Status of the CMS High Granularity CALorimeter

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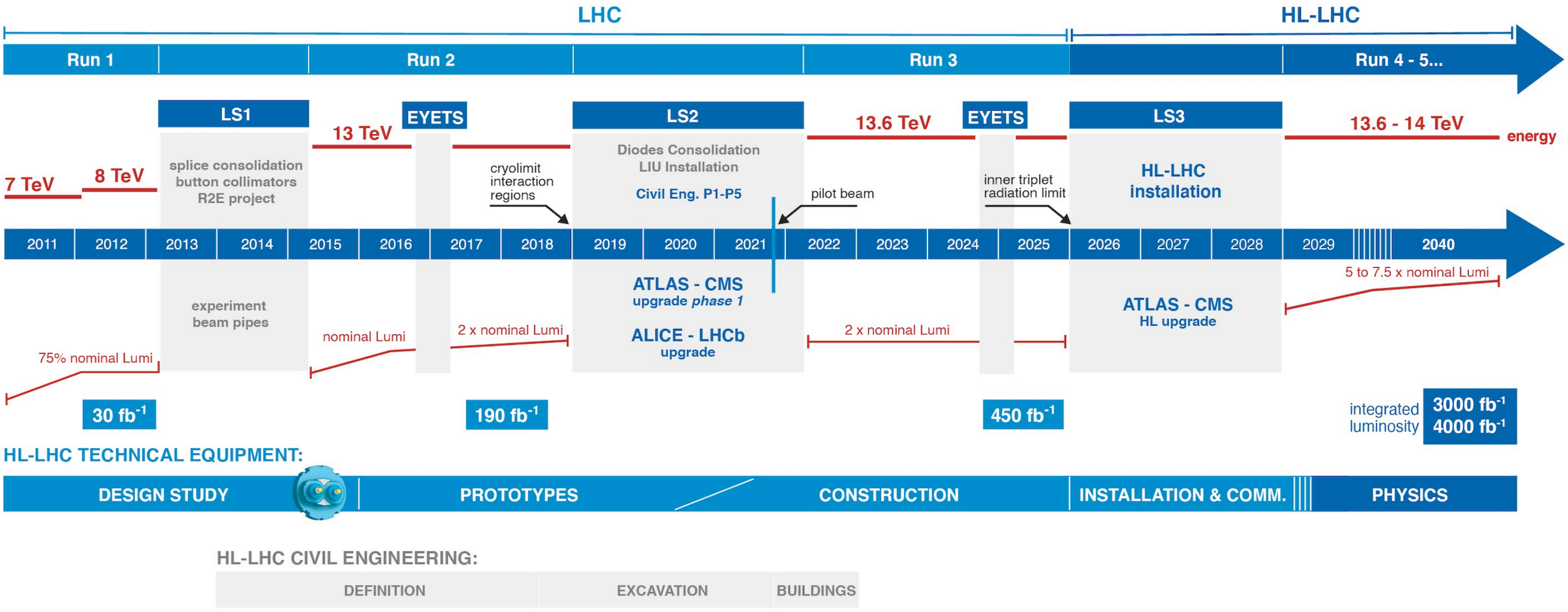
on behalf of the CMS Collaboration

CEPC International Workshop, Nanjing, China, 26-Oct-2023

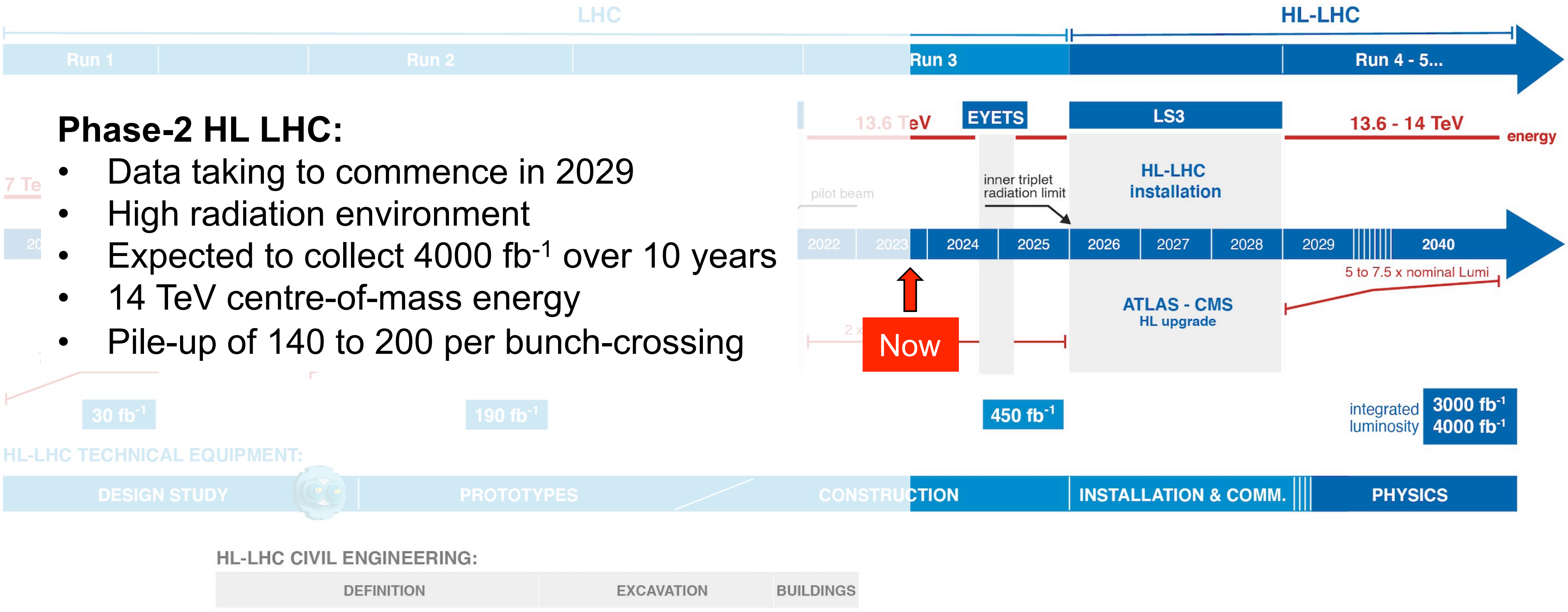
LHC / HL-LHC Plan



LHC / HL-LHC Plan

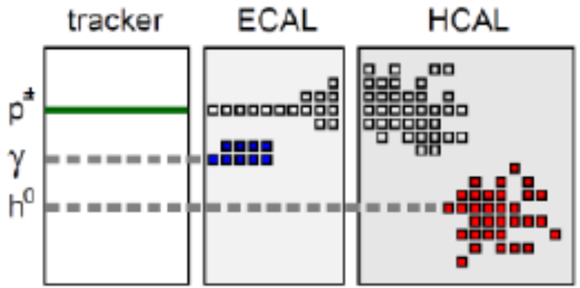
Phase-2 HL LHC:

- Data taking to commence in 2029
- High radiation environment
- Expected to collect 4000 fb^{-1} over 10 years
- 14 TeV centre-of-mass energy
- Pile-up of 140 to 200 per bunch-crossing

