The CMS High Granularity Calorimeter for the High Luminosity LHC

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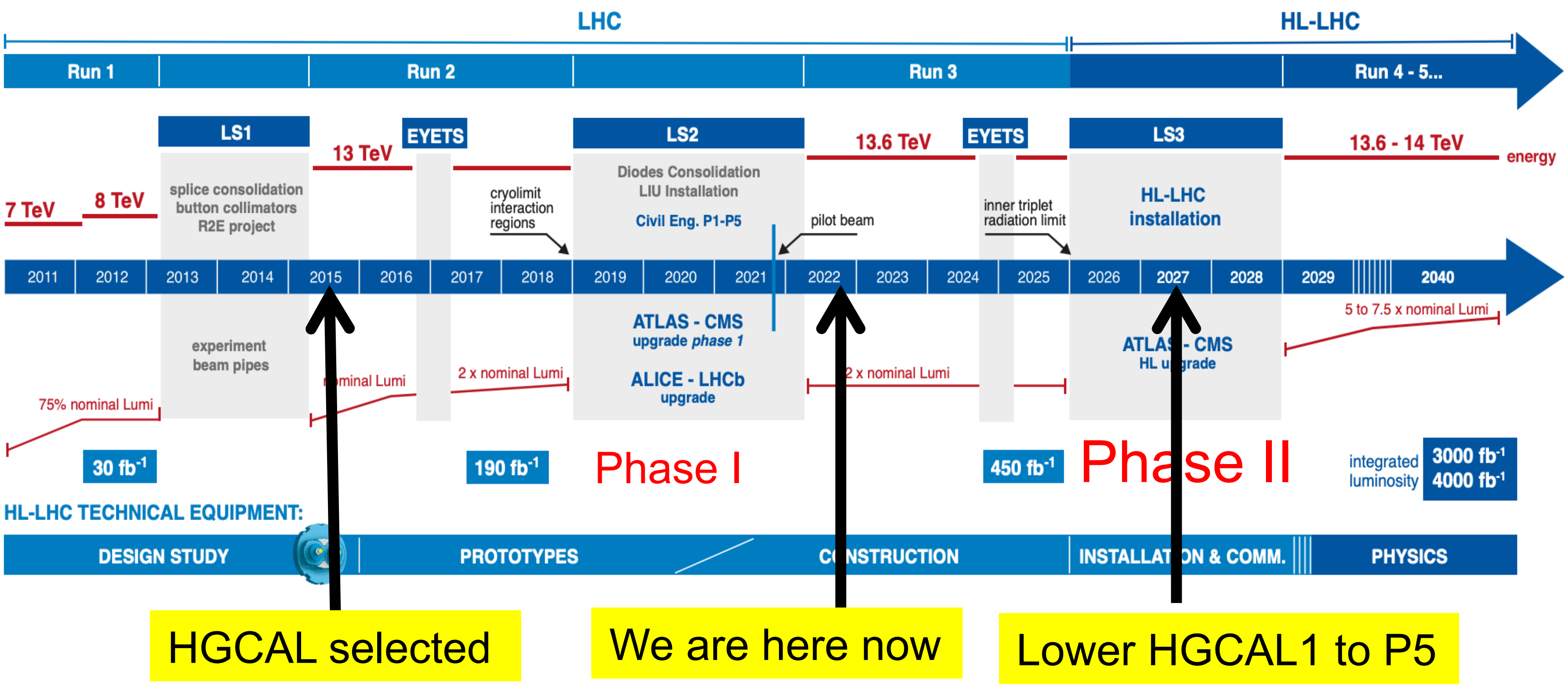
On behalf of the CMS collaboration

Outline

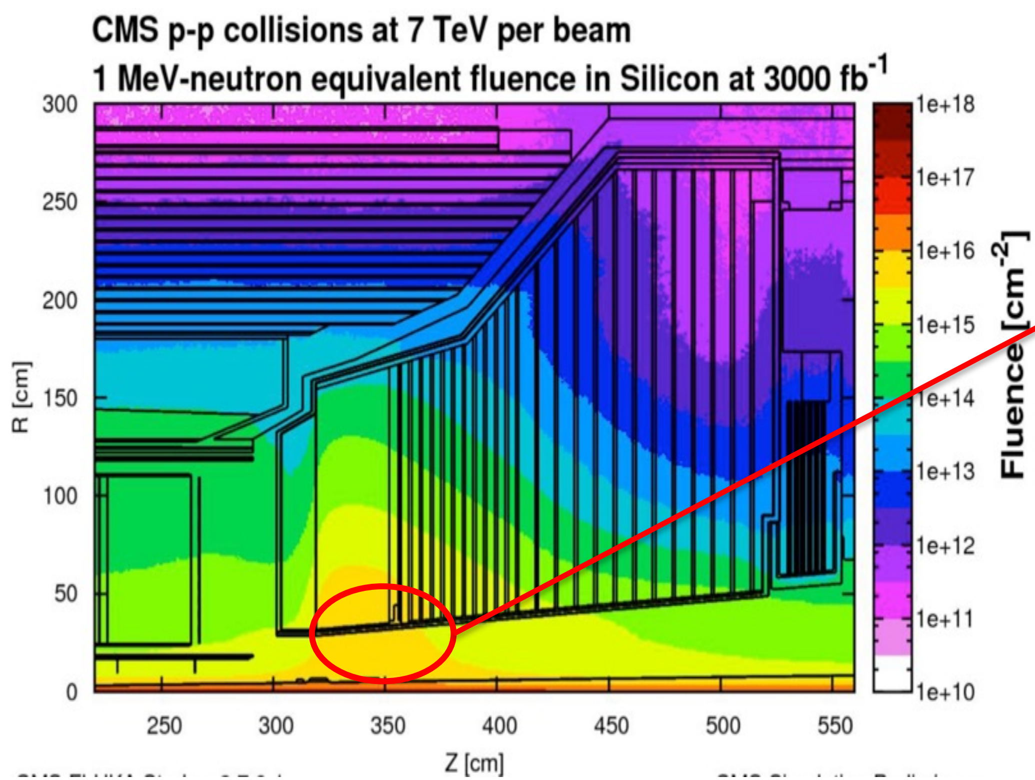
- Introduction
- The design/prototyping of HGCal
- HGCal performance
- Summary

LHC operation Roadmap



- The HL-LHC start 2029 will have 5-7 times instantaneous Lumi
  - Experiments at LHC need to upgrade detectors（Phase II）
    - 2015-2028 for design, construction, installation
  - CMS detector will upgrade
    - Inner tracker, Calorimeter, Muon, MTD, Trigger and DAQ

CMS endcap calorimeter phase II challenges



CMS @ HL-LHC:
~1x10^{16} 1 MeV n_{eq} cm^{-2} @ 3ab^{-1} and up to **2 MGy** absorbed dose in endcap calorimeters

