CMS High Granularity Calorimeter (HGCAL)

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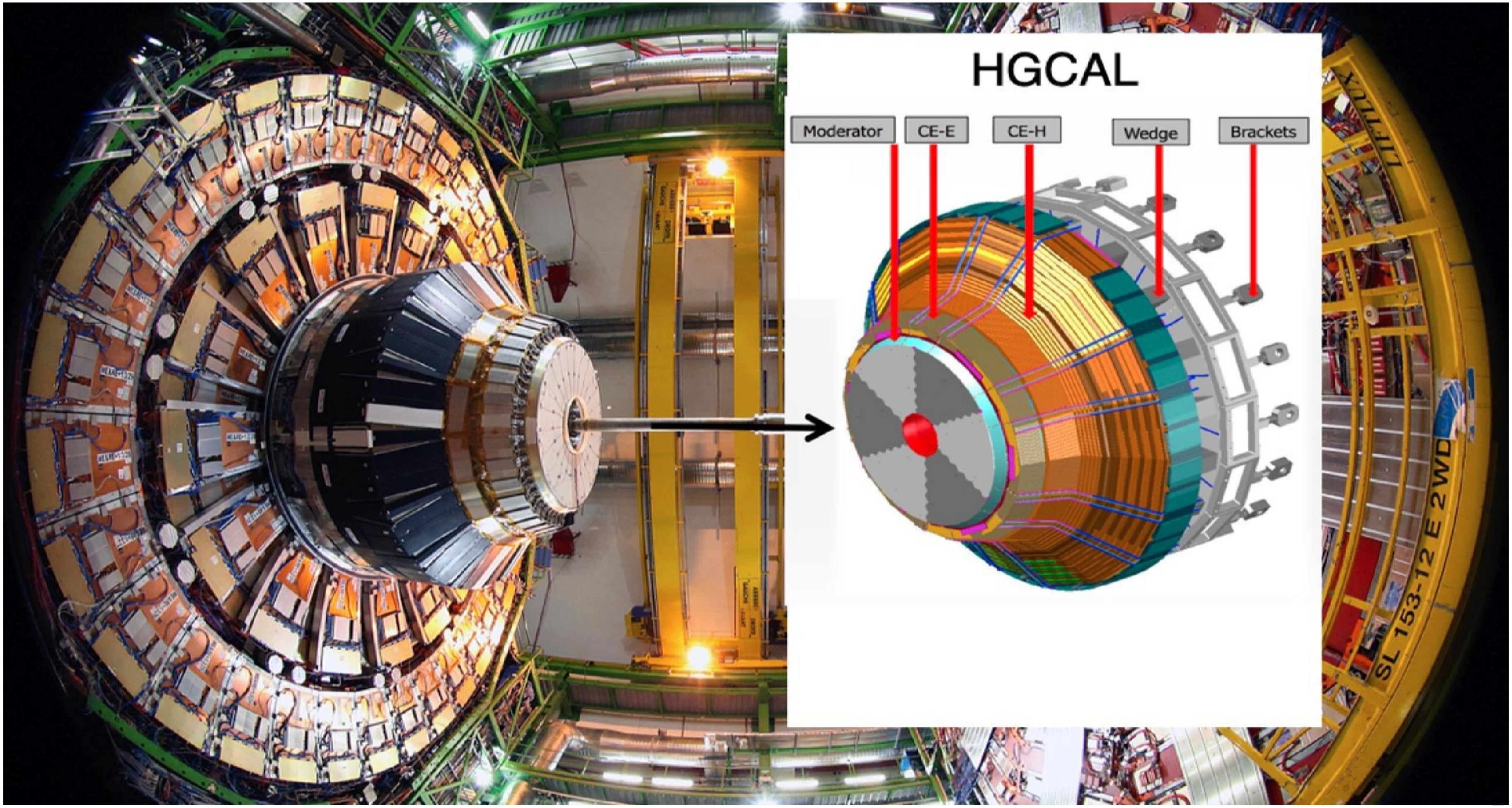
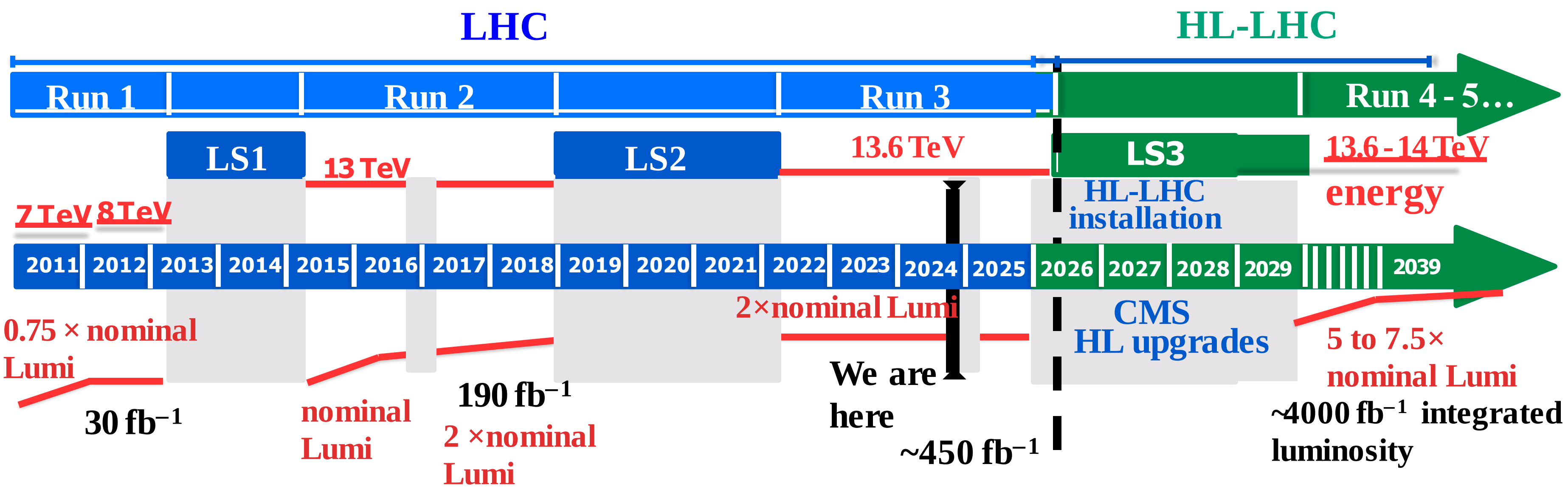
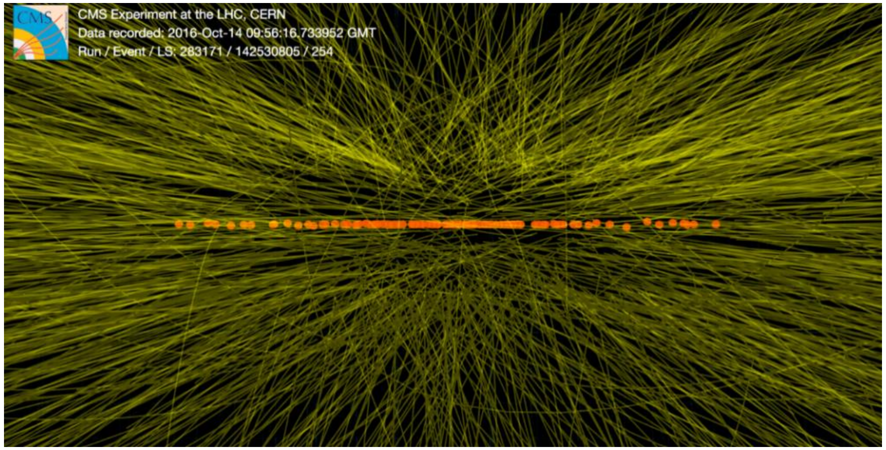
On behalf of the CMS collaboration



