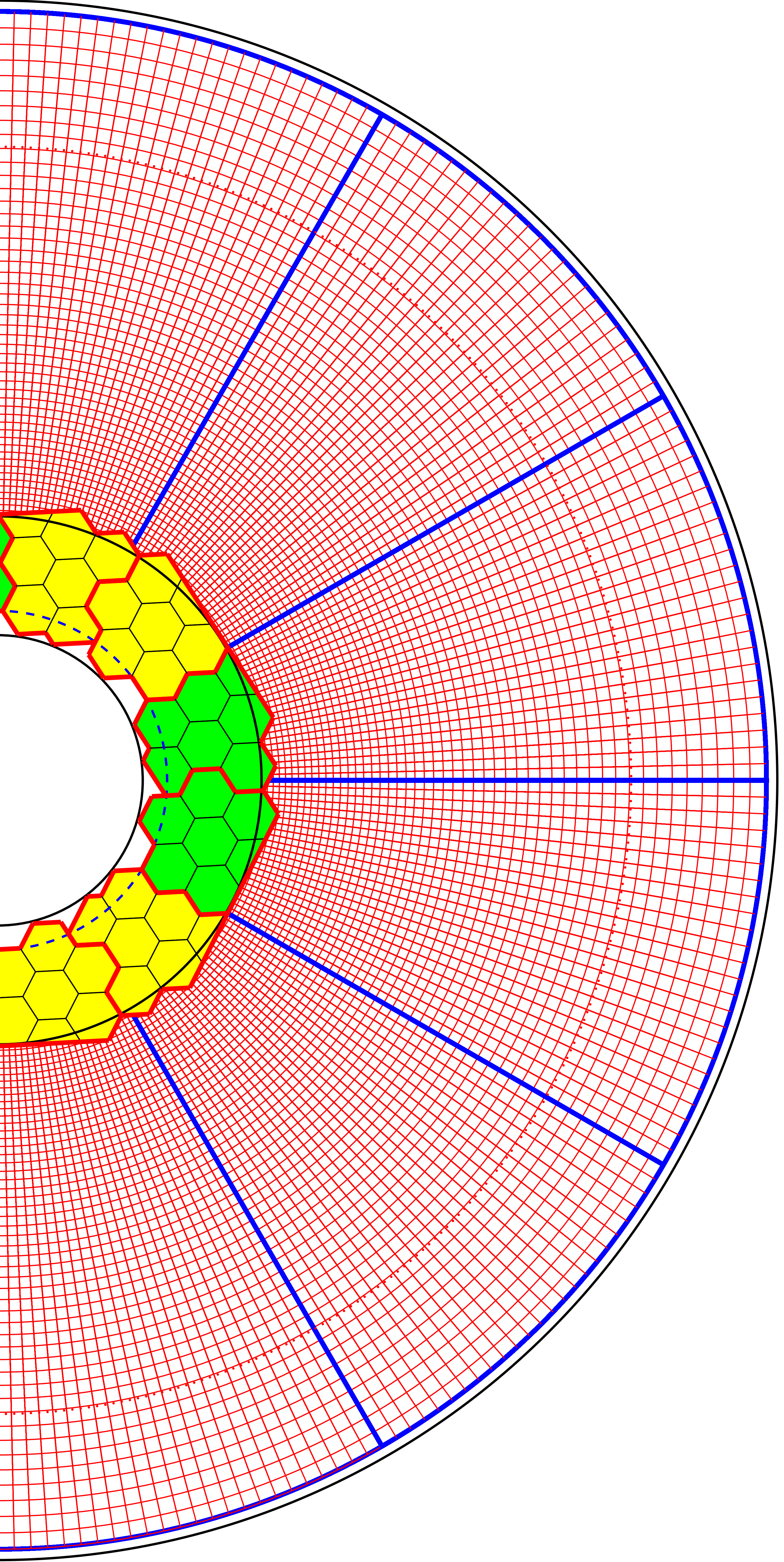


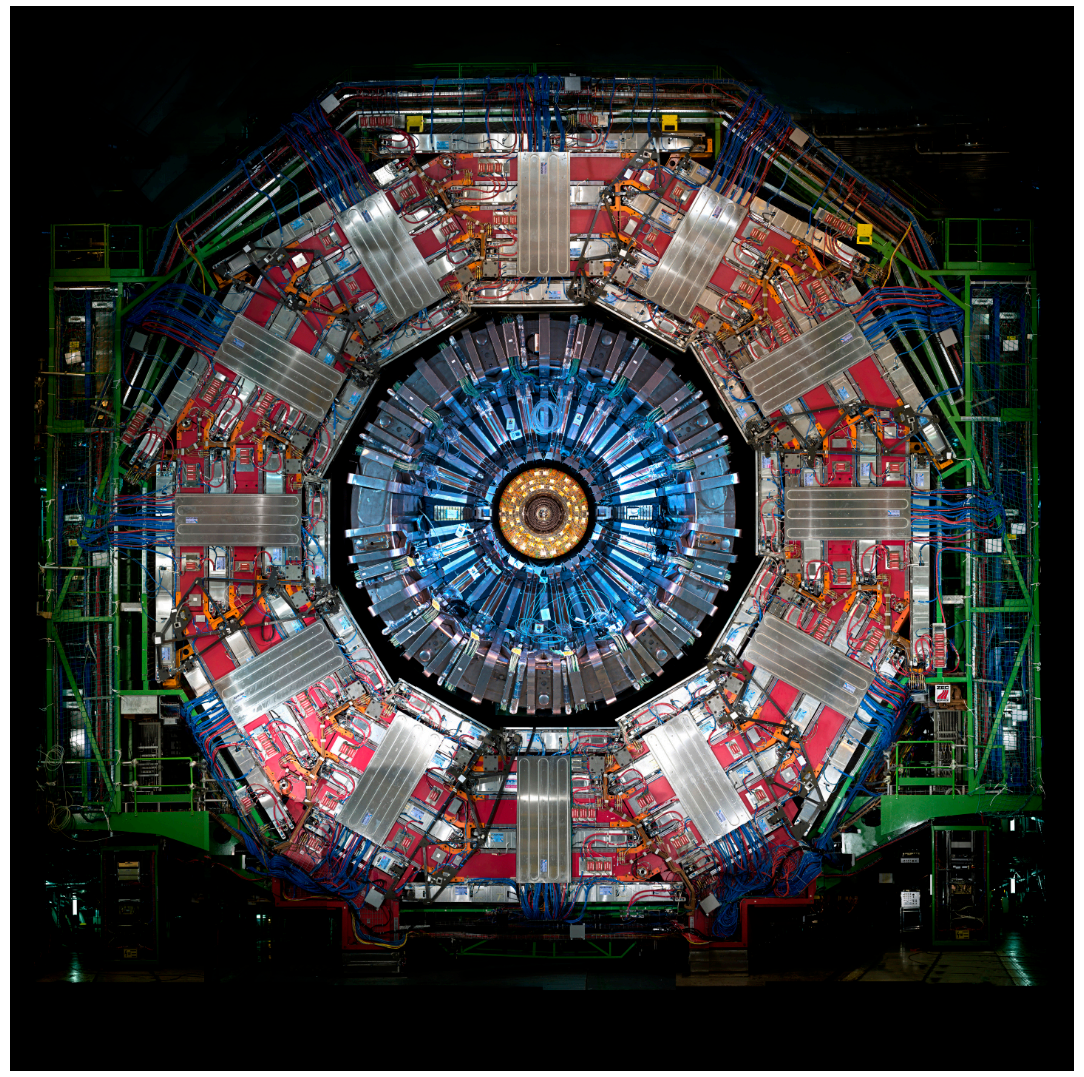
An overview of the CMS High-Granularity Calorimeter

Chiara Amendola
CERN

on behalf of the CMS Collaboration

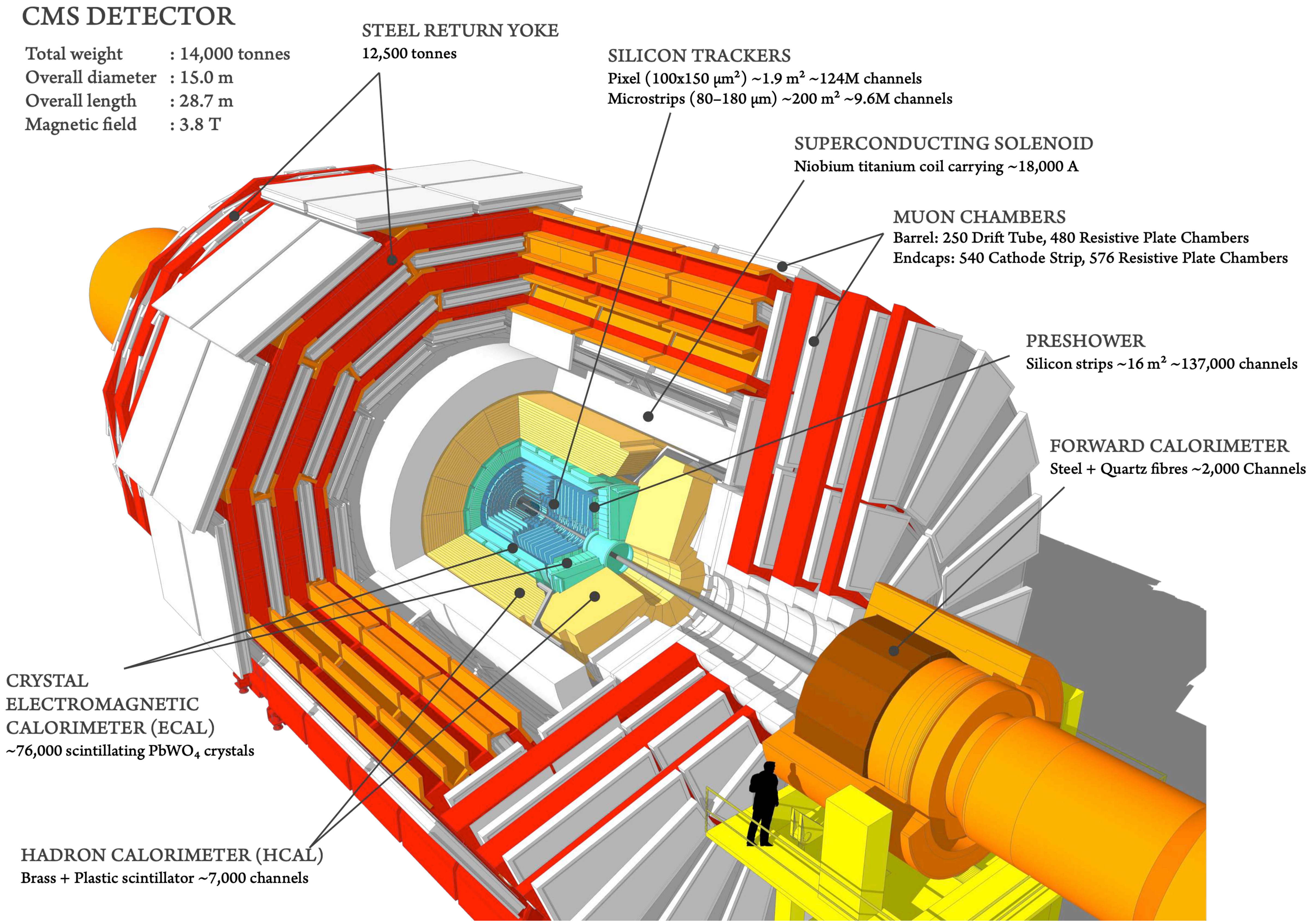
International Workshop on Radiation Imaging Detectors
July 1st, 2024

CMS: Compact Muon Solenoid



Operating at the Large Hadron Collider (LHC), CERN

- Multi-purpose experiment: Higgs sector physics, Standard Model (SM) precision measurements, searches Beyond the SM (BSM)...
- Several sub-detectors nested around the LHC collision interaction point

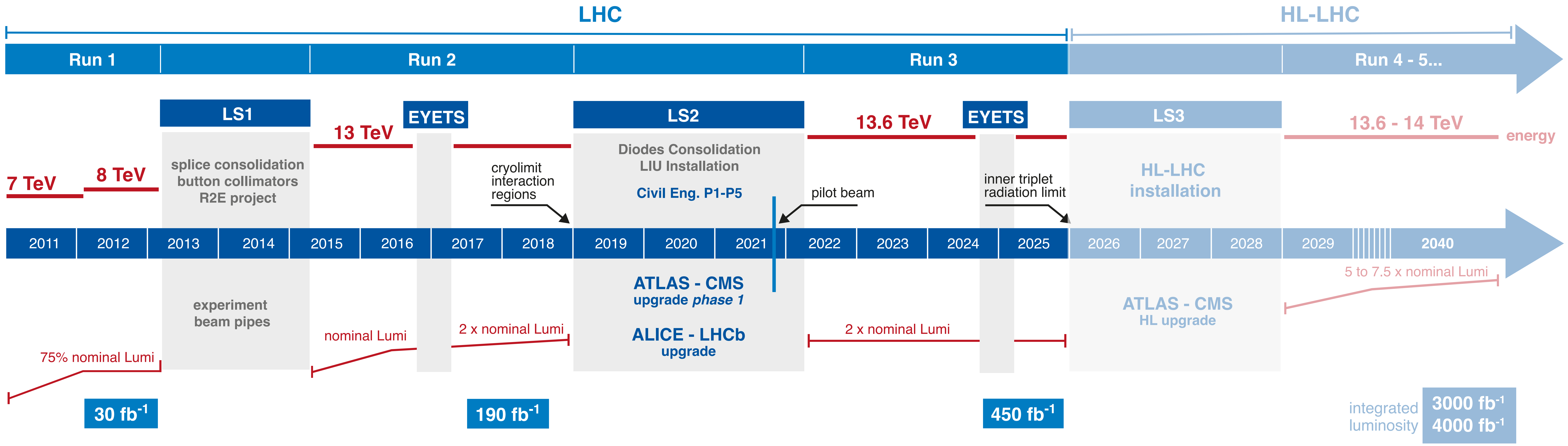


- Trajectory of the **charged particles** bent by the 3.8 T magnetic field
- Nature, energy and direction of the **stable particles** deduced from the combined information of all the sub-detectors
- **Higher-level objects** (jets, τ leptons, missing transverse momentum) built up from detected particles

Towards the High-Luminosity LHC (HL-LHC)

LHC operations target:

- Large **center-of-mass energy** to produce heavy particles (e.g. $m_H \sim 125$ GeV)
- Large **number of collisions** to probe rare processes (e.g. $\sigma_{gg \to HH} \sim 30$ fb)



High luminosity implies:

- Exposure of active material, readout sensors, and electronics to **high radiation dose**
- **Large pileup**, affecting the vertex and object reconstruction offline and at trigger level

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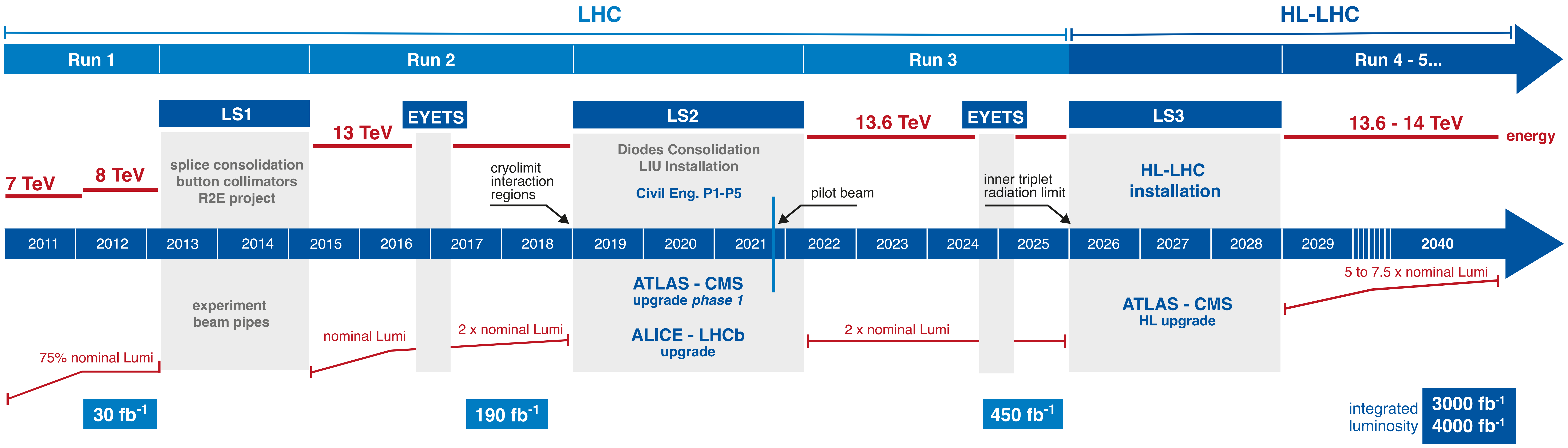
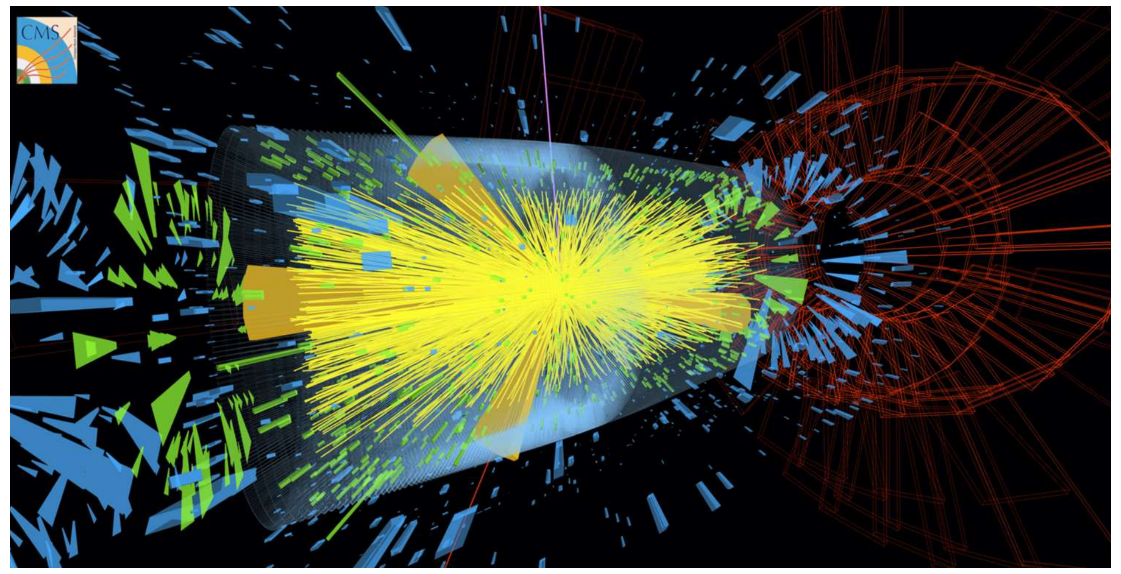
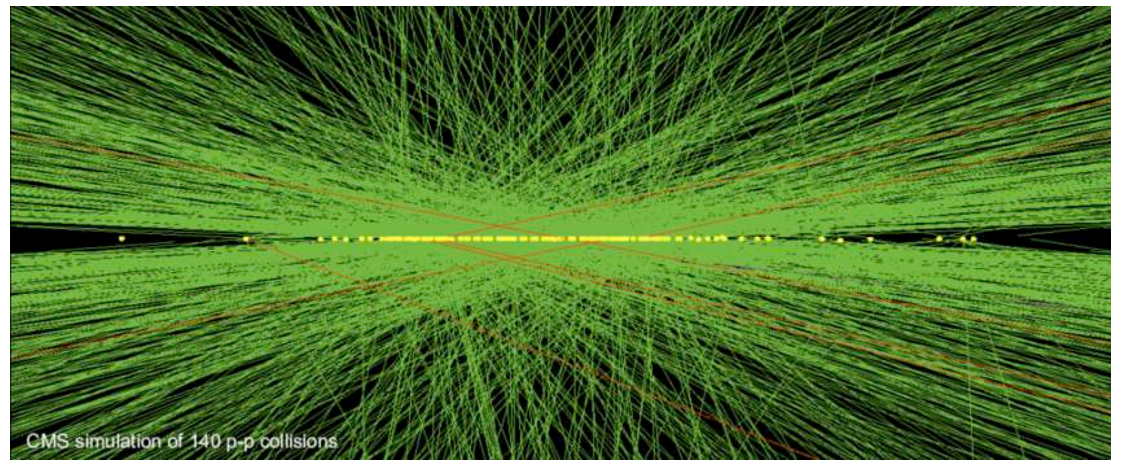


Pileup 140-200 at HL-LHC
(over 2x w.r.t. LHC busiest interactions)





