The CMS High Granularity Calorimetry

(challenges in energy and timing measurements)

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Innovative Detector Technologies and Methods

Lisboa, 12-14 September 2023

Introduction

The HGCAL concept

Sensors and modules

Electronics, readout and system integration

Mechanics challenges

Performance and simulation results

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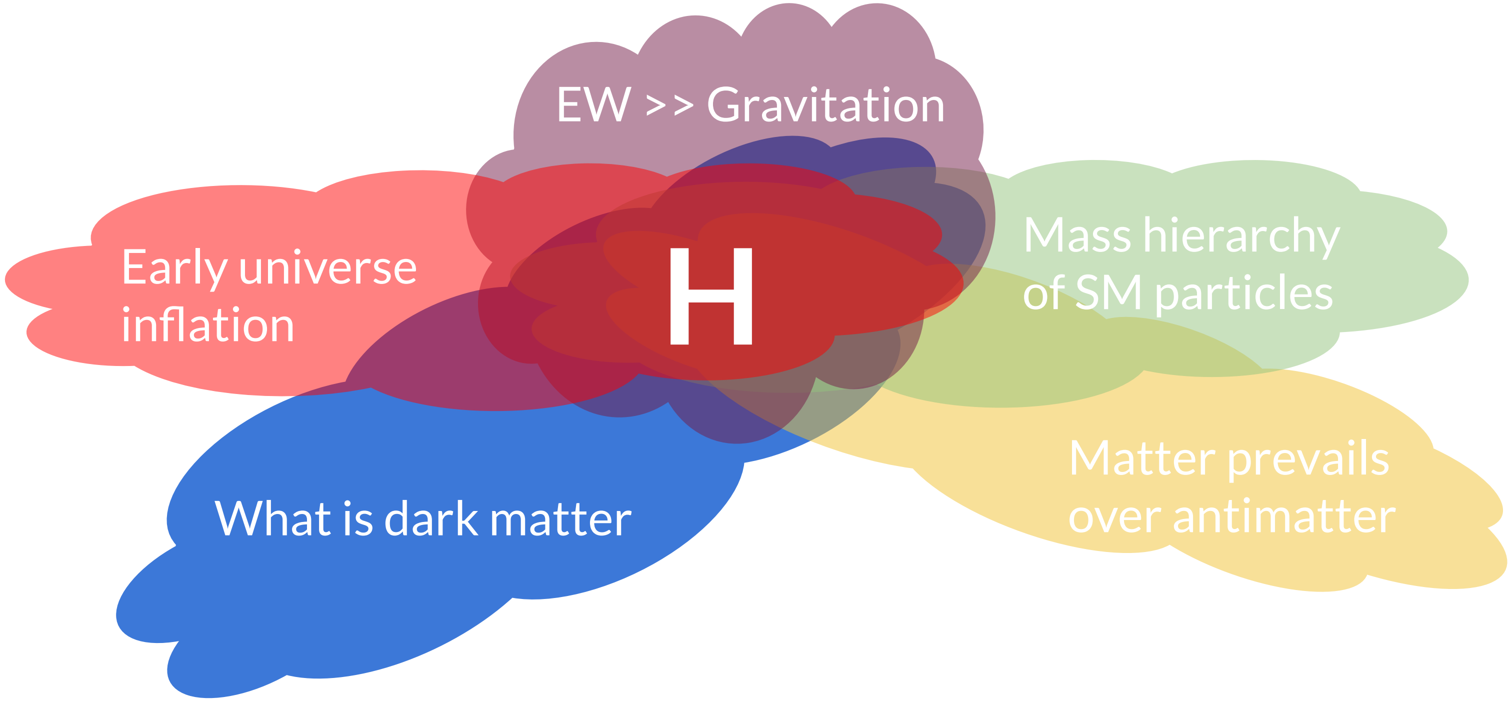
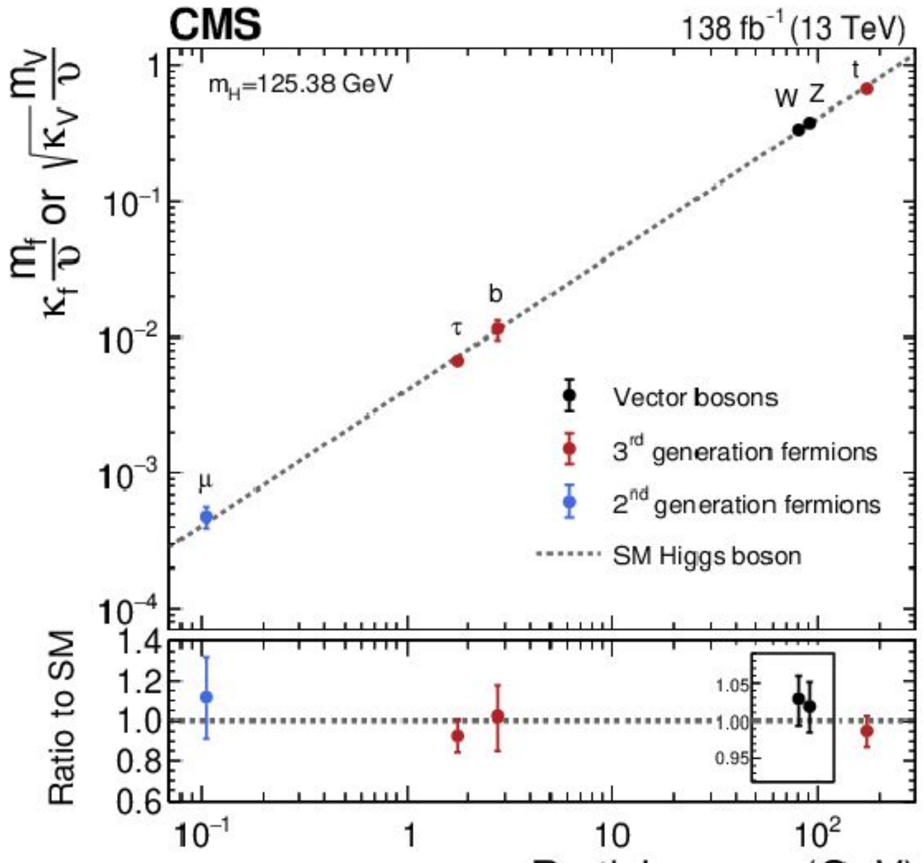
(Eleven years past) the Higgs discovery at the LHC

Central piece of the puzzle enlarges pool of fundamental questions





[Nature 607 (2022) 60-68]

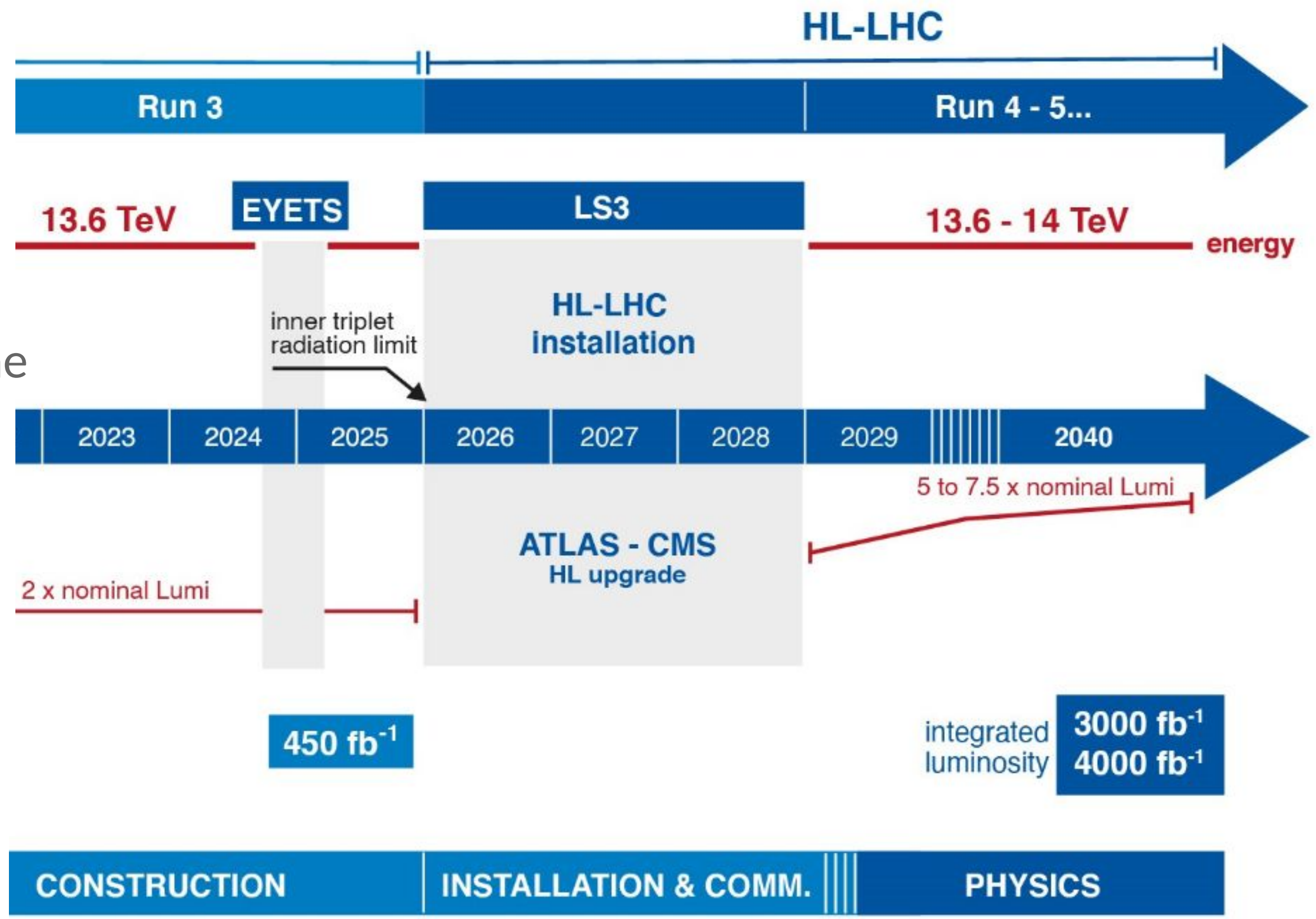
High Luminosity LHC = 10x more Higgs

- deepen fundamental questions
- in pursuit of what lies beyond the SM

The HL-LHC project

Luminosity jump to leveled 5×10^{34} $cm^{-2}s^{-1}$ (=250 fb^{-1} / year) requires innovative technologies

- 12T superconducting (SC) Nb_3Sn magnets
- Compact SC crab cavities (ultra-precise control for beam rotation)
- New beam collimation technology (machine protection and cleaning ion beams)
- High-power lossless SC links
- Upgrade of the injector chain (2018-2021)

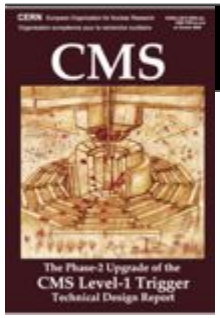


10.1142/9581 10.17181/CERN.7NHR.6HGC

Experiments to cope with HL upgrade

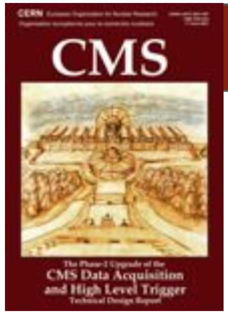
- 140-200 collisions each 25 ns crossing
- detectors exposed to high fluence (up to 10^{16} n_{eq}/cm^2) and dose (up to 2MGy) after 3 ab^{-1}

The CMS HL-LHC project explores new HEP paradigms



Level 1-Trigger

Reach 750 kHz in L1 output
with 40 MHz scouting
Tracks and particle flow @ L1

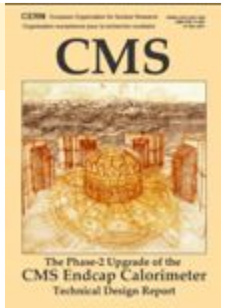


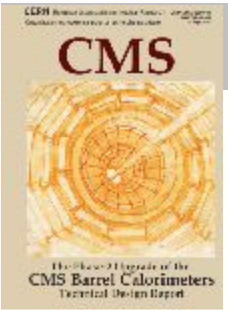
DAQ and HLT

Optical readout
Heterogeneous computing
7.5 kHz output
60 TB/s storage throughput

Endcap calorimeter

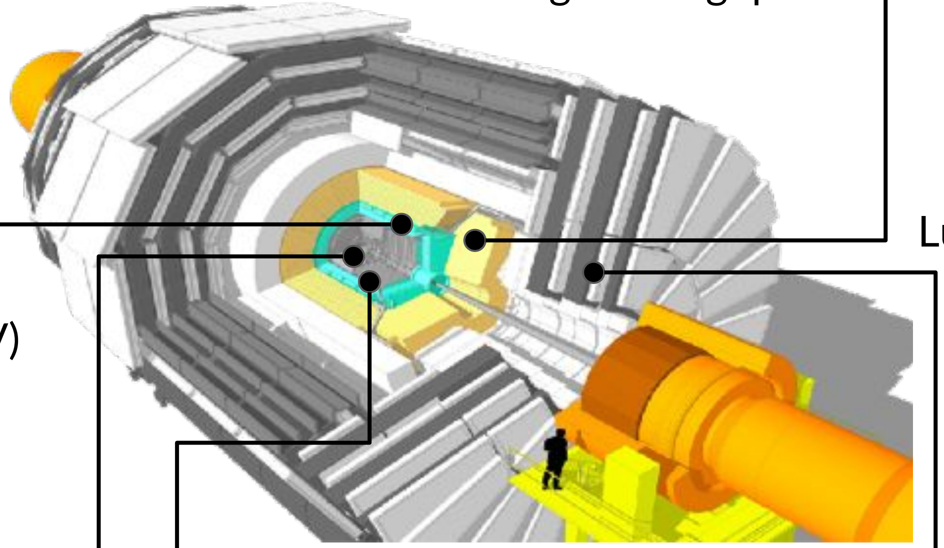
High granularity integrated E/HCAL
3D shower reconstruction
Precise (~30 ps) timing





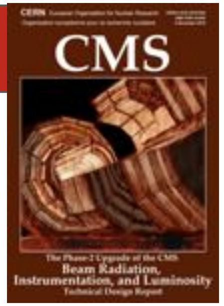
Barrel Calorimeters

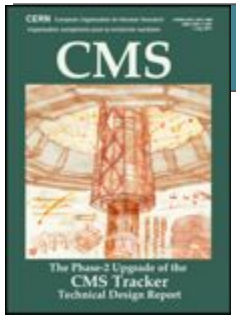
Updated electronics
Finer L1 trigger granularity
Precise e/γ timing (>30 GeV)



BRIL (beam rad./lumi.)

