An Overview of the CMS High Granularity Calorimeter

EPS-HEP 2023 - Hamburg

Gabriele Milella on behalf of the CMS collaboration

23.08.2023

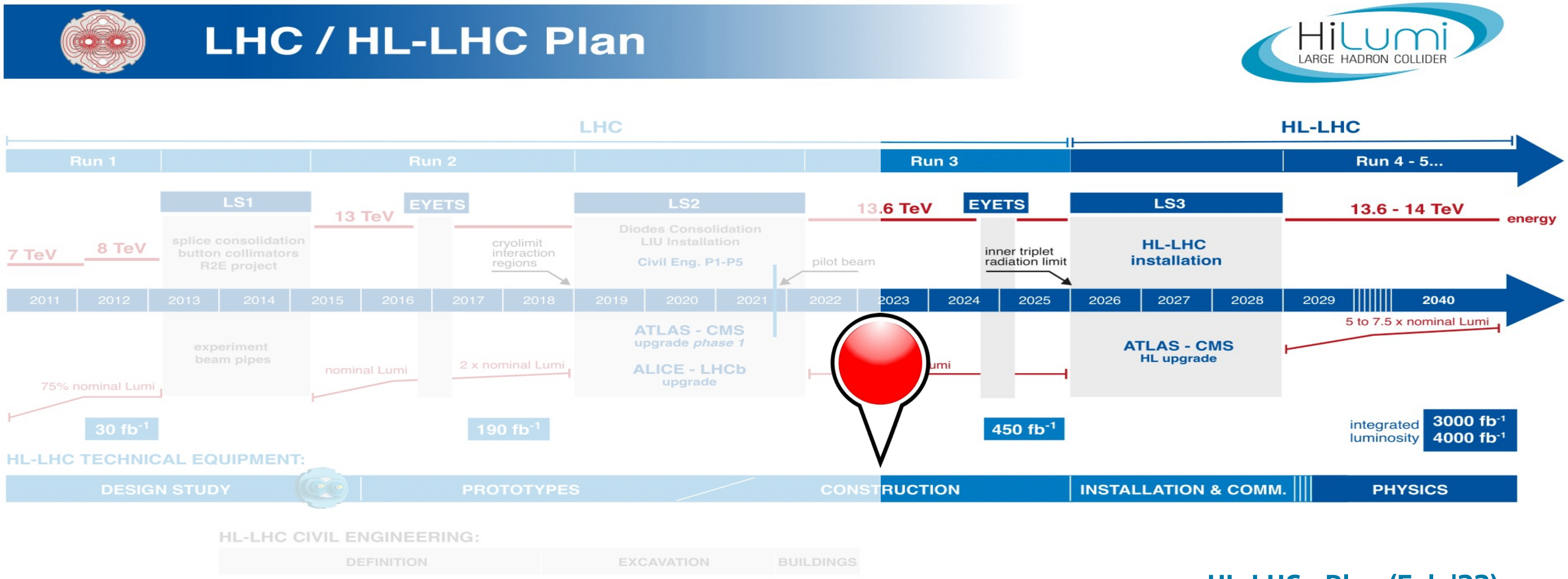
Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

DESY.

CMS

Future at CERN: HL-LHC

Where we are



HL-LHC - Plan (Feb '22)

Future at CERN: HL-LHC

A "bright" future

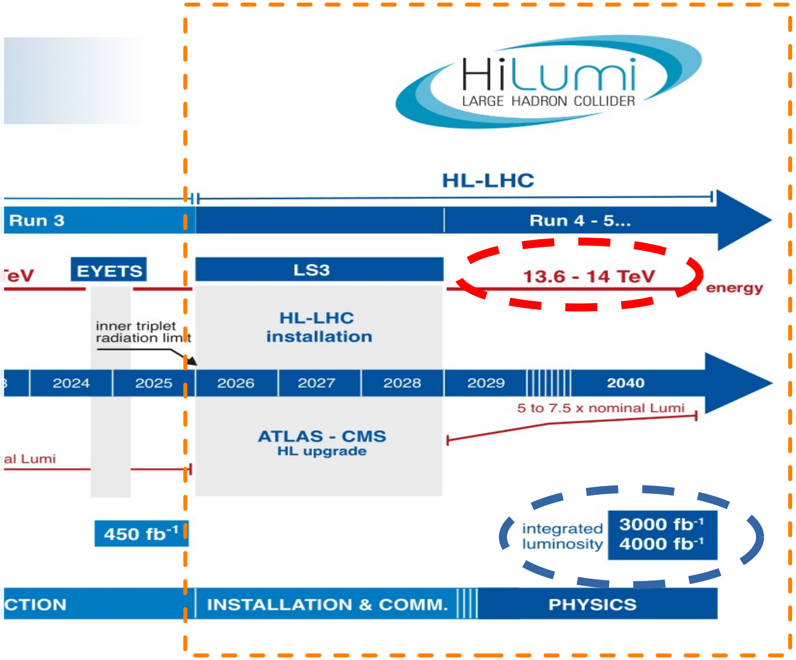
Phase 2- Pushing LHC to the limit…

- 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



HL-LHC - Plan (Feb '22)

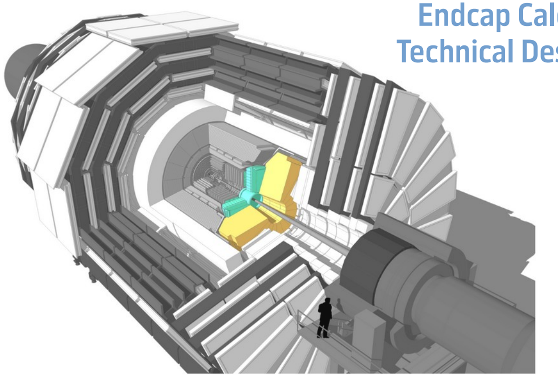
CMS during HL-LHC

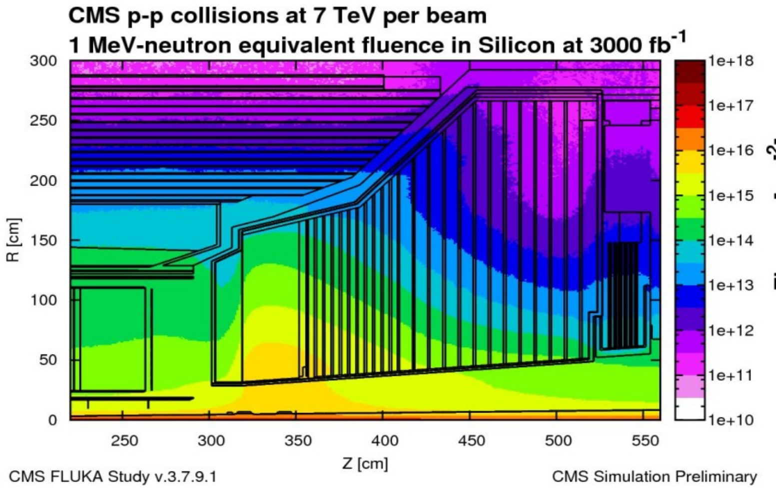
The challenges in the forward regions

- 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





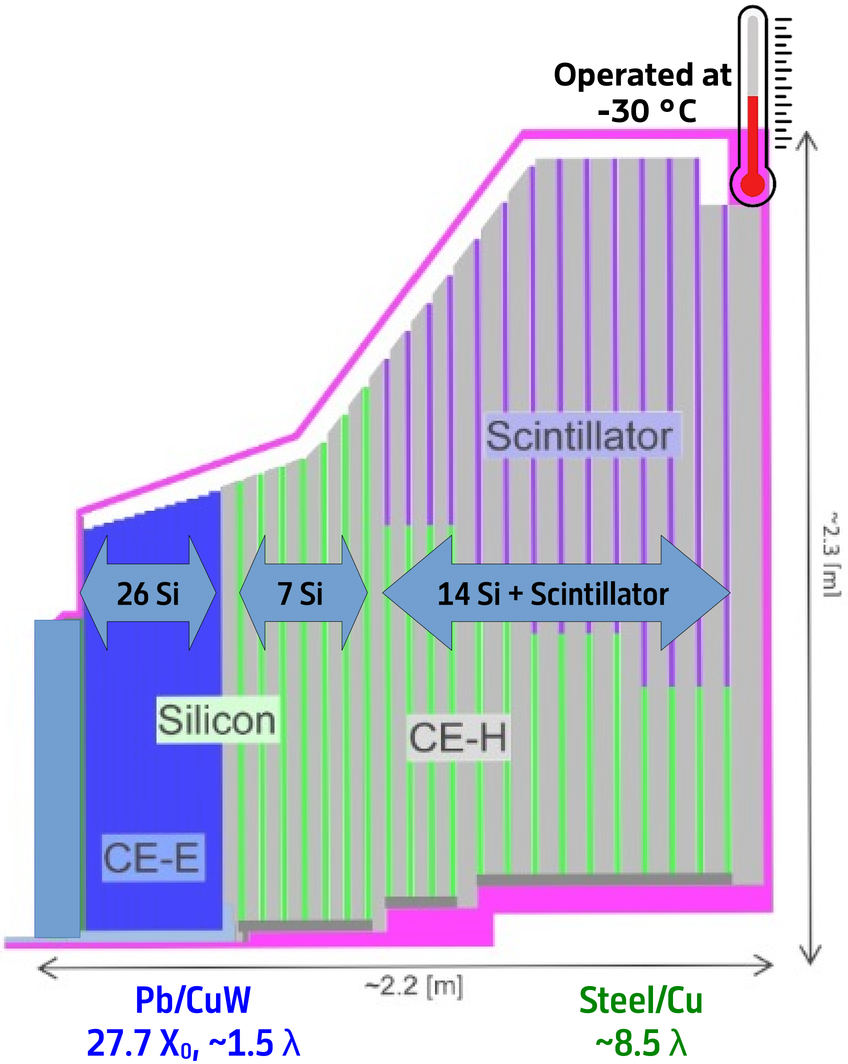
The HGCAL Project

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 m²)
  - **Plastic Scintillators with SiPM readout (CE-H)**
    - **240k** scintillator tiles (~370 m²)