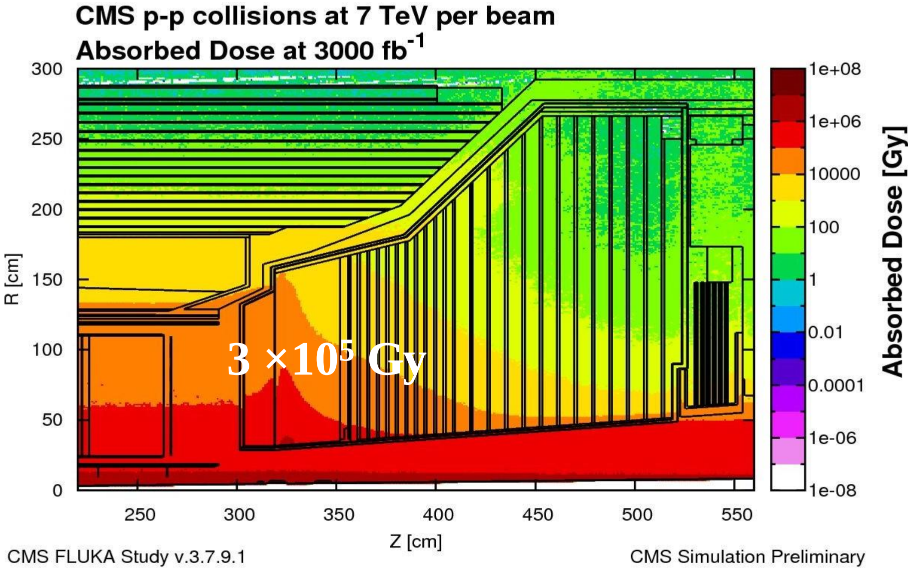
High Luminosity LHC program at CERN

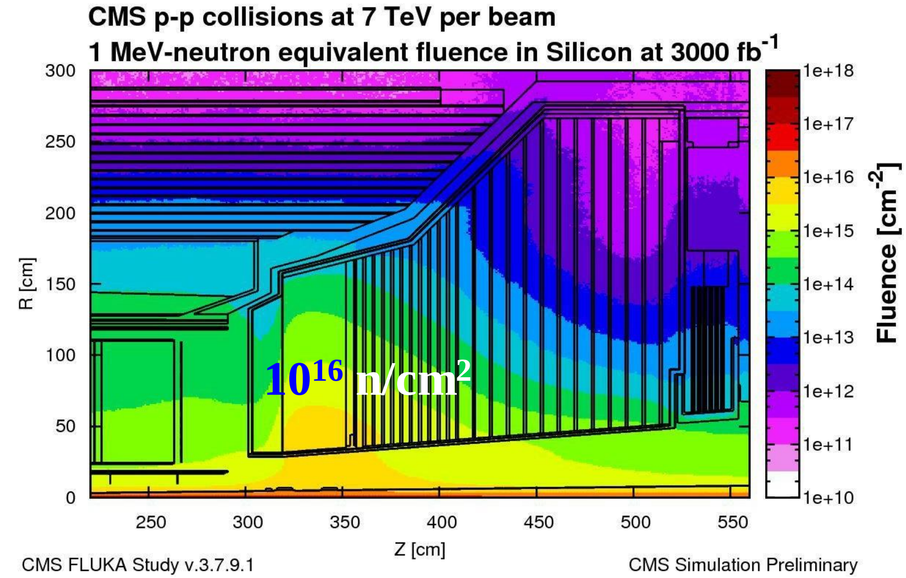


- **HL-LHC will provide PU up to 200 and higher luminosity.**
- **CMS will undergo a major upgrade for HL-LHC to sustain radiation levels, and resolve vertex density.**
  - **Detailed studies of the Higgs boson and SM processes, e.g., $H \rightarrow \gamma\gamma$**
  - **Trigger cleanly on and reconstruct the narrow vector boson fusion (VBF) jets, as well as merged jets for physics beyond the SM.**

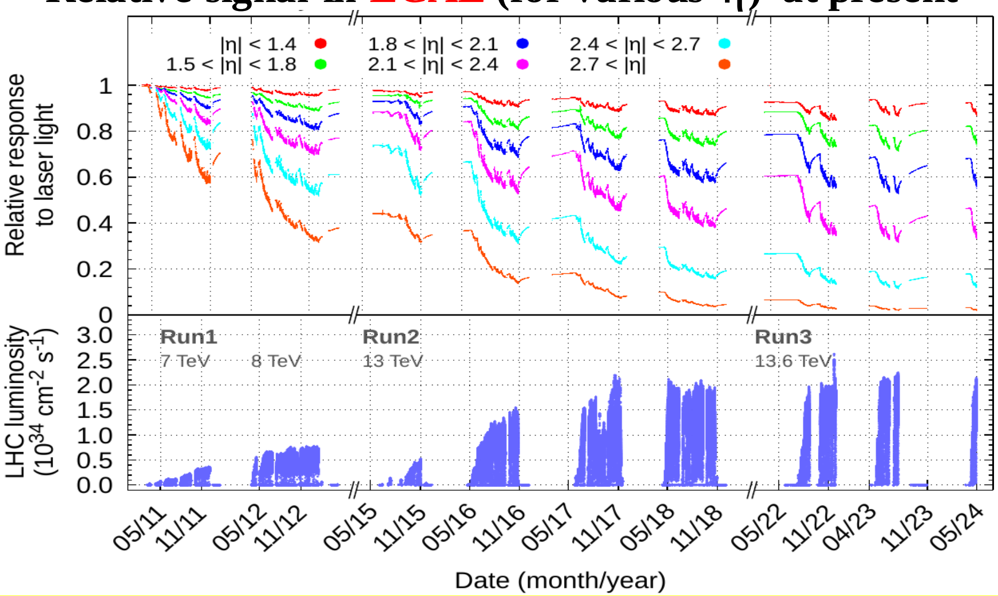


Radiation dose at the CMS and forward calorimeter

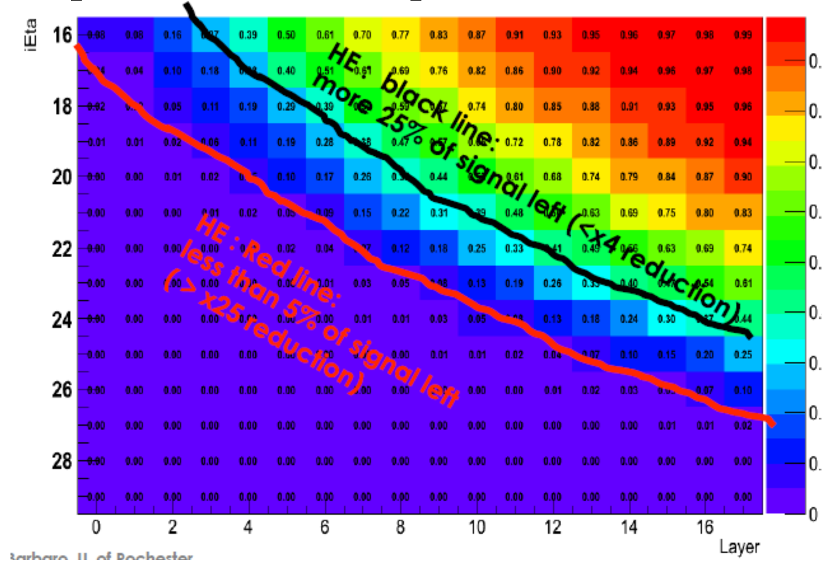




Relative signal in ECAL (for various η) at present



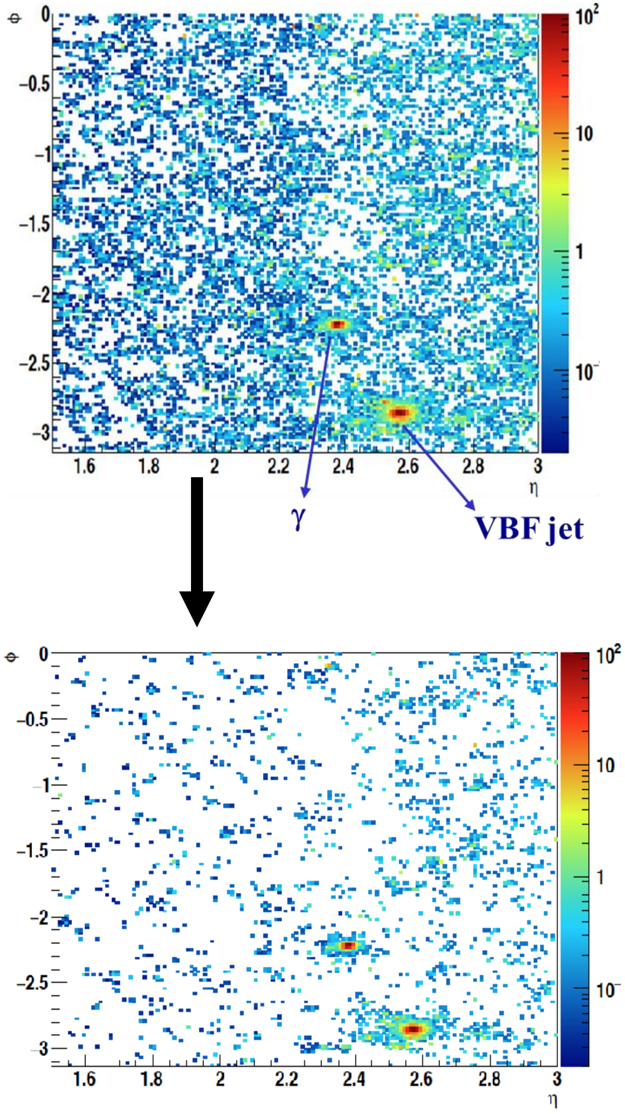
Expected scenario of present HCAL @3ab^{-1}