Luminosity/bunch: 1(2)% off(on)line
Beam abort and timing
Beam-induced background
n and mixed-field rad. monitors



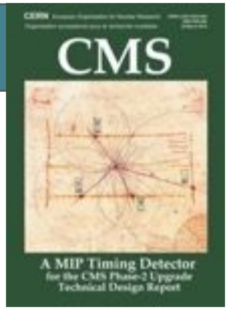


Tracker

Extended coverage to η ≃ 3.8
Reduced material overburden
Increased granularity (strip/pix)
Providing trigger primitives

MIP Timing Detector

Precision timing with
crystals+SiPMs (barrel) or
LGADs (endcap)



Muon systems

Extended coverage up to η ≃ 3
New readout electronics
GEM/RPC 1.6 < η < 2.4

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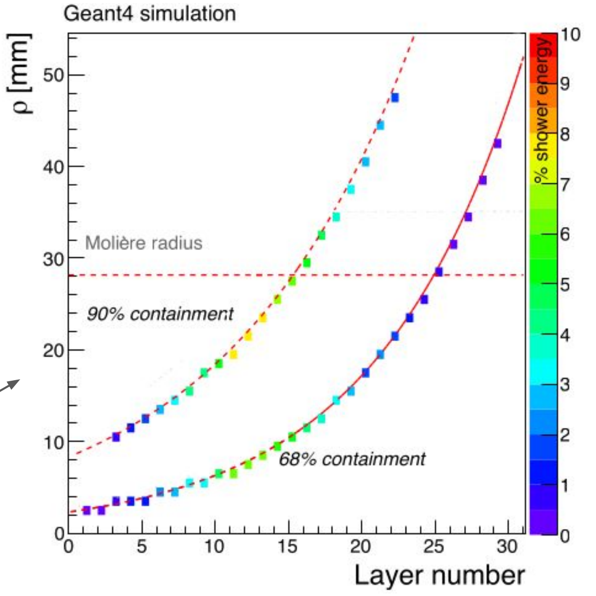
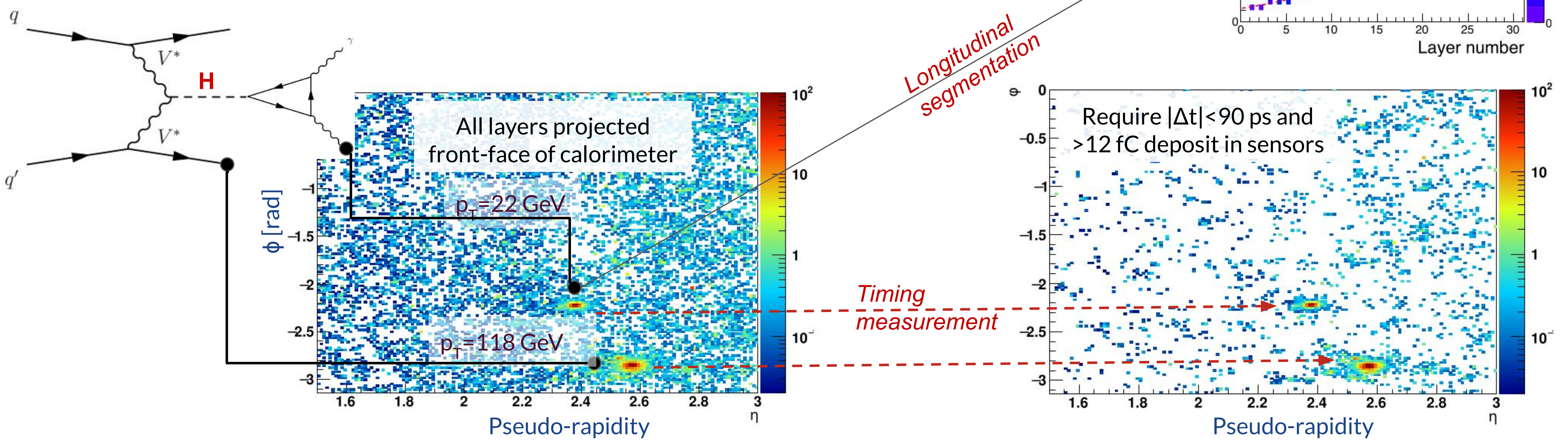
The endcap calorimeter physics requirements

Measure individual showers, characterise jet (sub-)structure, mitigate PU contamination

- $\langle dN_{ch}/d\eta \rangle_{inel}$ > 1.2k at 200 PU ⇒ challenging in the “compressed” forward region
- require high transverse granularity $\mathcal{O}(1\text{cm}^2)$ or smaller sensors
- benefit from longitudinal granularity to further discriminate signals from pileup
- use ~20 ps timing to further link to other sub-detectors and collision vertex





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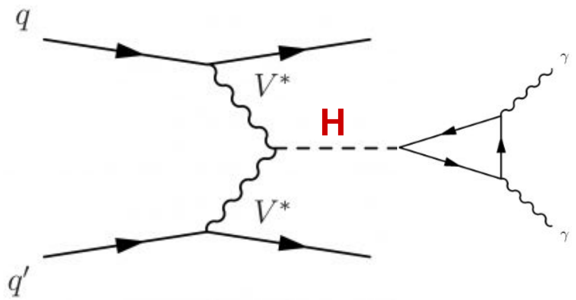


Good energy resolution is also needed: $\Delta E/E < 1\%$ for photons from $H \to \gamma\gamma$

- requires fine longitudinal sampling and thick enough sensors
- fine transverse granularity is also required to
  - correct as possible measurement of the damage caused by radiation effects
  - calibrate with fast and simple methods (e.g. MIP deposits)

Si (and plastic scintillators) were chosen as the main sensors to be used in the new CMS endcap calorimeter

- sustain radiation-hard environment with adequate S/N for MIP-based calibration
- provide measurements of energy, position and time exploiting 5D information at large scale

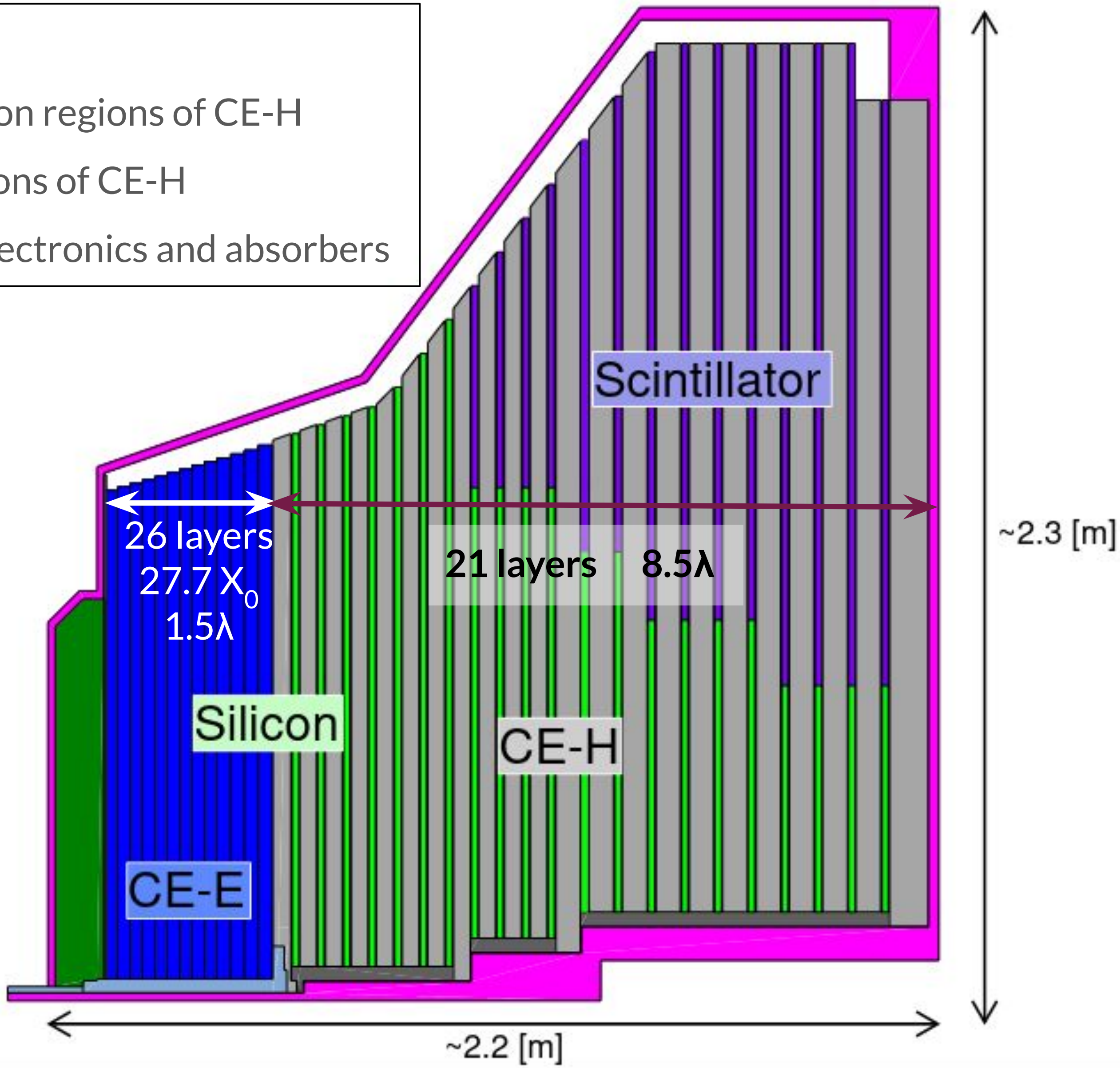
A High Granularity endcap calorimeter: HGCAL

Active Elements

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

Key Parameters

- Coverage: $1.5 < |\eta| < 3.0$
- Absorbers: Cu, CuW and Pb in CE-E, Steel in CE-H
- Si: 6M channels in 26k modules cover 620 m^2
- Tiles: 240k channels in 3.7k boards cover ~370m^2
- Projected power at end of HL-LHC: ~125 kW / endcap



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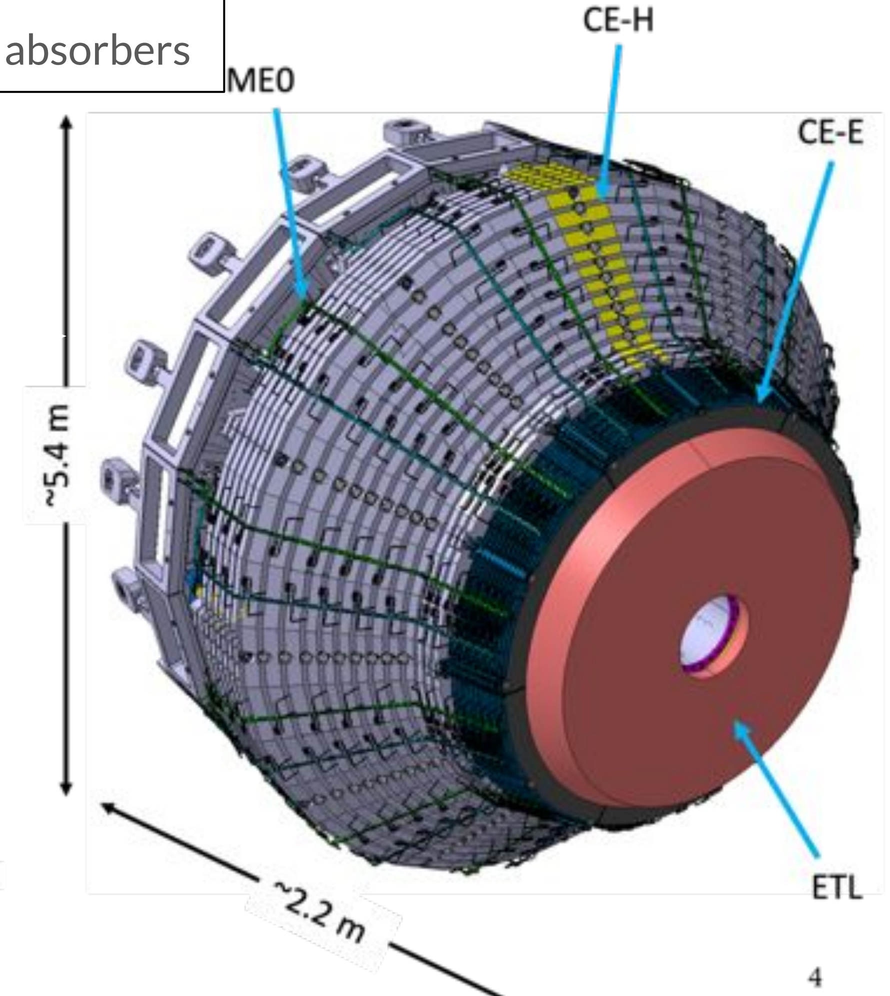
-30°C volume, 215 ton/endcap