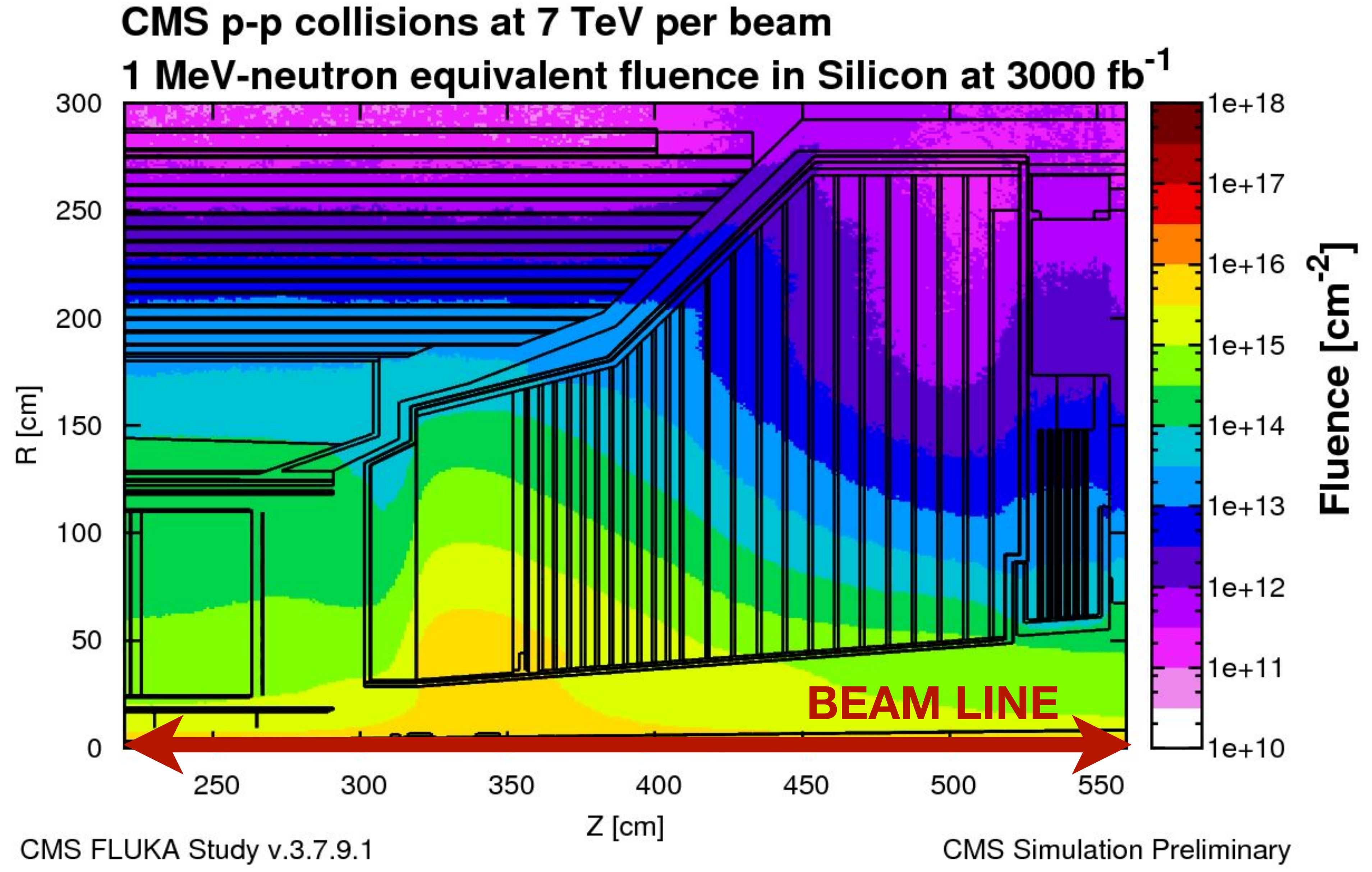
High luminosity implies:

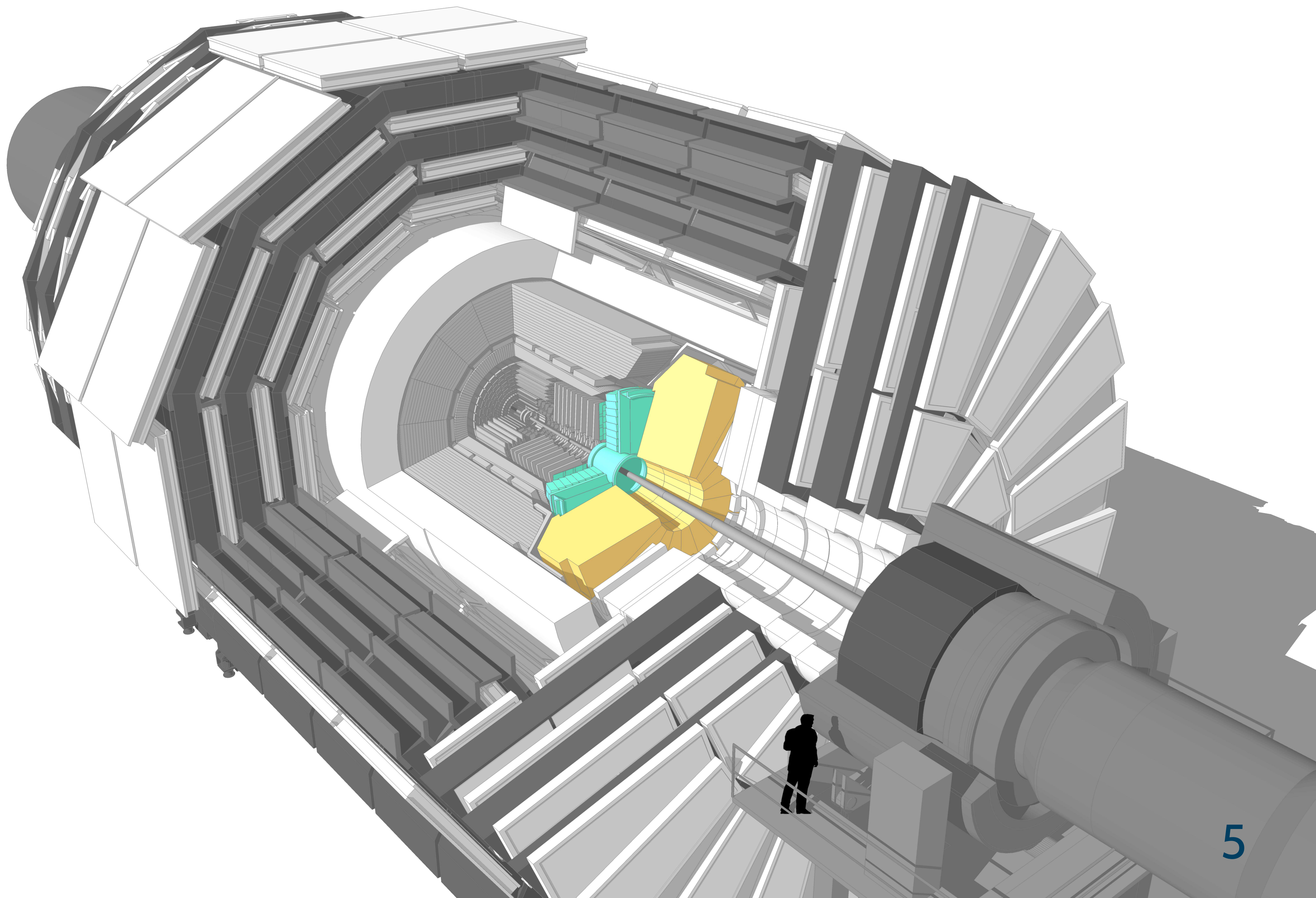
- Exposure of active material, readout sensors, and electronics to **high radiation dose**
- **Large pileup**, affecting the vertex and object reconstruction offline and at trigger level

The CMS subsystems will be upgraded to cope with the harsher radiation environment

A new forward calorimeter

- Existing endcap electromagnetic calorimeter ($PbWO_4$) and hadronic calorimeter (plastic scintillator) designed for 500 fb^{-1} integrated luminosity
- To be replaced by a novel **radiation-hard calorimeter,** which must withstand:
  - Fluence up to ~ 10^{16} n_{eq}/cm^2
  - Absorbed dose up to 2 MGy





Physics performance needs:

- High 3D spacial granularity and geometric acceptance on **forward physics**
- **Precision timing** (sub-nanosecond) to contribute to the improvement of vertex resolution

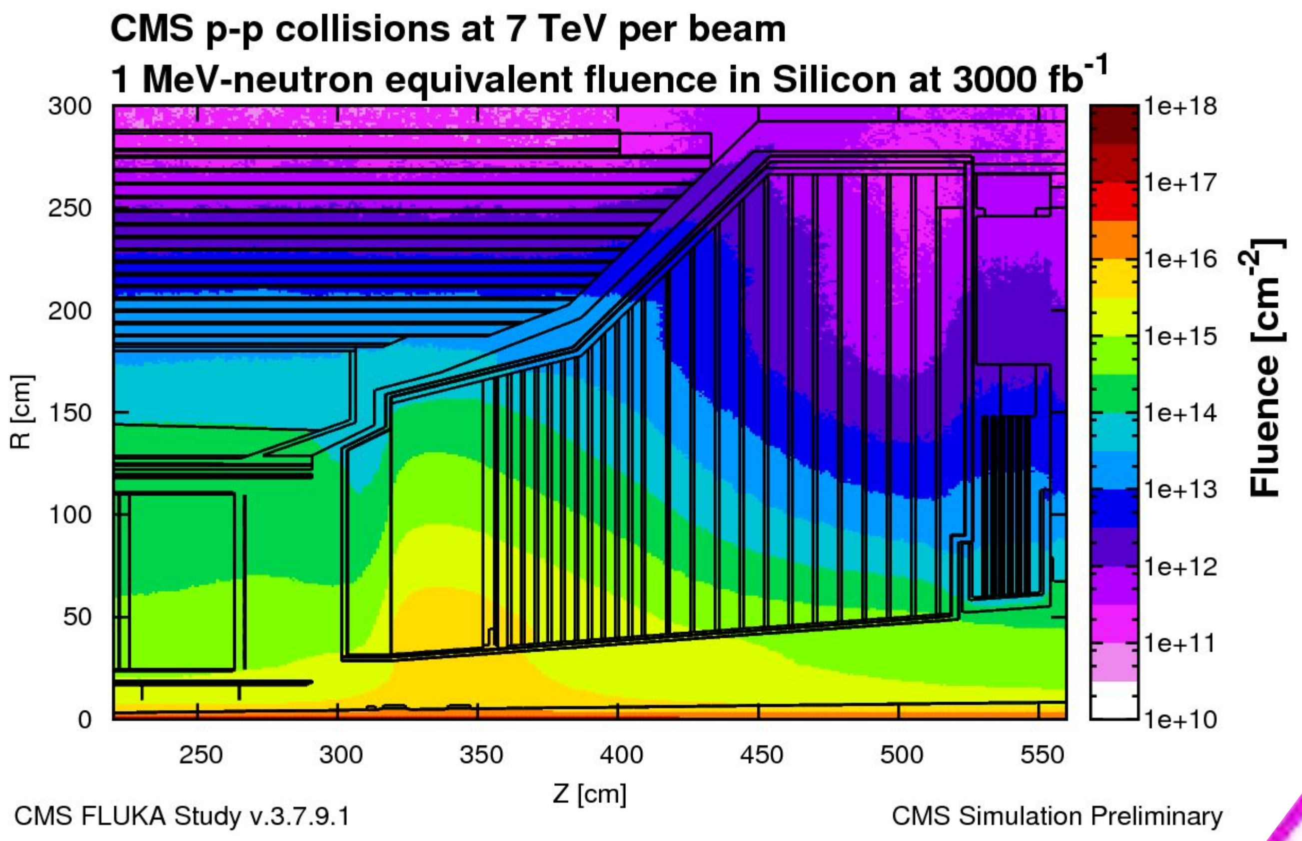
The High-Granularity Calorimeter (HGCAL) project

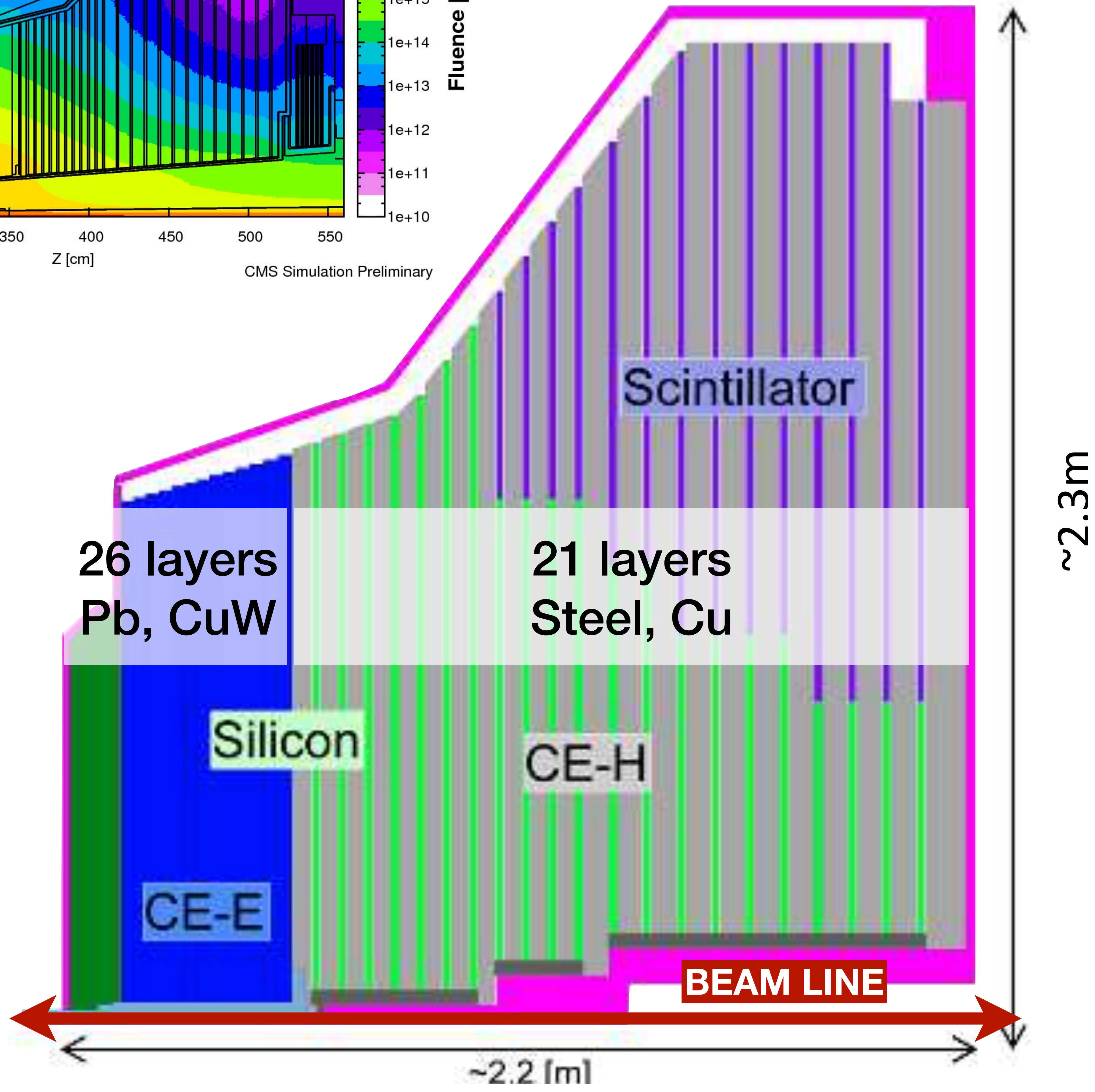
New silicon imaging electromagnetic calorimeter + Si and Si+Scintillator layers hadronic section

- **Silicon sensors** operate adequately up to ~ 1.5 x 10^{16} n_{eq}/cm^2
  - Variable thickness 120/200/300 µm to minimise radiation-induced noise
- **Plastic scintillator tiles** (SiPM readout) in the area with fluence < 4 x 10^{13} n_{eq}/cm^2
- Operational temperature of -35°C

Unprecedented transverse and longitudinal readout segmentation:

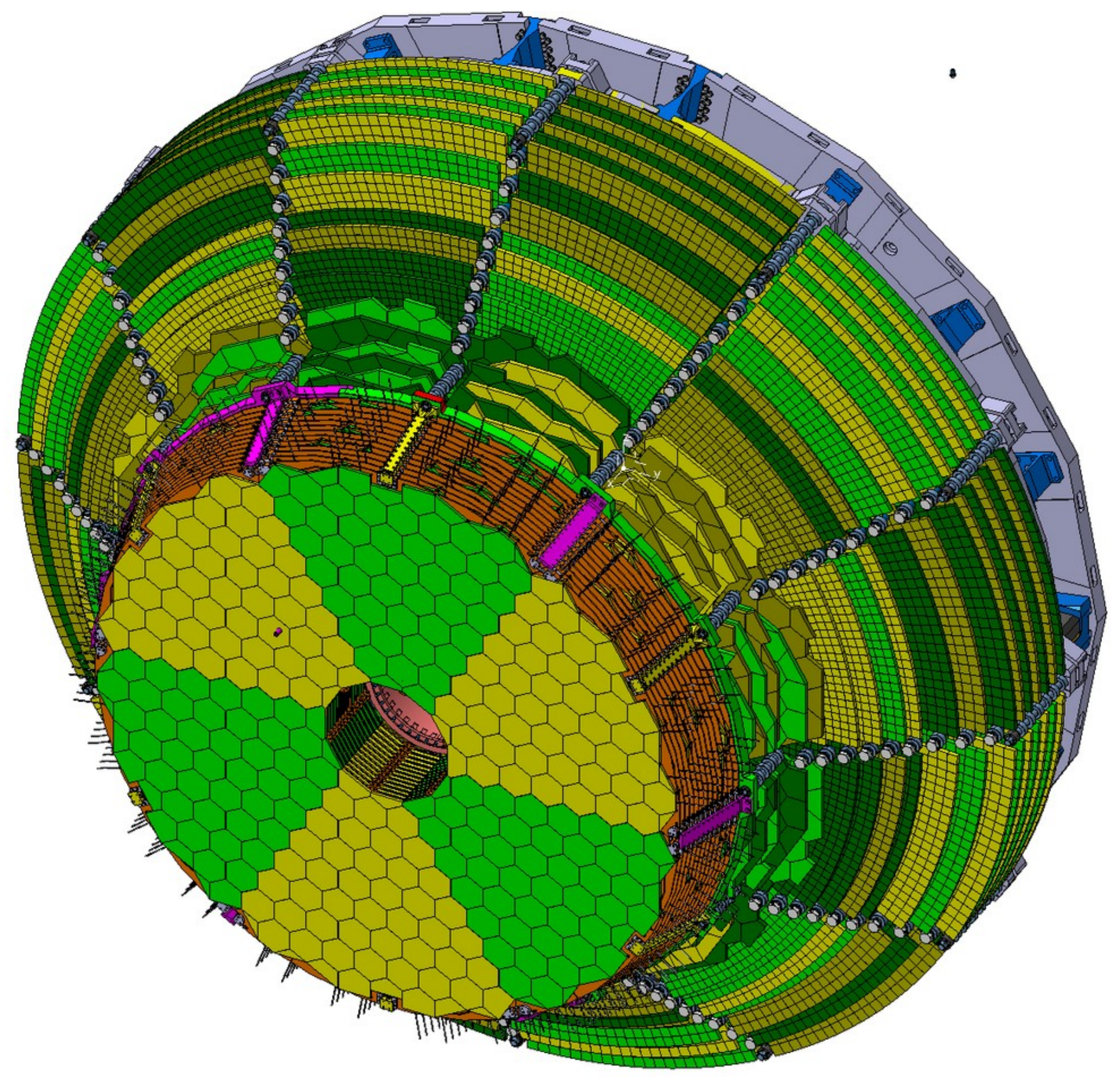
- 6M silicon pads of size 0.6 or 1.2 cm^2 (620 m^2 overall)
- 240k plastic scintillator tiles 4 to 30 cm^2 (370 m^2 overall)



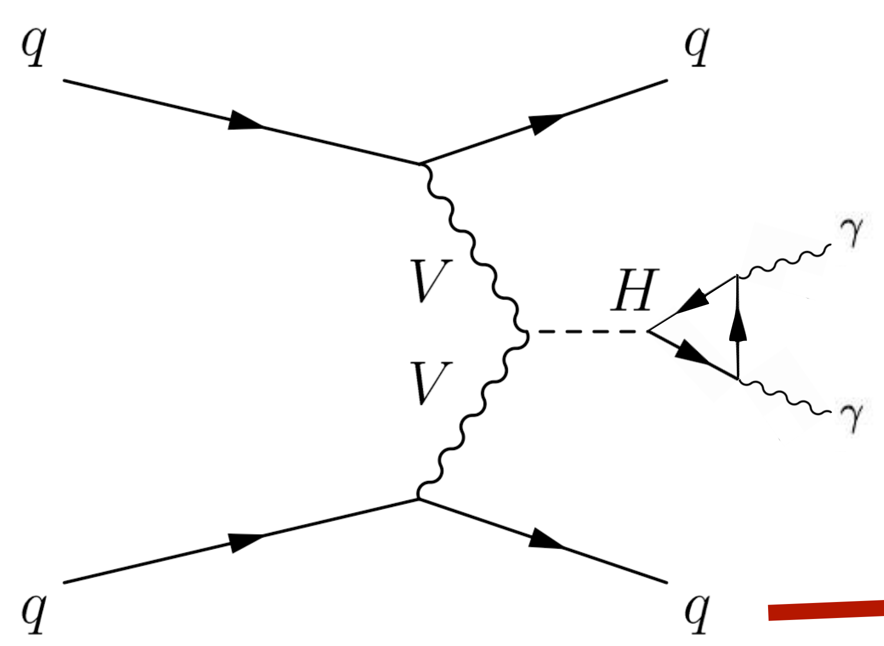


Key challenges

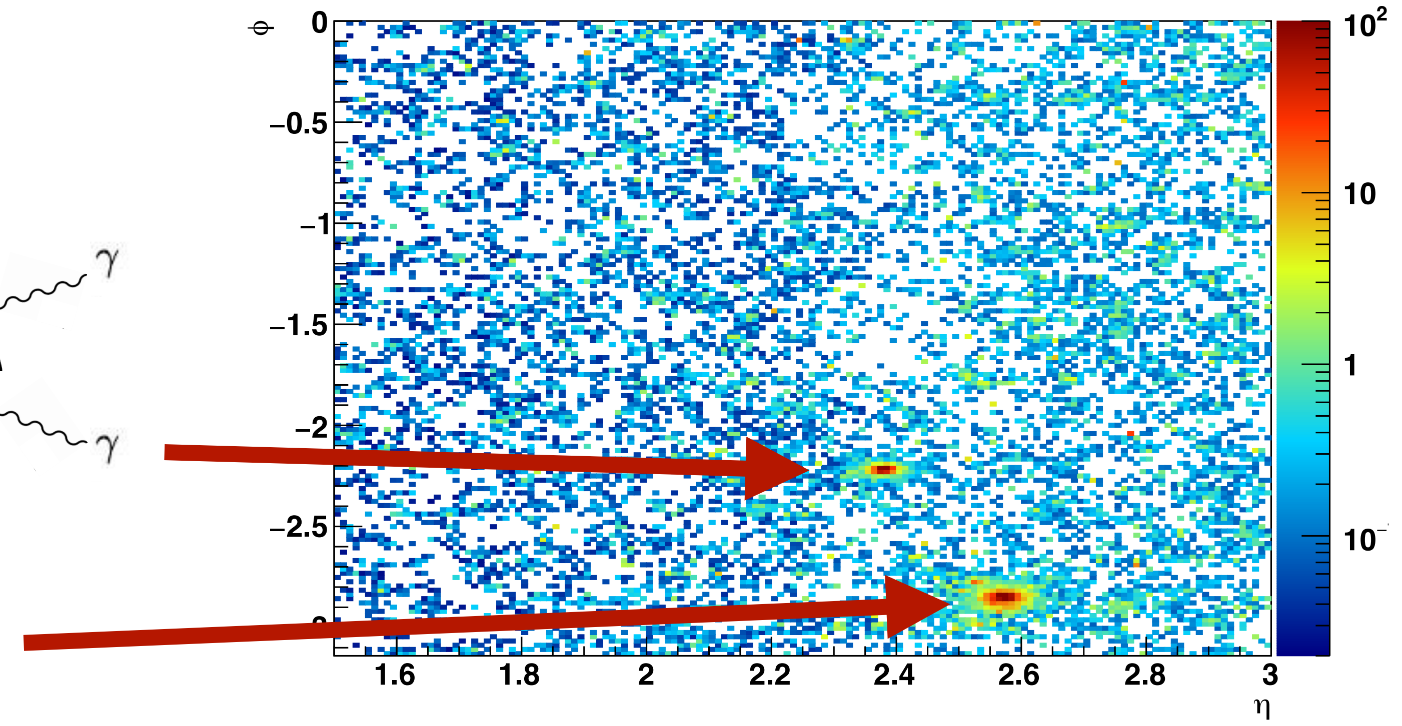
- Complex engineering (mechanics, services connections)
- Spacial **complexity**
  - Diverse detecting layer structures
- High **channel density**
  - **Large data volume** transmitted to trigger and DAQ systems