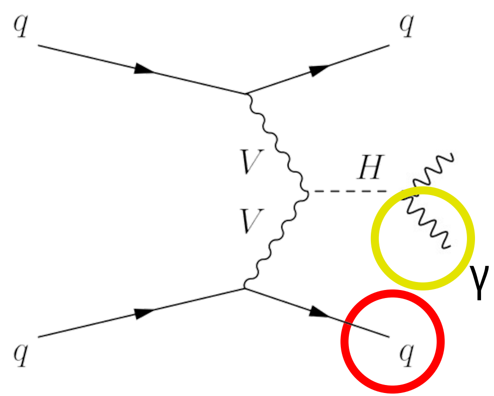
- **Passive materials**
  - Lead absorber plates, copper cooling plates, and CuW baseplates
  - Compact and dense object → 225 T



HGCAL: 5D Imaging Calorimeter

Forward jet signatures from VBF

VBF H → γγ + 200 PU



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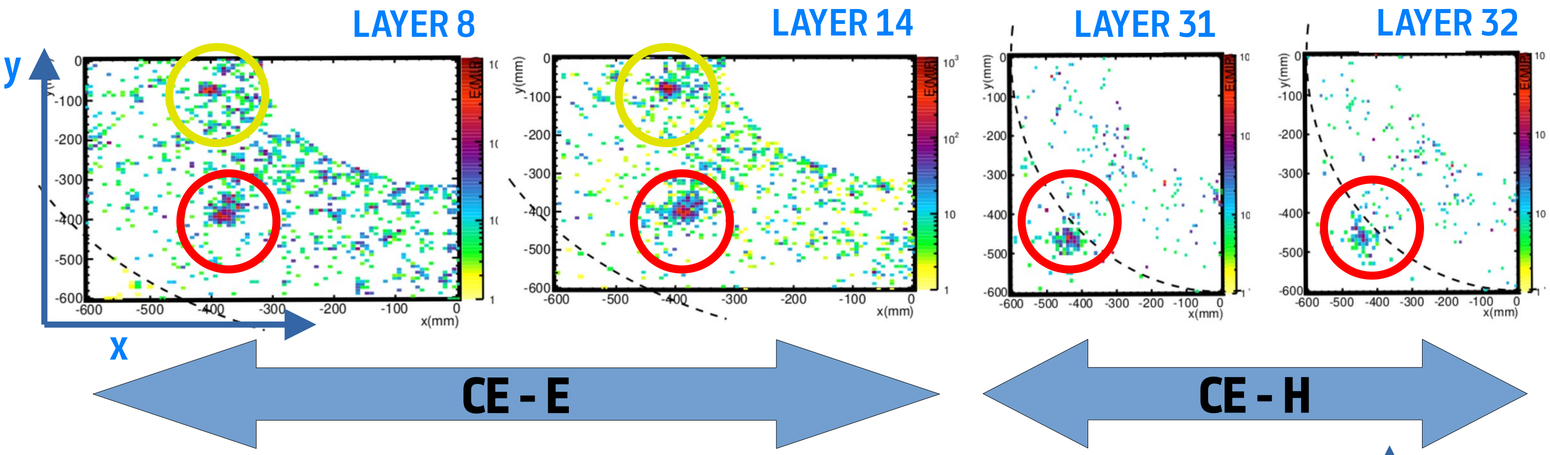
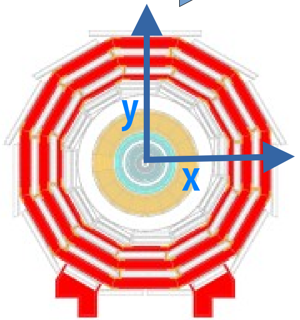


Spatial 3D Granularity

- 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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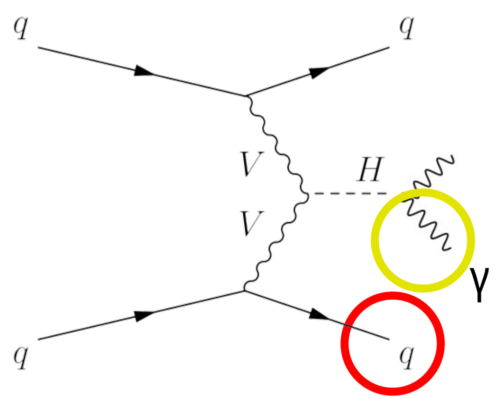
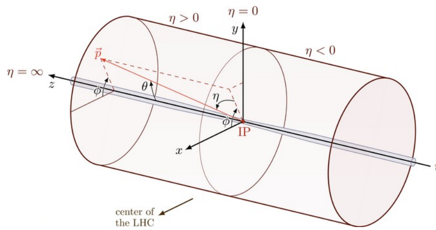
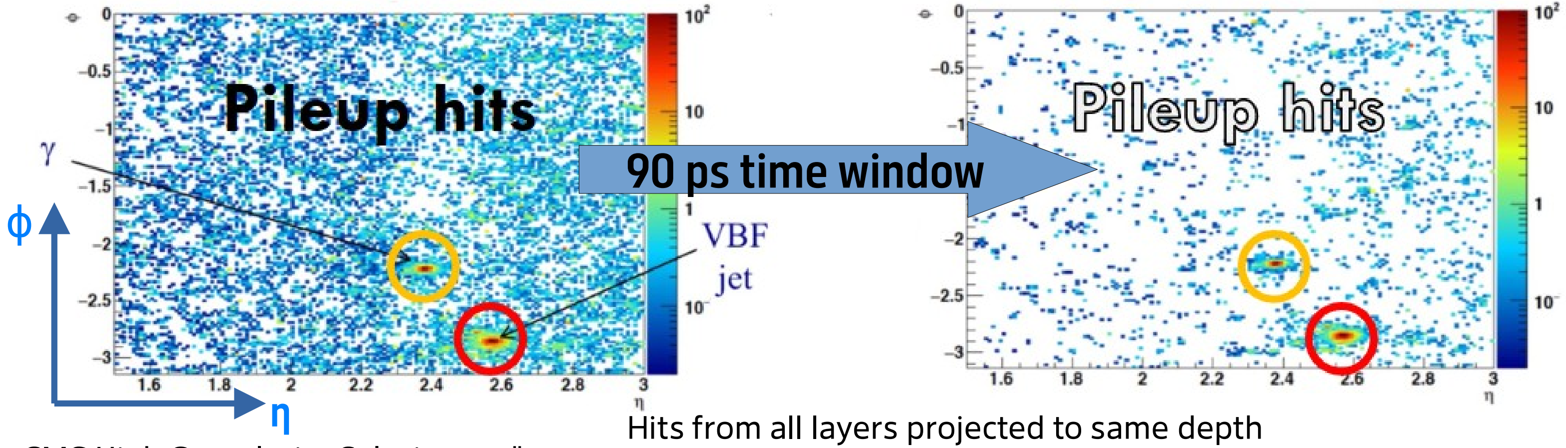


