An Overview of the CMS High Granularity Calorimeter

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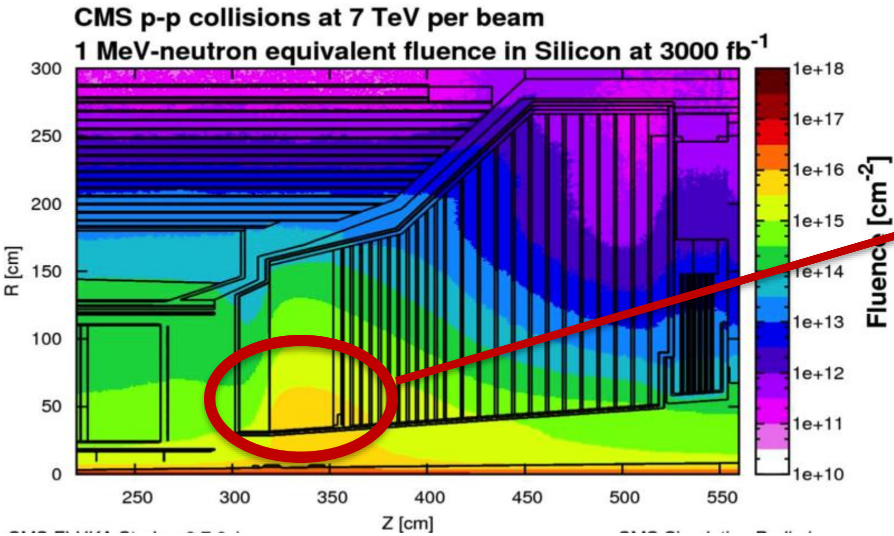
Asst. Prof. Bora Akgün – Boğaziçi University
on behalf of the CMS Collaboration

What is on the menu?

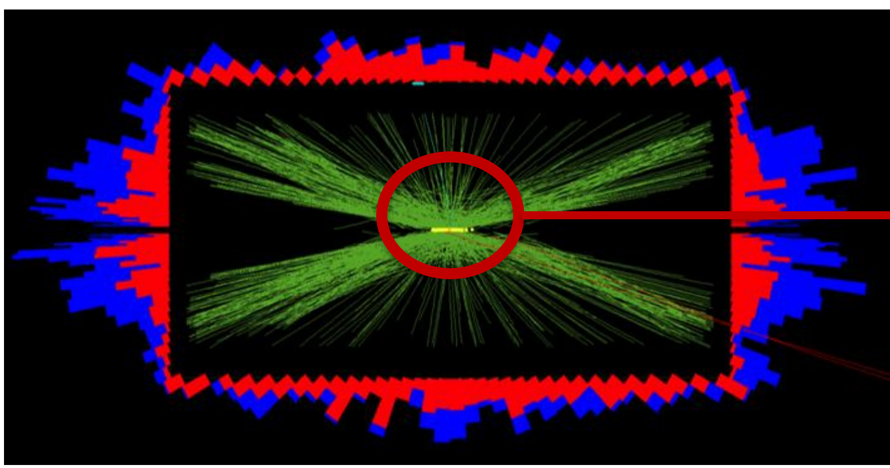
- Motivation for upgrading endcap calorimeters
- The choice of high granularity
- The CMS HGCAL design and prototyping
- System Validation and Beam Tests
- Status and production phase

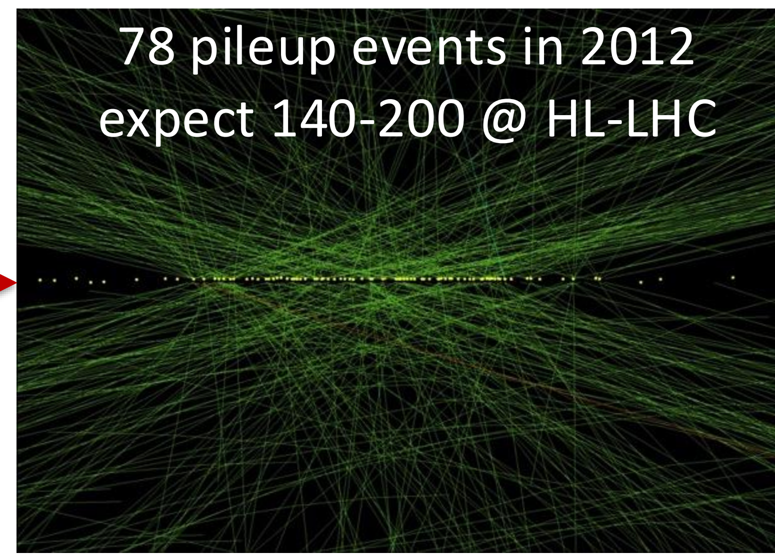
Future @ CERN : HL-LHC

CMS @ HL-LHC

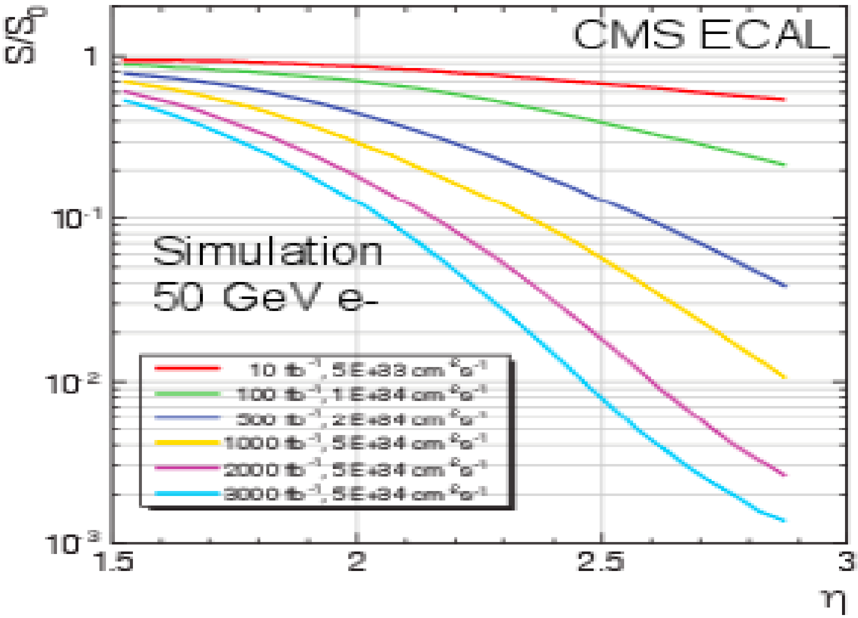


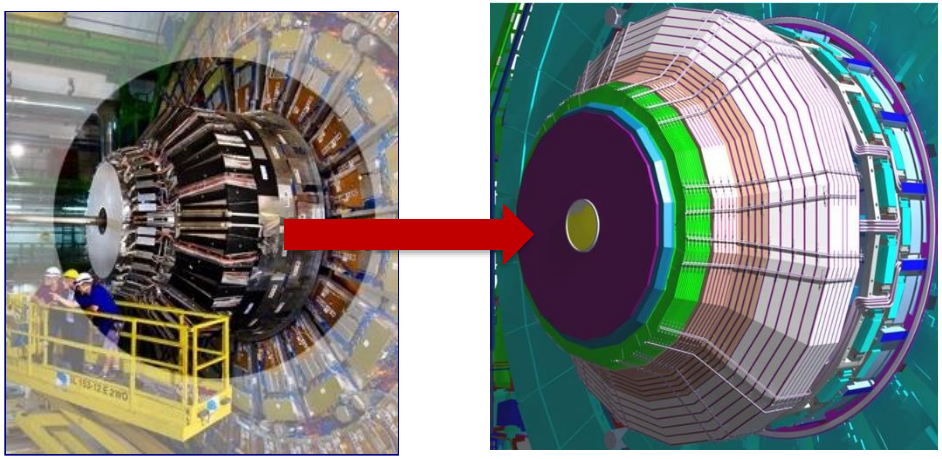
~**10^{16}** 1MeV n_{eq} cm^{-2} @ 3000 fb^{-1} in forward calorimeters w/ **pileup ~200** and up to **2 MGy** absorbed dose

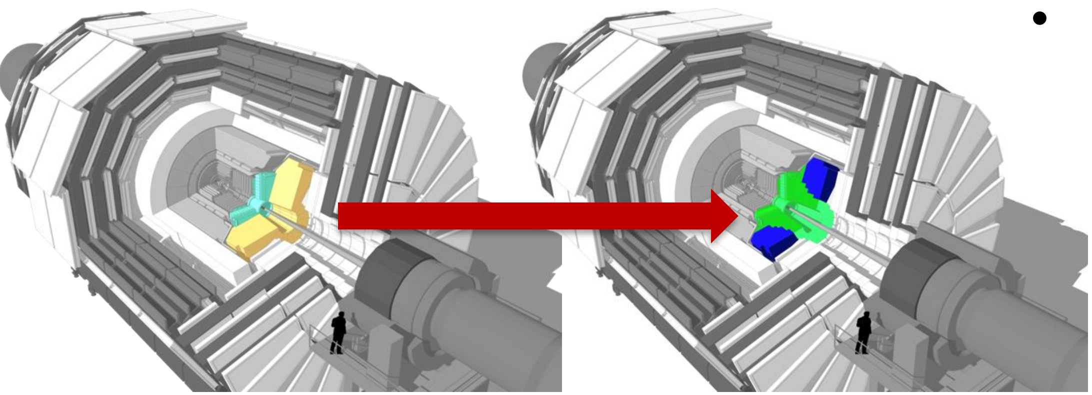




CMS High Granularity Calorimeter







- "Upgrade" is an understatement
- Completely replaces the existing endcap Preshower + ECAL + HCAL
- The detector concept : Sampling calorimeter of many layers. Will measure precisely
  - Energy
  - Spatial precision in 3D
  - Time

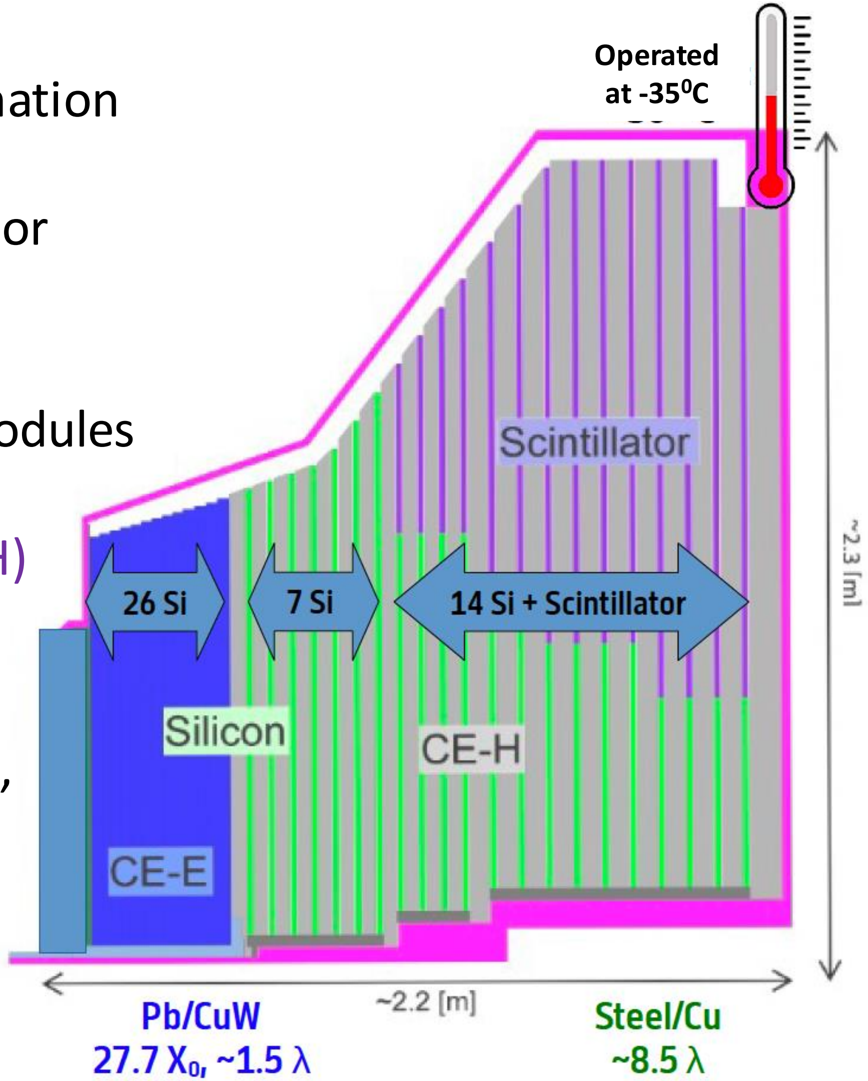
The HGCAL Project

5D imaging calorimeter
- 3D spatial granularity, energy, timing information
- HGCAL covers $1.5 < \eta < 3.0$
- Two separated sections in one single detector

Active Materials
- Silicon Sensors (CE-E and CE-H)
  - ~620 m^2 Si sensors in ~27000 silicon modules
  - ~6M Si Channels (0.5 or 1cm^2 cell size)
- Plastic Scintillators with SiPM readout (CE-H)
  - 240k scintillator tiles (~370 m^2)

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

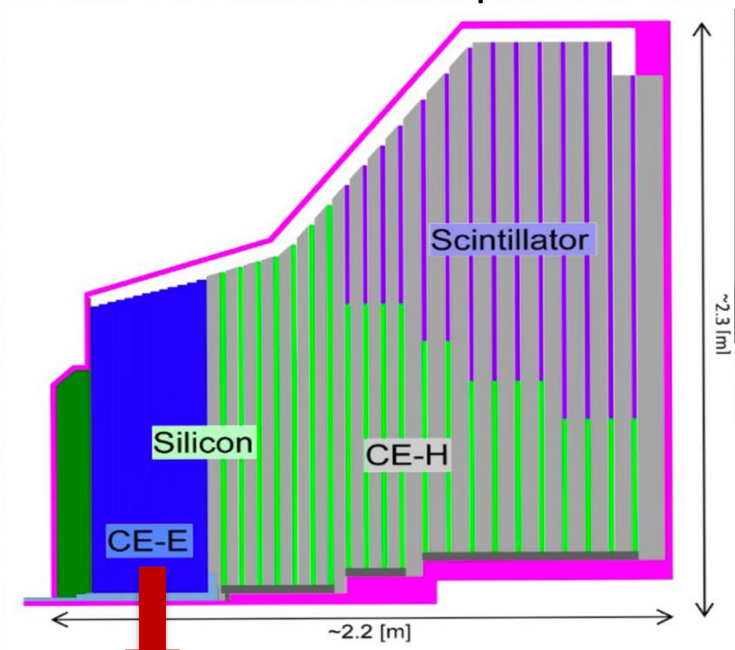
Power Consumption
- ~125kW per endcap



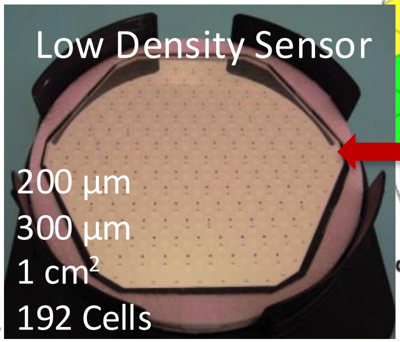
Active Material – Silicon

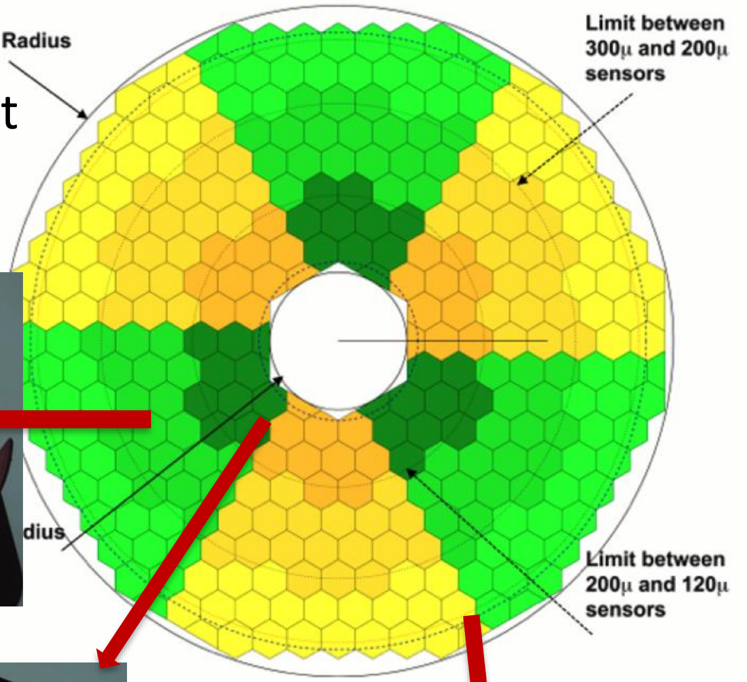
Silicon Sensors

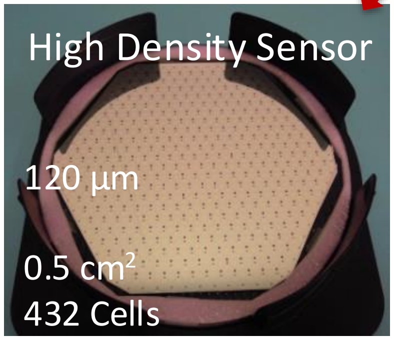
- 8″ hexagonal wafers
- Different cell sizes
  - Different em/hadronic shower development
- Partial design
  - Circular endcap from hexagons



