Overview of Latest Developments in the CMS HGCAL Upgrade Project

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On behalf of the CMS collaboration

IPRD 2019

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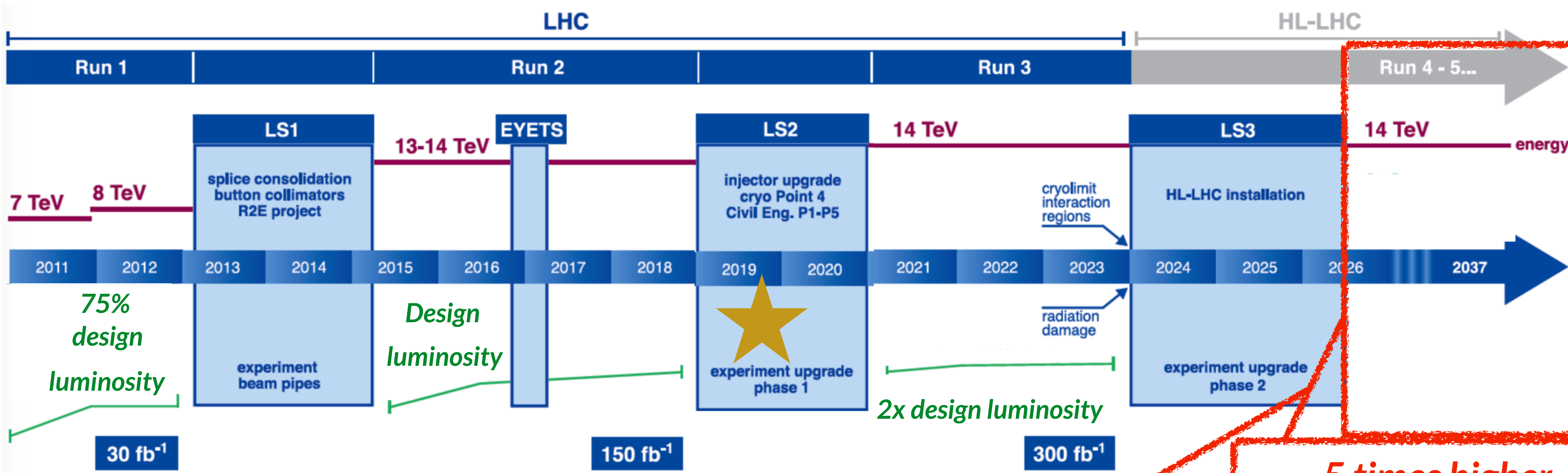
High Luminosity LHC



~ 10x more integrated luminosity (~ 3000 fb^{-1})

~ 5 times higher than design instantaneous luminosity

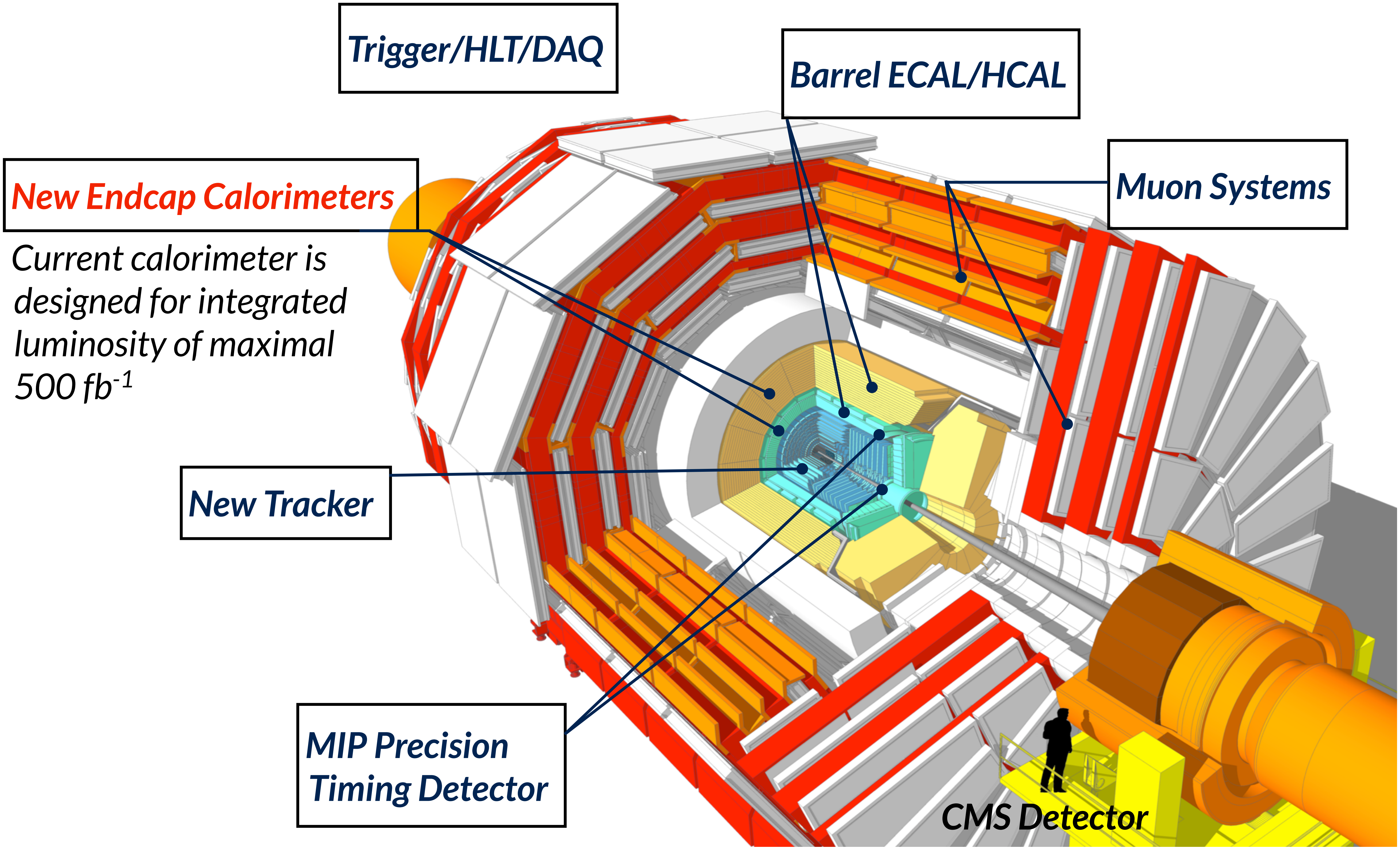
- **Two major challenges** for detectors:

- **Unprecedented radiation levels**
  - Fluences of up to ~ 10^{16} n_{eq}/cm^2 (Doses of up to ~2 MGy)
    - Requires
      - Radiation hard detector material and readout

- **High Pile-up**
  - Up to ~140-200 interactions per bunch crossing
    - Mitigated with
      - High granularity
      - Precise timing

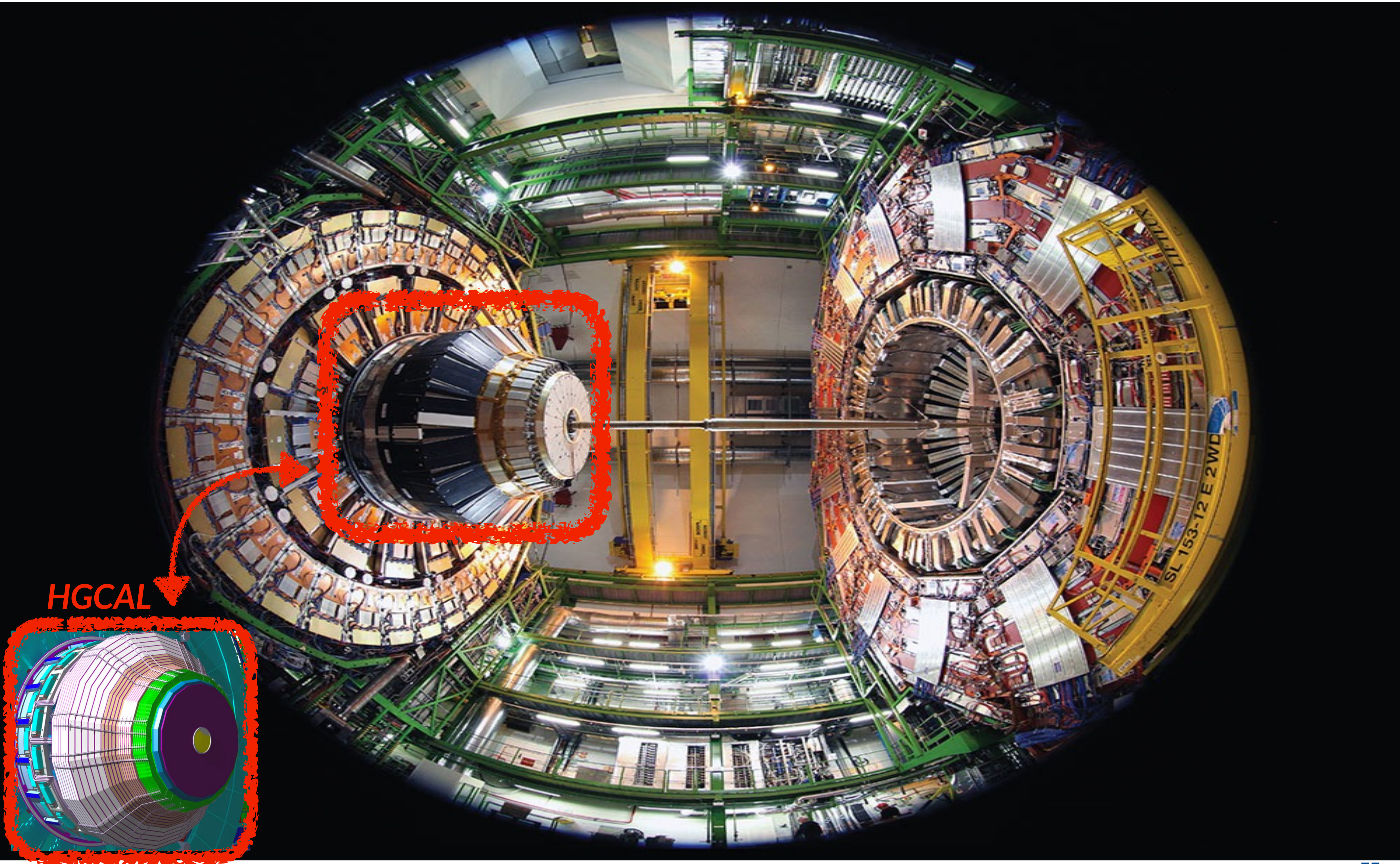
CMS HL-LHC Upgrades

- CMS will be going through major upgrades!



CMS High Granularity Calorimeter

- *CMS electromagnetic and hadronic endcaps will to be replaced*



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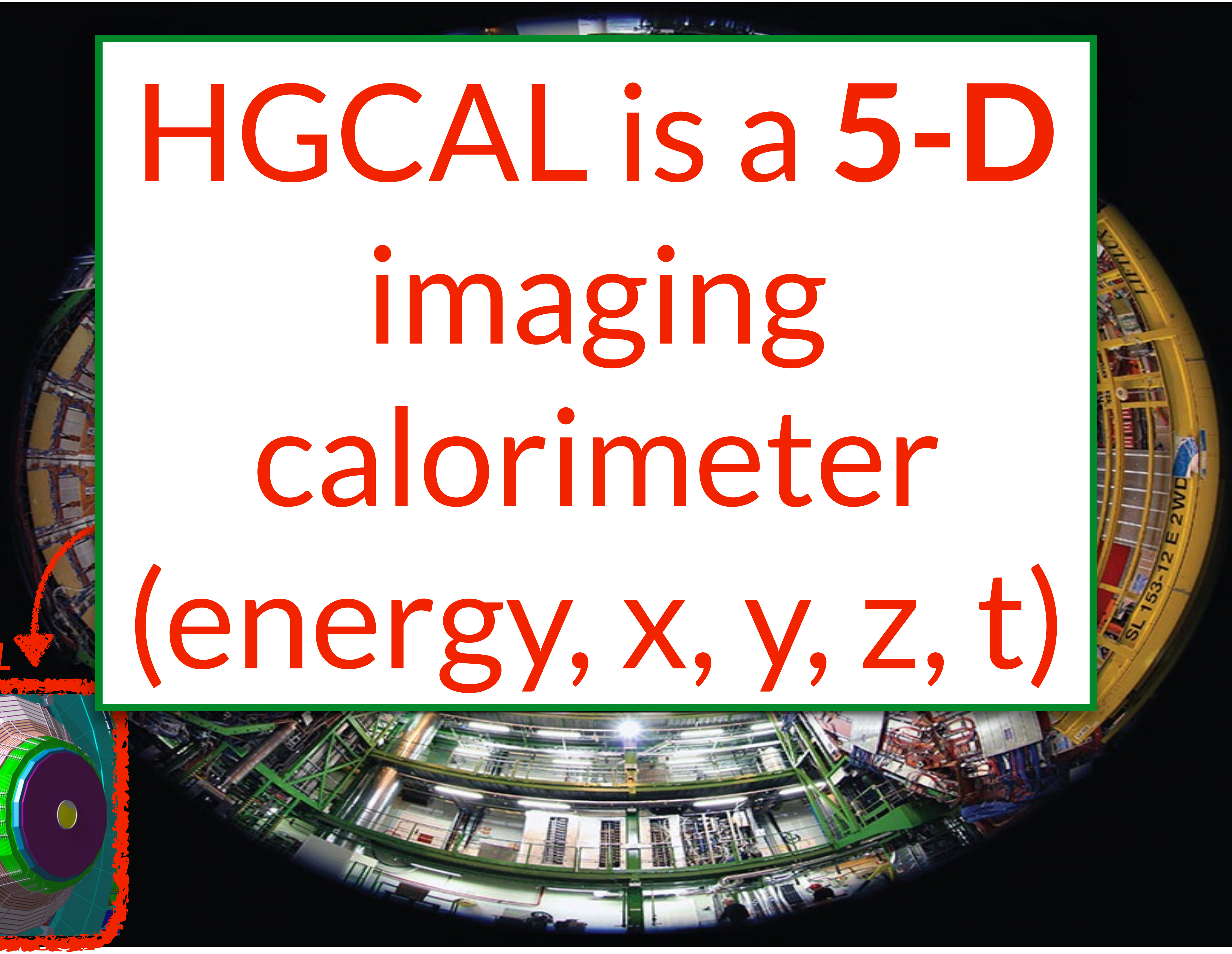
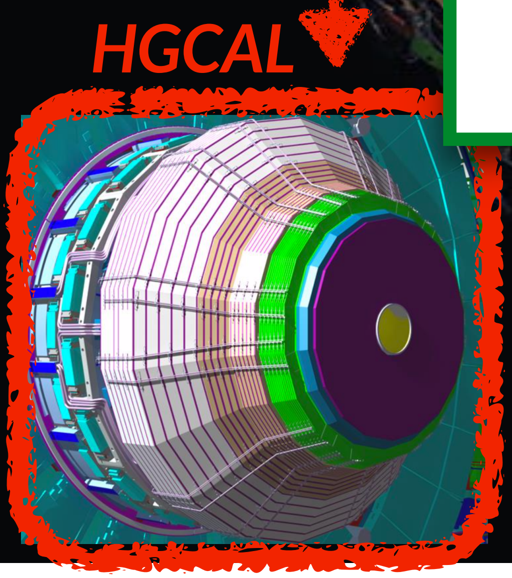
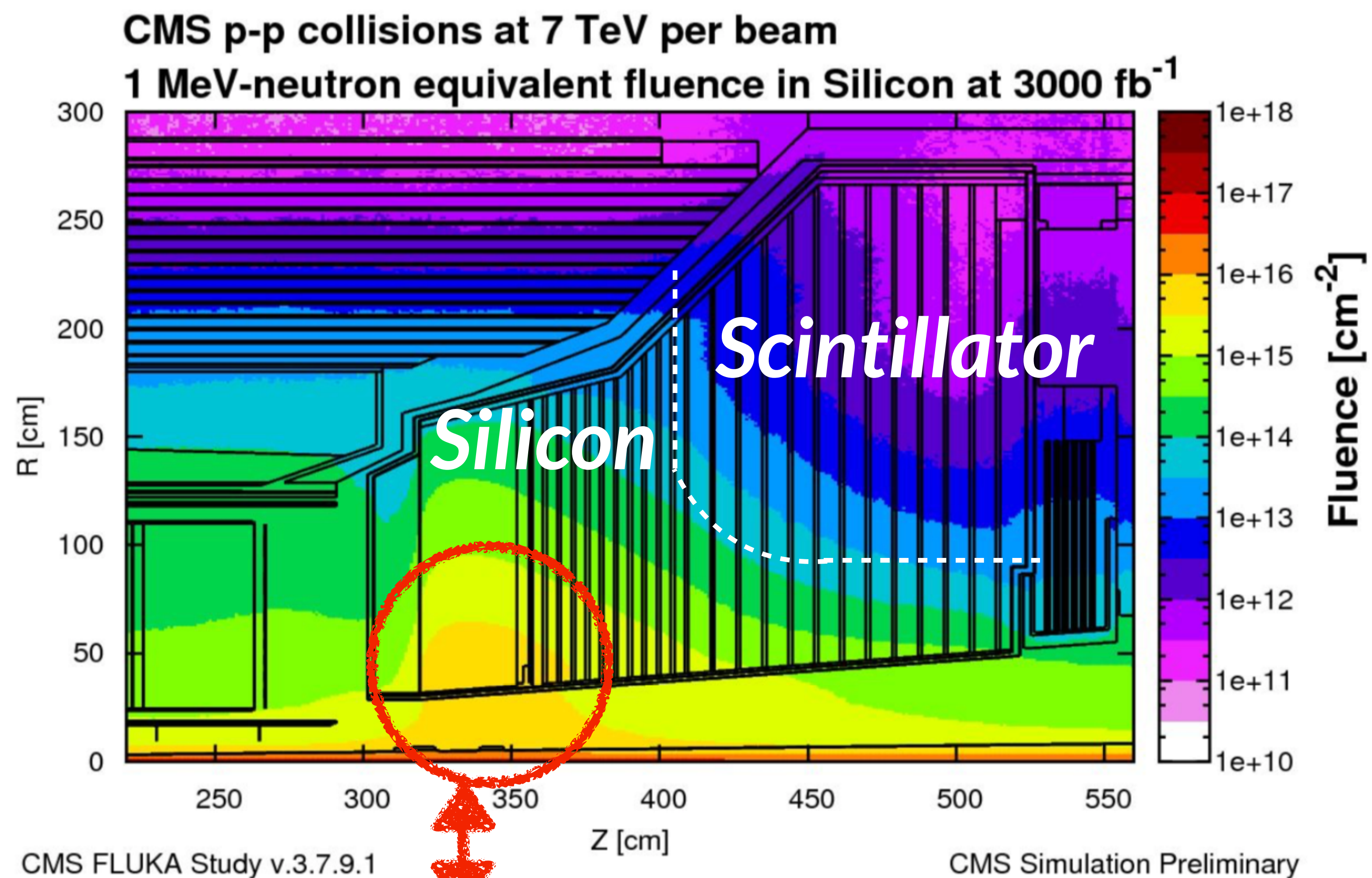


HGCAL is a **5-D** imaging calorimeter (energy, x, y, z, t)



High Granularity Calorimeter Active Elements

- *Silicon* detectors are
  - **Radiation tolerant** enough
  - **Fast** enough to mitigate pile-ups
  - Can be **finely segmented** to allow high granularity