"The Phase-2 Upgrade of the CMS Endcap Calorimeter"
Technical Design Report

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

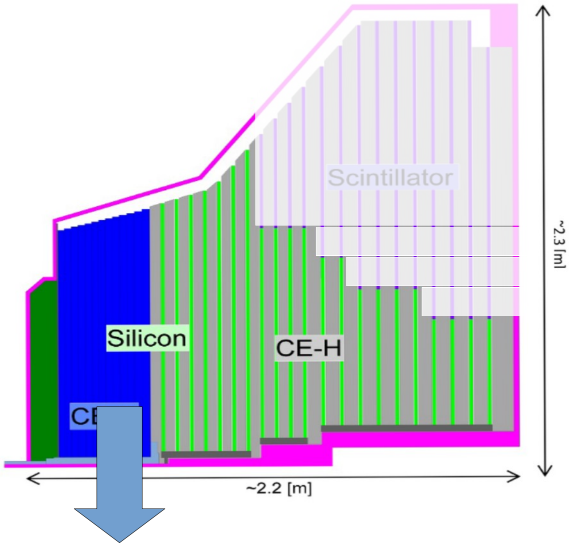




Hits from all layers projected to same depth

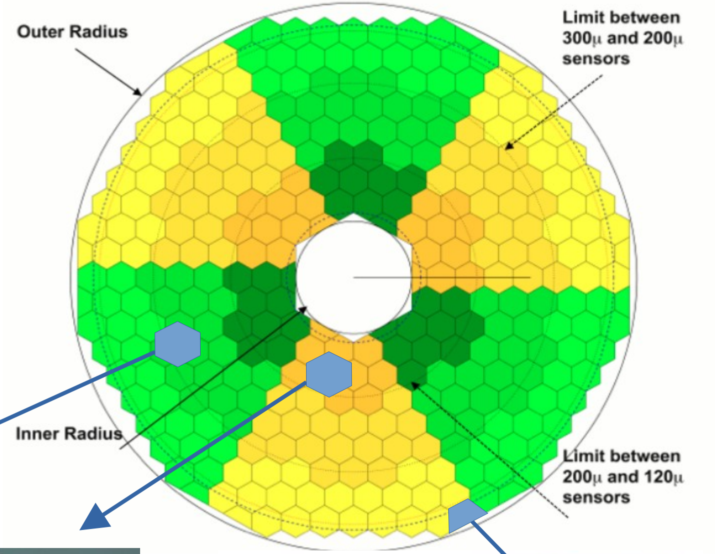
Active Material – Silicon

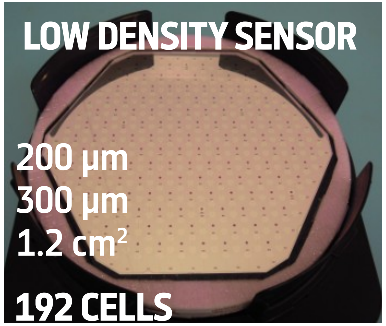
Silicon Sensors

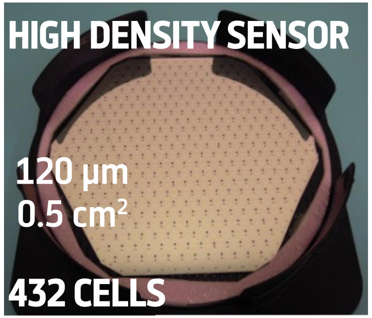


Radiation levels similar to pixel tracker

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



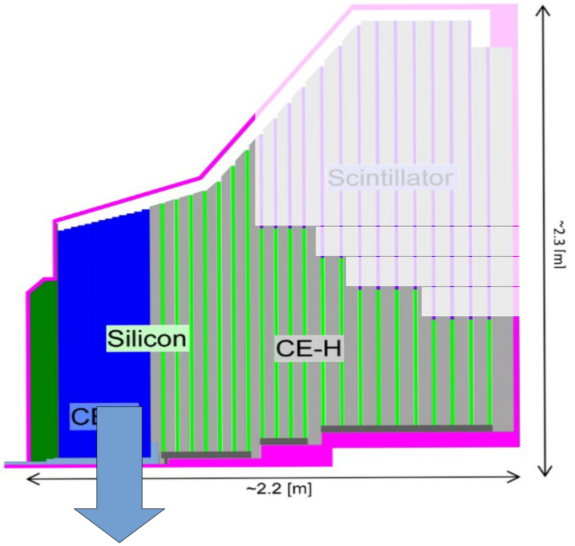




"Measurement of silicon-sensor prototypes for the CMS High-Granularity Calorimeter"
ICHEP 2022

Active Material - Silicon

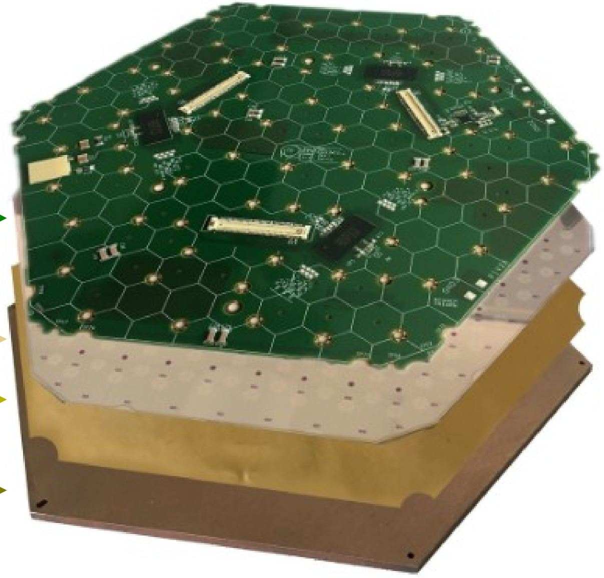
Silicon Module

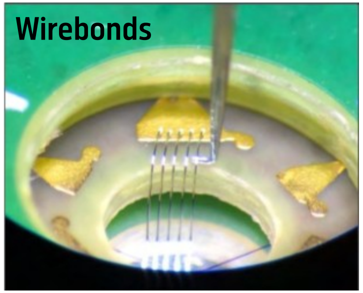


Radiation levels similar to pixel tracker

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

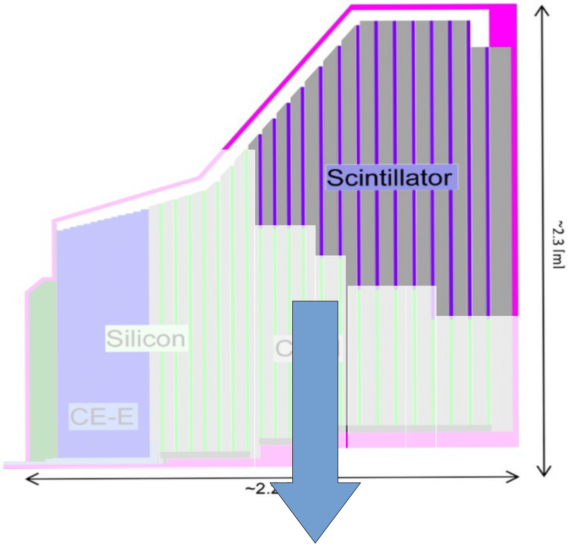
*PCB baseplate in the hadronic sector





Active Material - Scintillator

SiPM-on-tile



Less radiation levels than silicon section

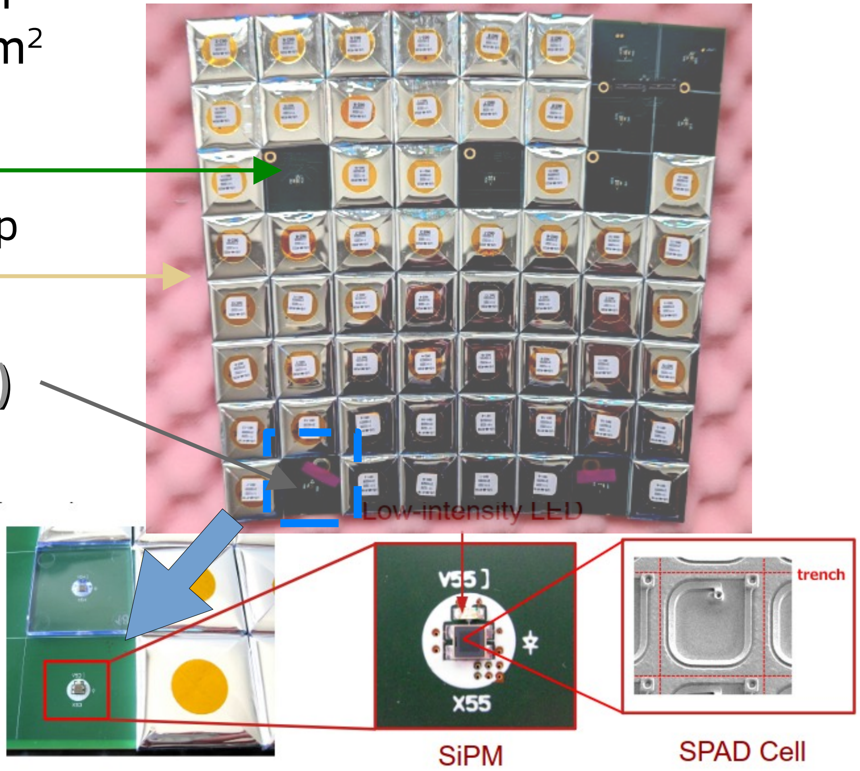
- Regions towards the rear
- Cell sizes from 4 to 30 cm^2