Present ECAL & HCAL need to be replaced by a new calorimeter during HL-LHC

Requirements for the new Endcap Calorimeter

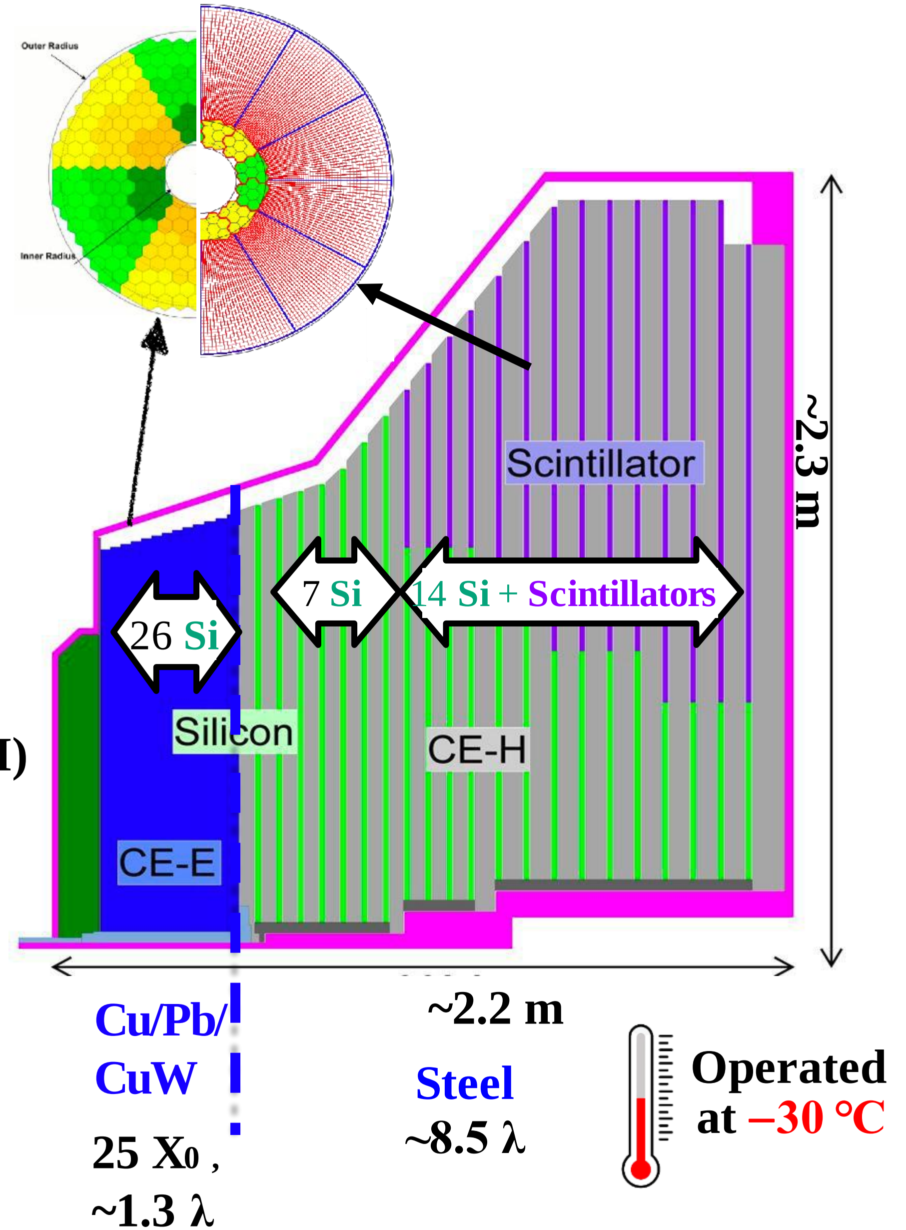
- **Radiation tolerance**
  - **Preserve energy resolution and calibration capability till 3000fb^{-1}**
- **Dense calorimeter**
  - **To preserve lateral compactness of showers**
- **Fine lateral granularity**
  - **To help shower separation, identification of narrow jets, reduction of pile-up effect and help calibration**
- **Fine longitudinal granularity**
  - **For good electromagnetic resolution, pattern recognition and pile-up suppression**
- **Precision measurement of time (~30ps)**
  - **Pile-up suppression and primary vertex identification**
- **Ability to provide trigger information at 40MHz**



High granularity imaging calorimeters is capable to fulfil all these criteria

CMS High Granularity (imaging) Calorimeter

- **Sampling calorimeter separated in two sections covering $1.5 < |\eta| < 3.0$**
  - **CE-E: electromagnetic , CE-H: hadronic**
- **Active materials:**
  - **Silicon sensors (CE-E and CE-H)**
    - **Hexagonal, 120/200/300 µm thick, 8" wafers.**
    - **Low ($192\times1.26\text{cm}^2$) and high ($432\times0.56\text{cm}^2$) density modules.**
    - **6M pads and 26k modules (620 m^2)**
- **Plastic scintillators with SiPM readout (CE-H)**
  - **240k tiles (4-30cm^2) and ~4k modules (370 m^2)**
- **Passive materials:**
  - **Pb & steel absorbers and Cu, CuW or C-fibre plates**
  - **Dense and compact → 230 Ton /endcap**
  - **Power : ~125 kW per endcap**



5D measurements in HGCAL

Energy measurement

Dynamic range:

0.2 fC - 10 pC

- **Calibrate on single MIP**
- **Measure energetic jets O(10k) MIP**

Spatial granularity

6M channels in ~40 m³

Cell sizes from 0.5 to 30 cm²

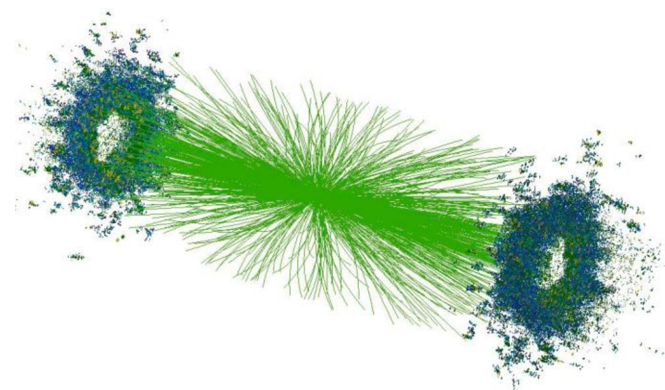
Timing for showers

O(25 ps) per channel energy above O(10) MIPs

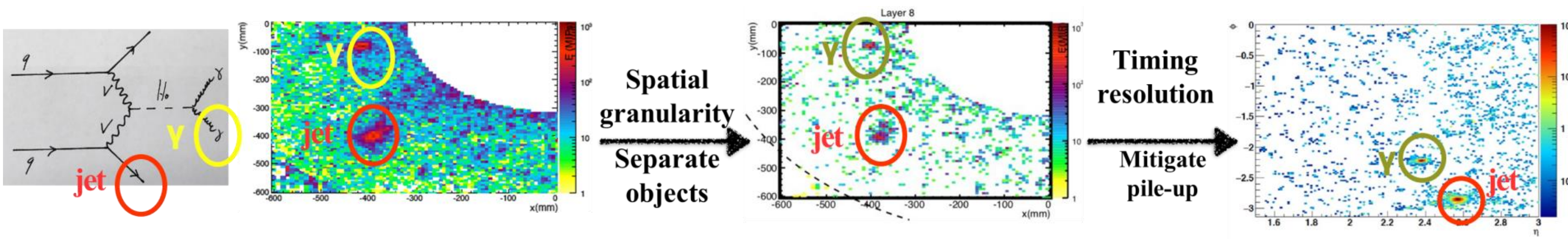
Essential to mitigate pileup at HL-LHC

Challenges:

- **140-200 PU → dense environments**
- **data transmission @40 MHz**
- **E_T for L1 trigger**



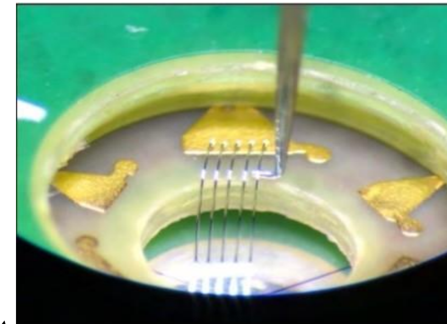
VBF jets + H→γγ



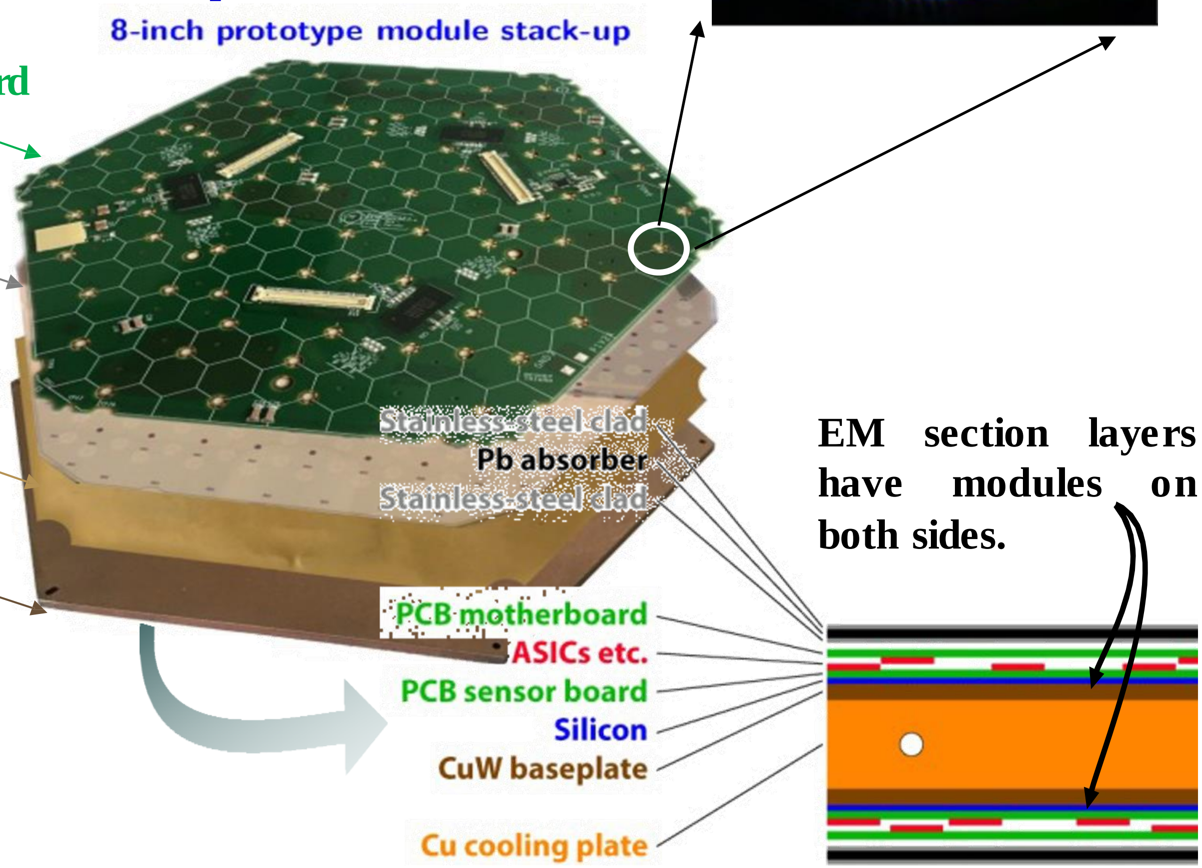
Needs dedicated reconstruction algorithms to exploit precise 5D information with high performance

The Building Blocks – Silicon Module

- **“Hexaboard” PCB**
  - **Connects sensor to readout ASIC (HGCROC).**
  - **Connects to the motherboard for control and data transfer.**



Si pads bonded to PCB



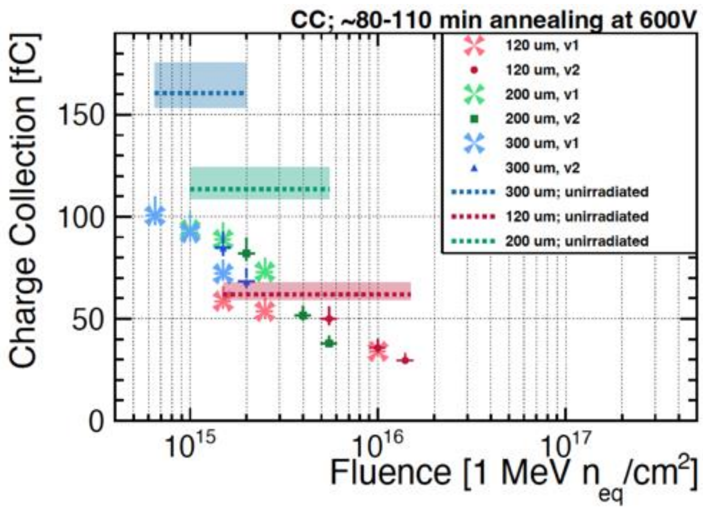
- **Silicon sensor**
- **New 8” process !**
- **Metalized kapton sheet**
- **Bias supply to sensor back side.**
- **Insulation from baseplate.**
- **Copper-Tungsten baseplate**
- **Rigidity contributes to absorber material.**

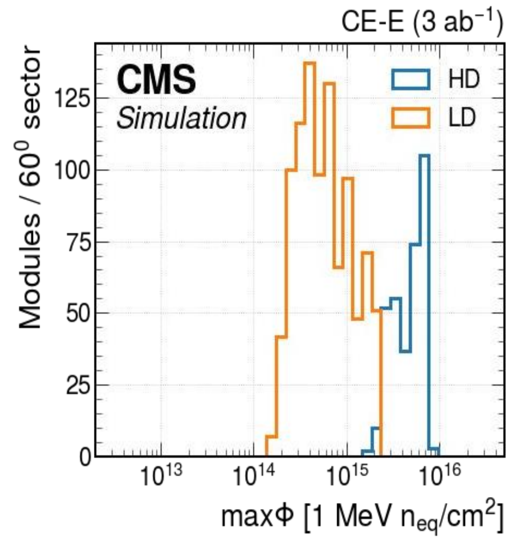
Silicon Sensor parameters

HGCAL considers three thicknesses (120, 200, 300 µm) and two densities (LD,HD)

Thickness : driven by expected exposure to non-ionizing radiation - up to O(10^{16}) 1 MeV n_{eq}/cm^2

Densities : driven by limiting the cell capacitance (also correlated with higher particle density in the regions with higher fluence)





main sensor parameters: MIP_{eq} ~70ke⁻/µm

Type	Active d (µm)	Density	Cell size (cm²)	Cell Cap(pF)	Fluence (×10^{15} neq/cm²)	Noise (e–)	Initial MIP S/N	MIP (L) S/N >3 ab^{-1}
Float Zone (FZ)	300	LD	1.26	45	0.1 - 0.5	1900	12.8/11	4.7
	200	LD	1.26	67	0.5 – 2.5	2000	8.4/6.6	2.3
	200	HD	0.56	30	0.5 – 2.5		6	2.3
Epitaxial (epi)	120	HD	0.56	48	2 - 7	2000	4.8/5	2.2