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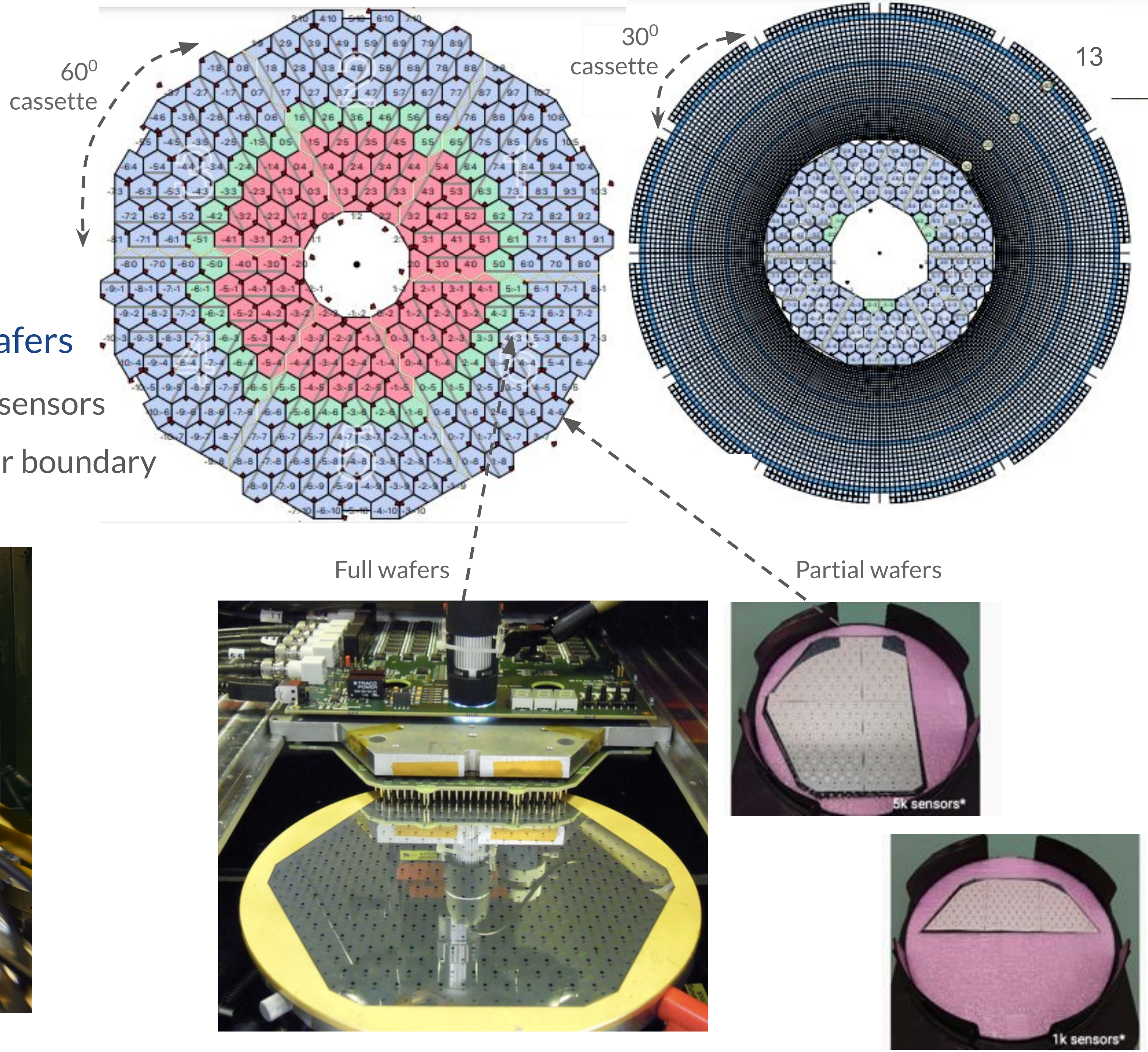
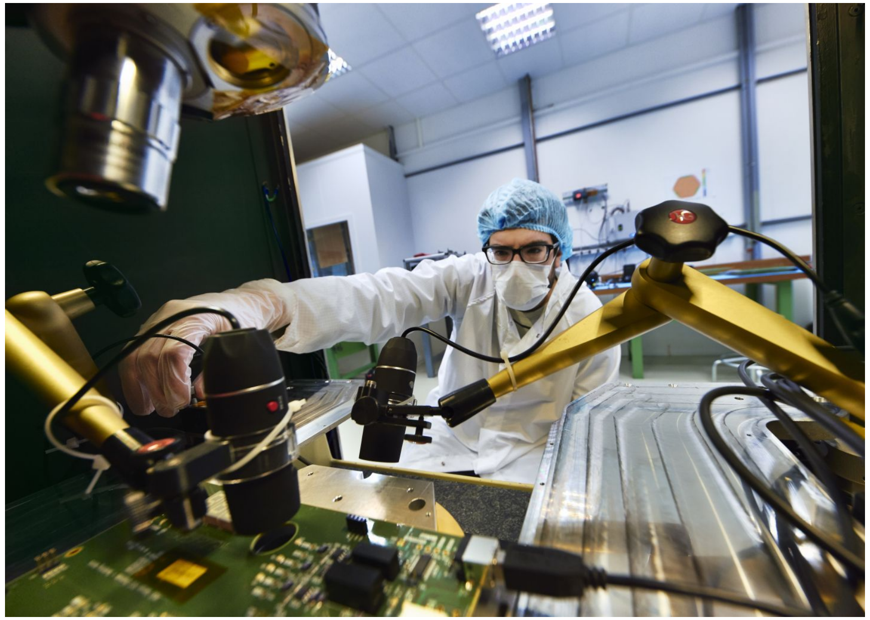
Si sensors

n-on-p sensors with p-stop cell isolation

Tiling of the endcap made with 8" hexagonal wafers

- Minimize number of modules by ½ wrt to 6" sq. sensors
- Need several partials to maximize coverage near boundary





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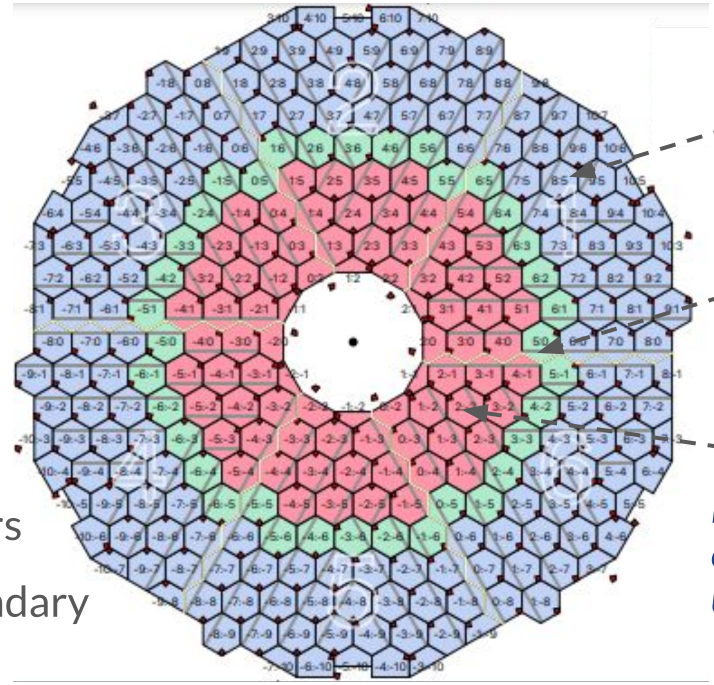


300 µm up to $2\text{x}10^{15}\ n_{eq}/cm^2$

200 µm up to $6\text{x}10^{15}\ n_{eq}/cm^2$

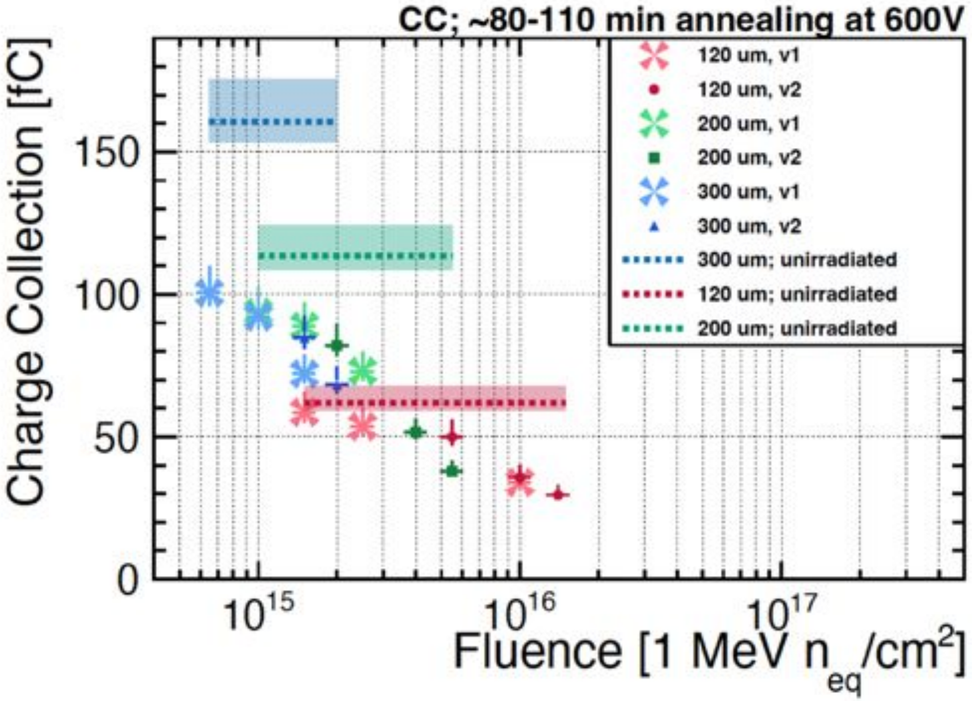
120 µm up to $1\text{x}10^{16}\ n_{eq}/cm^2$

Latest irradiation measurements and electronics/power considerations support usage up to these fluences

To ensure sufficient S/N for MIP calibration and optimized occupancy at the end-of-life:

- three sensor thicknesses: depending on fluence
- two different pad sizes: limit pad capacitance and I_{leak}

Type	Thickness [µm]	V_{dep} [V]	MIP_{eq} [ke$^-$/µm]	Density	Cell area	C [pF]
Epitaxial	120	42	67	HD	0.56	48
Float Zone	200	120	70	HD	0.56	29
				LD	1.26	67
	300	263	73	LD	1.26	45

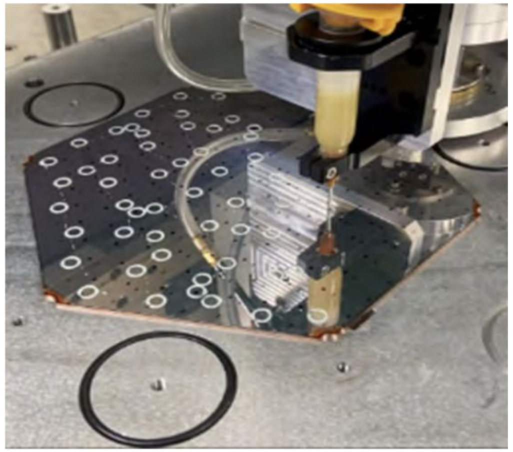


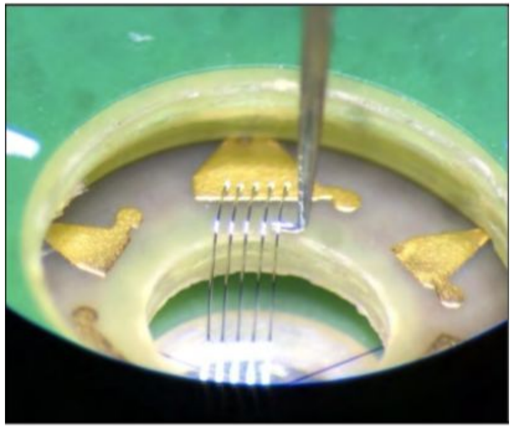
Si modules: highlights

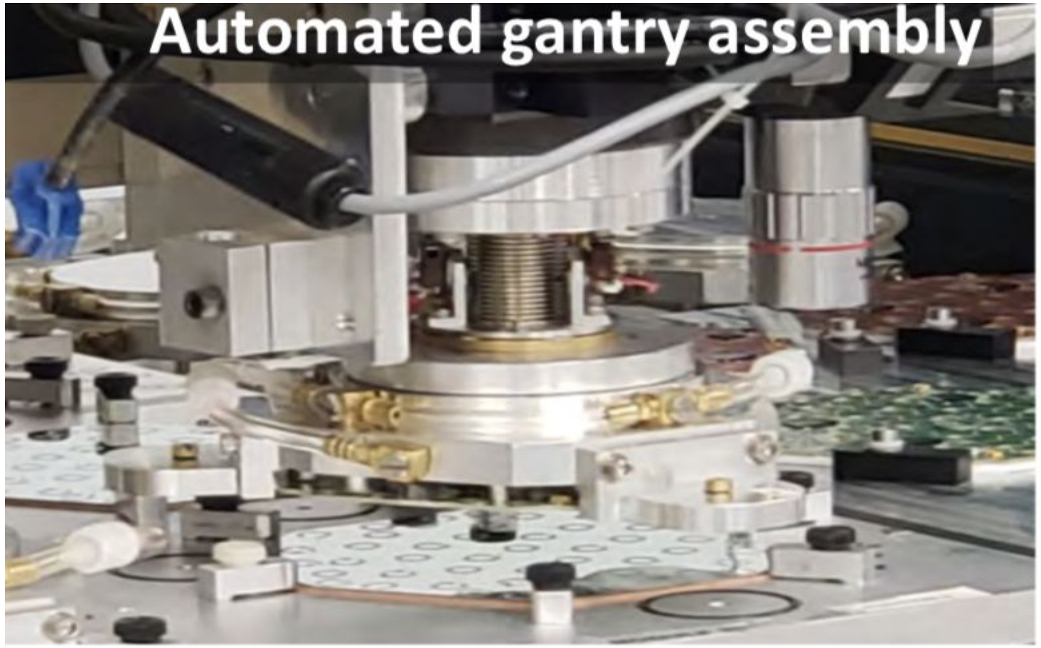
26k Si modules will be produced in 5 assembly facilities with pre-production starting mid-2024