Tileboard (TB) PCB
Hosting the readout chip

Wrapped Scintillating tile
Reflective foil

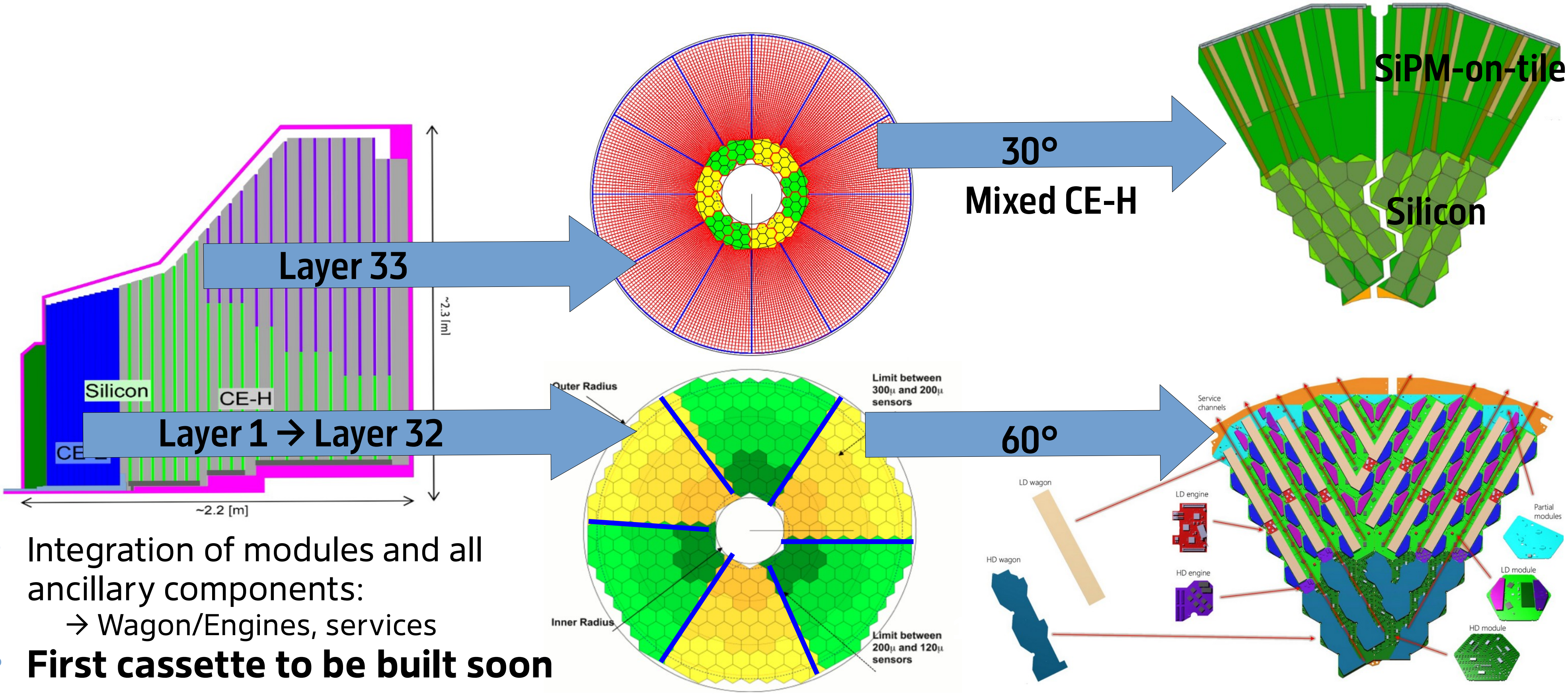
Silicon PhotoMultiplier (SiPM)
Calibration with LED

More details in M.De Silva's Poster



Active Material - Integration

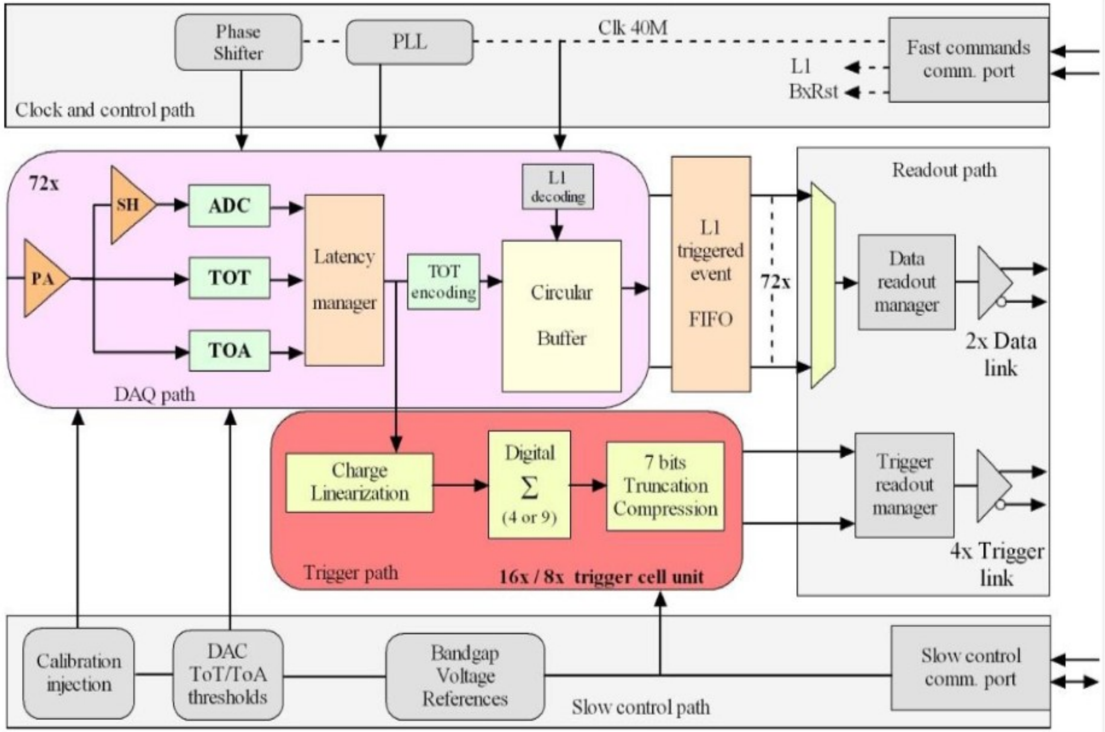
Cassettes



- Integration of modules and all ancillary components:
  → Wagon/Engines, services
- **First cassette to be built soon**

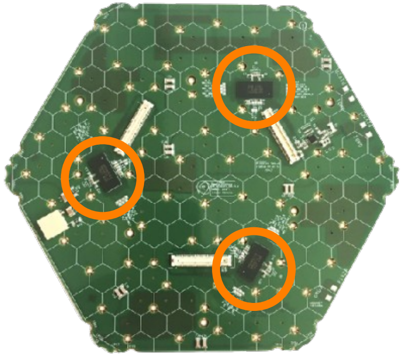
HGCAL Readout Chip

HGCROC

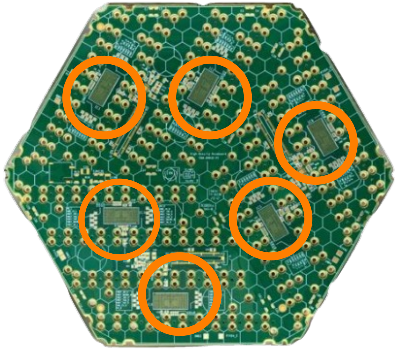


"The Phase-2 Upgrade of the CMS Endcap Calorimeter" Technical Design Report

- Front-end ASIC component
- **Charge** and **time** measurements
- Same design for Si and Scintillator with adaptations
- Two halves chip with 78 channels



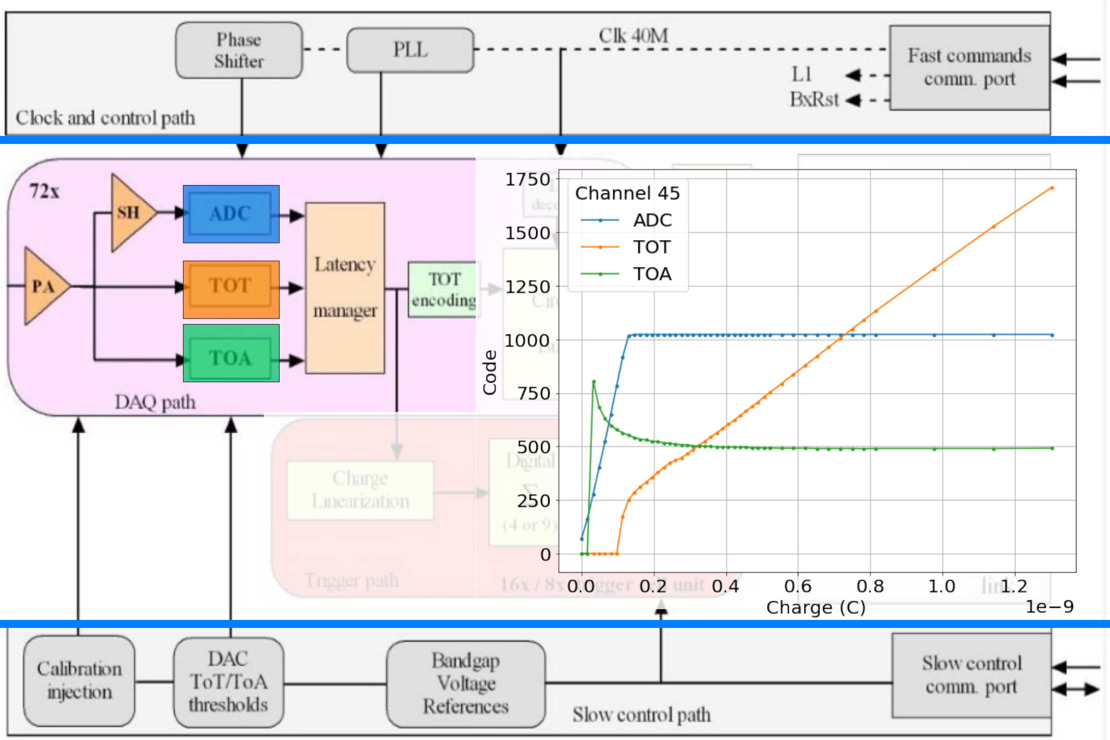
Low Density
3 ROC



High Density
6 ROC

HGCAL Readout Chip

HGCROC



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

- Synchronous fast control:
  → Custom 320 MHz (8 bit at 40 MHz)