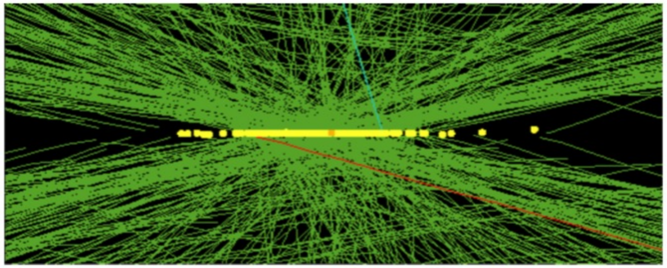


Figure 1.16: High pileup event with 78 reconstructed vertices taken in 2012

78 pileup

140-200 pileup in HL-LHC

Within the limited given budget…

- Radiation is the key driving force
  - Option selection & design
- Physics requirements on Jet energy resolution, pileup rejection…

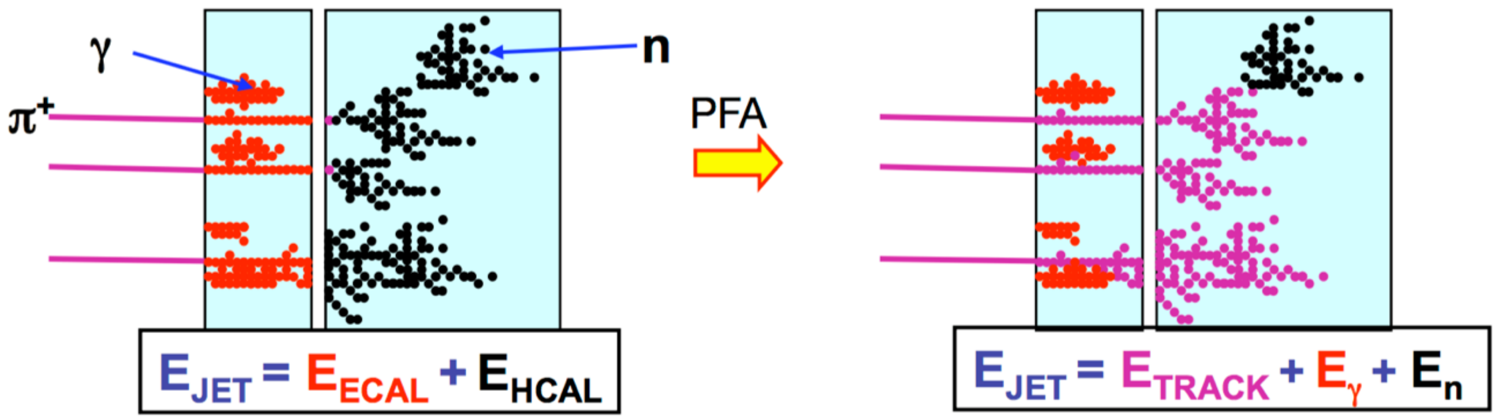
→ CMS HGCal

HGCAL TDR: https://cds.cern.ch/record/2293646

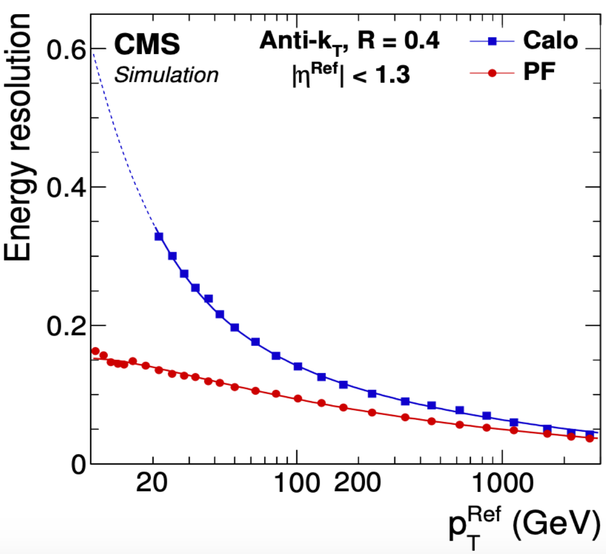
Principle for improvements

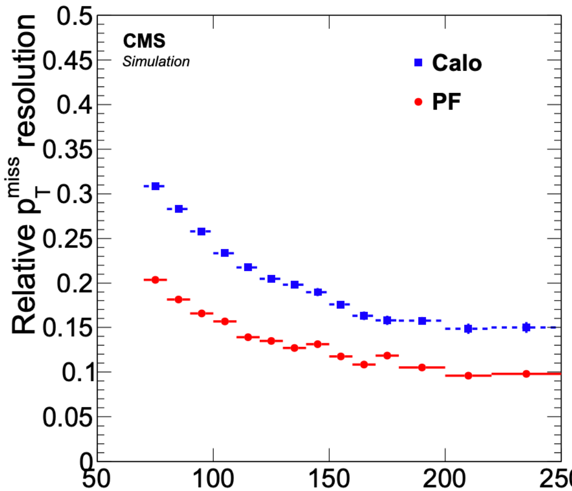
for each individual particle in a jet (MET), ==> Particle Flow Algorithm

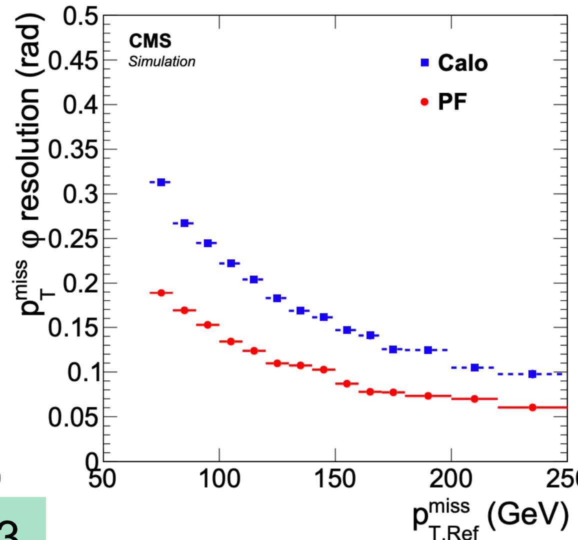
Charged tracks = Tracker; photons = ECAL; Neutral hadrons (only 10%) = HCAL