Radiation level comparable to pixel tracker

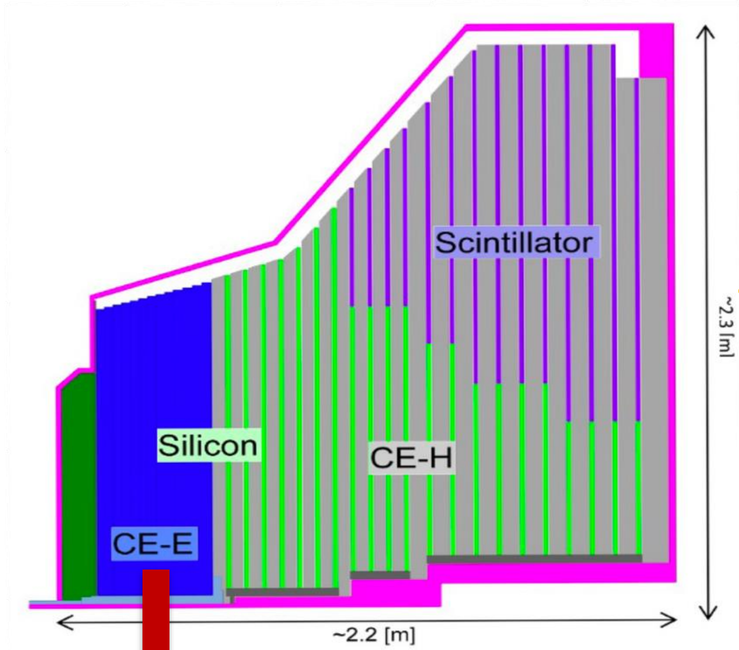






Active Material – Silicon

Silicon Modules



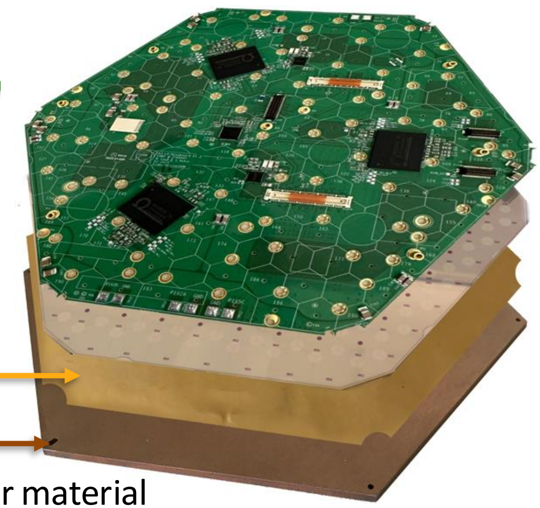
Radiation level comparable to pixel tracker