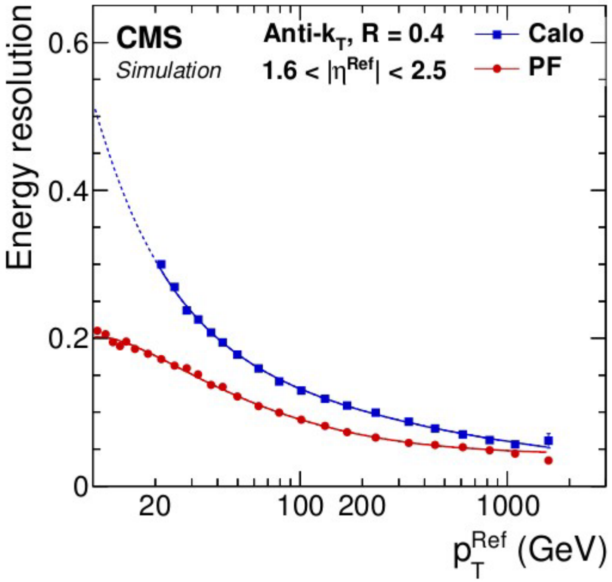


HG Calorimetry at 1.5<|η|<3.0

Case for HG Calorimeter in the forward region

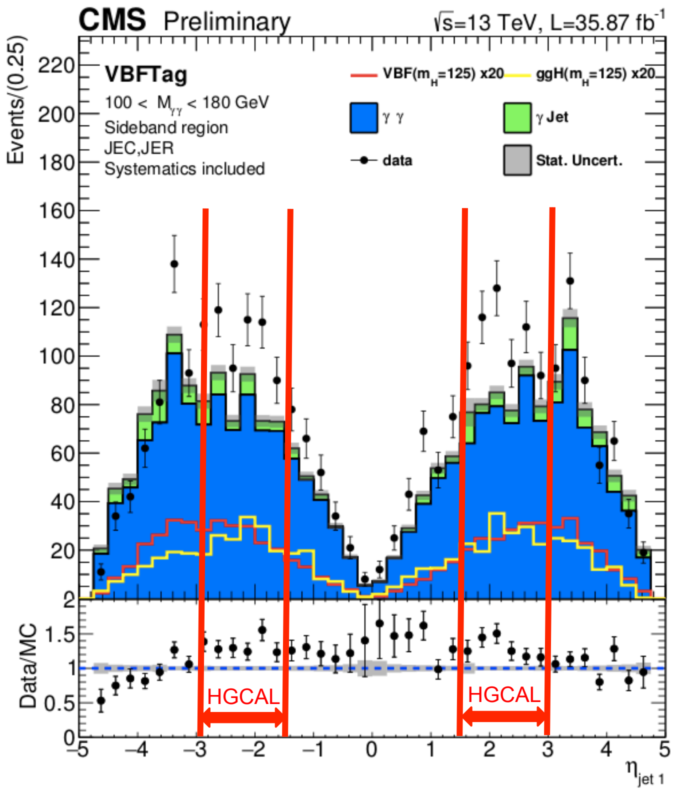


- Allows PF measurements to extend from the tracker into the calorimeter
- Allows the subtraction of the energy from pileup events leading to a good energy resolution even in a high pileup environment.



- 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/γ reconstruction/PID in the presence of PU in the forward region.
- Small constant term that typically dominates the energy resolution at high energies will lead to an EM resolution similar to the current detector.

Ideal coverage of VBS and VBF di-Higgs



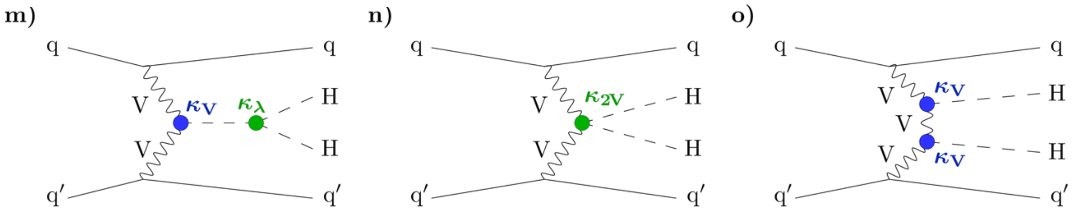
Back on the envelope VBF jet acceptance:

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

Bjorken x

Virtuality

However, for di-Higgs VBF production:



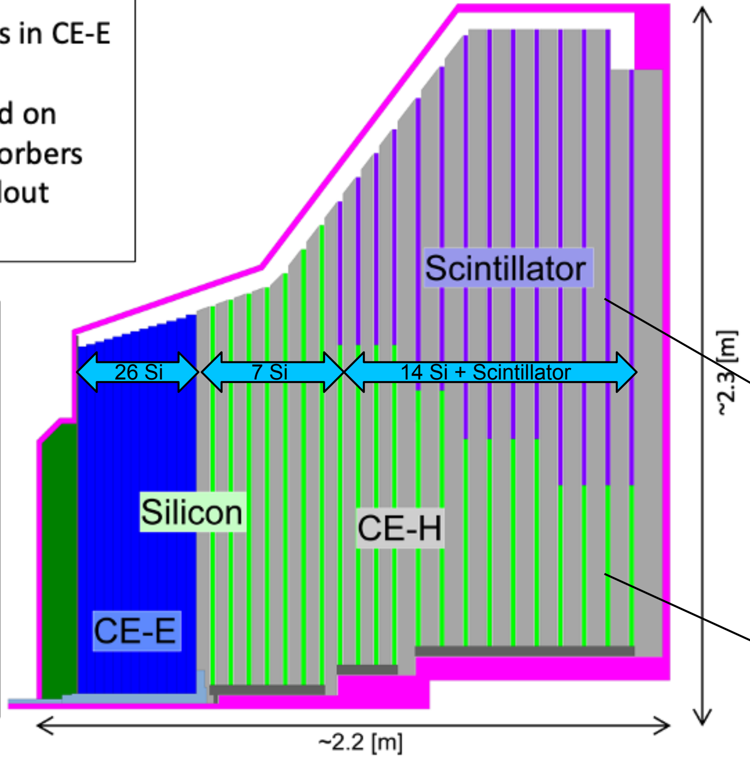
$$\boxed{\eta(\mathrm{HH}) = a\cosh\left(\frac{P}{M_H}\right) \sim 2.3}$$

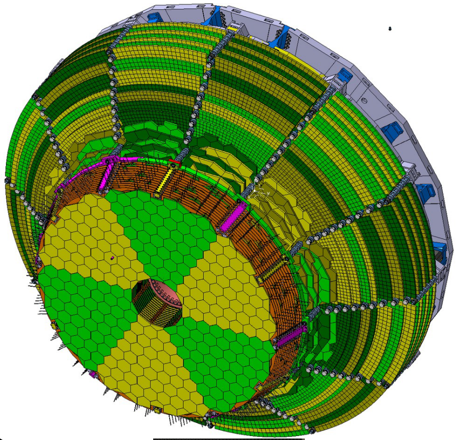
Quark jets go right in the center of HGCAL

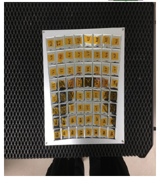
The CMS HGCAL

Active Elements:
- Hexagonal modules based on Si sensors in CE-E and high-radiation regions of CE-H
- "Cassettes": multiple modules mounted on cooling plates with electronics and absorbers
- Scintillating tiles with on-tile SiPM readout in low-radiation regions of CE-H

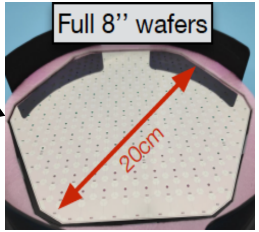
Key Parameters:
Coverage: $1.5 < |\eta| < 3.0$
~215 tonnes per endcap
Full system maintained at -30°C
~620m^2 Si sensors in ~26000 modules
~6M Si channels, 0.6 or 1.2cm^2 cell size
~370m^2 of scintillators in ~3700 boards
~240k scint. channels, 4-30cm^2 cell size
Power at end of HL-LHC:
~125 kW per endcap