- New algorithms to bring together the **5D information**
  - Highly granular 3D segmentation
  - Energy reconstruction
  - Precise timing



Boosted objects discrimination with high spacial granularity



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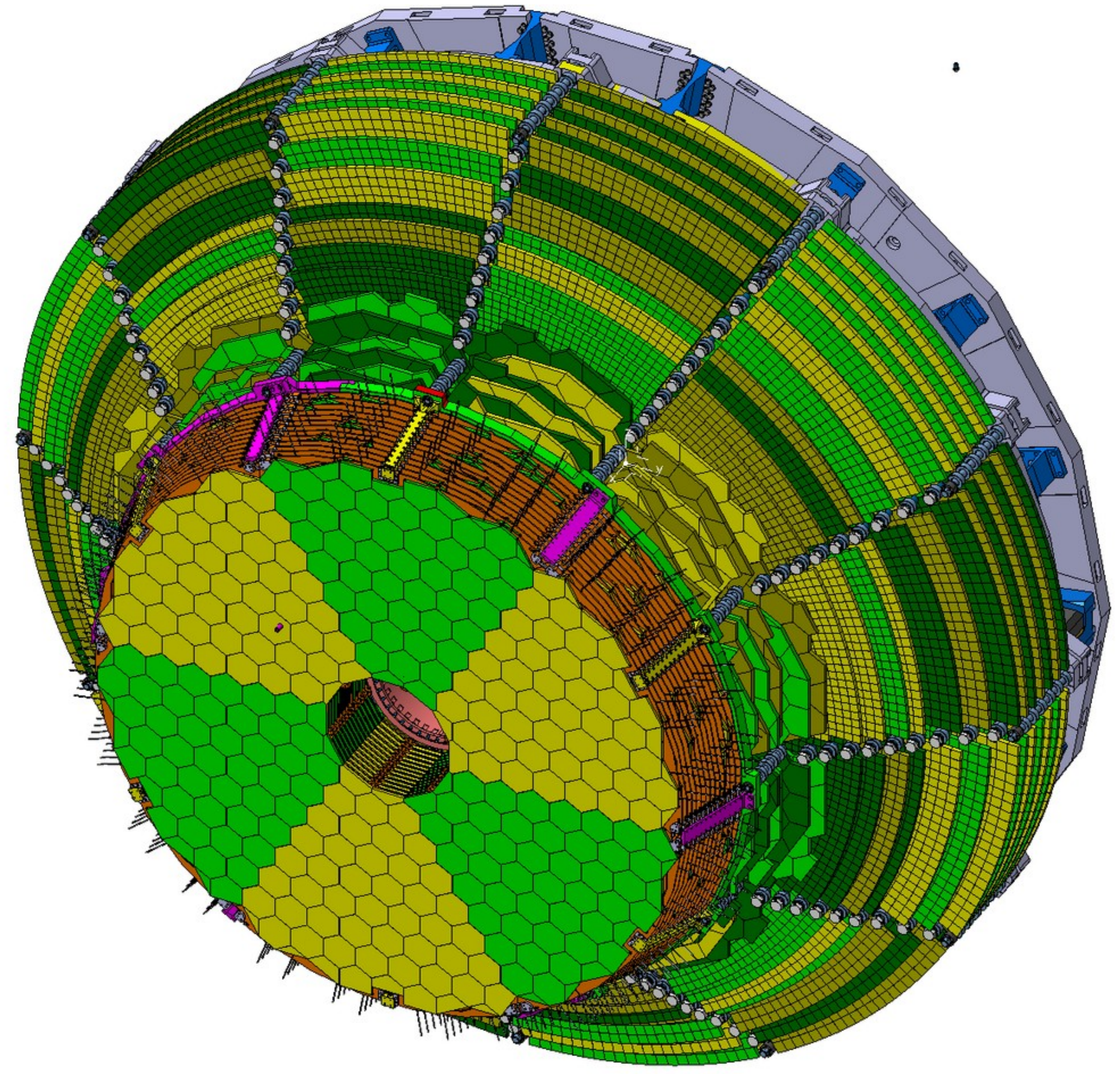

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- New algorithms to bring together the **5D information**
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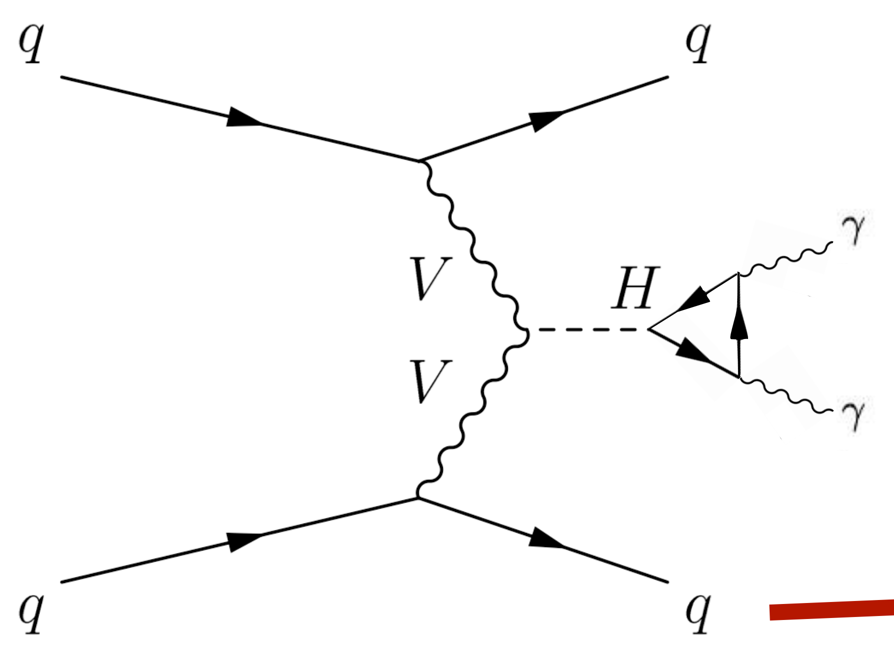
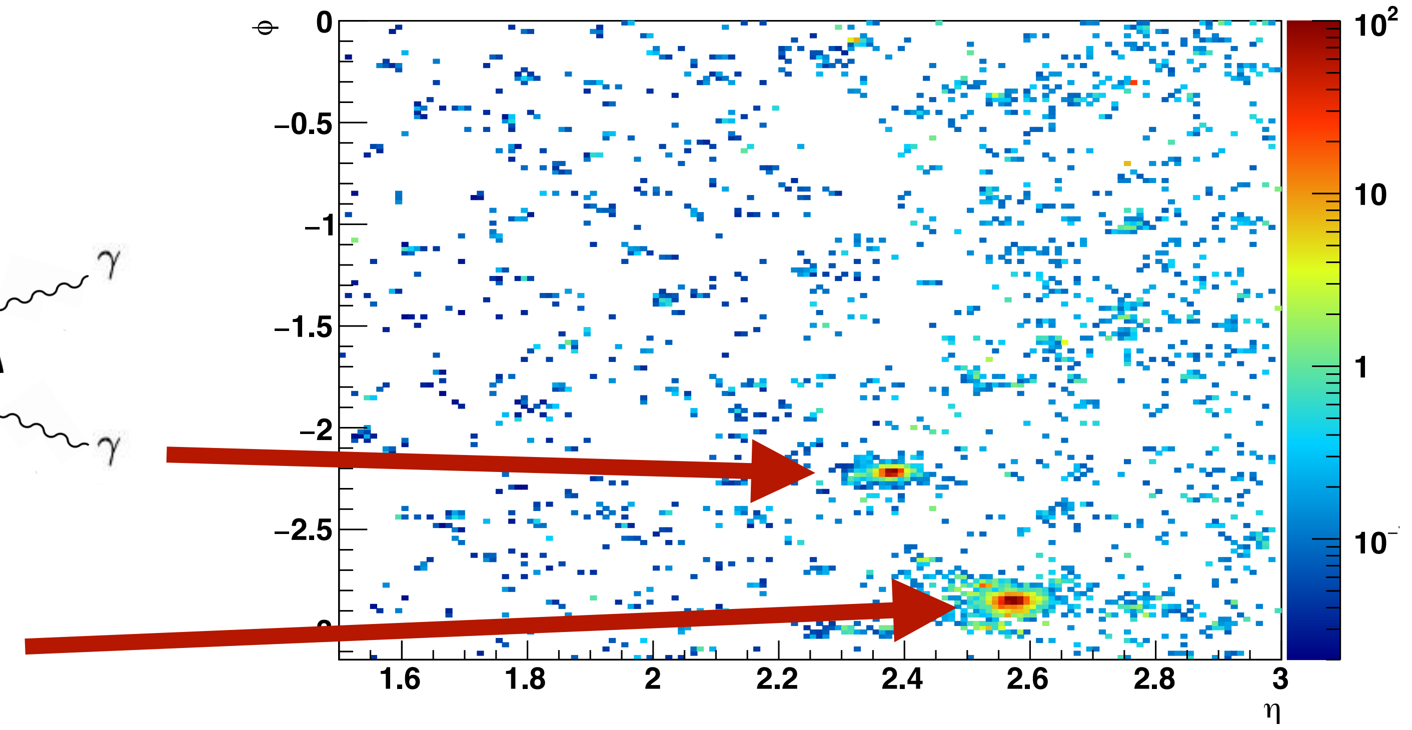
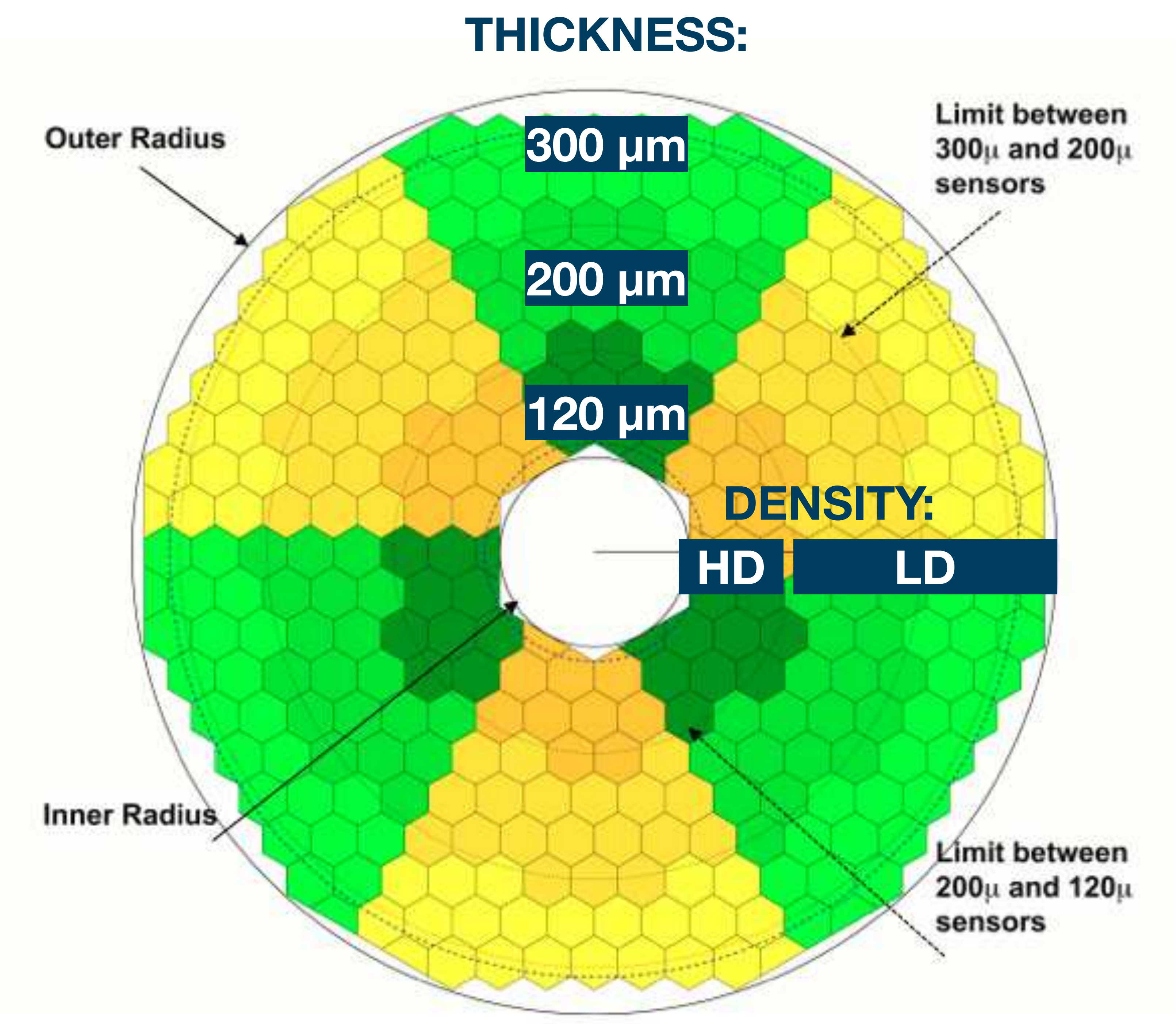


Discrimination against pileup energy deposits with 90 ps timing window selection



Silicon modules

- Hexagon-shaped modules tiling the electromagnetic calorimeter and partially the hadronic section, with hexagonal sensor shape
  - Maximised sensor area on wafer, partial sensors at borders
- **High Density** (HD) sensors: 0.6 cm^2 cells; **Low Density** (LD) sensors: 1.2 cm^2 cells



Hexaboard

- Readout of sensor cells with HGCROC custom ASICs and connection to motherboard for data transfer
- Bias supply voltage

Silicon sensor

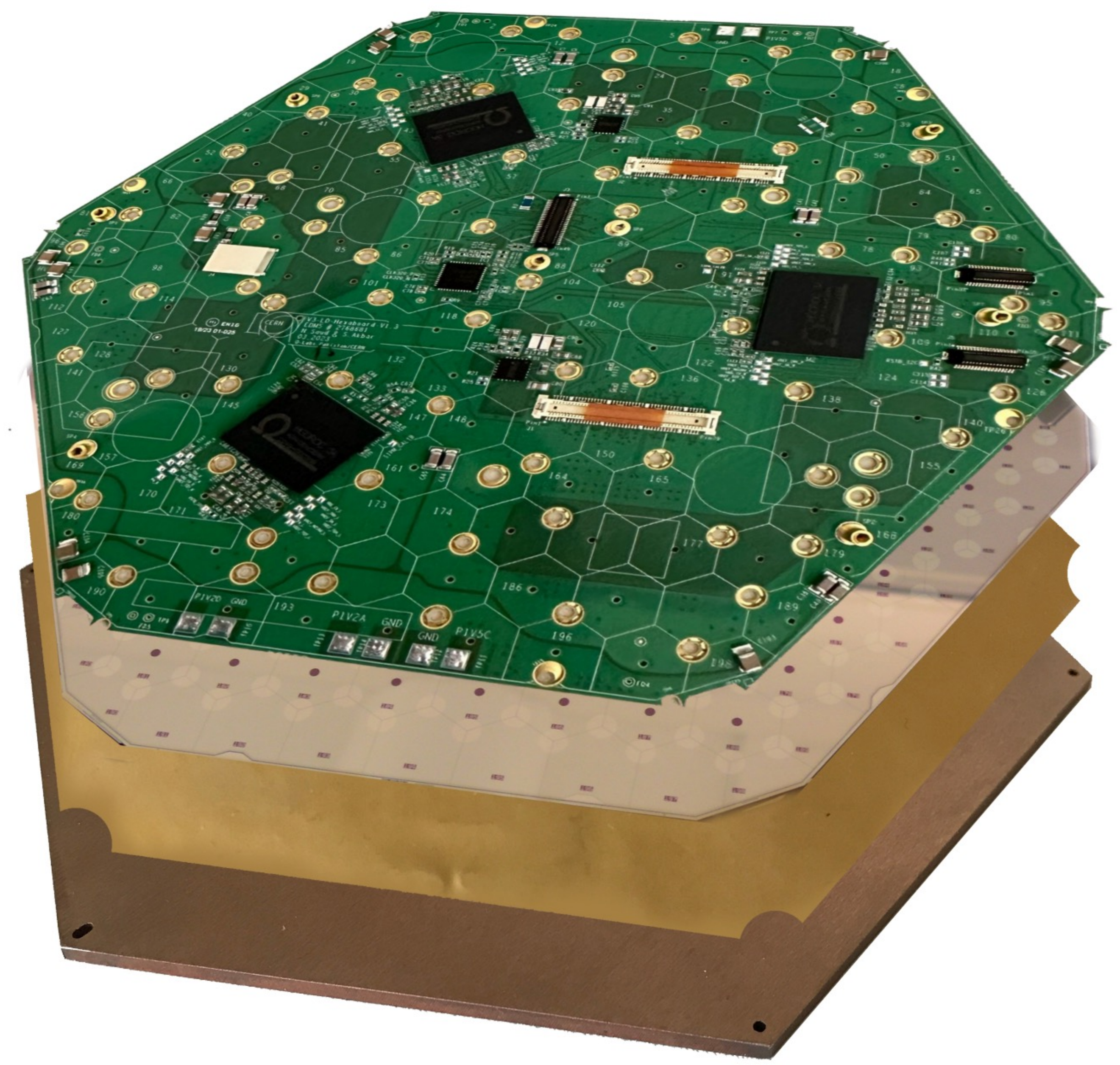
- 8-inch wafers
- Planar, DC-coupled, p-type sensors