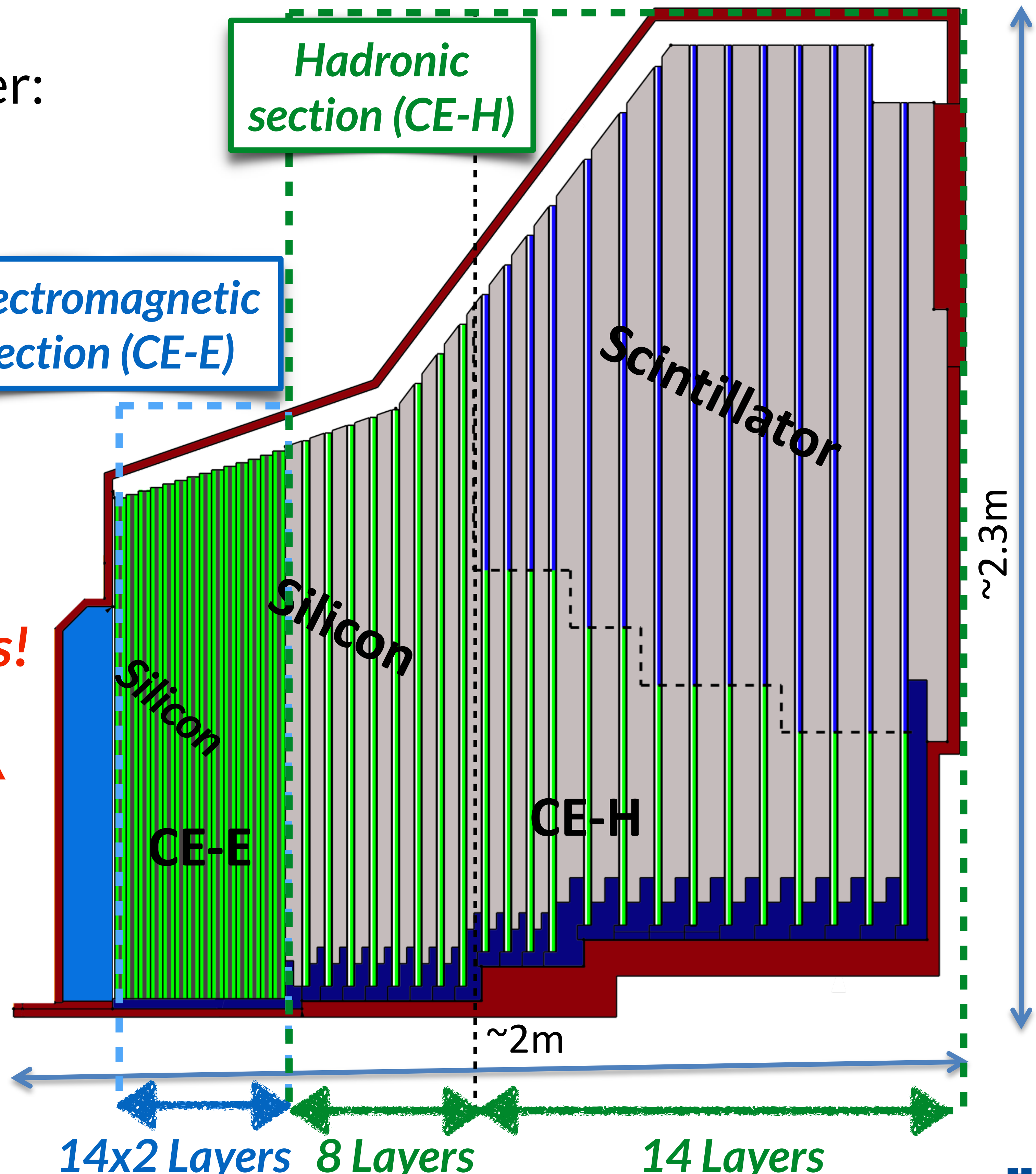
Fluences of up to $10^{16}\ n_{eq}/cm^2$
Doses of up to 2 MGy

Strong dependence on |η| and |z|

- ***Active elements of High Granularity Calorimeter:***
  - Silicon in high radiation area (600 m^2)
  - Scintillator in lower radiation area (400 m^2) ***(To reduce cost)***

Overall High Granularity Calorimeter Design

- HGCAL : A sampling Calorimeter:
- *Very high granularity*
  - *6 million Silicon channels*
  - *240 thousand Scintillator channels*
- *Weight per endcap: ~ 215 tonnes!*
- *Total longitudinal thickness: 9.8λ*
- *Electromagnetic longitudinal thickness: $25X_0$*



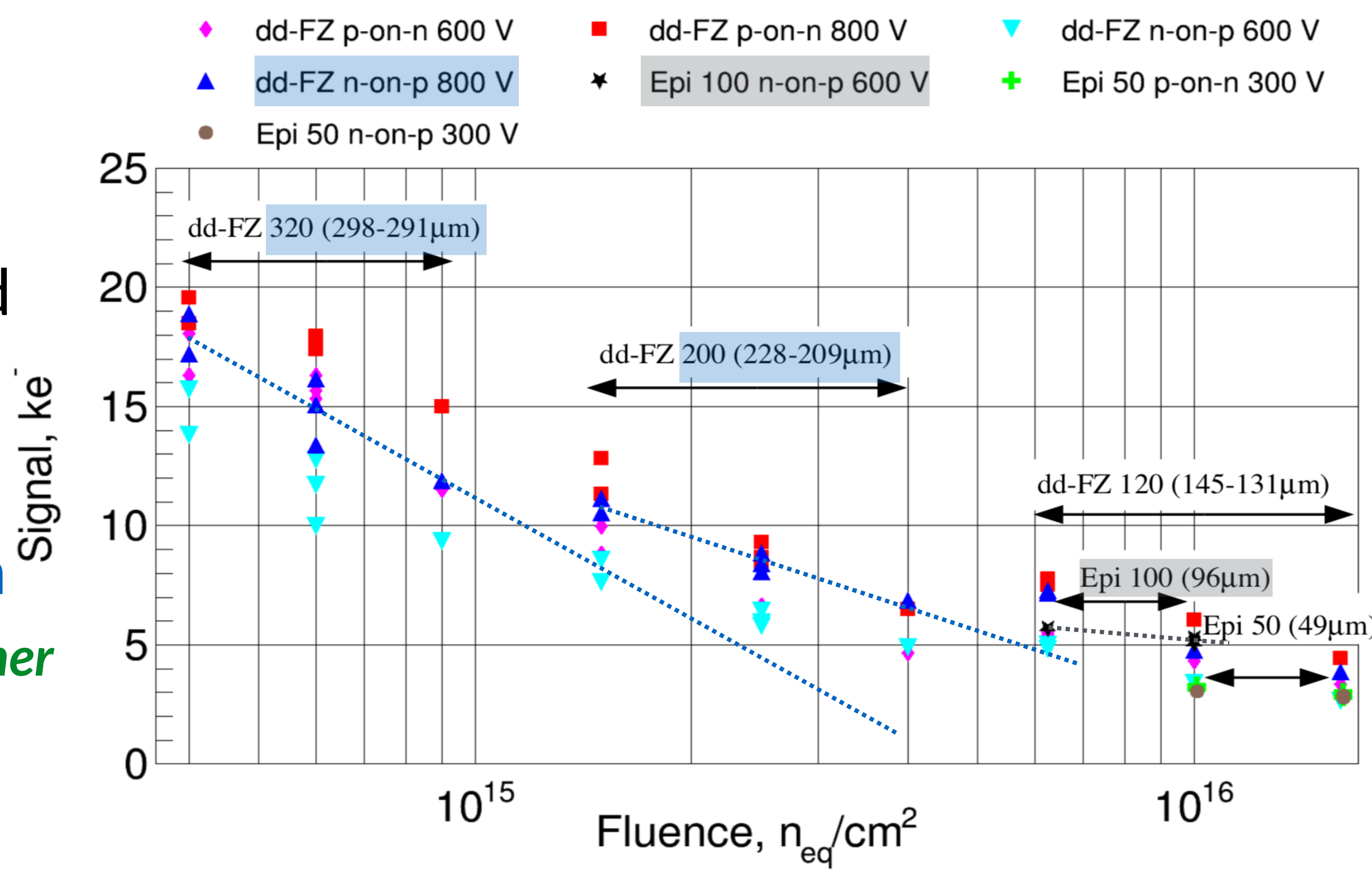
Silicon Sensors

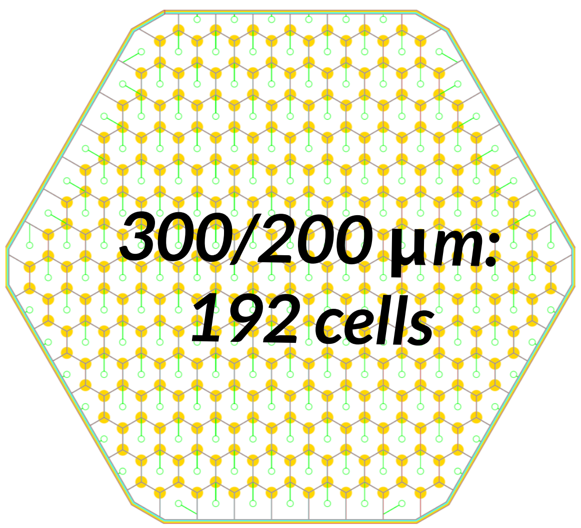
- 8 inch wafers
- Hexagonal sensor geometry
- Planar p-type DC-coupled sensor pads
- Active thickness:

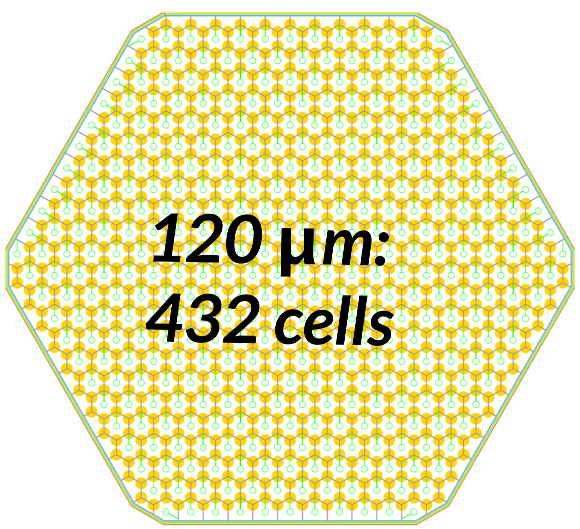
  300 µm, 200 µm, 120 µm

  - ***Advantage of deploying thinner sensors in the higher fluence regions***
    - ***More tolerant to large neutron fluences***

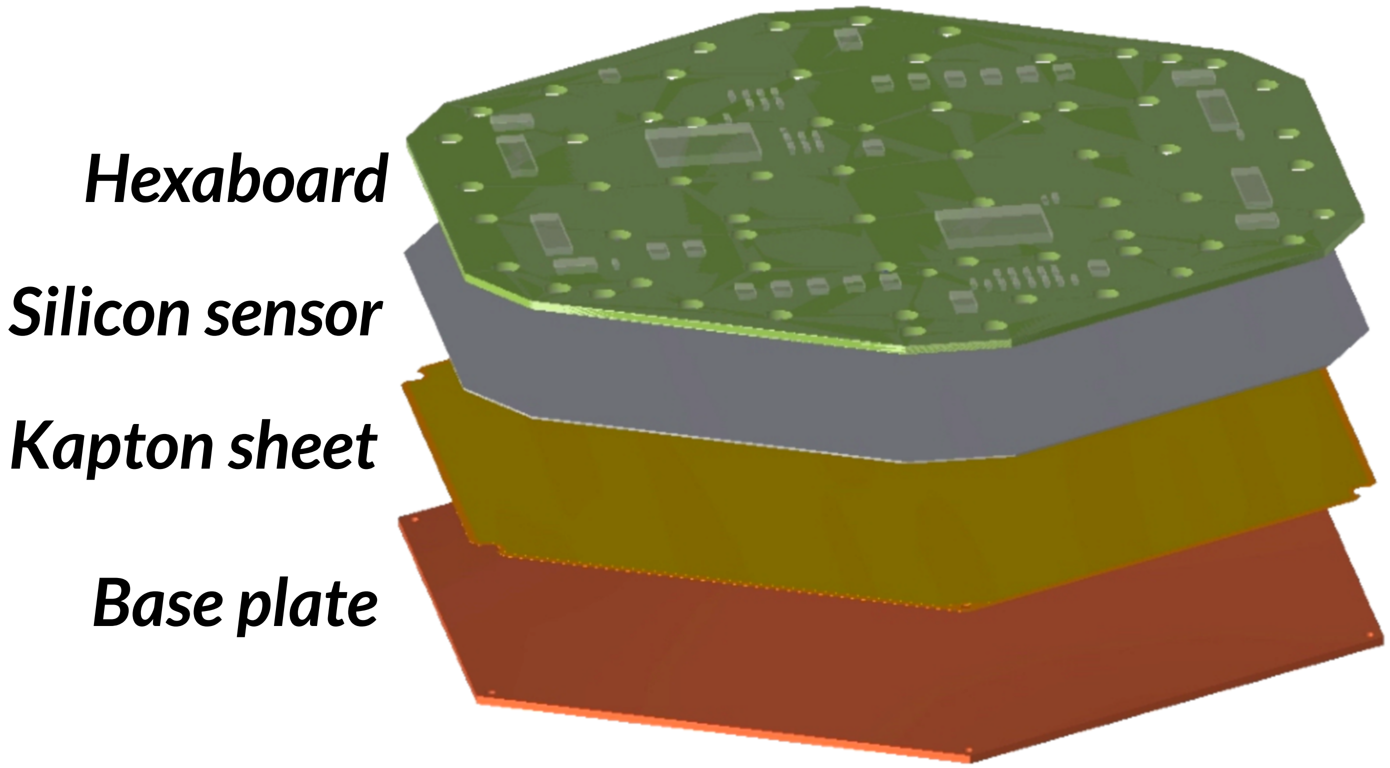
  - ***Reduced cell size in thinner sensors***
    - ***Keeping the capacitance reasonable***

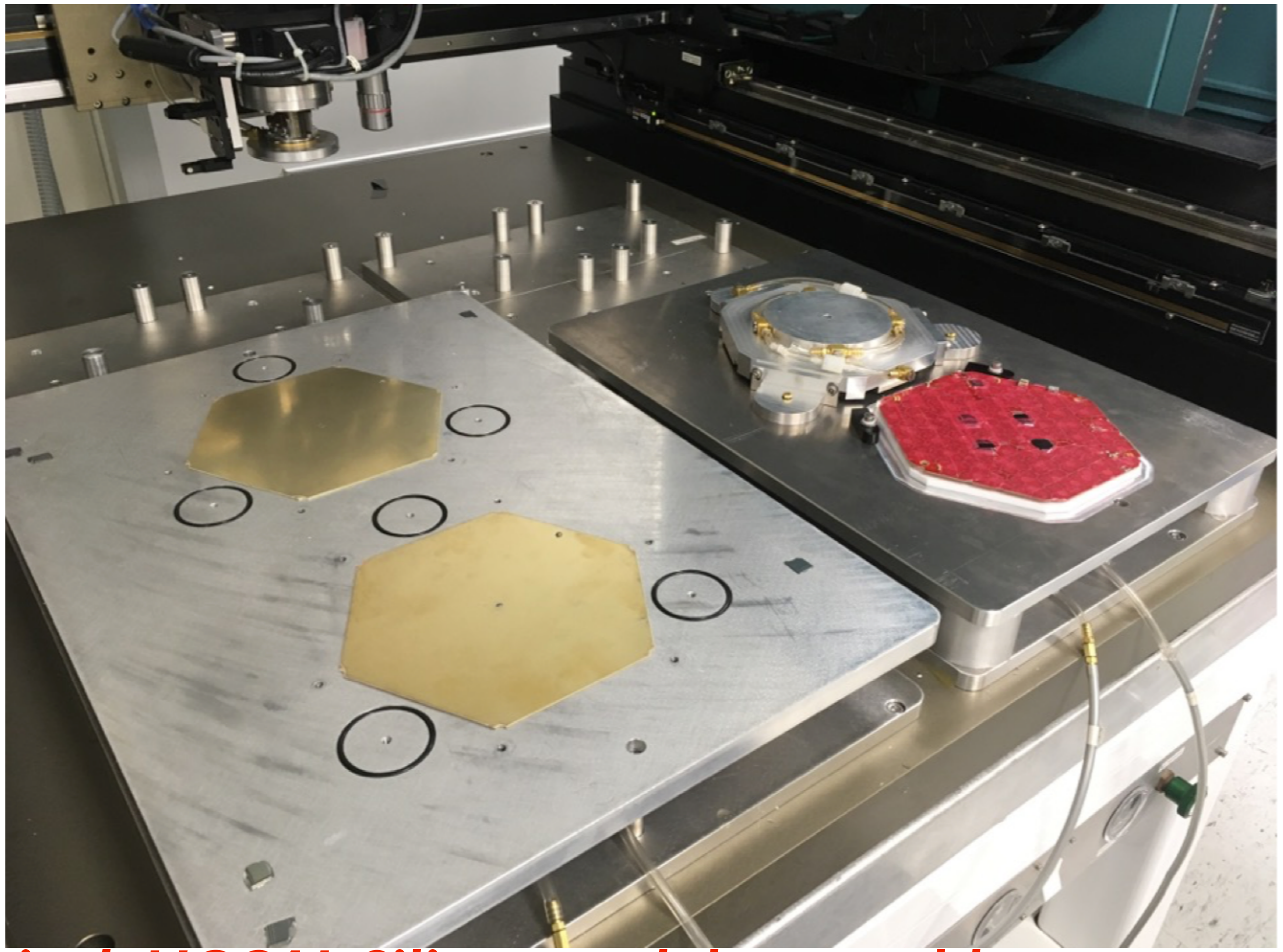






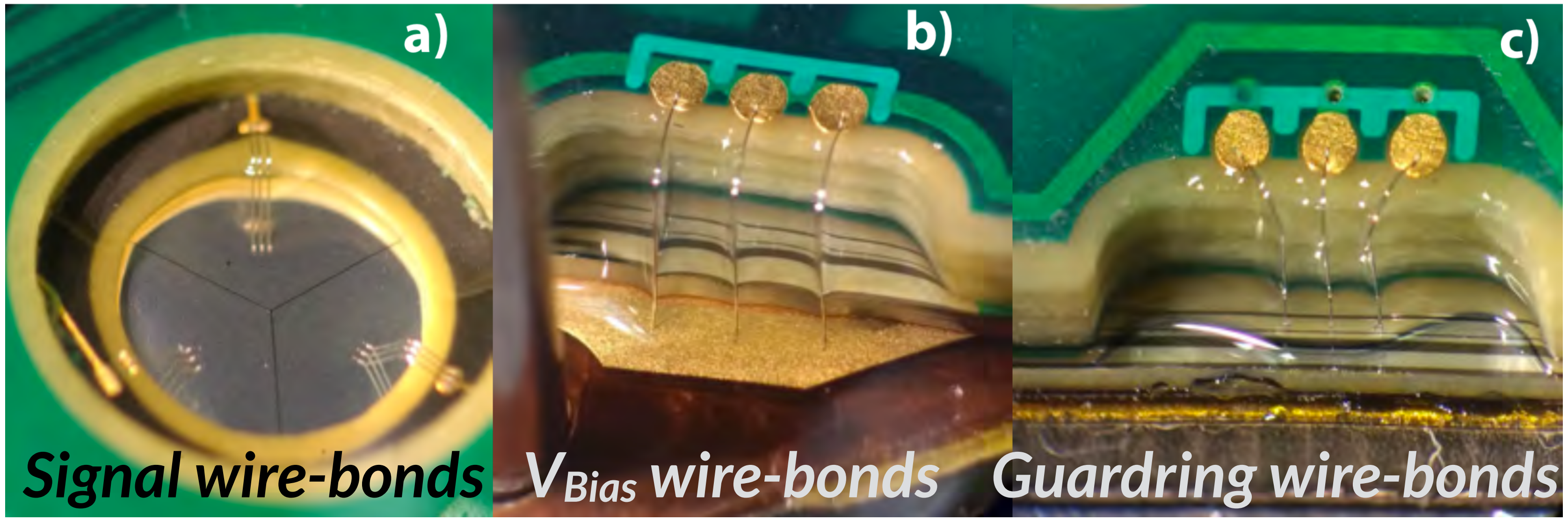
Silicon Modules





8 inch HGCAL Silicon module assembly set-up
(At one of the 6 module assembly centers worldwide)

