CMS High Granularity Calorimeter – Modules & Assembly

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HEP 2023, Ioannina

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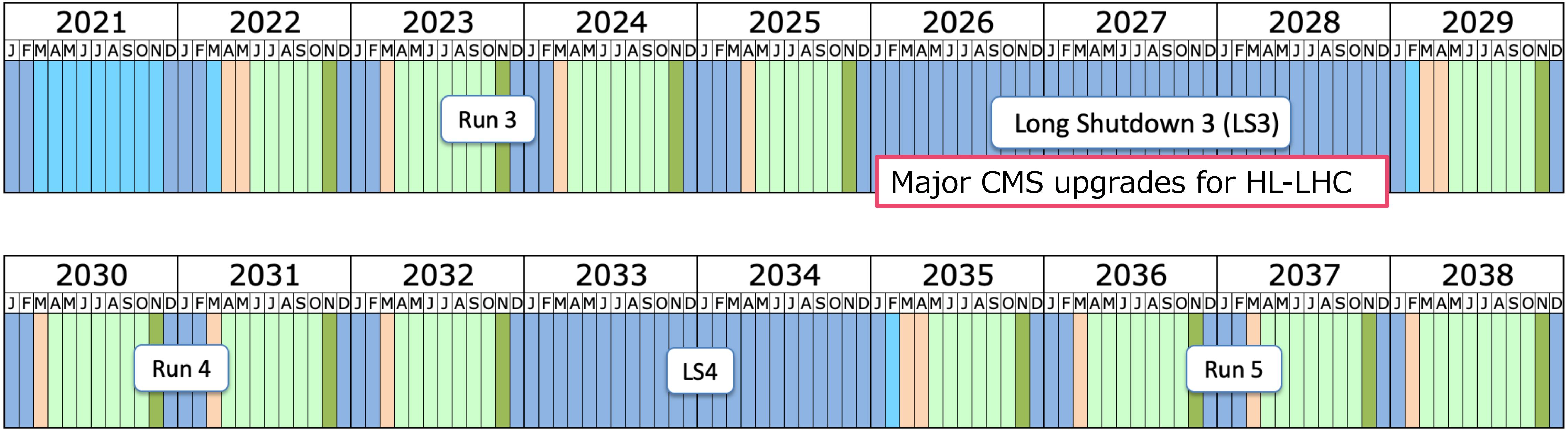
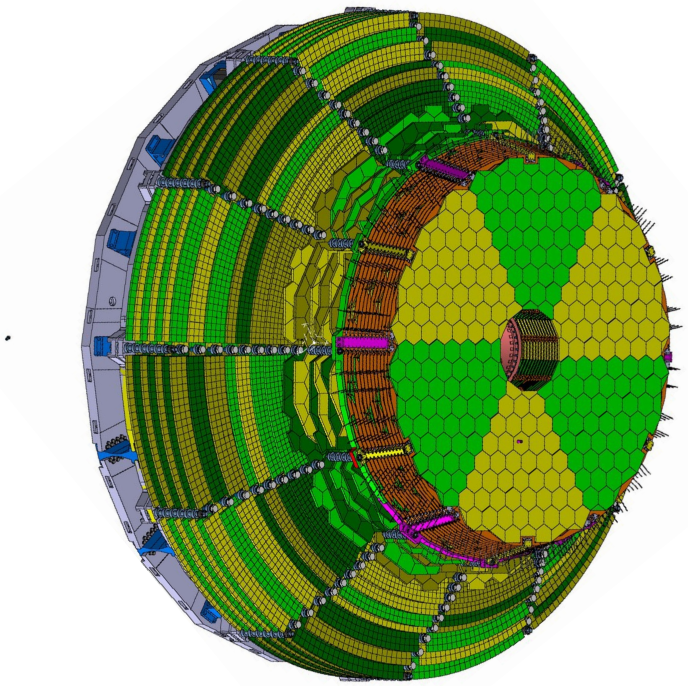
Why HGCAL



	LHC (now)	HL-LHC
Inst. Luminosity	$2 \times 10^{34}\ s^{-1}\ cm^{-2}$	$5\text{-}7.5 \times 10^{34}\ s^{-1}\ cm^{-2}$
Pileup events	O(40)	O(140-200)
Int. Luminosity	$300\ fb^{-1}$ (Run 3)	$3000\ fb^{-1}$

- More radiation, more pile-up, higher track density, more data ,.. → Detector Upgrades

HGCAL Overview

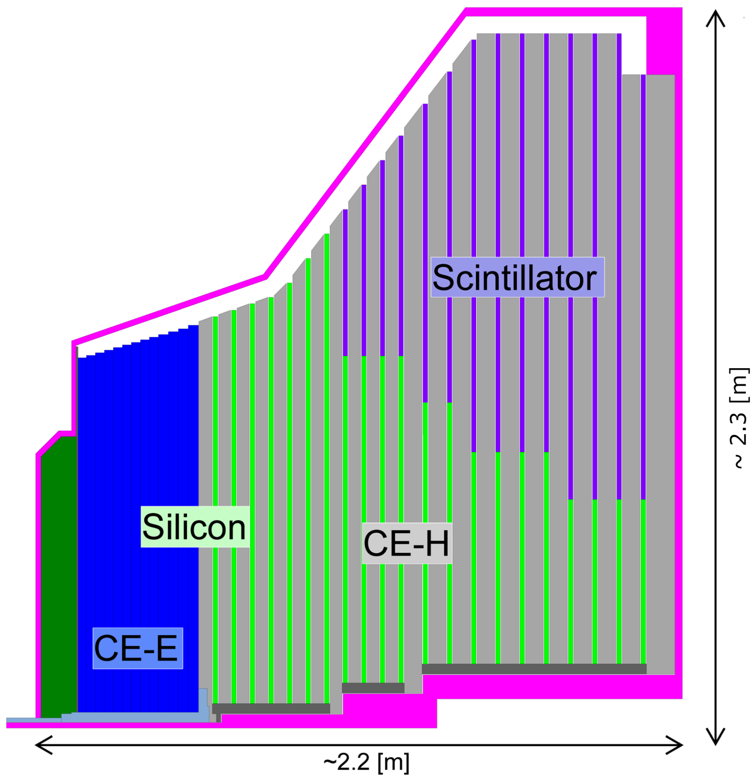


- CMS is constructing a High Granularity Calorimeter for the HL-LHC
- It will be composed of different technologies: Si sensors, SiPM-on-tile
- HGCAL characteristics
  - $1.5 < |\eta| < 3.0$
  - High granularity
  - Radiation tolerant
  - Precise hit/cluster timing
  - Particle flow
  - Operation at -30 C

HGCAL Design

Active Elements

- Hexagonal modules based on Si sensors in EM part (CE-E) and high radiation regions of the hadronic part (CE-H)
- Scintillating tile with on-tile SiPM readout in low radiation regions of CE-H
- Cassettes → multiple modules mounted on cooling plates with electronics and absorbers



Parameters

- ~620 m^2 Si sensors in ~26K modules
- 6M Si channels, cell size ~0.5 or ~1 cm^2
- ~400 m^2 scintillators in ~4K boards
- 240K sci channels, cell size 4-30 cm^2

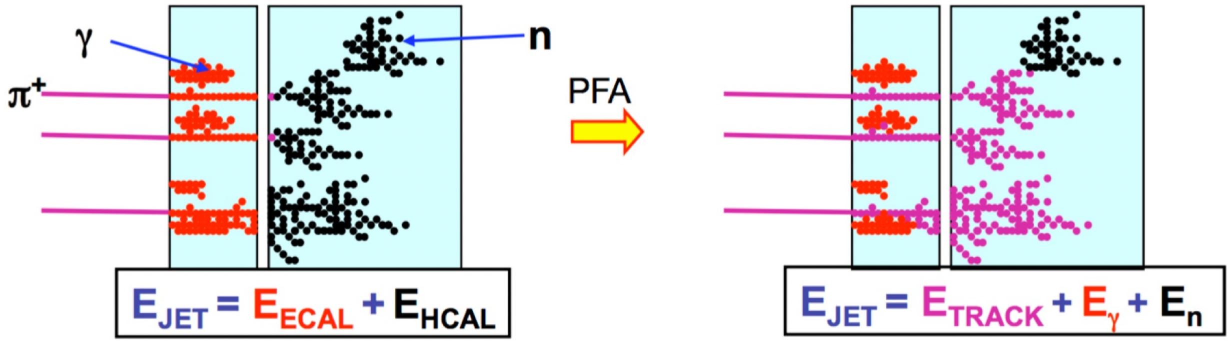
- EM calo (CE-E): Si, Cu/CuW/Pb absorbers, 26 layers, 27.7 X_0
- Hadronic Calo (CE-H): Si/scintillator, steel absorber, 21 layers, 8.5 λ