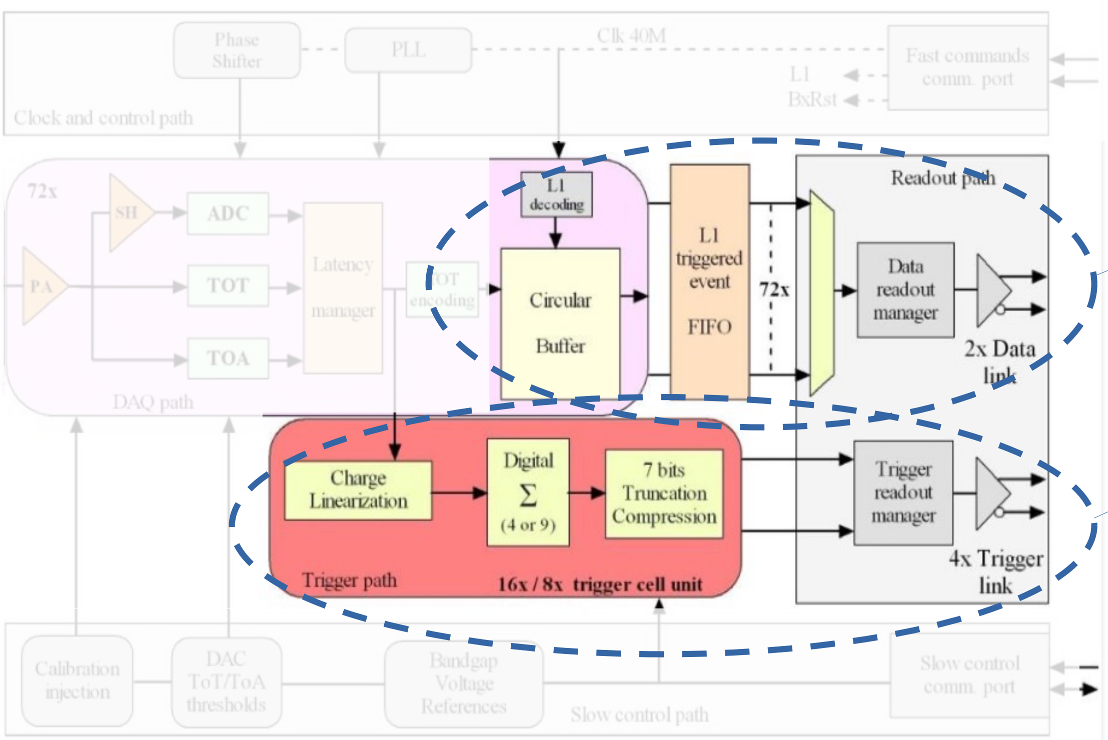
- **Charge/Energy:**
  - **ADC:** 10-bit 40 MHz → **MIPs**
  - **TOT:** 12-bit → **showers**

- **Time:**
  - **TOA:** 10-bit with 25 ps LSB

- Asynchronous slow control
  → I2C

HGCAL Readout Chip

HGCROC



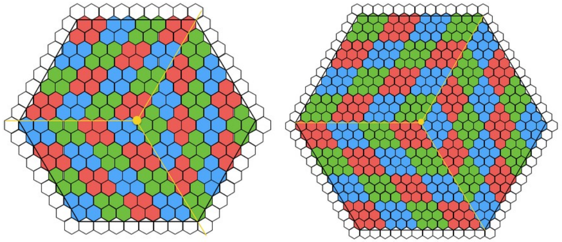
"The Phase-2 Upgrade of the CMS Endcap Calorimeter" Technical Design Report

DAQ Path

→ Data packets after receiving level-1 trigger

Trigger Path:

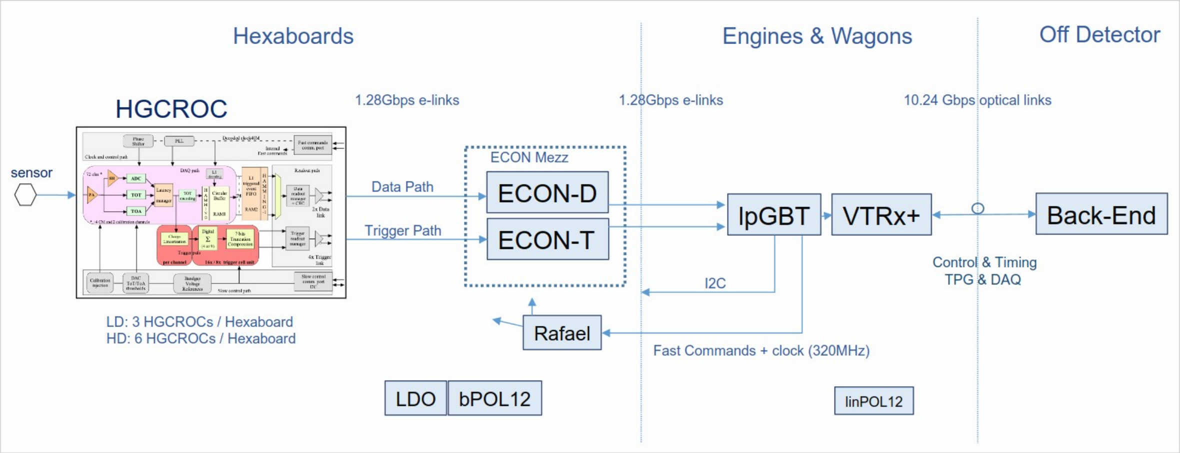
- Sum of 4/9 channels
- 1.28 Gb/s outputs



More details in J.Motta and M.Chiusi posters

HGCAL Full Readout Chain

Signal Flow



ECONs

- Concentrator chips
- ECON-T:
  - Select/compress trigger data
  - Transmission every 40 MHz
- ECON-D:
  - Process full resolution data after trigger
  - Perform zero suppression
  - Transmission at 750 kHz

Engines/Wagons

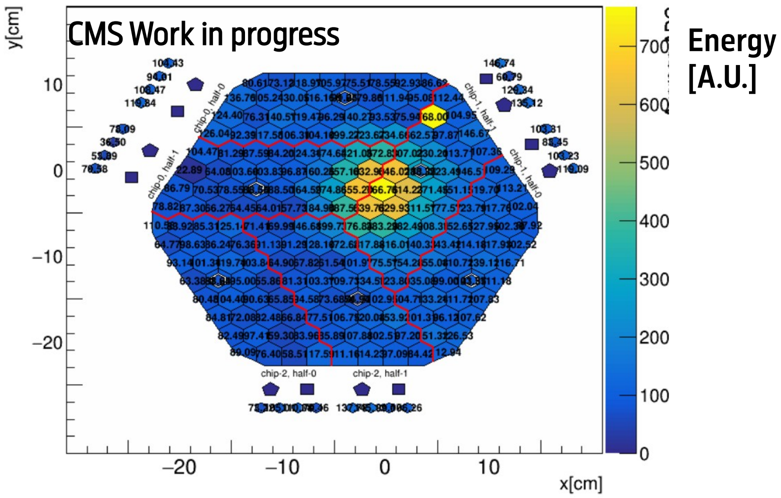
- Active/Passive elements
- Hosting lpGBT/VTRX
  - Transmission to DAQ back-end
  - Clock distribution
  - Fast commands/Configurations

HGCAL Full Readout Chain

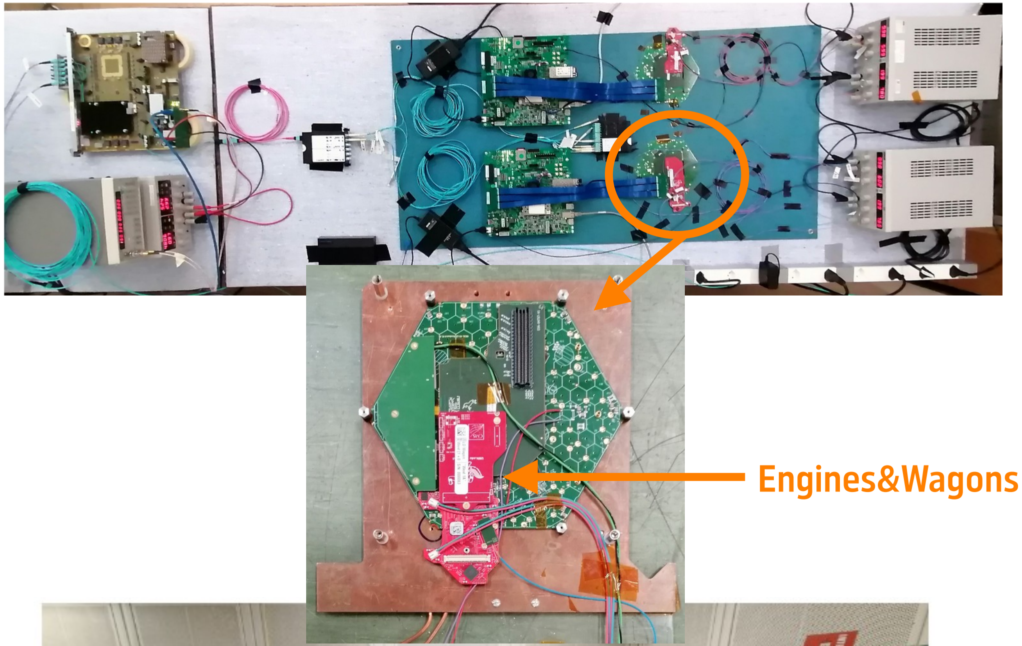
First test of the readout chain

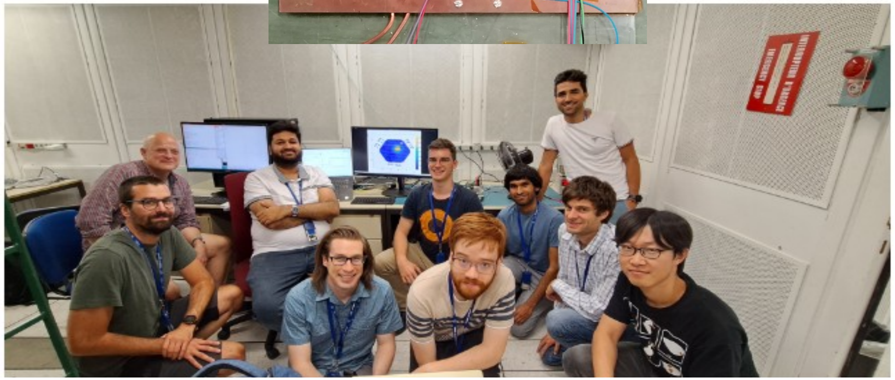
Testbeam at CERN - August 02-09

- Two low density silicon modules tested with full readout chain
- ECON-T/D emulators