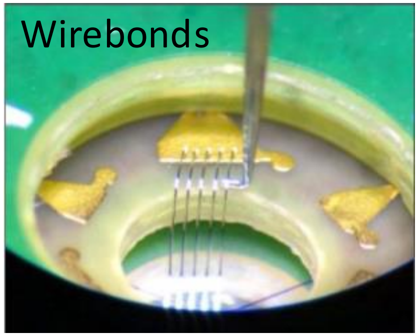
Hexaboard PCB
Hosting the readout chips

Silicon Sensor

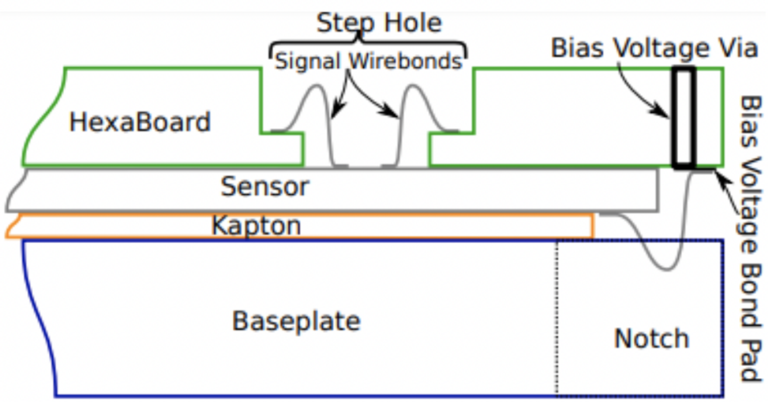
Metalized Kapton Sheet

CuW BasePlate*
Rigidity, contributes to the absorber material



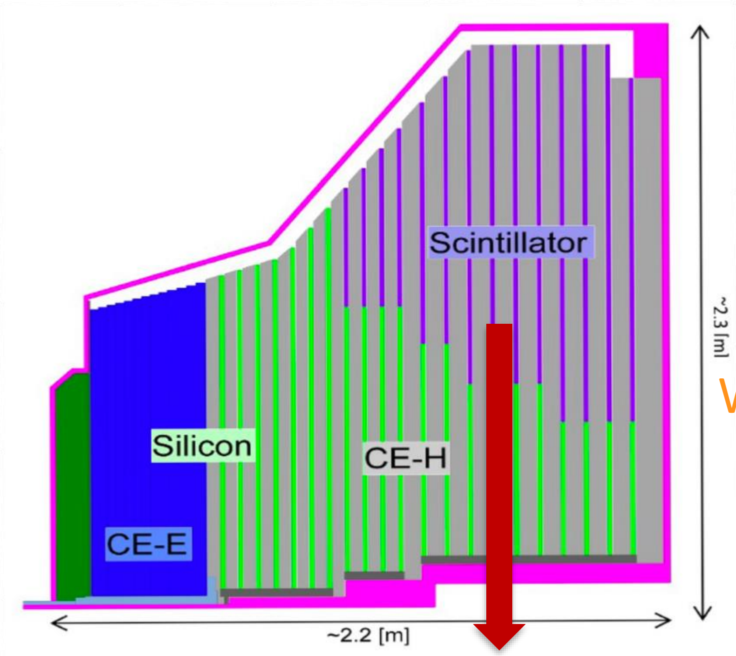


*PCB baseplate in the hadronic sector



Active Material – Scintillator

SiPM-on-tile

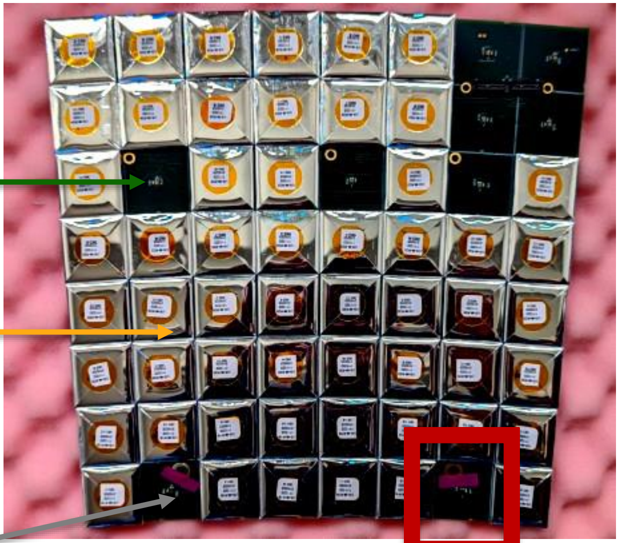


Lower radiation level than silicon sector

Cell sizes from 4 to 30 cm^2

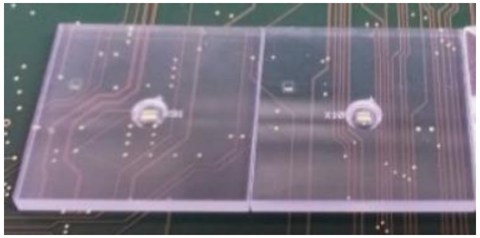
Tileboard PCB
Hosting the readout chips

Wrapped Scintillating Tile
Reflective foil

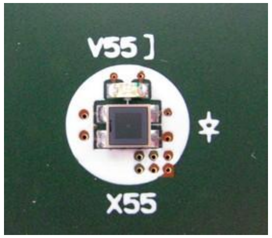


Silicon Photo Multiplier (SiPM)
Calibration with LED

Scintillator

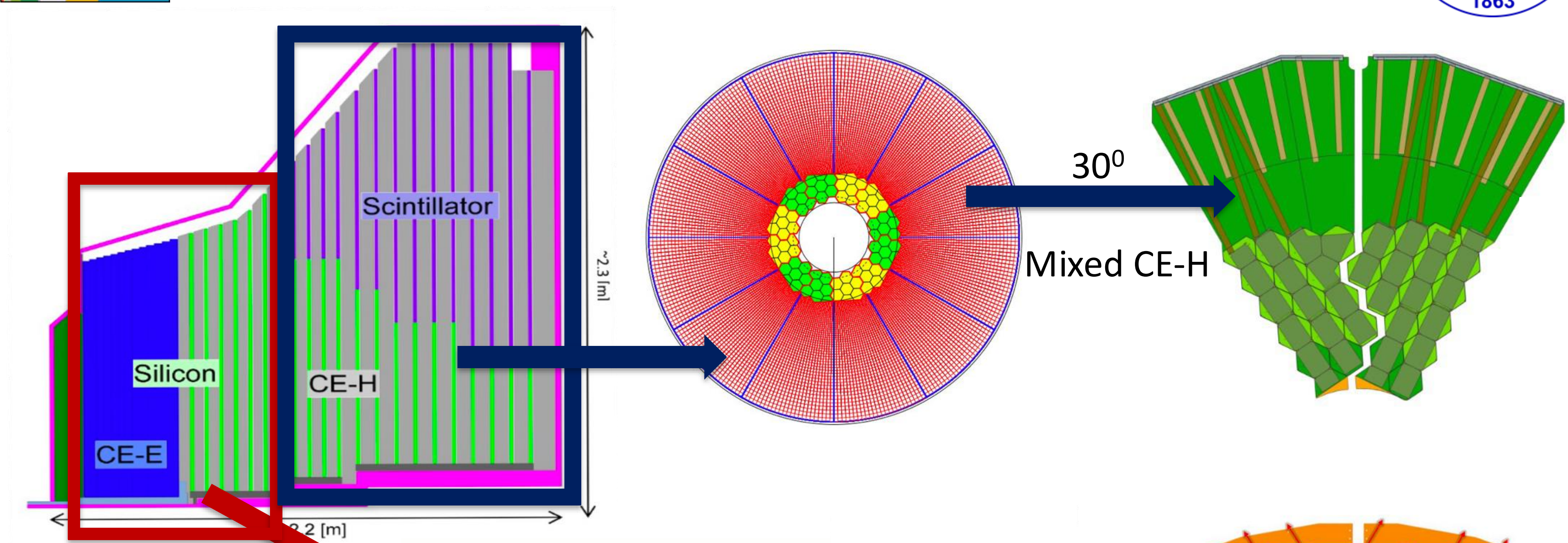


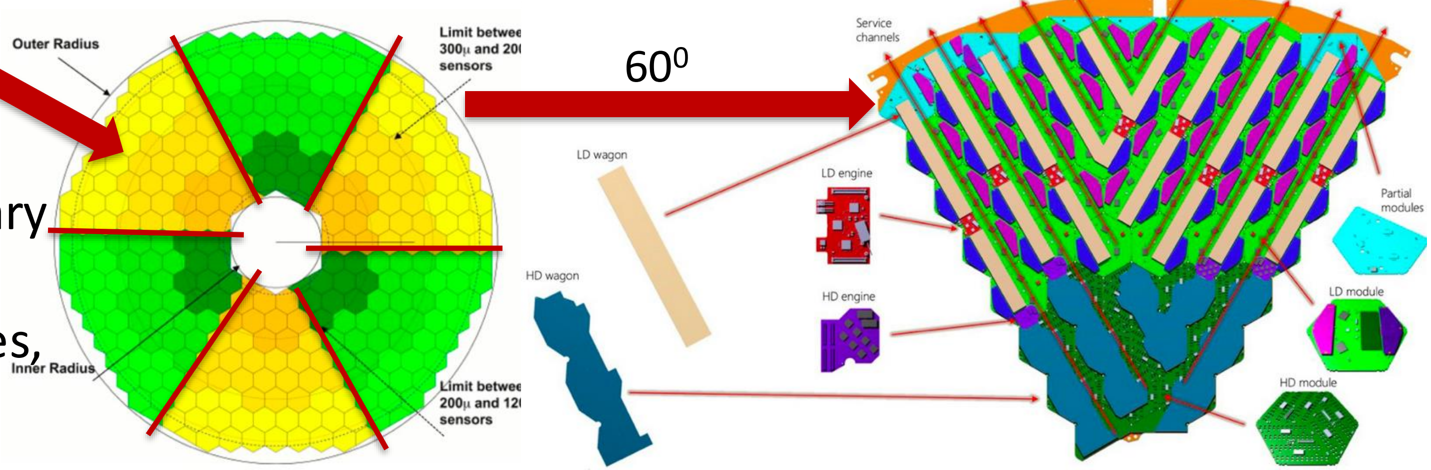
SiPM



Integration

Cassettes

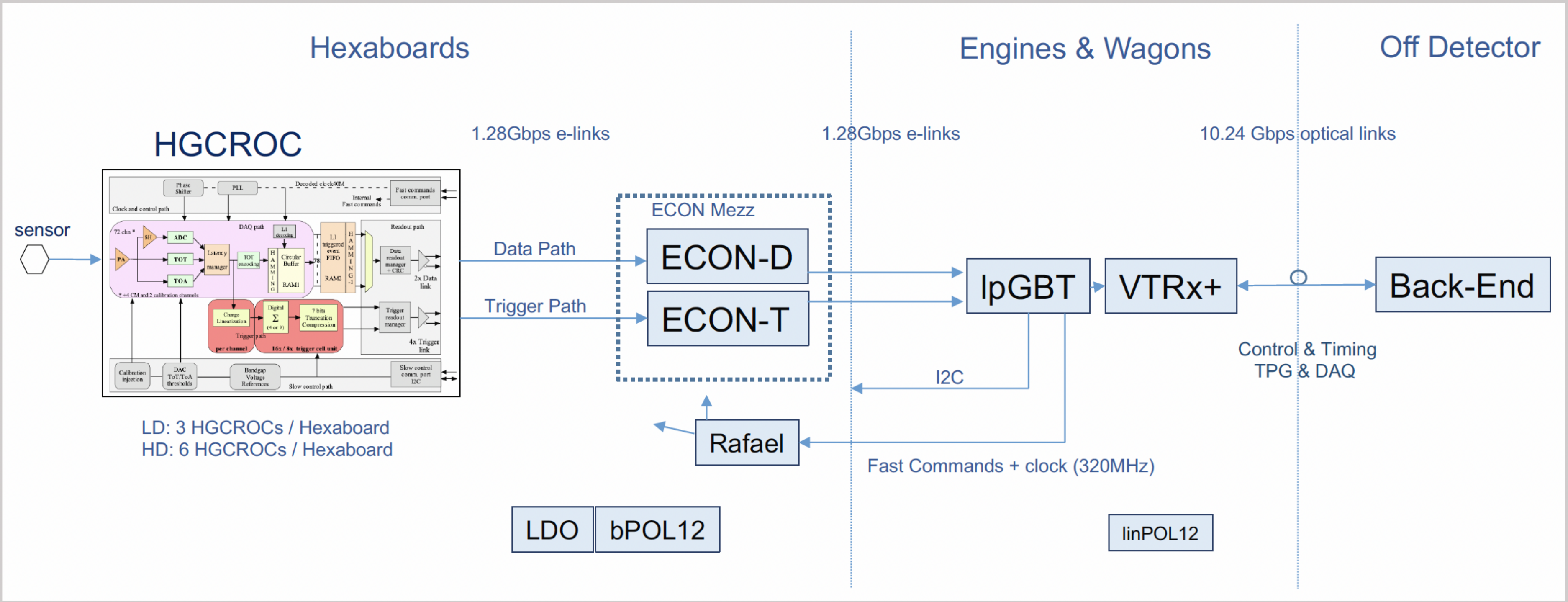




- Integration of modules and auxiliary components
  - Wagons/Engines, services

HGCAL Electronics

Main Components and Signal Flow



ASIC developments: HGCROC, ECON-T/D, LDO, Rafael

Generic components: lpGBT, VTRx+, DCDCs

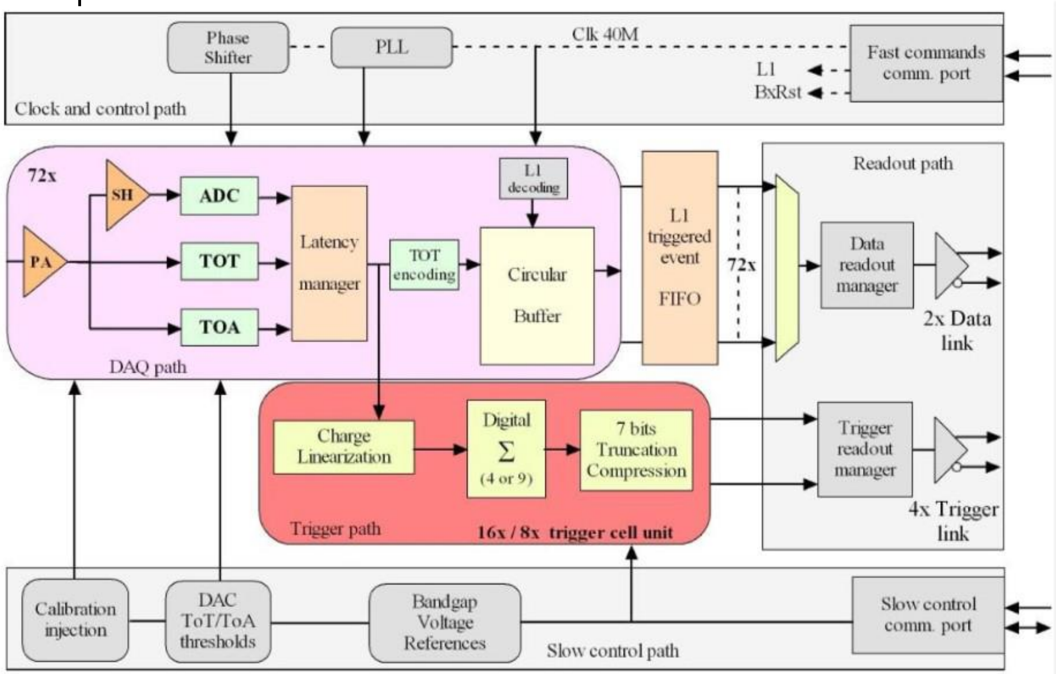
These are hosted on pcbs: Hexaboards, Engines/Wagons (CE-E/H) and Tileboards (CE-H)

The figure is for Si-Region. The scintillator region is very similar. It uses a different version of HGCROC, the SCA for Slow Control.

HGCAL Electronics

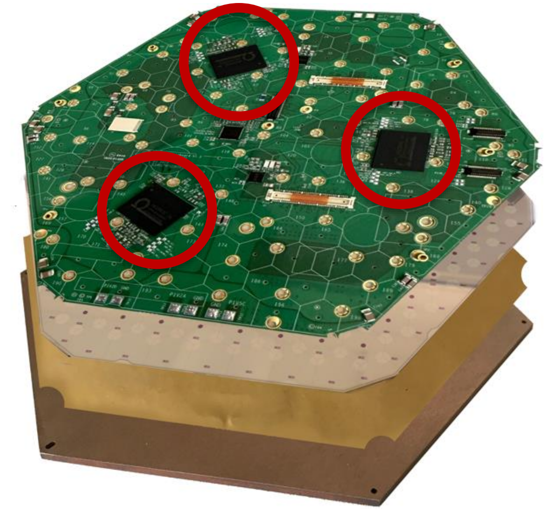
HGCROC

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

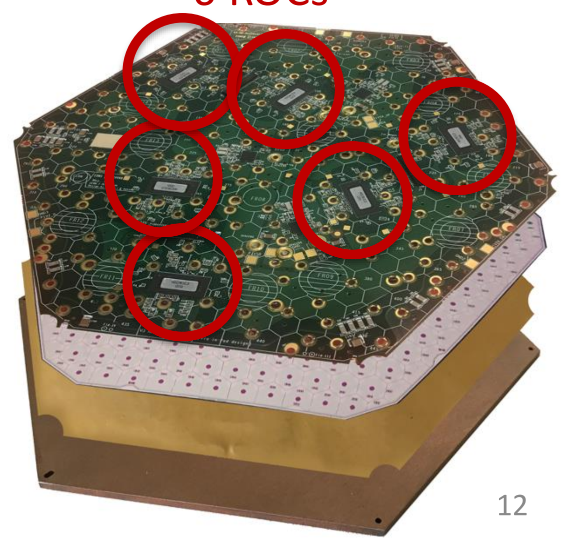


- Front-end ASIC
- Charge and time measurements
- Similar design for Si and Scintillator with adaptations
- Two halves chip with (up to) 78 channels
- Dynamic Range: ~0.2fC to 10pC

Low Density (LD)
3 ROCs



High Density (HD)
6 ROCs



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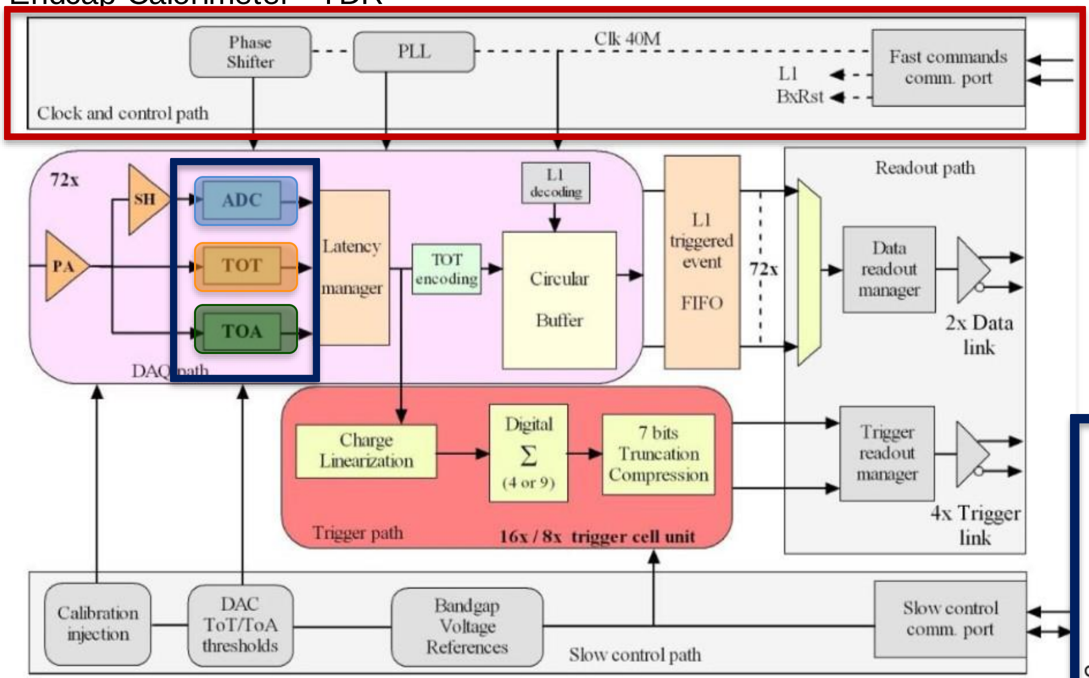
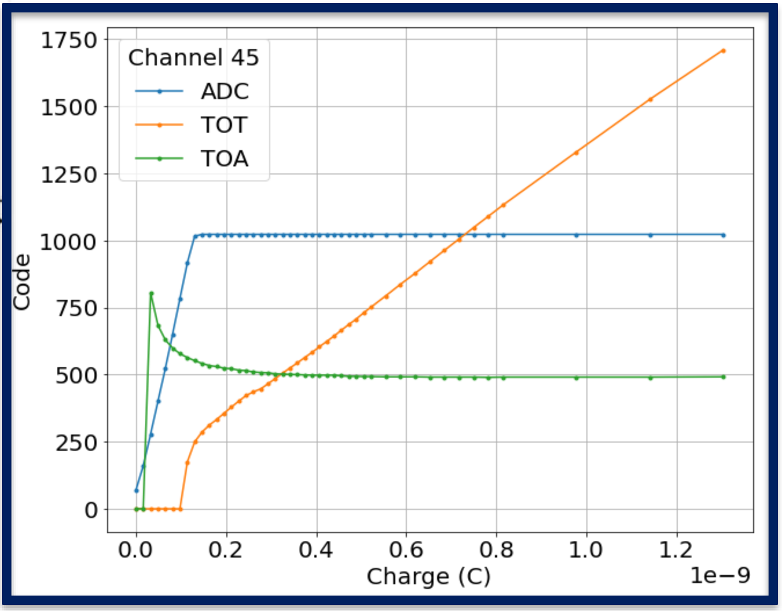
HGCROC

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



Synchronous fast control @ 320 MHz

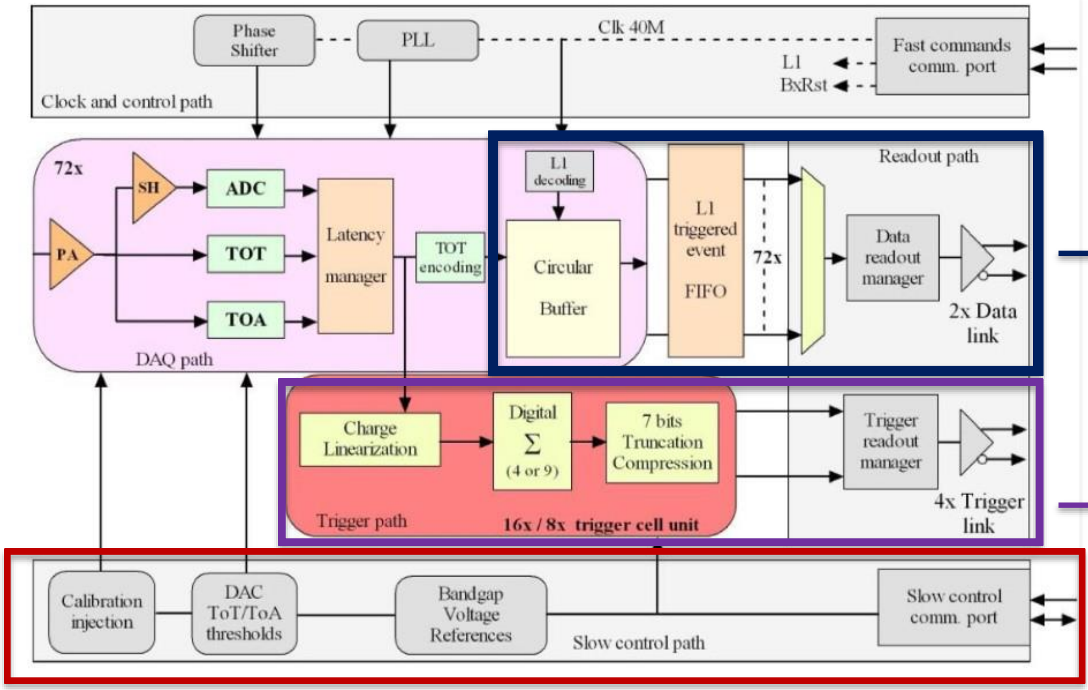


- Charge/Energy
  - ADC: 10-bit → MIPs
  - TOT: 12-bit → showers
- Time:
  - TOA: 10-bit → with 25 ps LSB (full range 25 ns)

HGCAL Electronics

HGCROC

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



Asynchronous slow control I²C

DAQ Path

Data packets after LV1A

LV1A latency up to 12.5 μs

2 outputs @ 1.28 Gbps

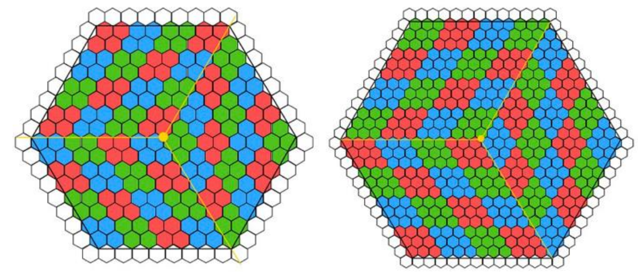
Trigger Path

Trigger primitives @ 40 MHz

Max latency of 36 bx

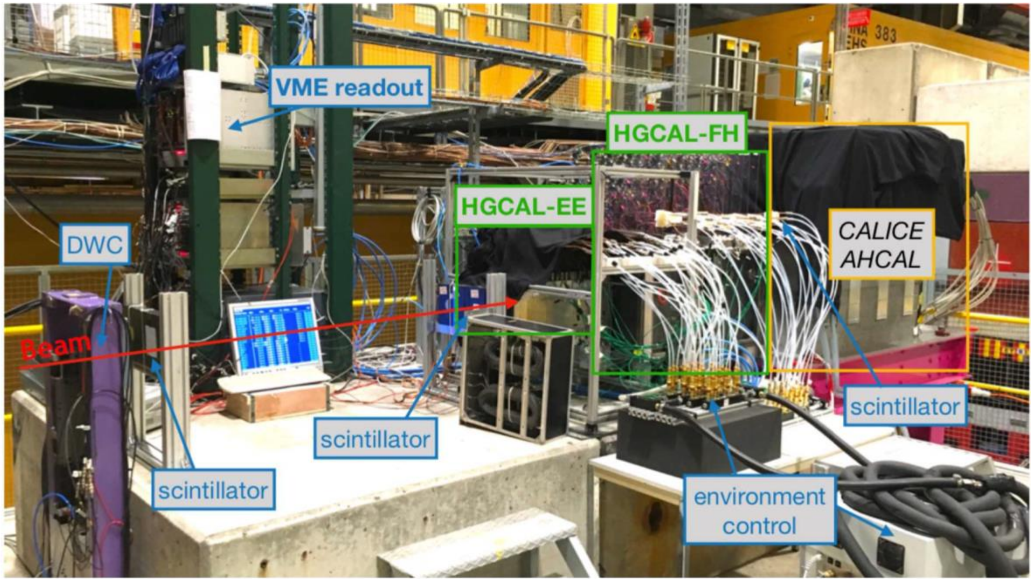
4 outputs @ 1.28 Gbps

Sum of 4/9 channels



Beam Tests

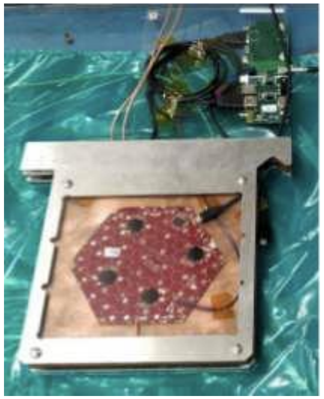
2018 Setup

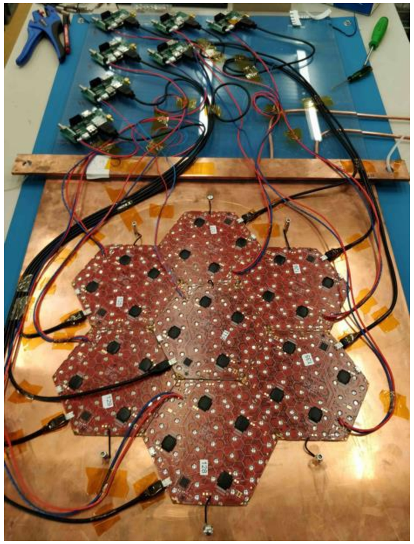


Carried out at the H2 beamline branching from SPS (Super Proton Synchrotron, CERN)