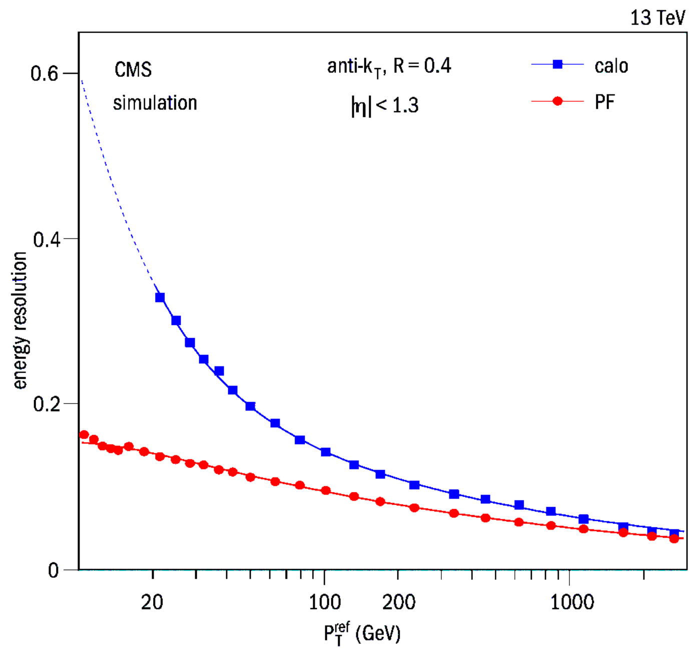
Particle Flow

- Particle Flow Algorithms → make best use of all detectors to measure jet energy

"Typical" jet content:

62% charged particles (mainly hadrons)	→ Tracker
27% photons	→ ECAL
10% neutral hadrons	→ HCAL
1% neutrinos	x



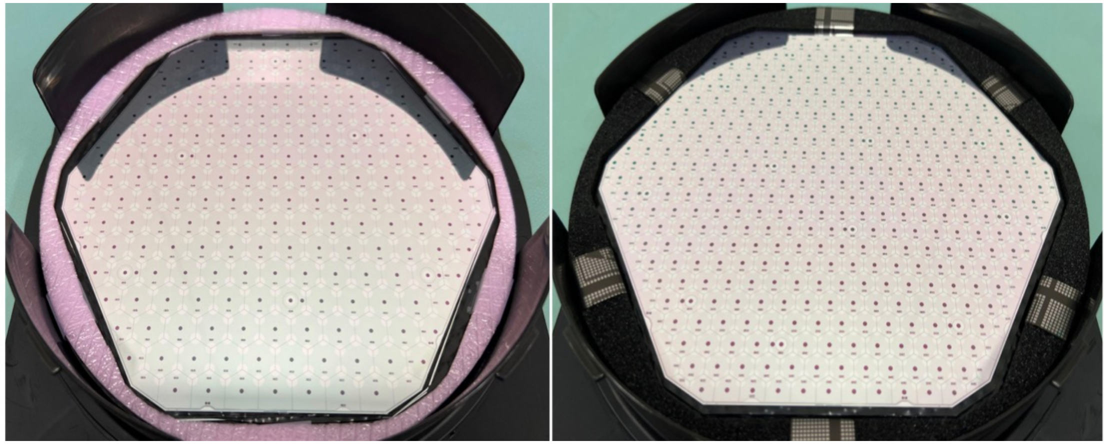


Better performance for PF compared to calo only

- Requires a highly granular calorimeter

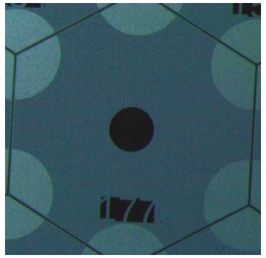
Si sensors

- 8″ wafer
- Hexagonal shape (and partials)
- Low and high density varieties (depending on where they are placed)
- 120, 200 or 300 μm sensors (depending on where they are placed)



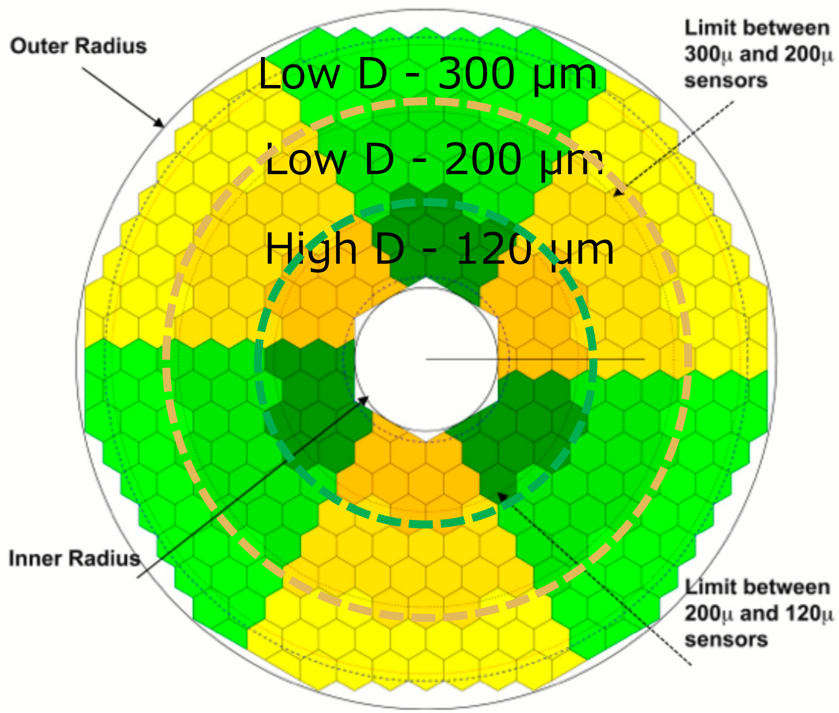
Low density sensor
~200 cells of 1 cm^2 size
200 or 300 μm thick

High density sensor
~400 cells of 0.5 cm^2 size
120 μm thick



Different partial shapes for coverage

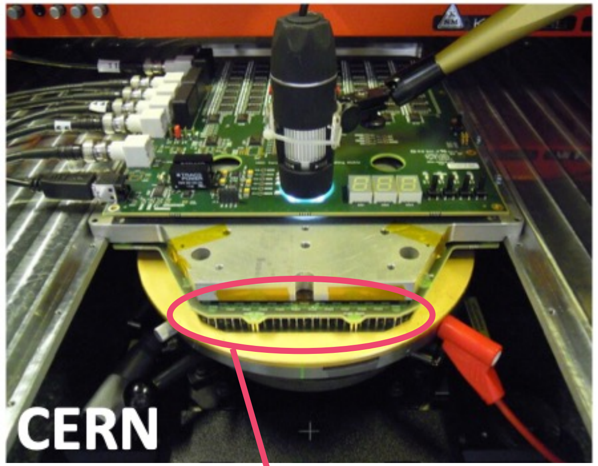
CE-E Layer 9

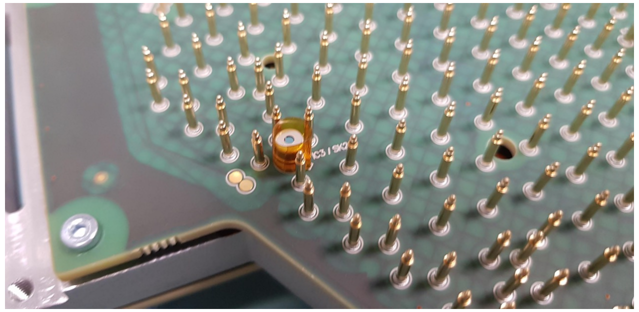


Close to the beam
- High radiation → thin sensors
- Higher track density → higher density sensor pads