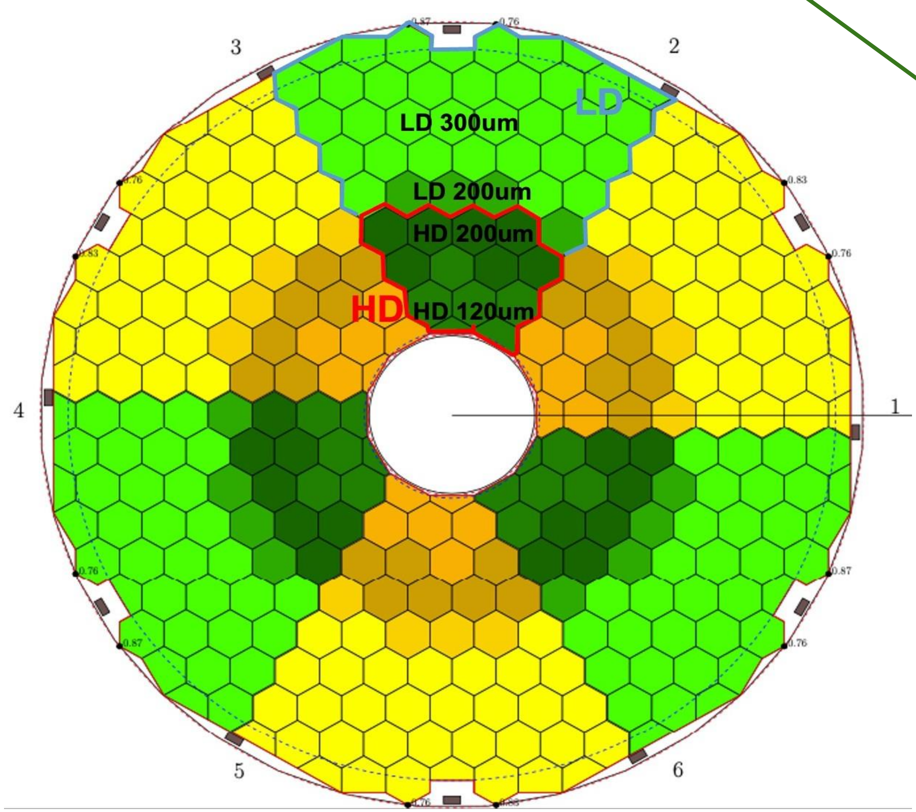
Modules : HD : ~5k (20%) LD : ~20k (80%)

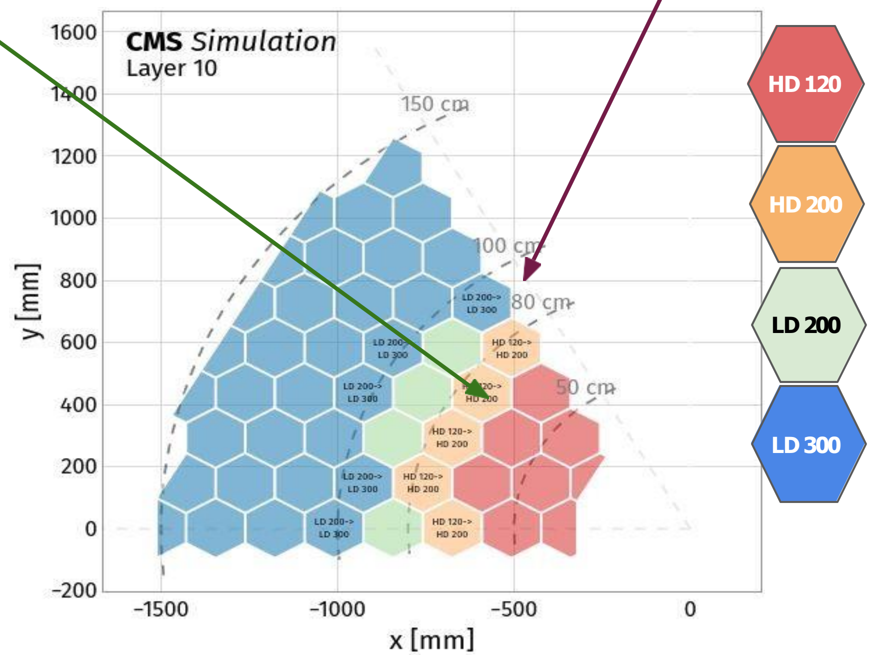
Optimization results for silicon sensors: e.g., layer 10

- **migrations are between LD {300,200} and HD {200,120}**
- **n-in-p sensors for superior radiation hardness**

HD200 sensors minimize the noise for almost similar signal, thus take over some HD120

LD300 sensors offer adequate performance even at high fluence, thus take over a few LD200





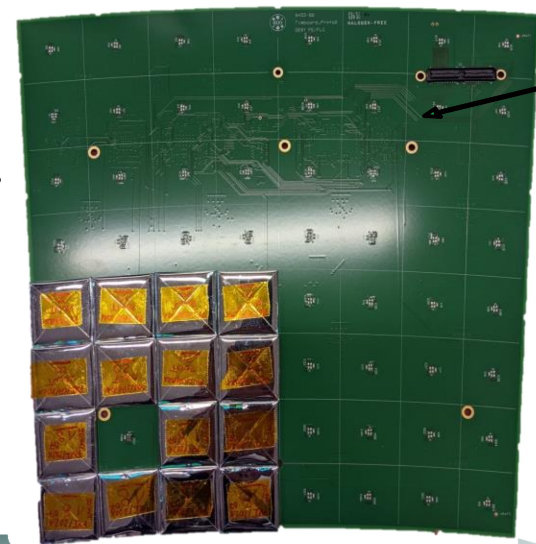
optimized lateral layout of layer 10

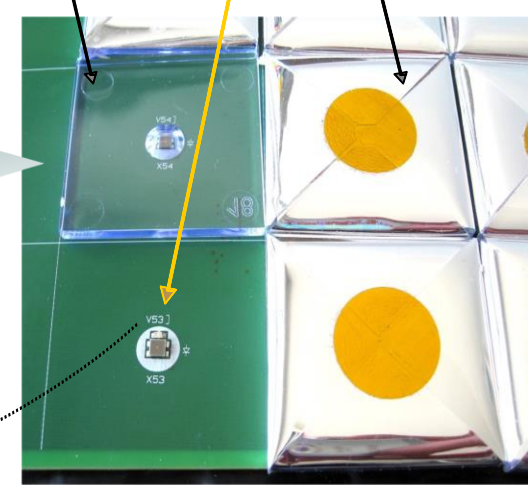
The Building Blocks : Scintillator Tile Module

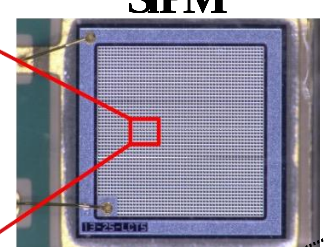
- “Tileboard” : 3744 PCB & Assembled tile modules (240k channels of size ~4 - 30 cm^2)
  - Small cast-scintillator tiles (207m^2) in high radiation zone, larger moulded scintillators (163m^2) in low radiation zone
  - Connects Silicon photomultipliers (SiPM) to HGCROC ASIC.
  - Connects to the motherboard for control and data transfer.
- Wrapped scintillating tiles
  - Reflective foil wrapping.
  - Light collected by SiPM (9mm^2).
  - Light injection LED.

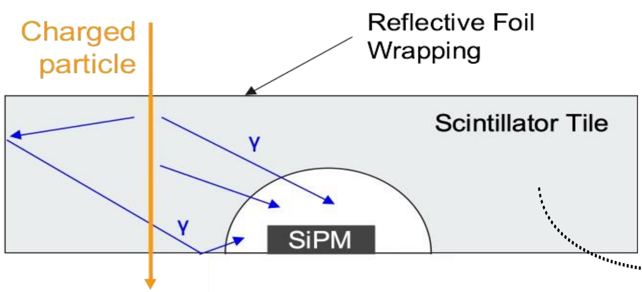
Design layout is optimized for S/N relative calibration with MIPs > 2.5 after 3000 fb^{-1}

