Collaboration



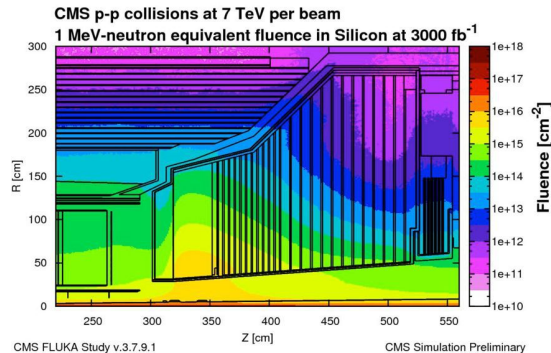
INSTR 2026

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- **Motivation:** HL-LHC and why the endcaps must be replaced
- **HGCAL design and structure**
- **Construction status**
 - Silicon modules
 - Scintillator tiles
 - Cassette integration
 - Front-end and back-end electronics
- **Physics performance and test beams**
- **Summary**

HL-LHC: why the endcaps must be replaced

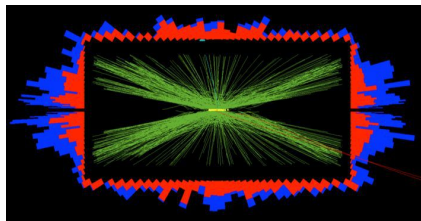
- Peak luminosity $5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$, pileup up to **200**
- Target **3000–4000 fb⁻¹**:
6–8× the full LHC dataset
- Current endcap calorimeters were designed for **500 fb⁻¹** and cannot survive the HL-LHC radiation levels



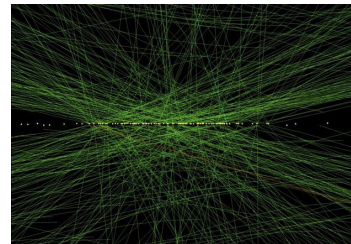
1 MeV-neq fluence in silicon at 3000 fb⁻¹ (CMS FLUKA study)

Existing calorimeters will suffer irreparable damage

Fluence up to $\sim 10^{16} \text{ n}_{\text{eq}}/\text{cm}^2$, dose up to $\sim 2 \text{ MGy}$

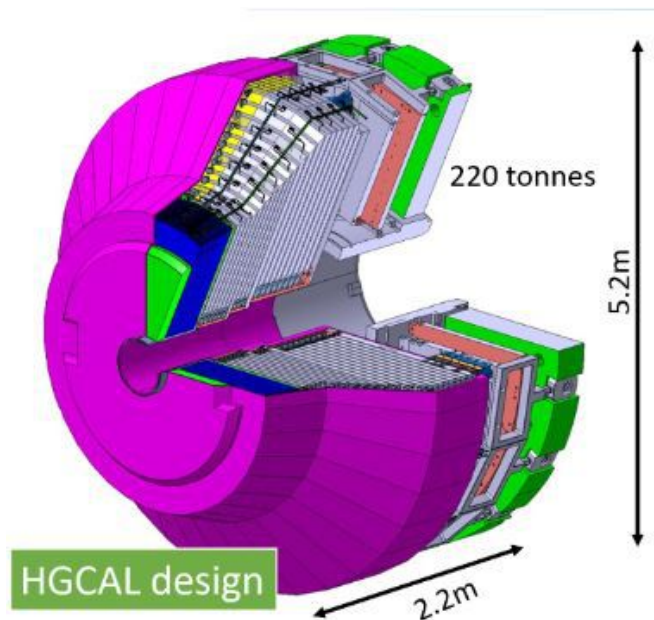


2012: 78 pileup events



HL-LHC: 140–200 pileup events

HGCAL: a 5D imaging calorimeter



HGCAL endcap cutaway (CAD rendering)

- **5D:** 3D position (x, y, z) + time + energy per hit
- Replaces the current CMS endcaps in Long Shutdown 3
- Silicon sensors in the high-radiation region, scintillator + SiPM elsewhere

~6 M

readout channels

~30 ps

timing resolution floor

0.2 fC – 10 pC

dynamic range

0.5 – 30 cm²

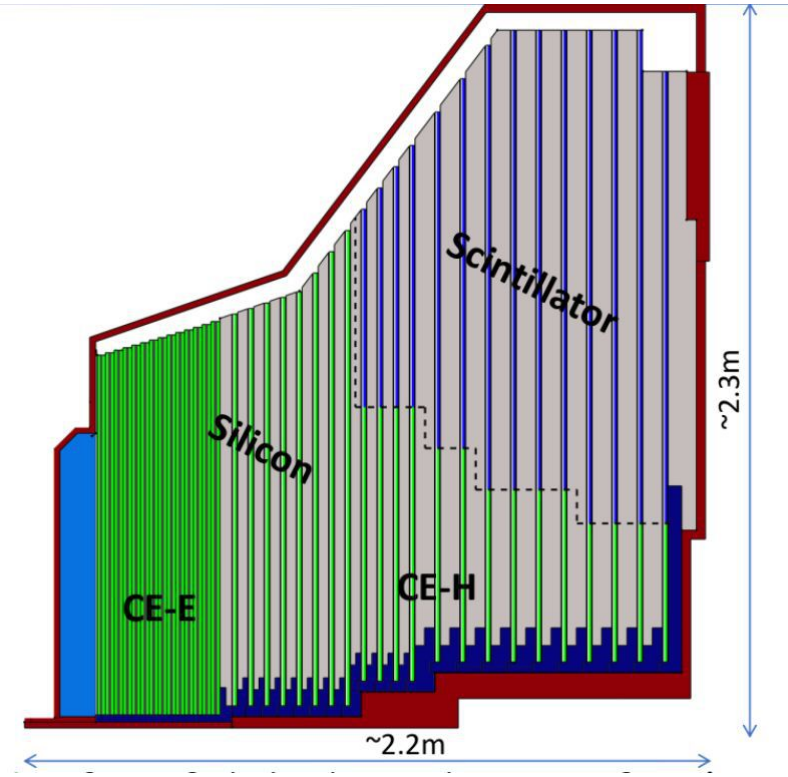
cell sizes

HGCAL structure

Structure: CE-E followed by CE-H, all at -30°C
Coverage: $1.5 < |\eta| < 3.0$, ~ 220 tonnes per endcap
 $\sim 620 \text{ m}^2$ silicon in $\sim 27,000$ modules
 $\sim 370 \text{ m}^2$ scintillator in ~ 4000 tile modules