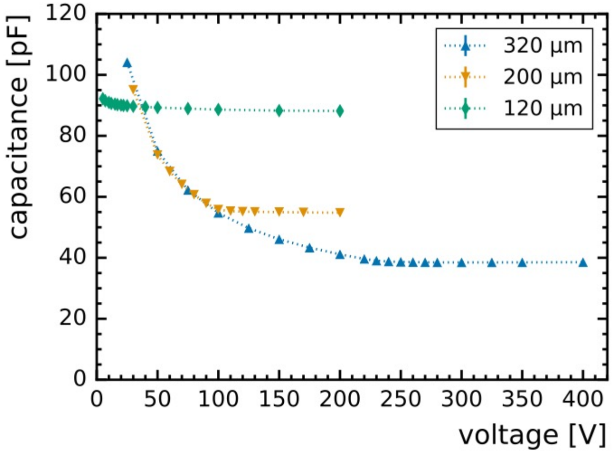
Si Sensors Testing

Setup

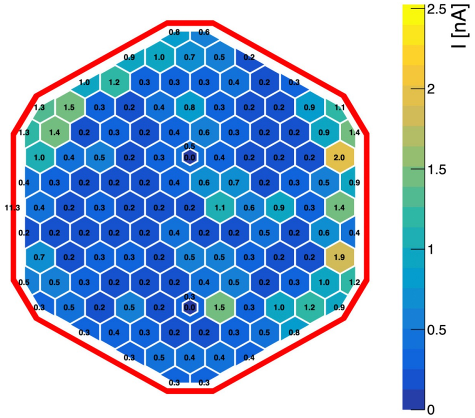




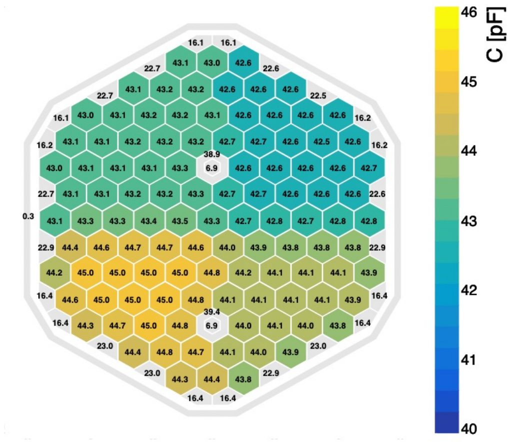
CV curves for sensors with different active thickness



Leakage current at 1000V

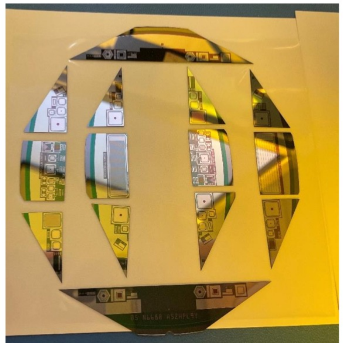


Capacitance at 400 V

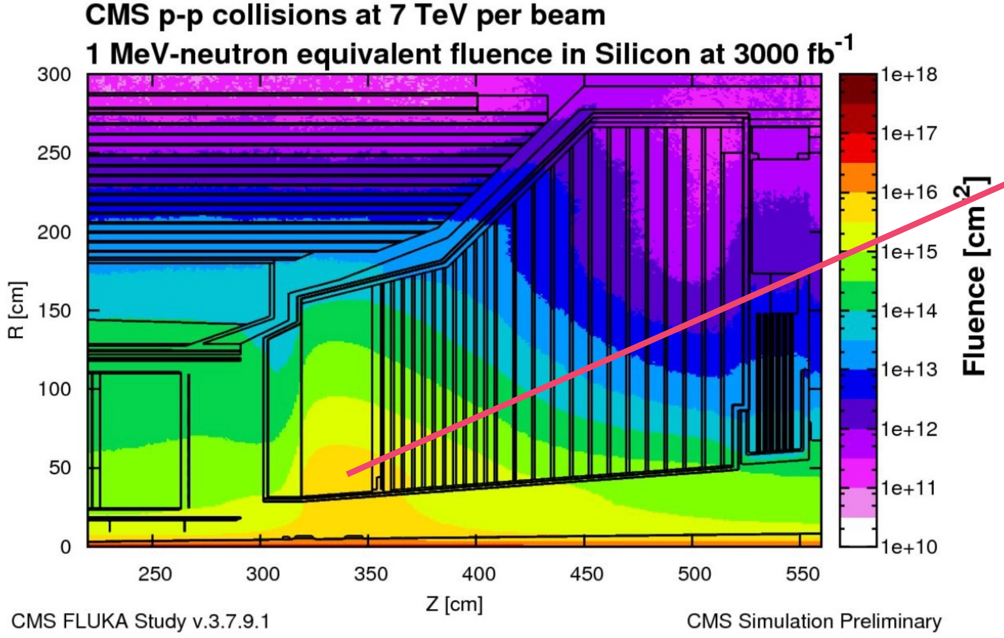


4 quadrants because of four different cell geometries on the sensor (varying inter-pad gap)

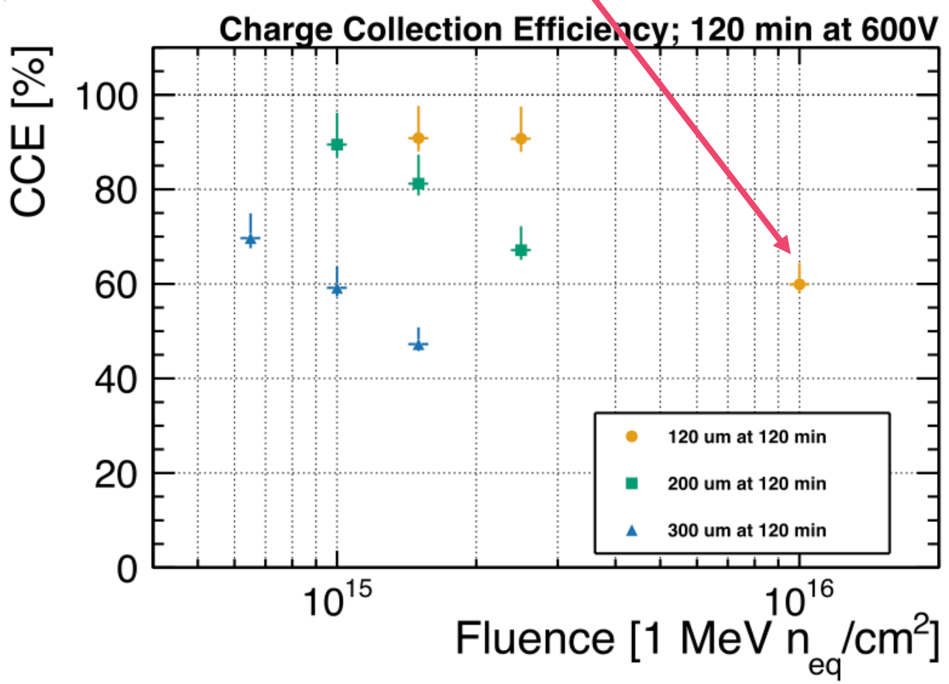
Test structures



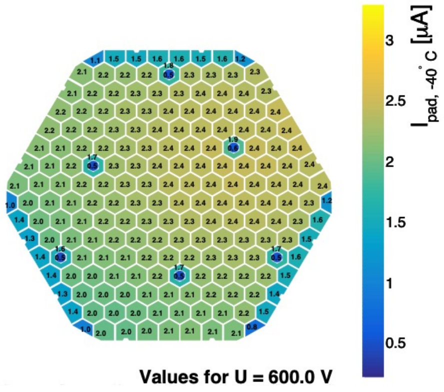
Si Sensor Radiation Hardness



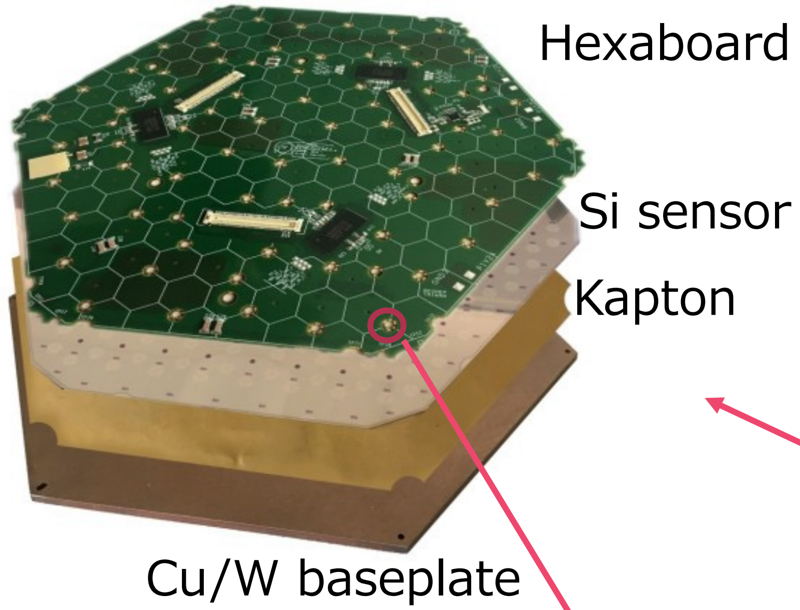
Area close to beam to be equipped with 120 µm sensors