- $e^{\pm}$, π, μ beam of 20 to 300 GeV energy
- Full GEANT4 simulation

- Electromagnetic section (HGCAL-EE)
  - Stack of 28 silicon modules
  - Double sided cassettes
  - Pb/Cu absorber (+ CuW baseplates)
- Hadronic section (HGCAL-FH)
  - 12 layers of up to 7 silicon modules assemblies
  - Steel absorber (+ Cu cooling/support plates)
  - Single sided cassettes
- Complemented by CALICE AHCAL
  - 39 layers of scintillator/SiPM-on-tile prototype
  - Steel absorber





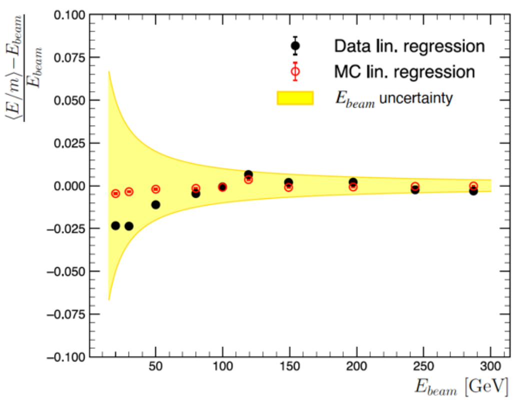
Beam Tests

2018 Results

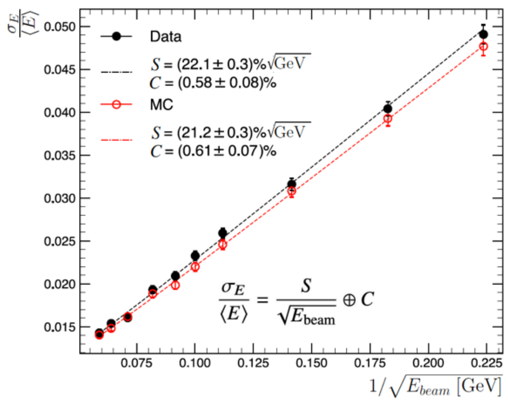
e^+ beam data, reconstructed in HGCAL-EE

[JINST 17 P05022]

Linearity



Energy resolution

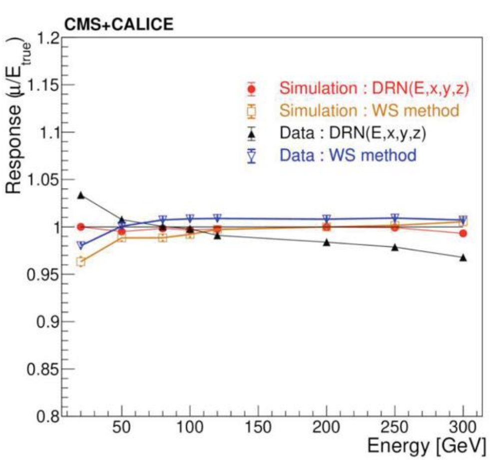


- Energy response linear within ±1.5% above 50 GeV
- Energy resolution within the physics performance target: 0.6% constant term
  - Compatible with performance of the current CMS electromagnetic calorimeter

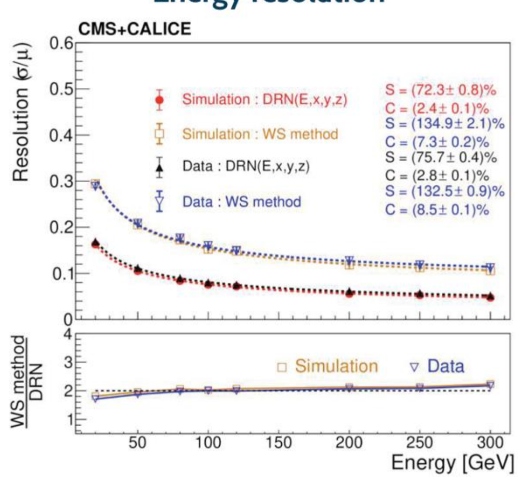
π beam data, reconstructed in HGCAL-EE,-FH and CALICE AHCAL
GNN-based reconstruction (DRN) to fully exploit the high-granularity and account for hadronic showers fluctuations

[arxiv. 2406.11937]

Linearity



Energy resolution

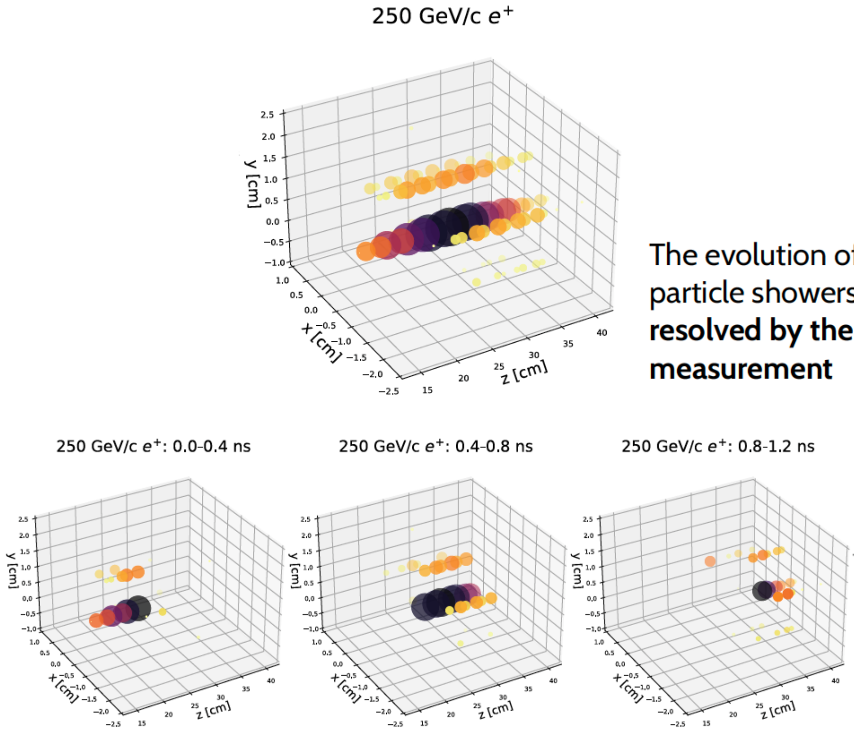


- Energy response linear within few %
- Excellent data/simulation agreement
- DRN method brings a x2 resolution improvement w.r.t. energy-dependent weighted reconstruction (WS)

Beam Tests

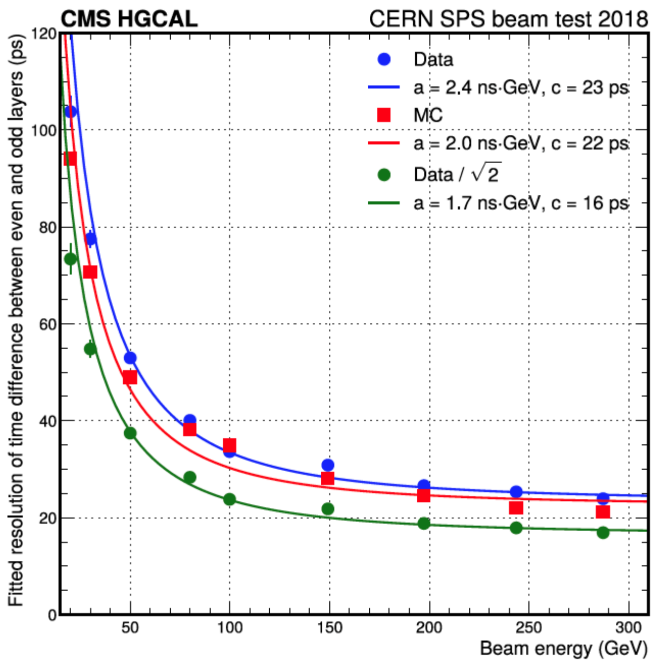
2018 Results

e⁺ beam data, reconstructed in HGCAL-EE



The evolution of real particle showers is **resolved by the timing measurement**

JINST 19 P04015



Resolution using half-showers in even/odd layers scaled by √2 as estimate of the performance with all layers

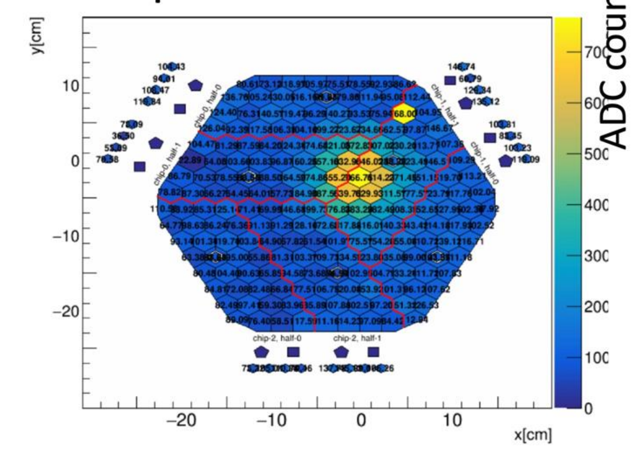
Performance meeting target: 16 ps constant term

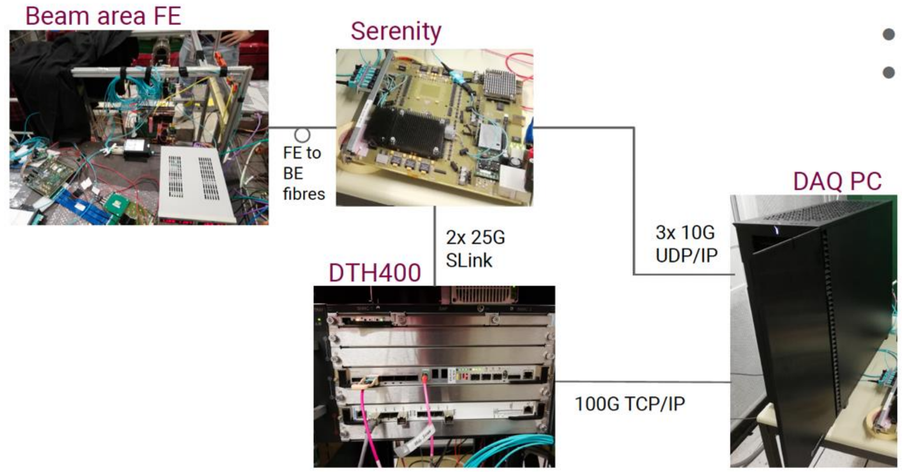
Beam Tests

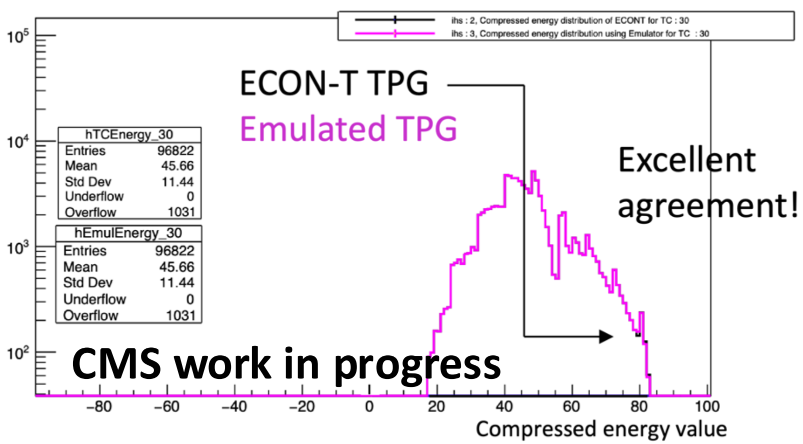
2023: Readout Chain Commissioning

- First test beam with full vertical readout chain in place
- Trigger and DAQ path read out at ~100 kHz
- Synchronization of all FE ASICs and BE FPGAs achieved
- DQM using reconstruction in CMS central software
- ECON-T and ECON-D configuration tests
  - Different trigger primitive algorithms exercised
  - Zero suppression data-taking mode
  - Pass through mode