240,000 individual tiles

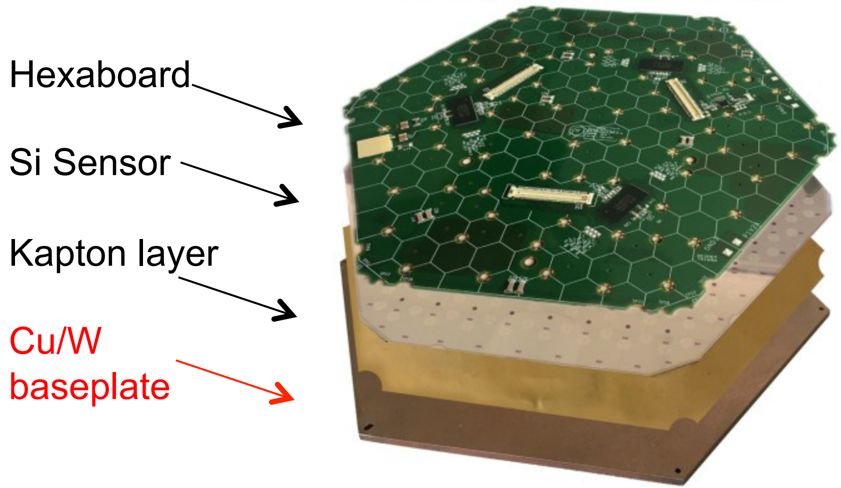


26,000 Sensors 6M Si Channels

Electromagnetic 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

Silicon Modules

8-inch prototype module stack-up



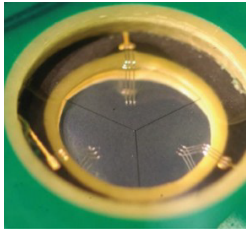
PCB ('Hexaboard') – Sensor
- Read-out (HGCROC) of sensor cells + bias supply
- Connects to motherboard for data transfer

Silicon sensor: 26k sensors, 6M pads

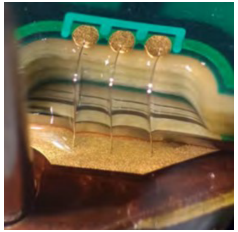
Kapton sheet
- Isolation to baseplate + bias supply to sensor back side

Baseplate
- Rigidity, contributes to absorber material

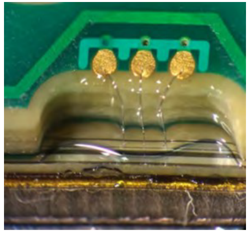
Si pads bonded to PCB



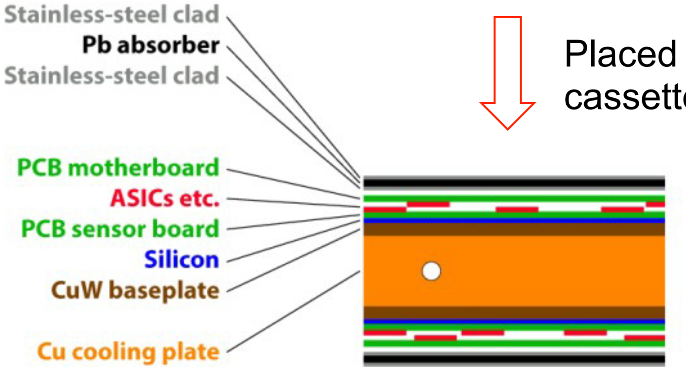
HV bias contacts



Guard ring contacts

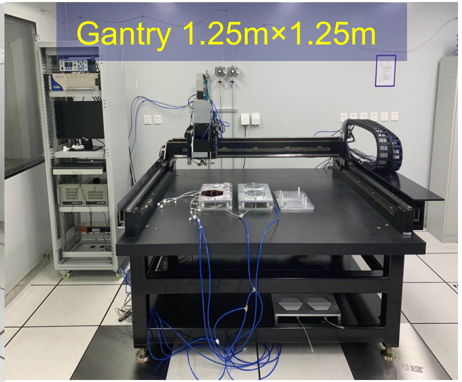


Placed in cassettes

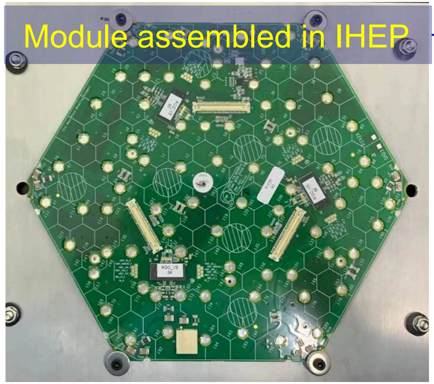


Si Module Assembly Centers

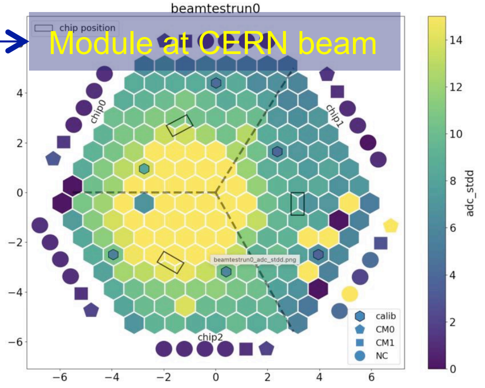
OGP ZIP635



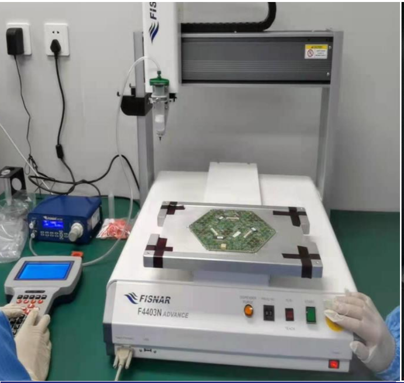
Gantry 1.25m×1.25m



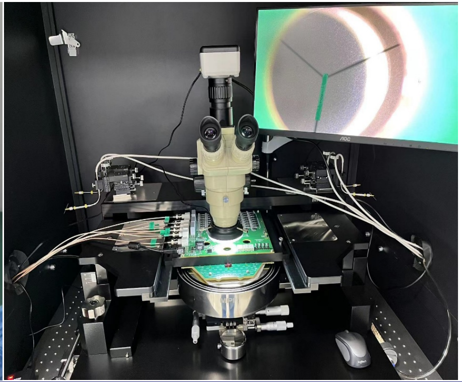
Module assembled in IHEP



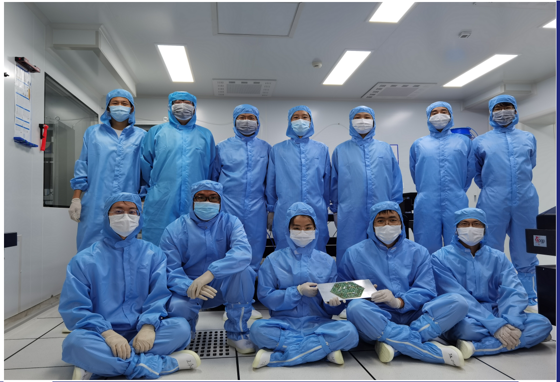
Module at CERN beam



Encapsulation gantry



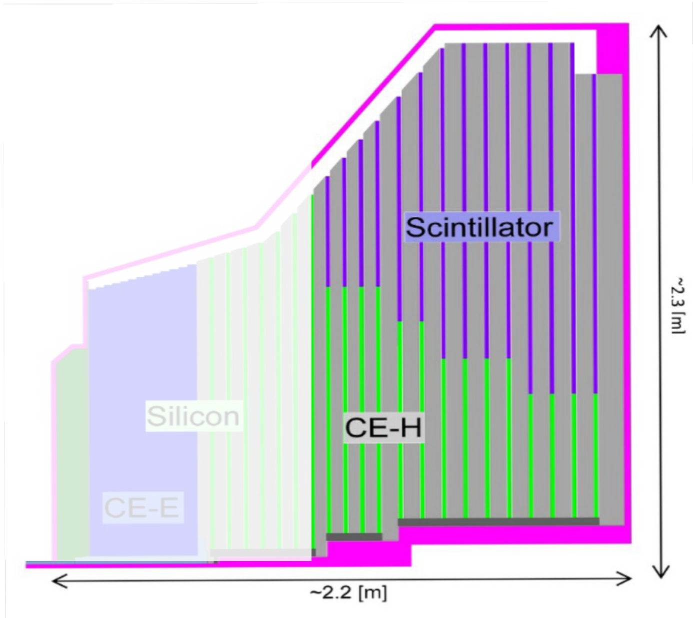
Probe station: MPI TS200



Beijing-IHEP MAC Team

- IHEP MAC: 140m^2 class 1000 cleanroom
- First working 8” module assembled in 2021
- 2023: expected to produce 14 modules
- Mass production to commence in 2024