Per-pad leakage current for sensor (after annealing): 200 µm, low density, irradiated to 1.9×10^{15} neq/cm^2



Si Modules

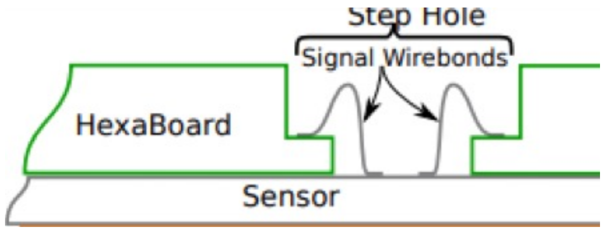


PCB ('Hexaboard') – Sensor
- Read-out (HGCROC) of sensor cells + bias supply
- Connects to motherboard for data transfer

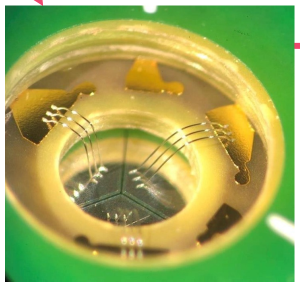
Silicon sensor

Kapton sheet
- Isolation to baseplate + bias supply to sensor back side

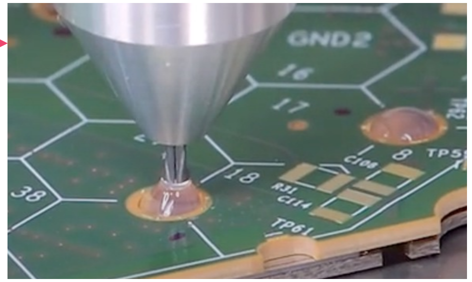
Baseplate
- Rigidity, contributes to absorber material

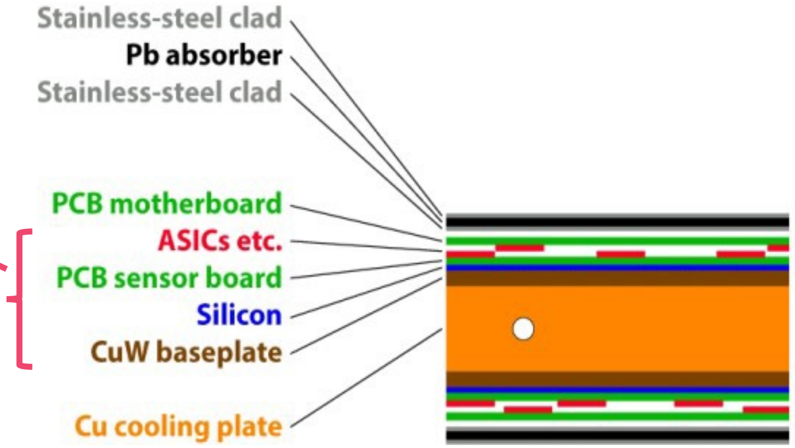


Step holes for wire bonding



Encapsulation



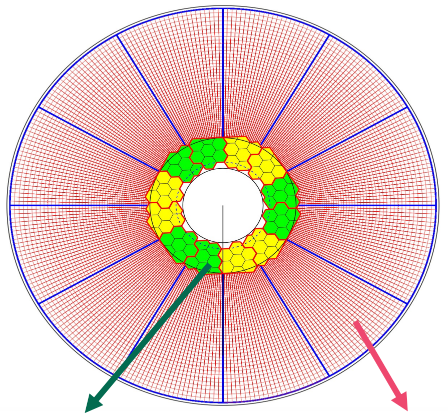


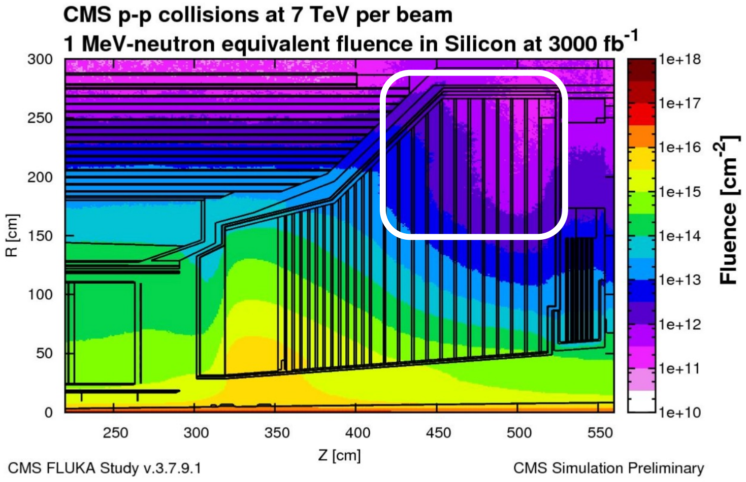
SiPM-on-Tile modules

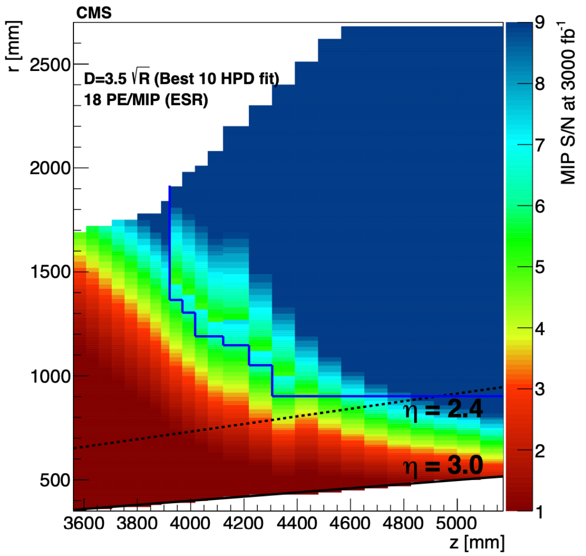
- SiPM-on-Tile: individually wrapped plastic scintillator tiles placed on silicon photomultipliers

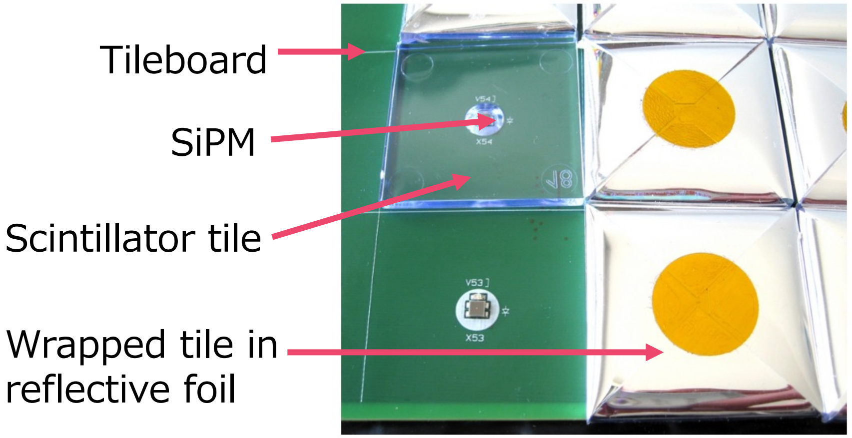
- Scintillator tiles with SiPM readout used in low radiation regions
- Require good MIP Signal/Noise after 3000fb^{-1}
- Tile size depends on radial-position (4cm^2 to 32cm^2) → smaller tiles at lower radii