Strong emphasis on simple, mechanically robust module design

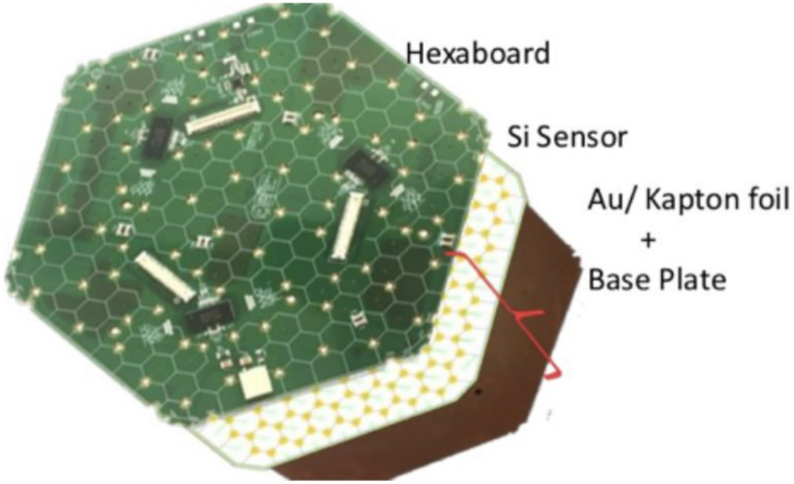
Adapted to be assembled automatically by robot and ease of handling







8” Silicon Sensor Modules



SiPM-on-tile modules: heirs to the CALICE R&D

Ensure S/N>2.5 throughout detector lifetime in the last 13 layers

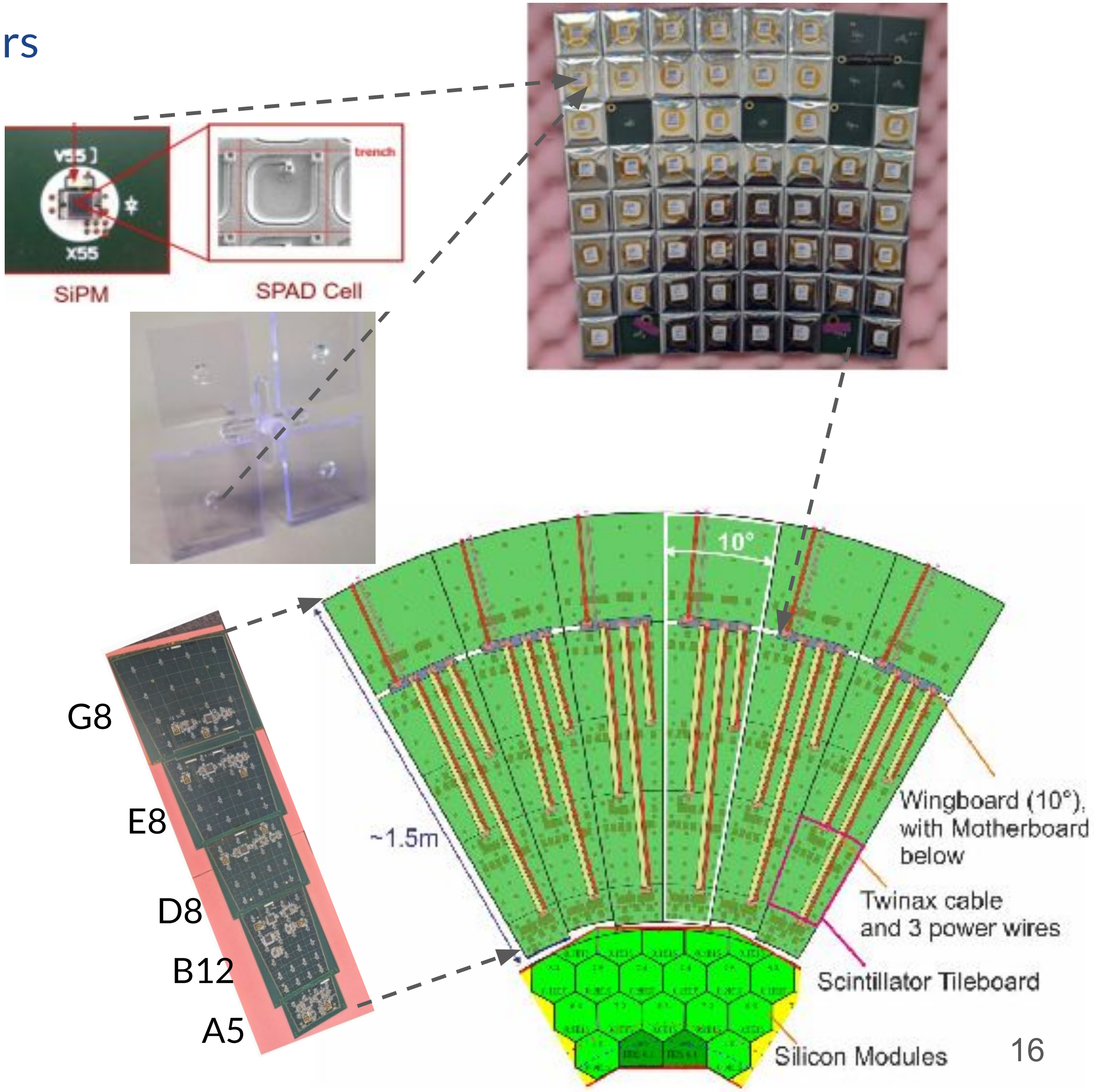
- where dose permits (<2.5 kGy, <0.1 Gy/h) $\phi<5\times10^{13}\, n_{eq}/cm^2$
- two different tile types: cast and injection-moulded
- two sizes (0.834^0 or 1.25^0)
- two SiPM sizes: 4 and 9 mm^2
- partial annealing (recover from dose damage under hypoxia) sets requirement of cold volume kept at 0^0C during shutdowns

LED-based calibration foreseen at startup

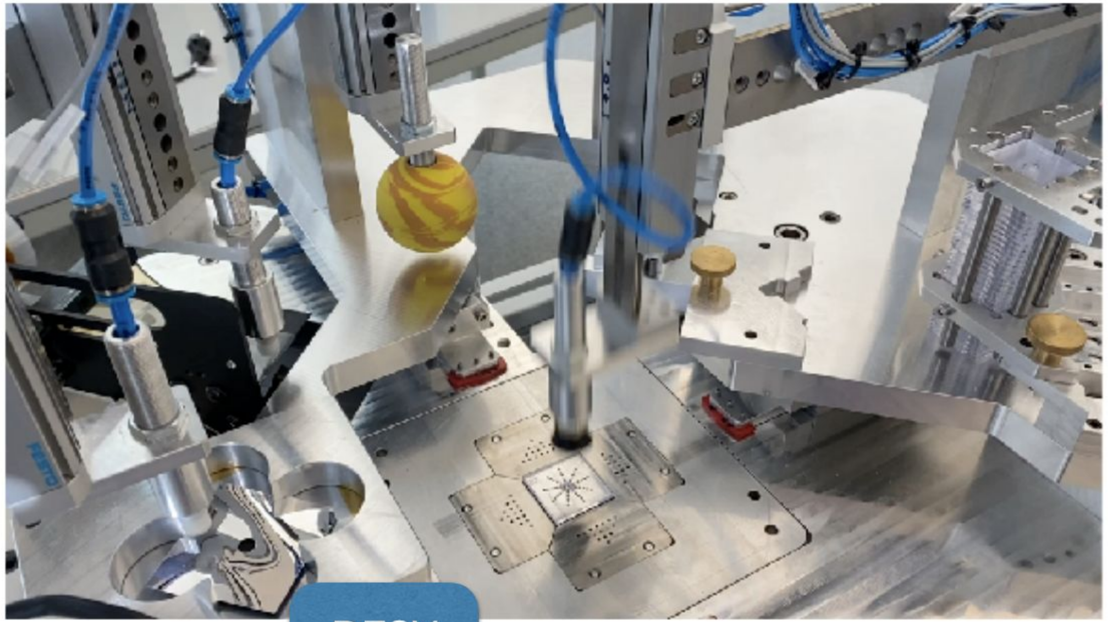
- rely on reconstructed muons throughout lifetime

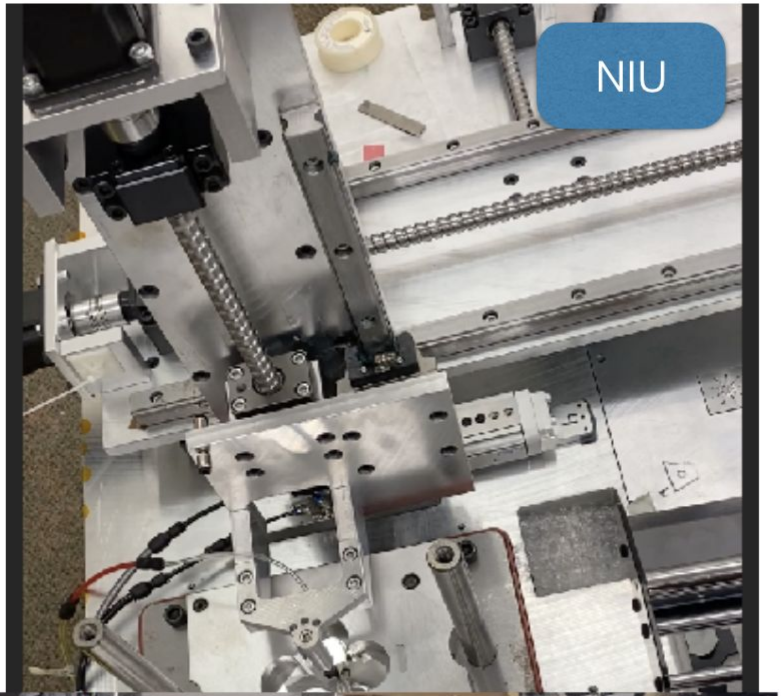
In total 240k SiPMs/tiles in in 3744 tilemodules

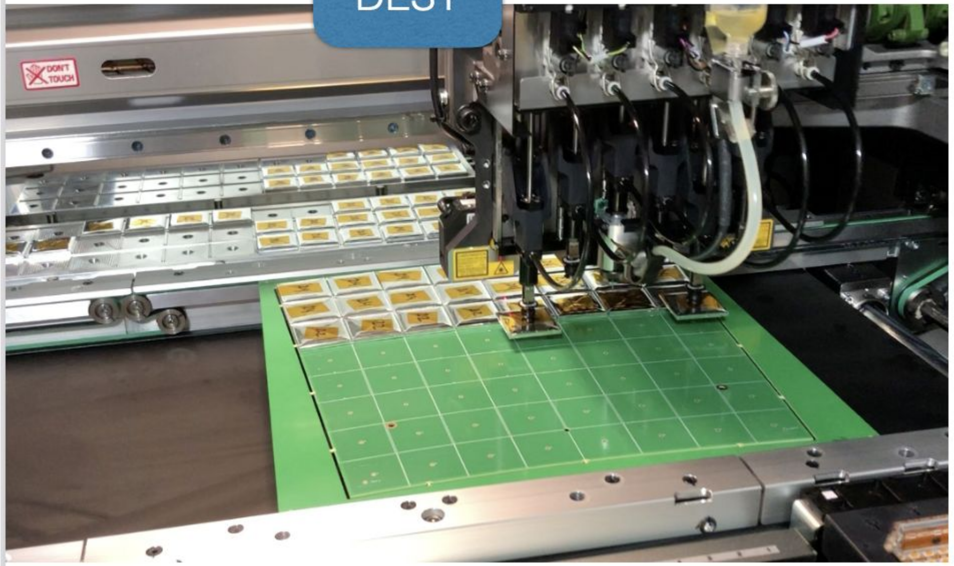
- 2 assembly facilities starting pre-production in mid 2024