Beam spot in LD full module

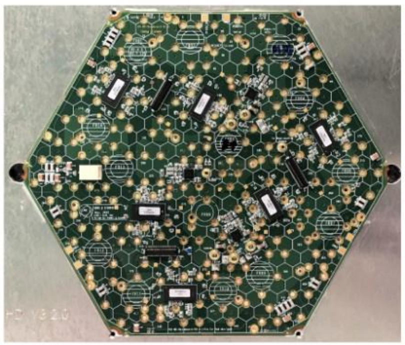




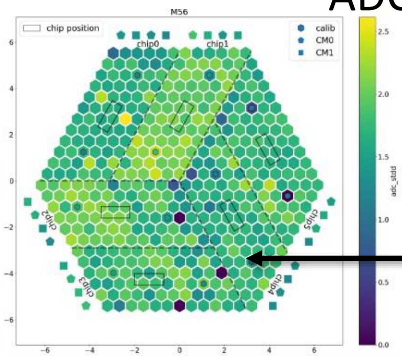


System Validation

Silicon and SiPM-on-tile modules



ADC



Work in progress

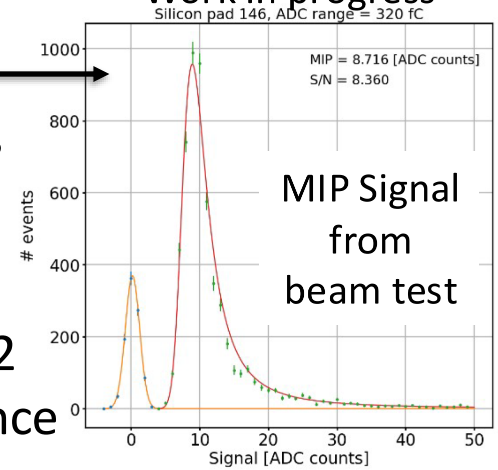
LD module

- Noise, S/N studies in beam tests

First HD module assembled Dec. 2022

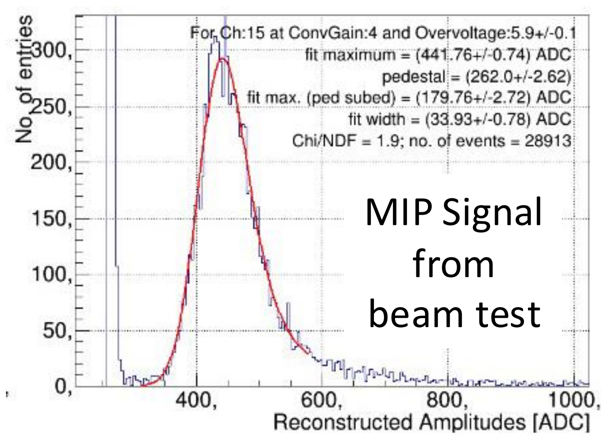
- Similar performance to LD modules

Work in progress

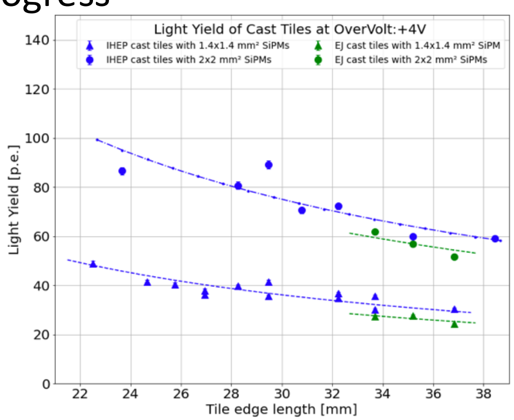


SiPM-on-tile

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



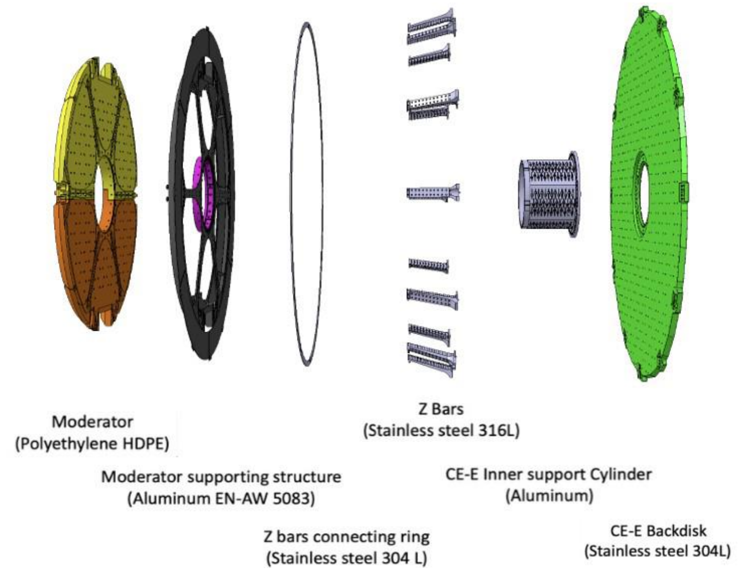
Work in progress



HGCAL Mechanics

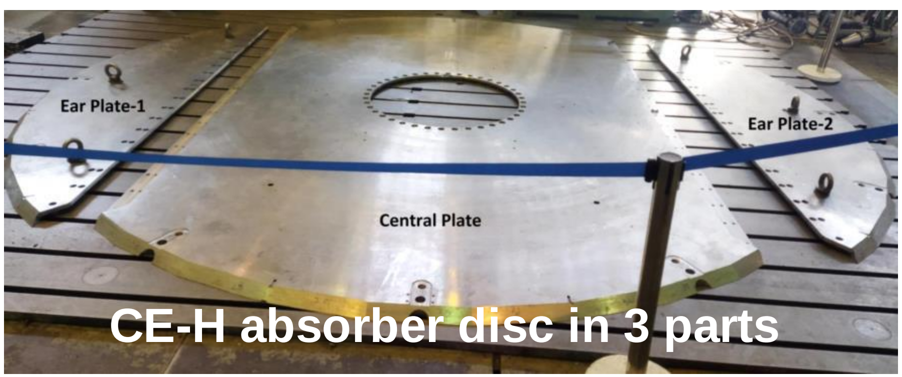
CE-E Mechanics

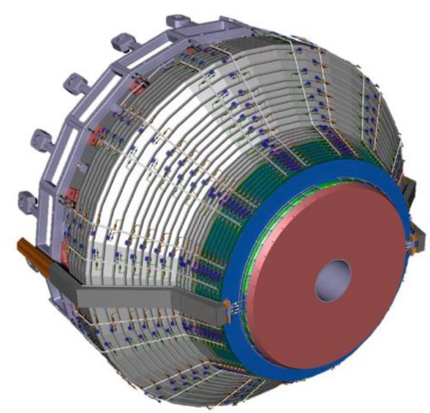
- Dense layering of cassettes, lead sheets, stacked on a stainless-steel back-plate
- In advanced design stage
  - To be made by CERN and industrial partners



CE-H Mechanics

- Layered stainless-steel structure
- Thick absorber plates (42-95 mm), each weighing up to 10 tones.



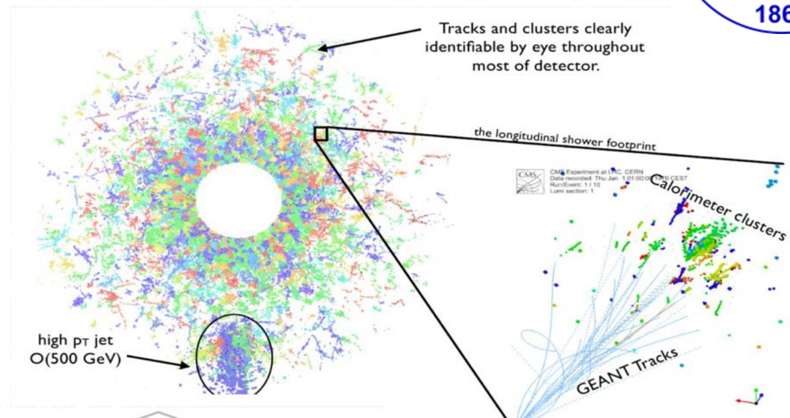


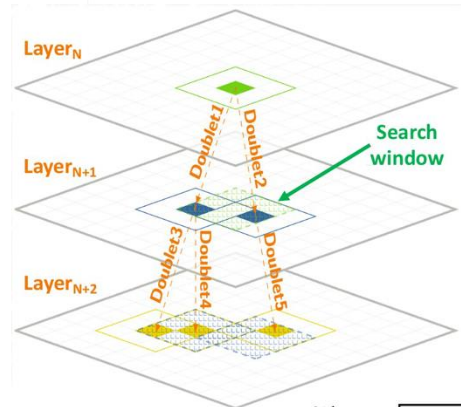
Simulation and Reconstruction

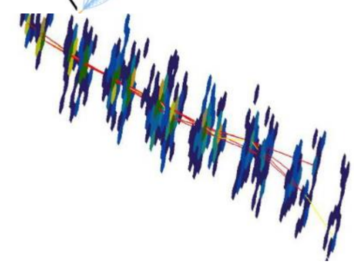
Detector Simulation
- Geometry close to final design
- Sensor/Electronics provide full end-to-end simulation
- Reconstruction with realistic end-of-life conditions

Reconstruction with CLUE and TICL
- Reduces the number of hit objects by building clusters of energy
- Can be parallelized and runs on GPUs
- Tested with beam-test data
- Iterative clustering
- RecHits → LayerClusters → Tracksters

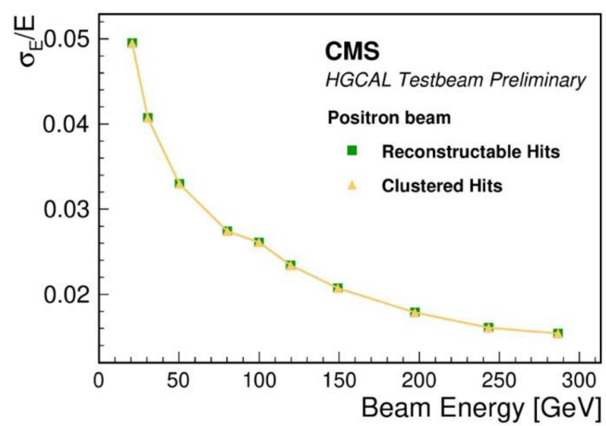
End-to-end Machine Learning
- Noise filter
- GravNet graph neutral network performs clustering on cleaned data



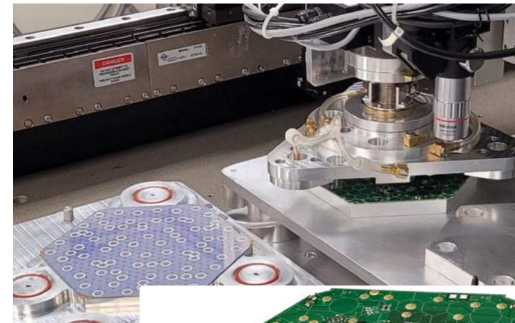


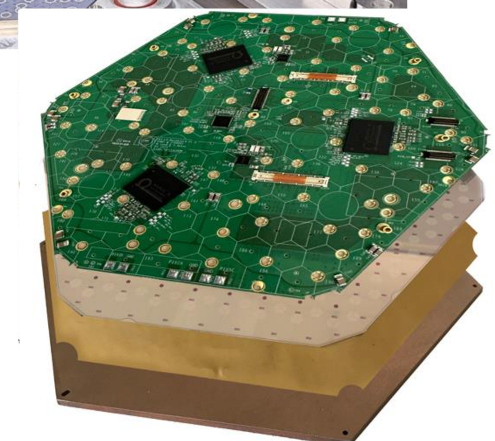


Trackster connecting several 2D LayerClusters



Mass Production





Silicon Modules
- ~27000 silicon modules
- Built and tested in 5 Module Assembly Centers (3 in US, 1 in Taiwan, 1 in China)

SiPM-on-tile modules
- 240k SiPMs/tiles
- ~4000 Tilemodules
- Built and tested in 2 Tilemodule Assembly Centers (1 in US, 1 in Germany)

Outlook

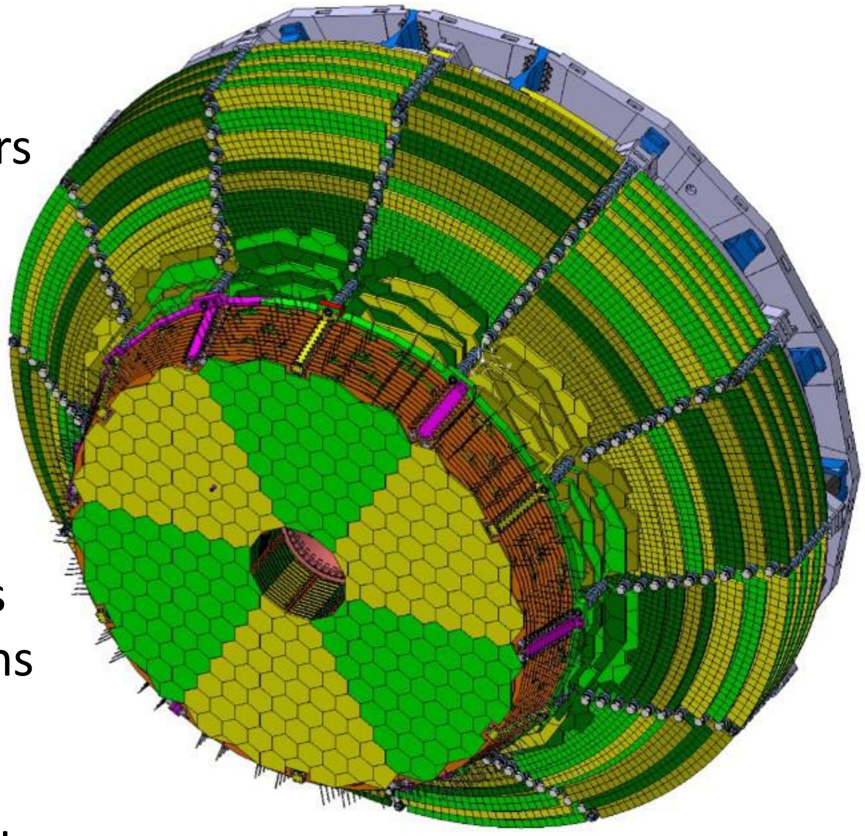
Cutting-edge detector design

- High spatial granularity detector
- Precise timing for showers
- Energy measurements from MIP to showers

>6M silicon & >200k scintillator channels in harsh radiation environment

Important progress and ongoing developments

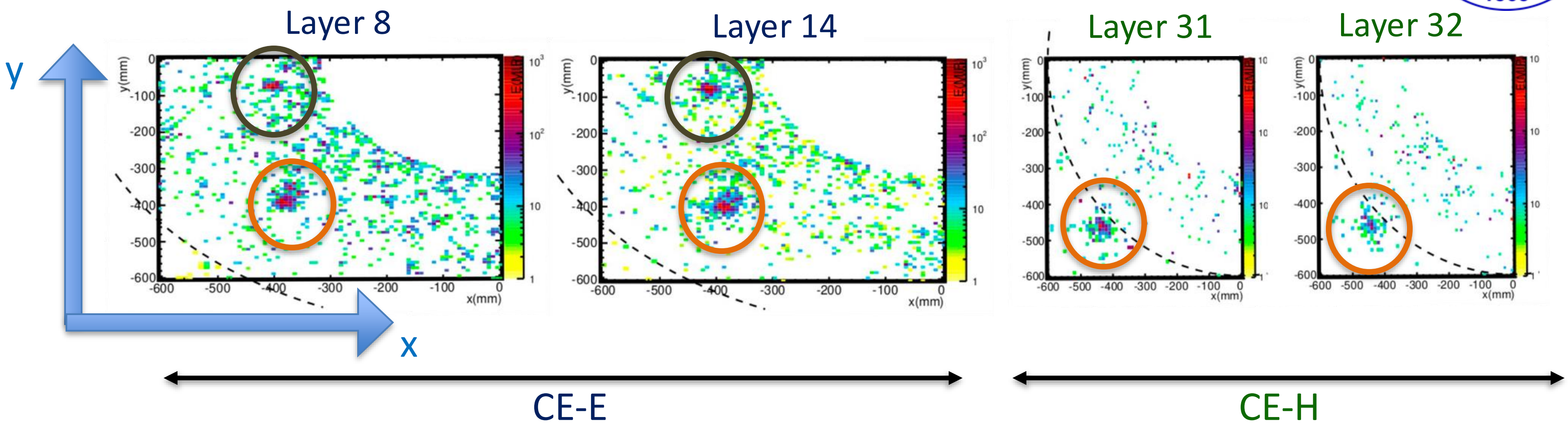
- System performance in beam and lab tests
  - Results in agreement with expectations
  - Full readout chain with all ASICs and final Back-End
- Ready for mass production of modules and cassettes in 2025



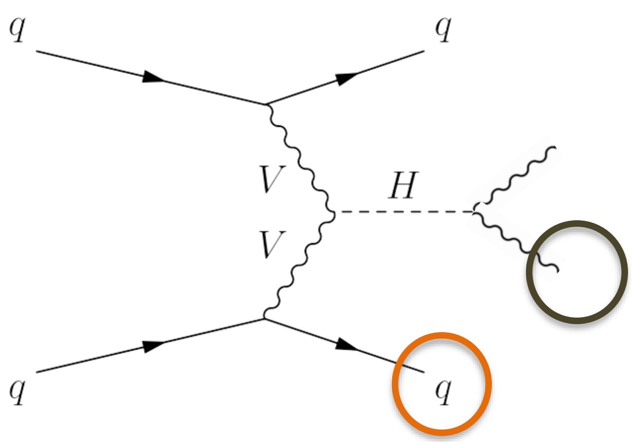
Backup

HGCAL: 5D Imaging Calorimeter

Forward jet signatures from VBF



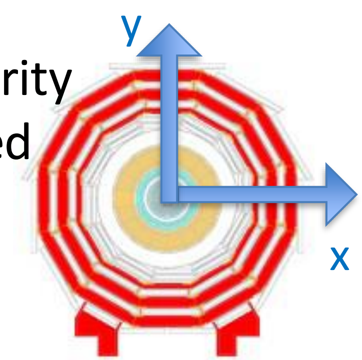
VBF H → $\gamma\gamma$ + 200 PU



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

Spatial 3D Granularity

- High lateral and longitudinal granularity
- Two showers can be clearly separated