CE-H mixed cassette



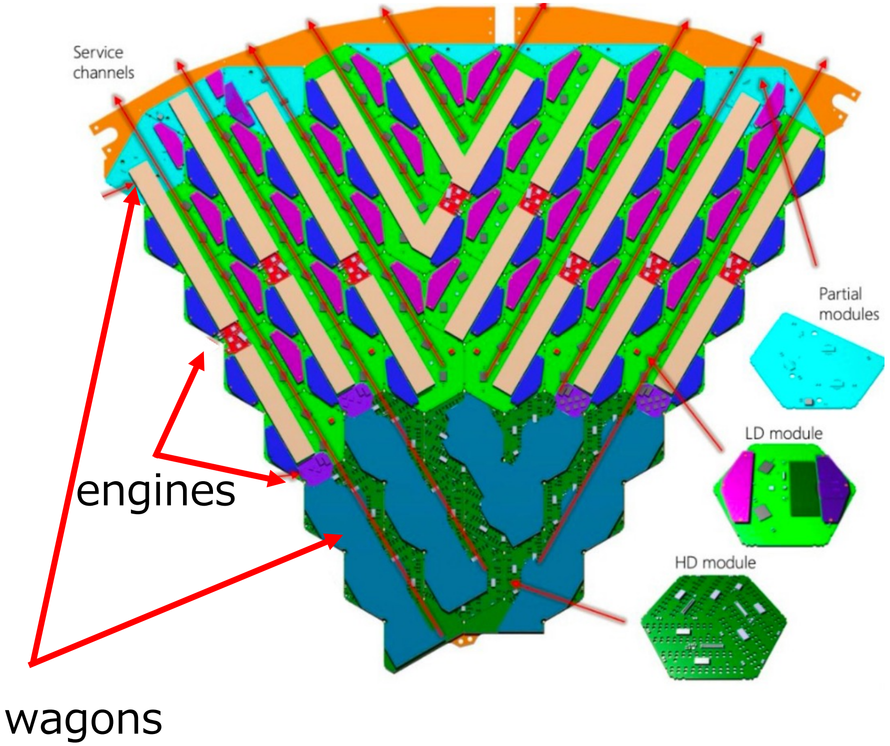




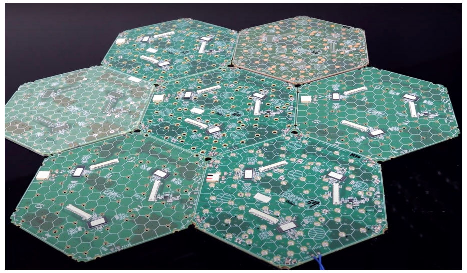


Cassettes

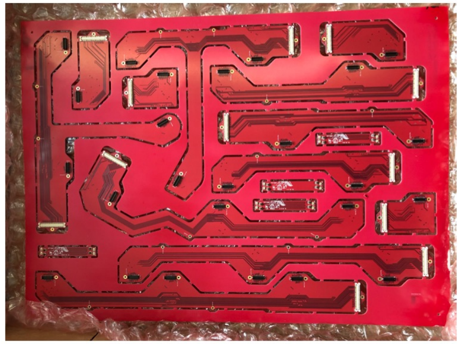
Full Si cassette (~400 components)



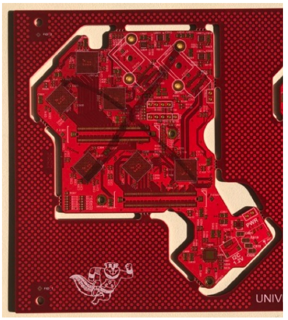
How to get there?



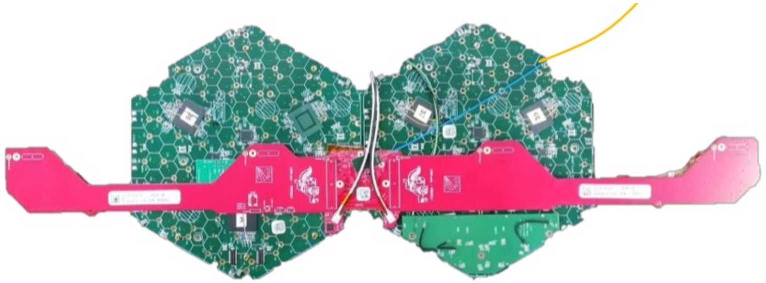
Hexagonal tiling



Wagons in different shapes. Connections from modules to engines



Engine boards collect data from wagons and send it to backend



Tests from 1-module to 2→ (multi) → trains → cassettes

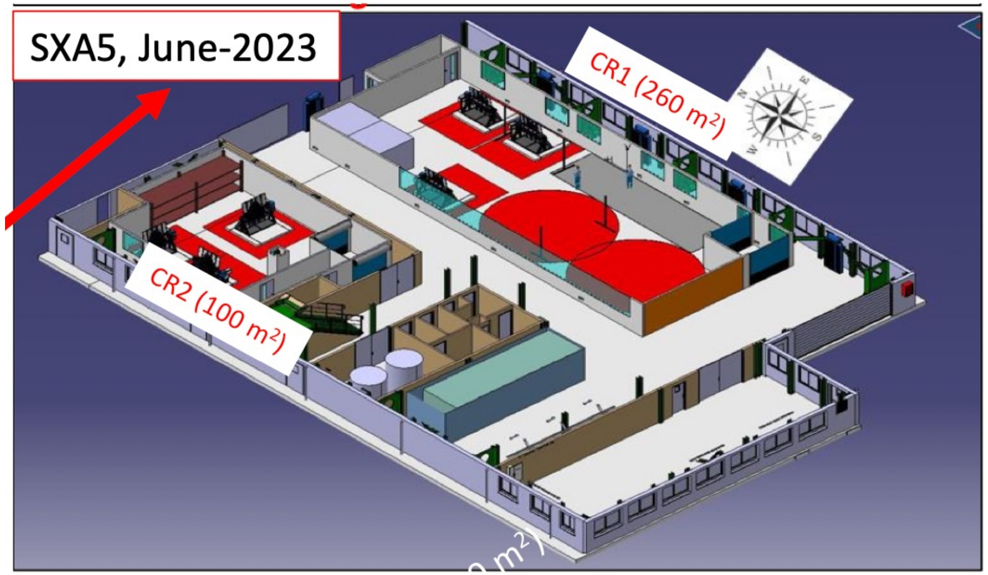
Slow control, fast control, data acquisition, testbeams,…

Cassette Assembly

Assembly centers: CERN, Fermilab

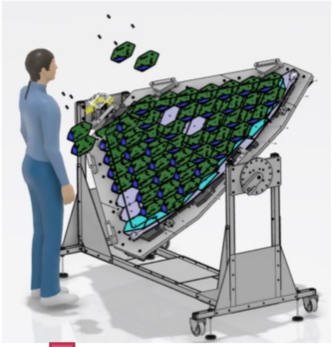
~700 cassettes

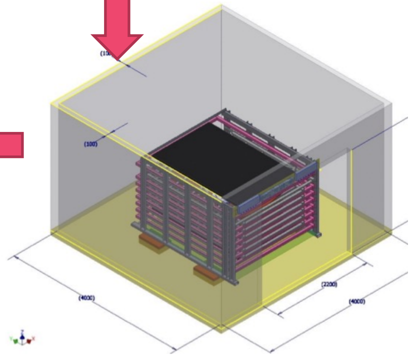
CERN p5, under construction



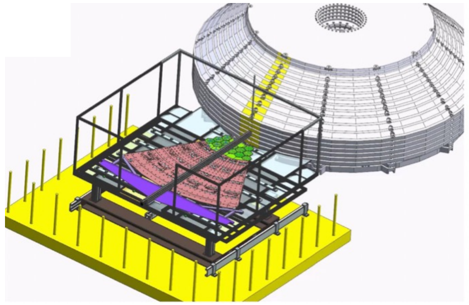
Cooling plate
CO_2 flow, -35 C
Few mm diameter
Few meters length