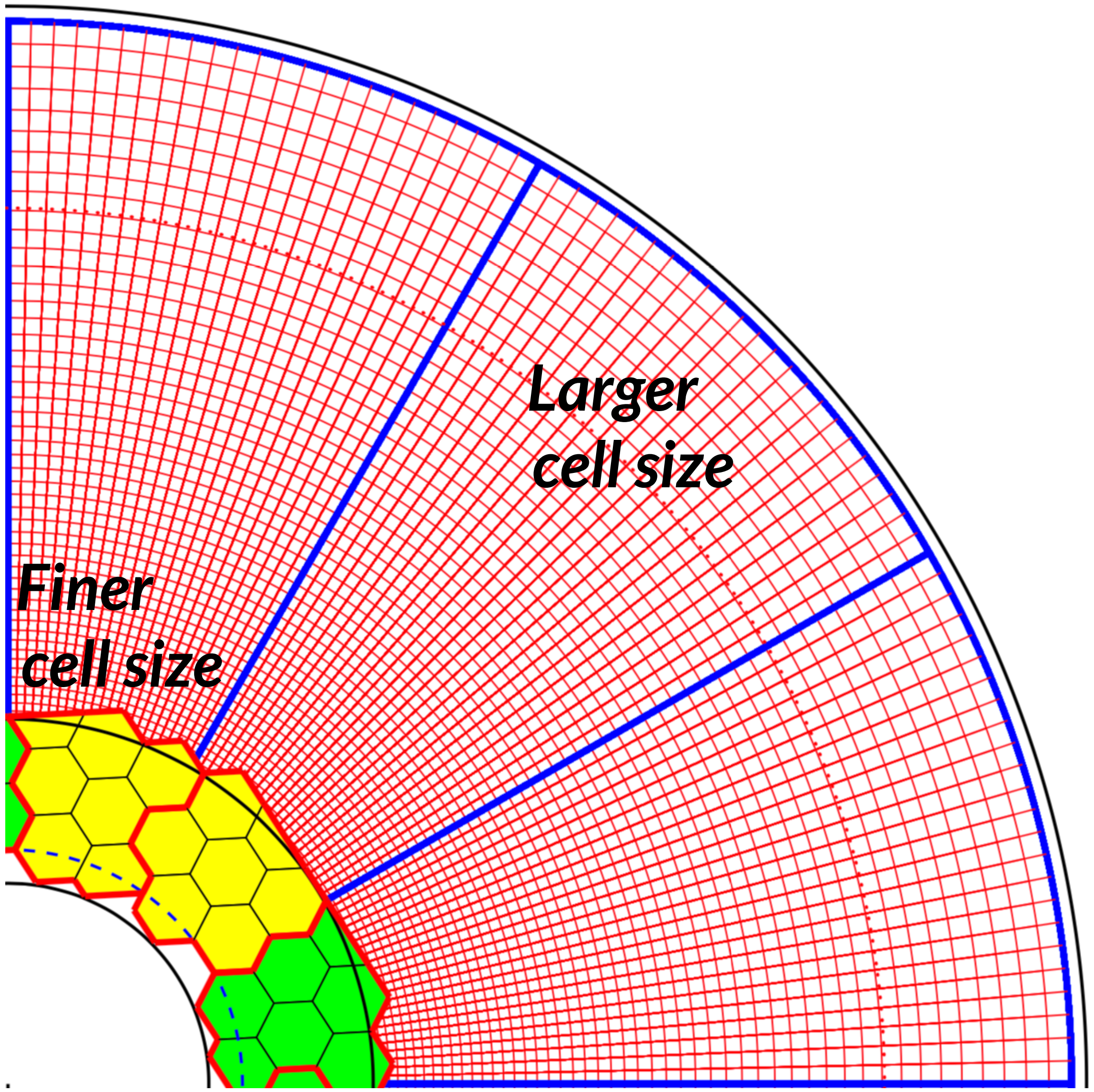
8 inch HGCAL Silicon module

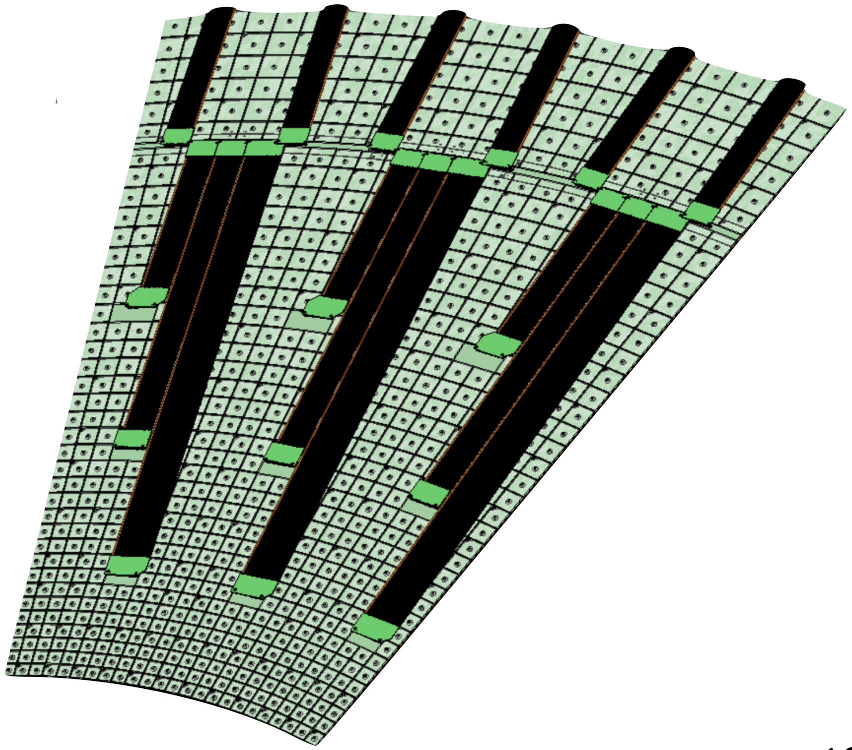


Plastic Scintillators and Scintillator Tile-Boards

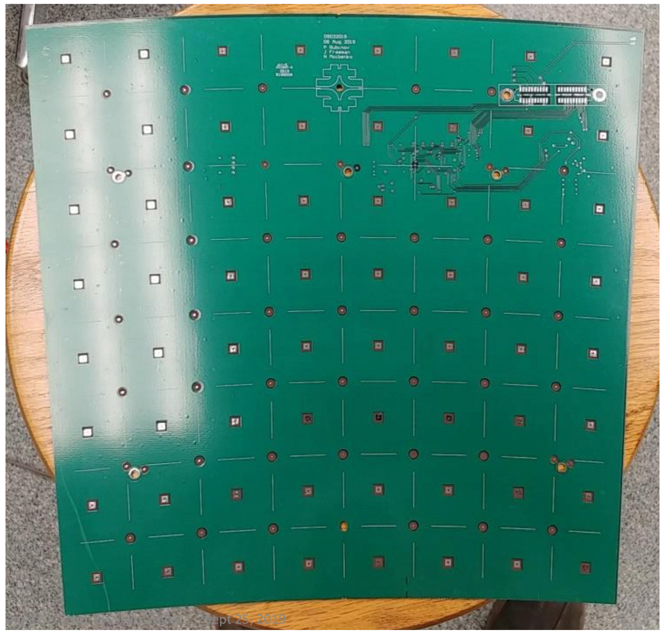
- SiPM-on-tile technology like in the CALICE AHCAL
- Scintillator cell sizes:
  - ~ 2x2 – 5.6x5.6 cm^2
- Tile board size: ~40x40cm^2

CALICE 3 × 3 cm^2 scintillator tiles mounted on a PCB that holds one SiPM per tile





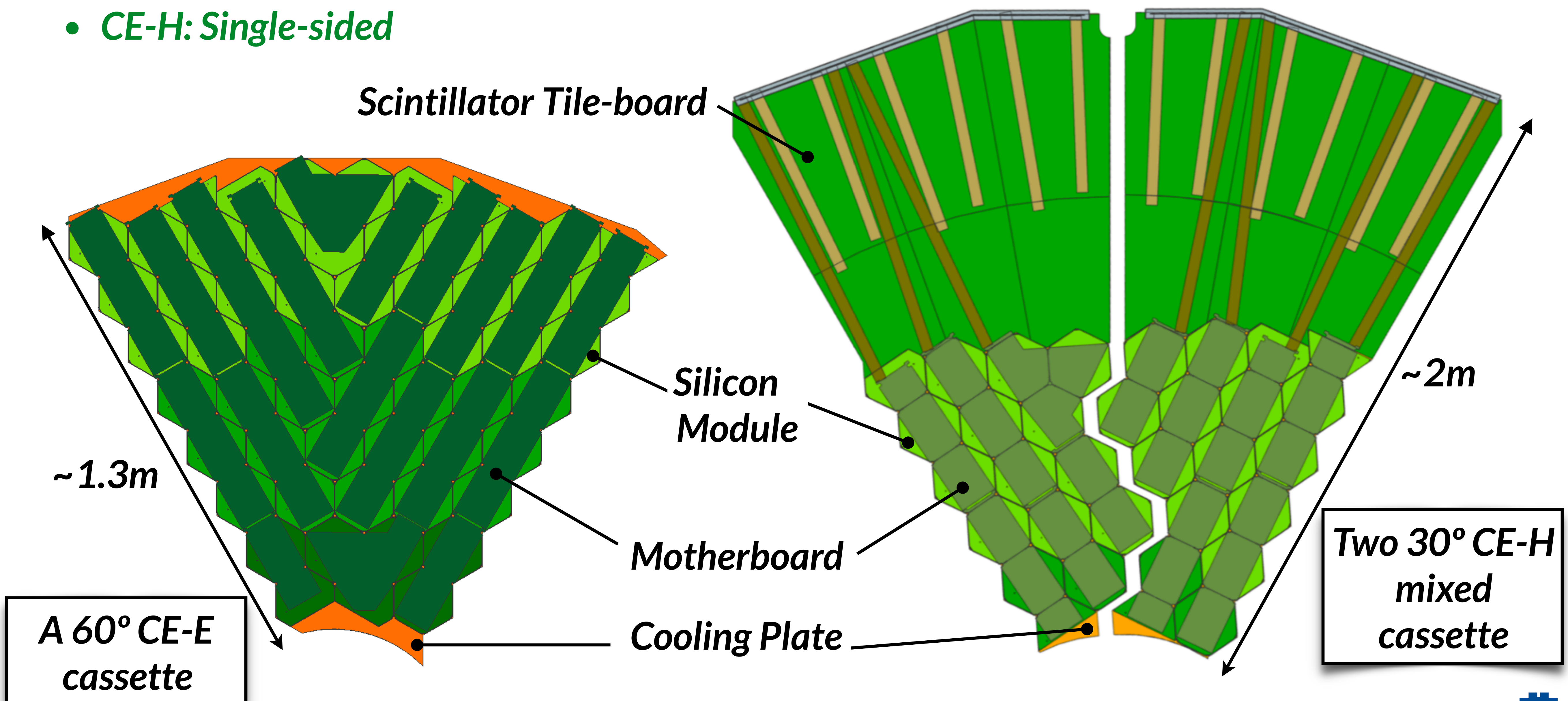
HGCal Scintillator tiles mount on tile-boards



Tile-board prototypes and tile assembly center preparations are in progress

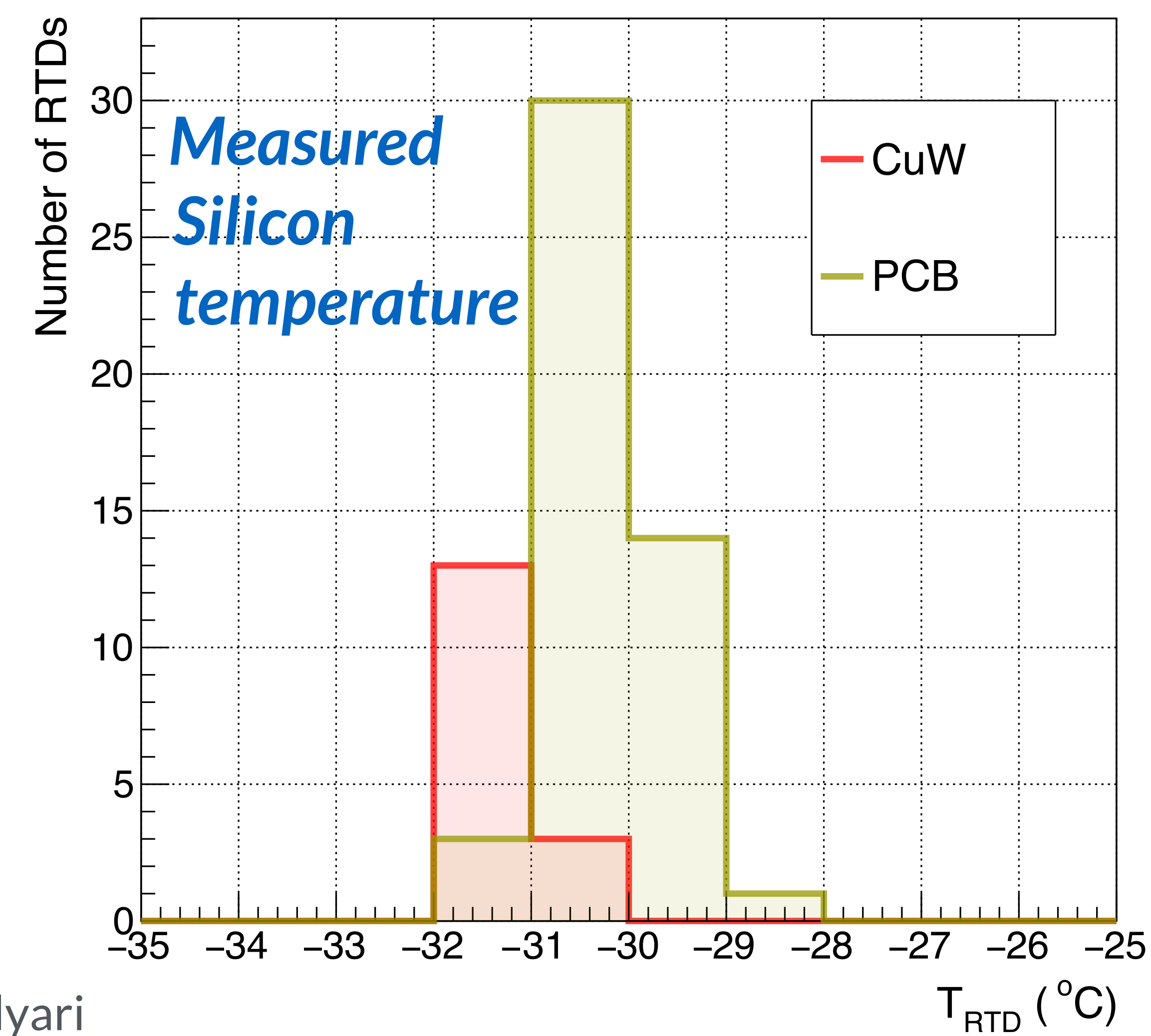
Cassettes

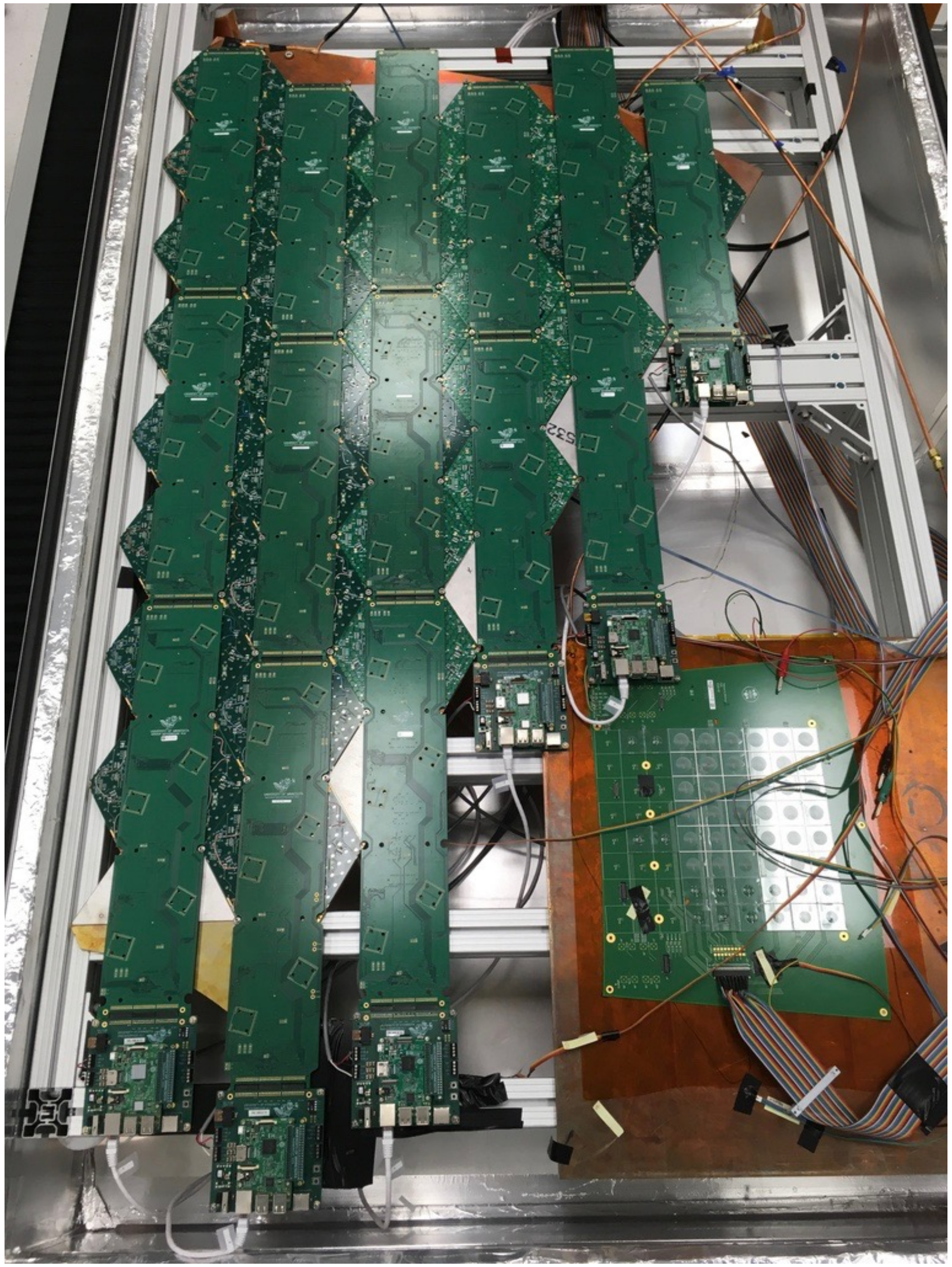
- Modules are installed on Copper plates with embedded tubing (both CE-E and CE-H)
  - *Coolant: two phase CO_2*
    - ***High latent heat of vaporization***
- *Cassettes:* Units of installations at CMS (between absorber layers)
  - *CE-E: Double-sided*
  - *CE-H: Single-sided*



First Thermo-Mechanical Mock-up

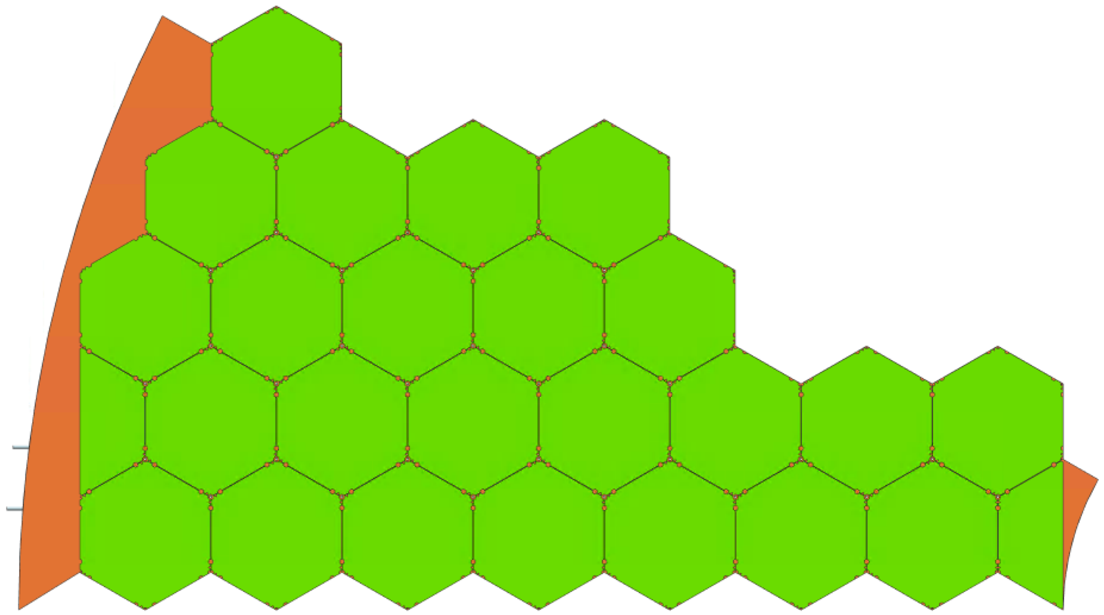
- First thermo-mechanical mock-up was designed and fabricated
  - Largest all-Silicon CE-H cassette
  - *Verified the dynamic mounting scheme*
  - *Verified the Silicon module and cassette cooling performance*
    - ***Applied 270 W heat load***
    - ***Successfully maintained:***
      - ***CO_2: -35 °C***
      - ***Silicon: -30 °C***