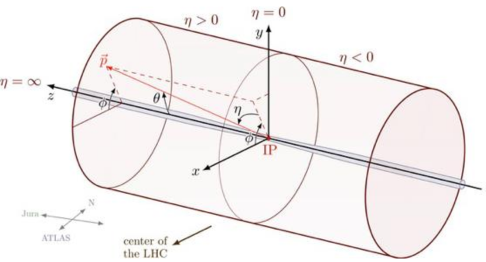


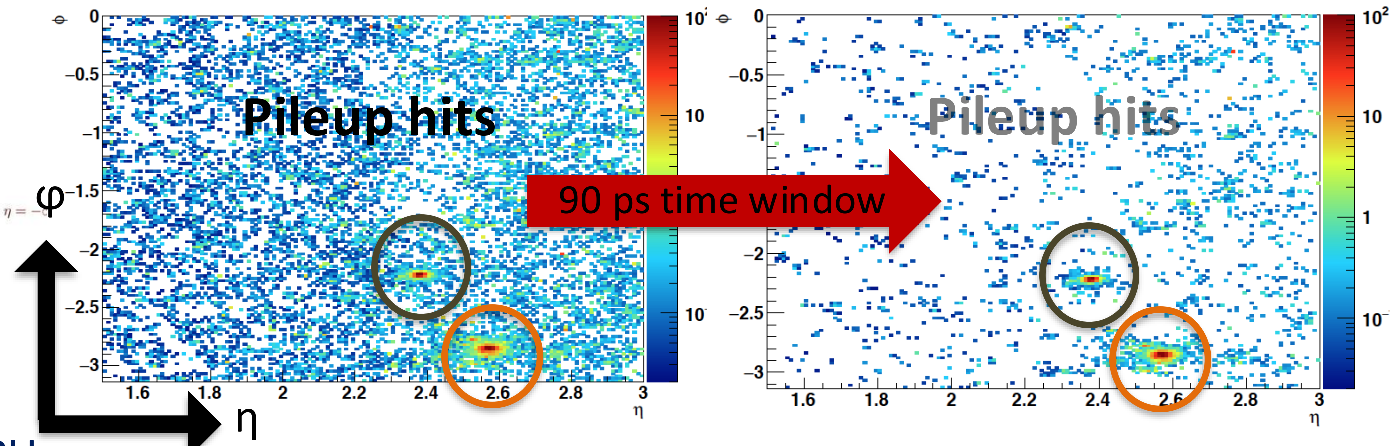
Energy Measurements

- Large dynamic range
- From MIP calibration to showers

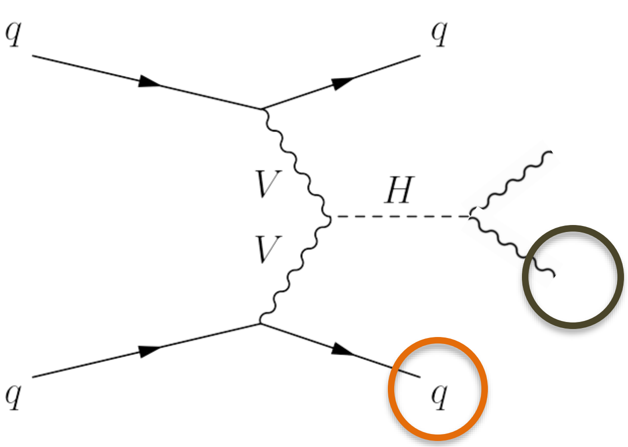
HGCAL: 5D Imaging Calorimeter

Forward jet signatures from VBF





VBF H → $\gamma\gamma$ + 200 PU



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

Plots show cells with Q > 12fC
(~3.5 MIPs – threshold for timing measurement)

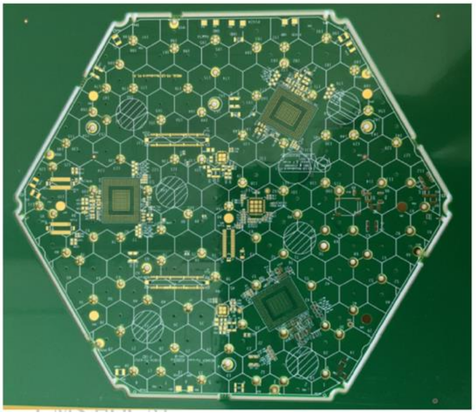
Timing Information and Resolution

- Ability to contribute to the level-1 CMS trigger
    - Pileup mitigation

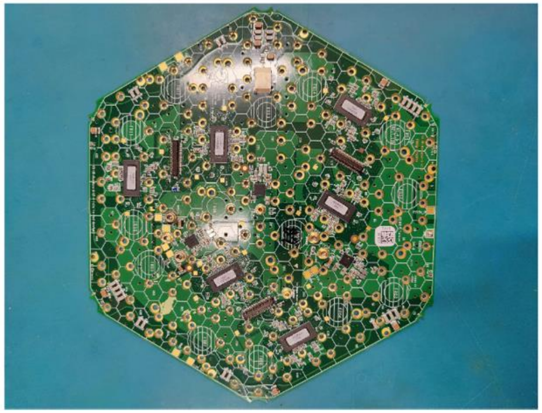
HGCAL Electronics

Hexaboards

LD

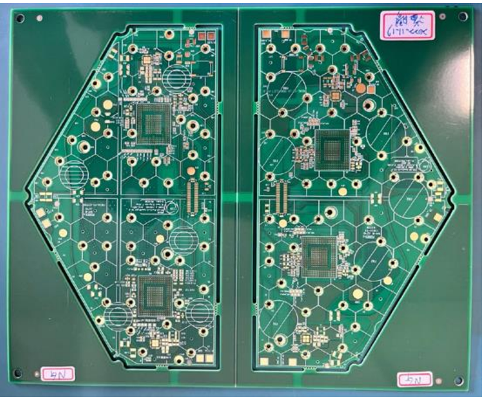


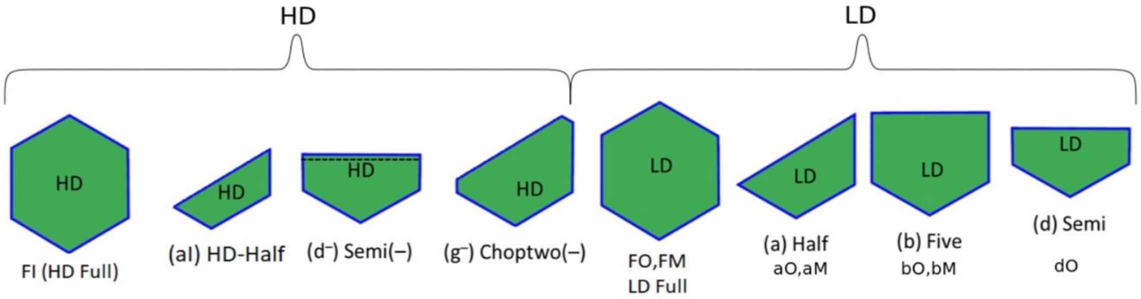
HD



- HB design process qualification
- HBs successfully demonstrated in system and beam tests
- Finalizing the design of all HB types
- Pre-production boards to fabricate and evaluate

Semi



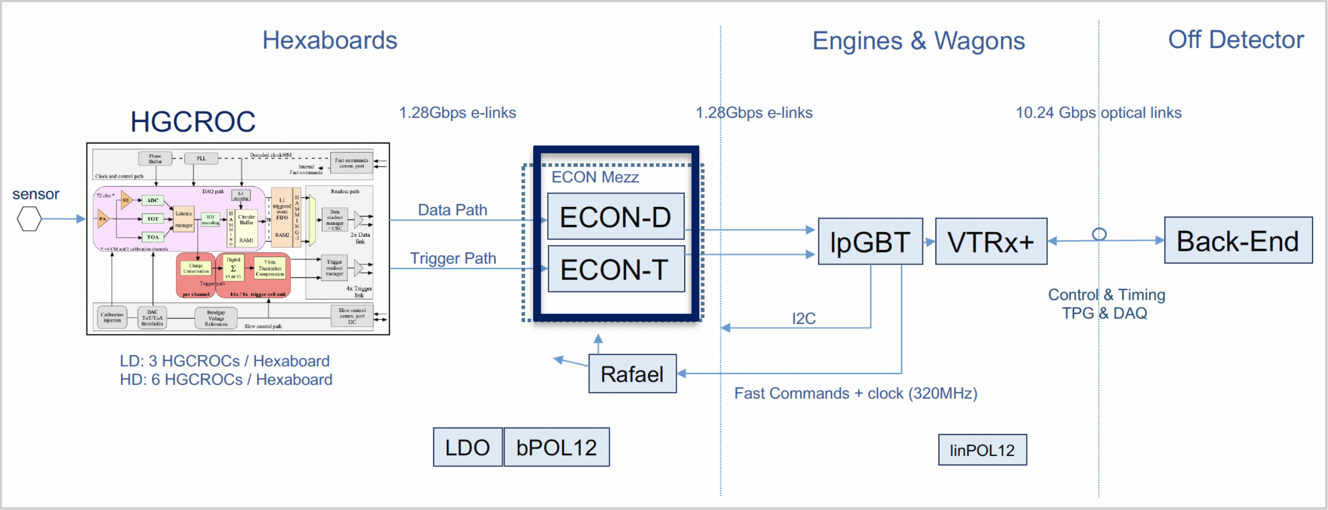


The design team from Optics Lab (Pakistan)

- Fakhri Alam Khan (now at CERN)
- Hafiza Ayesha Ahmed
- Noman Saud
- Rummaan Bin Amir

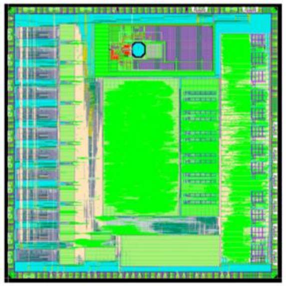
HGCAL Electronics

ECON-T/D



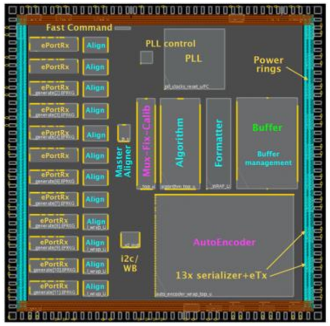
ECON-D:

- Receives HGCROC data packets after LV1A
- Performs zero suppression
- Transmission @ 750 KHz



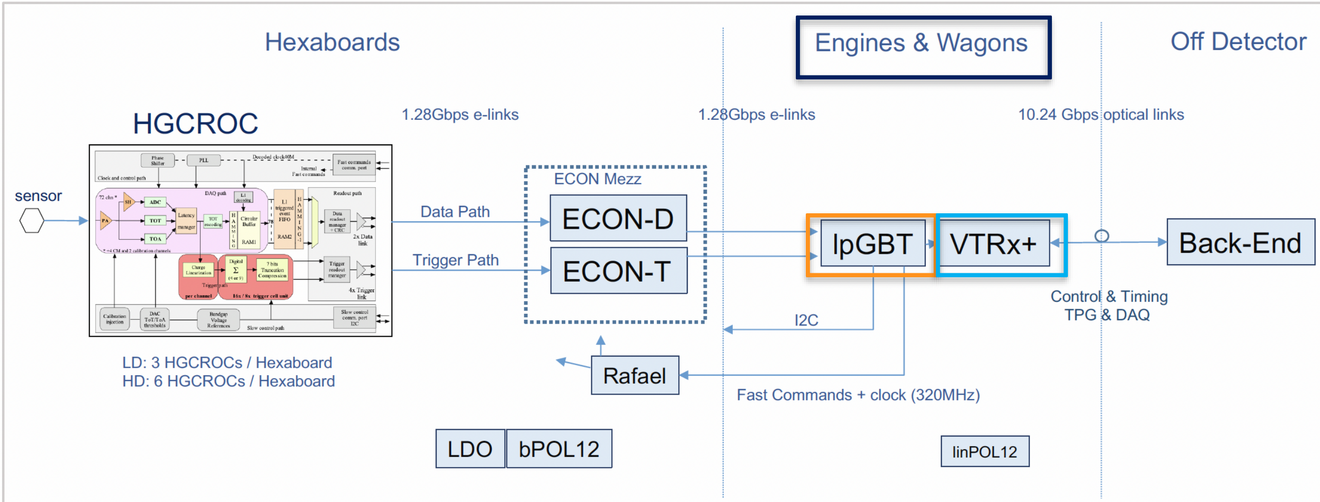
ECON-T:

- Select/compress trigger data
- Transmission every 40 MHz



HGCAL Electronics

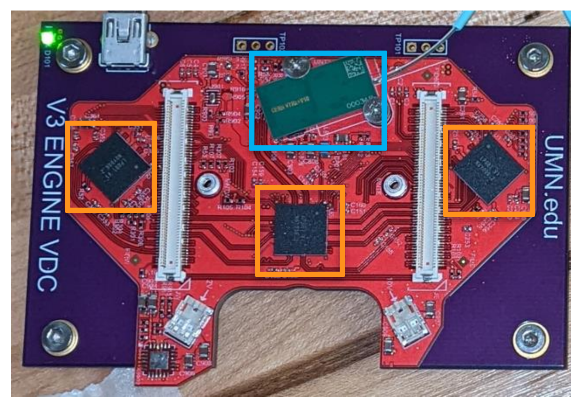
Engines/Wagons



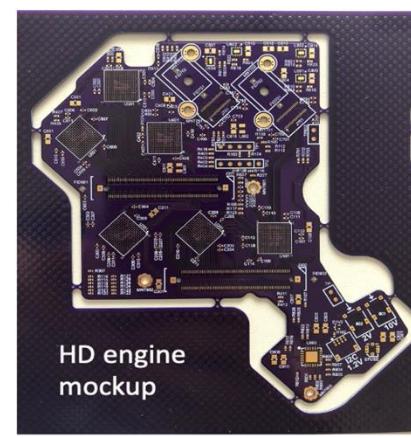
Engines/Wagons:

- Active/Passive elements
- Hosting lpGBT/VTRX+
  - Transmission to Back-End
  - Clock distribution
  - Fast commands/Configurations
- LD Engine contains 3 lpGBTs and 1 VTRX+
- HD Engine contains 6 lpGBTs and 2 VTRX+