Moved to assembly station





Move to cosmic stack

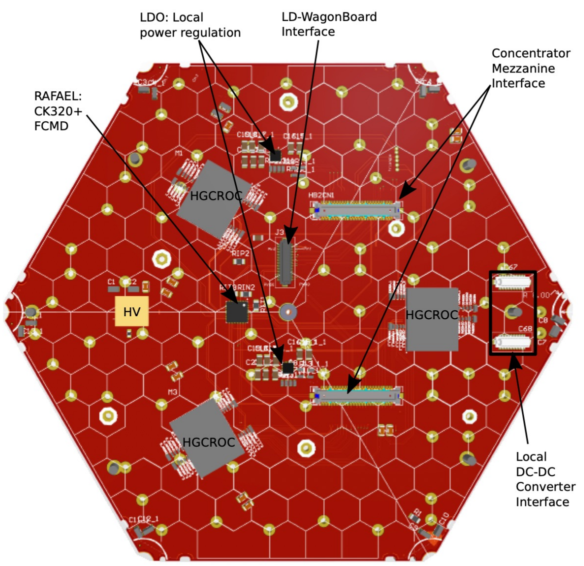


Insertion into absorber

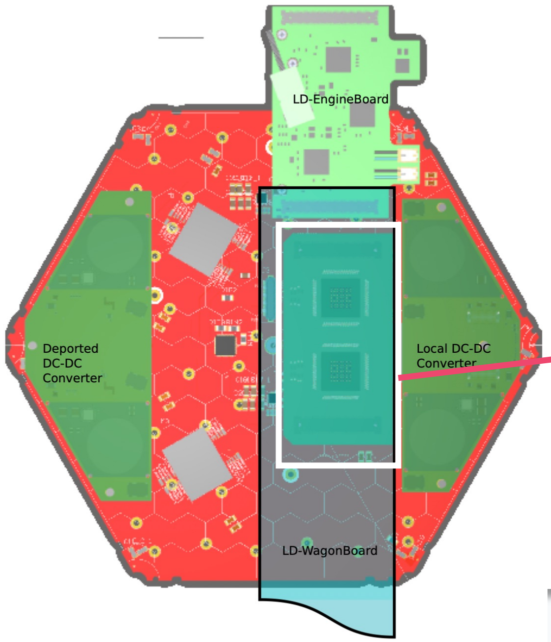
Electronics

- Different boards for the electronics
- Hexaboard for module → Different variants for HD/LD modules and partials
- HGCROC → ASIC used both for Si and SiPM-on-tile parts
- Requirements: high dynamic range (0.2 fC-10 pC), timing info (30ps), radiation tolerant, low power (<20mW per channel)

LD hexaboard



On detector → Off detector



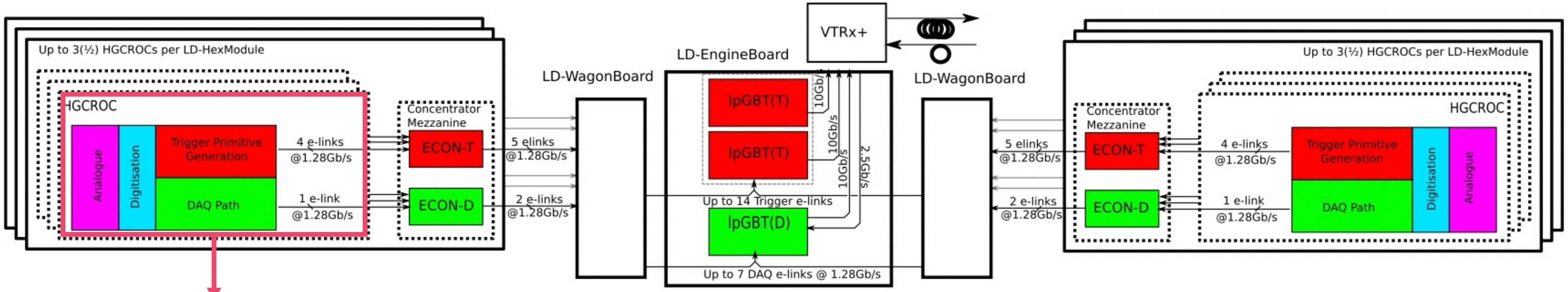
DAQ (Data, control)

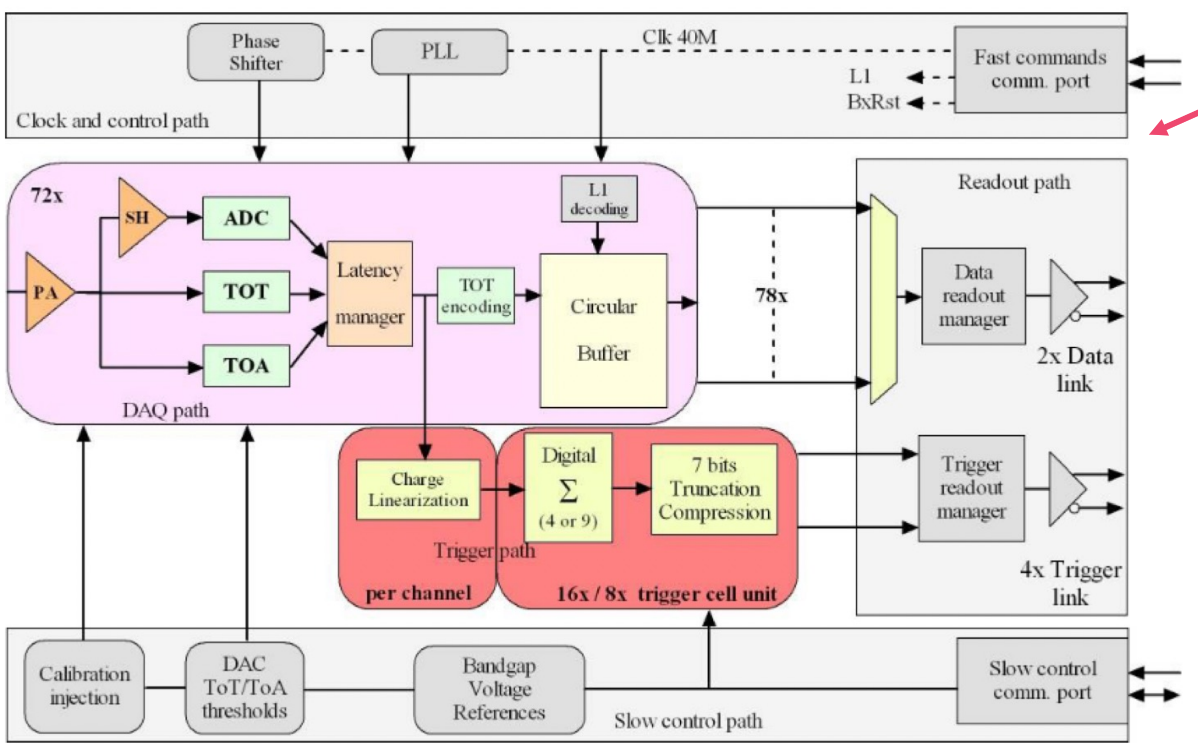
Trigger (Data)

ECON-T: Compression of cell sums for L1 trigger

ECON-D: Zero-suppression of triggered data

Front End Electronics & HGCROC





HGCROC architecture

Measurements

Charge
- ADC – 10 bits @ 40 MHz
- TDC – TOT (Time Over Threshold), 12 bits

Time
- TDC – TOA (Time Of Arrival), 10 bits

Two data flows
- DAQ path: Store ADC, TOT, TOA data
- Trigger path: Sum of 4 (9) channels, linearisation, compression