CE-E: 26 sampling layers, $\sim 27.7 X_0$, 1.5λ
Active: hexagonal Si sensors
Absorbers: Cu, CuW and Pb

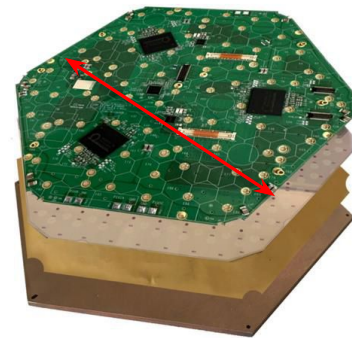
CE-H: 21 sampling layers, 8.5λ
Active: Si sensors + scintillators
Absorbers: stainless steel



HGCAL longitudinal cross-section (CE-E, CE-H)

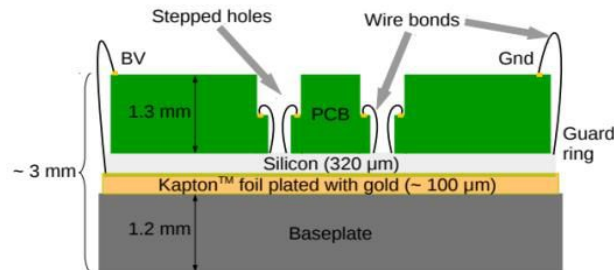
Silicon module

- Hexagonal module; the basic unit of the Si section
- Sandwich of:
 - **Hexaboard:** hosts HGCROCs for sensor-cell readout and data transfer
 - **Silicon:** active material
 - **Kapton:** electrical insulation from the baseplate
 - **Baseplate:** support and rigidity, also acts as absorber
- Sensor connected to the hexaboard by wire bonds, then encapsulated



166.94 mm

Silicon module stack

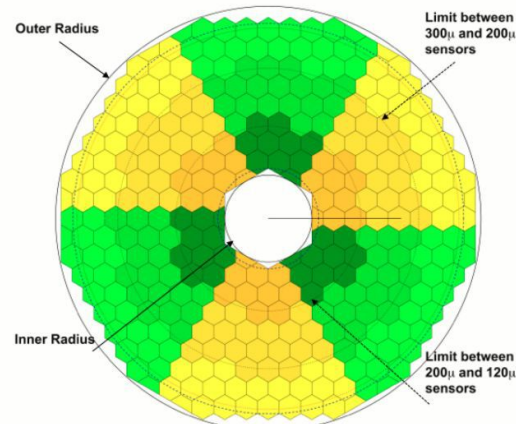


Module cross-section (wire bonds through stepped holes)

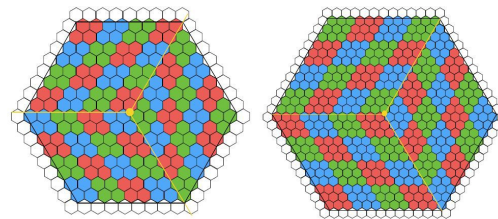
Silicon sensors

- Planar **p-type**, DC-coupled pads: better radiation hardness than n-type
- **Hexagonal** cells: minimal wafer wastage with full coverage
- Three thicknesses, **300 / 200 / 120 μm** , matched to the local fluence
- Cell size: 1.18 cm² (low density, 192 cells), 0.52 cm² (high density, 432 cells)
- **8-inch** wafers, tested with neutron irradiation up to $10^{16} \text{ n}_{\text{eq}}/\text{cm}^2$

More details: Talk by E. Fialová, “CMS HGCal silicon sensors: radiation damage and annealing studies”



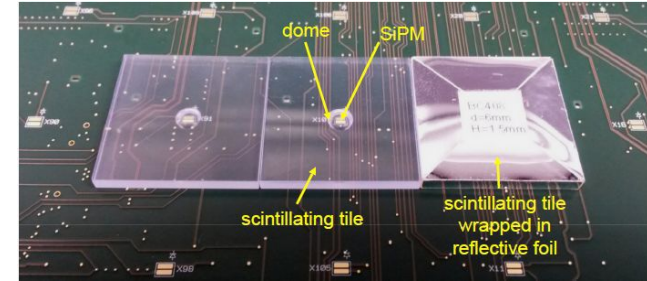
Sensor thickness regions



Cell layout: low (left) and high (right) density

Scintillator section: SiPM-on-tile

- Low-radiation region: **plastic scintillator tiles** read out by **SiPMs**
- Tiles of 4–30 cm², individually wrapped in reflective foil
- SiPM (4 or 9 mm²) sits in the dome of the tile for optimised light collection
- Tile module: HGCROC reads 72 channels, plus LED-based calibration system
- ~370 m² of scintillators in ~4000 tile modules