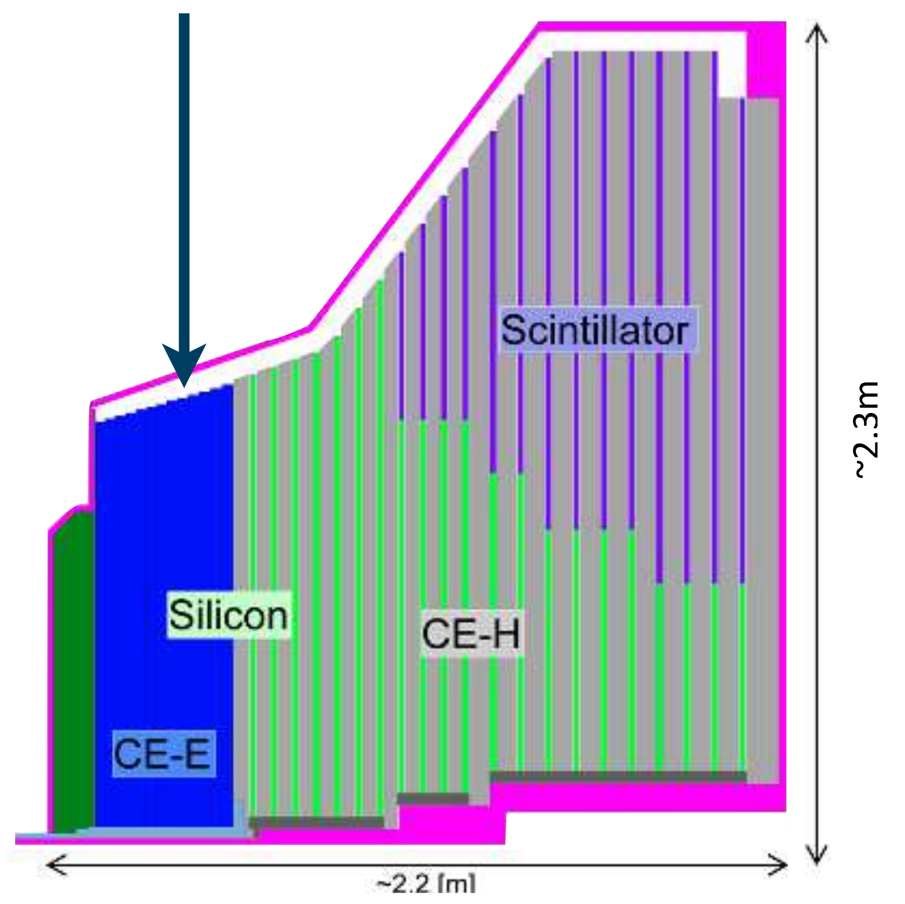
Kapton sheet

- Isolation to baseplate
- Bias supply to sensor back side

CuW baseplate

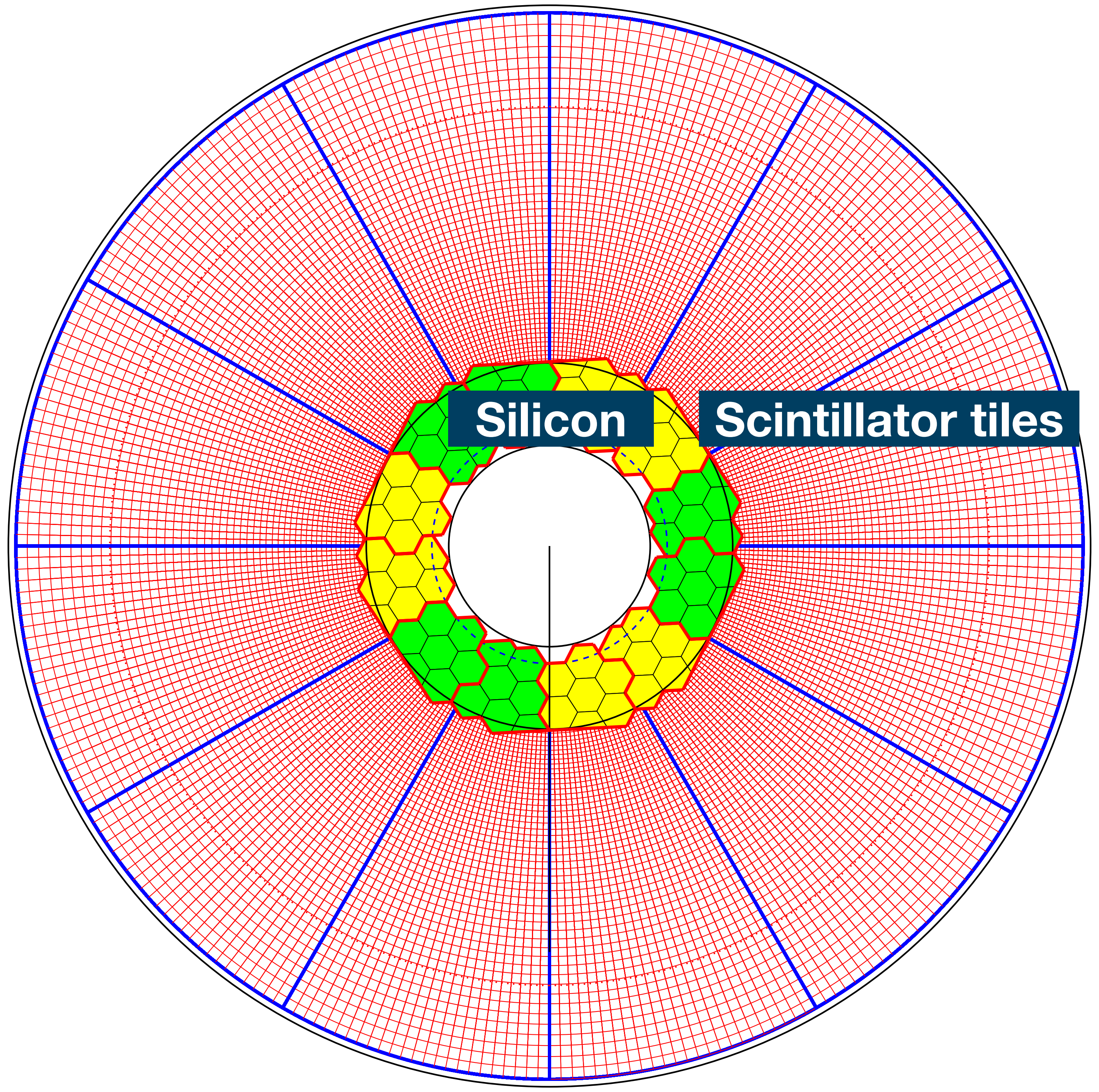
- Contributes to absorber material





Scintillating tile modules

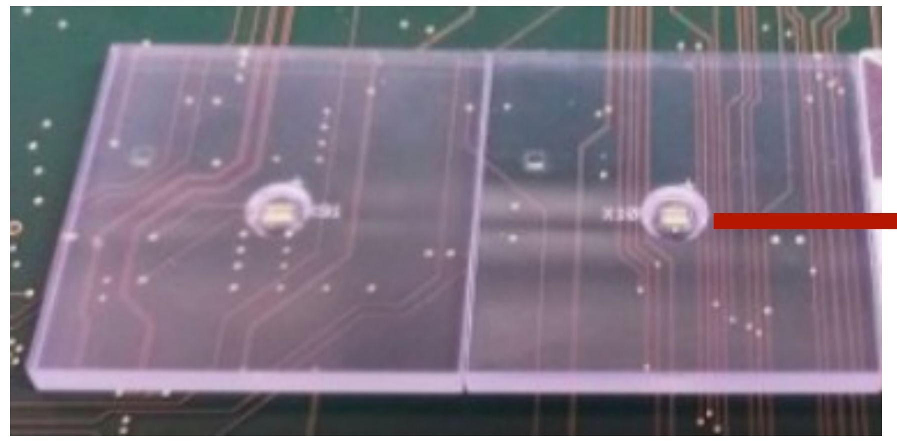
- Scintillator tiles sizes ranging from 4 to 30 cm^2 based on radial position
- Silicon Photo-Multipliers size of 9 mm^2

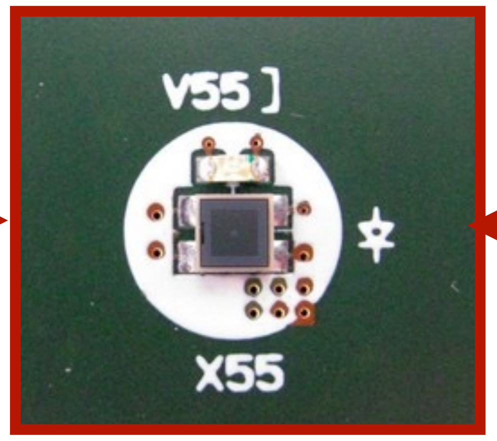


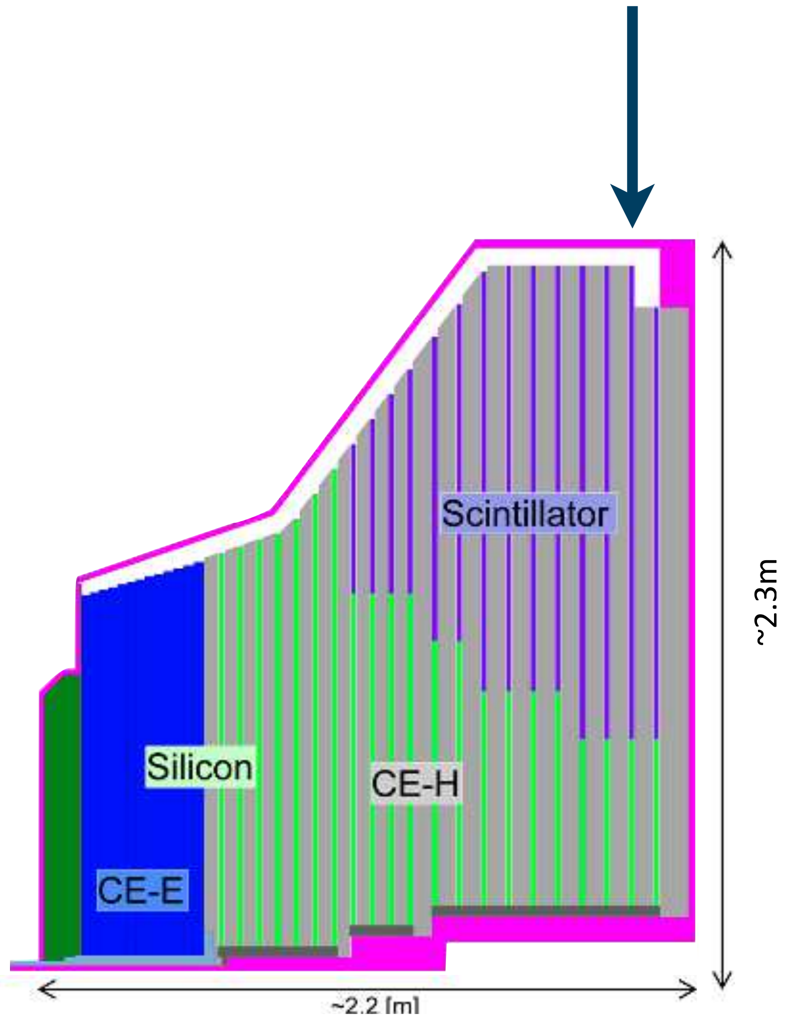
Tileboard
- Readout of SiPMs with HGCROC custom ASICs and connection to motherboard for data transfer

Scintillator tiles
- Wrapped in reflective foil

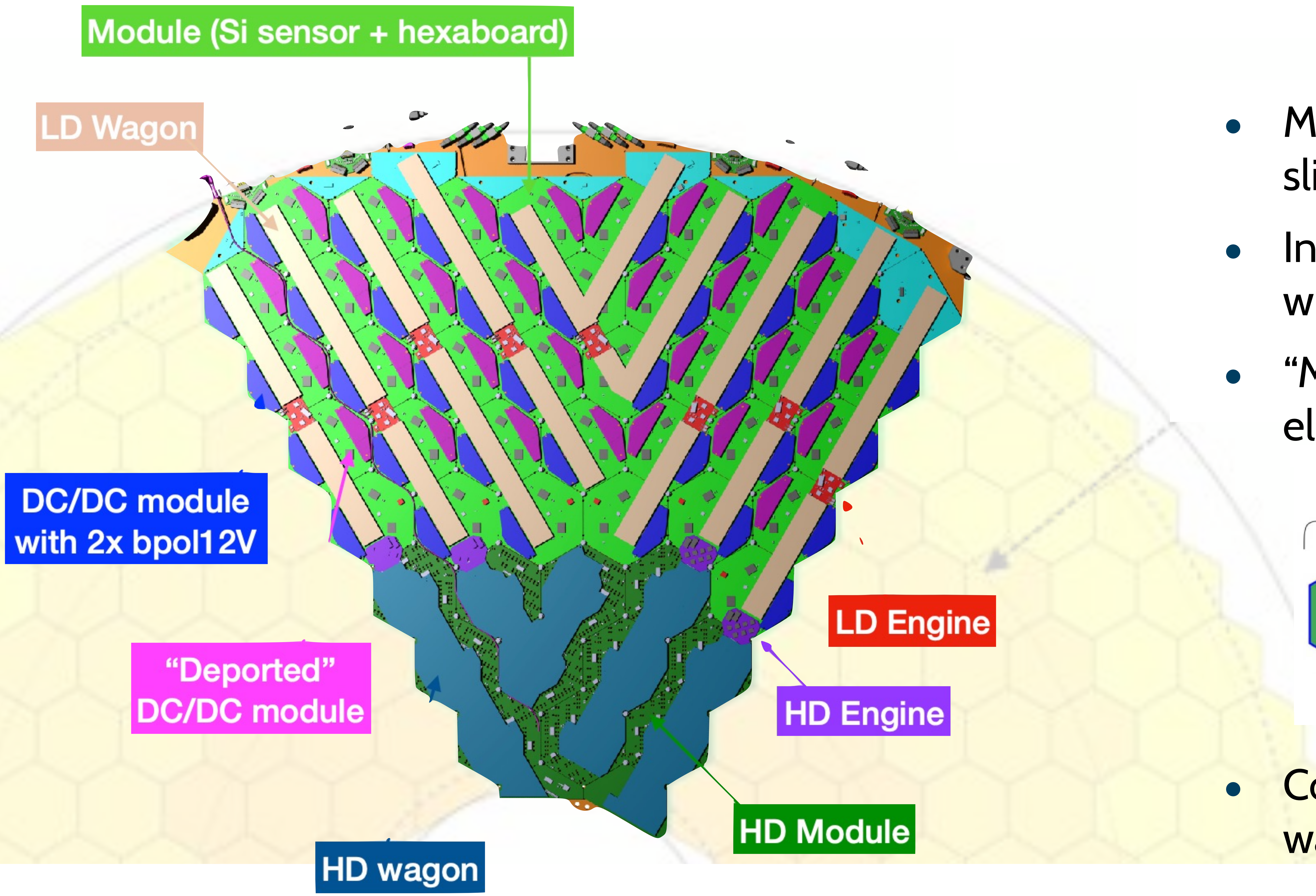
Silicon Photo-Multiplier
- Placed within a dome to maximise light collection
- LED injection for calibration



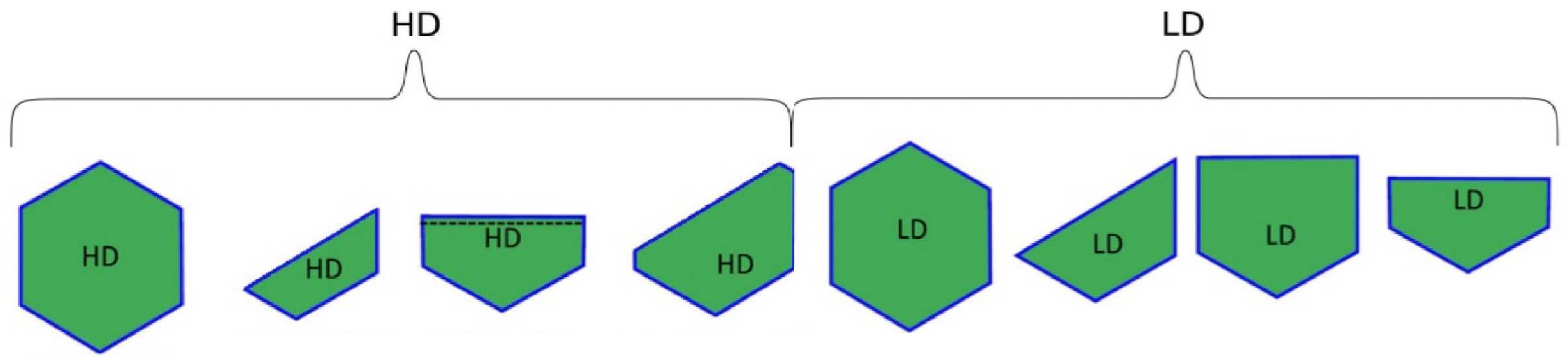




Modules integration



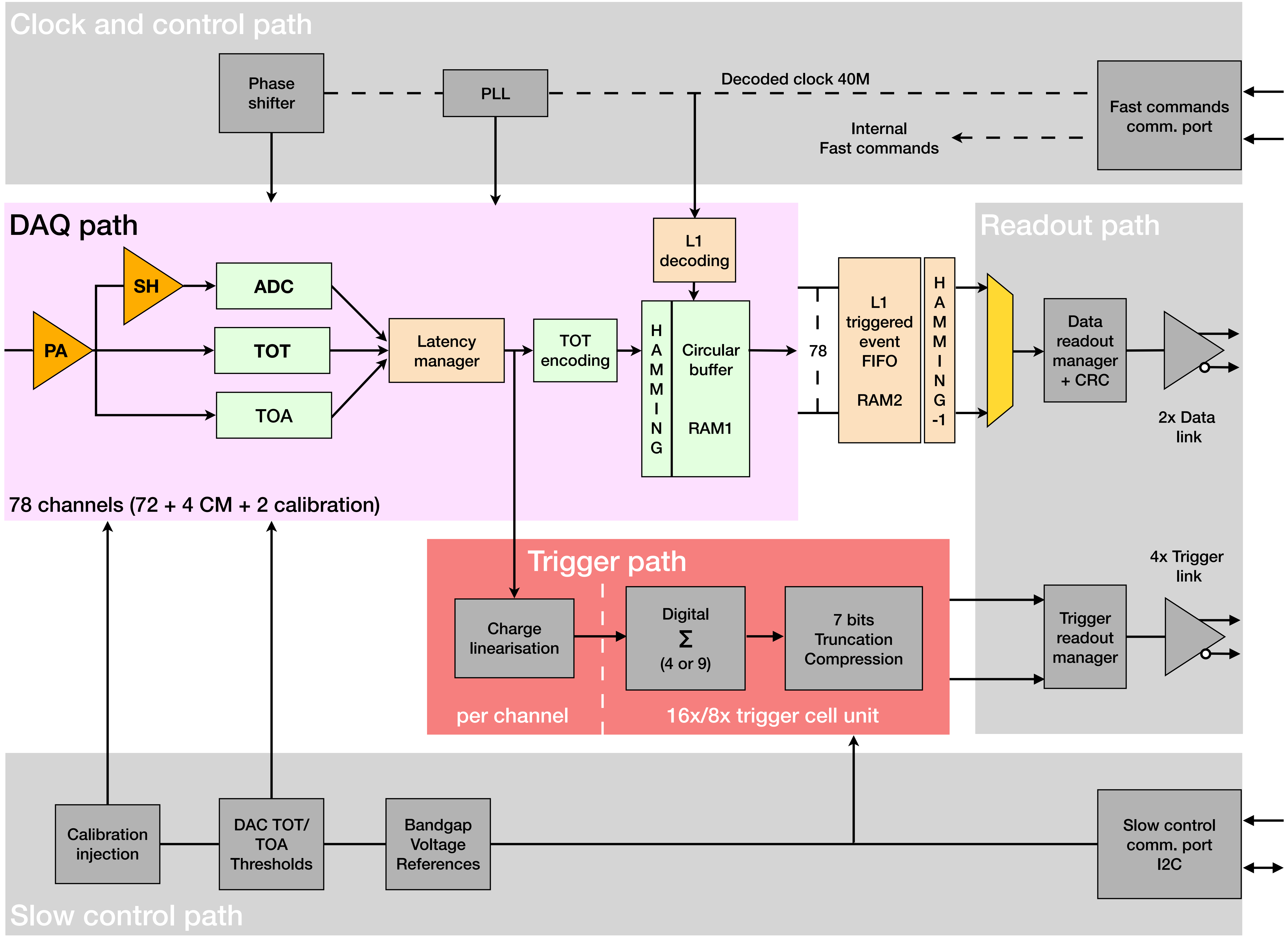
- Modules mounted in 30° or 60° wide copper plates slices
- In the electromagnetic section, cassettes are equipped with modules on both sides
- "Minimal" variations in the active and expensive elements



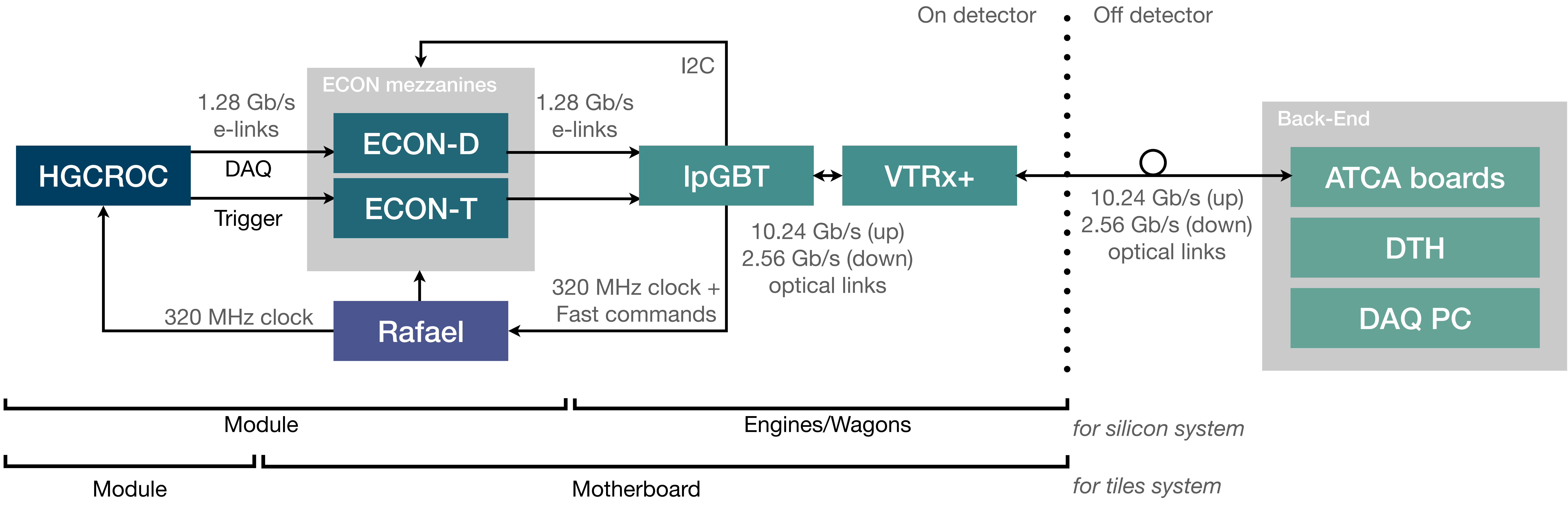
- Complexity transferred to lower cost elements such as wagons (over 50 variants)

Readout ASICs: HGCROC

- Radiation-hard front end chip receiving and digitizing signals from the sensors
  - One readout chip design for silicon and tile modules, with minor adaptations
- Provides 3 measurements
  - charge (**ADC**) with 0.2fC – 10pC dynamic range
  - preamplifier saturation time (**TOT**) with 200 ns dynamic range
  - Time of arrival **(TOA)** with 25ps resolution
- Two data flows over 1.28 Gb/s links:
  - 2x **DAQ path** (ADC, TOT, TOA)
  - 4x **Trigger path** (sum of 4 (9) channels, linearization, compression to 7-bit)