Tile boards : 8 basic types, 35 sub-types in total





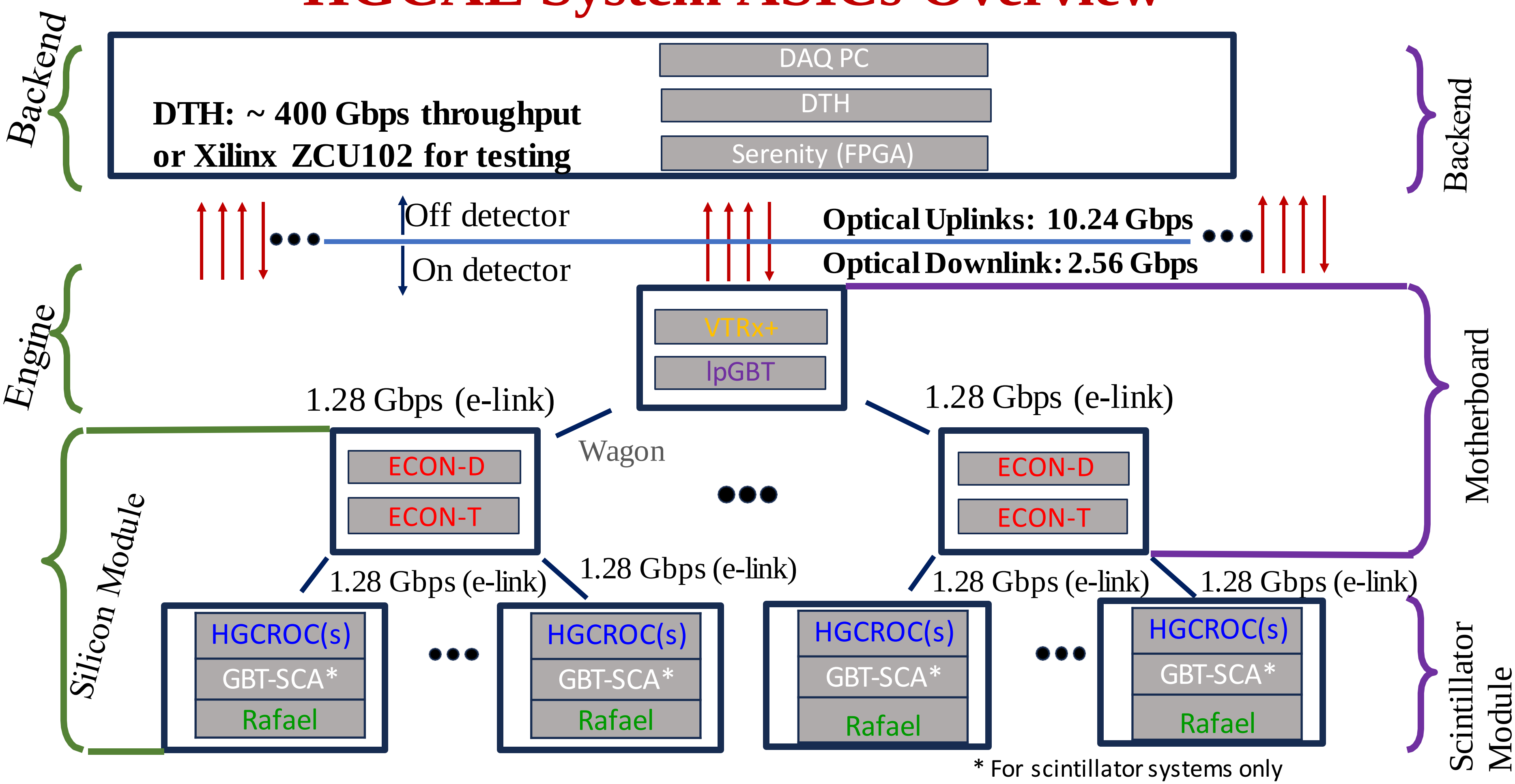




Requirements of Readout Electronics

- **Low noise (<2500e⁻) and high dynamic range (~0.2fC → 10pC)**
  - **Identify MIPs (~3.5fC in 300µm silicon) with S/N > 3 for whole lifetime of HL-LHC**
  - **Use 130nm CMOS with 1.5V supply**
- **Provide timing information to tens of picoseconds**
  - **Need clock distribution jitter 10-15ps (same specs as for other CMS detector upgrades)**
- **Have fast shaping time (<20ns) to minimize out-of-time pileup**
- **On-detector digitization, data concentration and zero suppression**
- **On-detector creation of trigger sums**
- **Buffering of data to accommodate 12.5µs L1 latency**
- **High-speed readout links to interface with 10 Gb/sec lpGBT chipset**
- **<20mW per channel (roughly limited by cooling power)**
- **High radiation resistance (~2MGy and 10^{16} n_{eq}/cm^2)**

HGCAL System ASICs Overview



HGCROC : Front-end readout chip, receives and digitizes signals from the Si sensors

ECON-D: Front-end concentrator chip for DAQ
ECON-T: Front-end concentrator chip for trigger

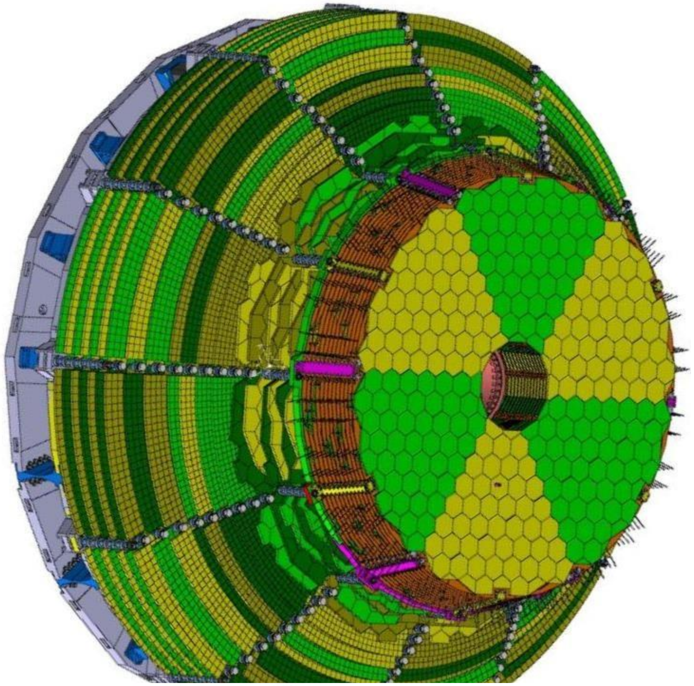
Rafael chip for clock and fast control fanout

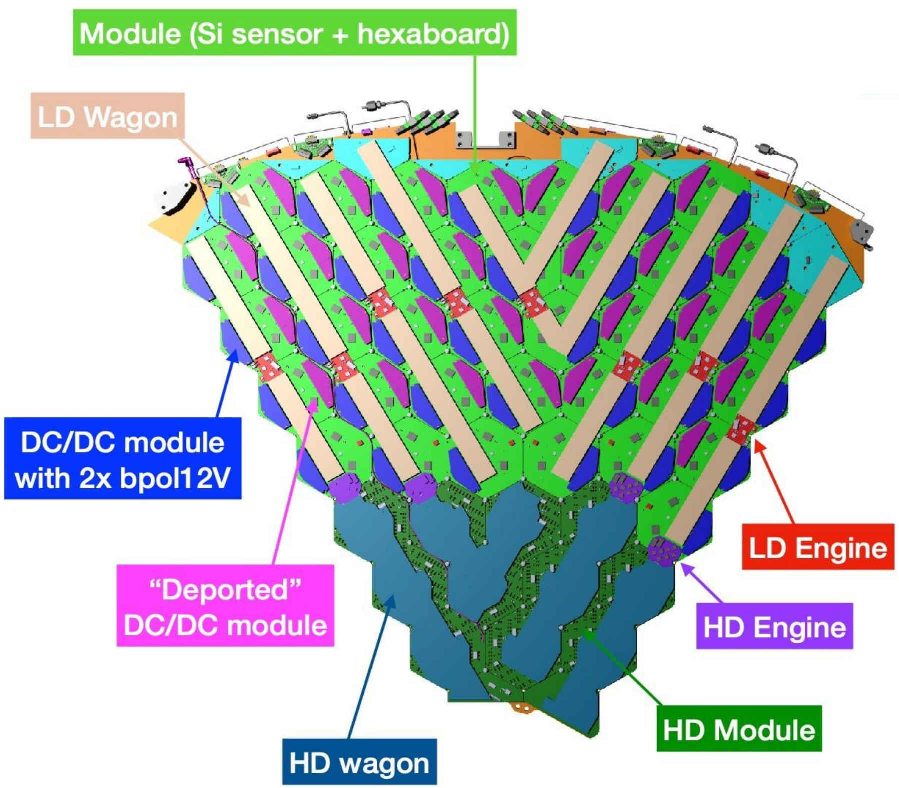
lpGBT : Send and receive data/clock/control signals