Good Shower separation：High Granularity is crucial







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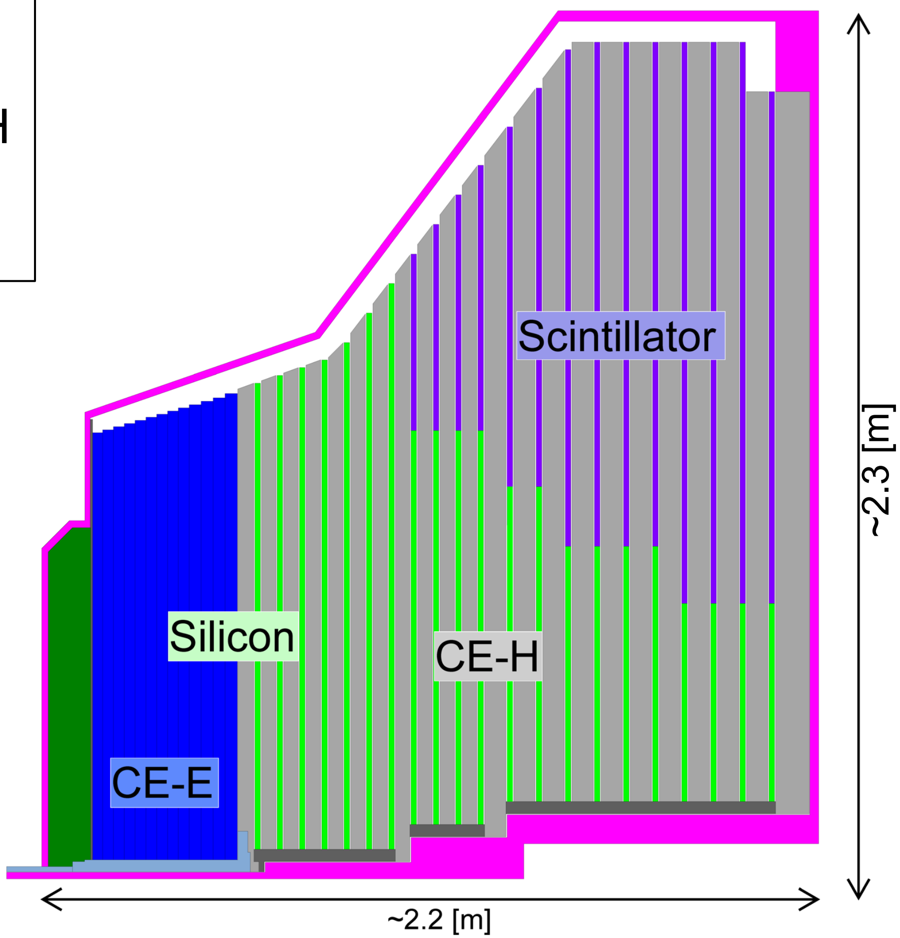
CMS HGCAL: a 47-layer sampling calorimeter

Active Elements:
- Hexagonal modules based on Si sensors in CE-E and high-radiation regions of CE-H
- Scintillating tiles with SiPM readout in low-radiation regions of CE-H

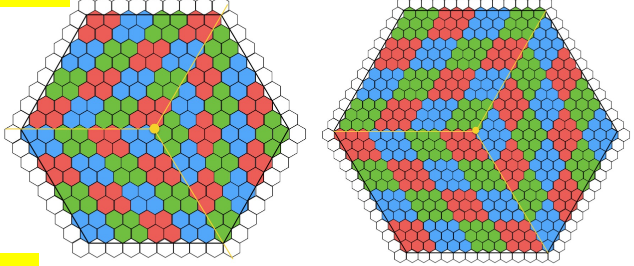
Key Parameters:
Coverage: $1.5 < |\eta| < 3.0$
~215 tonnes per endcap
Full system maintained at -30°C
~620m² Si sensors in ~26000 modules
~6M Si channels, 0.6 or 1.2cm² cell size
~370m² of scintillators in ~3700 boards
~240k scint. channels, 4-30cm² cell size
Power at end of HL-LHC:
~125 kW per endcap



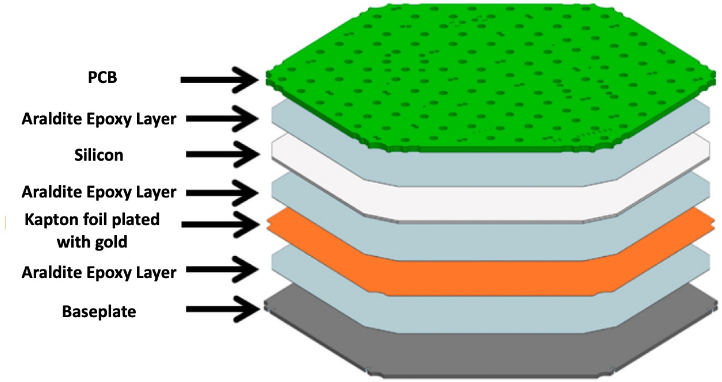
EM calorimeter (**CE-E**): **Si**, Cu & CuW & Pb absorbers, 26 layers, 27.7 X_0 & ~1.5λ
Hadronic calorimeter (**CE-H**): **Si** & **scintillator**, steel absorbers, 21 layers, ~8.5λ

The HGCal design

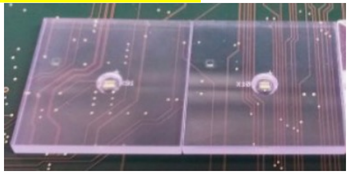
Si Sensor 8inch, 1.18cm^2（192）/ 0.52cm^2（432）