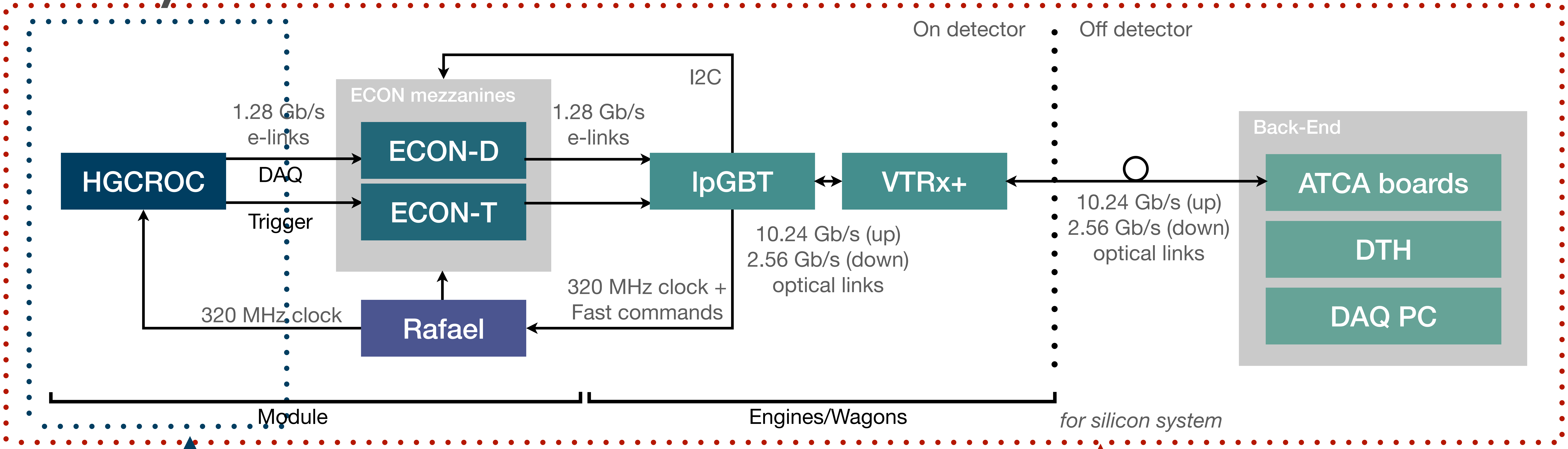


Readout chain



- **ECON mezzanines**: **concentrator chips** for DAQ (750 kHz) and trigger (40 MHz) data transmission
- **Rafael: fanout chip** for clock and fast control distribution
- lpGBT: fast, radiation-hard **link chips paired to** VTRx+ **transceivers**, transmitting data and distributing clock, slow control and fast control signals
- Back-end **ATCA-based system**, which receives and buffers data and distributes clock, slow control, and fast control signals, interfacing with the CMS DAQ and Timing Hub (DTH)

Silicon system test



Large scale setup at 2018 test beam

- **94 modules** in 28 (**electromagnetic section**) + 12 (**hadronic section**) layers
- HGCROC prototype electronics

PHYSICS PERFORMANCE STUDIES

End-to-end readout at 2023 test beam

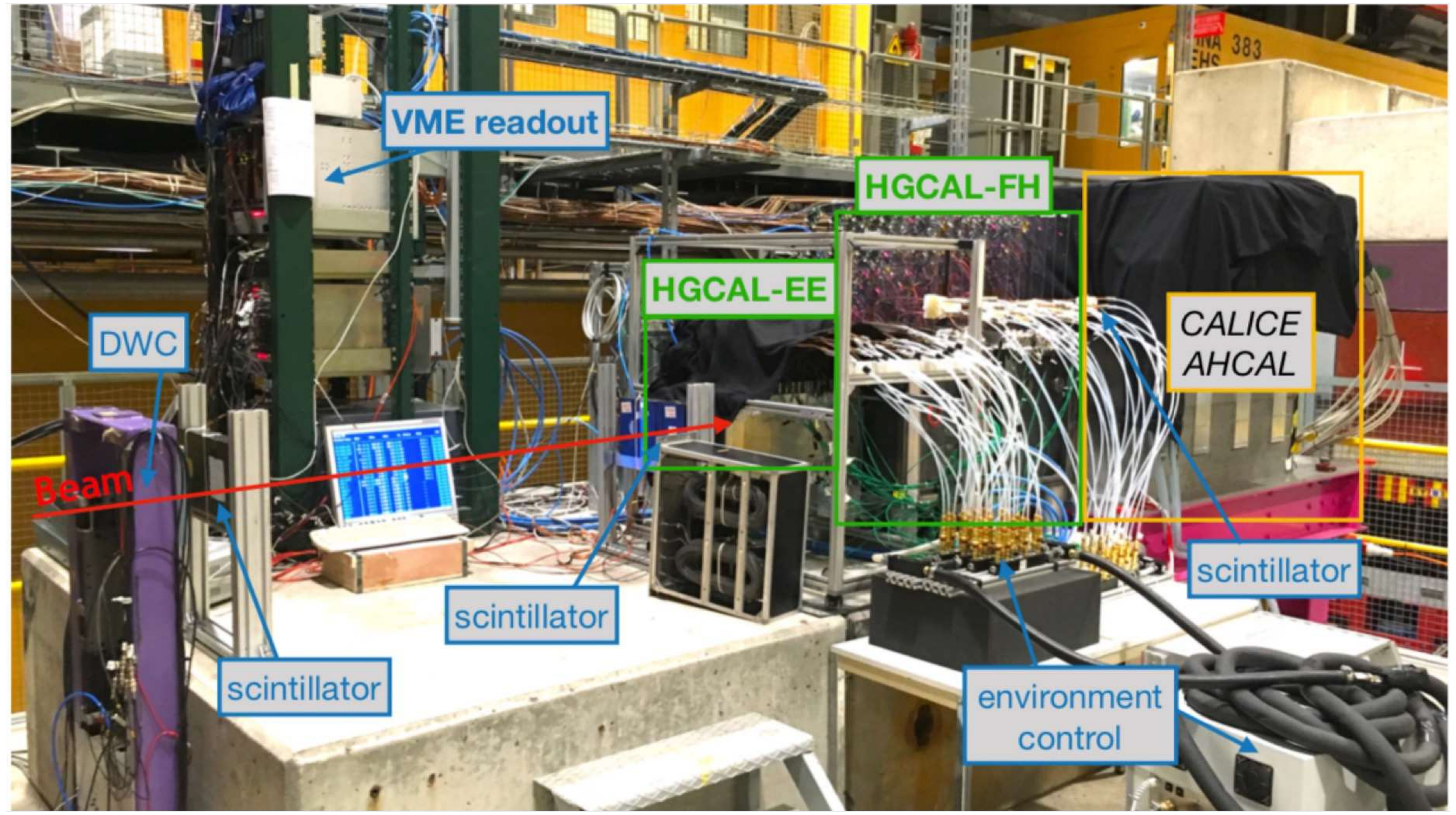
- **Final-like electronics**
- 2 single-modules

DATA TRASMISSION, DATA QUALITY AND SYSTEM STABILITY

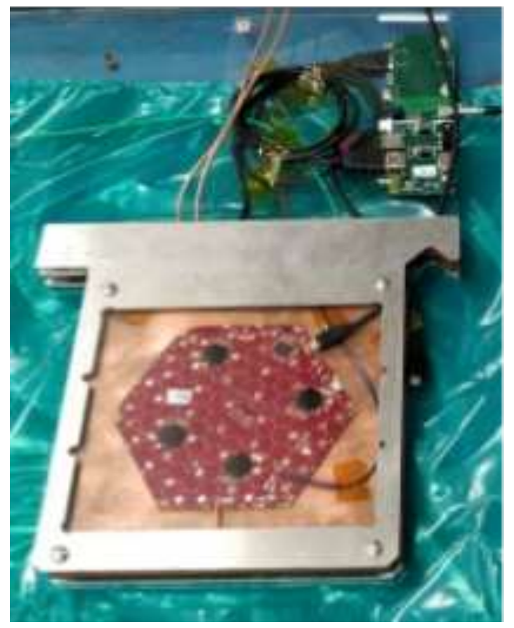
2018 test beam setup

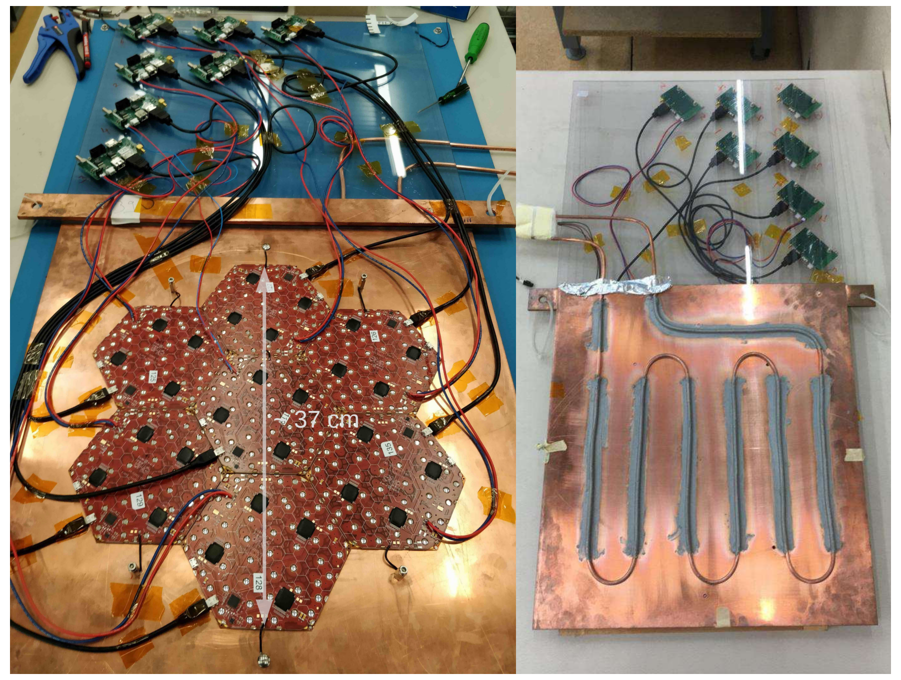
Carried out at the H2 beamline branching from SPS (*Super Proton Synchrotron*, CERN)

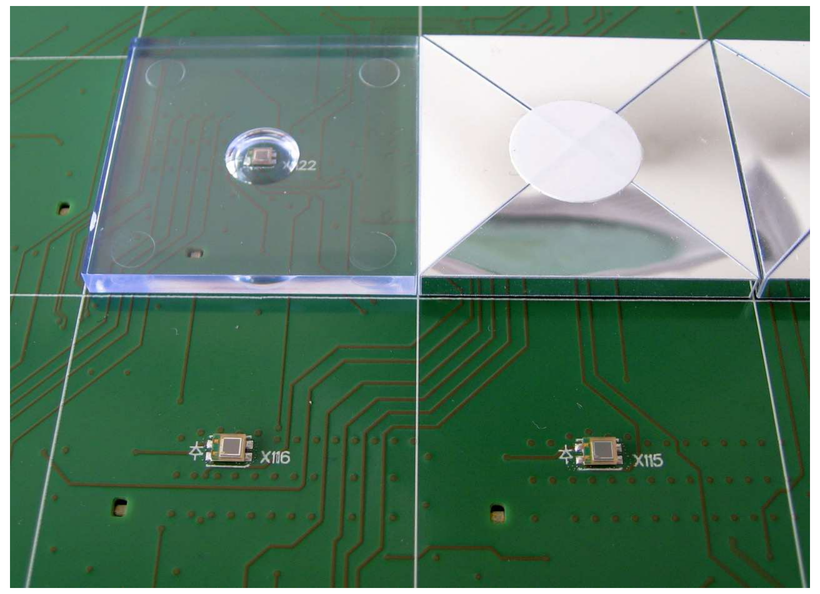
- $e^{\pm}$, π, μ beam of 20 to 300 GeV energy
- Full GEANT4 simulation
  - Used for GEANT4 regular physics validation [docs]



- Electromagnetic section (**HGCAL-EE**)
  - Stack of 28 silicon modules
  - Pb/Cu absorber (+ CuW baseplates)
  - Double sided cassettes
- 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





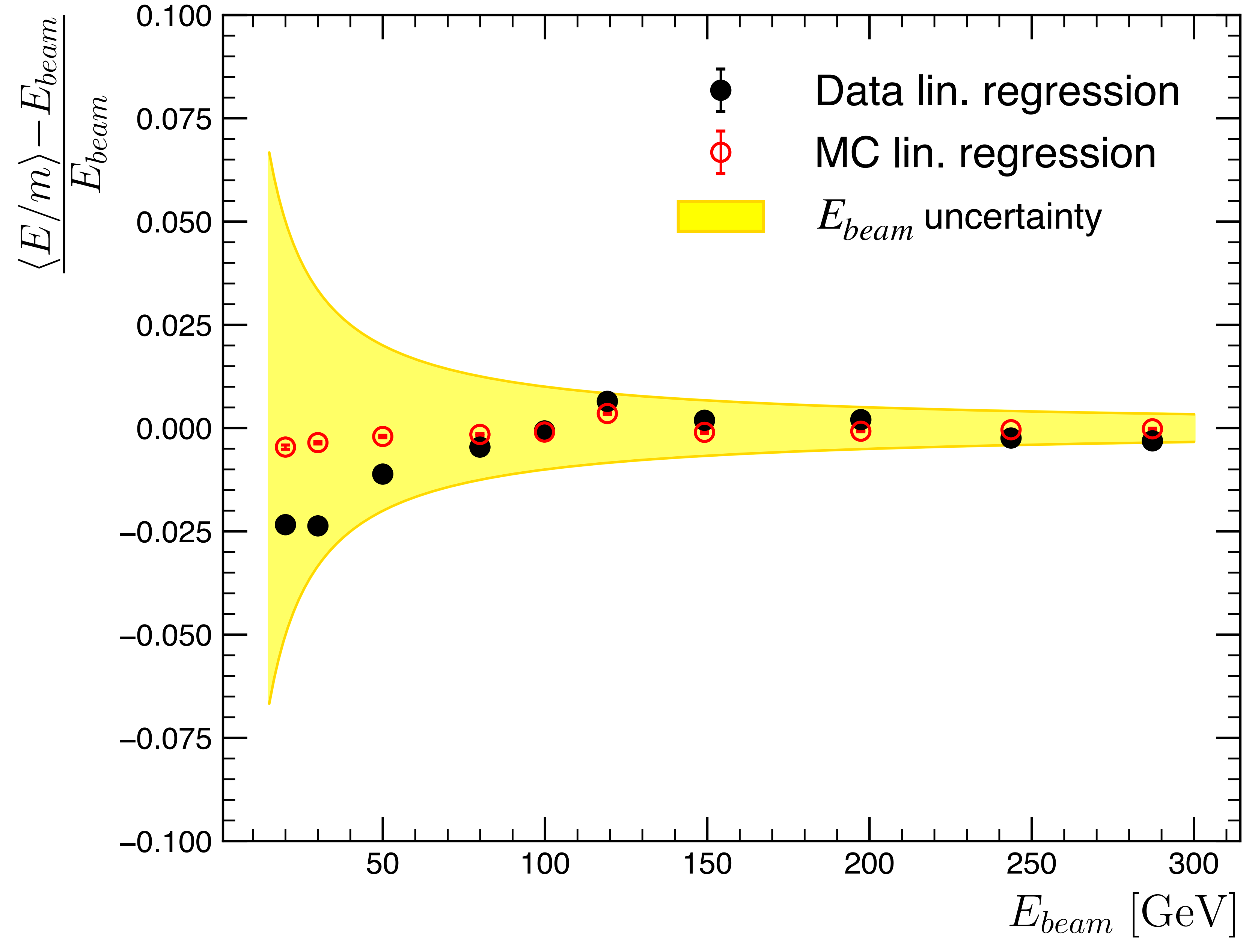


JINST 17 P05022

2018 test beam results: electromagnetic performance

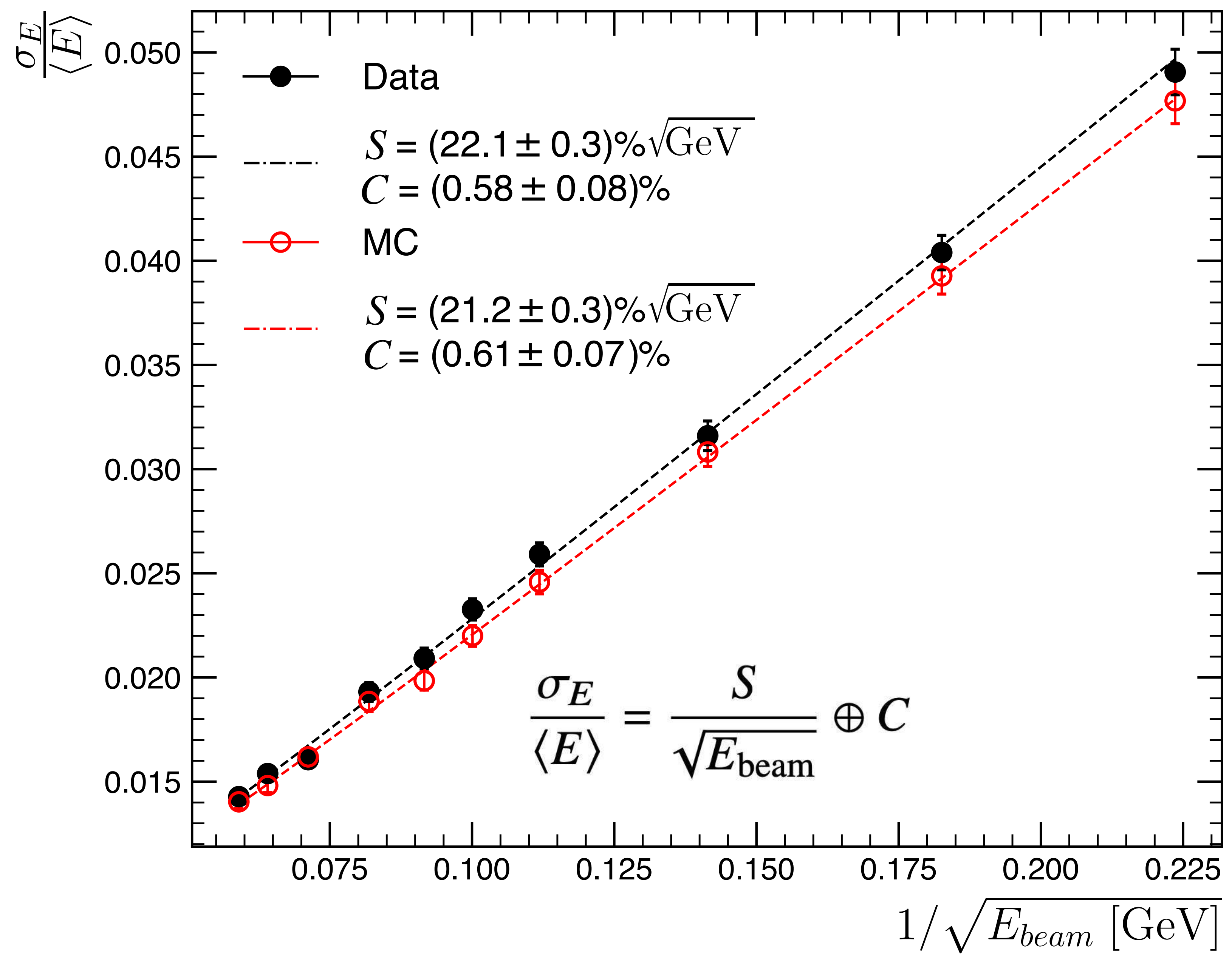
- e^+ beam data, reconstructed in HGCAL-EE