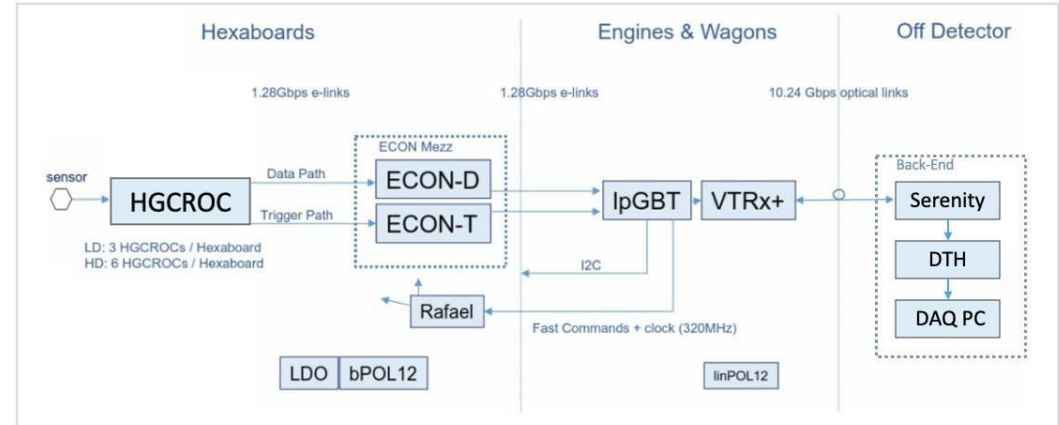
Scintillating tile with SiPM



Tileboard

Front-end electronics: HGCROC

- **Dynamic range** 0.2 fC – 10 pC, linearity < 1% (ADC/TDC)
- **Noise** < 2500 e⁻ (~0.4 fC), for MIP visibility over the detector lifetime
- **Timing** ~30 ps resolution floor, shaping peak < 25 ns
- **Radiation hard:** 200 Mrad design, tested to 310 Mrad
- **Cooling limit** < 20 mW per channel



Front-end readout chain

Construction status

Status: Silicon modules

~ 3000

modules built across the collaboration

- Rates up to **16 modules/day** reached (IHEP, TTU) before a production pause in spring 2026
- **Pause:** a Kapton-to-baseplate lamination defect. A fix is in progress and MACs are preparing to ramp back up
- **Ramp-up plan:** full target rates by early-to-mid 2027

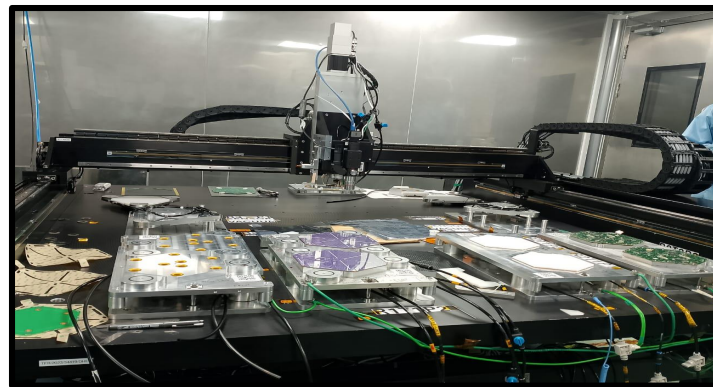
Carnegie
Mellon
University



Institute of High Energy Physics
Chinese Academy of Sciences



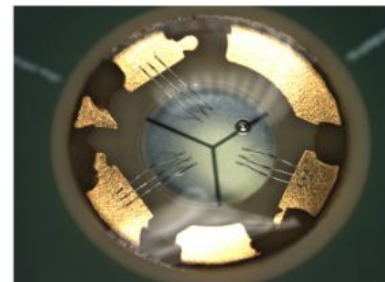
UC SANTA BARBARA



Assembly gantry at TIFR



Encapsulation

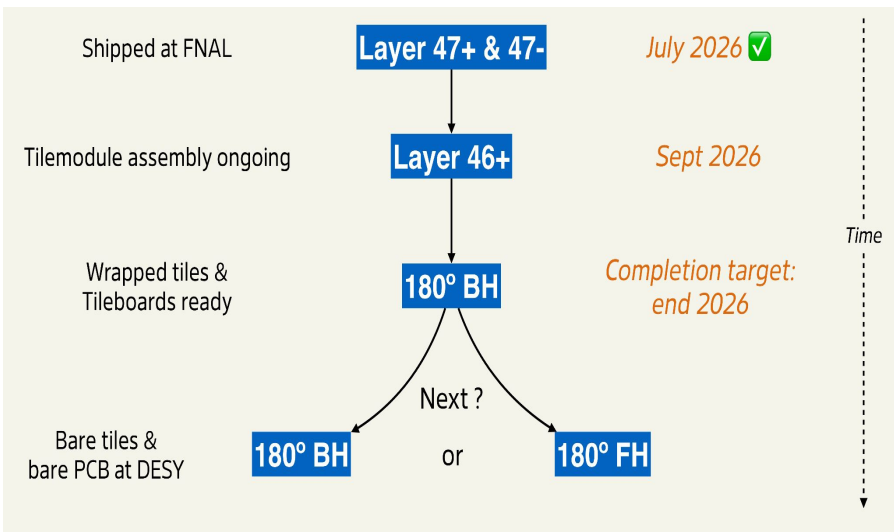


Encapsulated bonds

Silicon Module Assembly Centres (MACs)

L. Satterthwaite, HGCal Rentrée (Modules), 3 Sep 2026

Status: Scintillator tiles



DESY tile-assembly planning
A. Laudrain, HGICAL Rentrée (DESY TAC), 3 Sep 2026

- Scintillator tiles instrument the outer, lower-radiation part of HGICAL.
- **DESY:** ~108,000/151,200 bare tiles received; tileboards 32% complete
- Layer 47 (150 modules) shipped to FNAL (complete)
- **US side:** 195 tile modules assembled (was 91 in June)
- Bottleneck: cosmics QC throughput. Migrating to an easier, less error-prone test framework