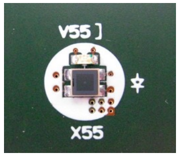


Silicon Module



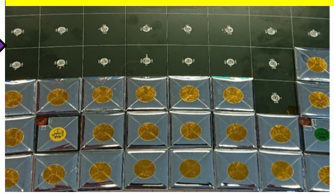
Sci. tile

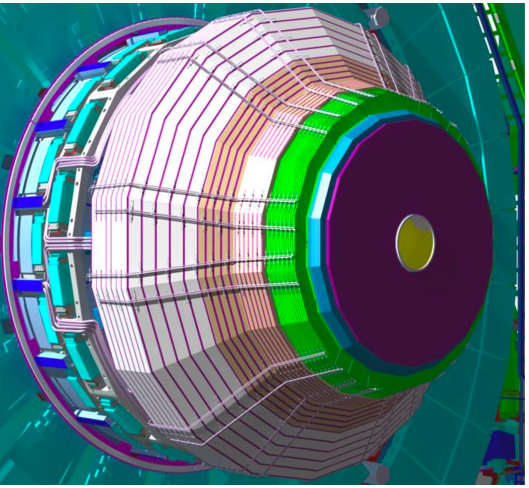


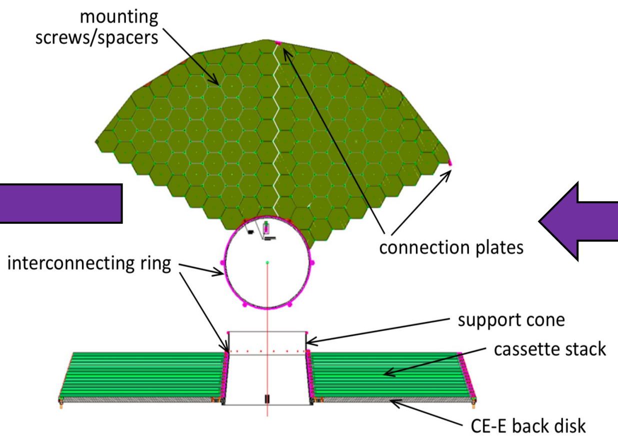


Scintillator + SiPMs

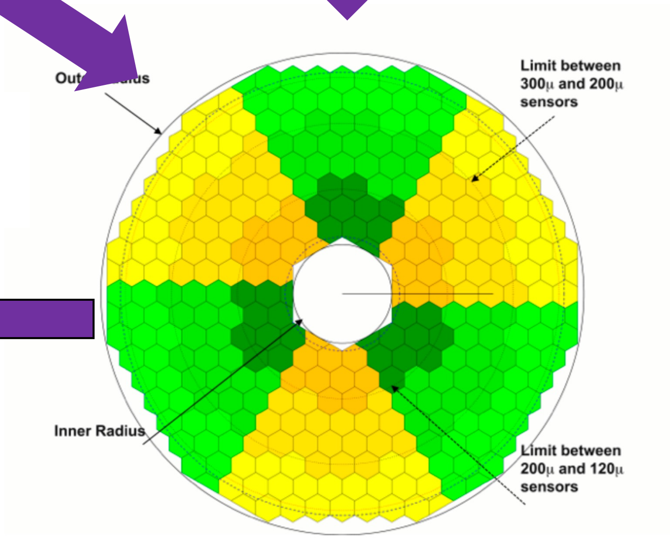
Tile module





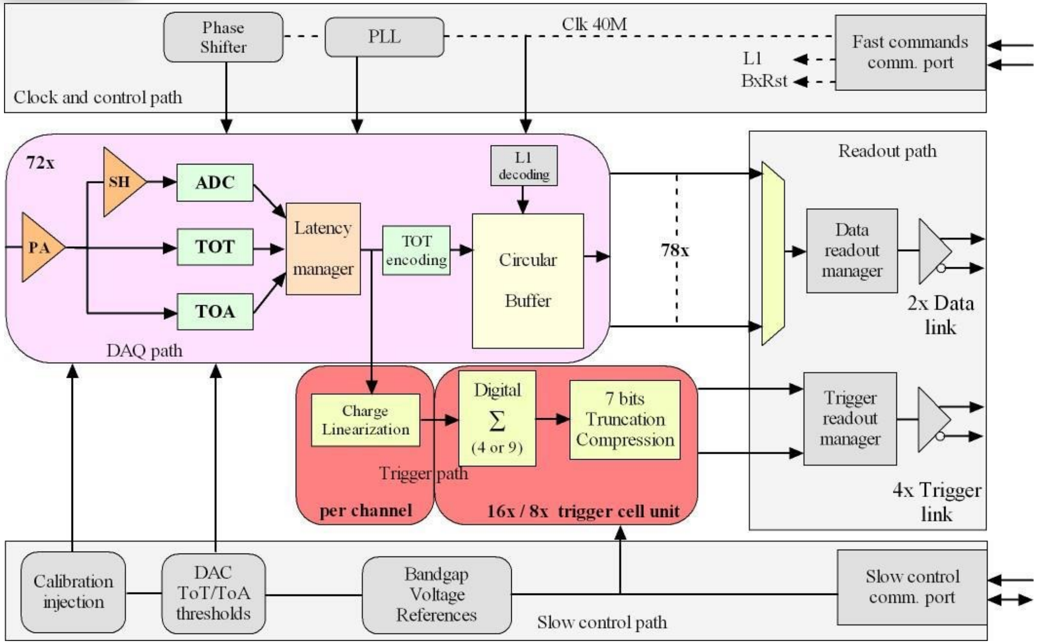


Stacking



Tiling

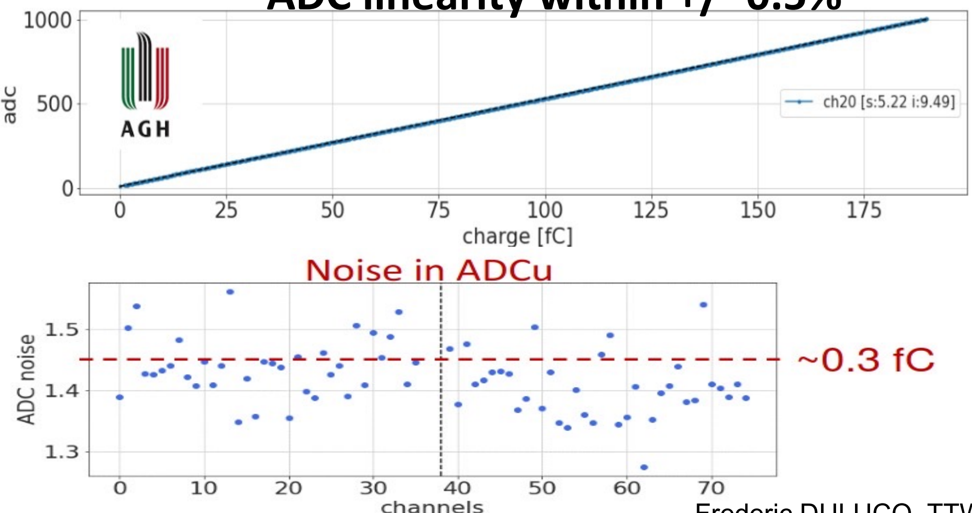
The HGCal Front End electronics: HGCROC



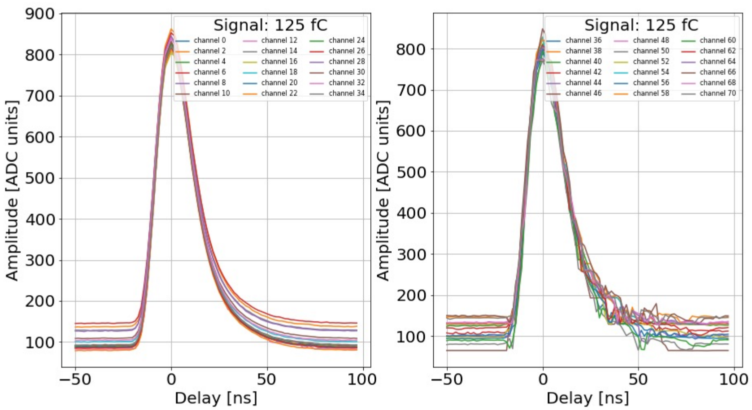
HGCROCV3: Final FE chip for HGCal

- Two versions: Silicon and SiPM
- Rad. hard (200 Mrad, 1.10^{16} neq/cm2)
  - 310 Mrad
- Low noise: <2500e (0.4fC)
  - ~1800e（0.3fC）
- Charge: 0.2 fC to 10 pC
  - Linearity <1% for ADC/TDC
- Fast shaping (peak < 25 ns), precise timing capability (25 ps)
  - Jitter: TOA <13 ps, TOT < 25 ps