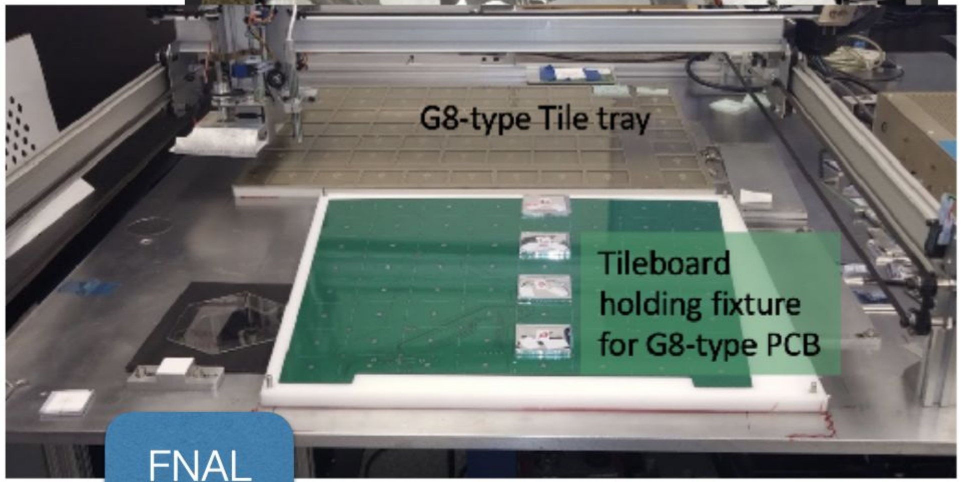


Tilemodules: automated wrapping and pick tool









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HGCROC: the frontend ASIC

Covers full dynamical region required by both Si and SiPM in the electromagnetic and hadronic section

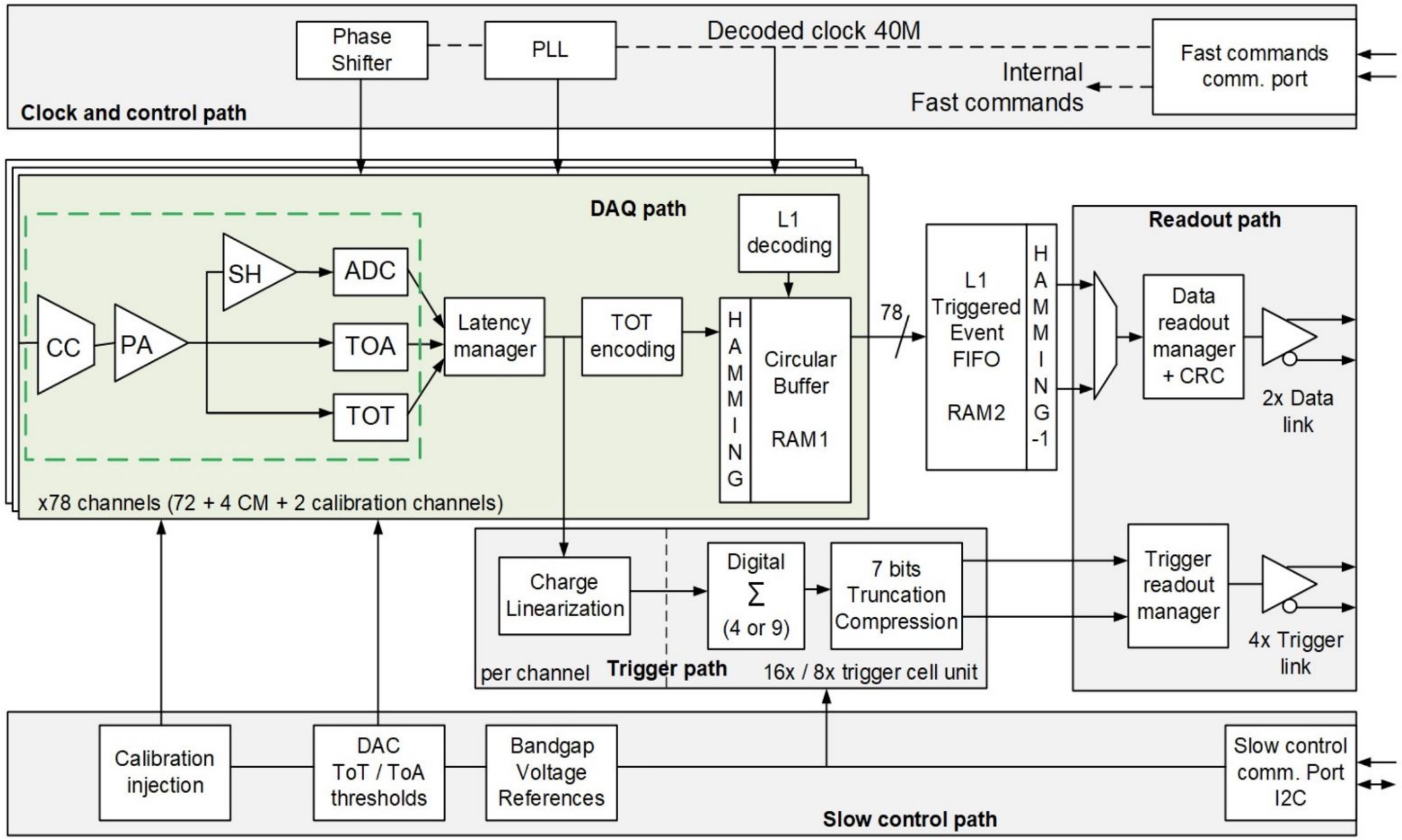
Analogue architecture

- Programmable pre-amplifier gain
- ADC for small values: 10-bit 40 MHz SAR
- TOT TDC at large values: 12-bit, 50ps LSB
- Timing: TOA TDC 10-bit and 25ps LSB

Each chip is in charge of 78 channels

Outputs 1.28 Gb/s

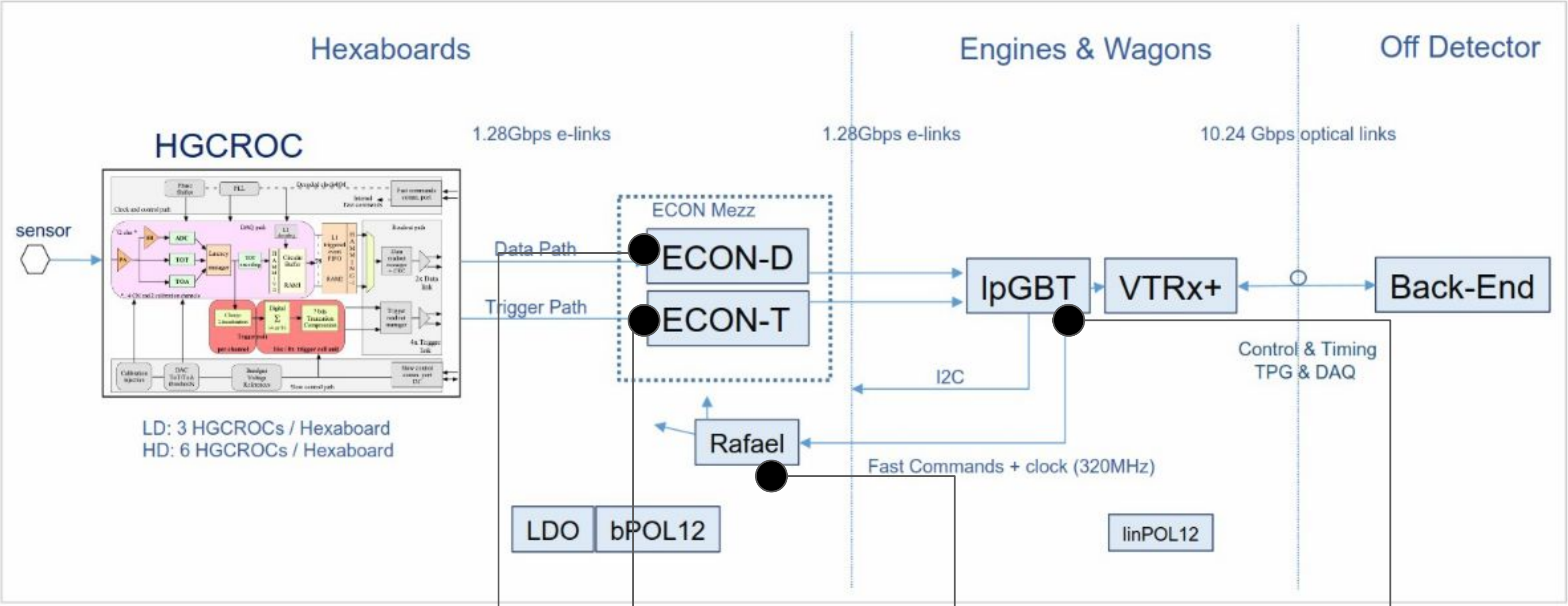
- Trigger primitives: Sum of 4 (9) channels linearization +7b compression (float pt)
- DAQ: 12.5 µs latency buffer (500-deep) for ADC/TOT/TOA and ADC(BX-1).
- 32-event de-randomizer buffer



Control

- Synchronous fast control: 320 MHz (8 bit @ 40 MHz)
- Asynchronous slow control: I2C

HGCAL on-detector readout and control chain



ECON-D

- frontend concentrator chip for the DAQ path
- Channel alignment and ZS after L1 accept

Rafael

- Clock and fast control fanout

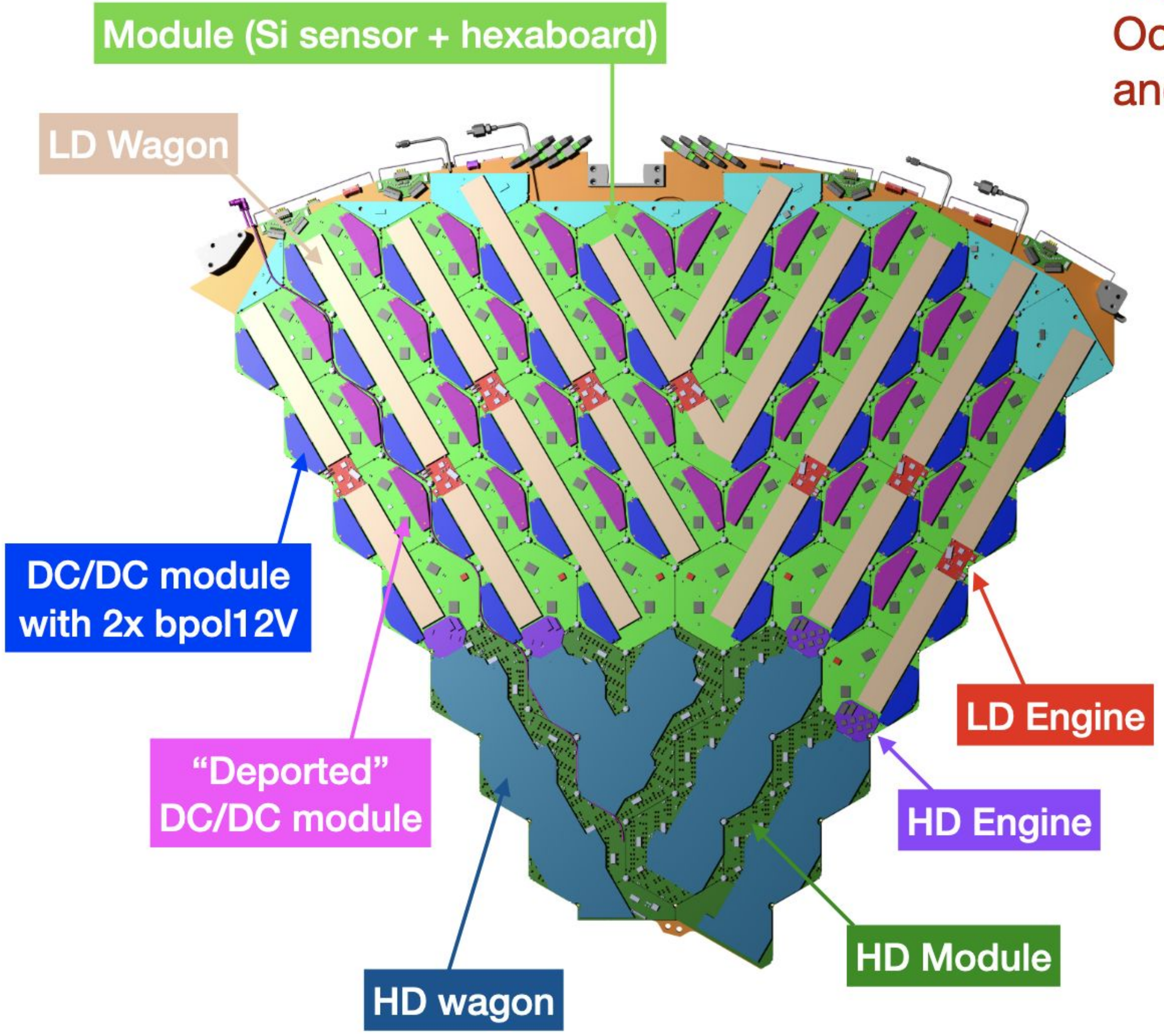
ECON-T

- frontend concentrator chip for the trigger path
- Concentrates data via ¼ trigger algorithms

lpGBT

- Handle data/CLK/control signals
- Via optical link (and VTRX+)
- Integrated in an engine board