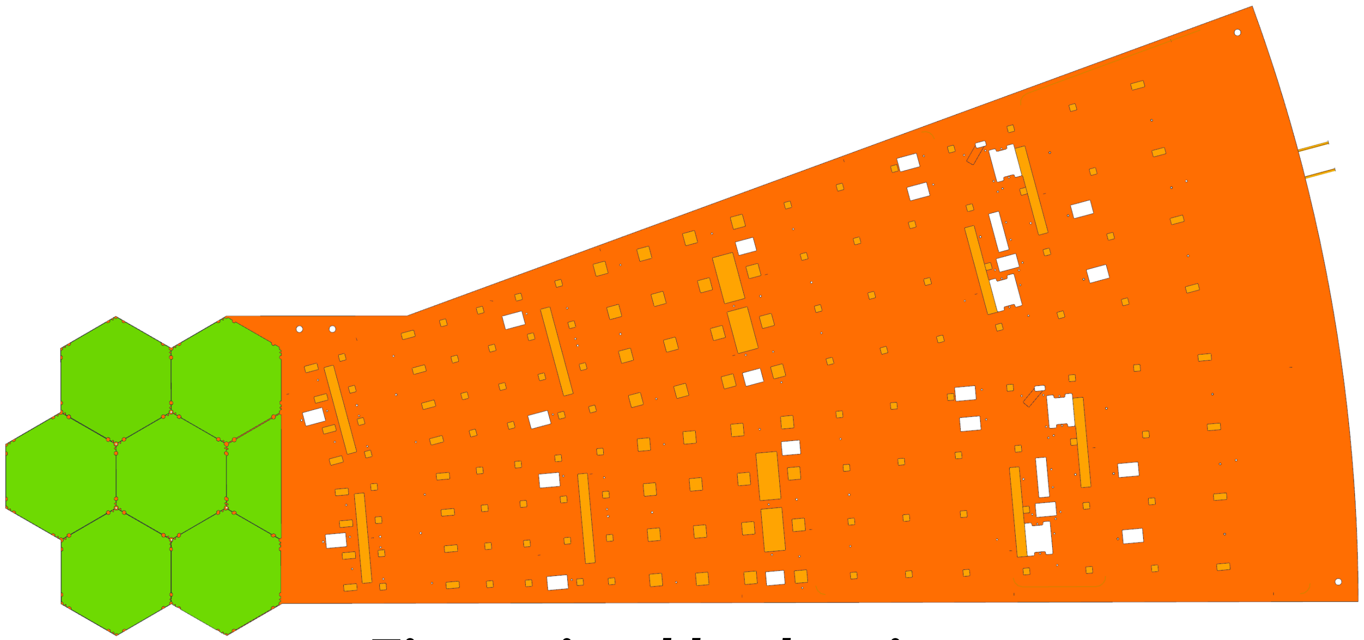


Cassette Prototypes

- Design verification is in progress through various cassette and assembly prototypes



First all silicon hadronic cassette to verify the readout chain



First mixed hadronic cassette

First electromagnetic copper plate prototypes

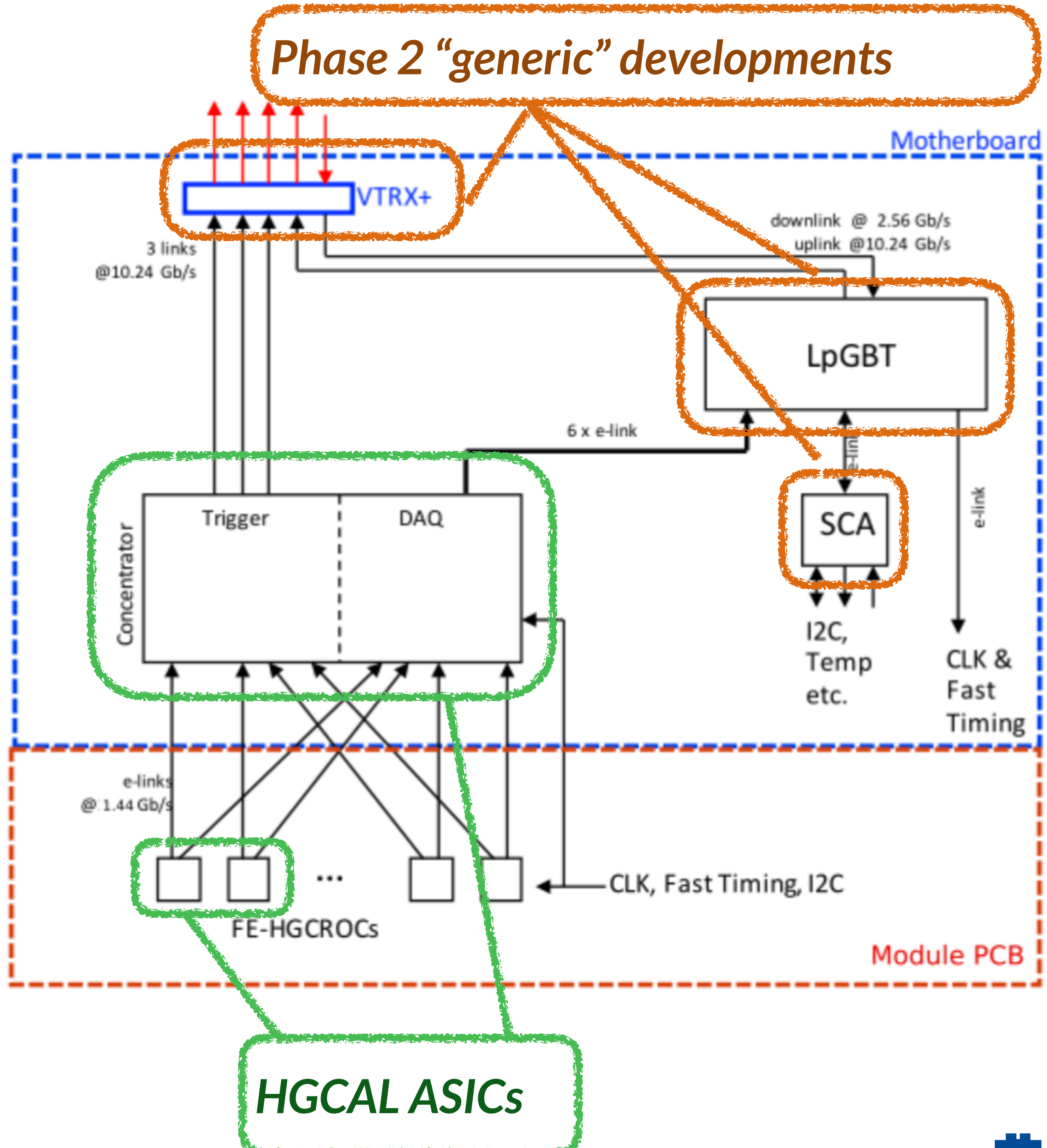
One layer assembly prototype

Read-out Chain

- The front-end electronics
  - Measures and digitizes the charge
    - 10bit ADC (0.2fC - 100fC)
    - 12bit TDC (50fC to 10pC)
  - Provides a high precision measurement of the time of arrival of the pulses
    - 10bit TDC with 25ps bins
  - Transmits the digitized data to the back-end electronics

- Similar front end electronics for the readout of the SiPMs

Silicon modules read-out chain

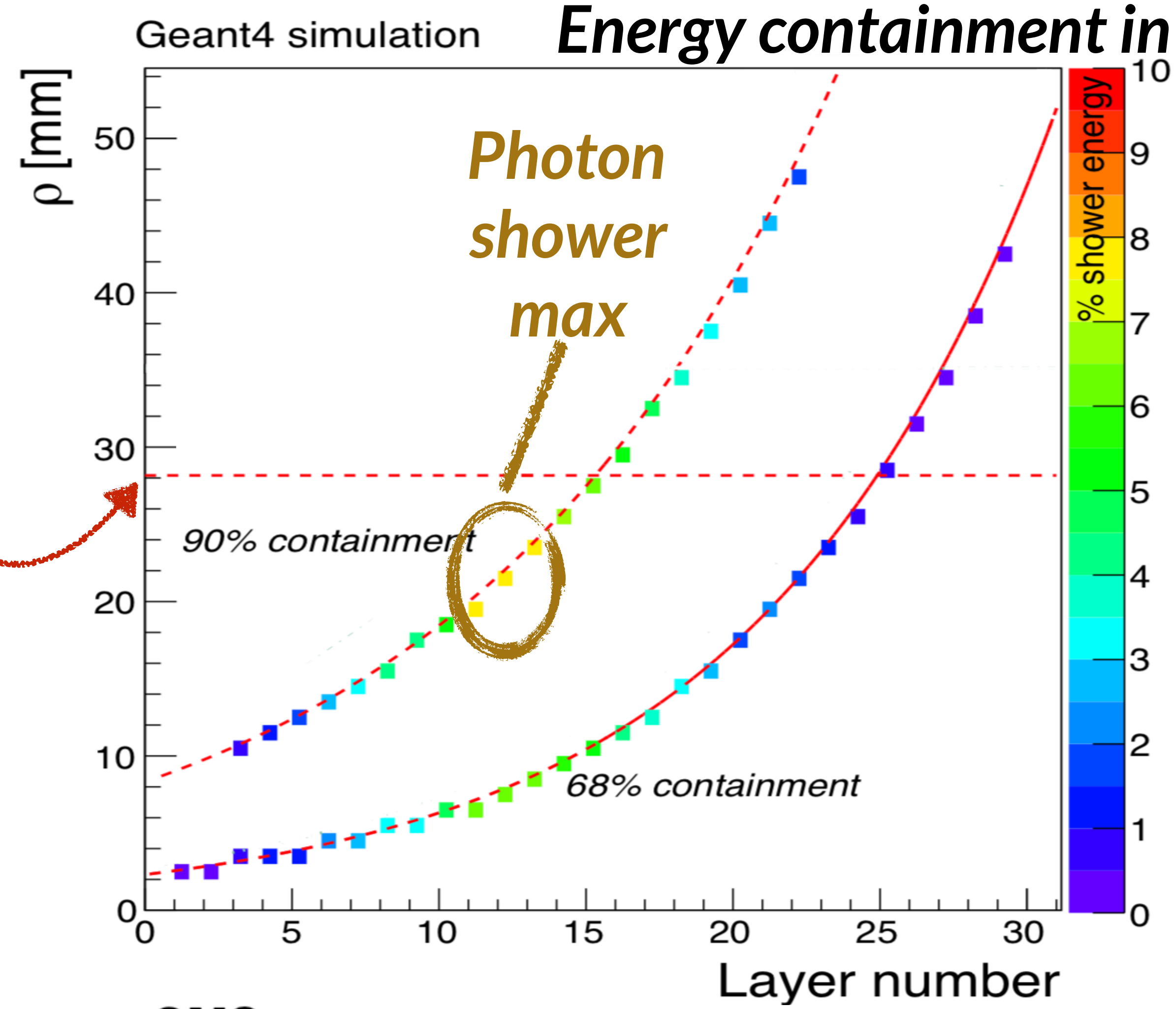


Expected Performance

- ***High granularity*** and ***compact design***:
  - Narrow showers
  - Good particle separation
  - Pile-up rejection within the first layers

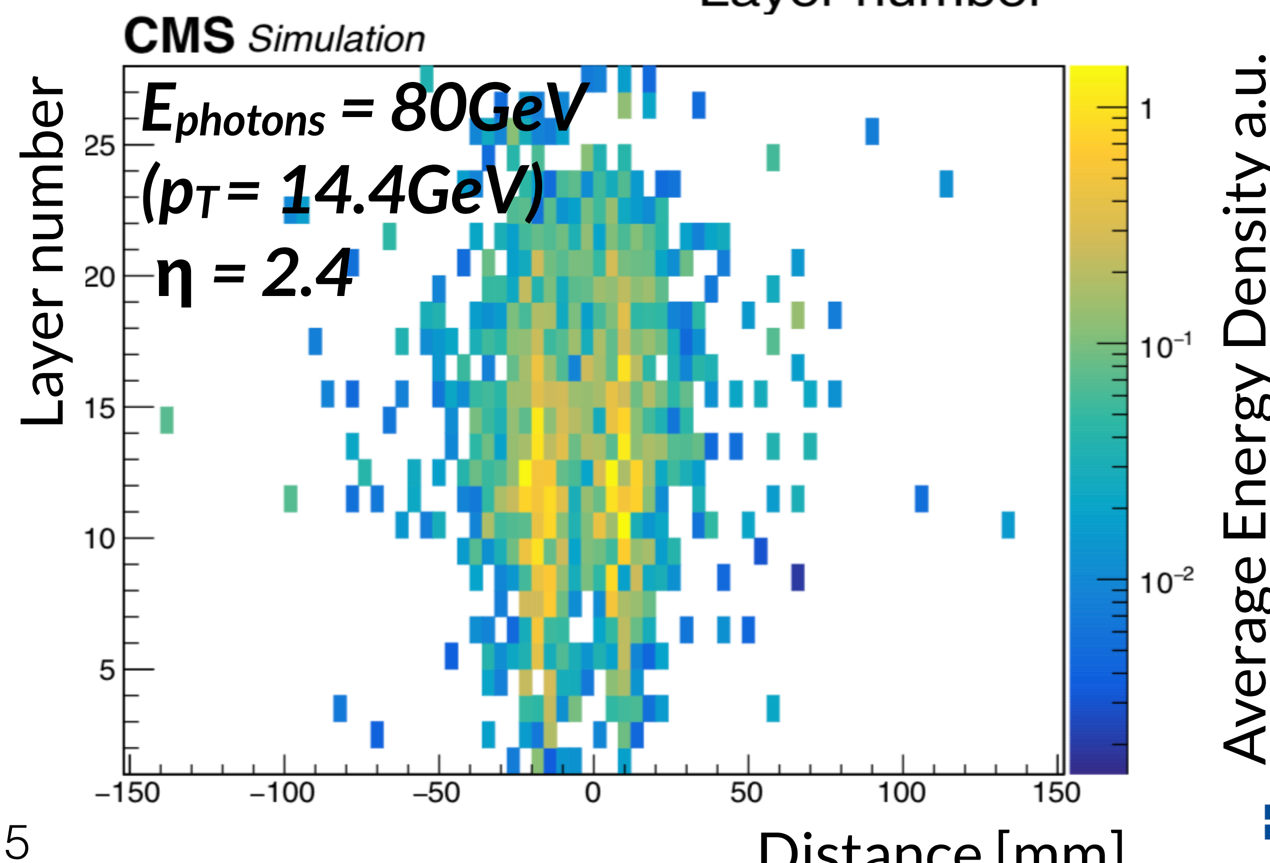
Molière radius of HGCAL

Energy containment in CE-E



- Significant Silicon coverage:
  - High-precision timing capabilities
    - ***Time resolution: ~25 ps***

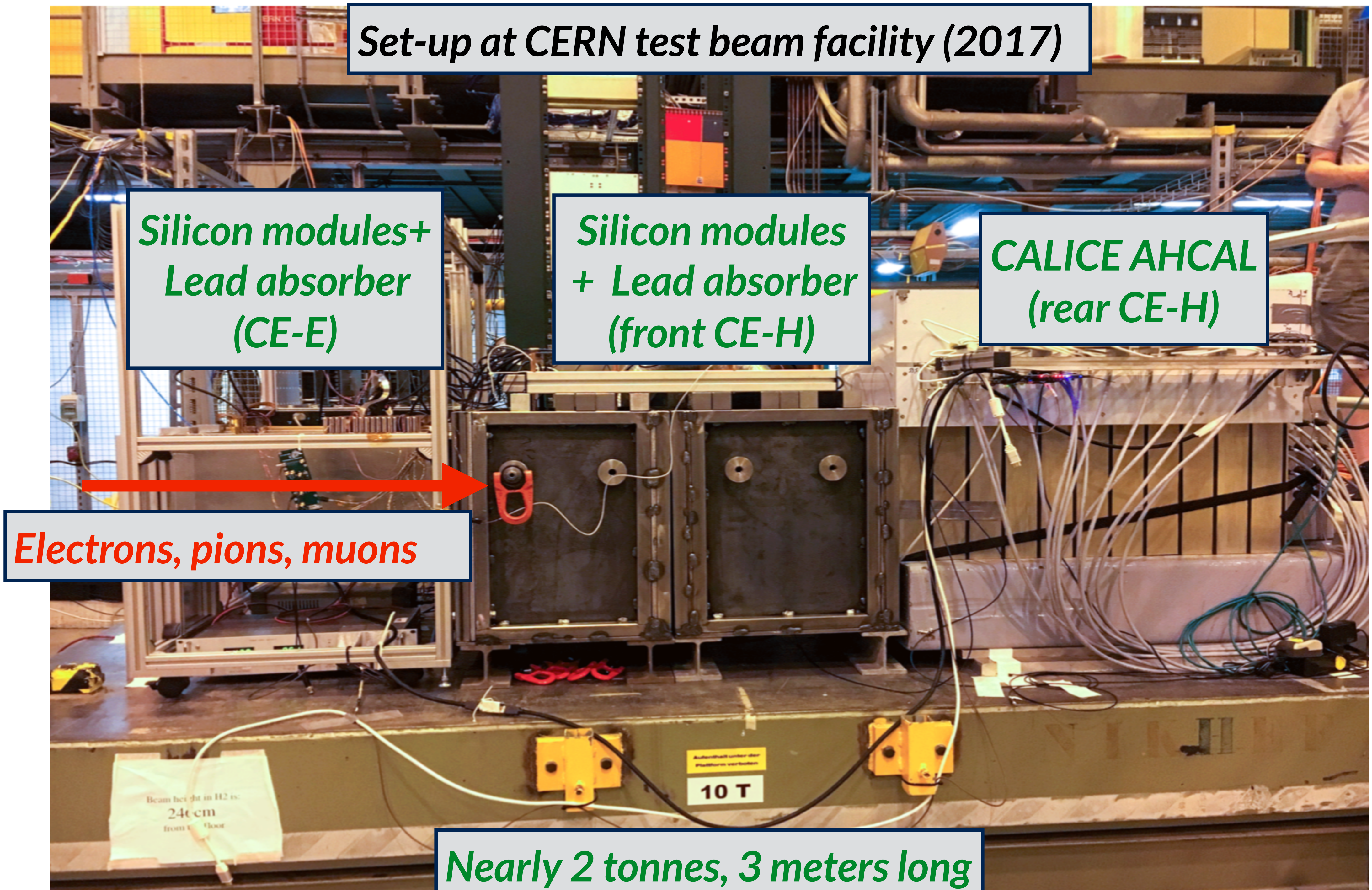
      (for an energy deposit equivalent to ~ 50 fC)