ADC linearity within +/- 0.5%

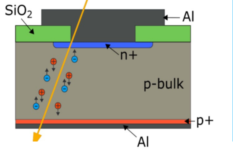


Frederic DULUCQ, TTWEEE2021



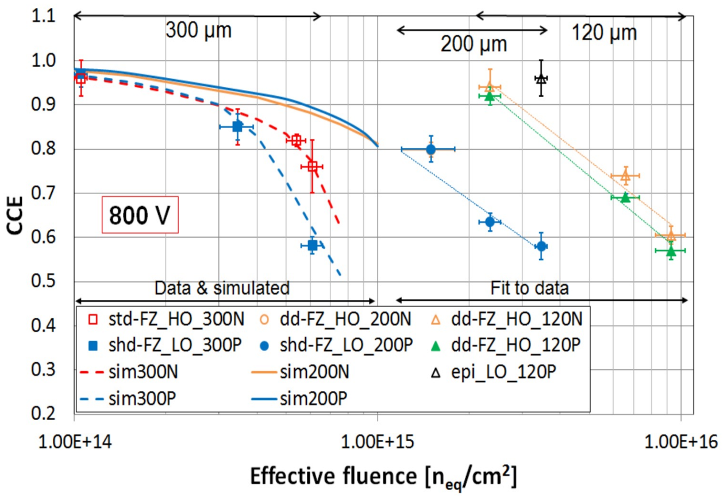
310 M rad (in 5 days) and 2 days annealing

Silicon sensors

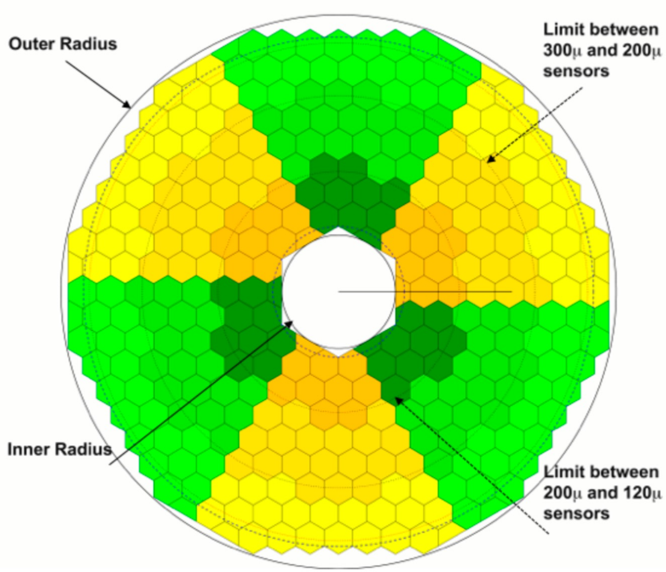


8'' High-Density sensor
432 cells with ~0.5cm2 size
120µm active thickness

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



2020 JINST 15 P09031



Planar p-type DC-coupled sensor pads
- simplifies production technology; p-type more radiation tolerant than n-type

Hexagonal sensor geometry preferred to square
- reduces number of sensors produced & assembled to modules (factor ~1.3)

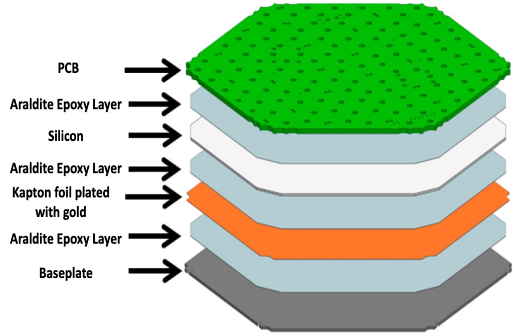
300µm, 200µm and 120µm active sensor thicknesses
- match sensor thickness (and granularity) to radiation field for optimal performance

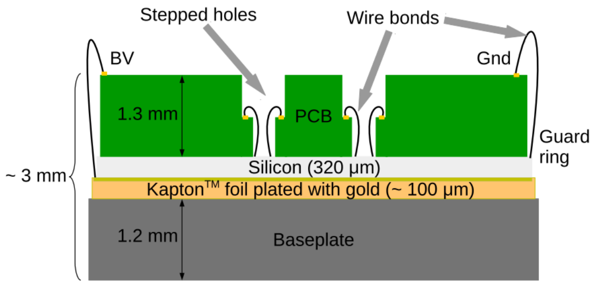
Simple, rugged module design & automated module assembly
- provide high volume, high rate, reproducible module production & handling

Neutron irradiation of 8"-sensors to 10^{16}n /cm² at RINSC, US

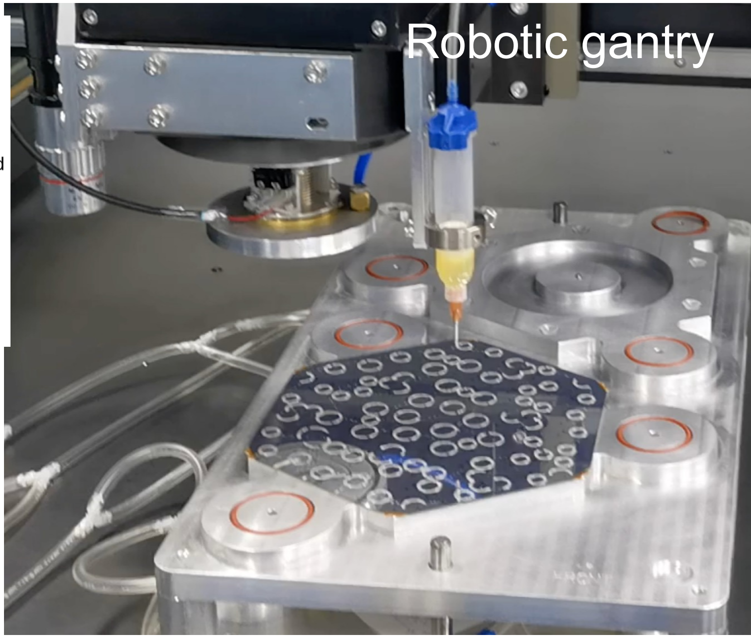
Irradiated + tested different production splits / different sensor geometries
- Identified best production process
- Proven radiation hardness of silicon sensors