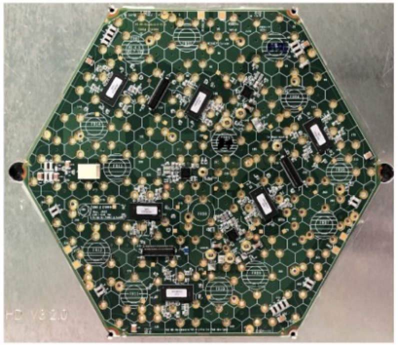
Full chain with ECONs ASIC to be tested in September testbeam at CERN

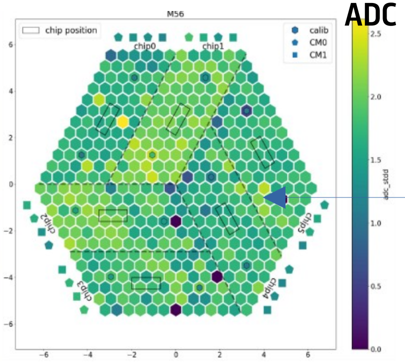




System Validation

Silicon and SiPM-on-tile modules





CMS Work in Progress

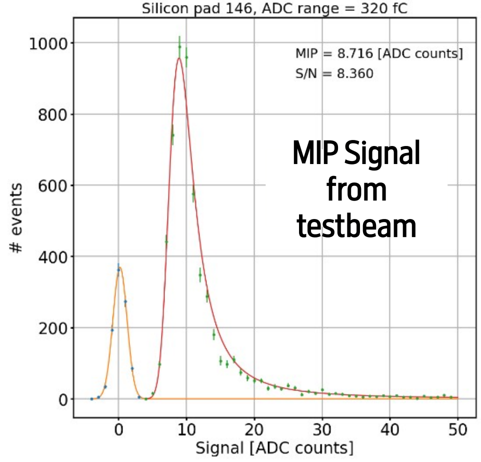
Low Density

→ Noise, S/N studies in testbeams

First **high density** module assembled and tested in December

→ Performance similar to the low density modules

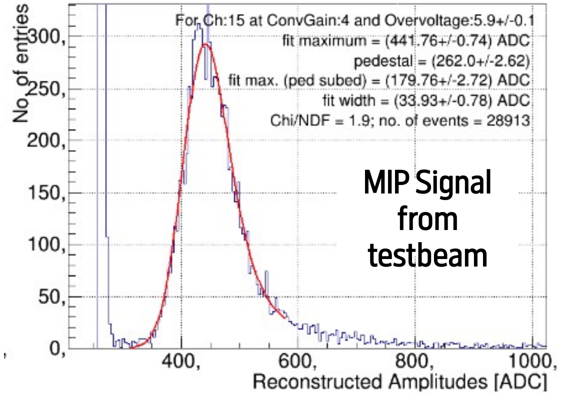
CMS Work in Progress

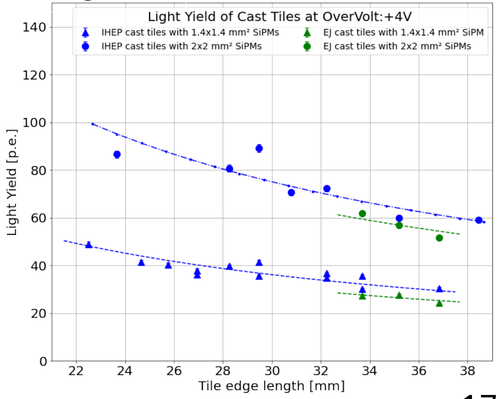


SiPM-on-tile

- Closed to final tileboard module commissioned and tested in test beams
  - S/N studies
  - Scintillator light yield calculations

CMS Work in Progress

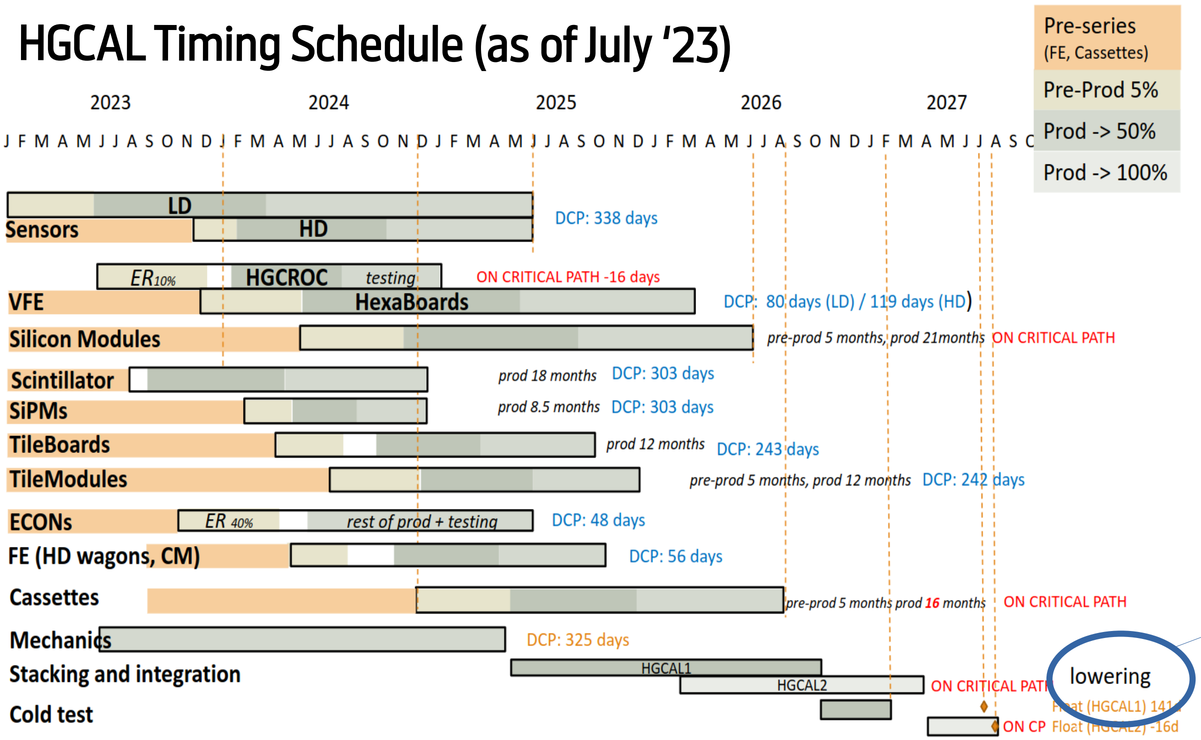




Status of the Project

Preparation of mass production

HGCAL Timing Schedule (as of July '23)



- **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

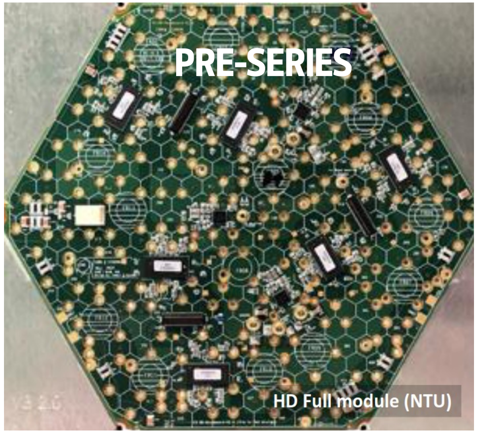
In time for the scheduled lowering in 2027