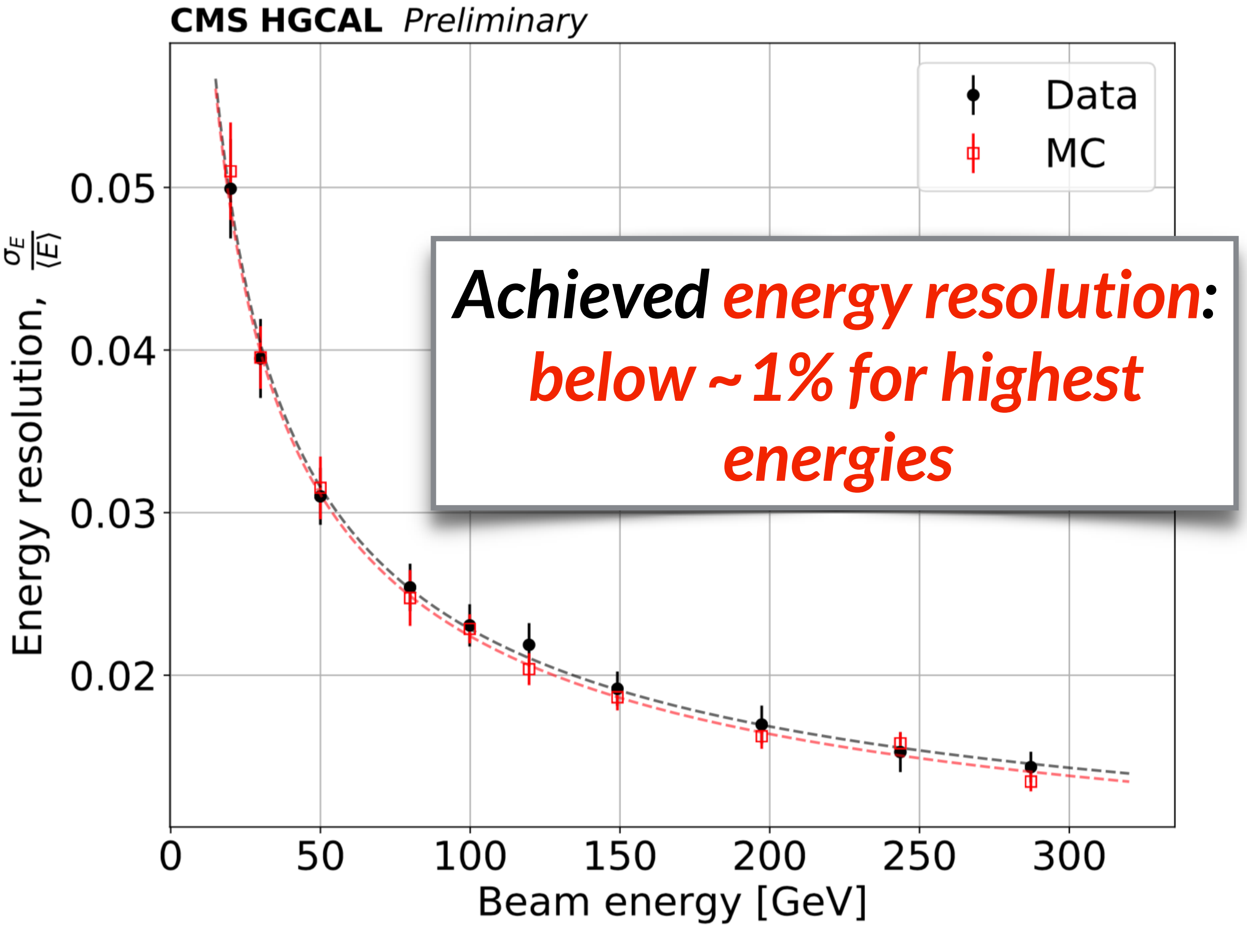
plots: ISBN 978-92-9083-459-5

Beam Tests

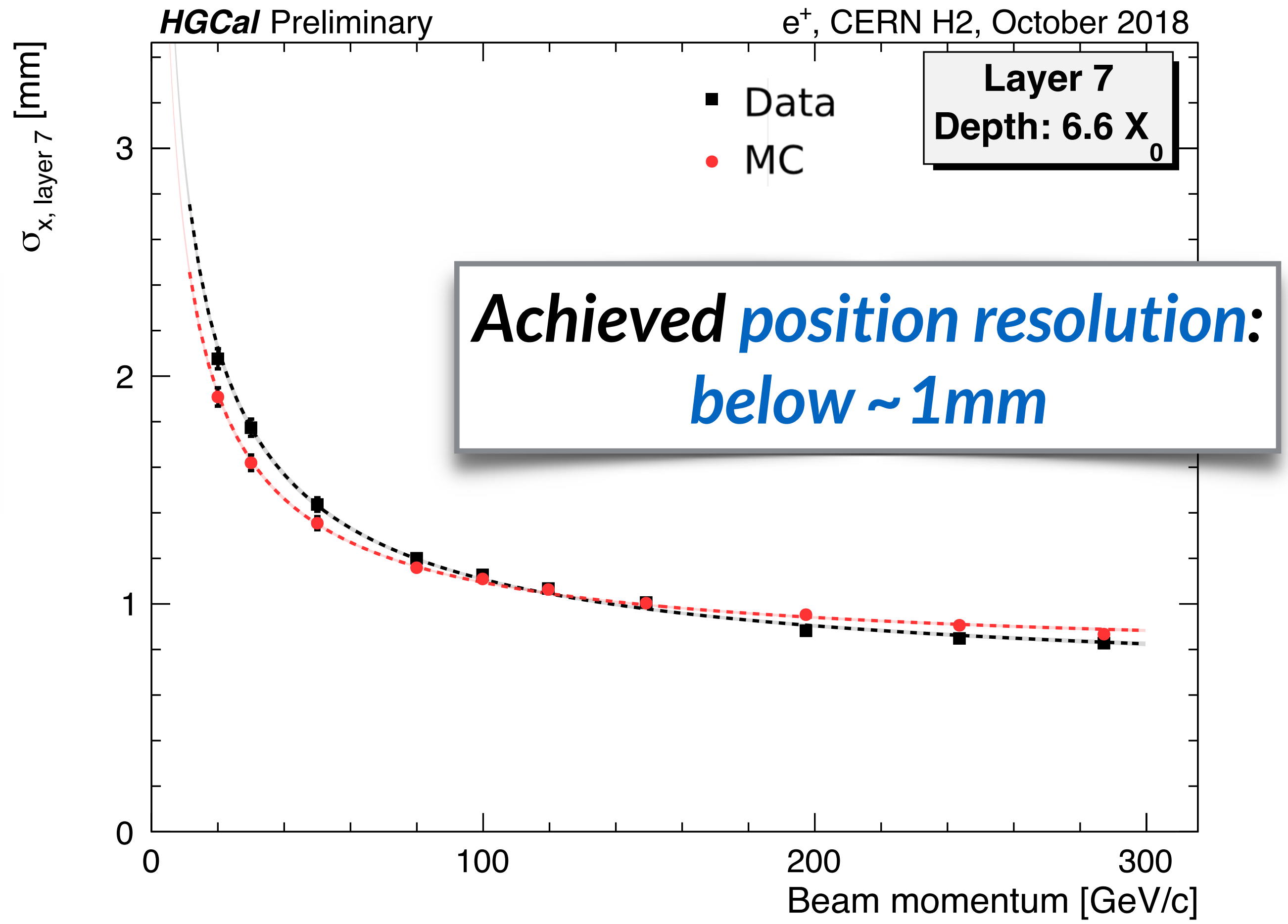
- Various test beam studies at **Fermilab** and **CERN** during 2016-2018
- Various configurations were explored
  - *Measure the performance and compare with a detailed simulation*
  - *Validate the HGCAL design*



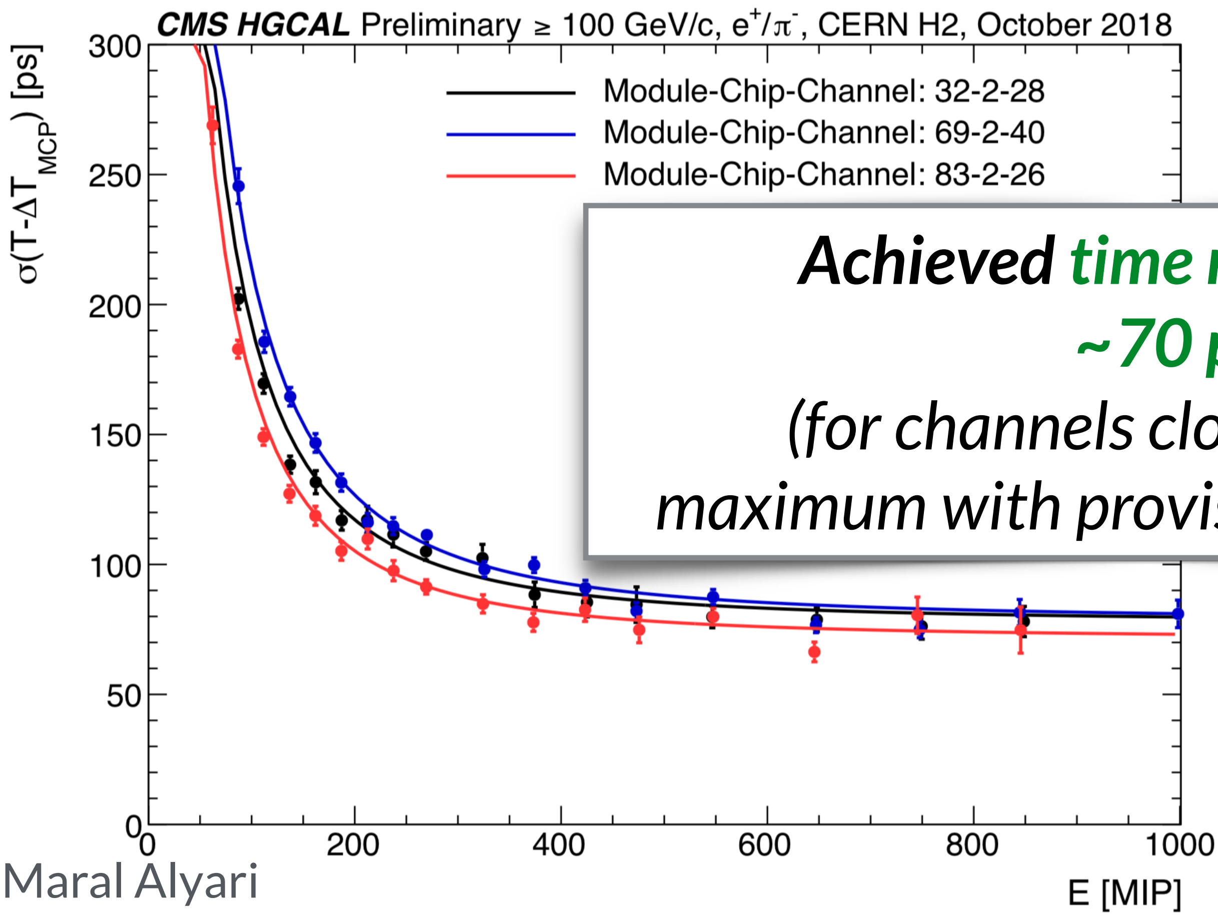
Achieved Energy, Position,Time Resolution



Achieved energy resolution: below ~1% for highest energies



Achieved position resolution: below ~1mm



Achieved time resolution: ~70 ps (for channels close to shower maximum with provisional electronics)

October 2018 beam test @CERN-SPS

More information: Matteo Bonanomi's poster! "BEAM TESTS OF CMS HIGH GRANULARITY CALORIMETER PROTOTYPES AT CERN "

Summary

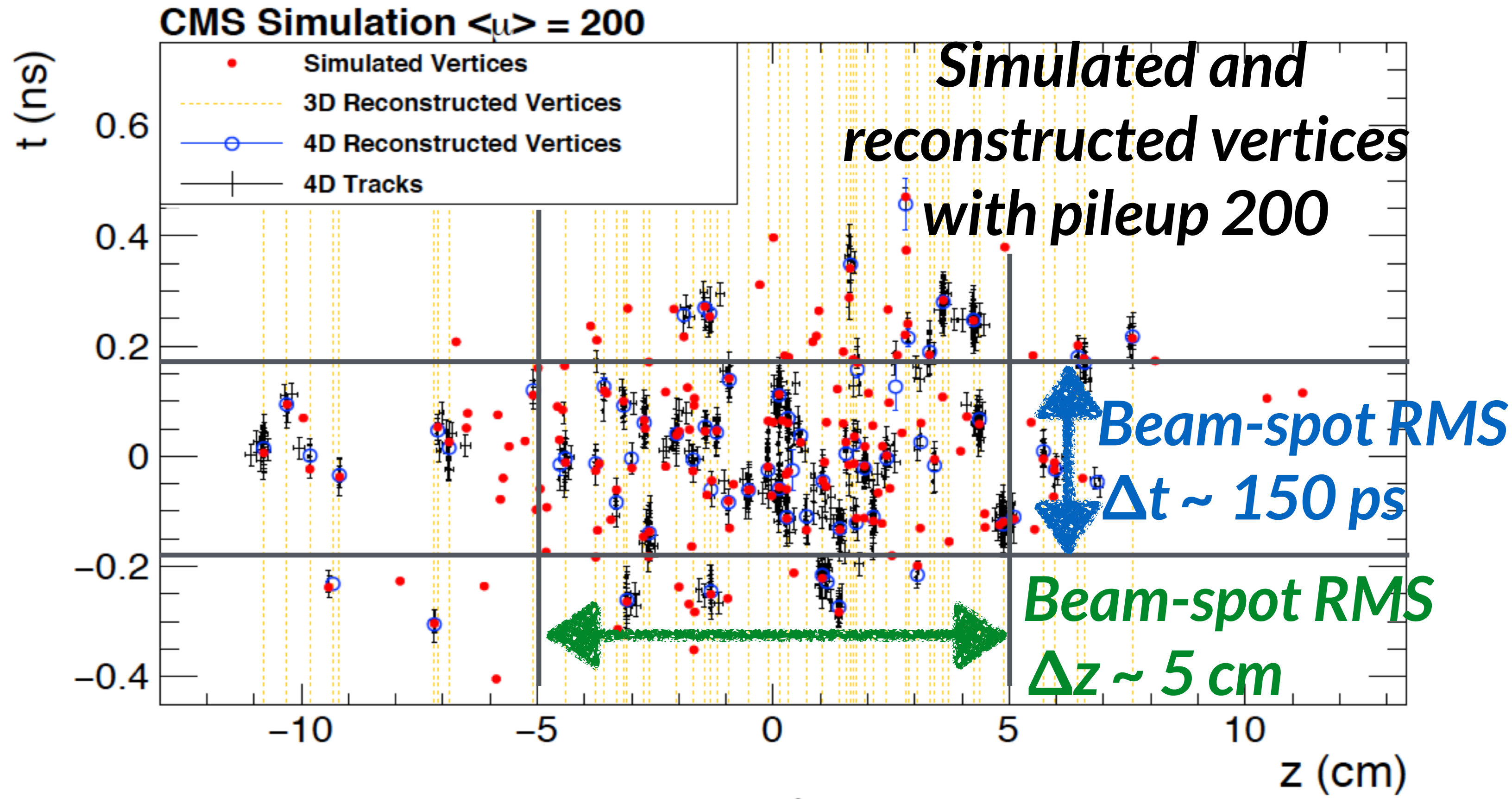
- Detector design faces two major challenges at HL-LHC:
  - Unprecedented radiation dose
  - High pile-up
- To address these challenges at the CMS endcap calorimeters:
  - The endcaps will be placed with the HGCAL, a high granularity **5-D** imaging calorimeter
    - 600 m^2 of Silicon coverage
- The expected performance of HGCAL is demonstrated
  - Mitigates the pile-up well, providing cleaner signals
  - Mitigates the high radiation HL-LHC environment
- Currently going through intensive phase of prototyping
- Preparations for production are going well at the assembly centers

HGCAL will play a major role in maintaining the overall CMS Physics performance throughout the full HL-LHC period

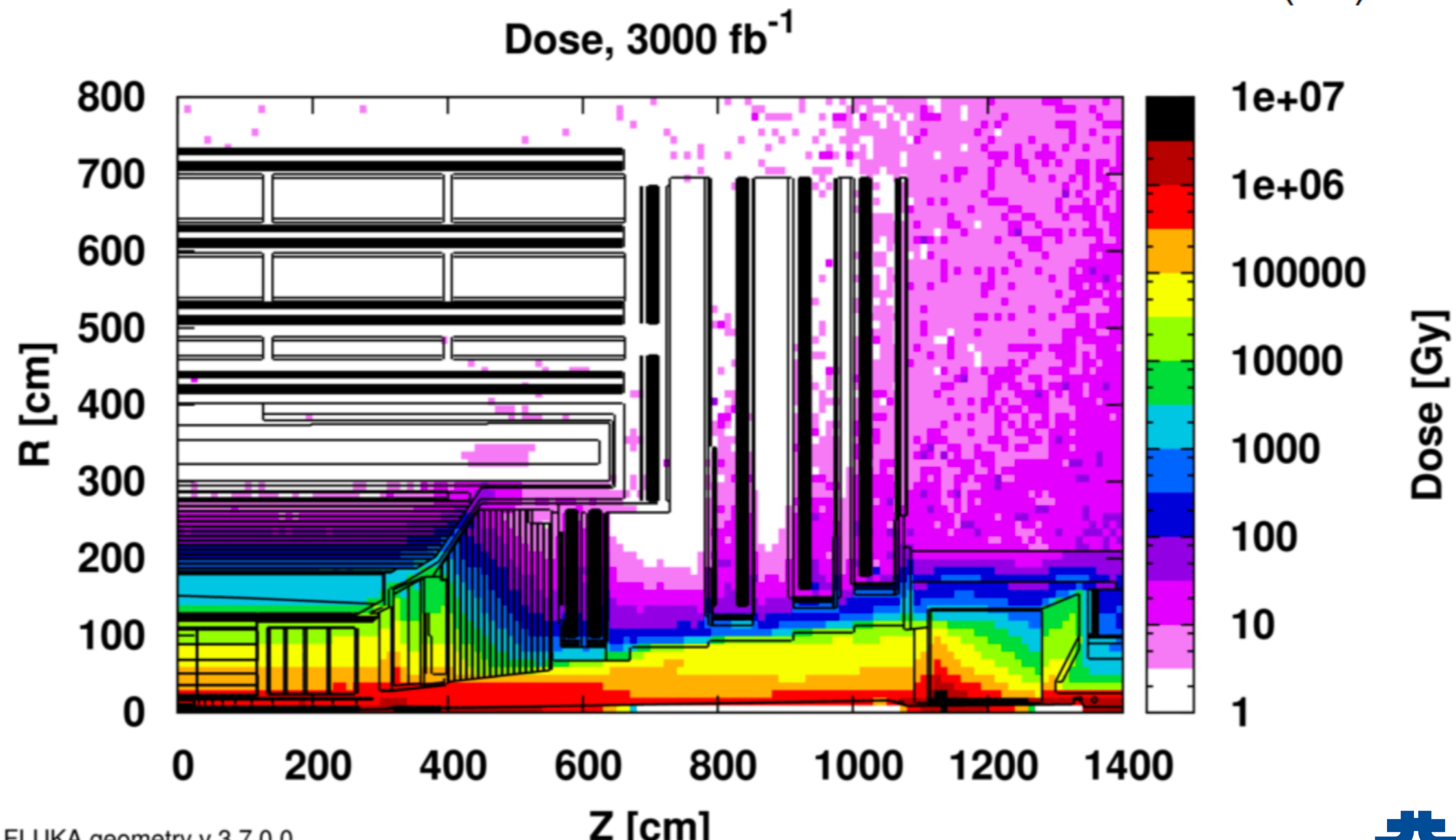
Back-up

Challenges at HL-LHC

- **Two major challenges** for detectors:
  - **High Pile-up challenge**
    - Mitigated with
      - High granularity
      - Precise timing

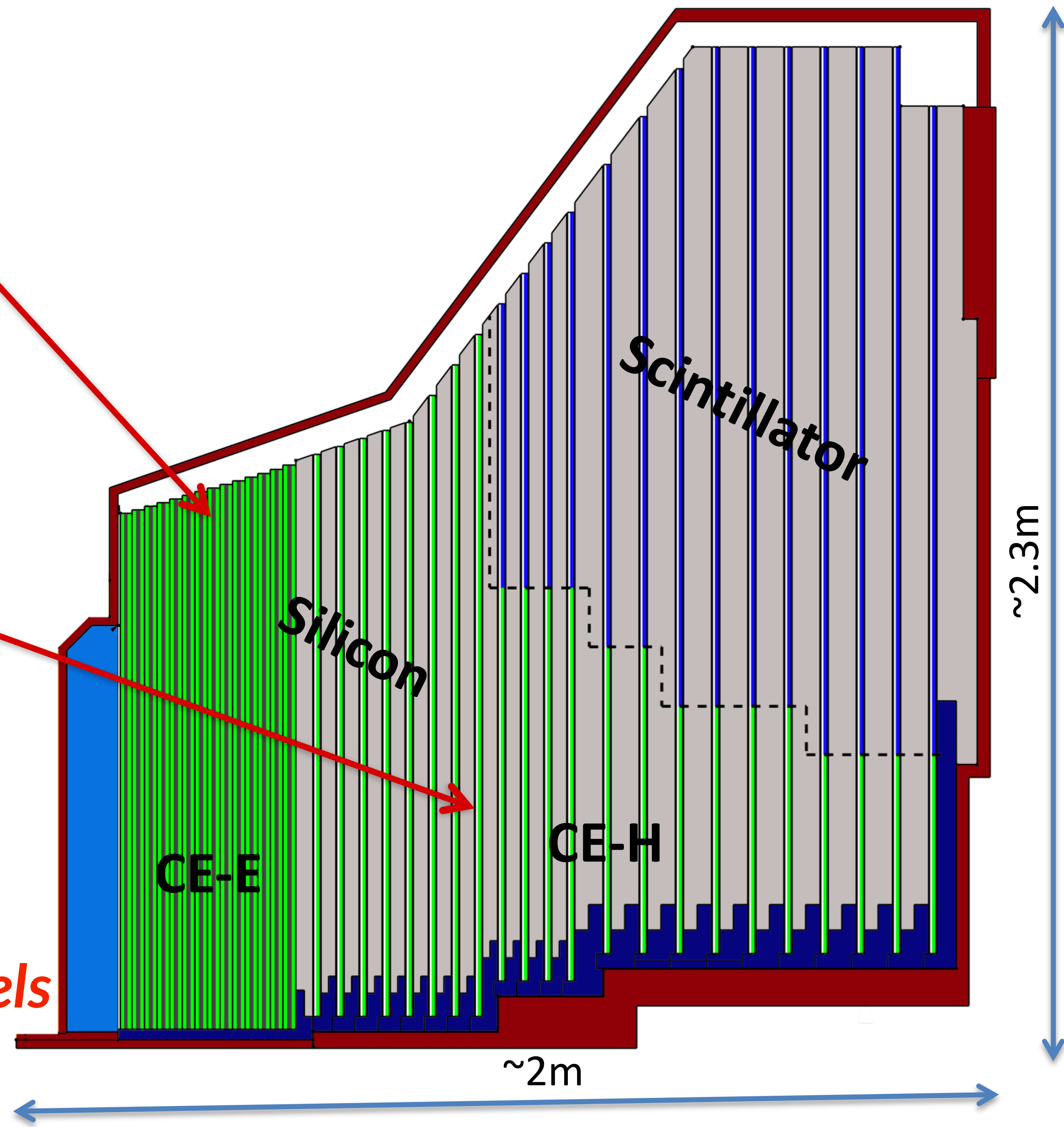


- **Unprecedented radiation dose challenge**
  - Requires
    - Radiation hard detector material and readout