Silicon module

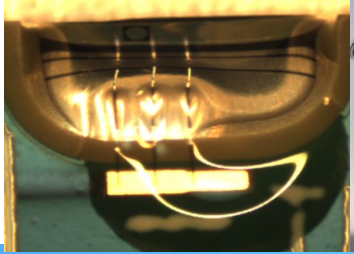


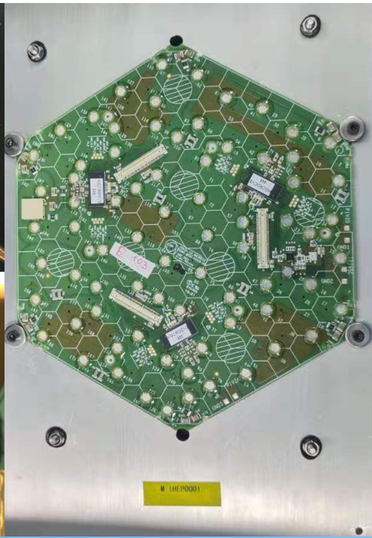


- Silicon modules used in Ecal and Hcal with high radiation does
- High-precision sandwich structure glued by gantry
- Connect sensor to FE-PCB(Hexaboard) with bonder and encaplated
- Automated procedure developed based on experience of CMS silicon tracker production (UCSB)
  - 6 production sites across US/Asia
- Pre-production in ~2023

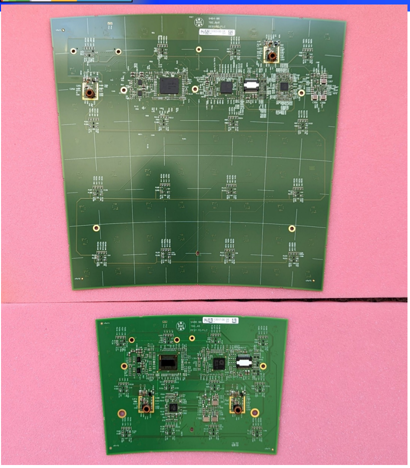


8 inch module production at IHEP

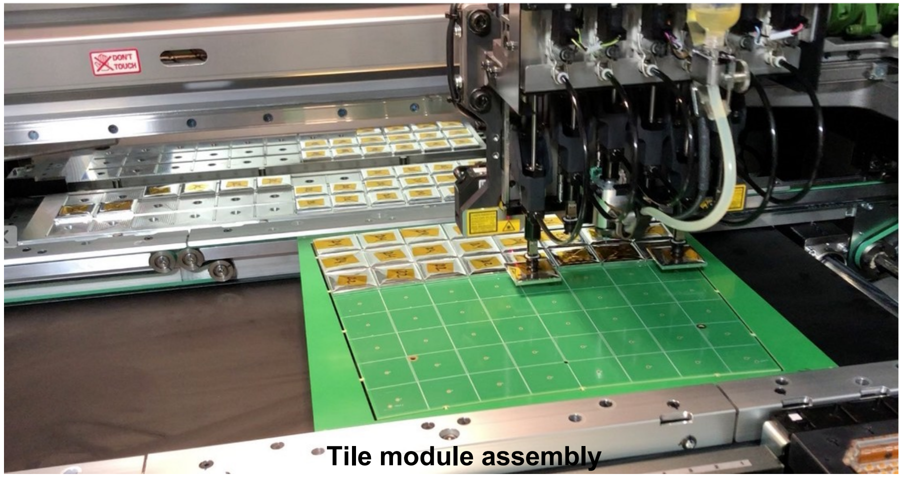




Tile module

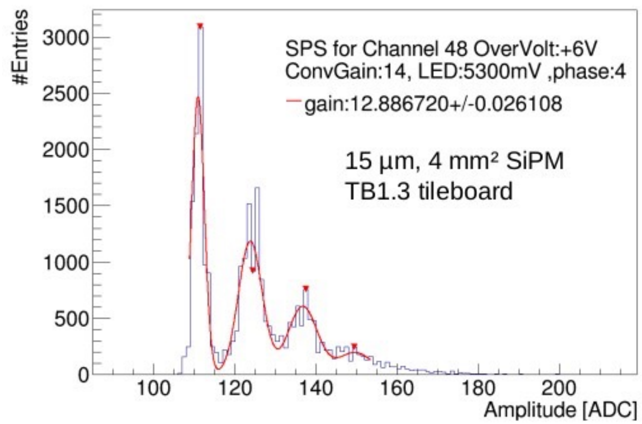


Tile board with HGCROCV3



Tile module assembly

Irradiated SiPMs with ISMA tiles

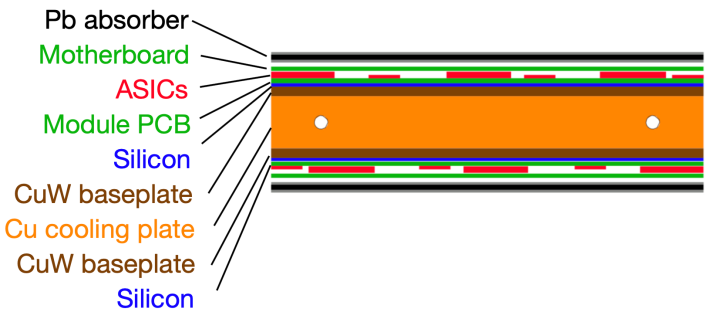


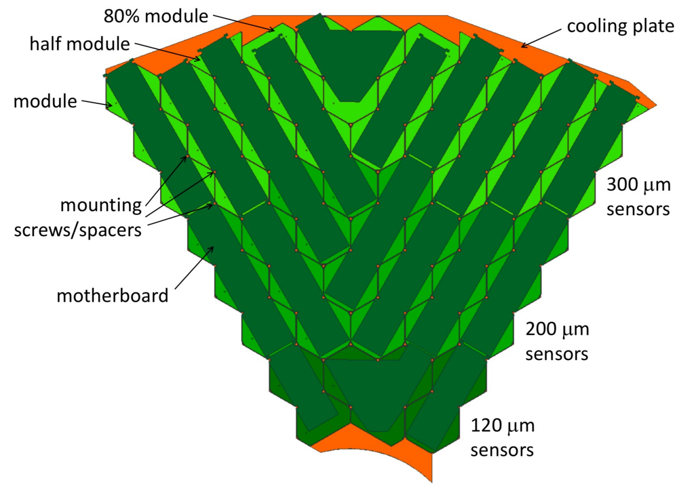
Scintillator + SiPM AHCal like module

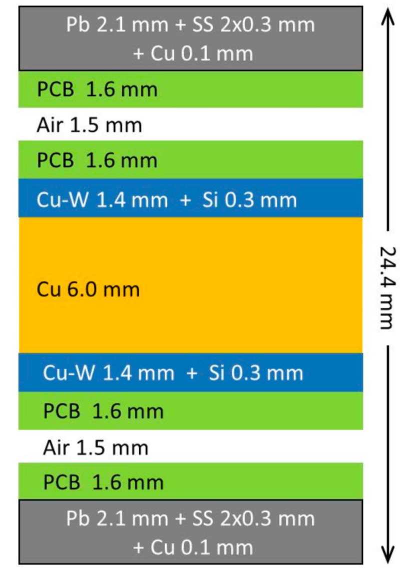
- Tile size depends on radial-position
  - $4cm^2$ to $32cm^2$
- Signal strength depends on tile and SiPM geometry → Larger tiles at higher radii
- Pre-production in ~2023