VTRx+ : Optoelectronics transmission

Modular implementation

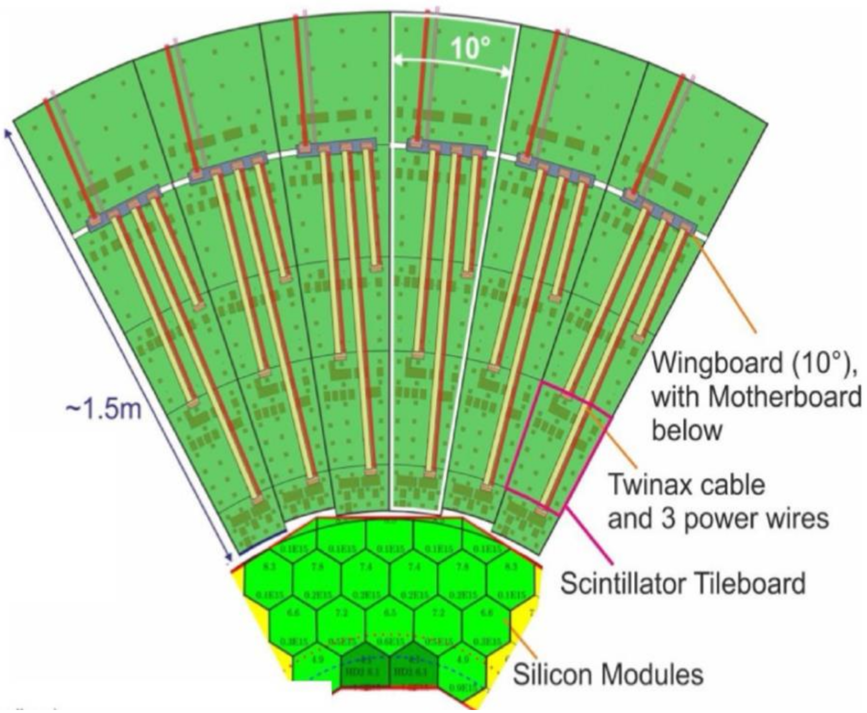
- Cassettes are collections of trains mounted on copper cooling plates
- Silicon only trains in electromagnetic section
- Mixed (silicon and scintillator) trains in hadronic section
- Each layer is different!
  - Occupancies vary greatly within and between layers



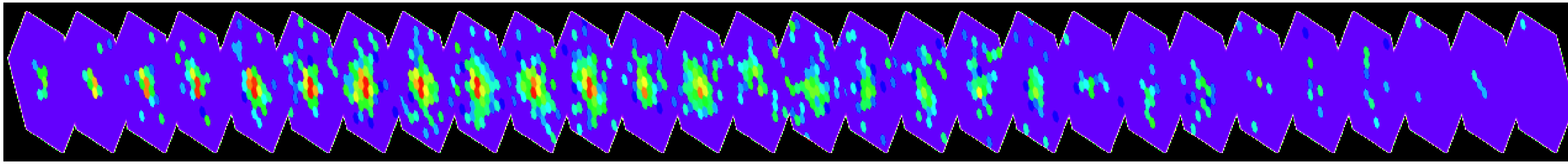


LOW

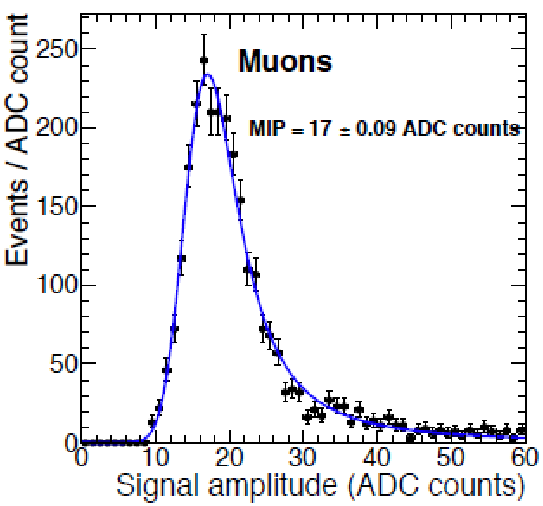
HIGH



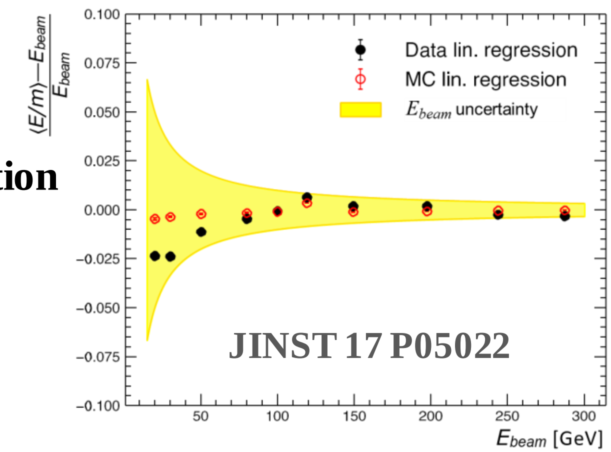
Performance : CERN beam test in 2016-2018 for the validation

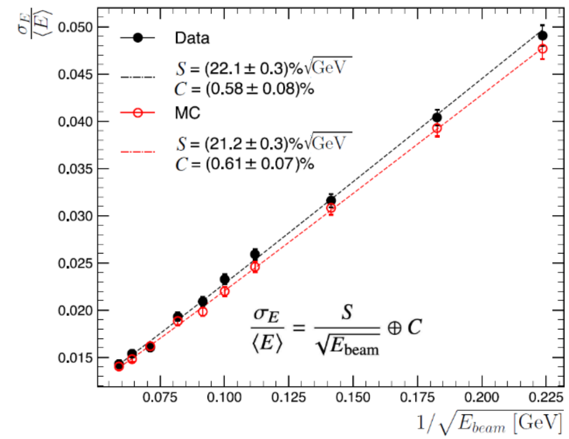


- **6” modules with different depth configuration to demonstrate**
  - **MIP calibration**
  - **EM + HAD Shower reconstruction**
  - **Time tagging of core showers (meeting target 16ps)**