Status: Cassette integration



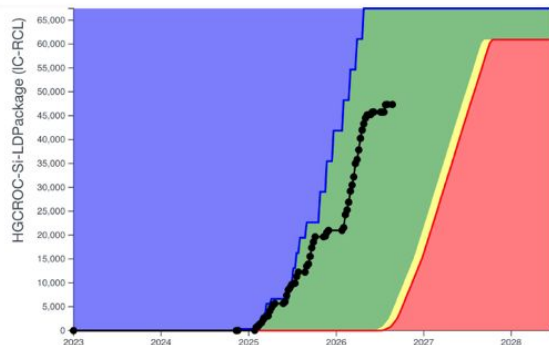
Cassette testing during assembly at CERN

- Cassettes are the basic mechanical building block of HGCal, stacking into full detector disks.
- Assembly started end of July 2026: **first 3 cassettes** assembled
- Parts on hand support ~4–6 cassettes; supply gaps (DC-DCs, busbars) limit further production for now
- **Next steps:** first warm operation of the cassettes (20°C), then cold operation; stacking tool commissioning in November

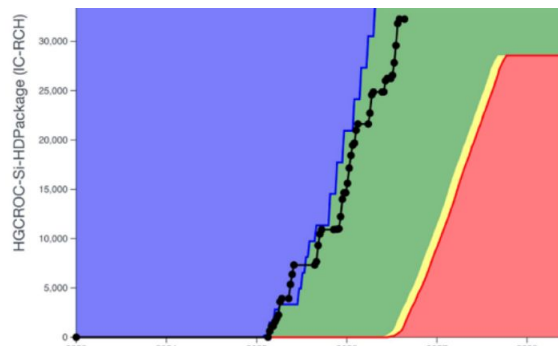
D. Tsionou, A. Zghiche, HGCal Rentrée (Cassettes), 3 Sep 2026

Status: Front-end electronics

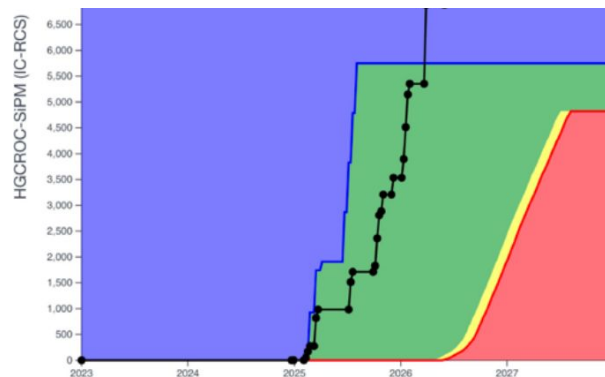
LD-Si



HD-Si



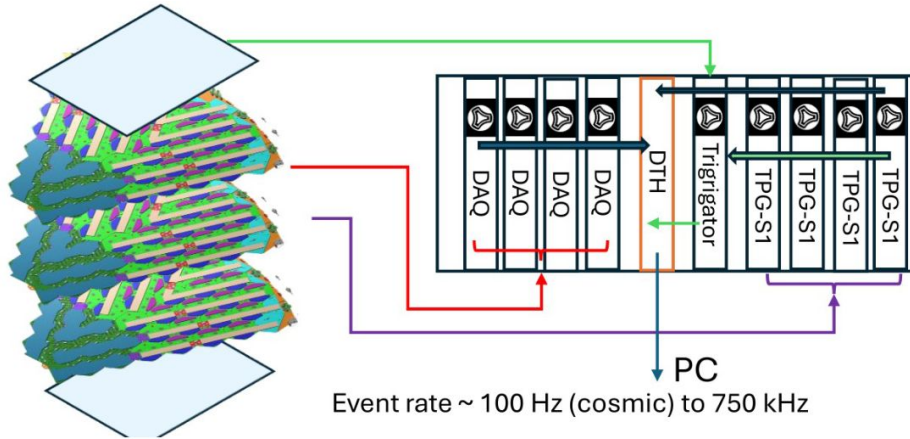
LD-SiPM



P. Aspell, HGCal Rentrée (Electronics), 4 Sep 2026

- Front-end electronics digitize and timestamp every channel, in real time, for the life of HL-LHC.
- **HGCROC chips delivered:** LD Si 70%, HD Si 96%, LD SiPM **100%** complete
- **Hexaboards:** LD >99% yield; HD 96.5% pass rate
- **Wafers:** 194 HGCROC3d wafers received (~90% yield), enough to equip the full detector

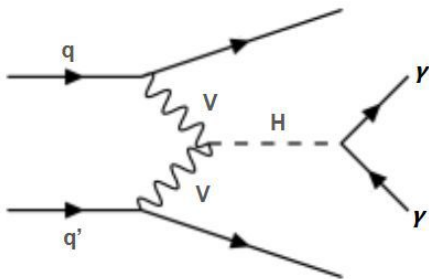
Status: Back-end electronics & DAQ



J.-B. Sauvan, HGCal Rentrée (Back-end), 4 Sep 2026

- Back-end electronics and DAQ move every channel's data from HGCal to CMS's central trigger and storage.
- **43** Serenity boards in hand (CERN + first 2 from TIFR)
- DAQ boards from **TIFR**; trigger (TPG) boards from CERN
- Multi-Cassette Test System (commissioning well advanced) will validate the full chain: 100 Hz (cosmic) up to 750 kHz event rate