The frontend system integration in cassettes

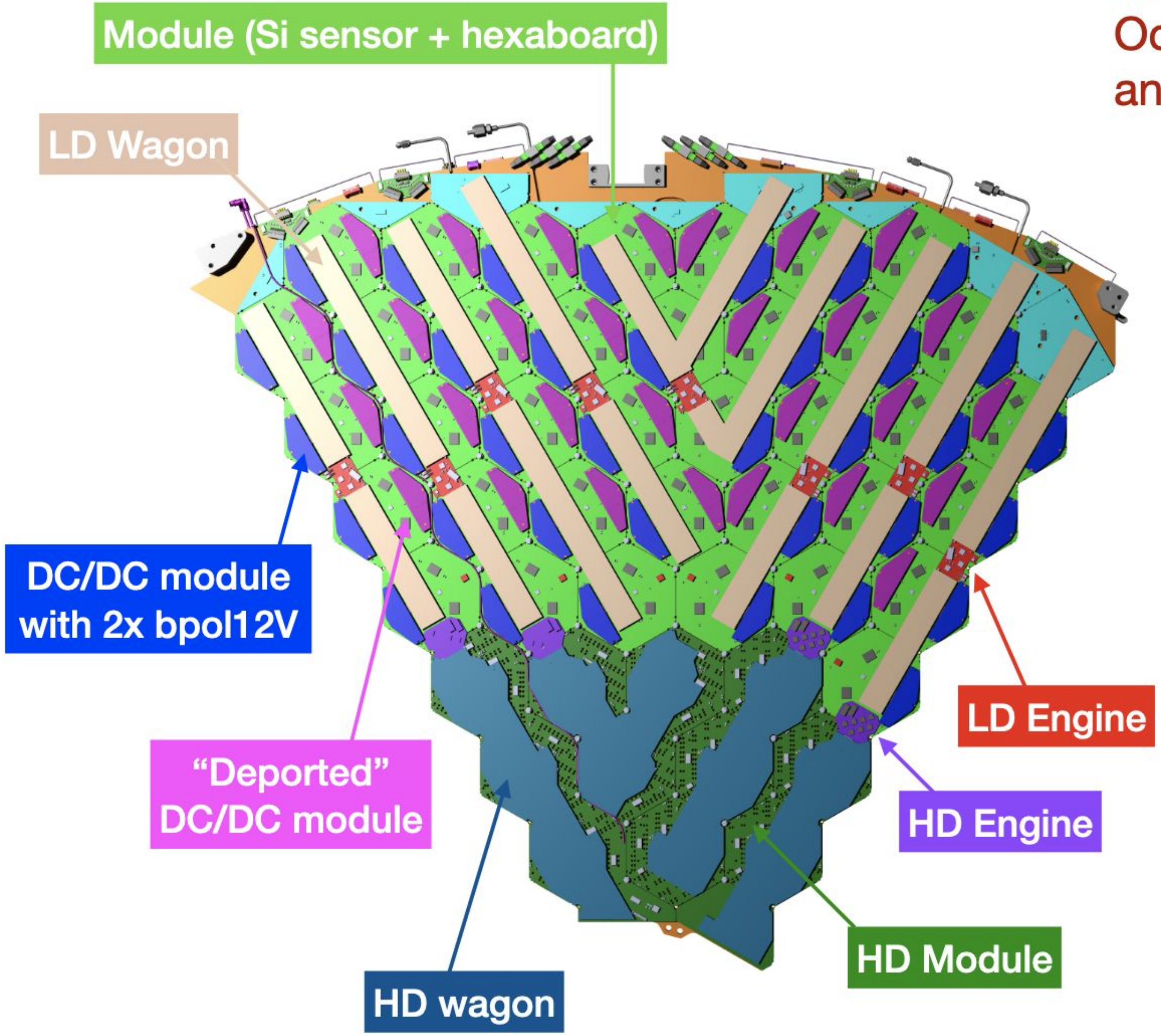


Note: each layer is different!
Occupancies vary greatly within and between layers

Low density region
- Si sensor 200 or 300 μm thickness
- 192 channels (3 HGCROC) per 8" hexagonal module

High density region
- Si sensor 120 μm active thickness
- 432 channels (6 HGCROC) per 8" hexagonal module

The frontend system integration in cassettes



Note: each layer is different!
Occupancies vary greatly within and between layers

Readout train = engine + wagon(s)

Engine:

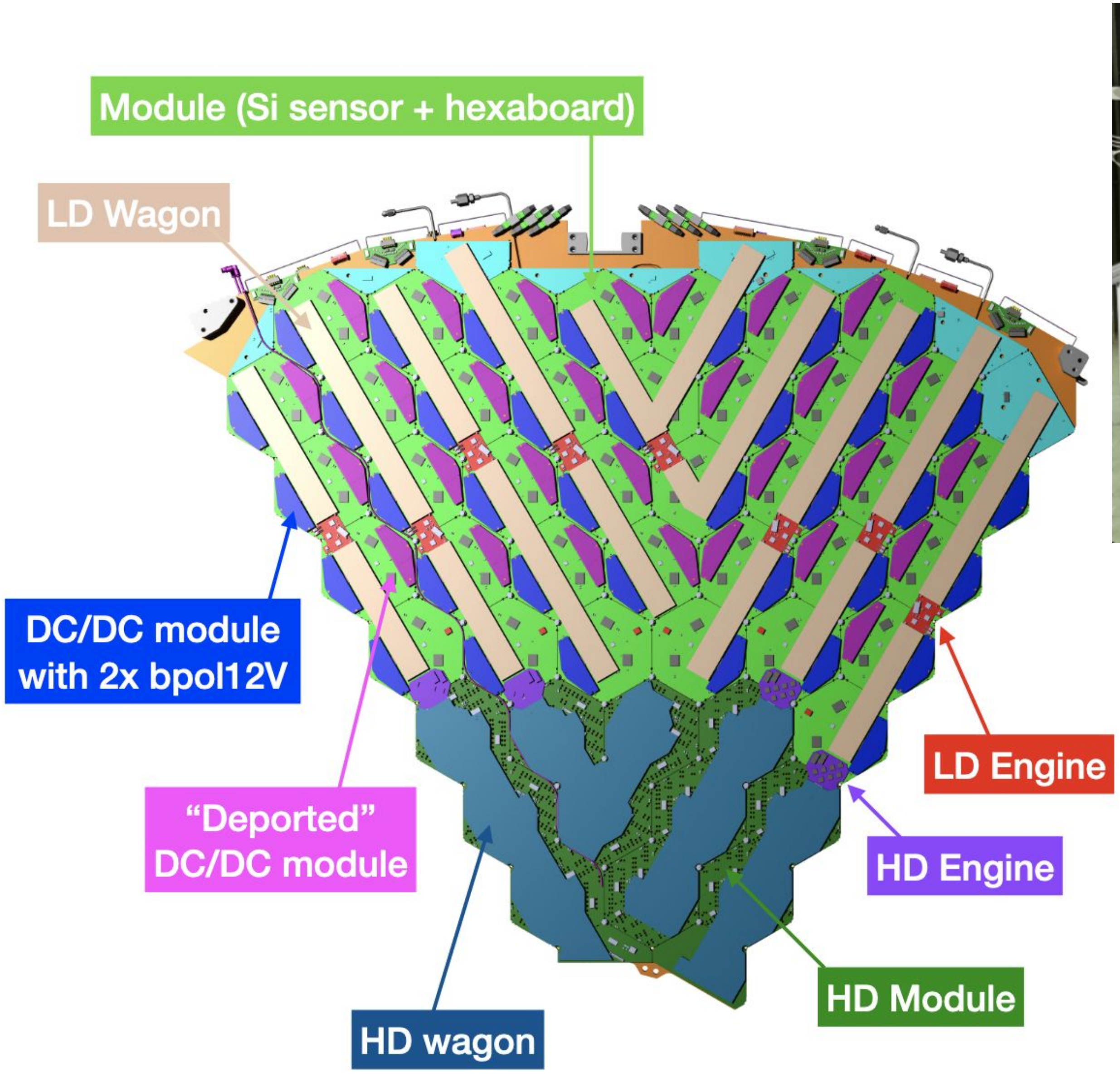
- complex components
- few varieties

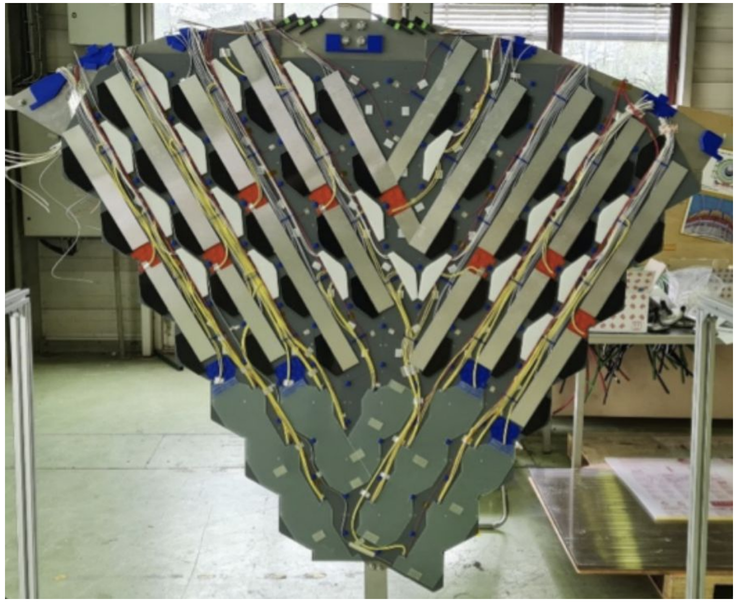
Wagons:

- "rigid wires" absorb the geometrical complexities
- many varieties

Additional design constraints from need to route services

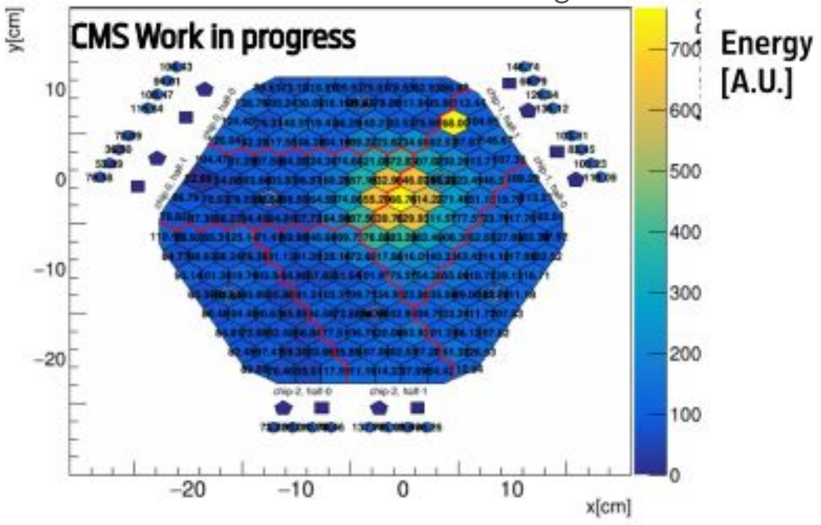
The frontend system integration in cassettes

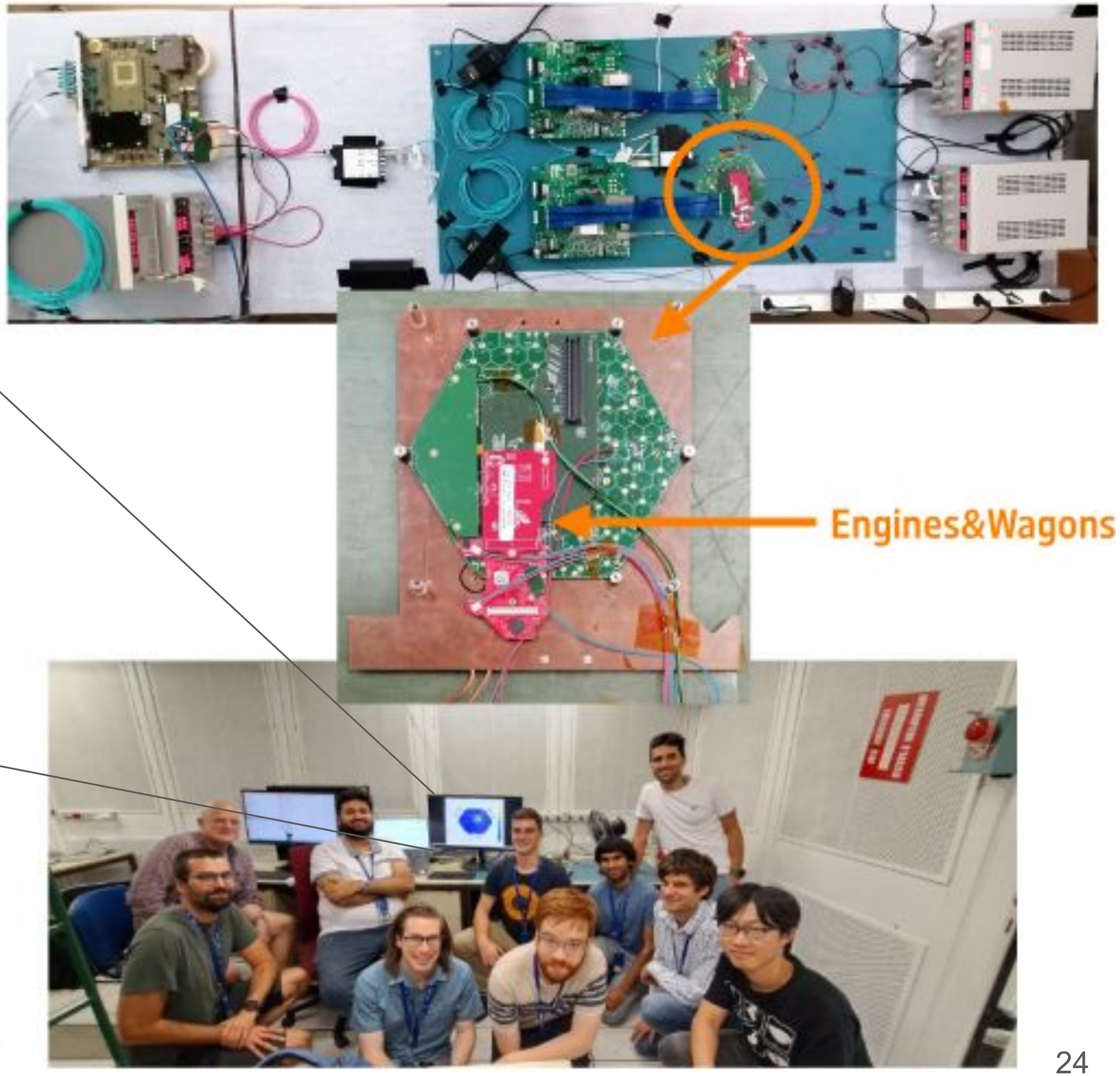




The frontend system integration in this year's beam tests

04-09 Aug'23





The full chain including real ECON-D and ECON-T ASICs will be tested during the next two weeks in the beam test starting tomorrow !