Cassetes

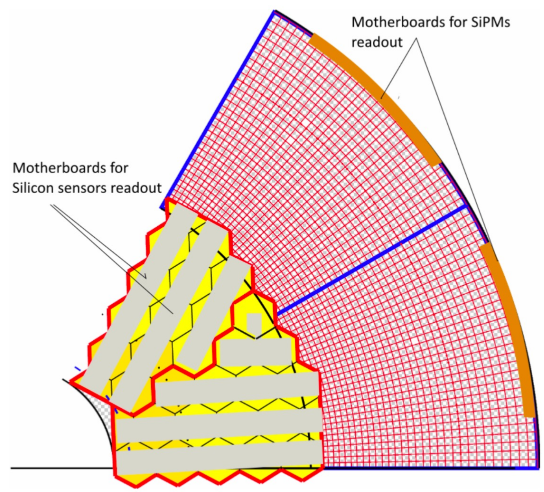
- Ecal: Modules placed on both sides of Cu cooling plane and “closed” with Pb plates
  - All silicon layers

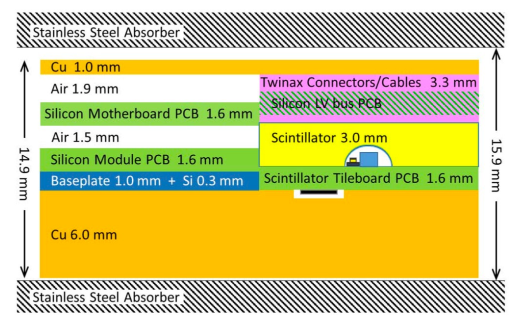






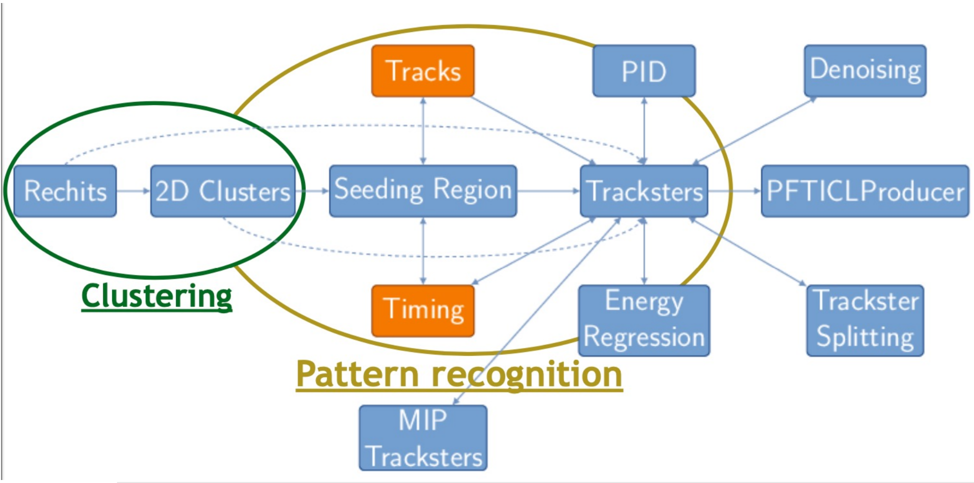
- Hcal: Single-sided cassettes, mounted between steel absorbers
  - All-Si or mixed cassettes (Si modules, SiPM-on-tile modules) layers

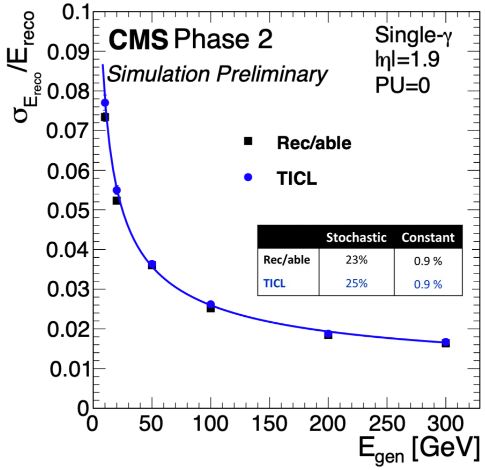




TICL (**T**he **I**terative **CL**ustering) Framework is used

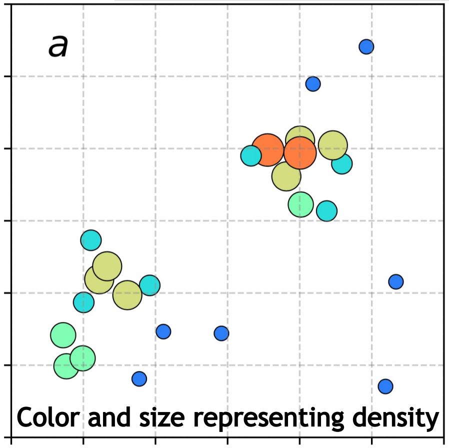
ref: https://hgcal.web.cern.ch/

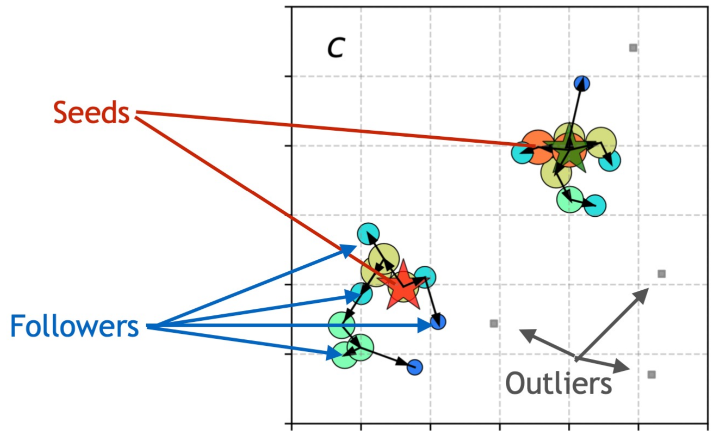


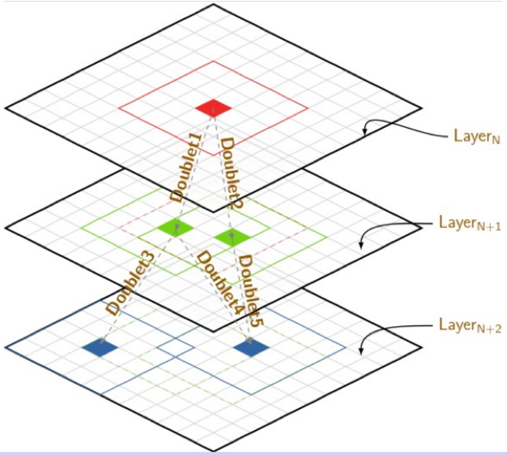


2D clustering algo. (CLUE) inspired by the imaging algorithm[doi:10.1126/science.1242072]