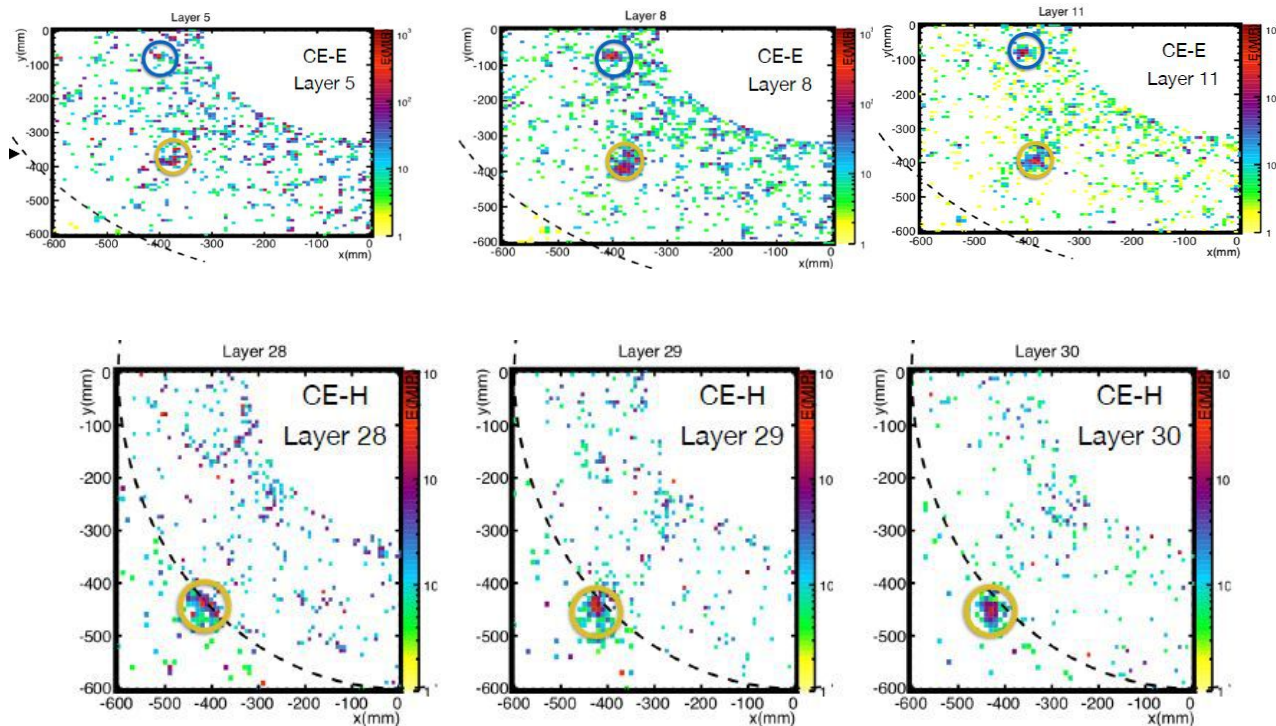
Physics performance: granularity



VBF $H \rightarrow \gamma\gamma$ simulation, PU = 200

Evolution of the VBF jet and the γ through the HGCal layers

Each layer is a snapshot of the shower as it develops.

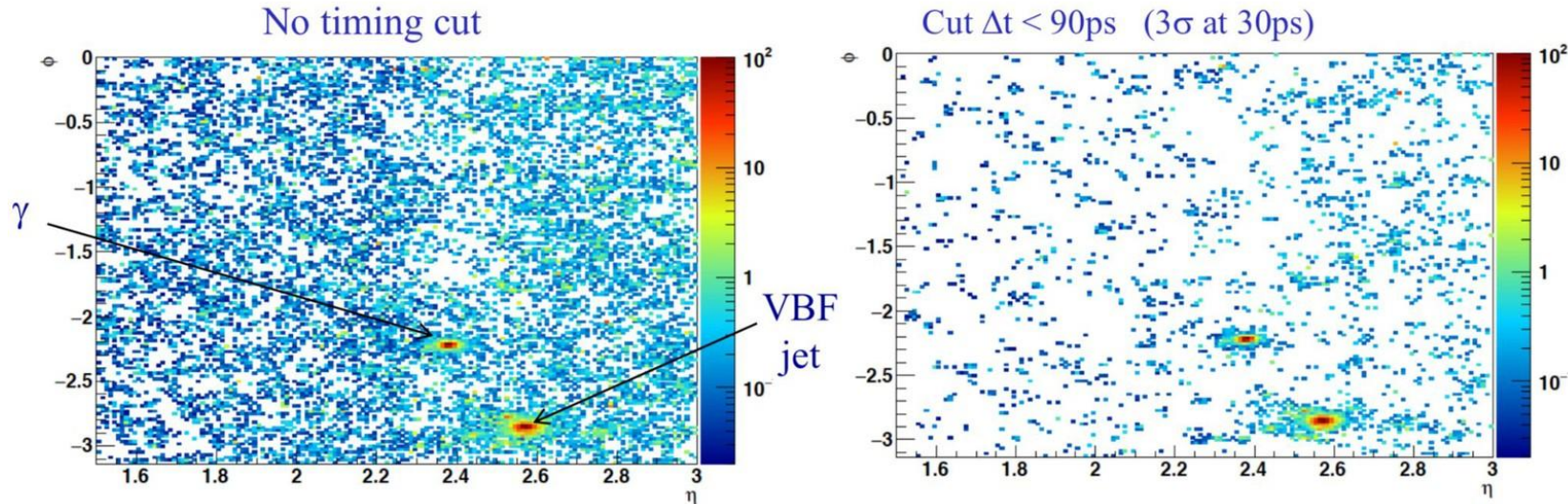


The Phase-2 Upgrade of the CMS Endcap Calorimeter, CMS-TDR-019

Physics performance: timing

Precision timing (~ 30 ps) removes pileup hits: VBF $H \rightarrow \gamma\gamma$ event, one photon and one VBF jet in the same quadrant