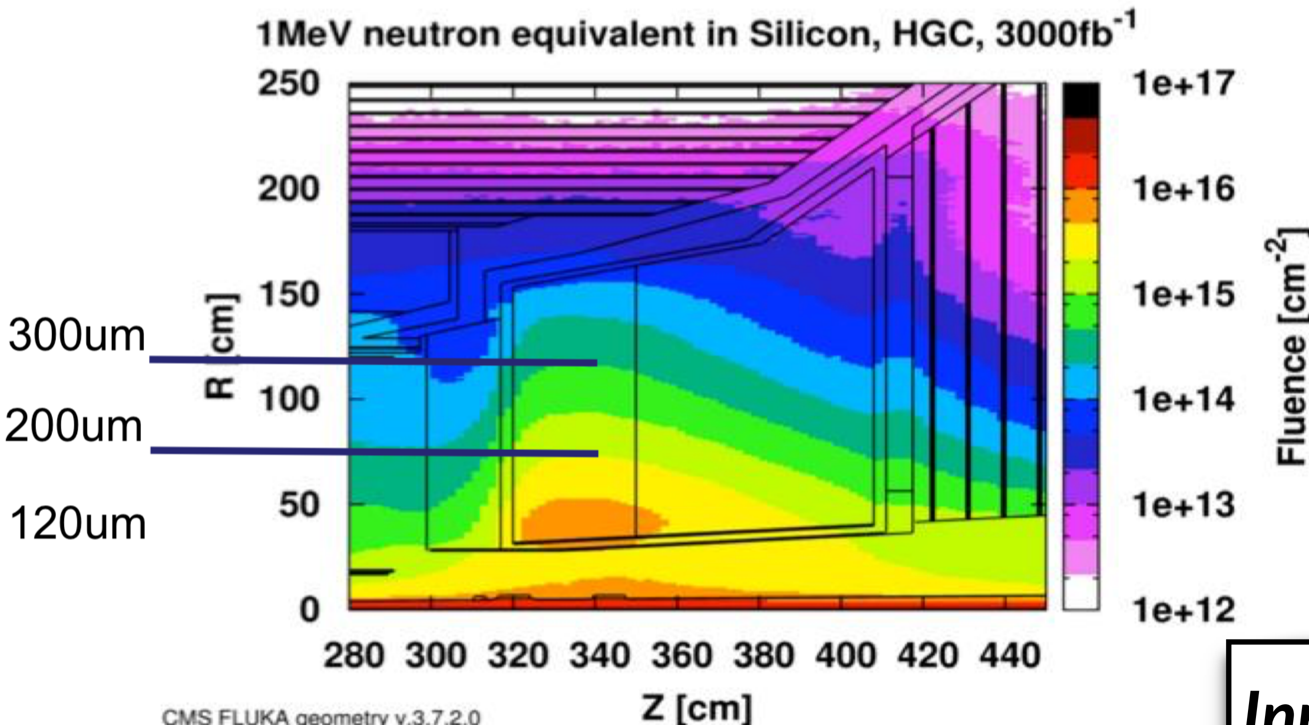


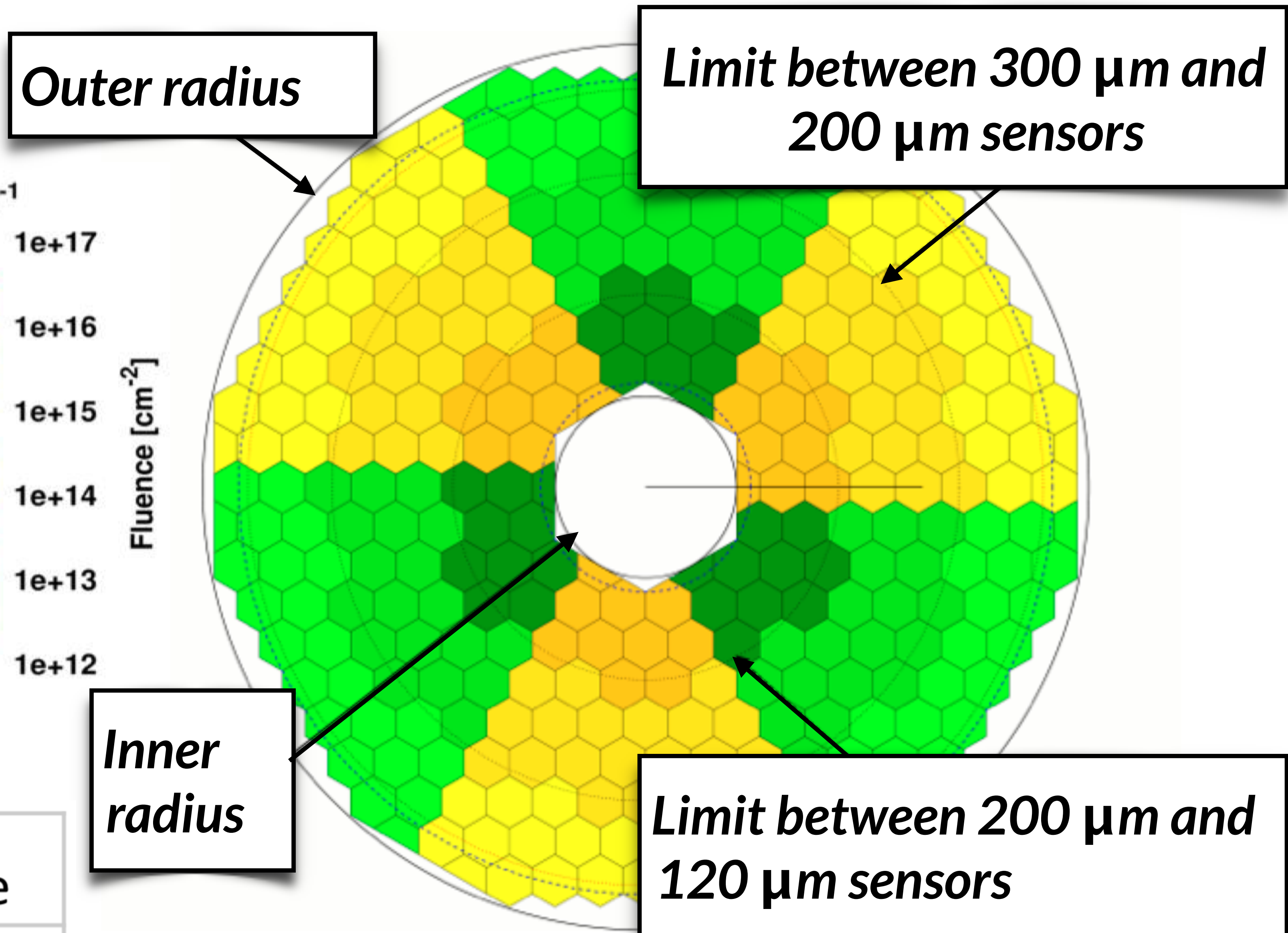
Overall High Granularity Calorimeter Design

- HGCal : A sampling Calorimeter:
  - *Electromagnetic section (CE-E)*
    - *Active element: Silicon*
      - *14 x 2 layers*
    - *Absorber: Lead, Copper-Tungsten, Copper*
  - *Hadronic section (CE-H)*
    - *Active elements:*
      - *Silicon*
        - *Layers 1-8*
      - *Silicon & Scintillator*
        - *Layers 9-22*
    - *Absorber: Stainless Steel*
- ***Very high granularity***
  - ***6 million Silicon channels***
  - ***240 thousand Scintillator channels***
- ***Weight: ~ 215 tonnes per endcap!***
- ***Total longitudinal thickness: 9.8λ***
- ***Electromagnetic longitudinal thickness: 25X_0***



300 µm, 200 µm and 120 µm Sensors





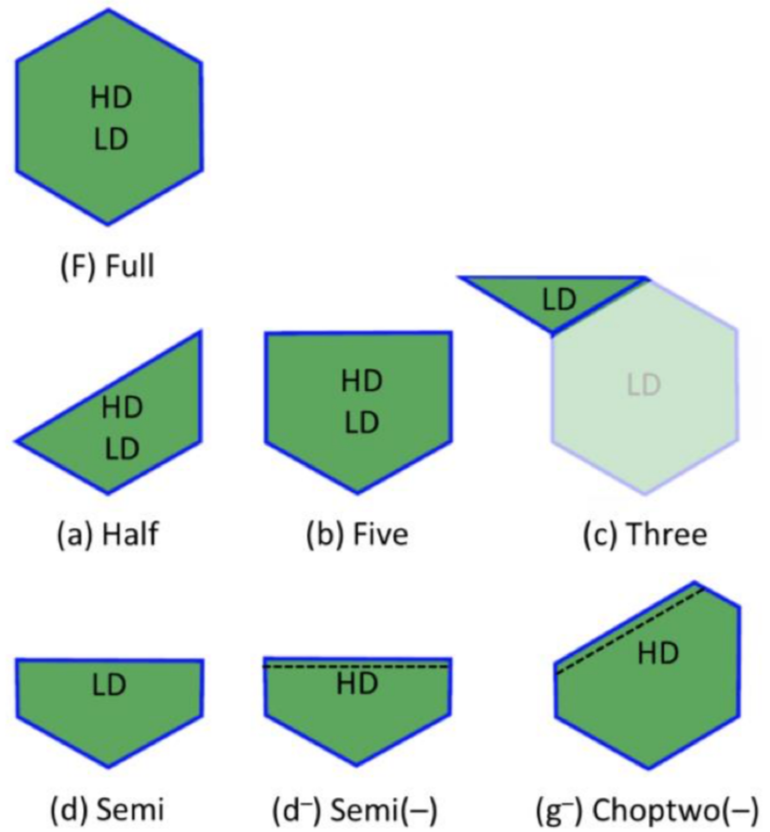
Thickness [µm]	Expected dose range
300	1E14-5E14
200	5E14-2.5E15
120	2.5E15-1E16

Silicon Sensors Key Technical Specifications

- **Sensor breakdown voltage V_{break}** > 800V, I_{800} < 2.5 x I_{600}
- **Current @600V (at 20℃):** ≤ 100 µA integrated over the sensor and guard rings
- **Current @600V I_{600} (at 20℃):** ≤ 100 nA/pad

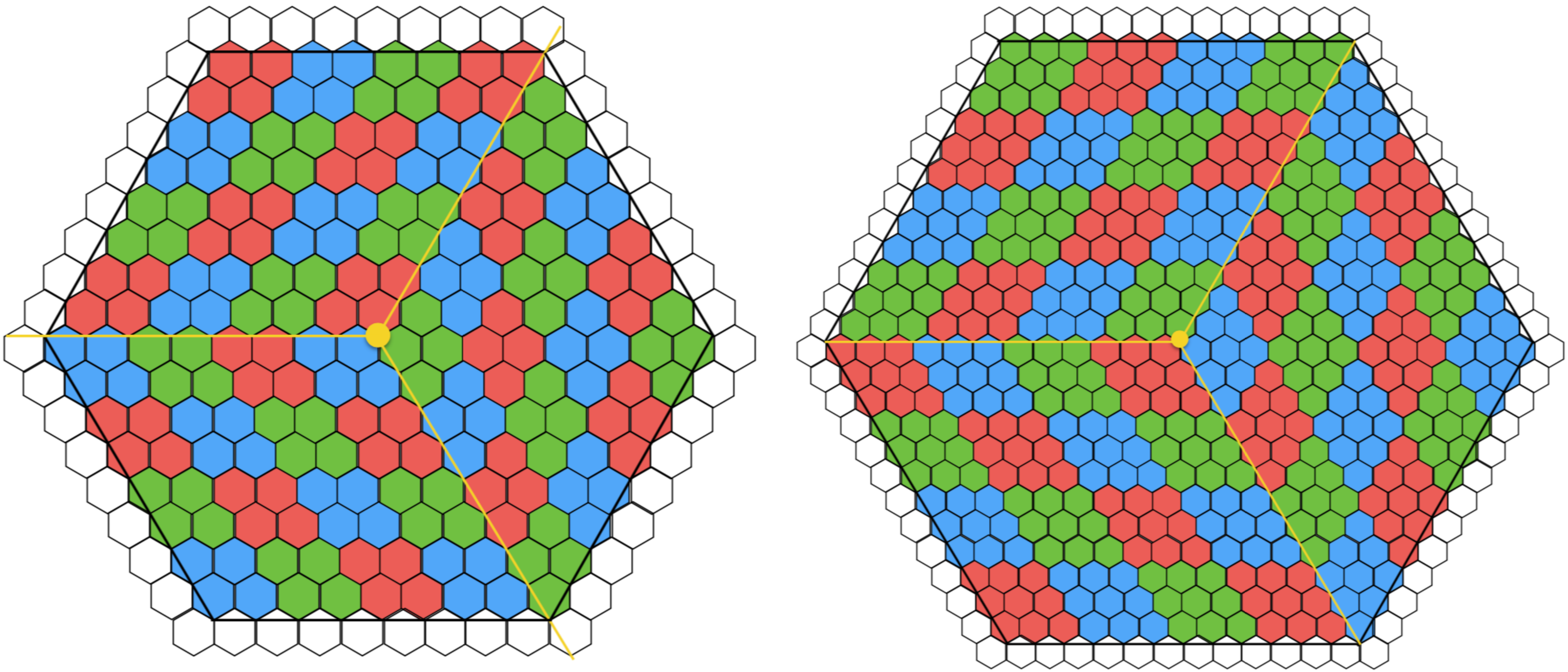
- **Allowed number of bad pads:**
  - ≤ 8 for full-sized sensors
  - ≤ 4 for half and semi
  - ≤ 6 for choptwo and five types
  - ≤ 2 for chopfour and three types
  - Not more than two adjacent bad pads

  Corresponds to roughly 2%-4%



Sensor type	300 µm	200 µm	120 µm	Total
(F) Full	11400	9096	3840	24336
(a) Half	1404	144	108	1656
(b) Five	990	144	48	1182
(c) Three	1290	0	0	1290
(d) Semi	720	0	0	720
(d-) Semi(-)	0	0	336	336
(g-) Choptwo(-)	0	0	336	336

Trigger Cells



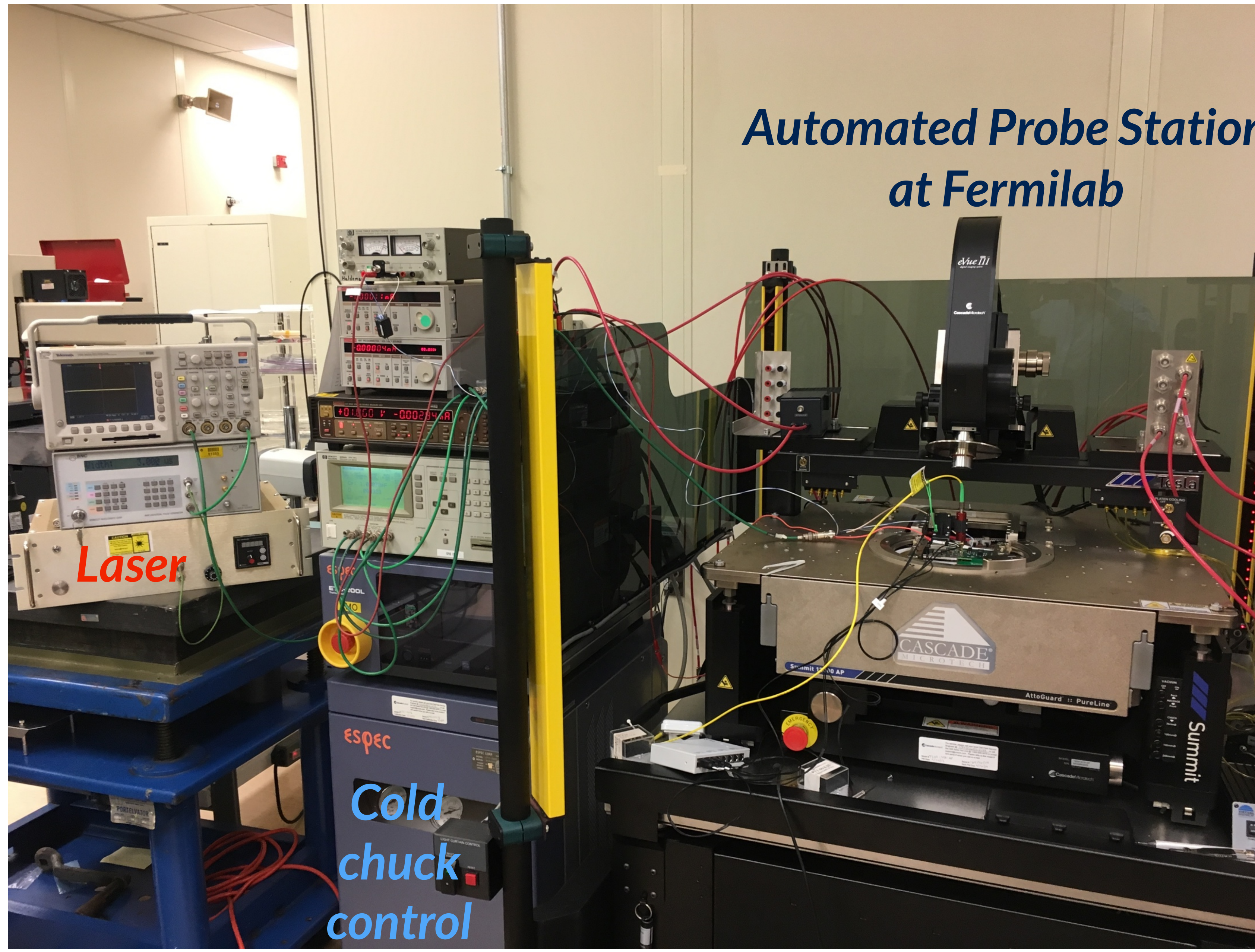
Schematic illustration of the three-fold diamond configuration of sensor cells on hexagonal 8” silicon wafers, showing the groupings of sensor cells that get summed to form trigger cells , for the large, 1.18 cm^2, sensor cells (left), and for the small, 0.52 cm^2, cells (right).