Linearity



- Energy response **linear within ±1.5%** above 50 GeV

Energy resolution



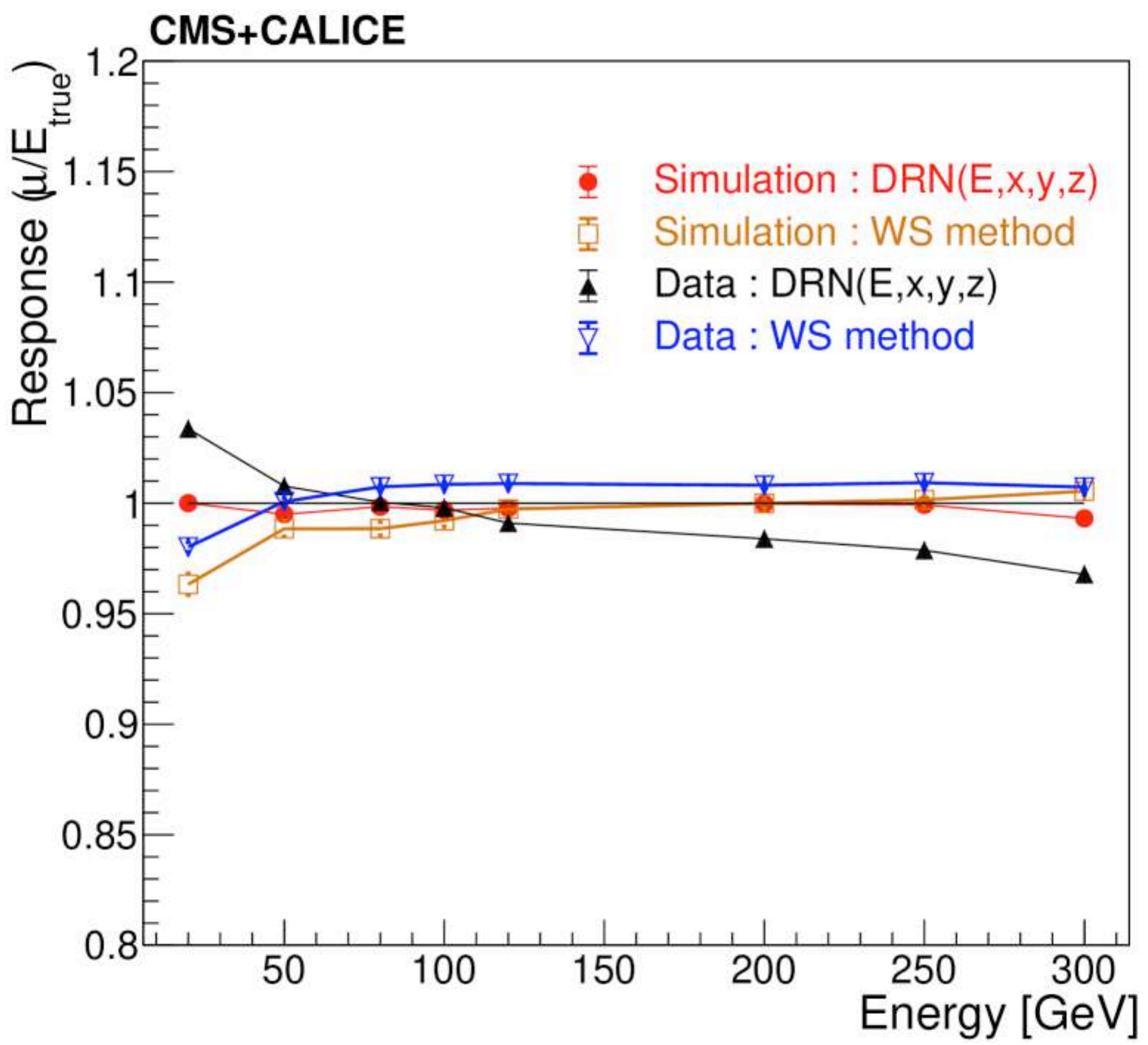
- Energy resolution within the physics performance target: **0.6 % constant term**
  - Compatible with performance of the current CMS electromagnetic calorimeter

arxiv:2406.11937

2018 test beam results: hadronic performance

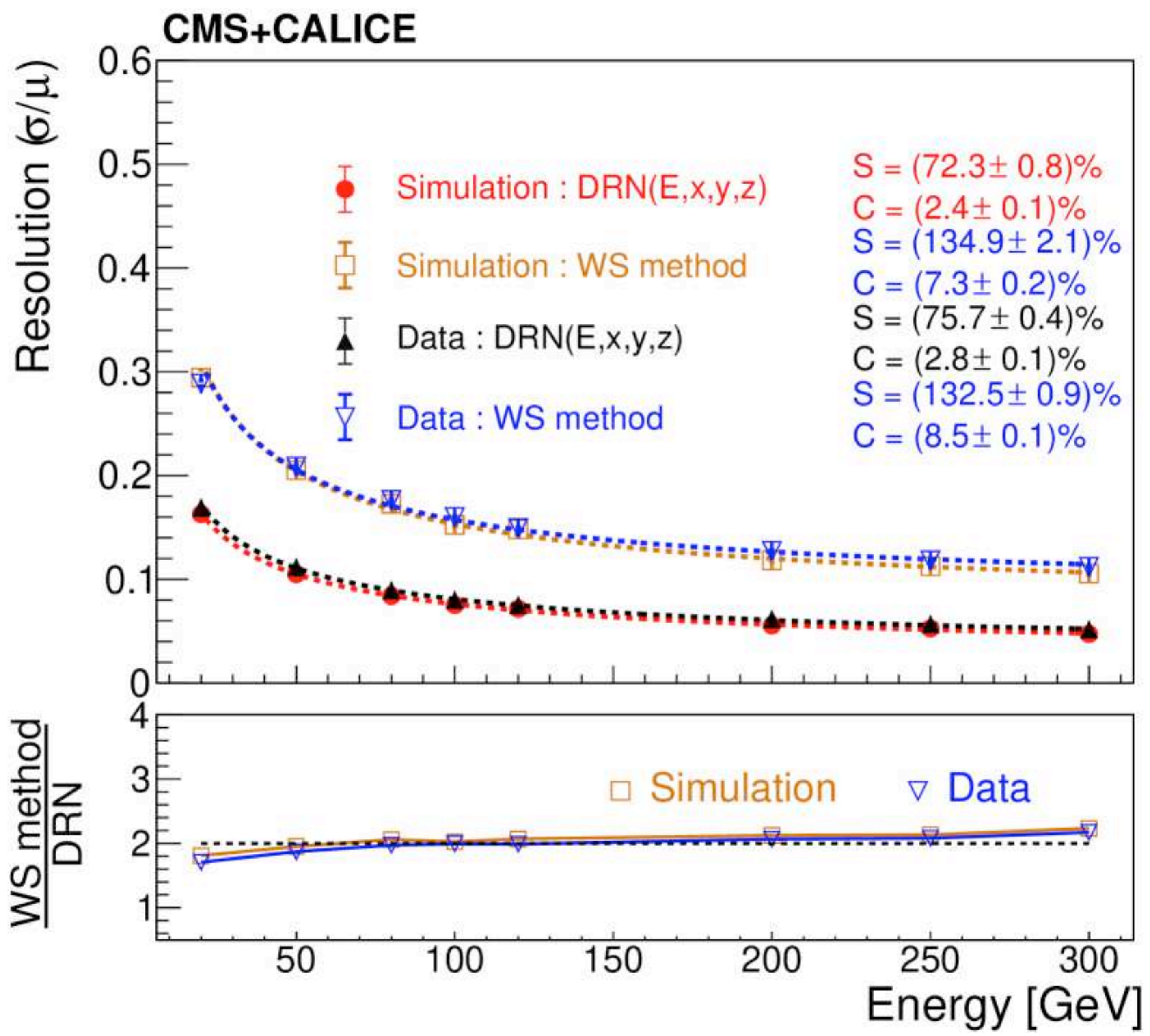
- π beam data, reconstructed in HGCAL-EE, HGCAL-FH and CALICE AHCAL
- **GNN-based reconstruction (DRN)** to fully exploit the high-granularity and account for hadronic showers fluctuations

Linearity



- Energy response **linear within few %**

Energy resolution

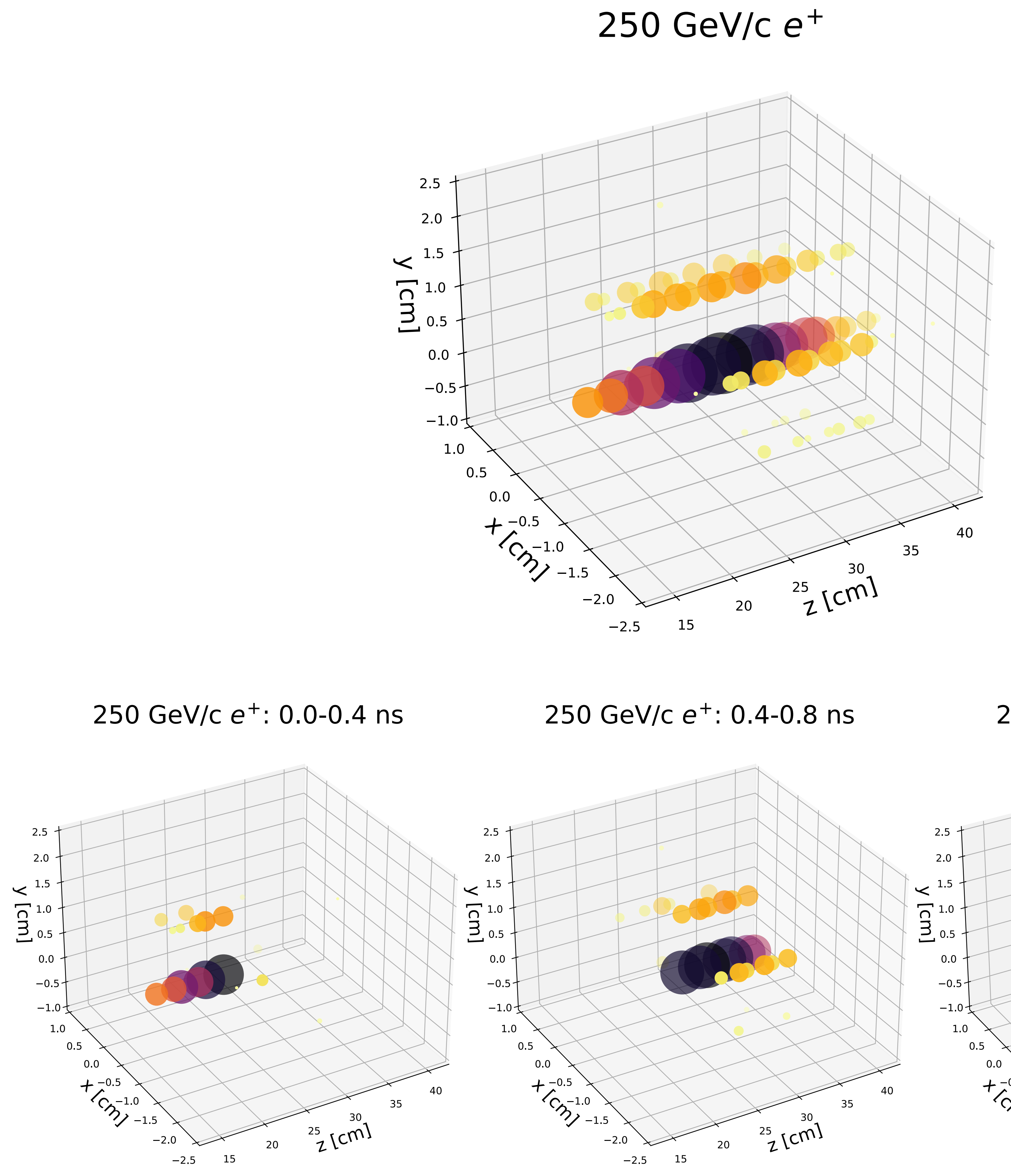


- Excellent data/simulation agreement
- DRN method brings a **x2 improvement** of the resolution w.r.t. energy-dependent weighted reconstruction (WS)

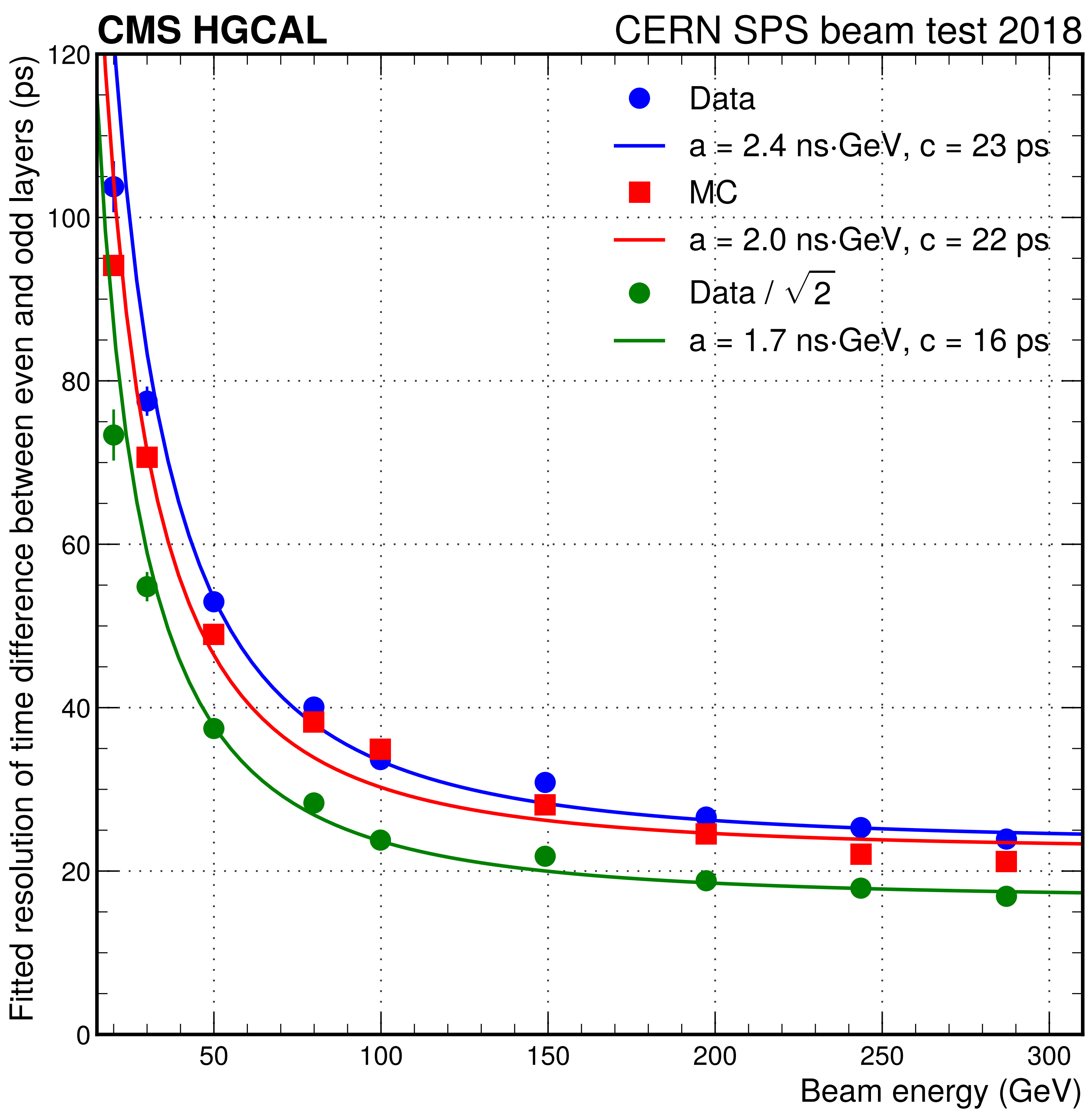
JINST 19 P04015

2018 test beam results: timing performance

- e^+ beam data, reconstructed in HGCAL-EE



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

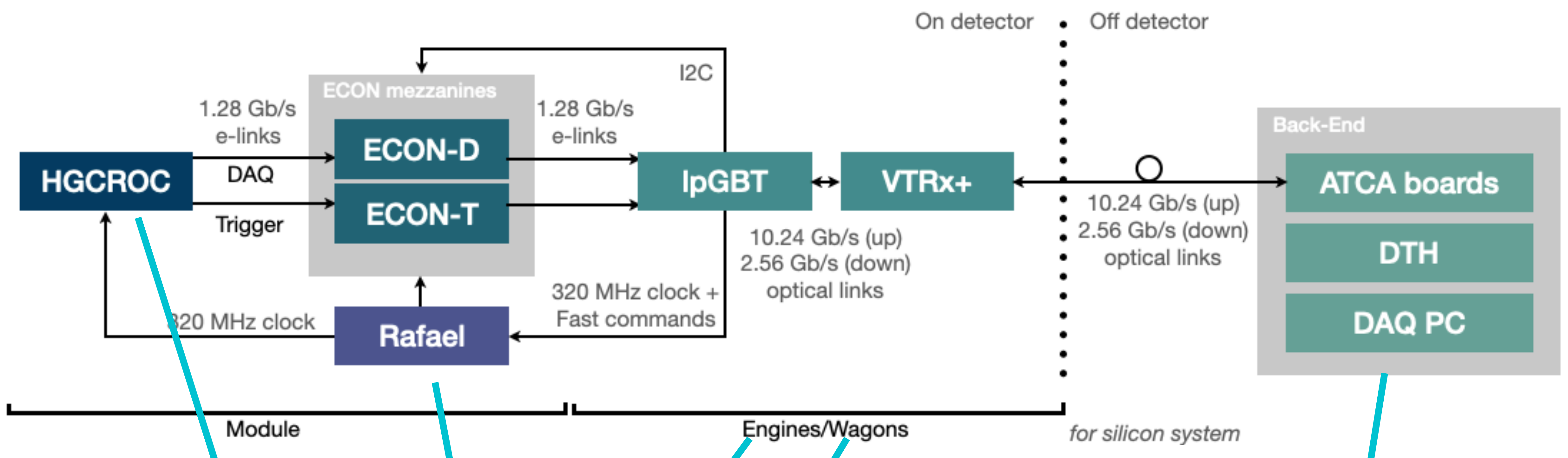


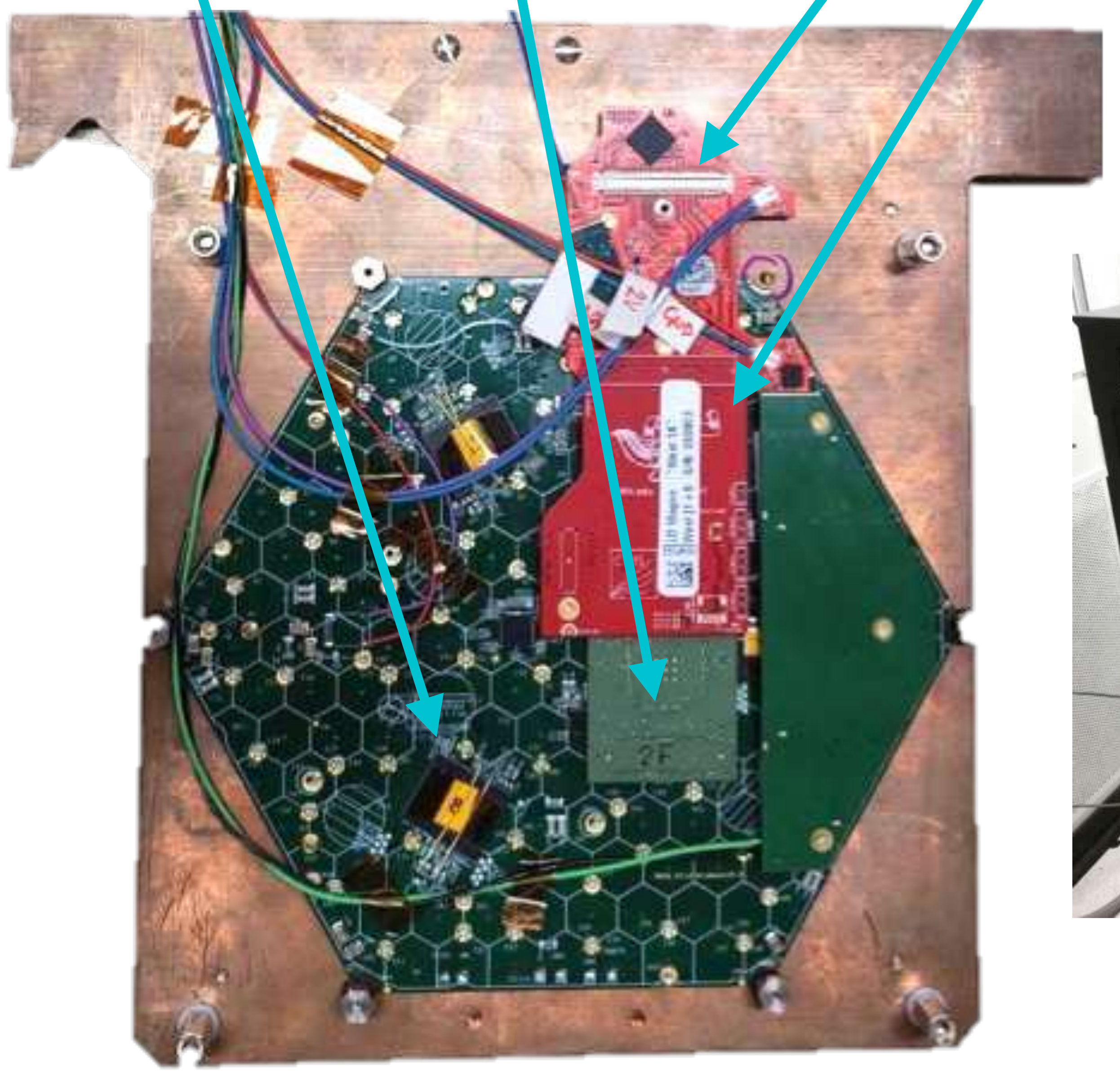
Resolution using half-showers in even/odd layers scaled by √2 as estimate of the performance with all layers

Performance meeting target: **16 ps constant term**

2023 test beam: readout chain commissioning

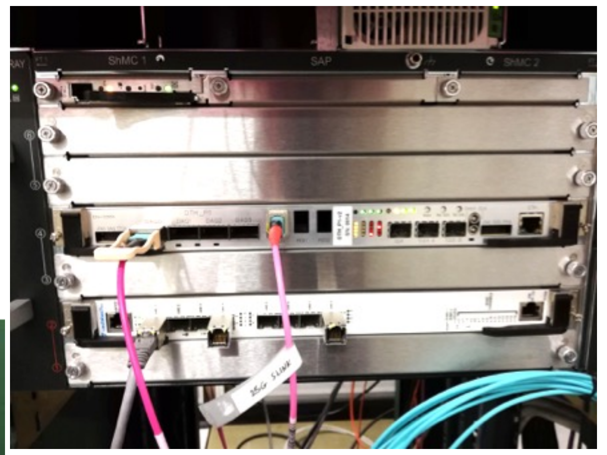
- First test beam **with full vertical readout chain** in place
- Trigger and DAQ path read out at ~100 kHz
- Synchronisation of all FE ASICs and BE FPGAs achieved
- DQM using reconstruction in CMS central software
- ECON-T and ECON-D configuration tests
  - Different trigger primitive algorithms exercised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