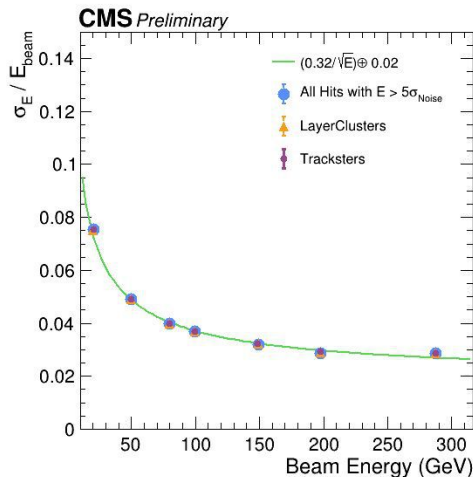
VBF ($H \rightarrow \gamma\gamma$) event with one photon and one VBF jet in the same quadrant,



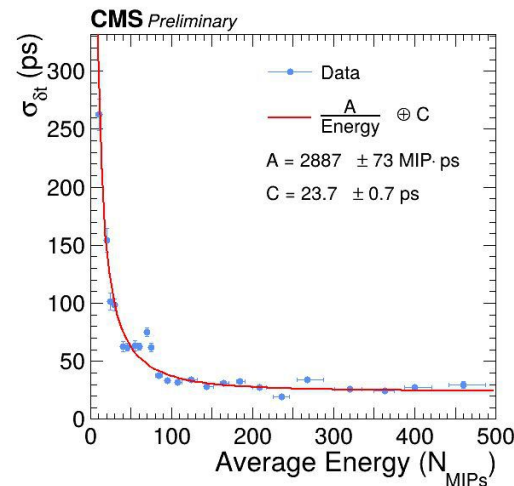
The Phase-2 Upgrade of the CMS Endcap Calorimeter, CMS-TDR-019

Test beams: 2025 results at CERN H2

- 10 layers of preseries LD 300 μm modules (HGCROC3c); e^- 20–300 GeV, μ 200 GeV, π 100 GeV
- MIP calibration with 200 GeV muons: $S/N \approx 8$, cell noise ≈ 0.43 fC
- Energy resolution $32\%/\sqrt{E} \oplus 2\%$ with only 10 layers (much coarser sampling than HGCAL); linear to $\sim 1\%$
- Timing: channel-pair constant term ~ 24 ps for central cells



Energy resolution (e^-)

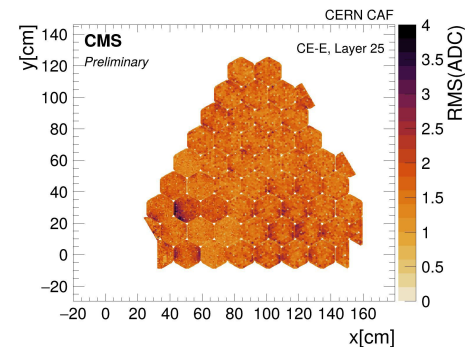


Channel-pair timing

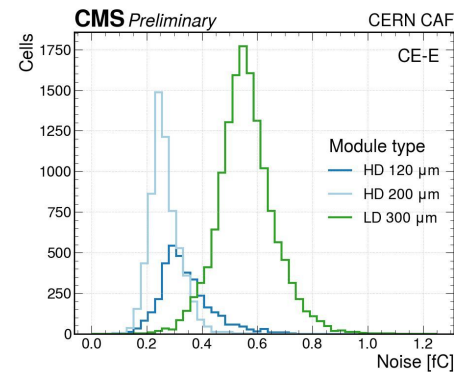
Commissioning of preseries cassettes

- Si-only preseries cassettes assembled and tested at the CERN and FNAL assembly facilities
- Full control, trigger, DAQ and offline (CMSSW) chain exercised, with automated DQM
- Readout connectivity validated by injecting fixed test patterns
- Cell noise in CE-E: ~ 0.25 fC (HD) and ~ 0.55 fC (LD) modules
- One CE-H cassette (layer 33) also operated cold at -25 °C

[CMS-DP-2026/058](#)



CE-E cassette noise map (CERN CAF)



Cell noise by module type (CE-E)

Summary



- HGICAL will replace the CMS endcap calorimeters to meet the **HL-LHC challenges**
- Unprecedented granularity and precision timing enable **5D particle reconstruction** in high pileup
- **Silicon sensors and scintillator tiles** combine for optimal performance in different radiation zones
- Every subsystem (modules, electronics, cassettes) is in active construction, with real engineering challenges being worked through in real time

Thank you

Backup

Backup: scintillator S/N & SiPM properties

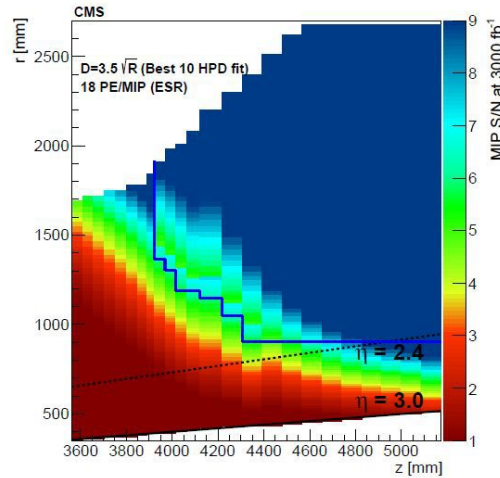


Figure 2.14: Signal-to-noise ratio for a MIP, after an integrated luminosity of 3000 fb^{-1} , shown as a two-dimensional map in r and z . The region, at larger z and r , in which SiPMs mounted on scintillator tiles can provide $S/N(\text{MIP}) > 5$ after 3000 fb^{-1} is outlined.