Silicon Sensor Characterization

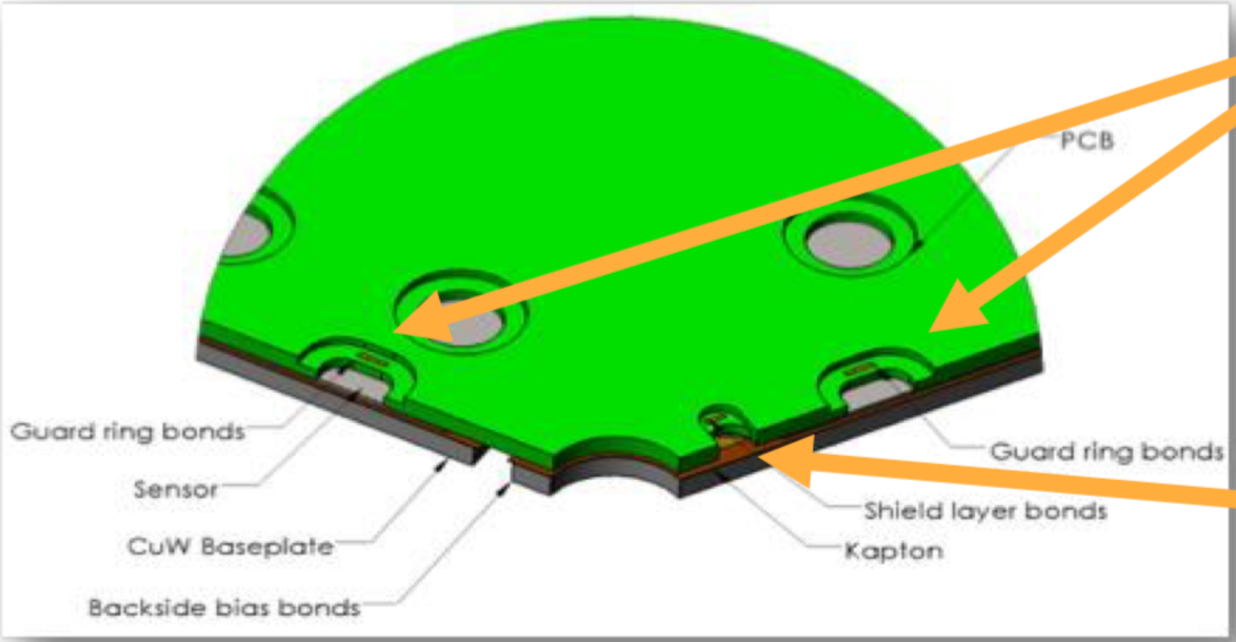
- Various efforts on *characterizing* Silicon wafers and test structures at different temperatures
  - ***Measuring:***
    - Leakage currents
    - Interpad resistance
    - Charge collection
    - Depletion voltage

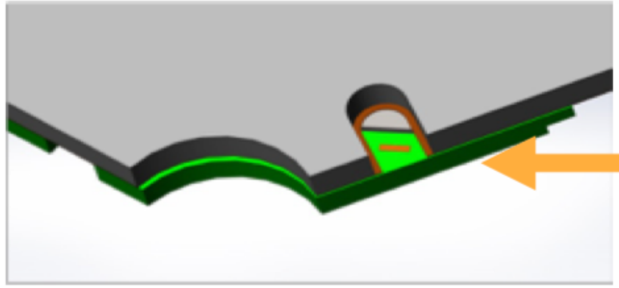
      (Two techniques:
      - *7 needle*
      - *full hexa-board)*

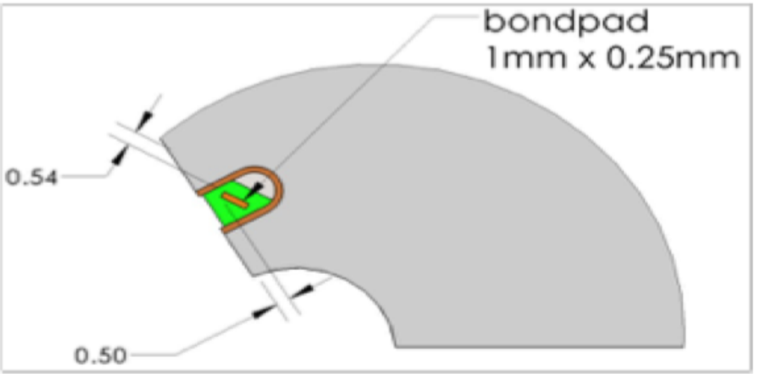
  - ***Studying irradiation effects***
    - Neutrons
    - Protons
    - Electrons



Wire-bonding Notches

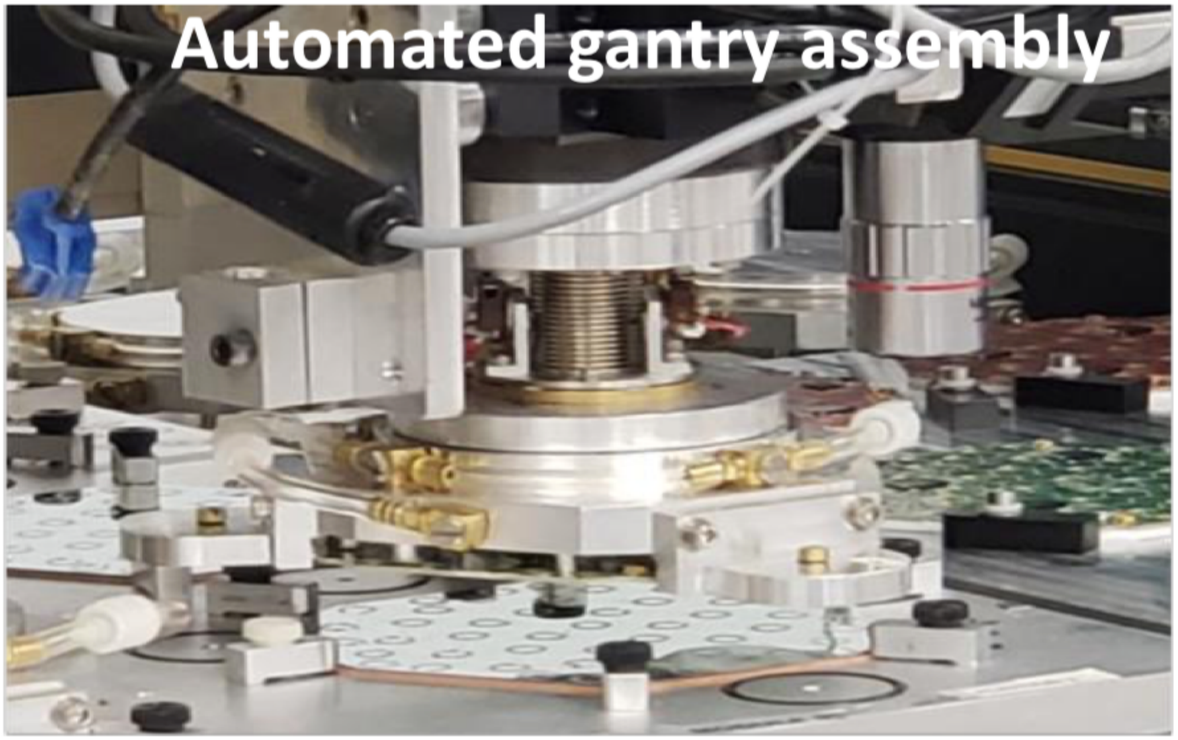


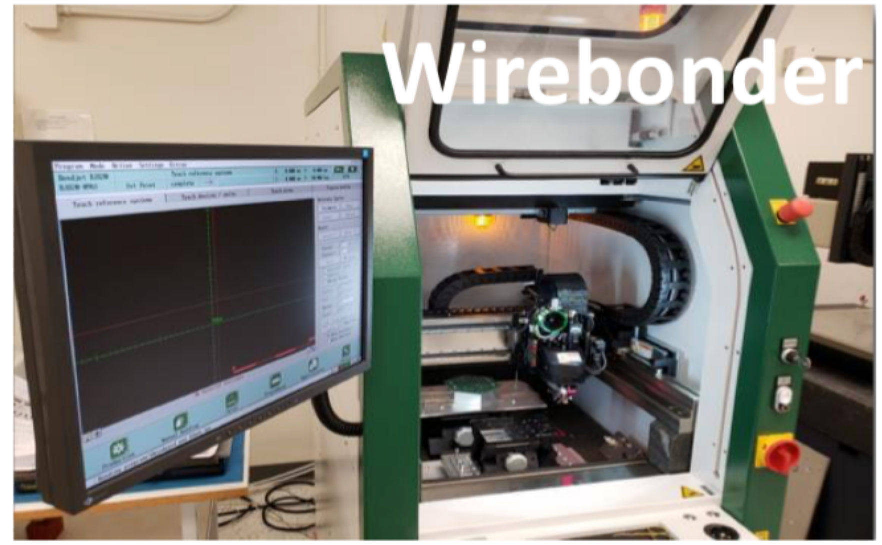




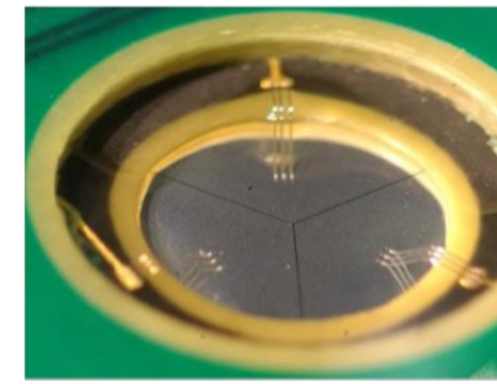
- 12 notches for guard ring bonds
  - stepped design to keep bond wires below PCB surface for protection
  - moved closer to mouse bite to be less likely to be touched during handling
- 6 notches in PCB for bonding to shield in Kapton or PCB baseplate
  - Also close to mouse bite, opposite side from baseplate notch
- 6 notches in baseplate (at mouse bites) for backside bias bonds
  - Adding bond pad on an inner step on underside of PCB

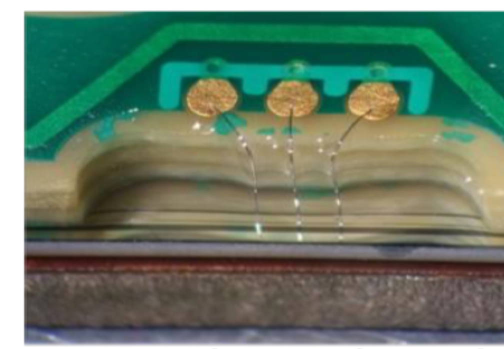
Module Assembly and Testing



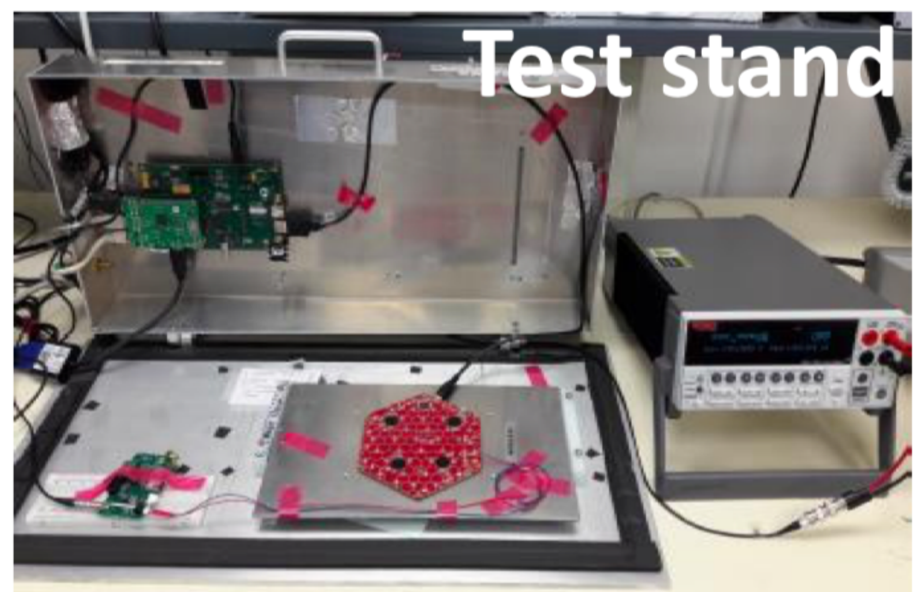


Signal bonds at stepped holes



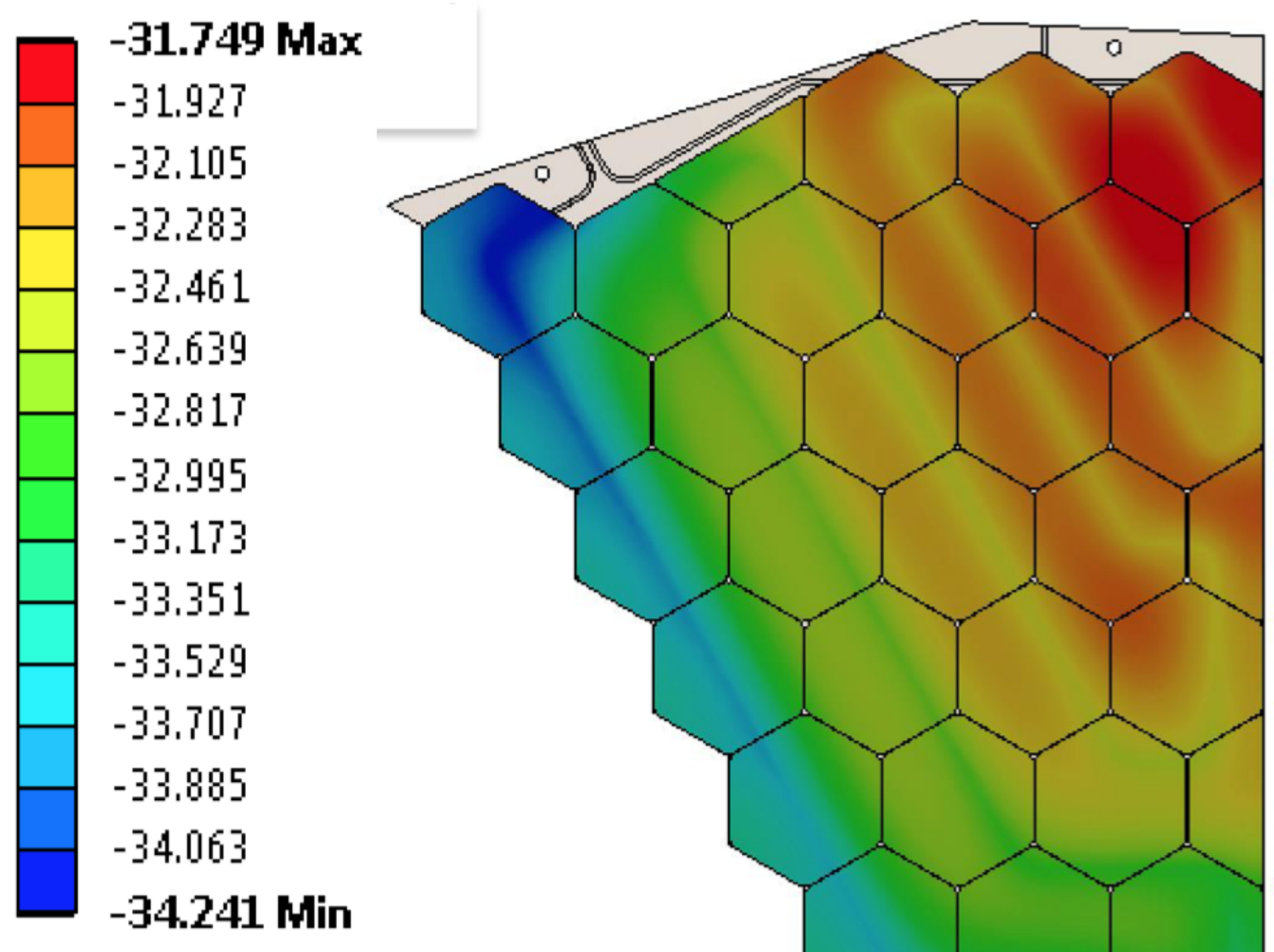


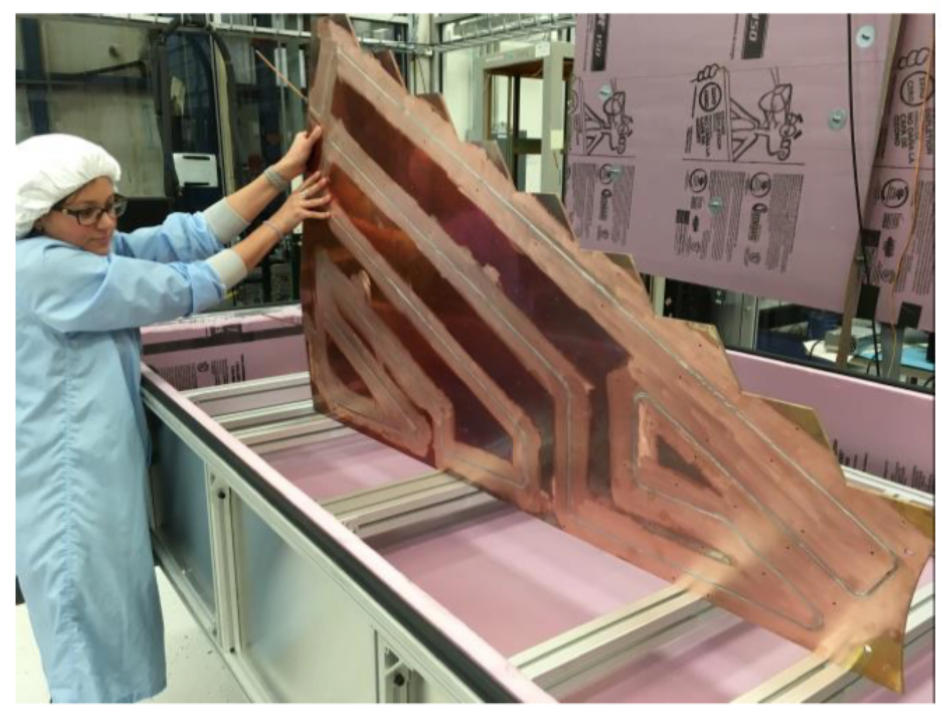
Guard ring bonds at edge



Thermo-mechanical Mock-up Cooling Plate

- FEA calculations have been made for a heat load of 270W
  - Expected at end of life
- 6.8 meter long tube, 3/16" OD, 0.03" wall thickness
- 3.3 g/sec CO_2 flow (35% vapor quality)
- Pressure drop = 0.8bar
- Outlet temp = -35C (inlet -33C)
- Maximum temperature of copper plate is below -32C
- Cooling plate has been fabricated at Fermilab





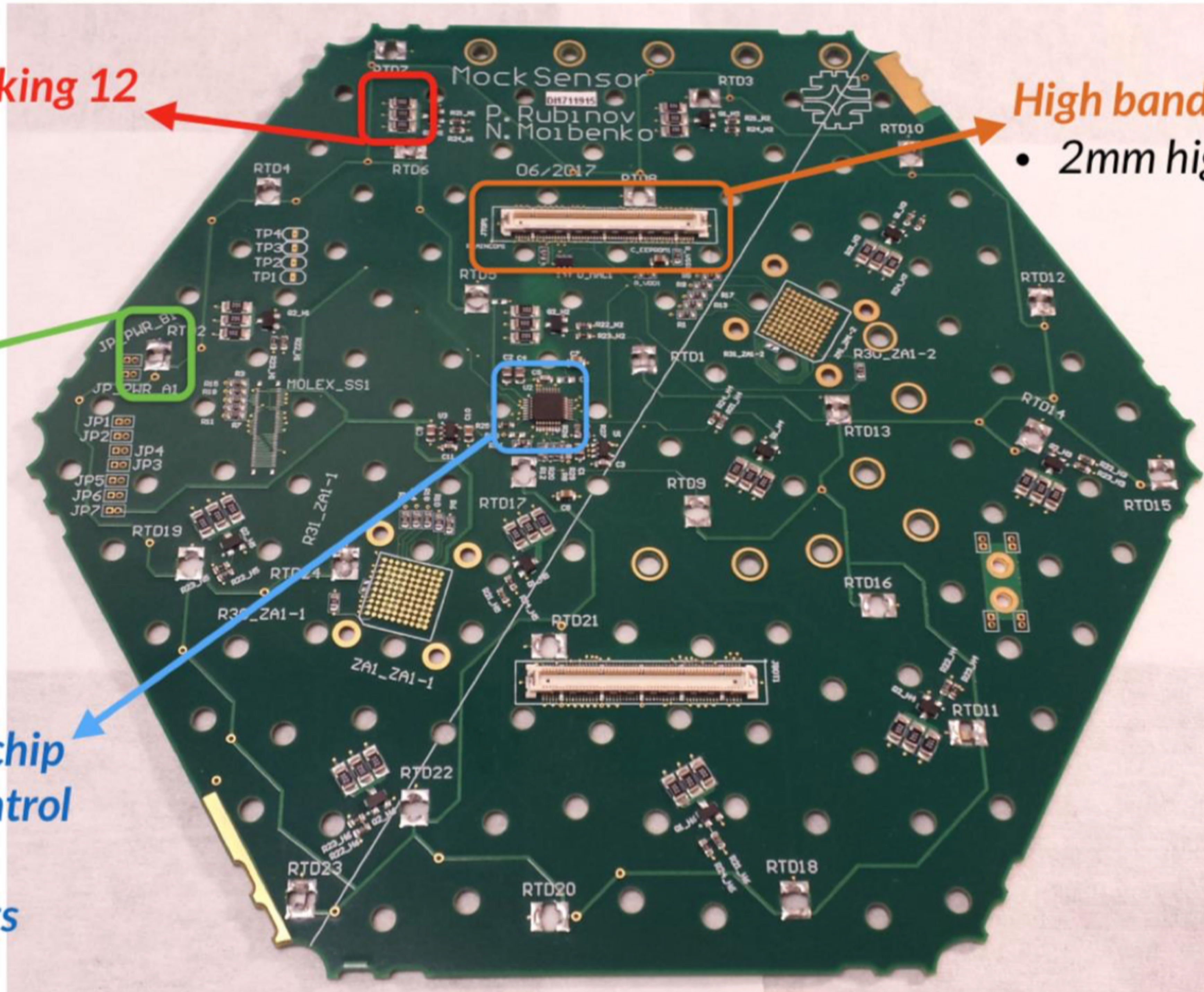
Thermo-mechanical Mock-up Hexaboard

- Mockup of 432 channel module board
  - Designed to *apply heat loads* and *measure temperature of the silicon*