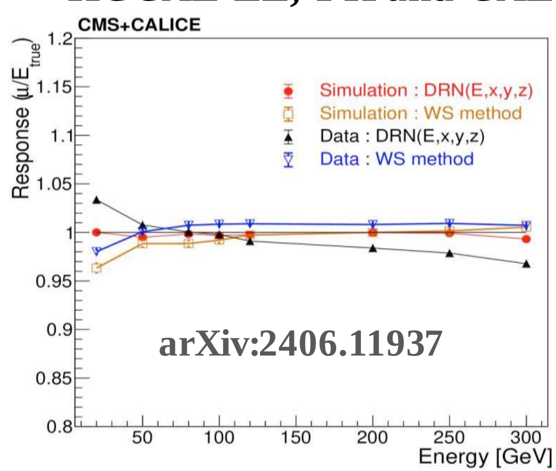


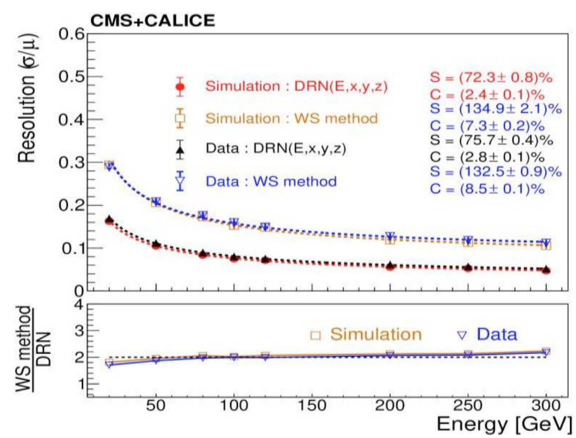
ECAL Performance with e+ beam in 2018





HGCAL-EE, FH and CALICE AHCAL with π beam in 2018

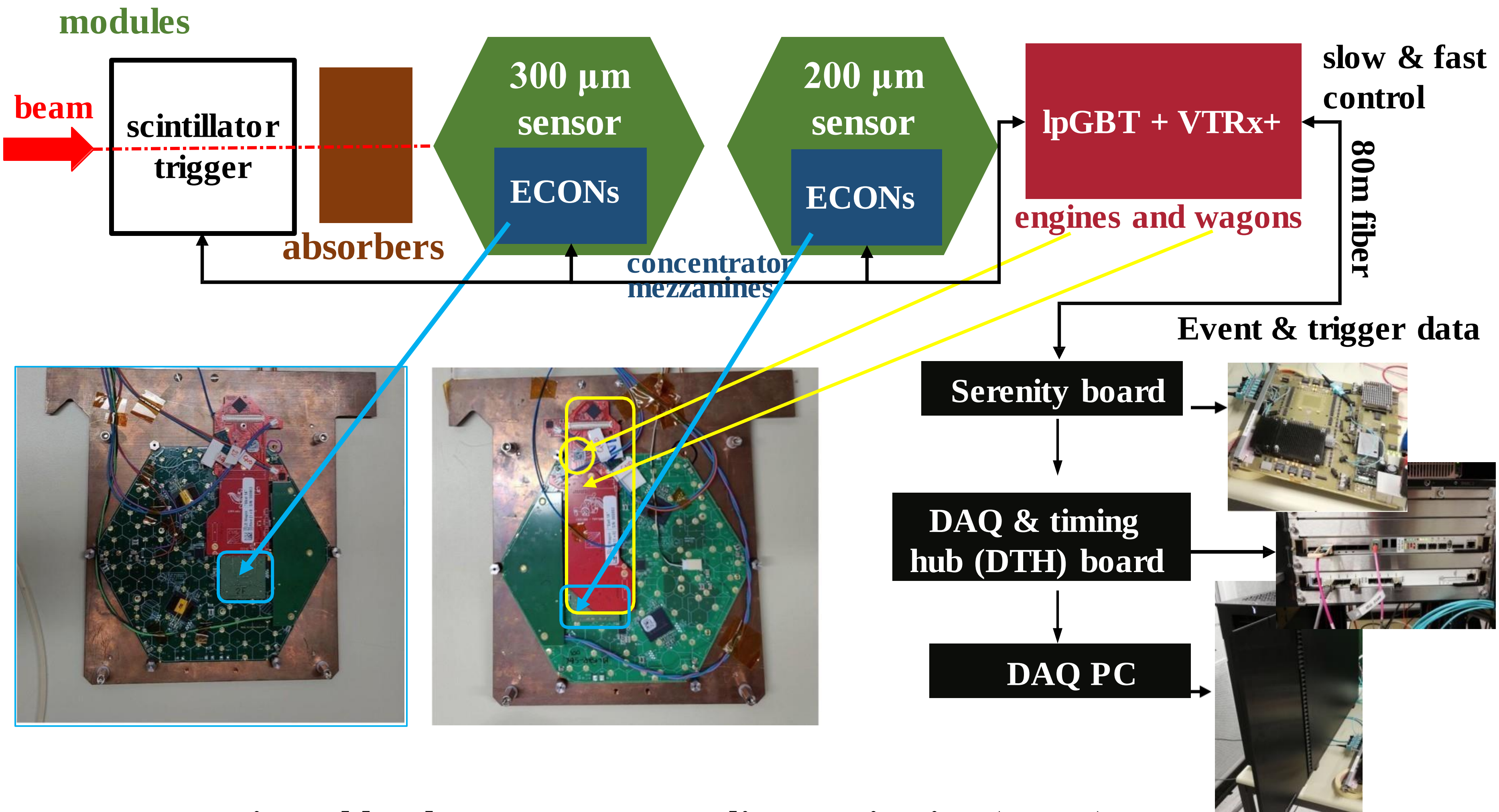




Excellent agreement in Data/MC

Test of the full electronics chain : 2023 TB setup

- The full electronics chain is assembled, from ECON-D / ECON-T to lpGBT to VTRx+, and to back-end.
- Two modules are tested: both full LD modules, one with 300 µm sensor, the other 200 µm.

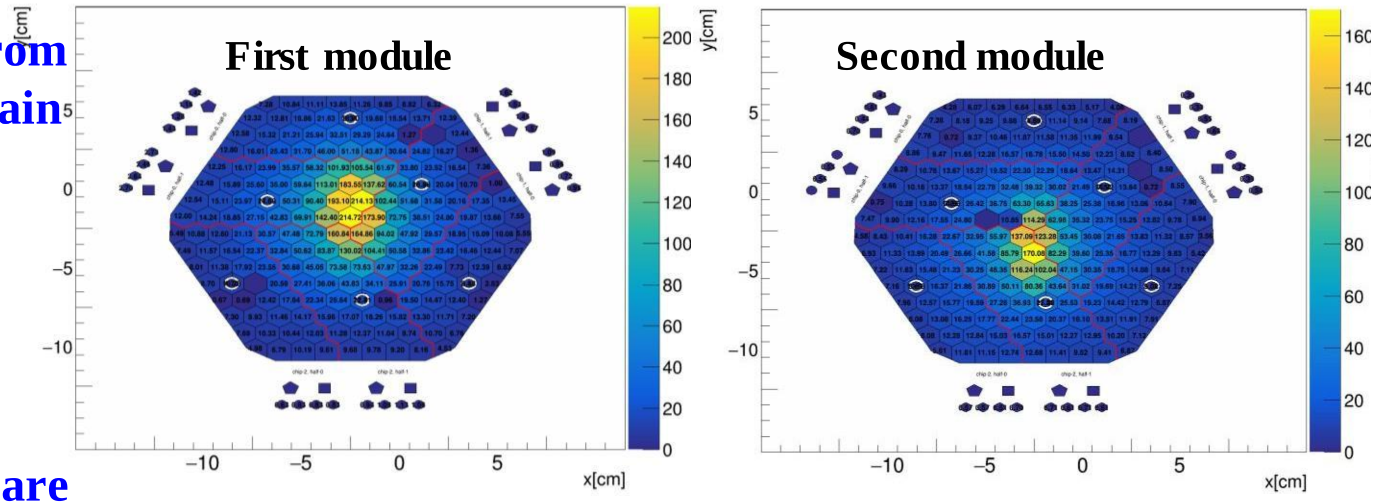


- System monitored by the CMS Data Quality Monitoring (DQM) system.

Test of the full electronics chain: first results

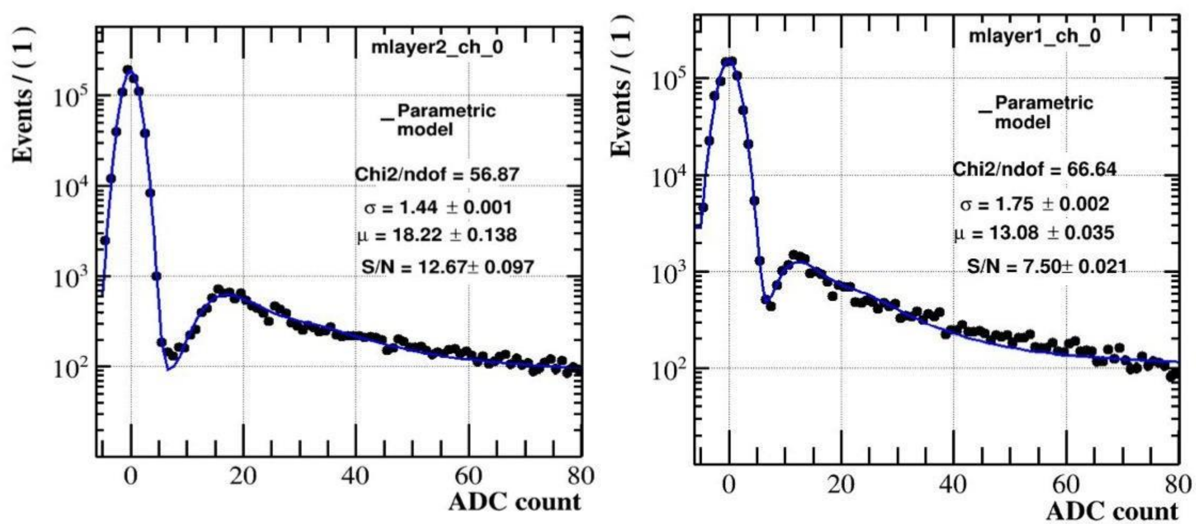
- **Successful readout from the full electronics chain**
  - **Beam spot from a electron run**

ADC std from a electron run @CMSDQM



- **Similar MIP studies are performed with the long overnight muon beam runs.**

ADC count with MIPS from a muon run



- **Averaged S/N:**
  - **12.5 for 300 μm sensor (single module test: 12.8; expectation: 12.1)**
  - **8.1 for 200 μm sensor (single module test: 8.5; expectation: 6.6)**

Good S/N and compatible with single module test!

Conclusion & Outlook

- **HGCAL will be the first large scale calorimeter with Silicon and SiPM-on-tile technologies providing unprecedented granularity and time resolution.**
- **Designs are now becoming reality**
- **Concept and the performance of the HGCAL are proven through the several Test beam results**
- **Installation of the detector is planned for LS3**