SiPM-on-Tile Scintillators



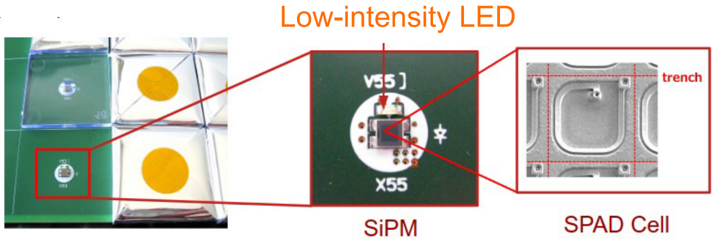
In the back of HGCAL:
14 hybrid Si-Scintillator layers

Scint-Pad cells (SPAD): ranging from 2 to 30cm^2

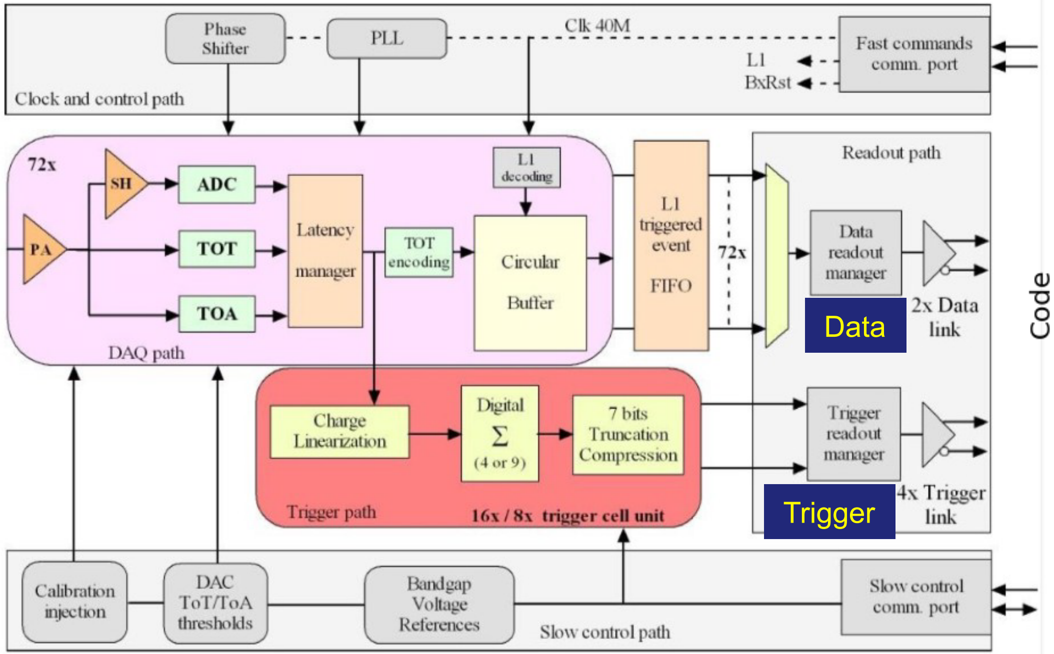
Tileboard PCB hosting the readout chip

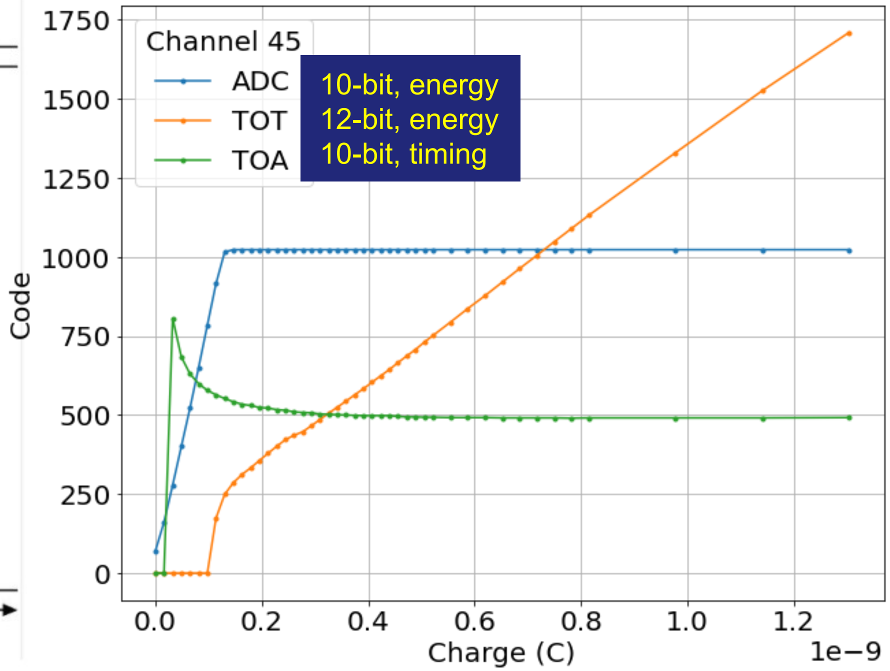
Wrapped scintillating tiles by reflective foil