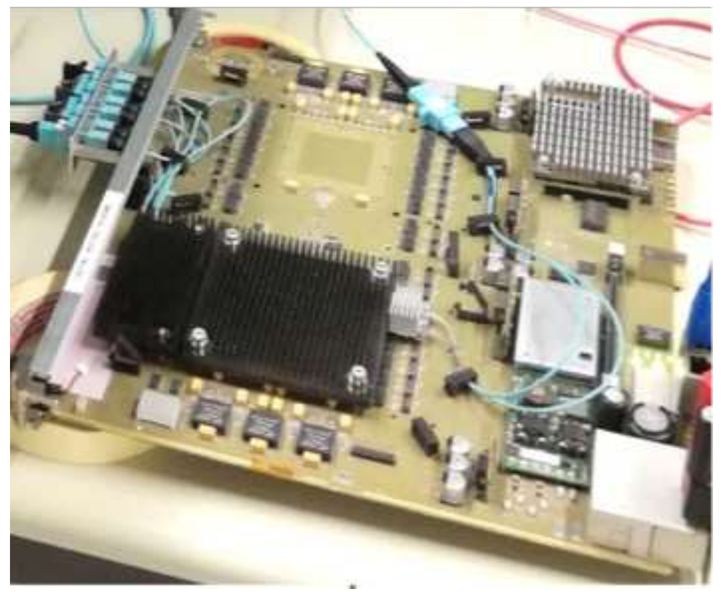




DAQ PC

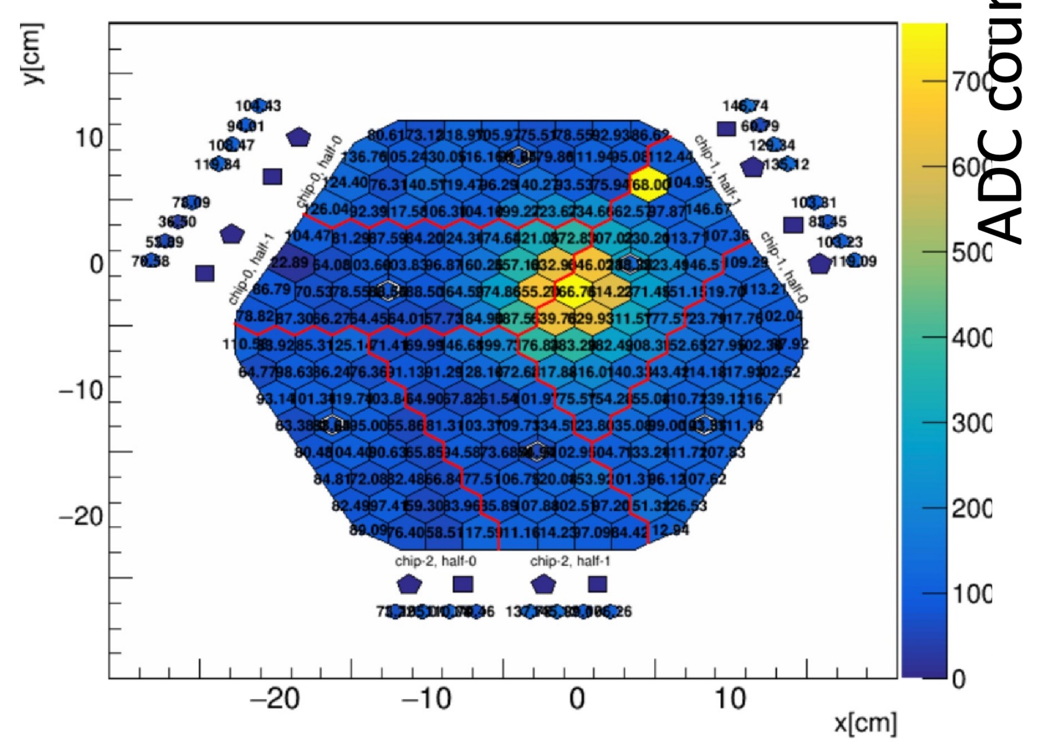
DTH

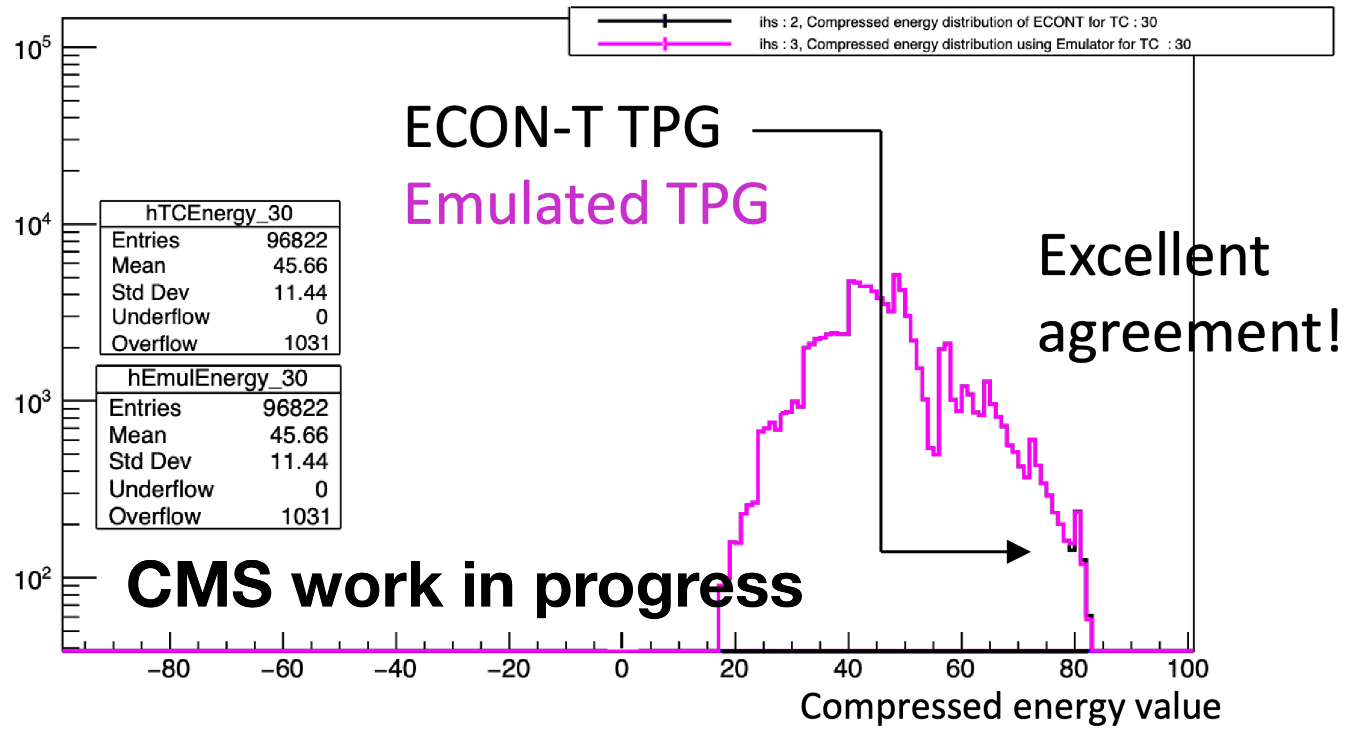




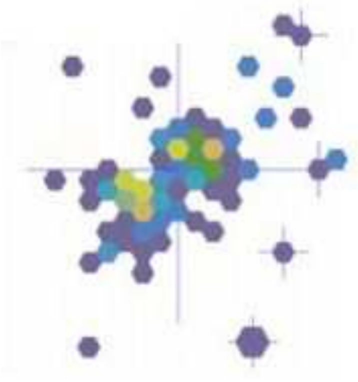
Serenity ATCA-based board

Beam spot in LD full module



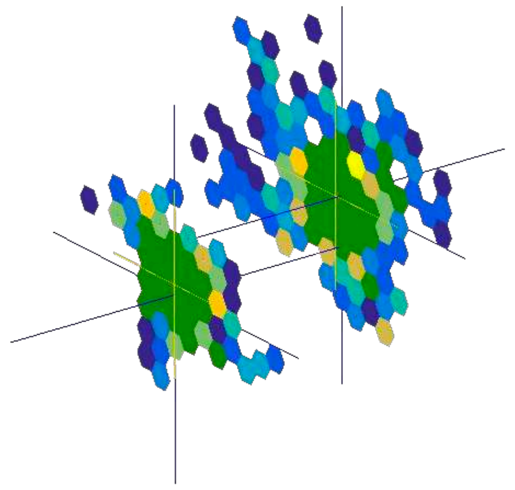


Reconstruction with the Iterative Clustering (TICL) framework



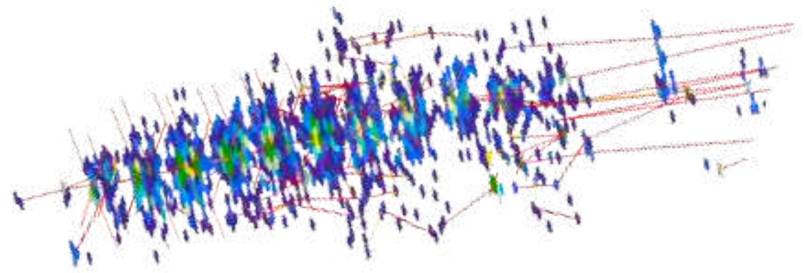
Reconstructed hits

CLUE - clustering through **energy density**
- Reduce by 10x the dimensionality and remove noise
- Fast operations (300 events/s) on parallel GPUs



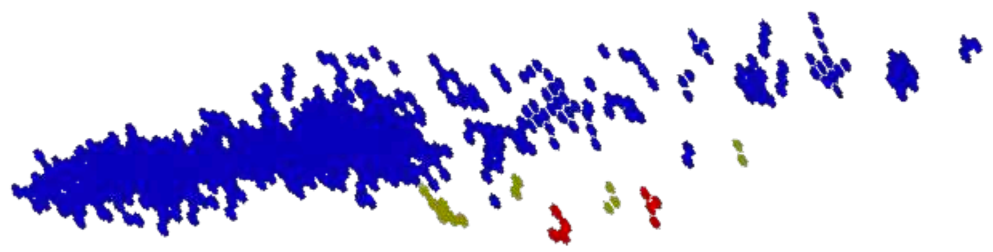
Layer-clusters (2D)

CLUE 3D
- Re-cluster with longitudinal dimension
- Over 200 events/s on parallel GPUs



Tracksters (3D)

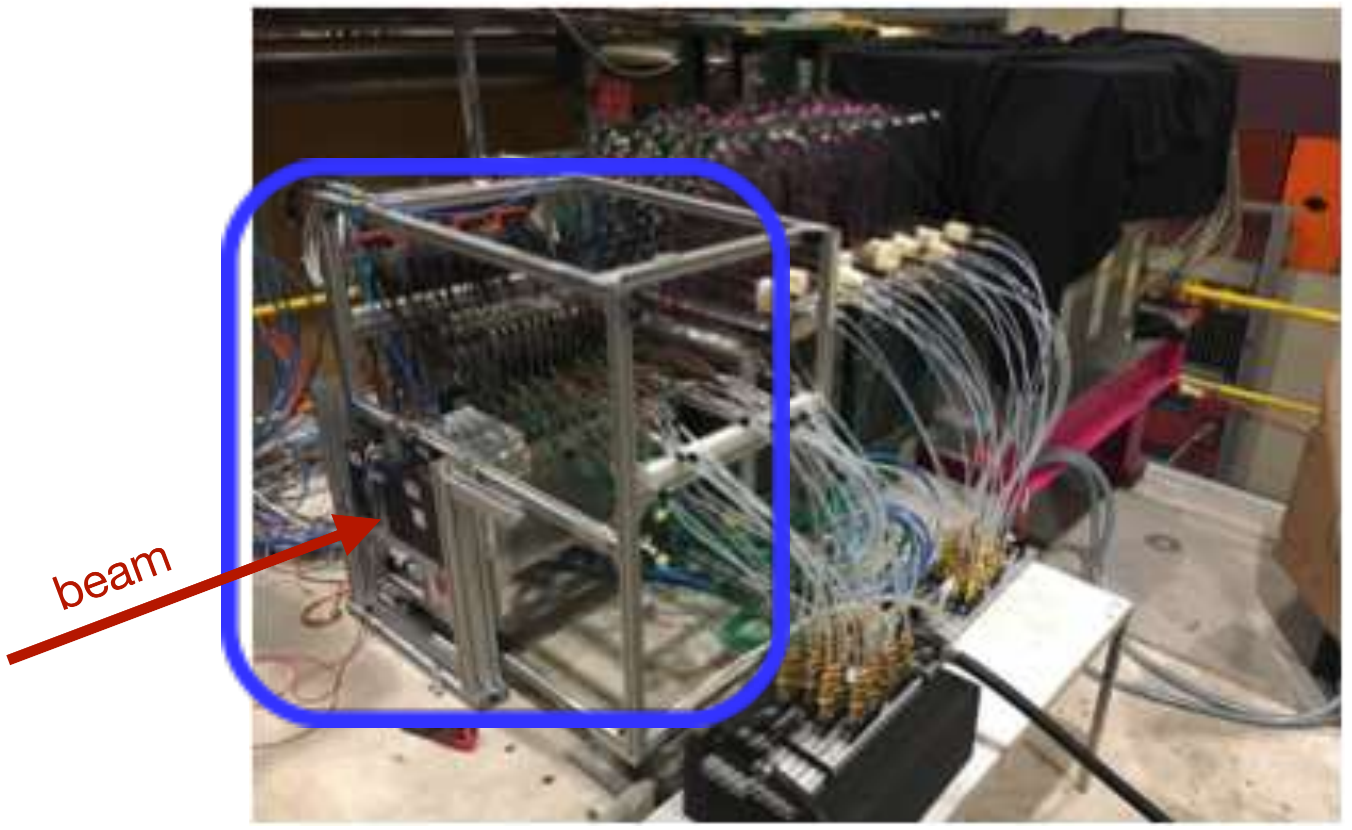
Particle flow
- Geometrical linking of layer-clusters with timing and energy compatibility
- Build showers/particles and assign properties and probabilities



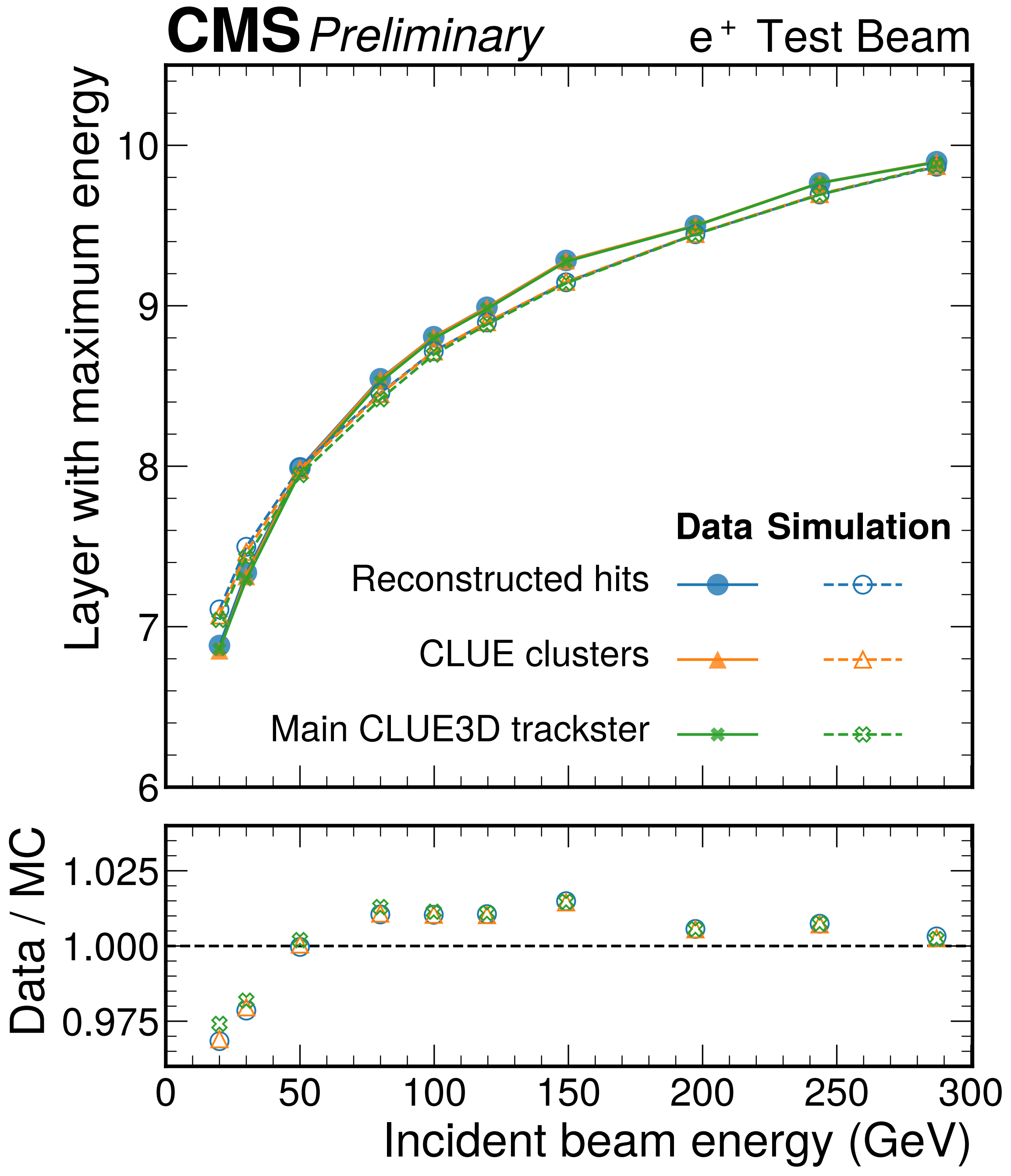
Particles (5D)

CLUE and CLUE 3D performance with test beam data

- 2018 test beam campaign data:
  - **28 single-module layers HGCAL-EE section**
  - 20 to 300 GeV e⁺ beam
- Full GEANT setup simulation

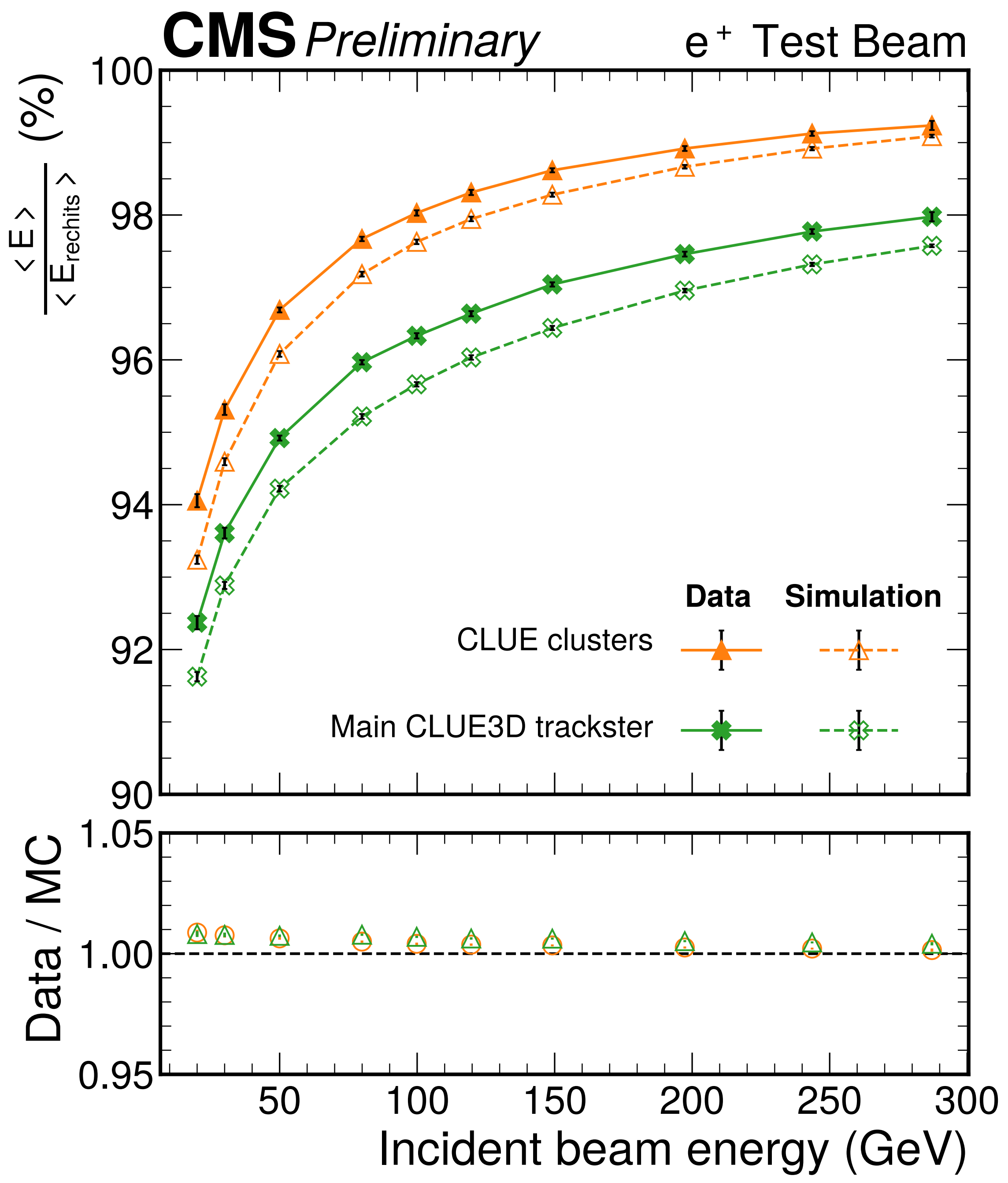


Longitudinal profile



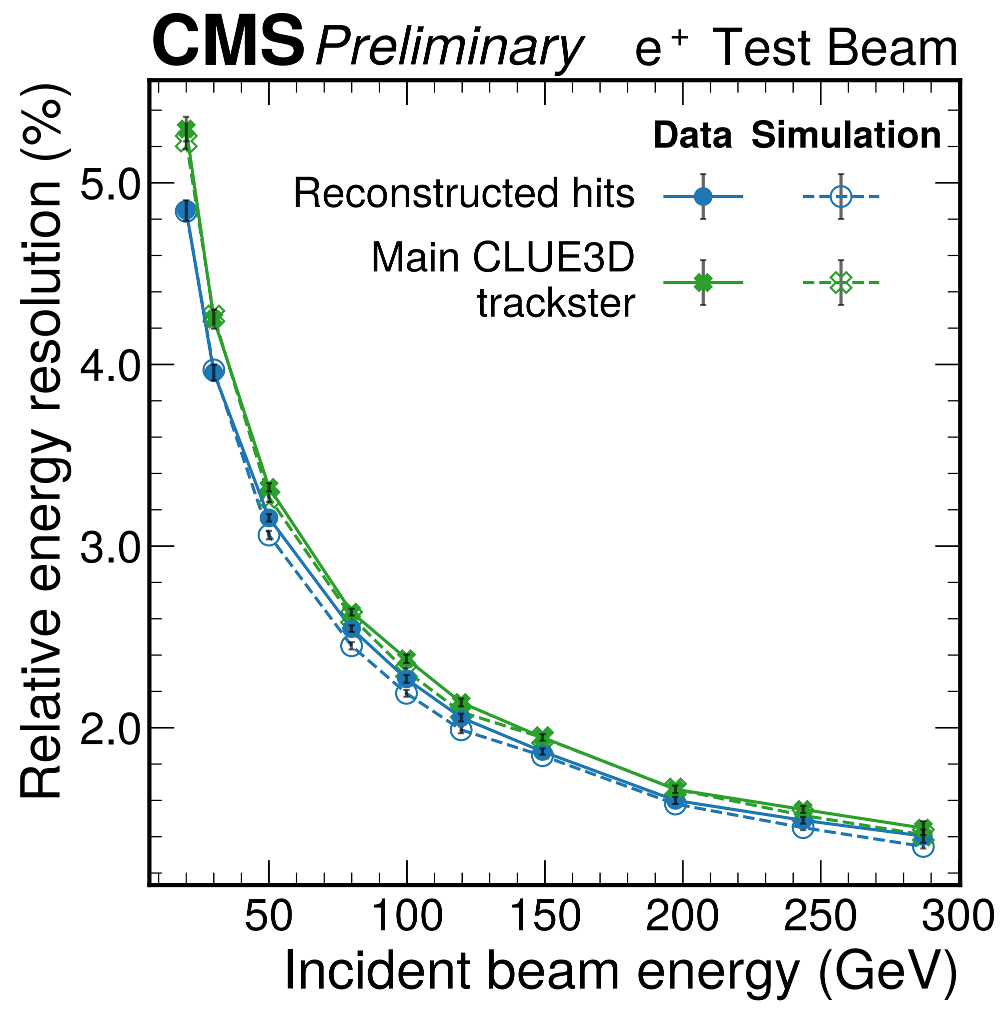
- Data/MC agreement within 1% over 50 GeV