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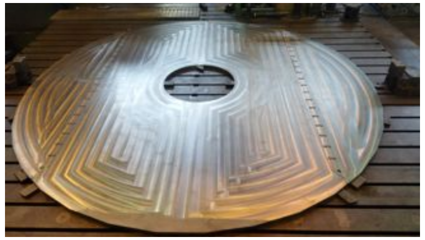
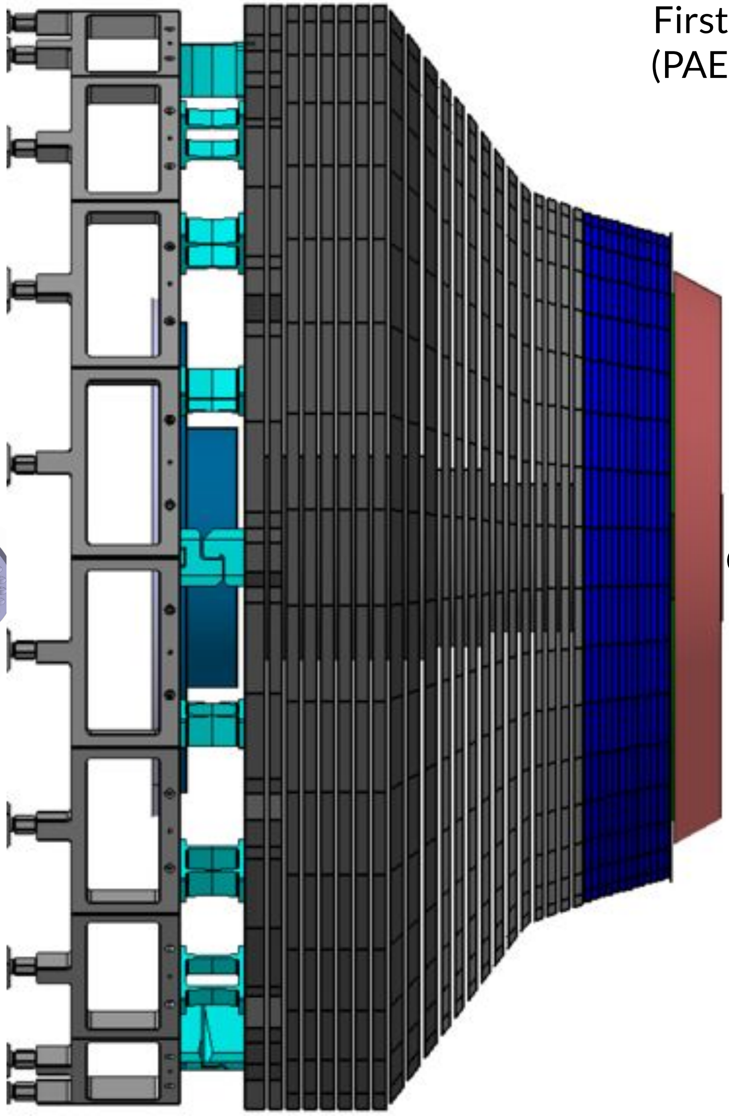
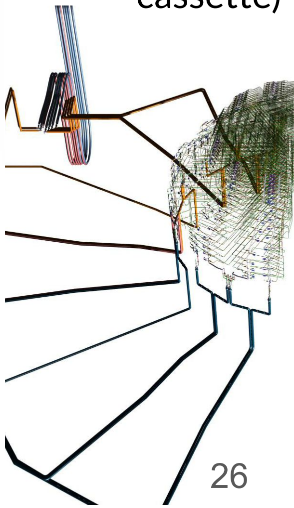
High precision, high density and heavy
Packed electronics and services integrated into each layer
Warm-cold transition
Insertion tooling
Lower 230 ton down into the cavern (-100 m underground)
Tight constraints from fixed envelope within CMS

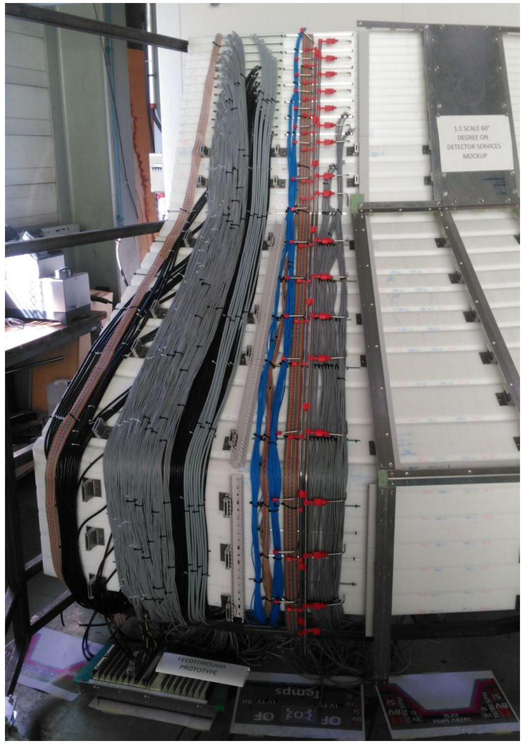


First absorbers
(PAEC/HMC-3)



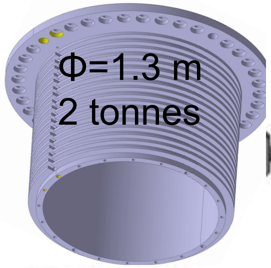


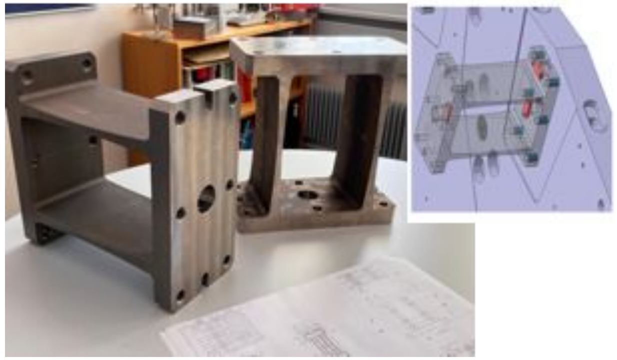
View of the
CO_2 cooling plant
(-35^{0}C exiting
cassette)



Services routing
mock-up (CERN)

Inner cylinder
(CERN)





Support wedges (KIT)

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Calibration

Routine operations are expected to be performed mostly without need for dedicated runs

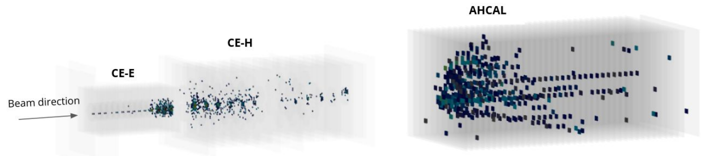
- Aim for fast application of calibration constants (but also their derivation) by making use of heterogeneous computing
- Full event data unpacking expected to take <50 ms and application of calibration constants <1 ms from first implementations

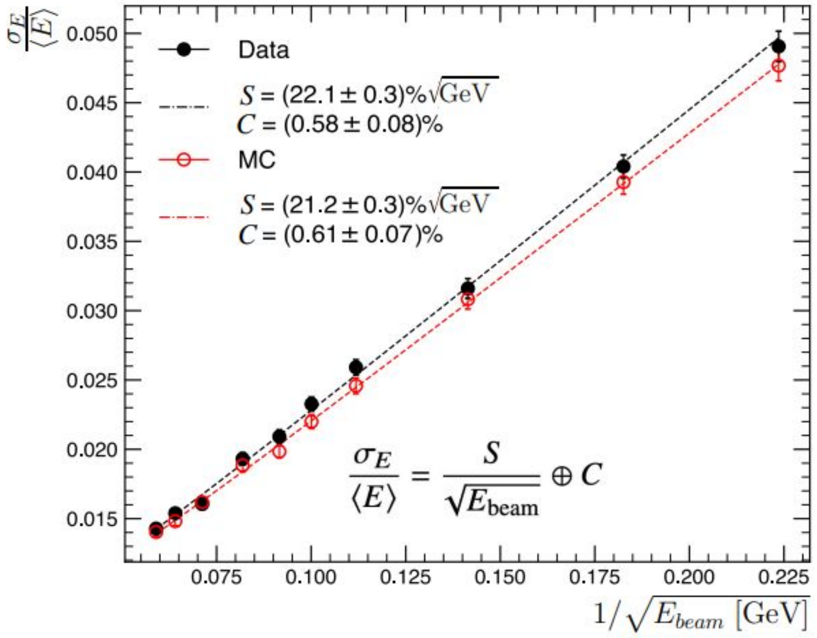
	Target	Dataset	Frequency	Notes
Relative calibration	3% in CE-E cells 5-15% in CE-H cells	standard triggers	few times / year	MIP at 10 ADC counts, ZS threshold at 0.5 MIP
Pedestal	0.3 LSB uncertainty			
Charge non-linearity	2%		infrequent	
Charge response monitoring		charge injection in special runs		
ToA time slew			infrequent	
SiPM non-linearity	O(10%)	LED data in special runs	commissioning and startup	single p.e. peak
SIPM-tile-understanding		LED data in standard runs		as required
TDC non-linearity	15 ps	random-clock events	infrequent	
Time zero-offset	15 ps	rtandard triggers		

Performance I

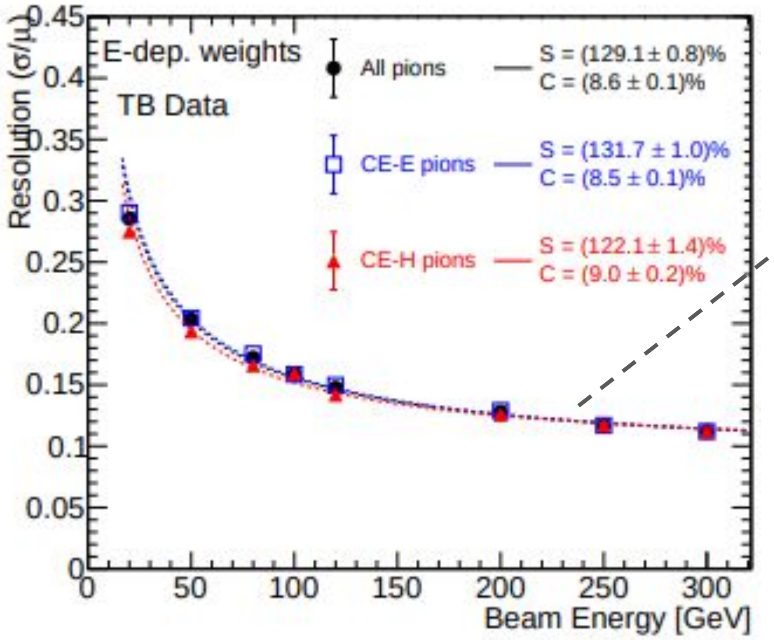
Results from early test beams are encouraging even if not yet with final system specs (sensors and electronics)

- Fine electromagnetic and hadronic energy reconstruction: linearity and resolution
- Fair agreement between data and simulations in the transverse and longitudinal shower profile
- Potential for compensation of em fluctuations in showers using advanced ML algorithms

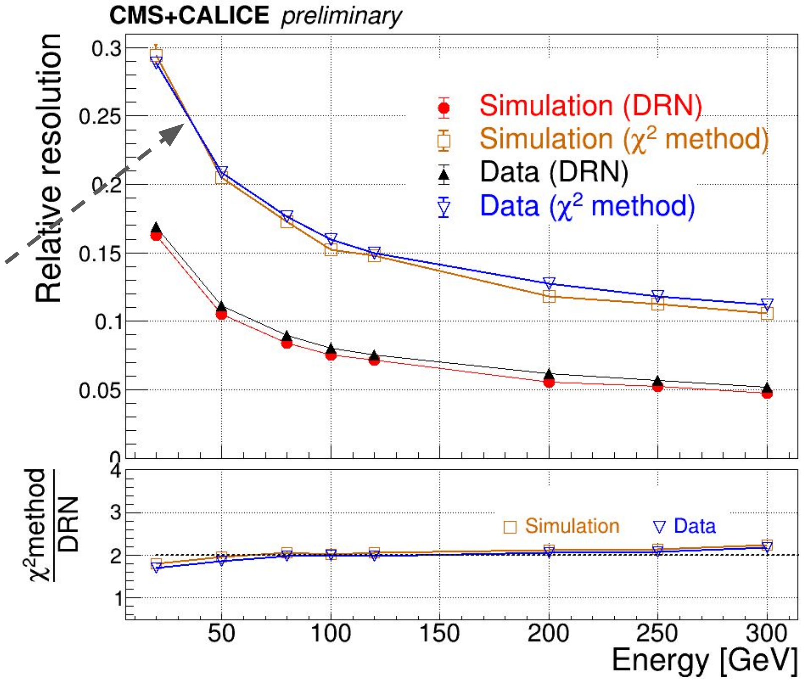




[JINST 17 (2022) 05, P05022](#)