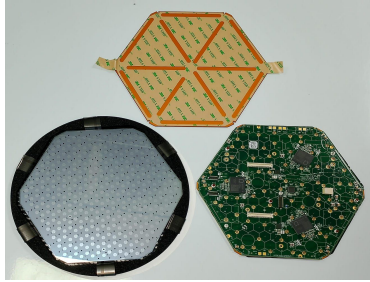
CMS-TDR-019, Figure 2.14

Table 2.5: Properties of a silicon photomultiplier from one vendor.

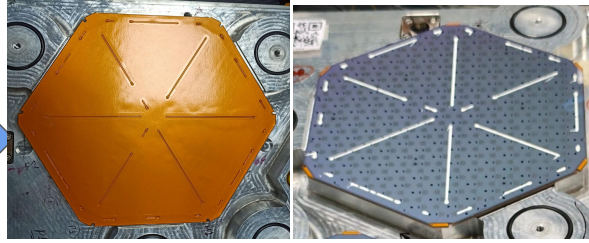
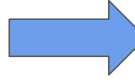
Effective photosensitive area	2 mm^2
Pixel pitch	$15 \mu\text{m}$
No. of pixels	7500
Geometrical fill factor	50%
Spectral response range	320–900 nm
Peak sensitivity	460 nm
PDE at peak sensitivity	30%
Gain	2×10^5
Pixel recovery time	10 ns
Breakdown voltage (V_{BR})	$65 \pm 10 \text{ V}$
Operating voltage	$V_{\text{BR}} + (2-3) \text{ V}$
Dark count unirradiated at 23°C	100 kHz

CMS-TDR-019, Table 2.5

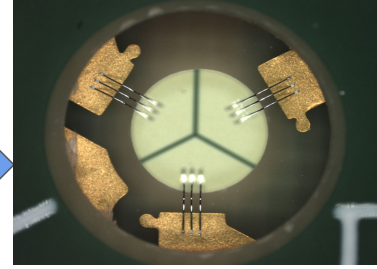
Backup: Silicon module assembly



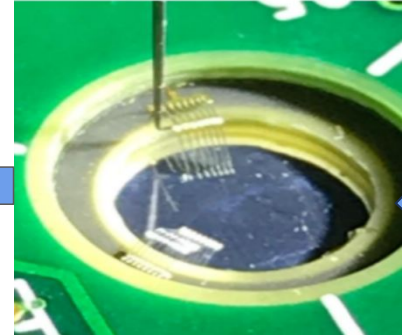
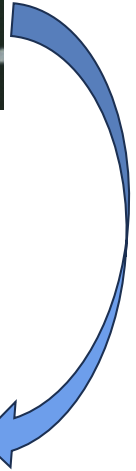
Component study



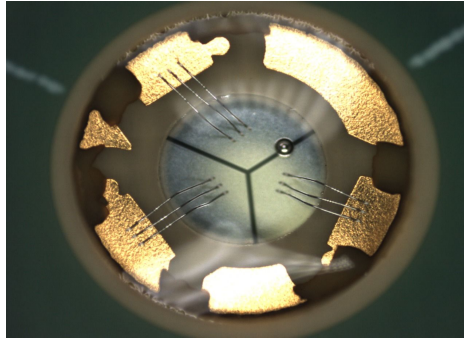
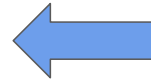
Gluing



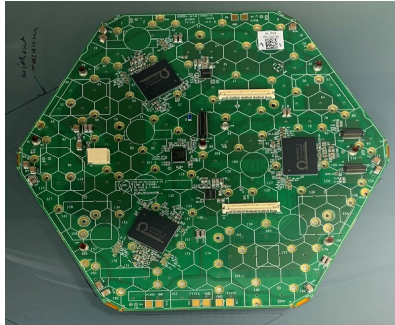
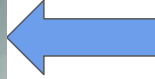
Wire-bonding