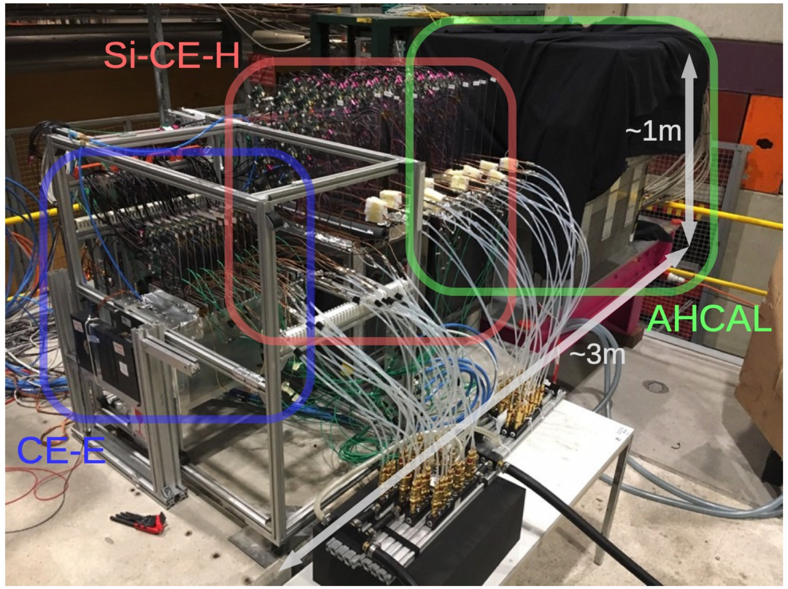
Beam Tests

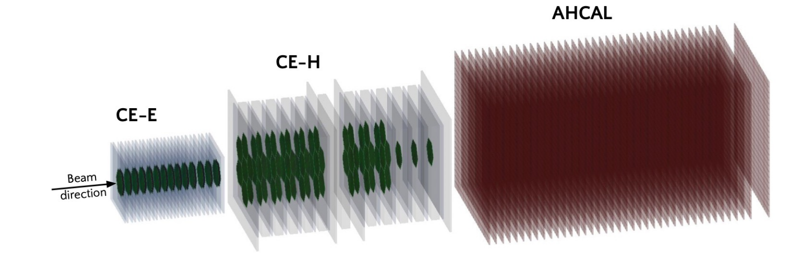
- Test beams during the past few years
- 2018: test beam at CERN. Positrons / pions 20-300 GeV, muons 200 GeV
- 2 planned at CERN for 2023

CE-E
- 28 layers of single Si modules
- ~26 X_0

CE-H
- 9 layers of 7 Si modules + 3 layers of single Si modules
- ~3.4 λ

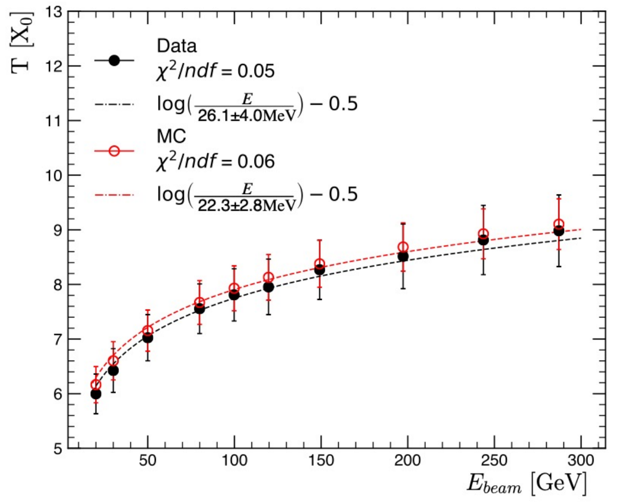
AHCAL
- 39 layers of SiPM-on-tile modules
- 22K scintillator tiles of size 3x3x0.3 cm^3
- ~4.4 λ



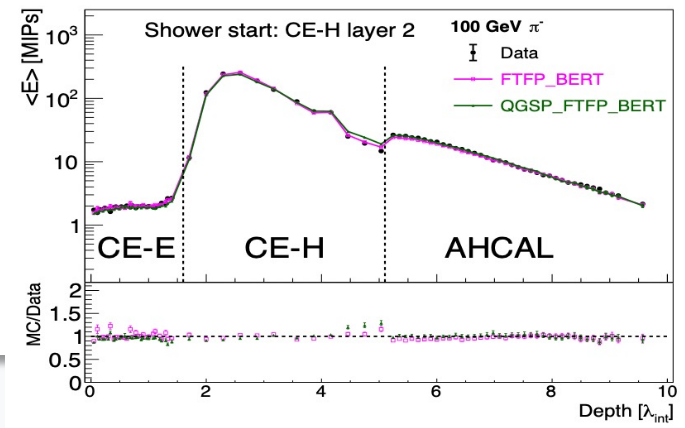


Longitudinal information

positron beam Shower max

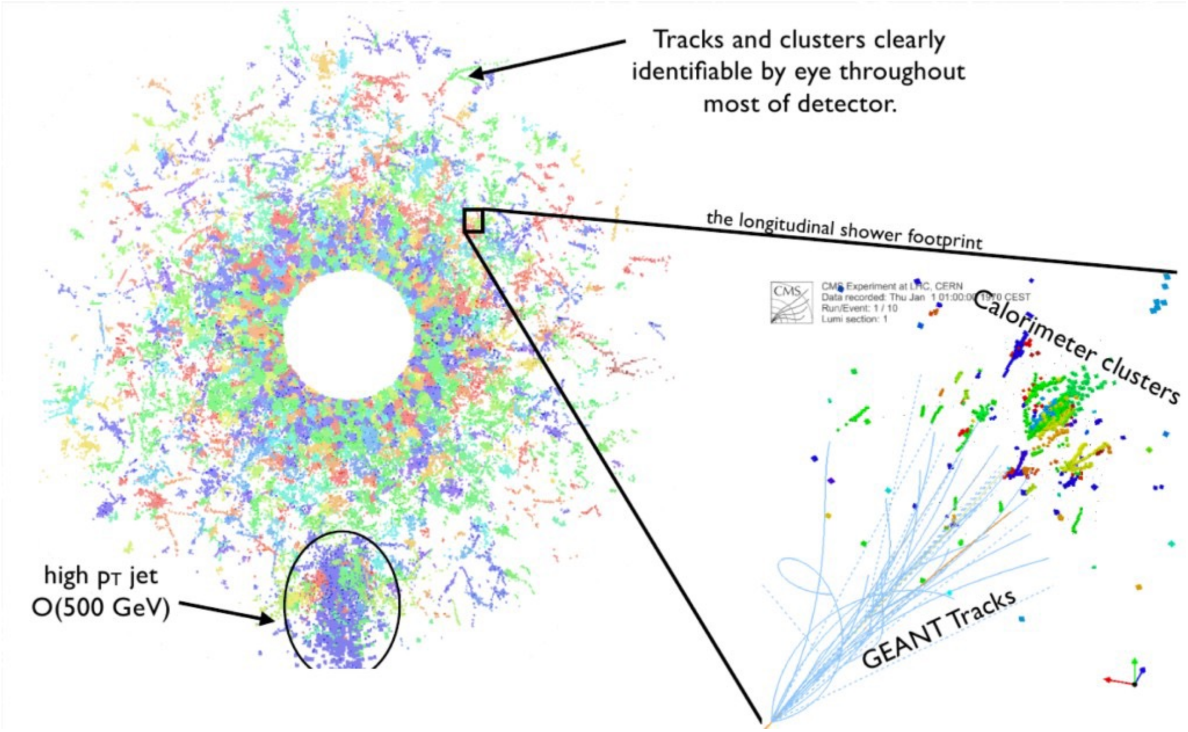


pion beam

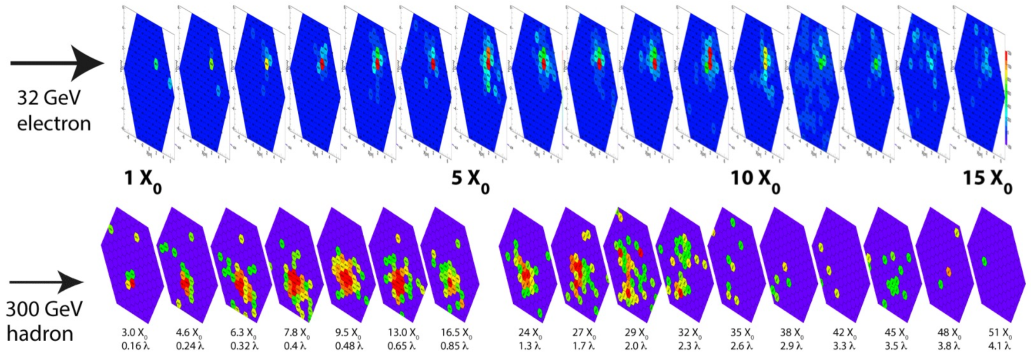


Reconstruction

- High Granularity Calorimeter → small cell size, 26 EM +21 Had layers
- Can use modern computing technologies and reconstruction algorithms
- GPUs can be used
- Machine learning for particle ID
- CLUE, CLUE3D, TICL and others explored



Development of EM (top) and had (bottom) shower in different test beams (FNAL, CERN)