LD Engine

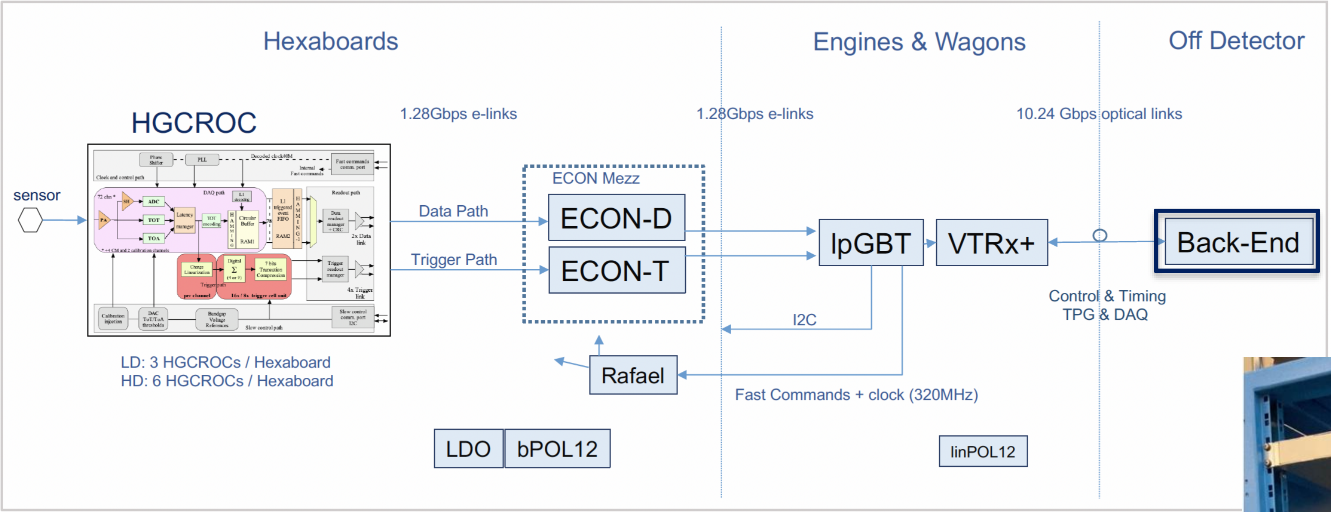


HD Engine



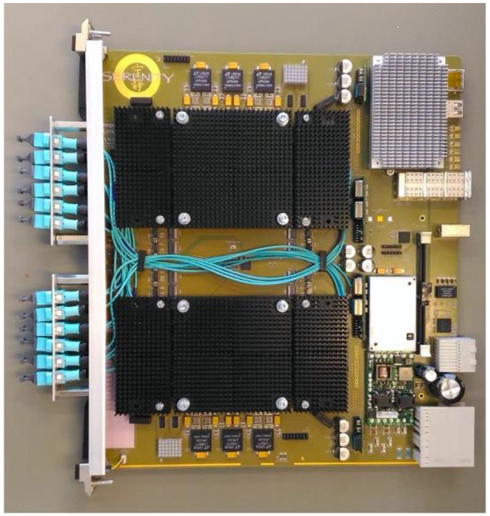
HGCAL Electronics

Back-End



ATCA-based custom readout FPGA boards (Serenity)

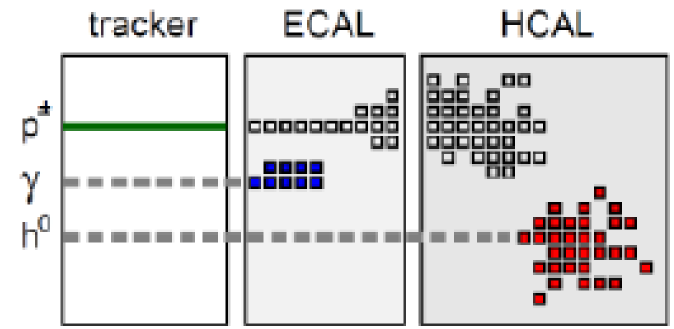
- Can host up to two FPGA daughter boards
- Receives data via optical fibers from VTRX+
  - 60x2/108 input channel - 10 Gbit/s
- Transmits data to DTH boards (central DAQ system)
  - 12 output channel - 25 Gbit/s

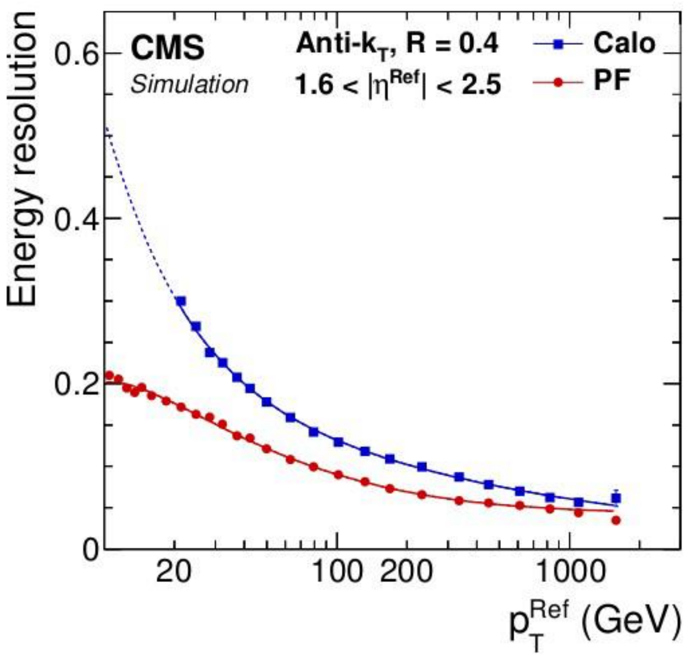


HG Calorimetry at 1.5 < |η| < 3.0

Case for HG Calorimeter in the forward region

- Allows PF measurements to extend from the tracker into the calorimeter
- Allows the subtraction of the energy from pileup events leading to a good resolution even in high pileup environment

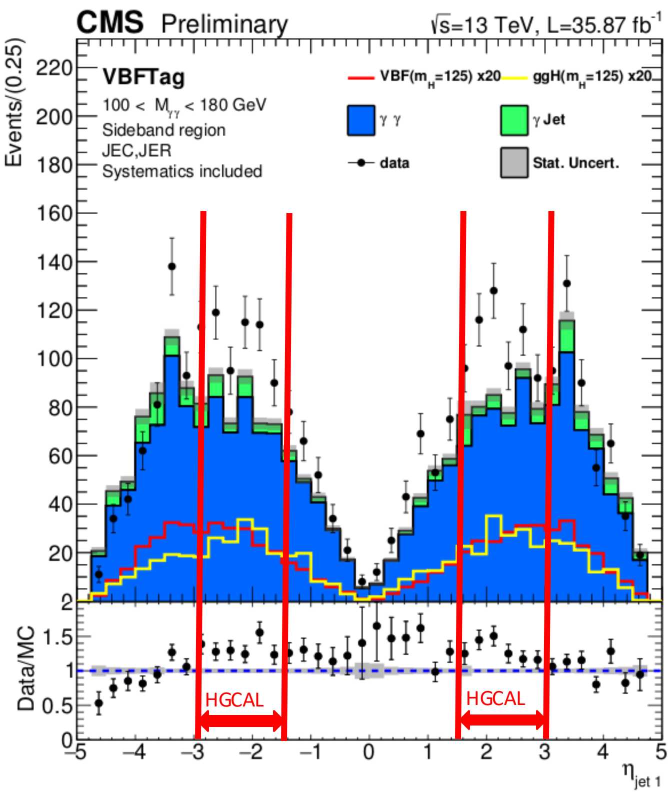




- Merged jets can be reconstructed with higher efficiency and better E resolution improving the boosted object reconstruction performance
- The high lateral granularity allows the tagging of narrow jets originating from the production mode of the VBF Higgs boson as well as jets from the weak vector boson scattering
- HG allows efficient e/g reconstruction/PID in the presence of PU in the forward region
- E resolution like the current detector at high energies

HGCAL: 5D Imaging Calorimeter

Ideal coverage for VBF di-Higgs



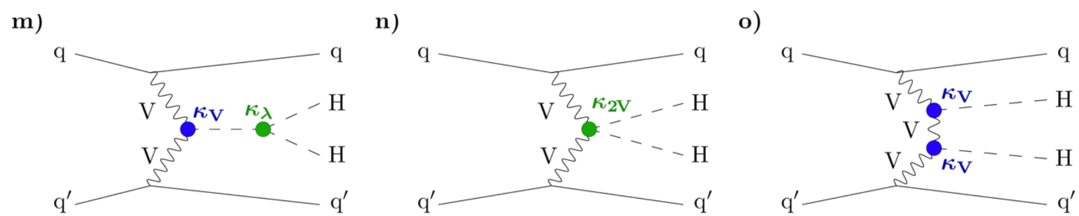
Back on the envelope VBF jet acceptance:

Bjorken x

$$h(\mathrm{VBF}) = a\cosh\left(\frac{P}{Q}\right) = a\cosh\left(\frac{P}{M_H/2}\right) = a\cosh\left(\frac{0.1\times 6.5\mathrm{TeV}}{0.063\mathrm{TeV}}\right) \sim 3$$

Virtuality

For di-Higgs VBF production:

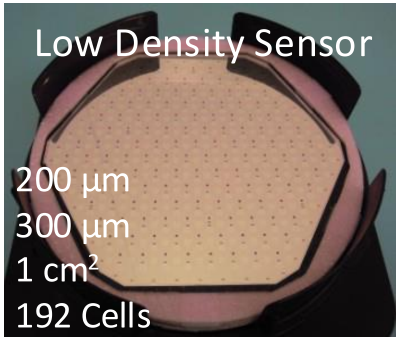


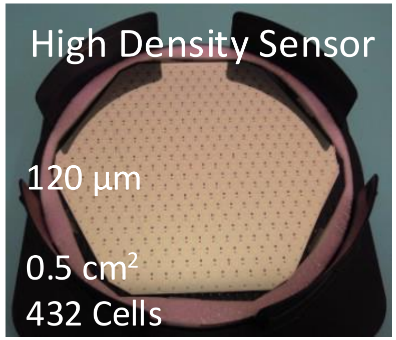
$$\boxed{h(\mathrm{HH}) = a\cosh\left(\frac{P}{M_H}\right) \sim 2.3}$$

Quark jets go right in the center of HGCAL

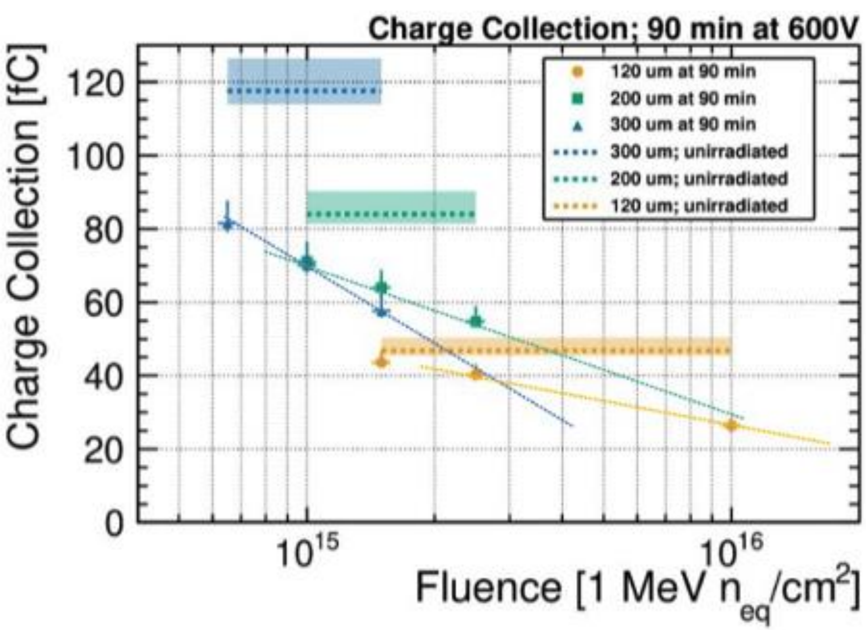
Active Material – Silicon

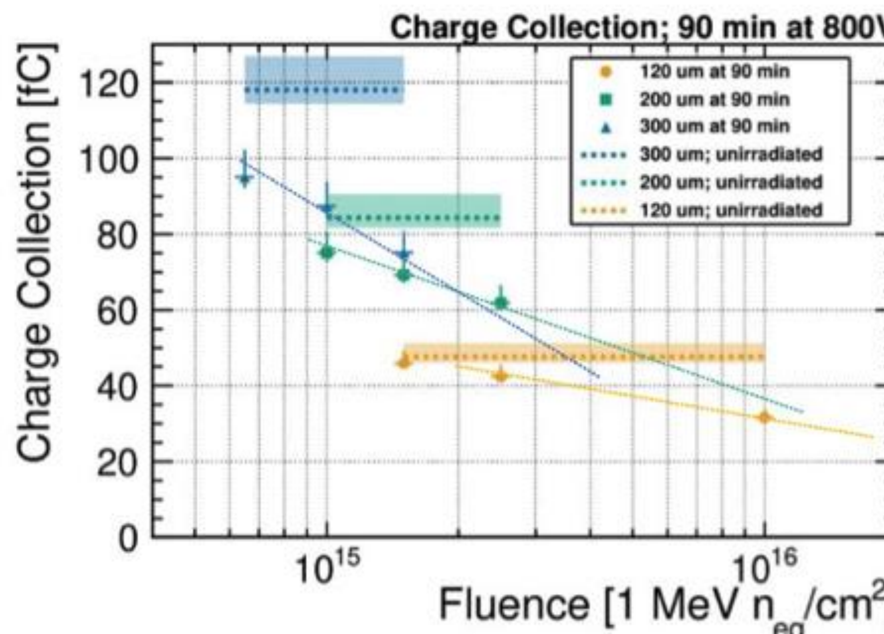
Silicon Sensors – Charge Collection vs Fluence





Similar charge collection for the 200 and 300 µm at 10^{15} and 1.5 x 10^{15} n_{eq}/cm^2