Pattern recognition based on "Cellular Automaton"



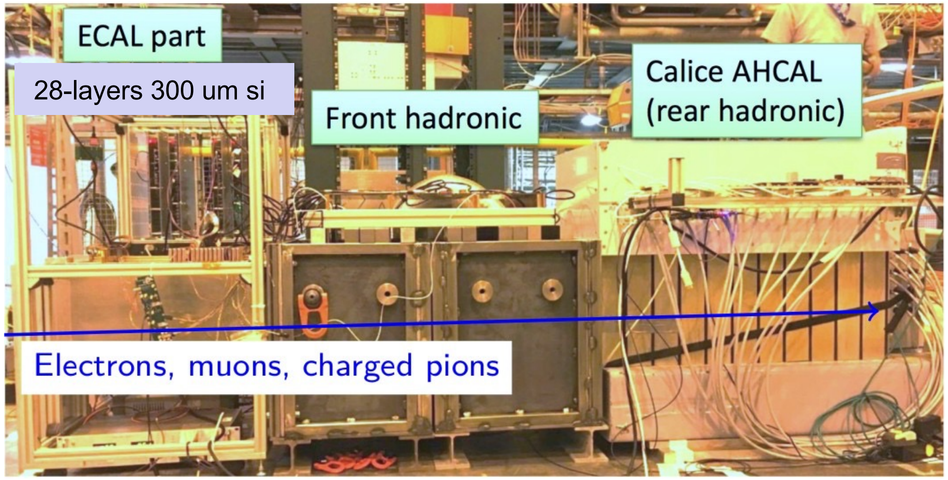


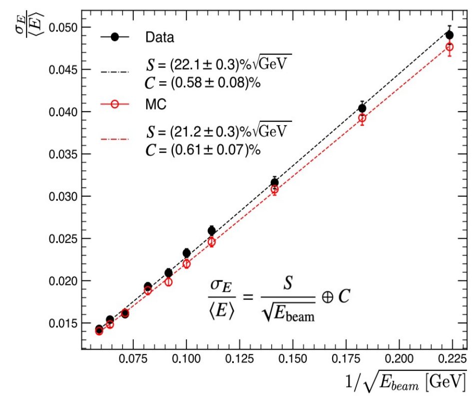


Other advanced reconstruction method (HDBSCAN, ML) are under development

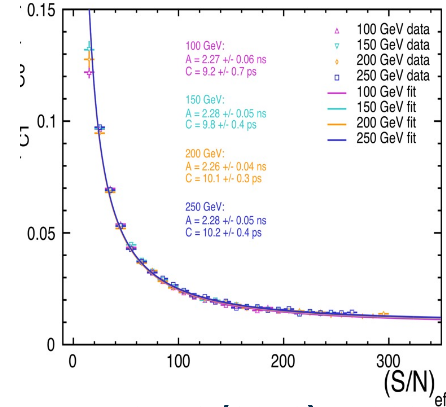
Beam tests

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





JINST 17 (2022) P05022



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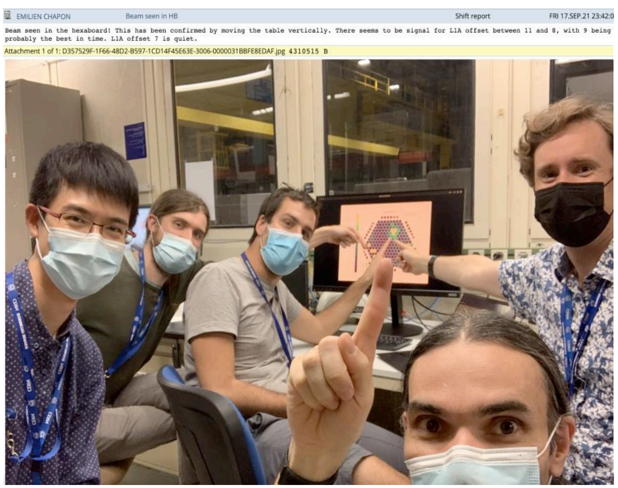
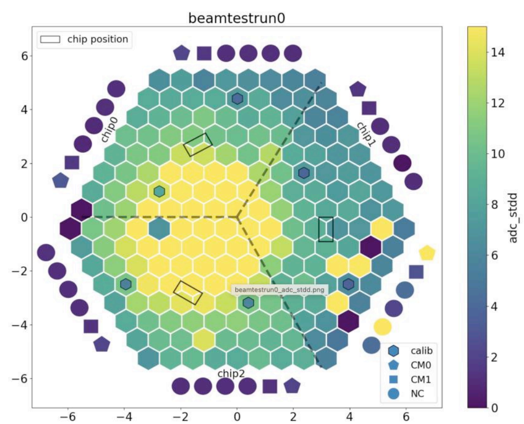
- **Switch to 8-inch silicon + HGCROC module at H2 beamline at CERN (SPS) Sept/Oct 2021**





Noise/MIP response in realistic environment in Si modules ROCv2 (Sep), ROCv3 (Oct), explored a range of working parameters with e- -beams

Analysis on going

IHEP LD Module with HGCROCv2, 300mm silicon in September 21 beam test

Summary

- **CMS is constructing a High Granularity Calorimeter for the HL-LHC**
  - 620m^2 of silicon and 370m^2 of scintillator
  - >6M read out channel
  - 5D information: High precision spatial / energy / timing
  - Radiation hard: ~**1x10^{16}** 1 MeV n_{eq} cm^{-2}
- **Key components are developed and verified**
  - Electronics systems well advanced,
    - HGCROCv3(final version) is tested
    - ECON-D/ECON-T close-to-final version
  - Silicon sensors / SiPM-on-Tile in pre-series
  - Validation of prototypes in test-beams successful
    - Full system tests with final components ongoing
- **Pre-production of silicon modules/SiPM-on-tile module, starting ~2023**
  - Installation in LS3, operation since 2029
- Challenges and opportunities ahead: reco., perf. ,Phys…