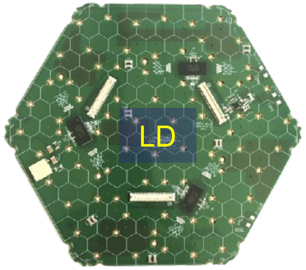
Silicon PMT (SiPM) with LED calibration

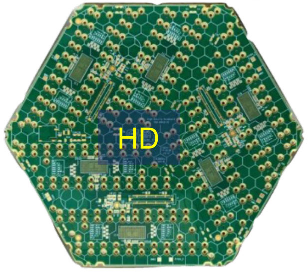


Front-End ASIC: HGCROC

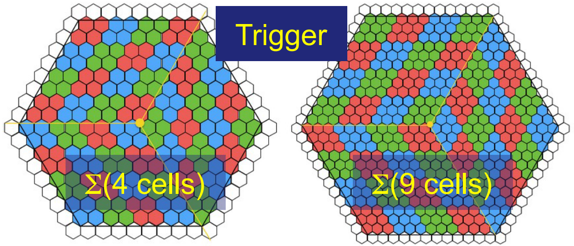




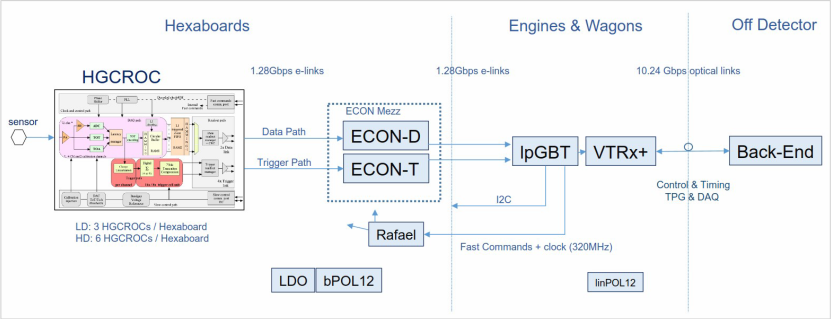


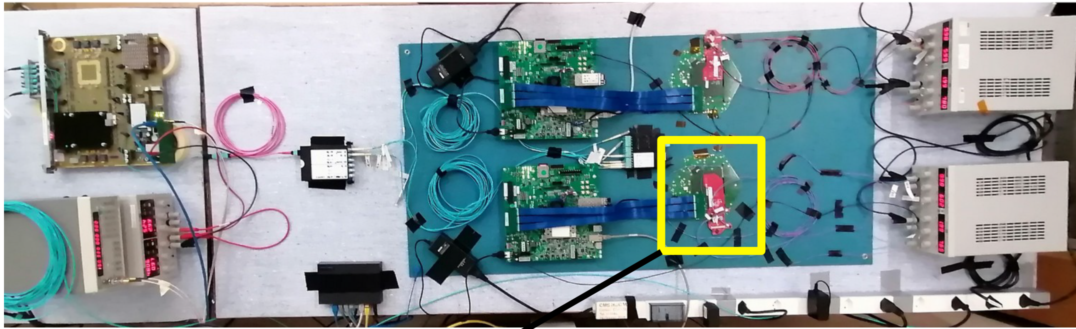


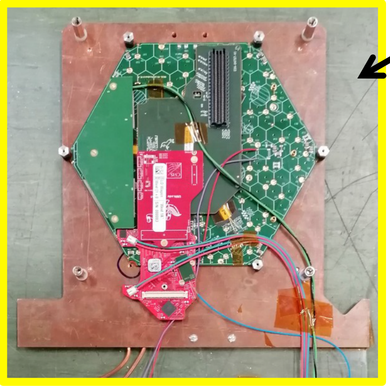
Low Density : 3×78 cells
High Density: 6×78 cells

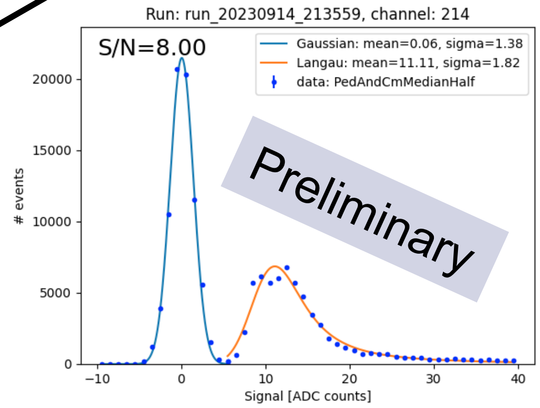


Electronics: full readout chain









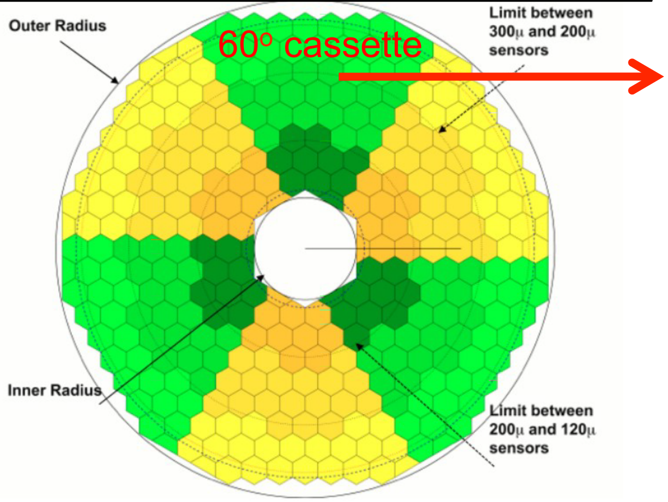
- HGCROCs hosted in hexaboards
- ECONs: Concentrator chips
  - ECON-T: select/compress trigger data, transmit at 40MHz
  - ECON-D: full resolution data after trigger accept, zero suppression, transmit at 750kHz
- Engines & Wagons: host lpGBT/VTRX, transmit to DAQ back-end, clock distribution, configuration.
- Back-End (off-detector electronics)

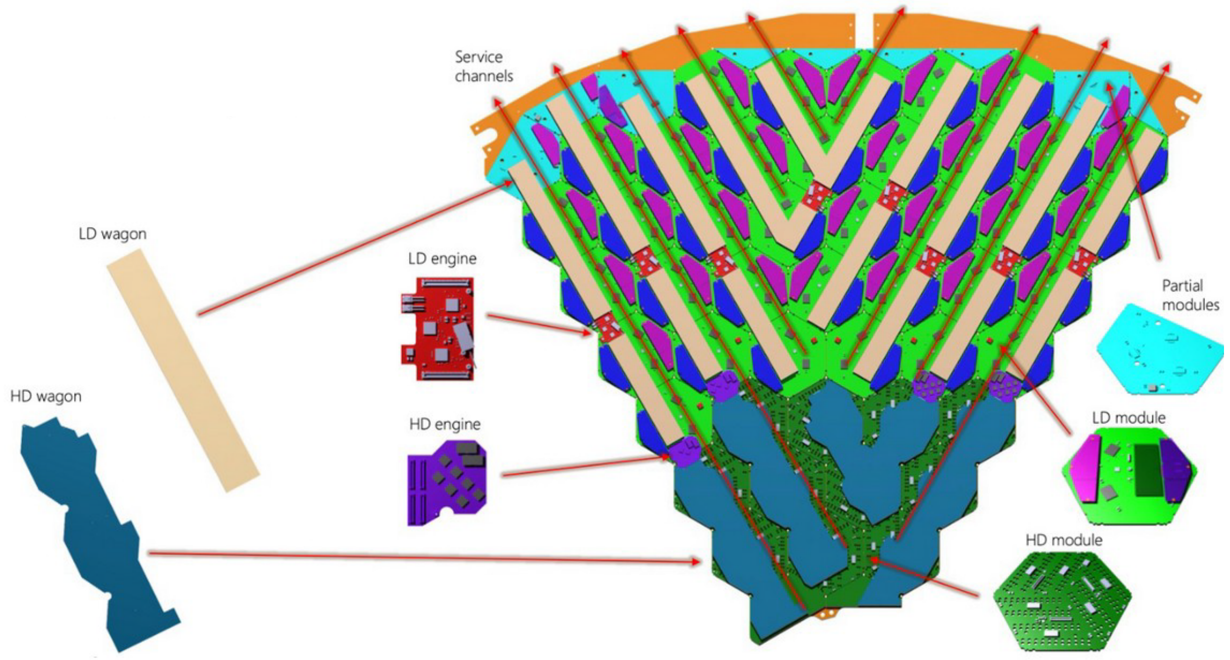
MIP analysis in the 2023 CERN test beam

Module integration into Si Cassettes

CE-E: EM section
- Double-sided cassettes, self supporting, integrated absorber (Cu cooling plate, Pb cover)

CE-H: Hadronic section
- Single-sided cassettes, mounted between steel absorbers
- All-Si and mixed cassettes (Si modules, SiPM-on-tile modules)