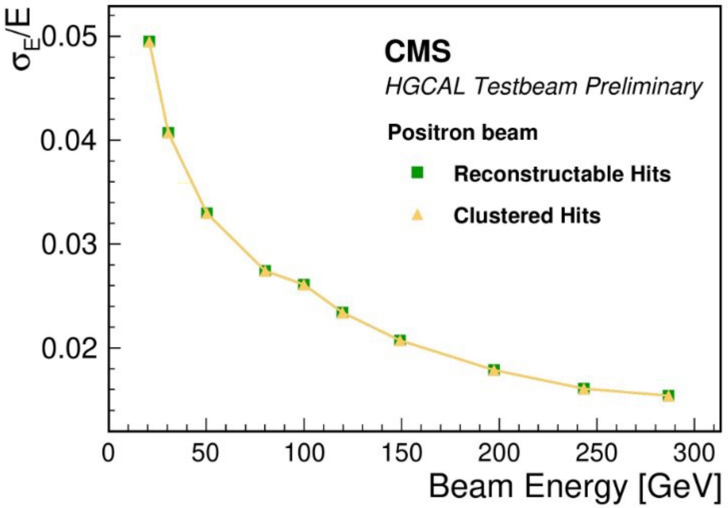


Reconstruction – Clustering Options

- Large number of recorded hits (~10^5 per event) → reduce info by building clusters

CLUE: algorithm for energy clustering:

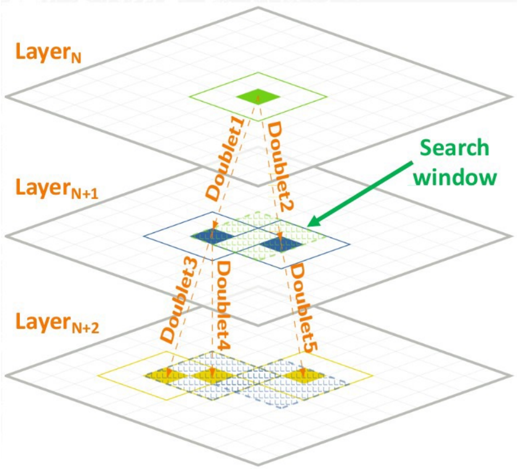
- Reduces the number of hit objects by building clusters of energy
  - Calculates energy density in a distance, defines seed/followers/outliers
- Can be parallelized and runs on GPUs
- Has been tested with testbeam data

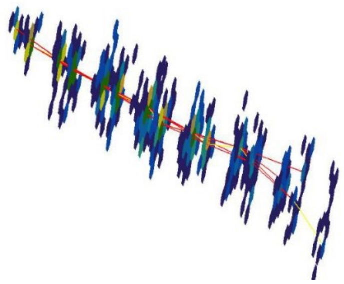


TICL: The Iterative Clustering

- Particles deposit energy and create 'Rechits'
- Rechits are clustered together to form 2D LayerClusters (CLUE algorithm)
- Clusters on different layers are linked together to form Tracksters (showers)

Iterative approach: Reconstruct simpler objects first → Mask reconstructed objects → Reconstruct more complex objects in following iterations



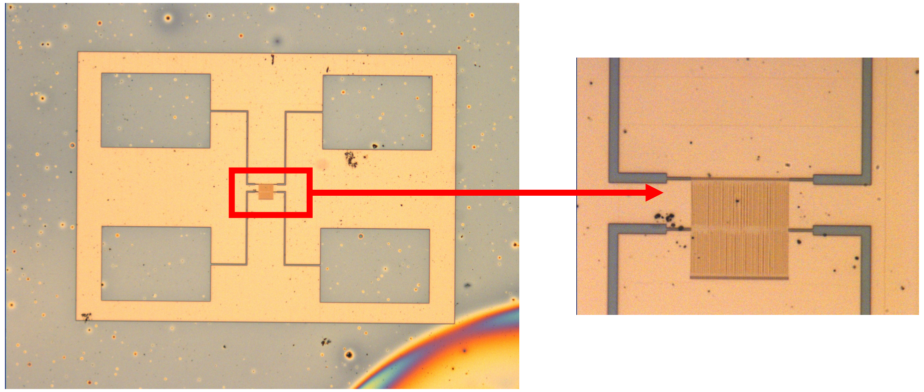


Trackster connecting several 2D LayerClusters

Other activities at NTU/TIDC

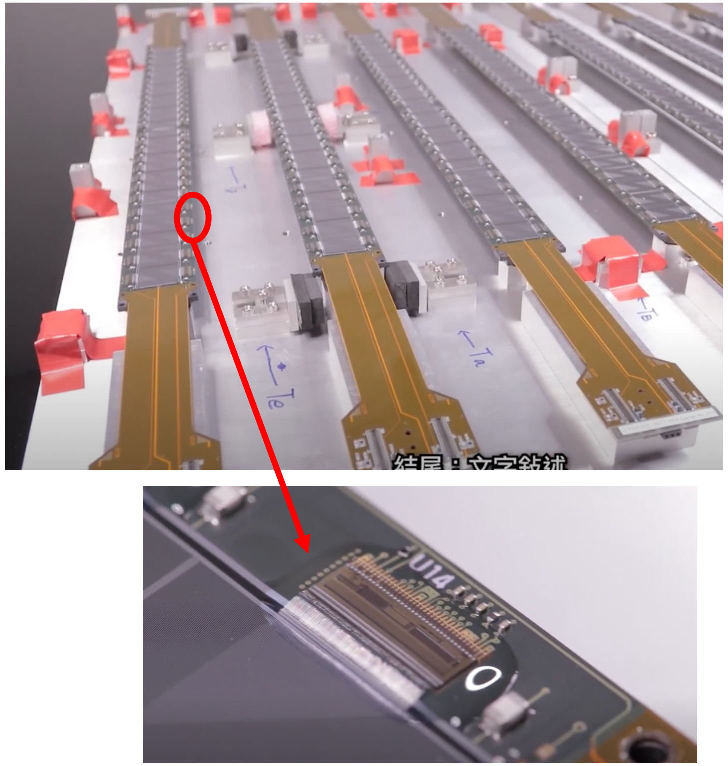
- Taiwan Instrumentation and Detector Consortium (TIDC)
- → Hardware for HGCAL, sPHENIX, STAR, AnaBHEL,..

Superconducting **N**anowire
Single **P**hoton **D**etectors:
SNSPDs
In-house manufacturing!



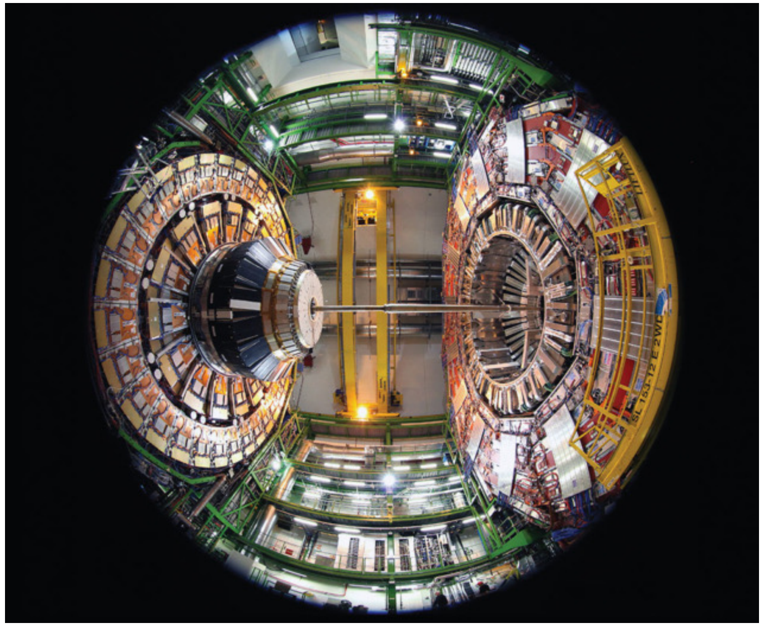
STAR
Forward Silicon Tracker

sPHENIX Silicon Strip Tracker



Summary

- High Granularity Calorimeter upgrade for CMS HL-LHC
- → Si & SiPM-on-tile
- High precision → energy, spatial, timing



- Sensors will start arriving soon
- Electronics close-to-final
- Module pre-series production to start soon
- Cassette pre-series production to start later in 2023
- Validation of parts and procedures → All sorts of tests to come! (module, cassette, testbeams)

- Exciting times ahead!

- Talk on CMS upgrades by J. Virdee tomorrow