[JINST 18 (2023) 08, P08014](#)

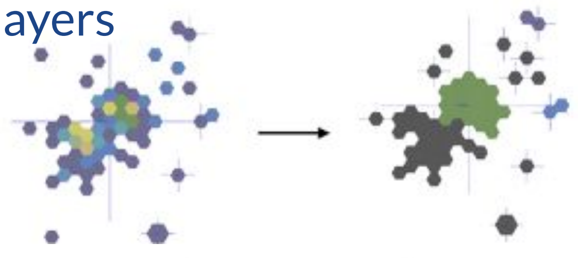


[CMS-DP-2022/022](#)

Performance II

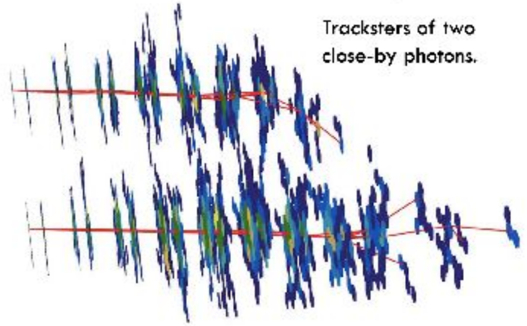
Baseline reconstruction based on CLUE – algorithm for energy Clustering within single layers

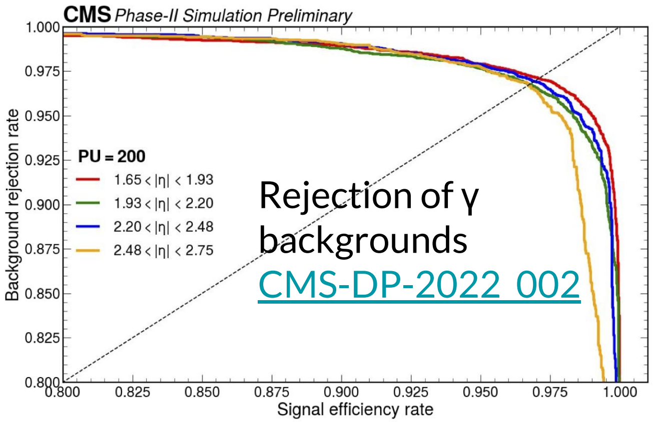
- Reduces combinatorics by ~10x
- Parallelized on GPUs



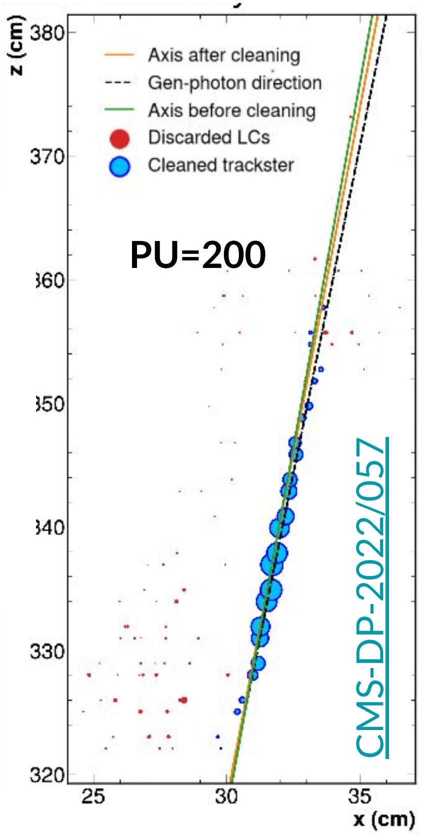
Linking and pattern recognition using TICL (The Iterative Clustering) algorithm

- Representation of showers as graphs (tracksters)
- Information regressed with ML techniques for PID and energy reconstruction

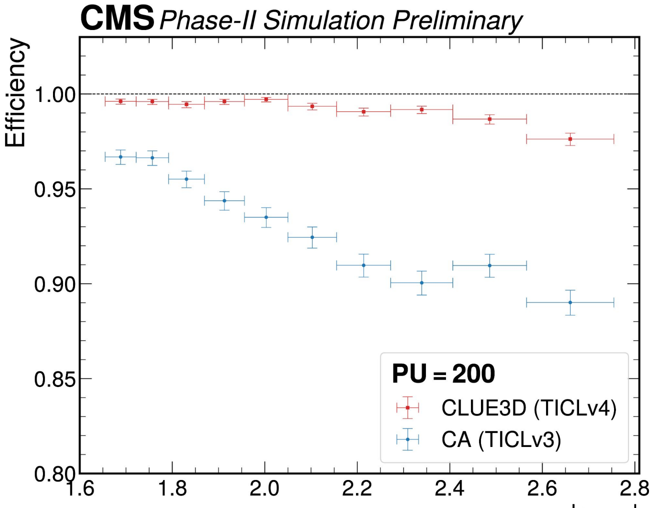




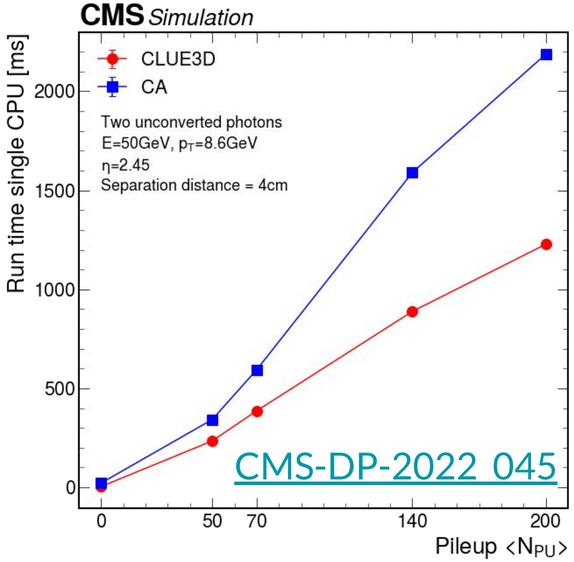
Rejection of γ backgrounds
CMS-DP-2022_002



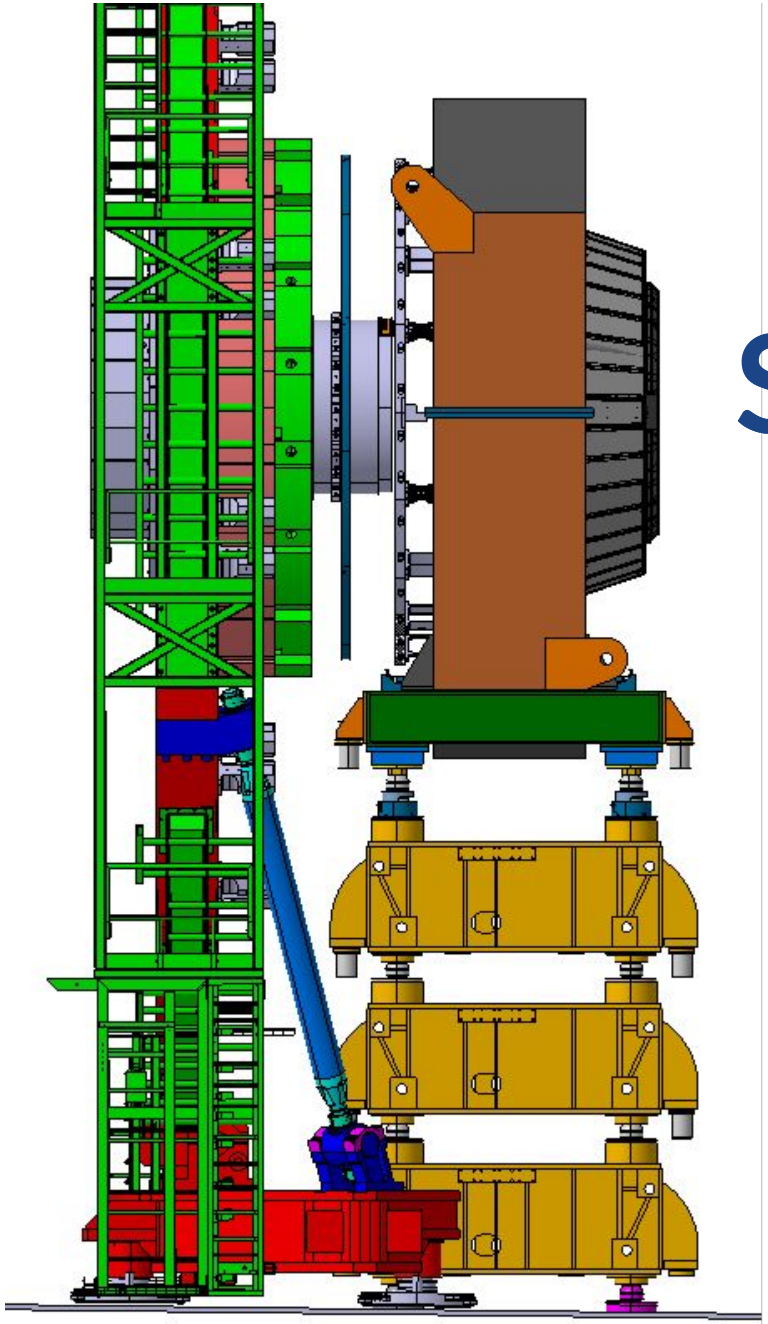
CMS-DP-2022/057



CMS-DP-2022/057



CMS-DP-2022_045



Summary

HL-LHC radiation environment and physics goal drive the choices of CMS HGCAL

This will be an unprecedented calorimeter in HEP leveraging on

- CMS's own experience with large Si detectors
- CALICE's extensive R&D and large scale SiPM-on-tile technology

5D shower imaging and reconstruction capability: crucial inputs for particle flow

- State of the art ASICS design
- Fast and robust reconstruction algorithms

crucial drivers for final performance

Good progress during the last years

- now transitioning to larger scale system integration and start of production

Backup

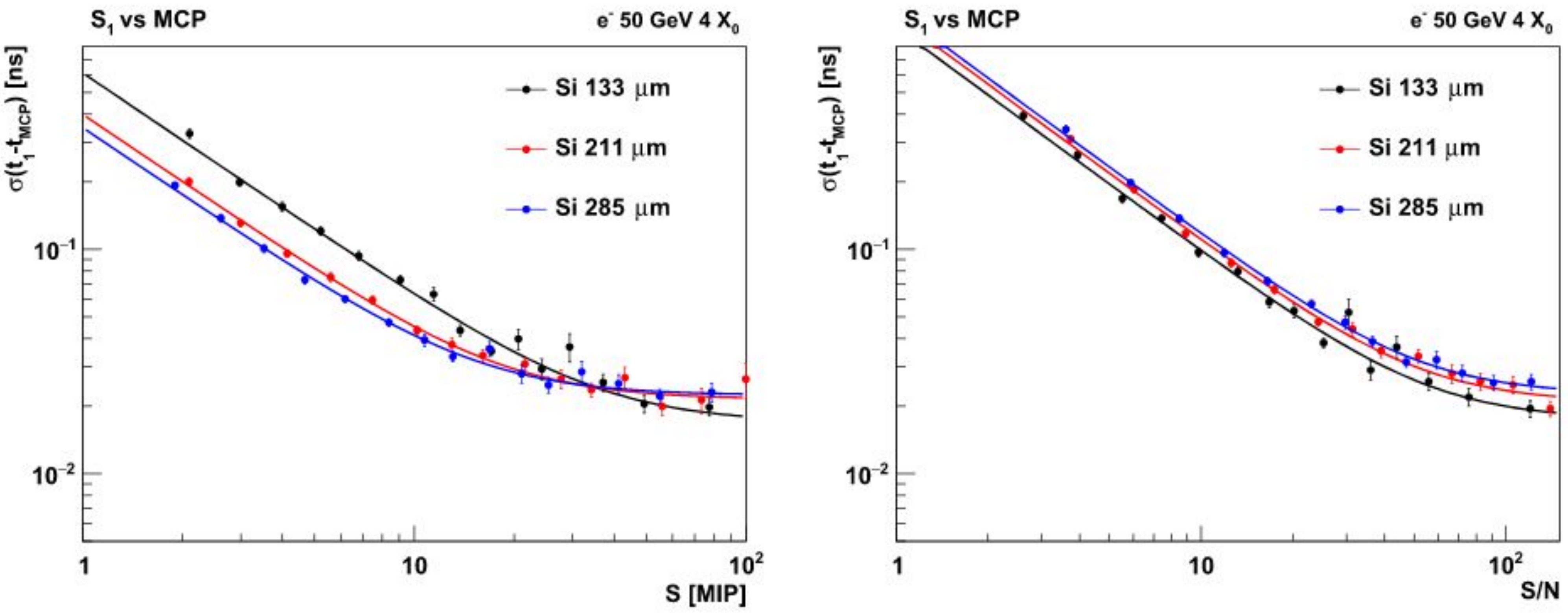


Fig. 9. The timing resolution between the first silicon sensor and the MCP as a function of the signal (left) and as a function of the signal-to-noise ratio (right). All three different thickness sensors are compared. The constant term, *C*, is dominated by the MCP resolution, estimated to be 21 ps.

[Nucl.Instrum.Meth.A 859 (2017) 31-36]