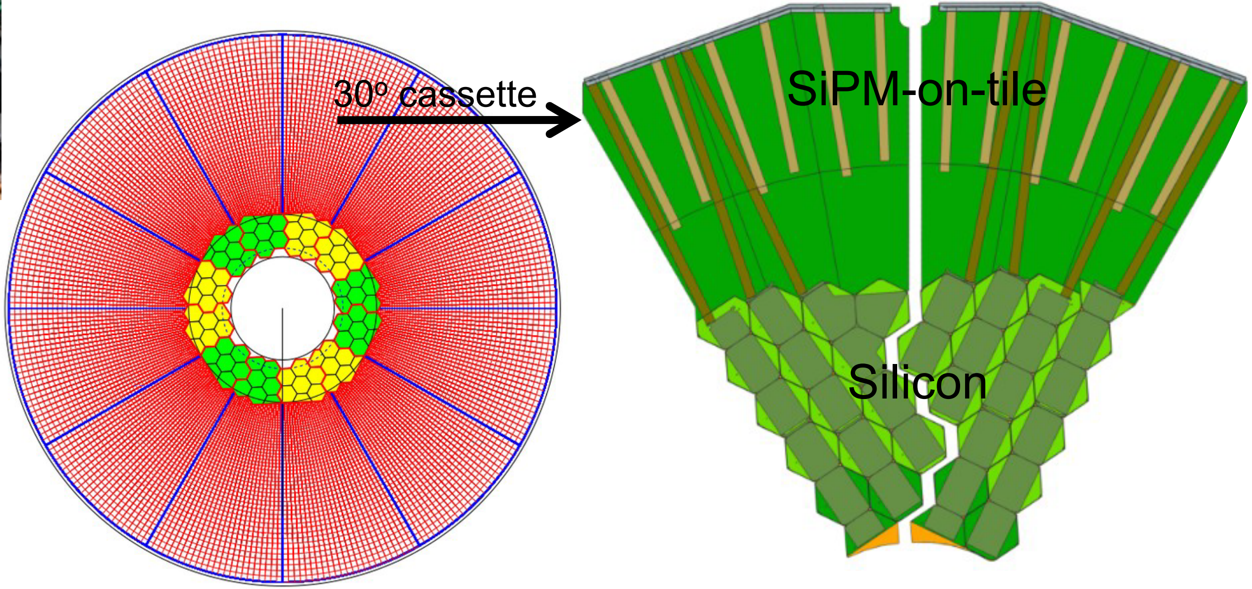


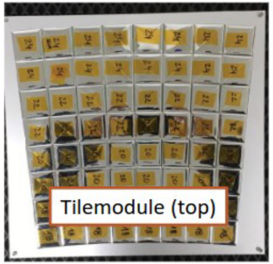


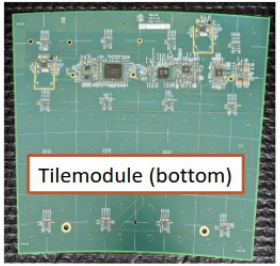
- Passive wagon board is connected to one to three modules
- LD, HD engine boards are connected to two wagon boards
- Data transmission via optical links to off-detector electronics

Module integration: mixed Cassettes

Tile modules are assembled in Tile Assembly Centers (TAC).
Tile and Si modules, the are about to be assembled in cassettes.