Pull testing

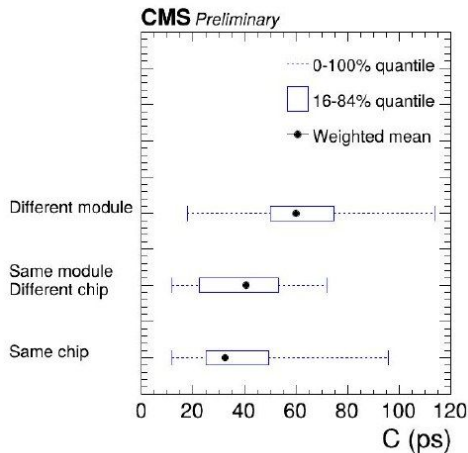


Encapsulation

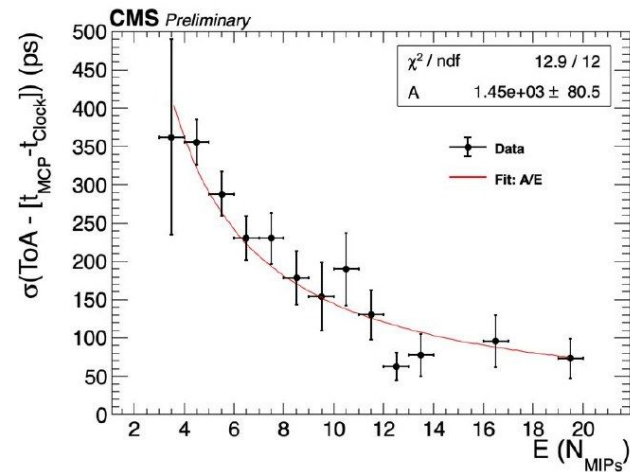


Module study

Backup: Timing performance in detail



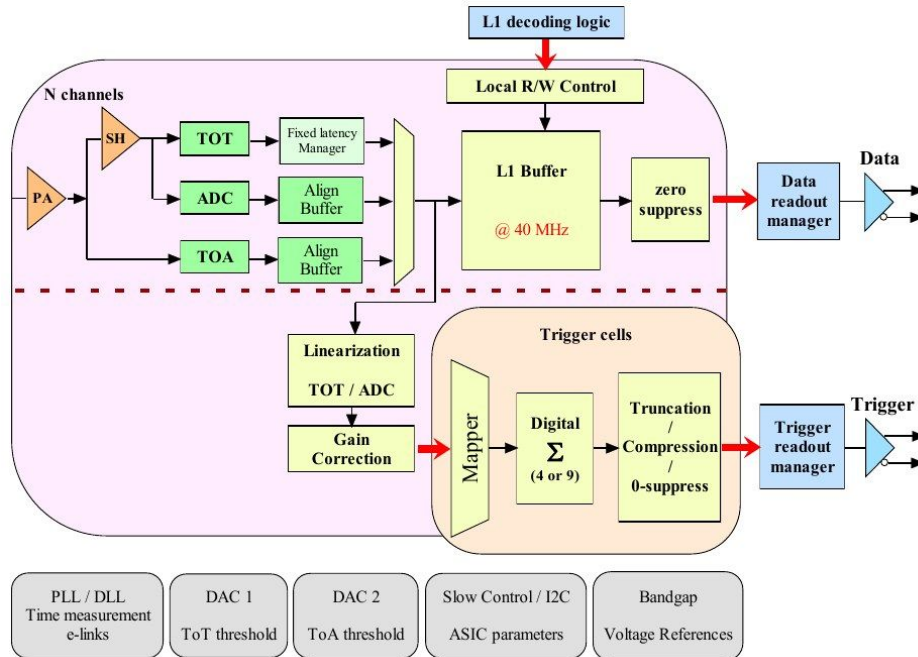
Channel pairs, 200 GeV e^+ : constant term C by location (DP2026_054 p.24)



Single channel vs MCP (< 10 ps), 200 GeV muons (DP2026_054 p.25)

- **Channel pairs:** weighted mean $C \approx 33$ ps (same chip), ≈ 41 ps (same module, different chip), ≈ 60 ps (different modules); range 20–110 ps
- **C grows with distance:** points to clock distribution between chips and modules; system target ~ 30 ps needs 10–15 ps clock accuracy (TDR §8.4)
- **Near threshold:** ToA threshold ~ 4 MIPs; $\sigma \approx 360$ ps at 4 MIPs, ≈ 75 ps at 20 MIPs (fit A/E , $A \approx 1.45$ ns·MIP)

Backup: HGCROC signal processing

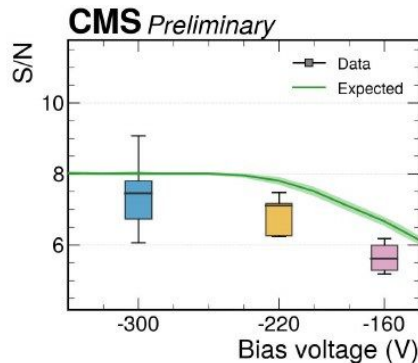
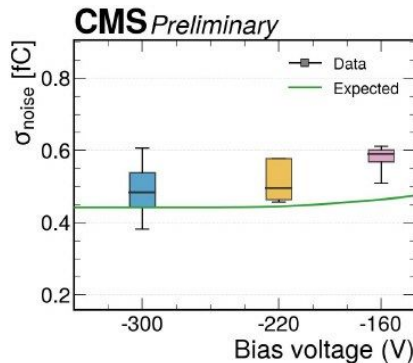
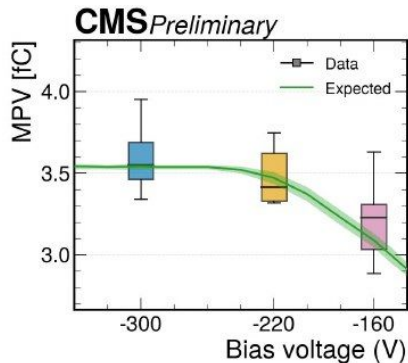


- **Preamp + shaper:** peak < 25 ns
- **Charge:** 10-bit ADC up to ~100–150 fC; ToT (12-bit TDC, 50 ps bins) from ~50 fC to 10 pC
- **Time:** ToA 10-bit TDC, < 25 ps LSB, 25 ns range
- **Storage:** 512-deep buffer at 40 MHz, 12.5 μ s L1 latency; zero-suppressed readout on L1A ($\leq$ 750 kHz)
- **Trigger:** linearised, summed over 4 or 9 cells, sent every crossing
- **Chip:** 72 + 2 calibration + 4 common-mode inputs; 130 nm CMOS; < 15 mW/ch

Sources: CMS-TDR-019 §3.1.2, §8.1.2

HGCROC schematic, CMS-TDR-019 Fig. 3.2

Backup: S/N vs bias voltage



100 GeV pions, ~10 central channels, 300 μm LD modules; data (boxes) vs expected (green) — CMS-DP-2026/054 p.10

- **Full depletion (300 V):** MPV ≈ 3.55 fC as expected; noise ≈ 0.48 fC (exp. ≈ 0.44); S/N ≈ 7.4 (exp. ≈ 8.0)
- **Lower bias:** mimics an under-depleted, irradiated sensor; S/N ≈ 6.8 at 220 V, ≈ 5.6 at 160 V
- **Signal as expected:** the small S/N shortfall comes from slightly higher noise
- **MIP still visible:** S/N stays above 5 even at 160 V