Clustered energy



- Large fraction of energy reconstructed into clusters

Energy resolution

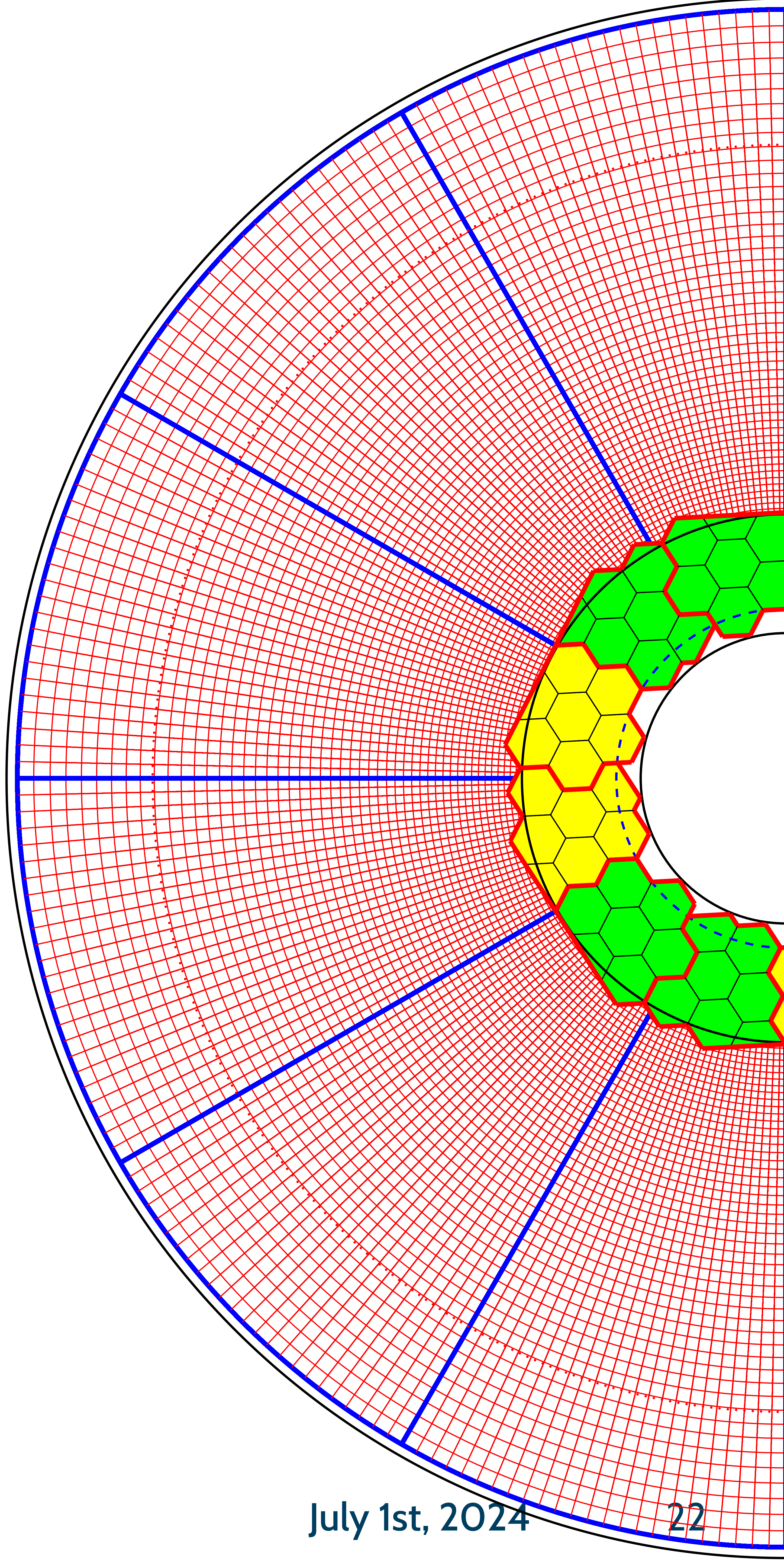


- Tracksters energy resolution compatible with that of reconstructed hits

Excellent performance on data and simulation

Conclusion and outlook

- The challenging HL-LHC conditions call for a **complete change of paradigm**
- The HGCAL will provide **excellent 5D performance**
  - Novel reconstruction algorithms are fast and robust
- System integration and validation is proceeding **at full speed**
  - **Upcoming 2024 test beam**: tests in magnetic field, further testing of the readout chain
  - **Scaling up**: mass production of cassettes and modules in 2025

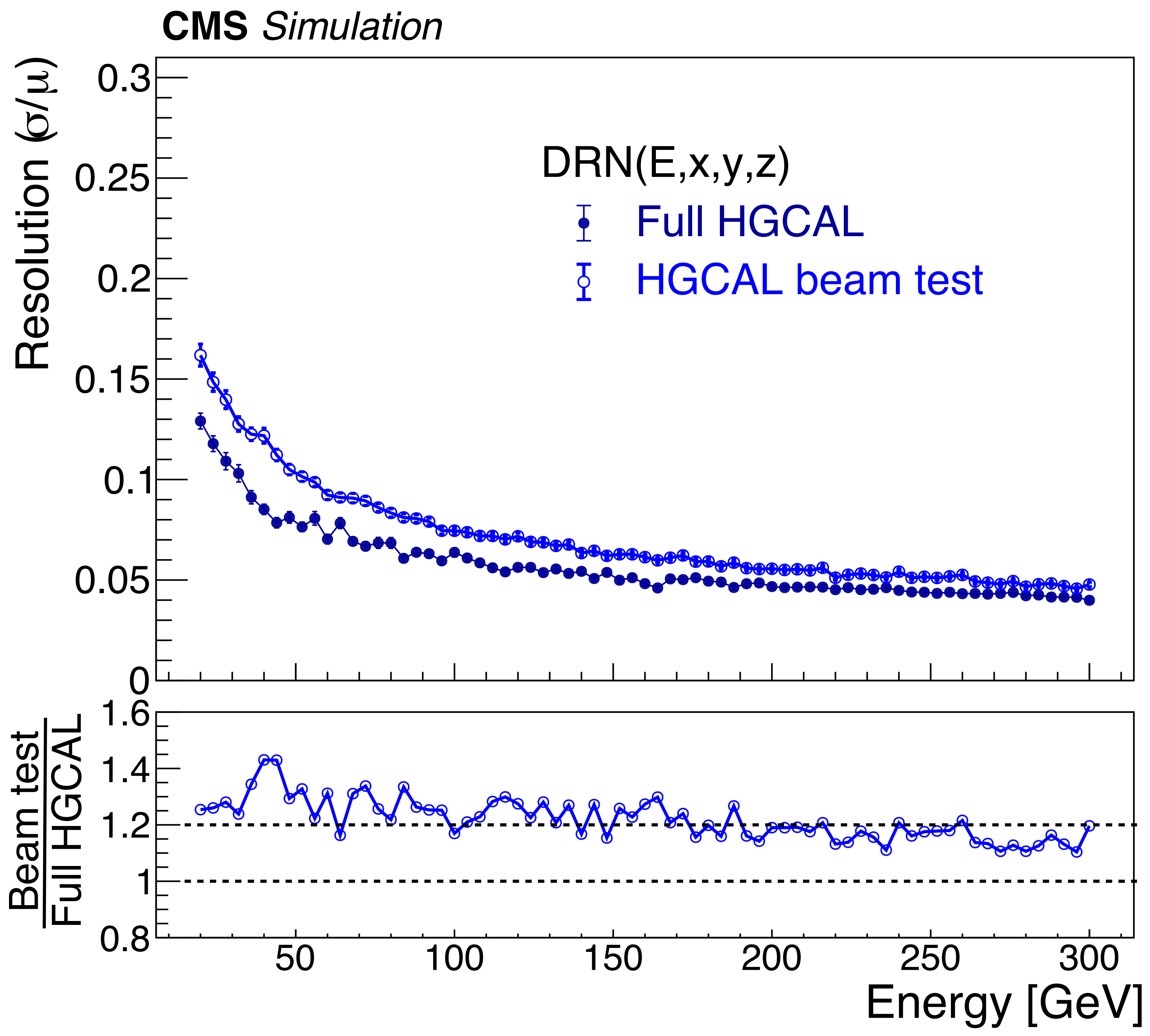


BACKUP

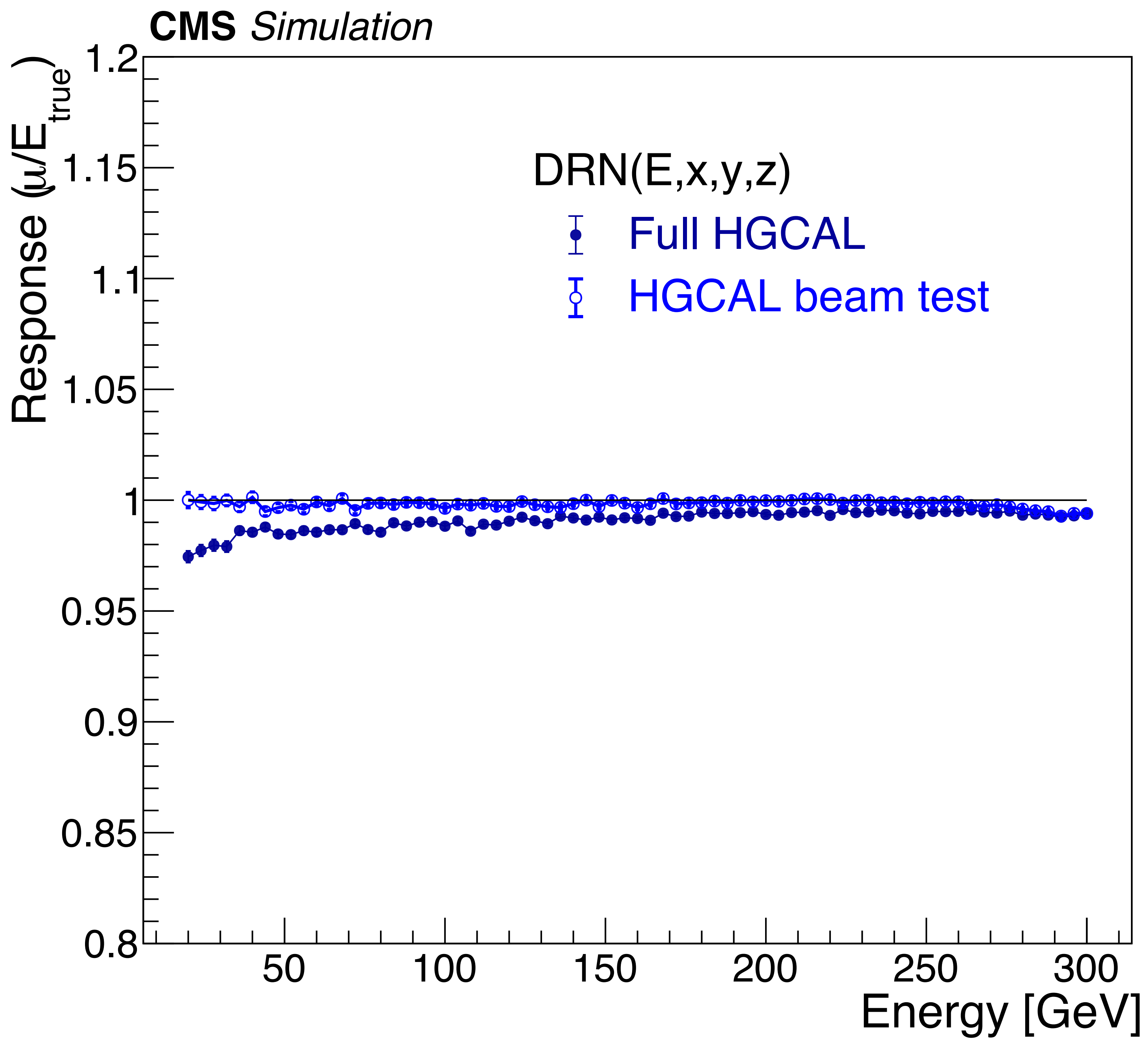
arxiv:2406.11937

GNN-based reconstruction (DRN) with full HGCAL

- Estimate of the potential energy leakage in the test beam prototype w.r.t. the full HGCAL system
  - GEANT4 full geometry setup



- 10 to 40% improvement with full HGCAL

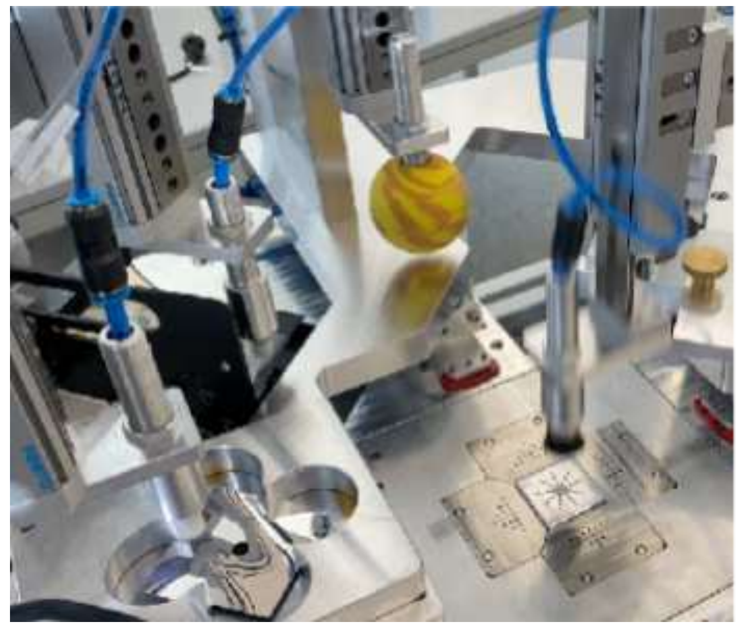


- Response < 1 due to longitudinal and transverse shower evolution modelling

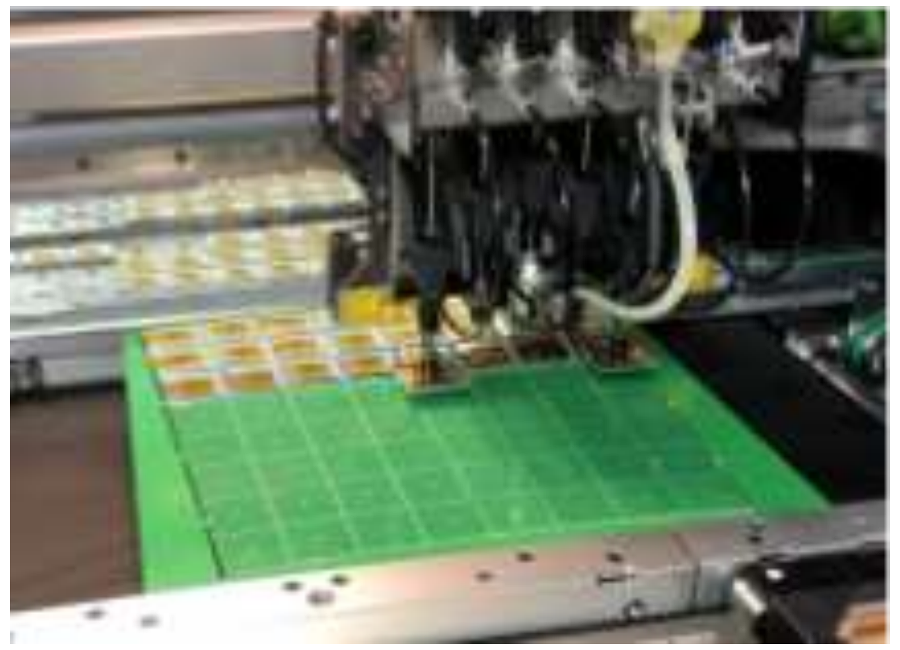
Scintillating tiles system test

- Readout elements and DAQ concepts close to those of the silicon system, with minor adaptations

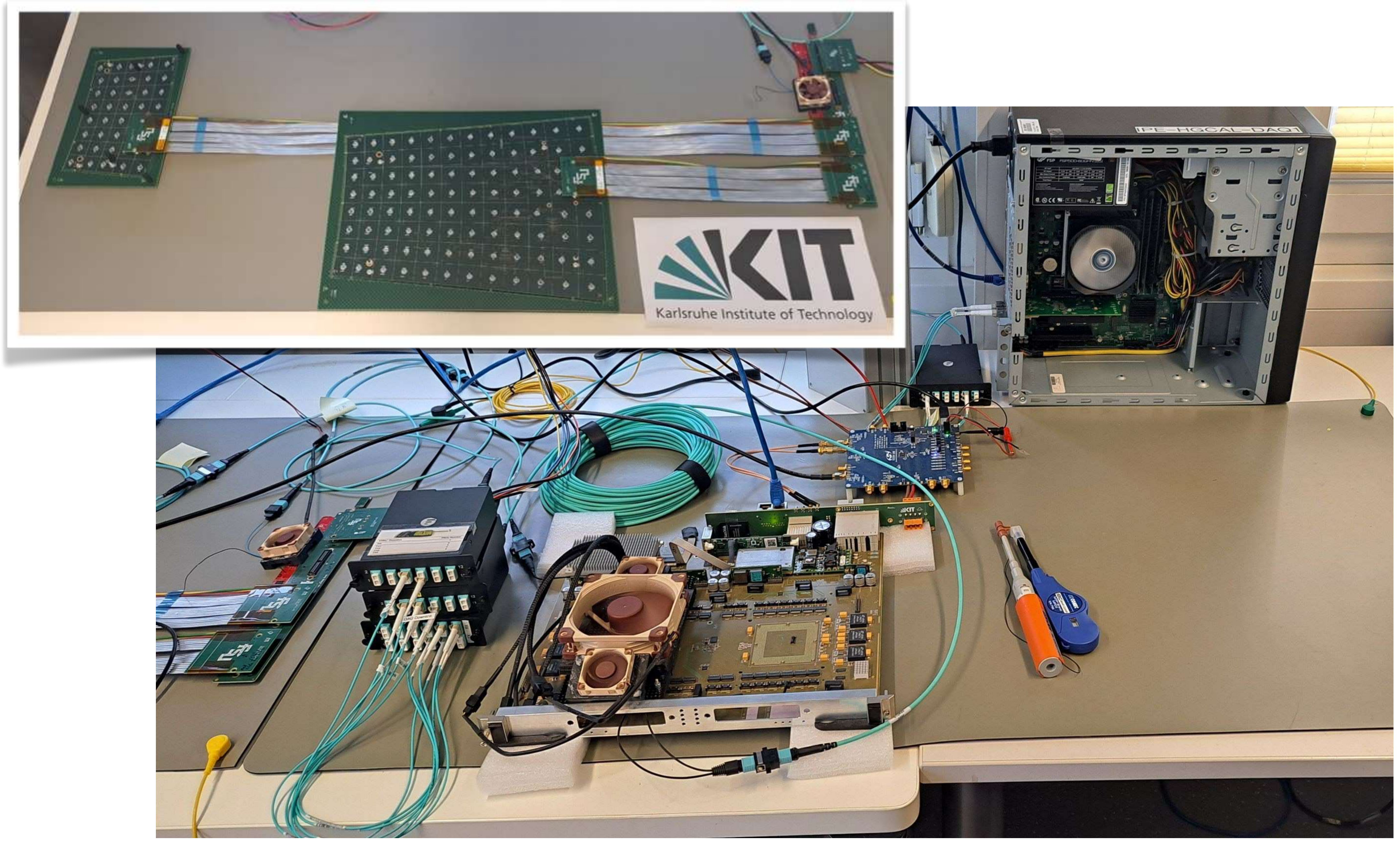
- Tile and SiPM production started
- Production phase of the tile modules starting summer 2024
  - Assembly at DESY/FNAL



Tile wrapping station (DESY)



Tile module assembly (DESY)



- Readout chain vertical tests advancing in parallel to silicon system test
  - Further testing at test beam campaigns at DESY