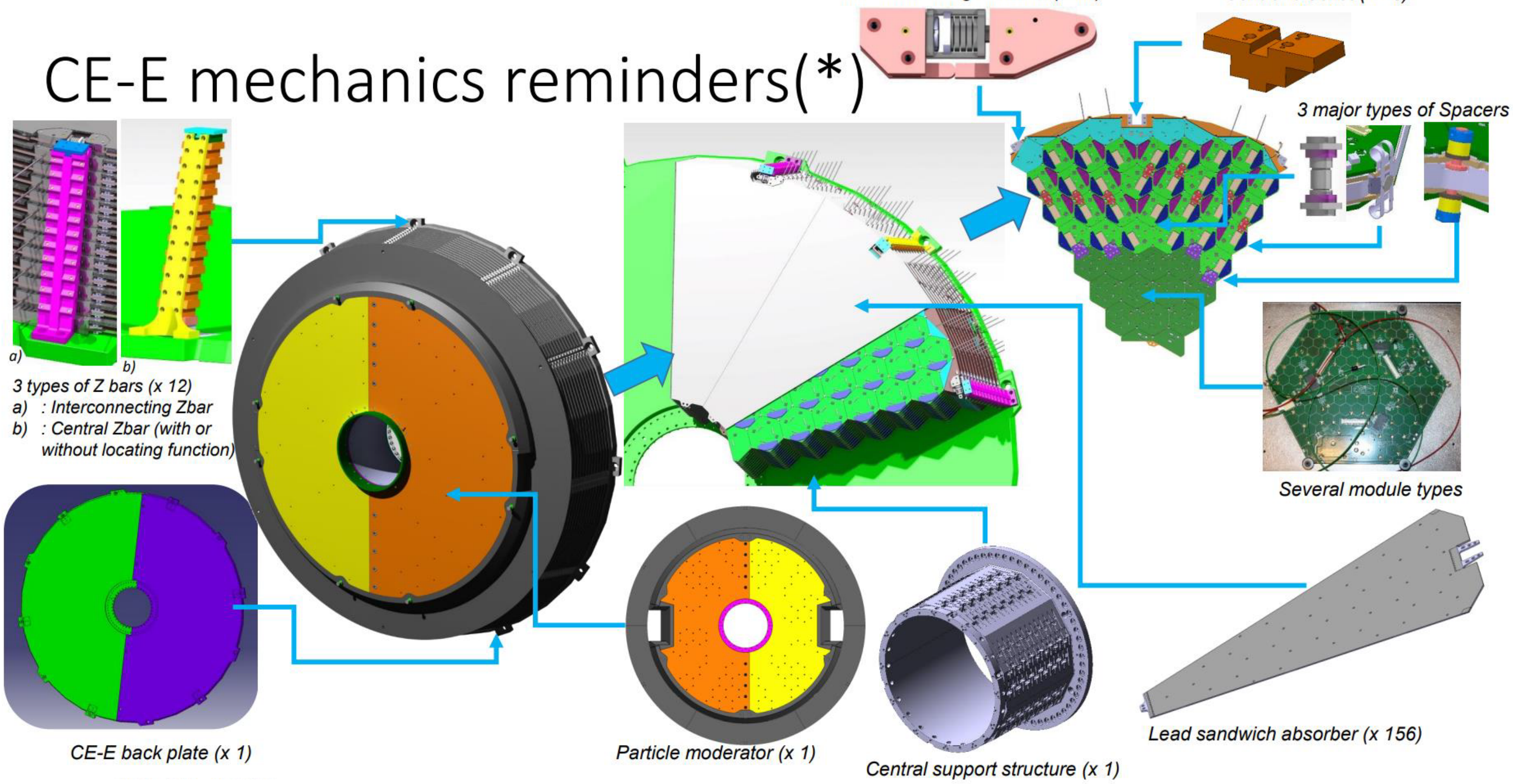




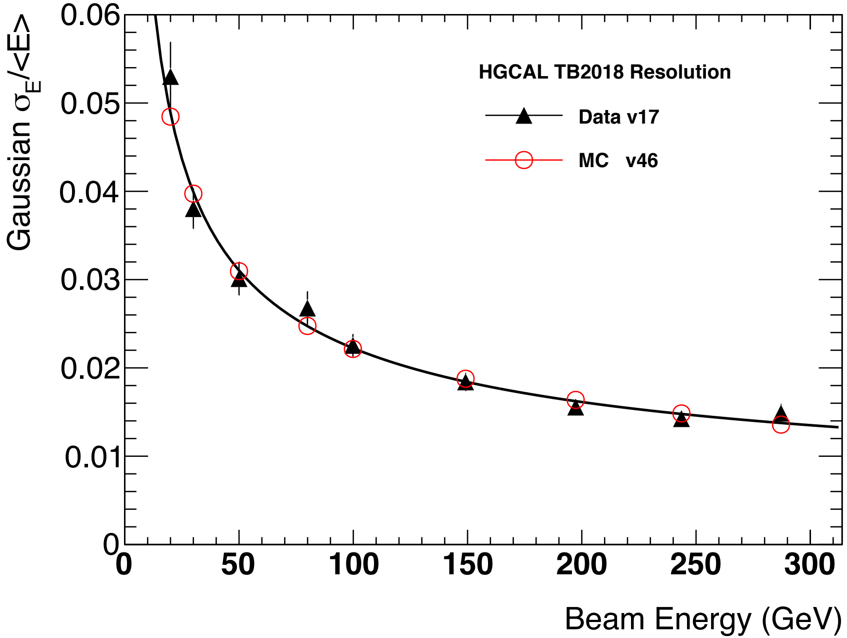
240k SiPM-on-tile
3744 Tilemodules

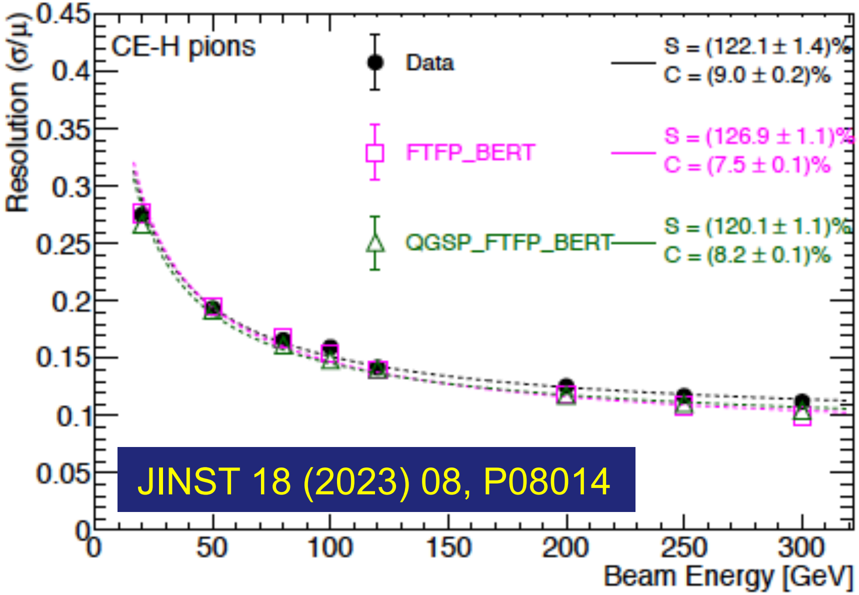
Integration into a full detector

Courtesy of the overall engineering team



Energy Resolution: TB2018





JINST 18 (2023) 08, P08014

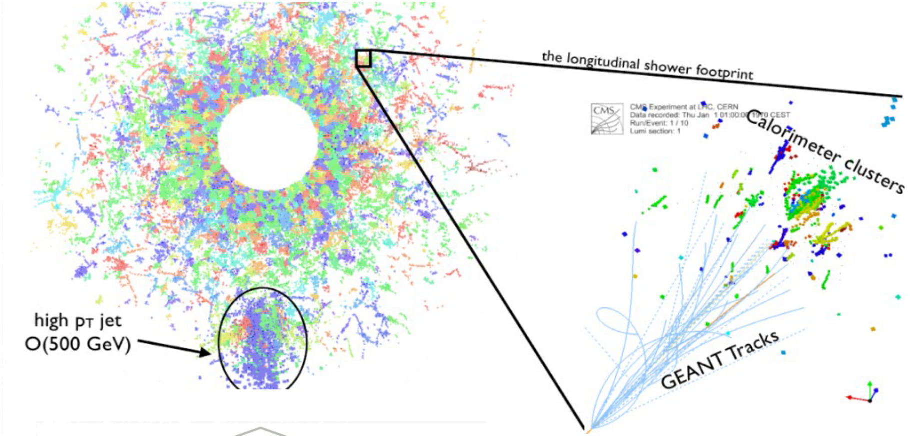
Data fit:
Stochastic term: 21.6±0.8%
Constant term: 0.52±0.23%

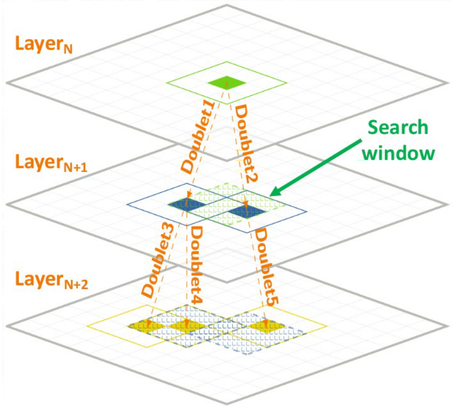
MC fit:
Stochastic term: 21.5±0.1%
Constant term: 0.54±0.03%

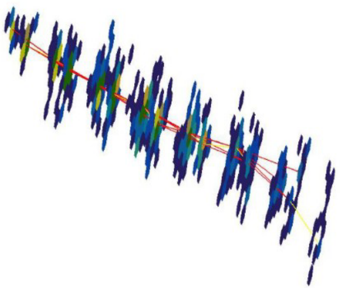
JINST 17 (2022) 05, P05022

Reconstruction of physics objects

Novel reconstruction algorithms are employed, including machine learning for PID



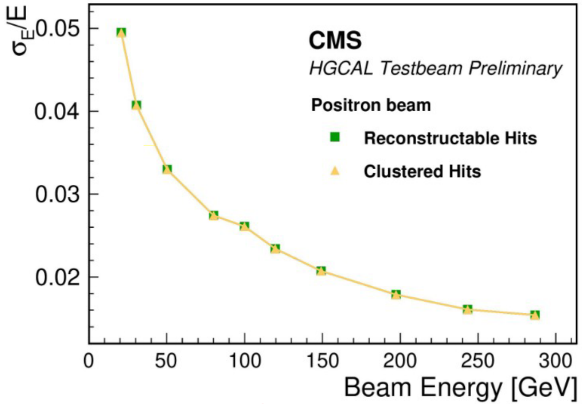




Trackster connecting several 2D LayerClusters

CLUE: algorithm for energy clustering

- Reduces the number of hit objects by building clusters of energy
- Can be parallelized and runs on GPUs
- **tested with beam-test data**



TICL: The Iterative Clustering

- Impinging particles create ‘Rechits’
- Rechits are clustered together to form 2D LayerClusters (CLUE algorithm)
- Clusters on different layers are linked together to form Tracksters (showers)

Summary

- The **H**igh **G**ranularity **CAL**orimeter is the choice for the upgraded CMS endcap for the phase-2, High-Luminosity LHC.
  - ~6M silicon & 240k scintillator channels: energy, position, timing.
  - High spatial granularity detector.
  - Precise timing for showers.
  - Energy measurements from MIPs to TeV showers.