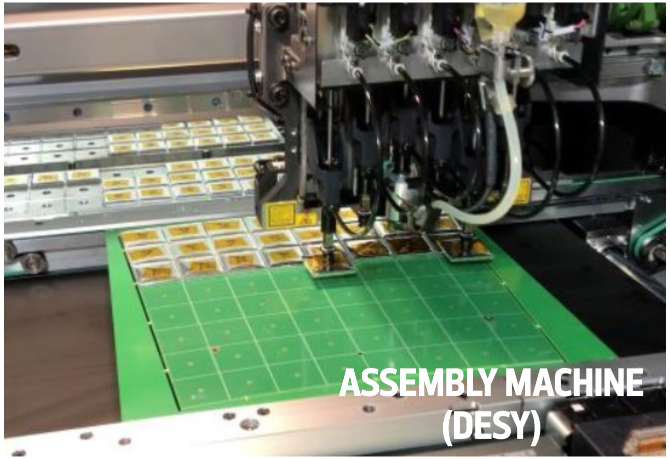
Preparation of Mass Production

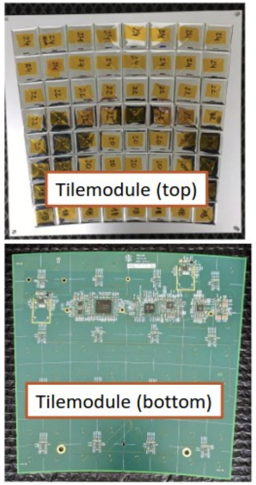
Tasks and Workflows

Silicon modules

- 26k modules in total
- Built and tested in 5 Module Assembly Centres (**MACs**)







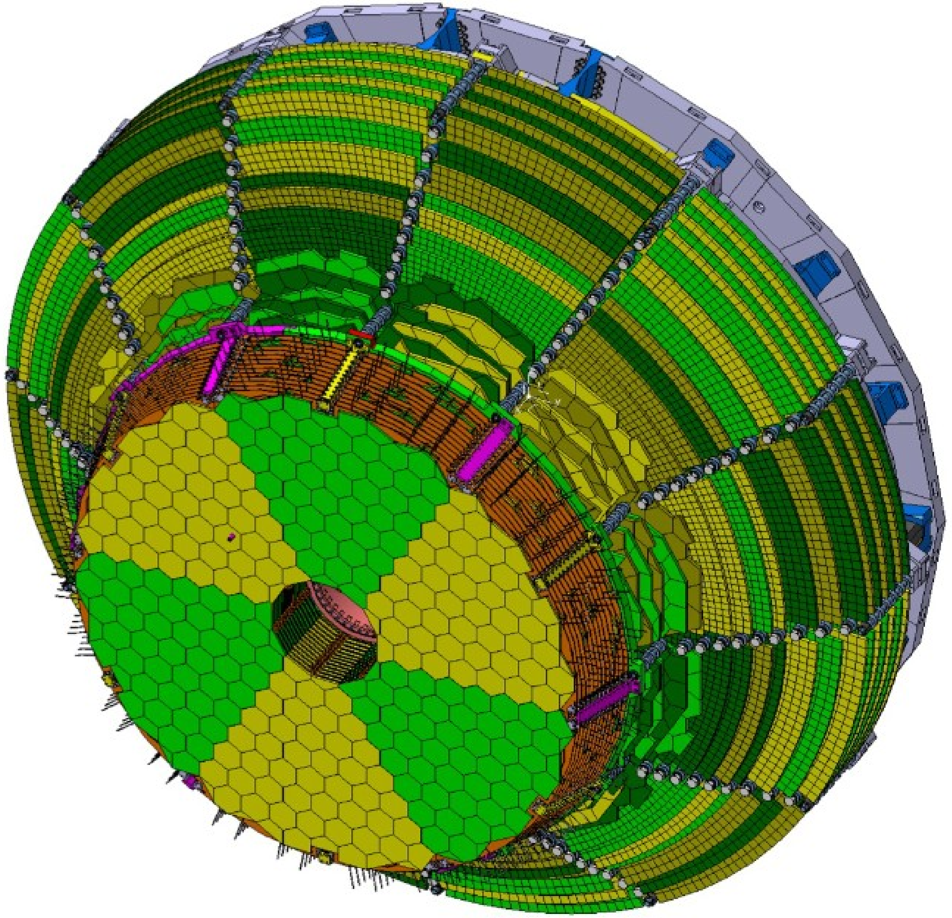
SiPM-on-tile modules

- 240k SiPMs/tiles in total
- 3744 Tilemodules in total
- Built and tested in 2 Tilemodules Assembly Centers (**TACs**)

Outlook

Journey to the CMS 5D Imaging Calorimeter

- **Cutting-edge detector design**
  - High spatial granularity detector
  - Precise timing for showers
  - Energy measurements from MIP to showers
- **>6M silicon & >200k scintillator channels in harsh environment**
- **Important progress and ongoing developments**
  - System performance in testbeams and lab tests
    → Results in agreement with expectations
    → Full readout chain with all ASICs to be tested soon
  - Readiness for mass production
    → Most components close to final design



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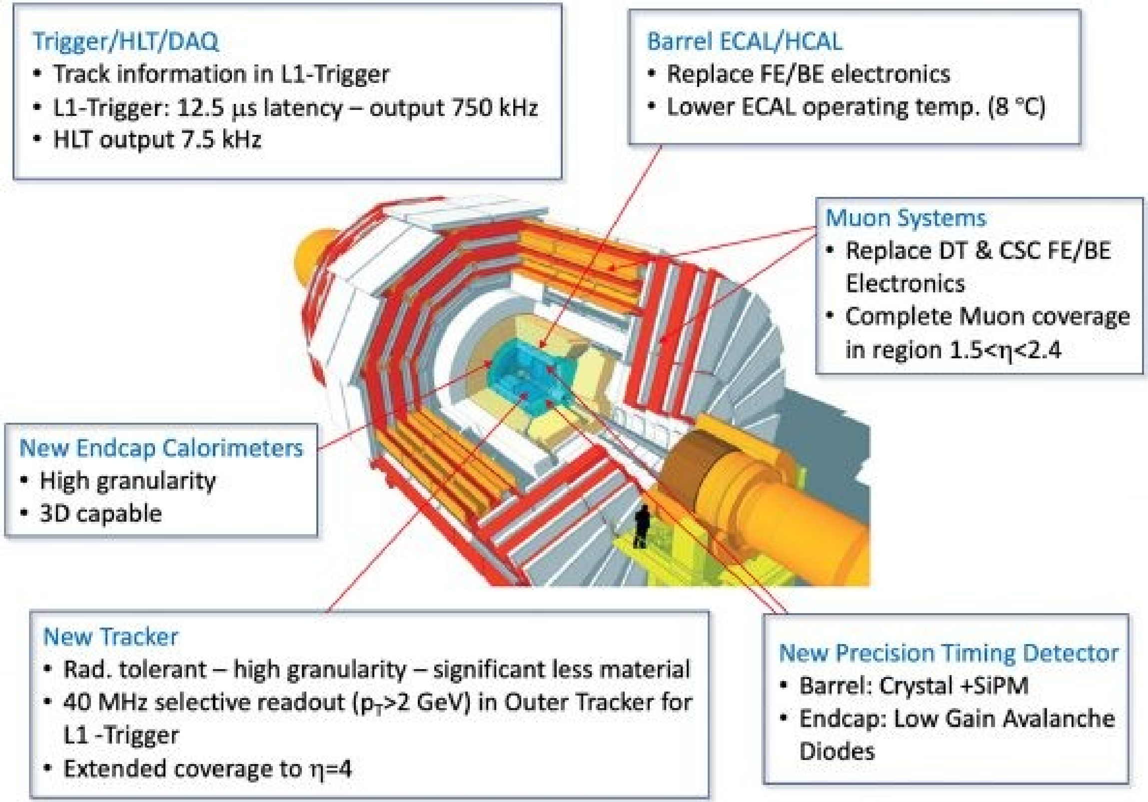
BACKUP

Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

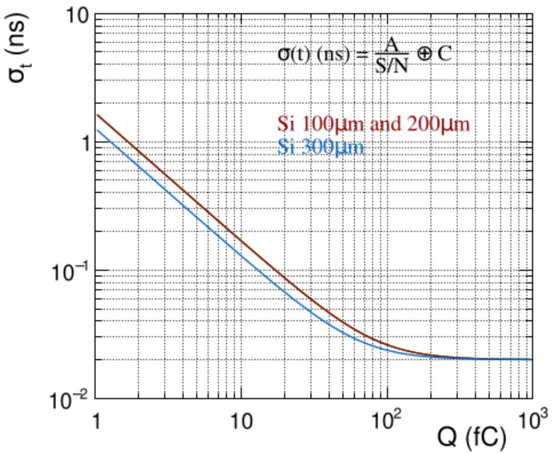
CMS during HL-LHC

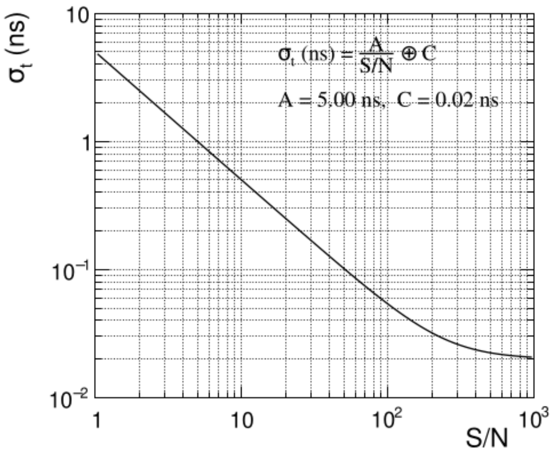
Upgrades overview



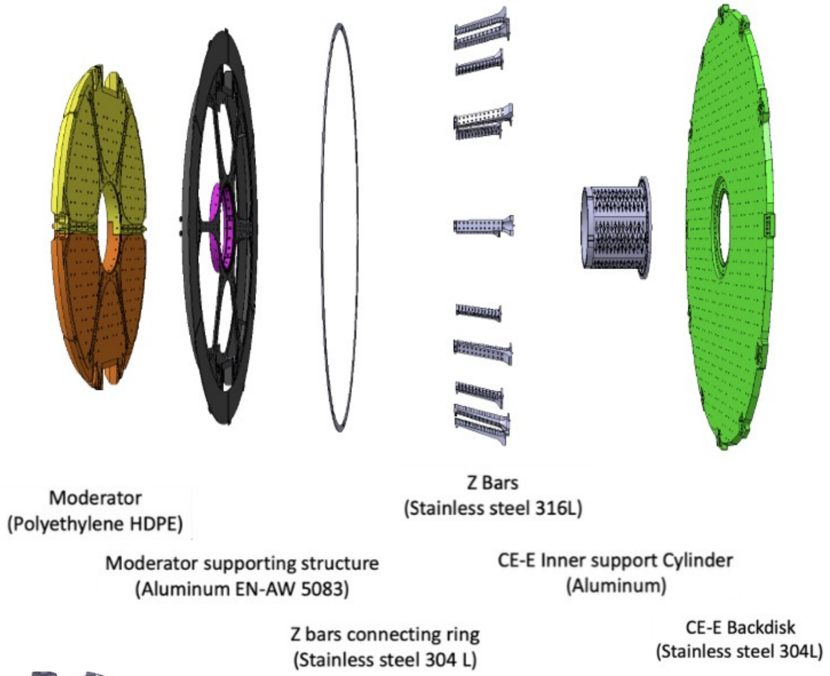
Timing Resolution
Specifications

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

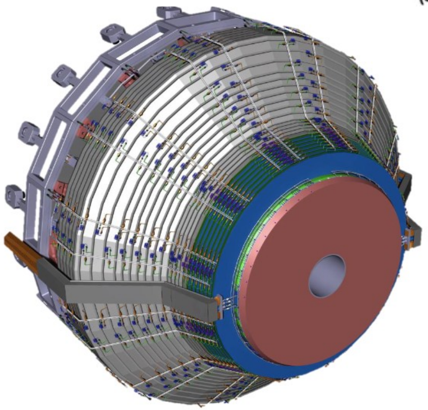


CE-E Mechanics:

- 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

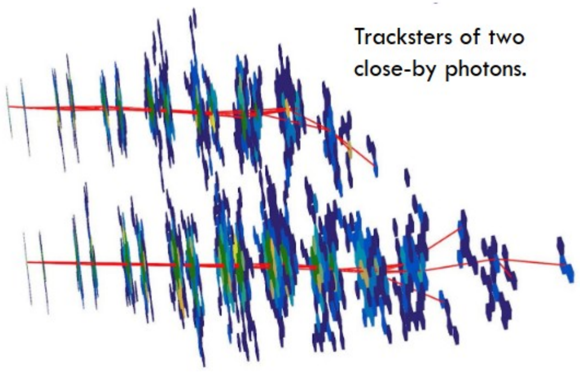
"The Phase-2 Upgrade of the CMS endcap calorimeter"
Technical Design Report

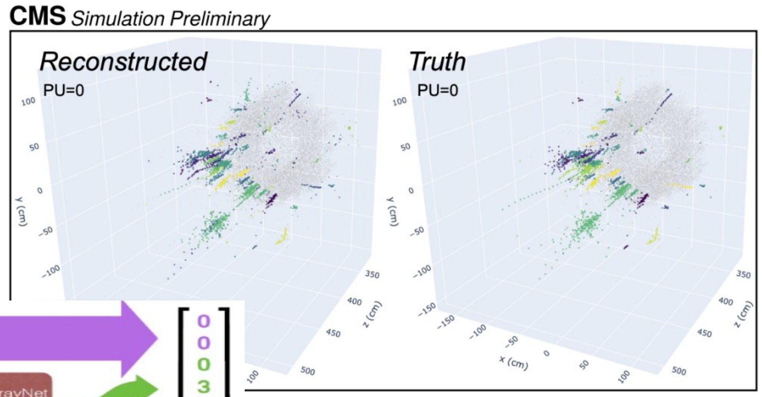
- Front-end ASIC component
- Same design for Si and Scintillator with adaptation
  → conveyor gain used as pre-ampflier
- Two halves chip with 78 channels
- Low noise, large dynamic range
  → from MIP to showers
- Accommodating 12 μs of latency
  → L1 requirement
- High speed readout links
  → 1.28 Gb/s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

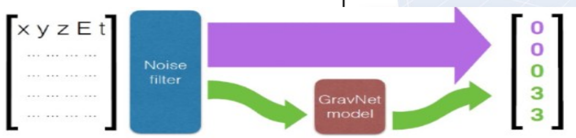
Simulation and Reconstruction

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

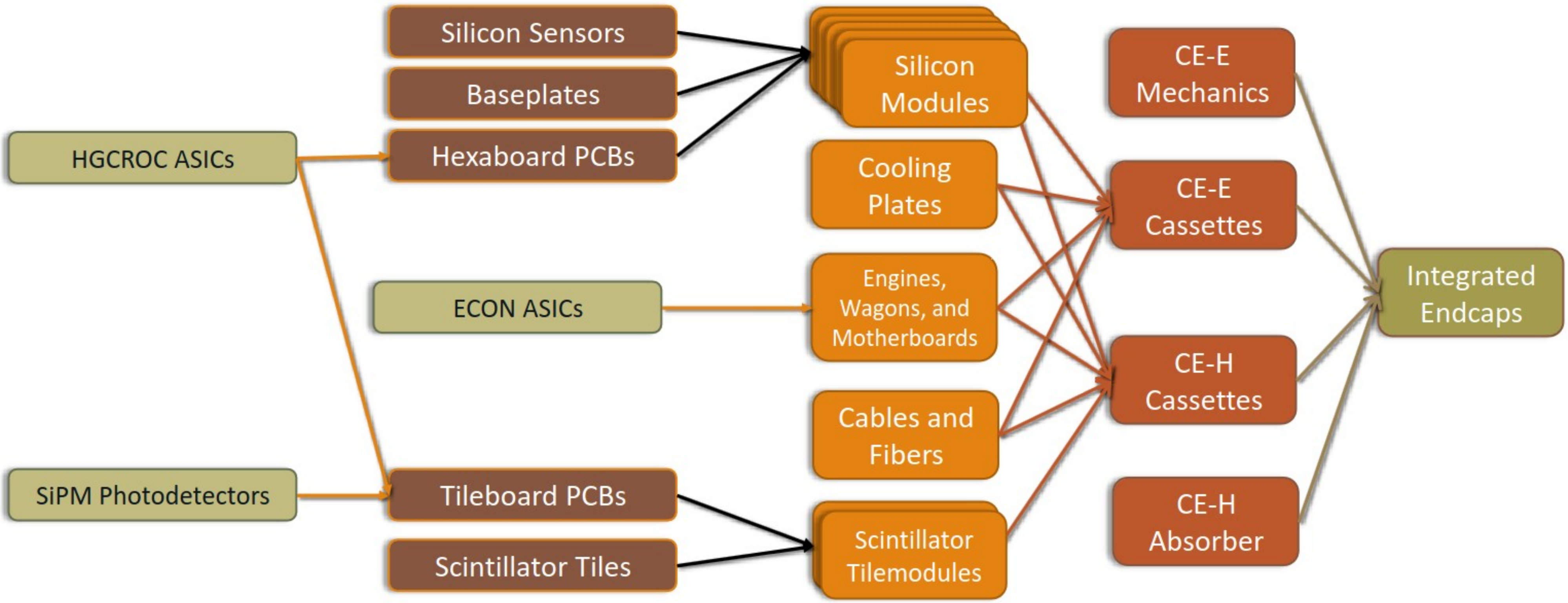






Status of the Project

Summary of the principal components and Workflow



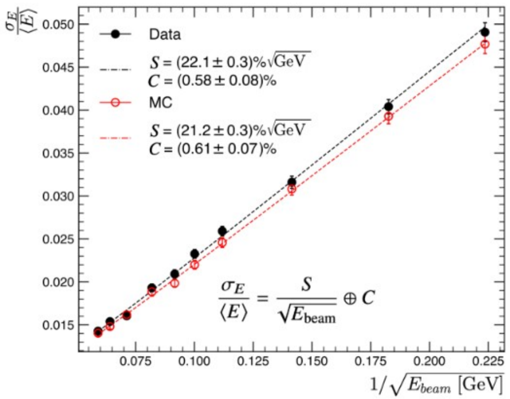
2018 Test Beam

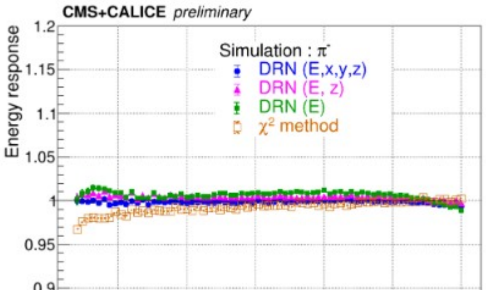
Prototype – HGCAL and CALICE AHCAL

- **Setup**
  - HGCAL EM and hadronic sections
  - CALICE AHCAL scintillator section
  - SKIROC2-CMS ASIC (readout chip)

- **Beams**
  - e+, μ-, π- up to 300 GeV

- Measurements of the performance of **energy resolution** and **timing**





Dynamic reduction network tested for energy regression