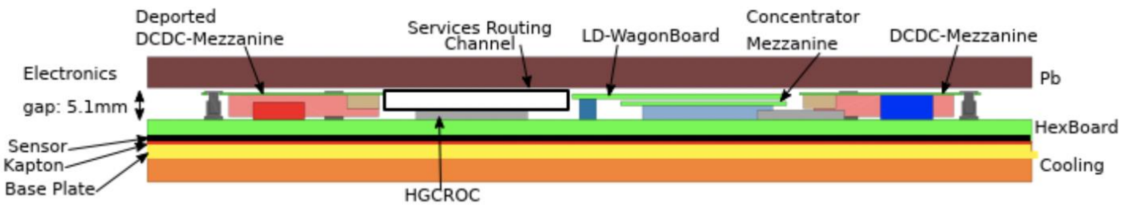


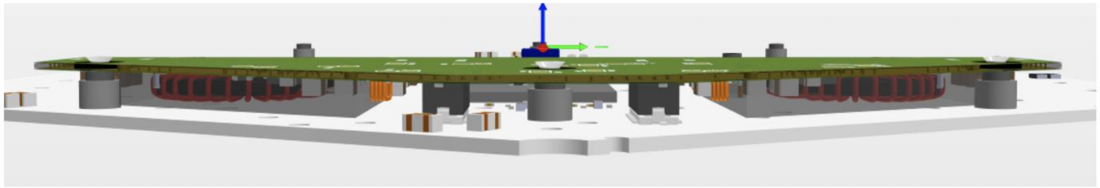


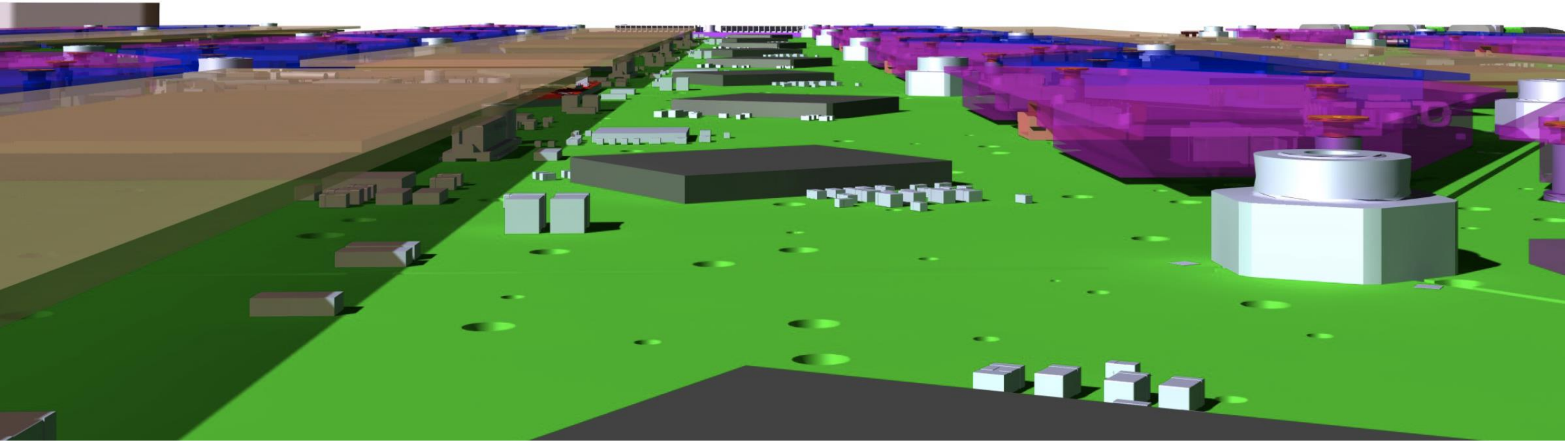
Integration

Physical Space

Only 5.1 mm to put all electronics



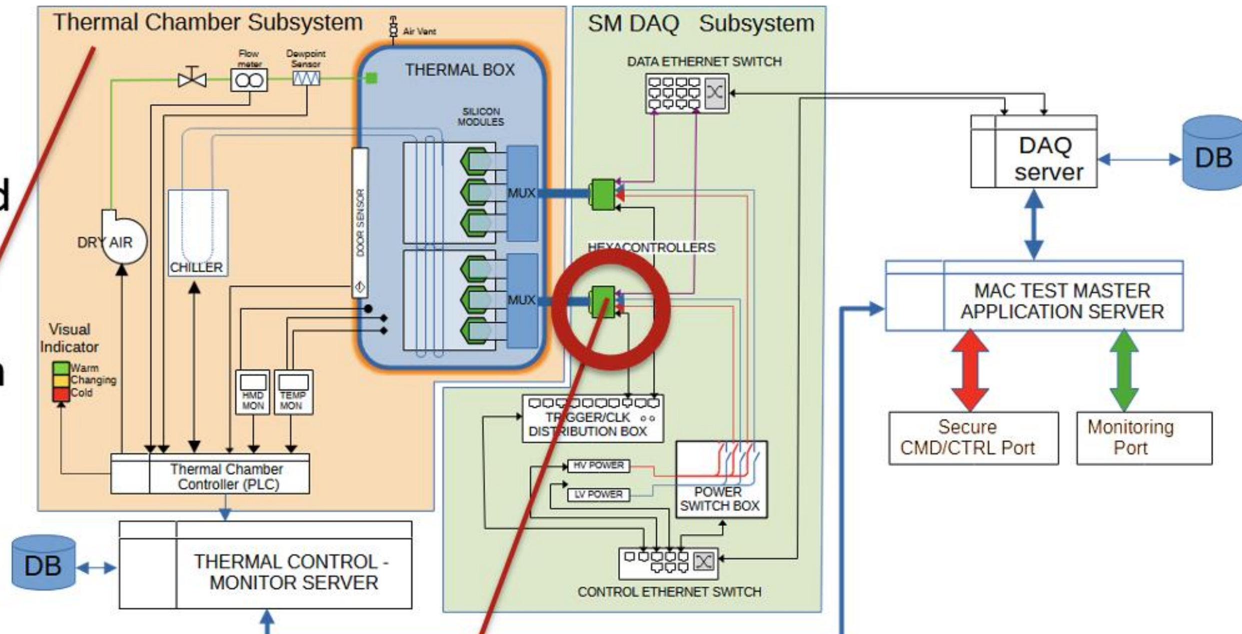


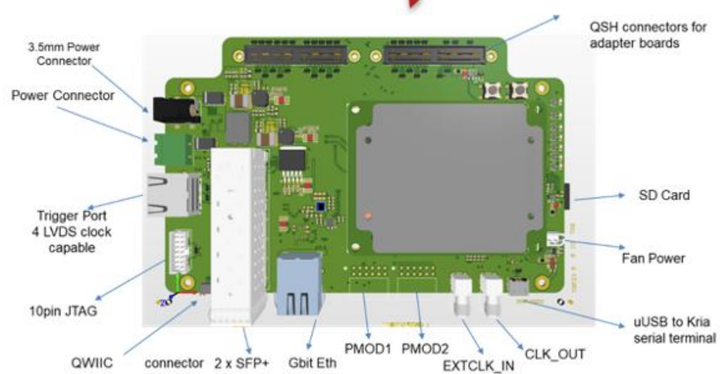


Mass Production
Silicon Module Testing

Thermal Chamber
- Chiller controller
- Dry air controller
- Sensor network (Thermal and humidity sensors)

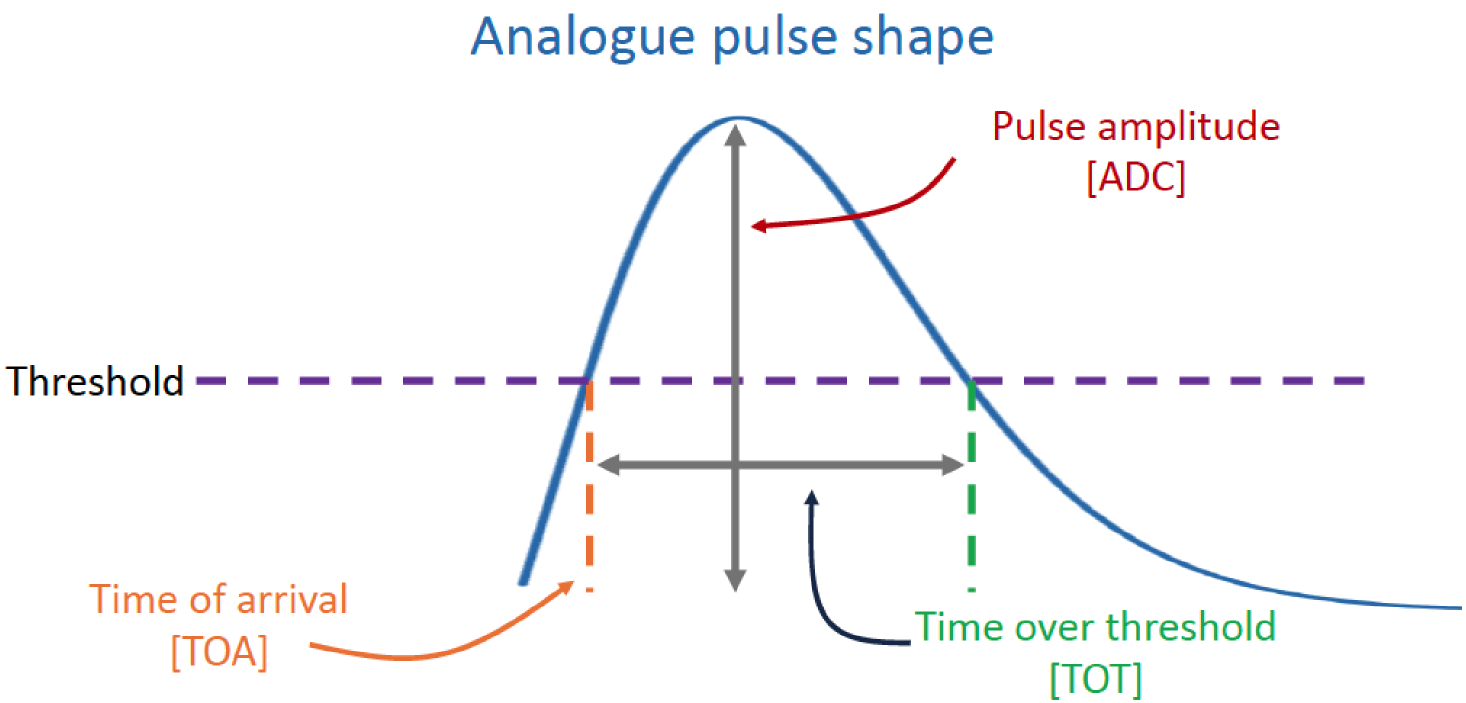
SM DAQ Subsystem;
- SOC FPGAs for capturing high speed data
- DAQ server for evaluating results.





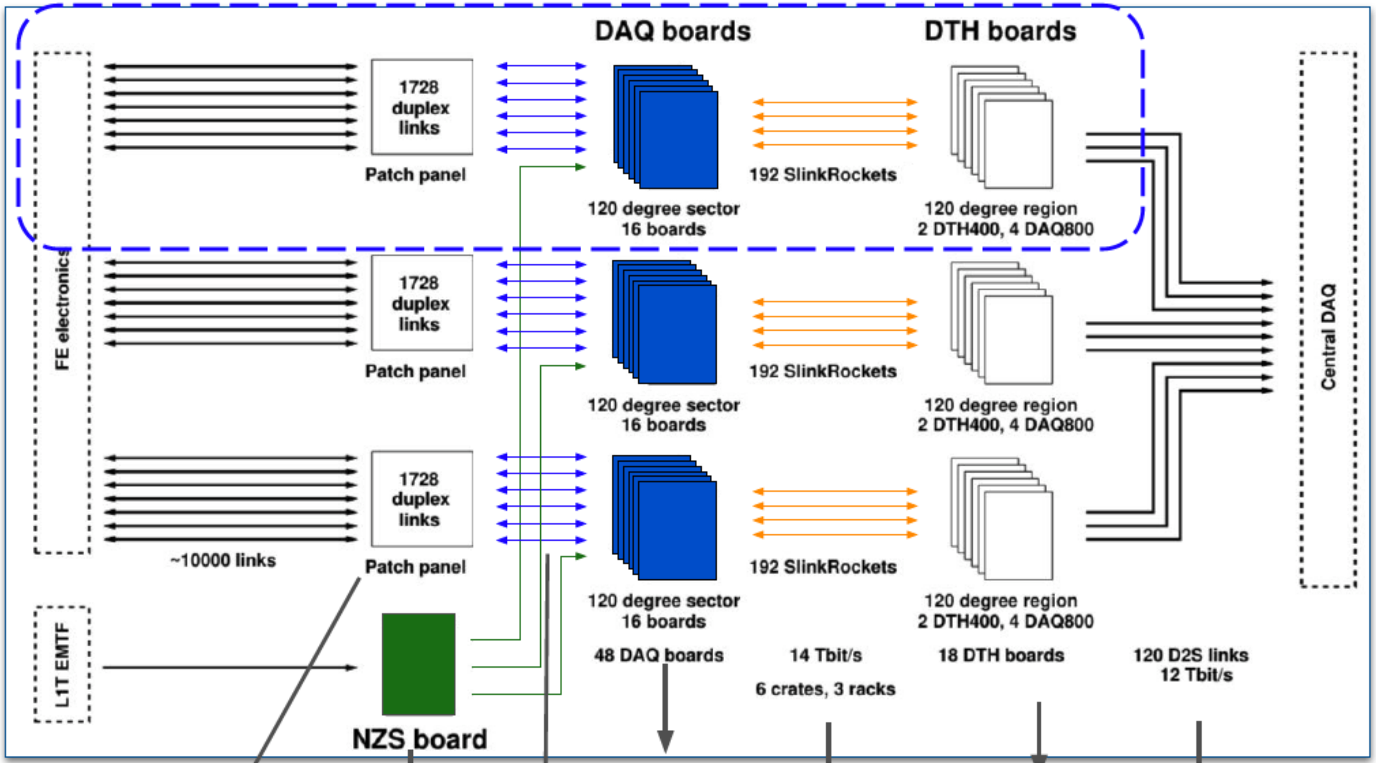
ADC/TOA/TOT

- To measure charge
  - Read out ADC for small charge deposits (small pulses)
  - TOT used for large charge deposits (large pulses)
- Time of arrival of a signal (TOA) also measured



Structure of DAQ BE system on one endcap

The HGCAL structure has a 120° azimuthal symmetry in each endcap and the two endcaps are identical.
→ the FE consists of six identical 120 sectors.



Patch panels (if necessary) to provide load-balancing

NZS board: ATCA Boards (Serenity/VU13P) 121 RX / 109 TX optical links

10 Gb/s , 2.5Gb/s Bi-directional lpGBT links

DAQ: ATCA Boards (Serenity/VU13P) 108 RX / 12 TX optical links

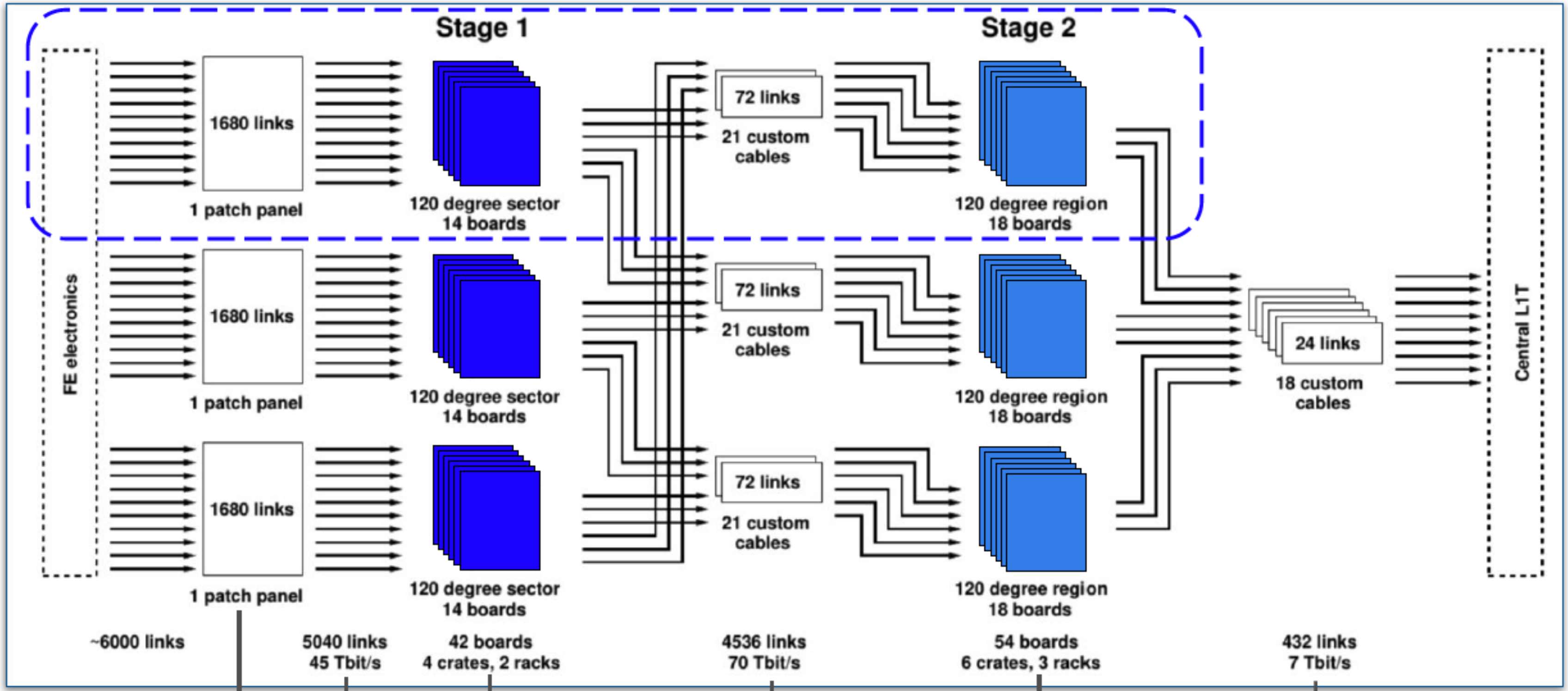
25 Gb/s Bi-directional SlinkRocket Links (custom cables)

DAQ & TCDS2:
- DTH400 board: 24 RX / 5 TX
- DTH800 board: 48 RX / 10 TX

100 Gb/s TCP/IP Data-to Surface links (D2S)

Structure of Trigger BE system on one endcap

The HGCAL structure has a 120° azimuthal symmetry in each endcap and the two endcaps are identical.
→ the FE consists of six identical 120° sectors.



Patch panels (if necessary) to provide load-balancing

10 Gb/s unidirectional lpGBT links

Stage-1: ATCA Boards (Serenity/VU13P) 121 RX / 109 TX optical links

Time Multiplexed: 16 Gb/s CMS Standard Protocol (CSP) links

Stage-2: ATCA Boards (Serenity/VU13P) 85 RX / 13 TX optical links

Time Multiplexed: 25 Gb/s CMS Standard Protocol (CSP) links