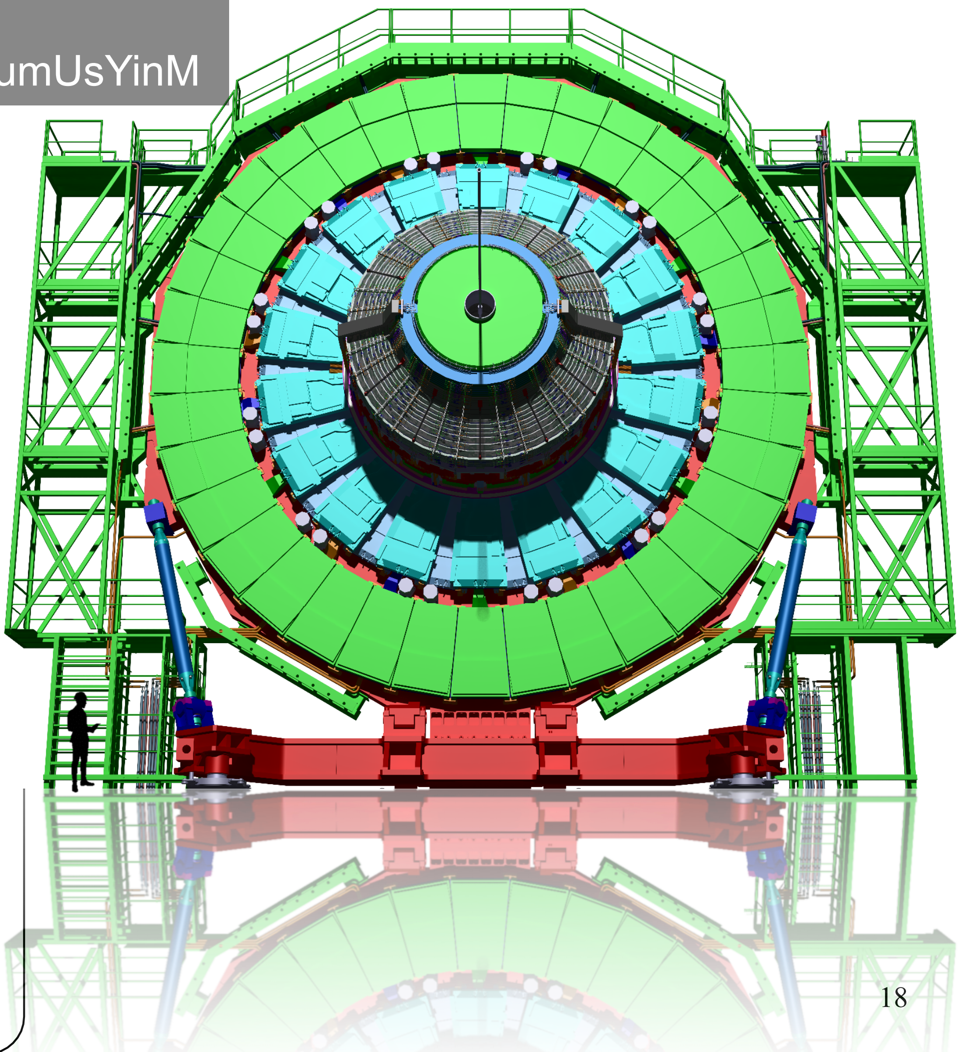
- HGCAL has just completed the R&D phase: entering the construction phase.
  - System performance successfully tested in testbeams and lab tests.
  - Results in agreement with expectations.
  - Full readout chain with all ASICs tested.
  - Integration to Si/tile cassettes about to start.
  - Most components close to final design.

HGCAL integration animation: https://www.youtube.com/watch?v=5EKumUsYinM

- The Phase-2 Upgrade of the CMS Endcap Calorimeter, TDR, CMS Collaboration, CERN-LHCC-2017-023 / CMS-TDR-019

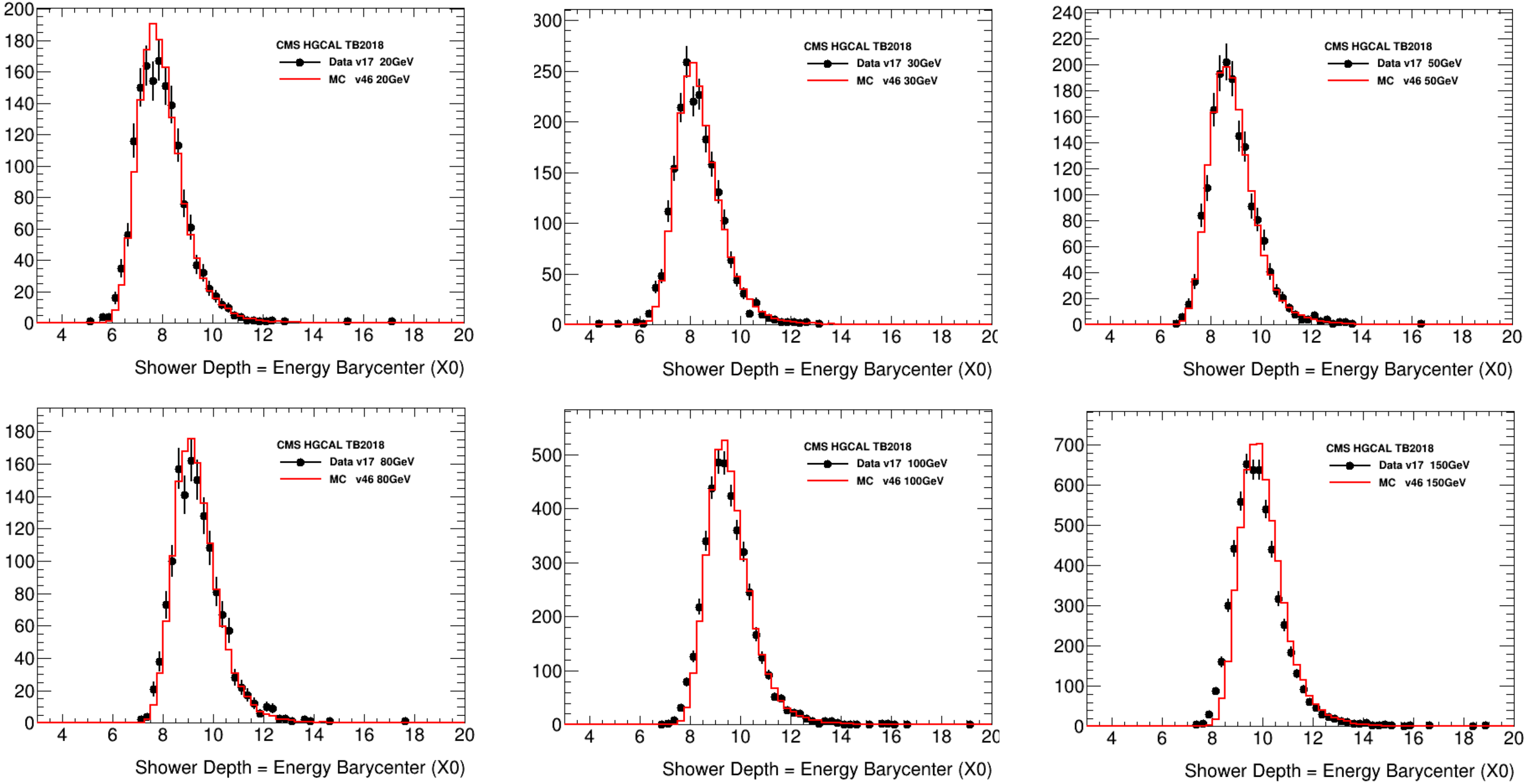
Sample Publications:

- Performance of CMS High Granularity Calorimeter prototype to charged pion beams of 20-300 GeV/c, JINST 18 (2023) 18, P08014
- Neutron Irradiation and Electrical Characterization on the First 8" Silicon Pad Sensor Prototypes for the CMS Endcap Calorimeter Upgrade, JINST 18 (2023) 08, P08024
- 'Response of a CMS HGCAL silicon-pad electromagnetic calorimeter prototype to 20-300 GeV positrons', JINST 17 (2022) 14, P05022
- The DAQ system of the 12,000 channel CMS high granularity calorimeter prototype, JINST 16 (2021) 04, T04001
- Construction and commissioning of CMS CE prototype silicon modules, JINST 16 (2021) 04, T04002
- Charge collection and electrical characterization of neutron irradiated silicon pad detectors for the CMS High Granularity Calorimeter (L-A), N. Akchurin et.al., JINST 15 (2020) 09, P09031
- First beam tests of prototype silicon modules for the CMS High Granularity Endcap Calorimeter, JINST 13 (2018) 10, P10023



Extra Slides

Shower depth



Shower depth