12 heaters mocking 12 read-out chips

8 RTDs in contact with Silicon

ADS124S0x chip for heater control and temp measurements

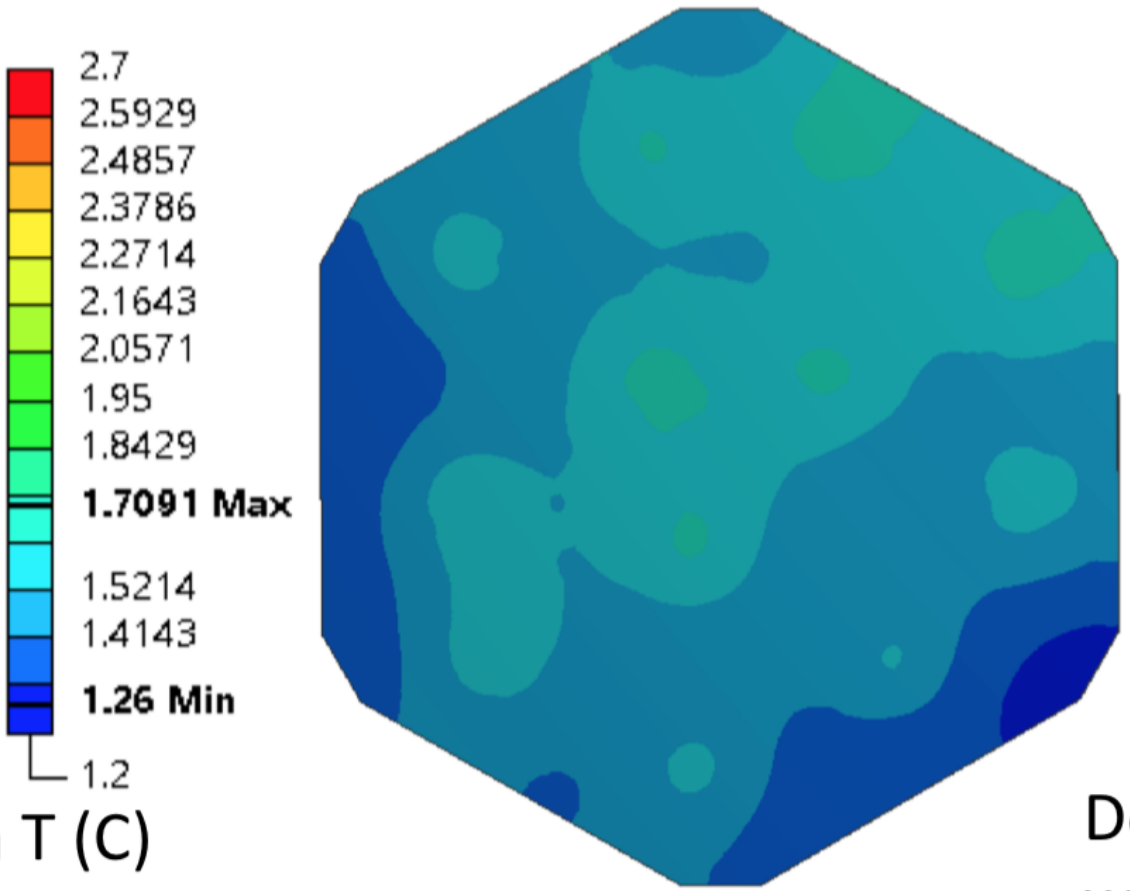


High bandwidth connectors
- *2mm high rigid*

8" mock-up module board

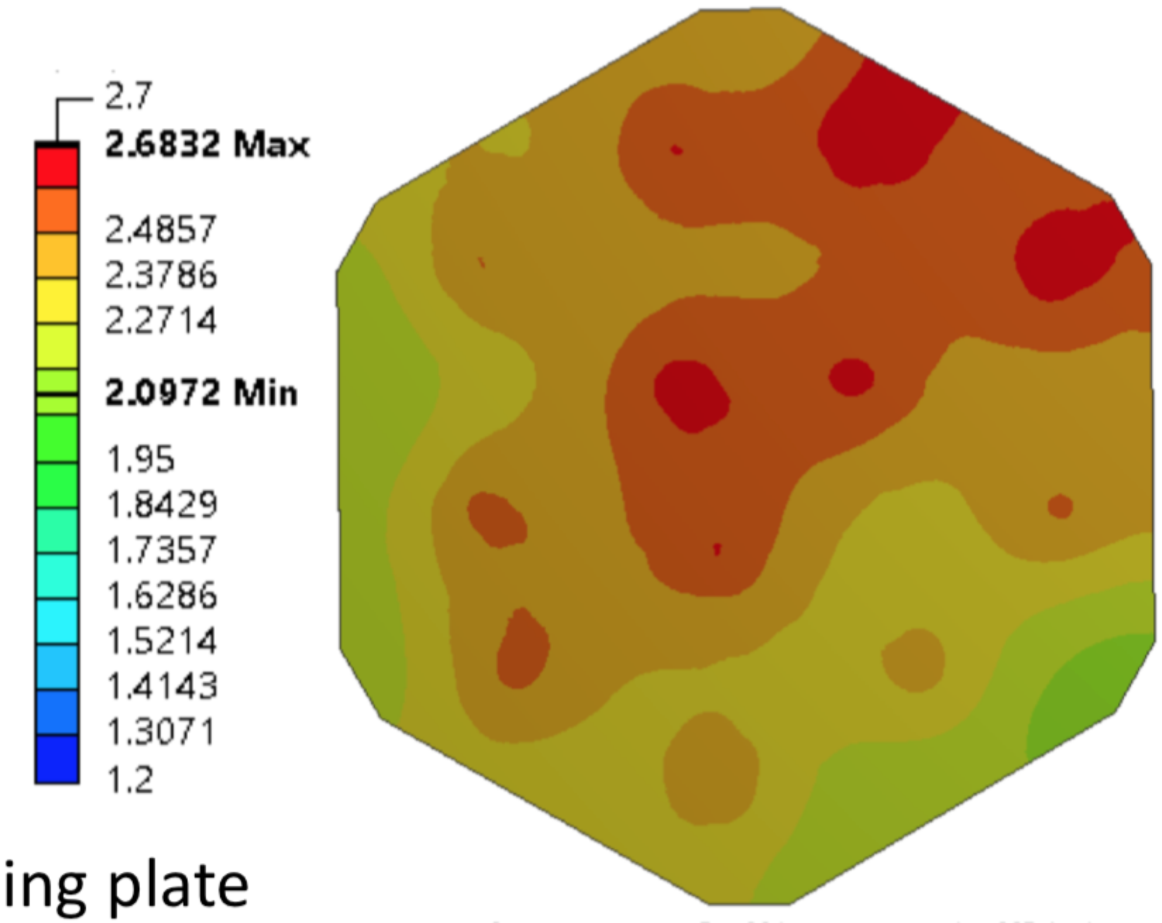
Simulated Temperature Distribution of Silicon

Base Plate Material: CuW 20/80

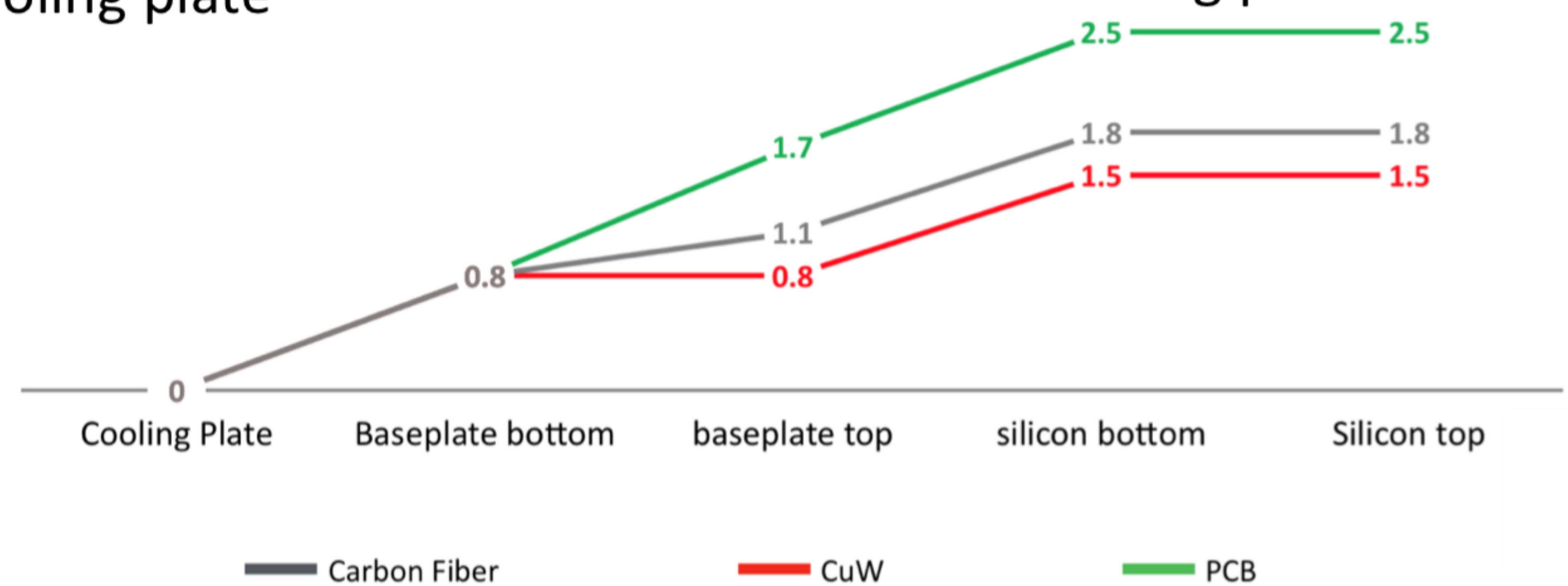


Delta T (C)
wrt to cooling plate

Base Plate Material: PCB

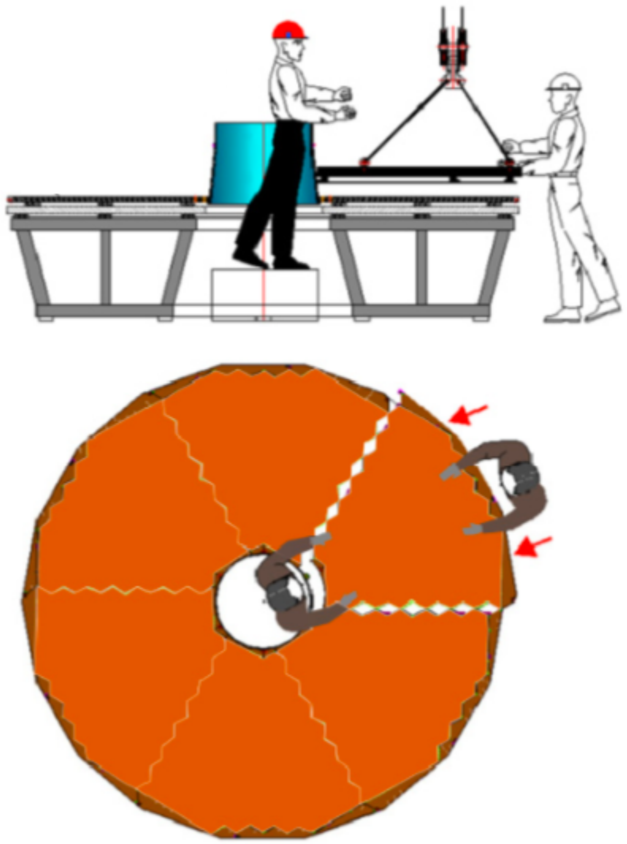


Delta T (C)
wrt to cooling plate

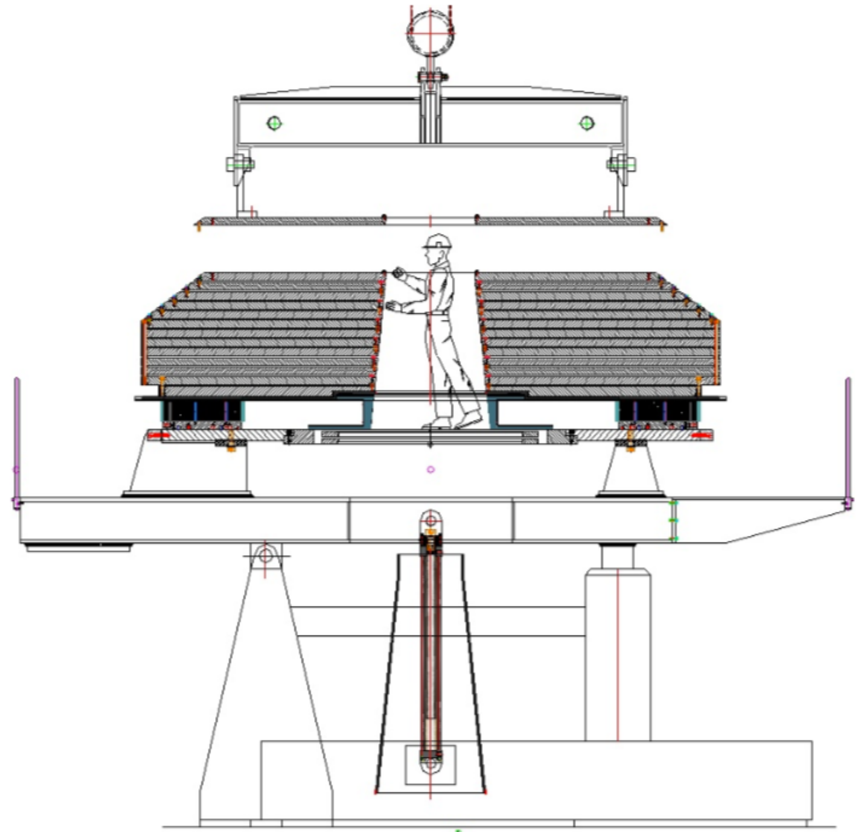


Unit: °C

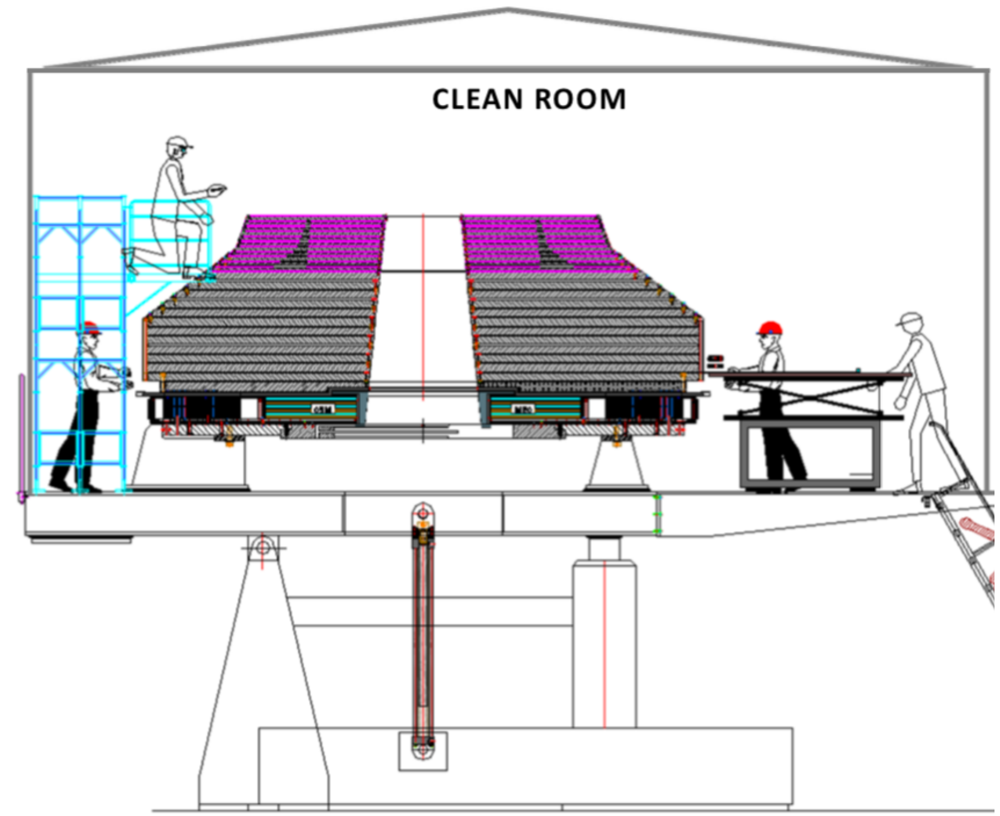
Assembly and Installation



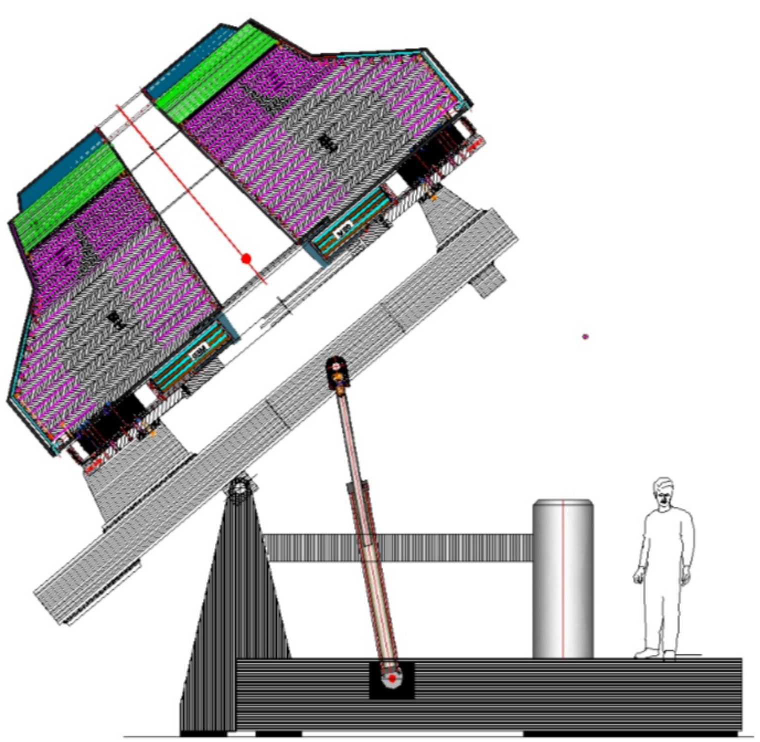
Stacking of CE-E cassettes



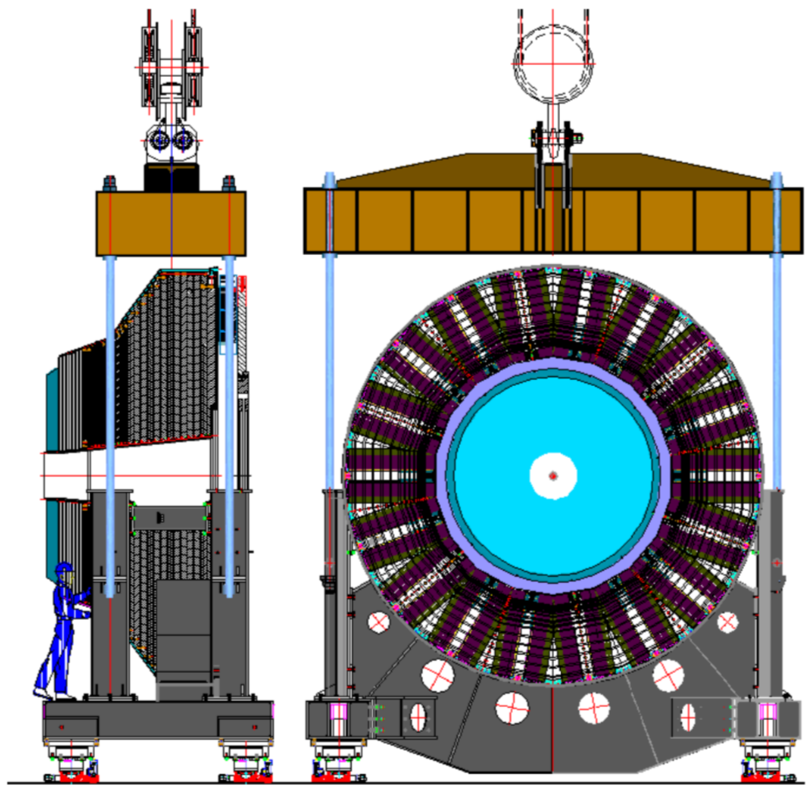
Assembly of CE-H absorber structure

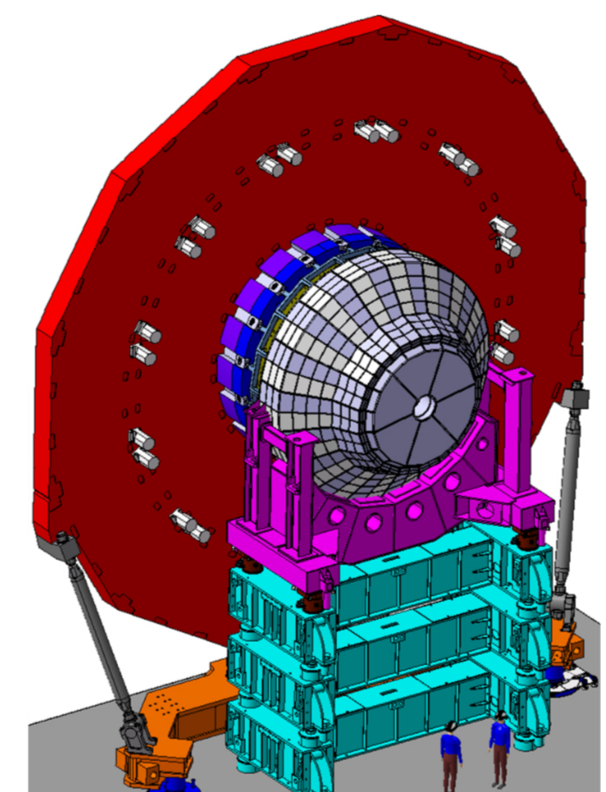


CE-H cassette insertion



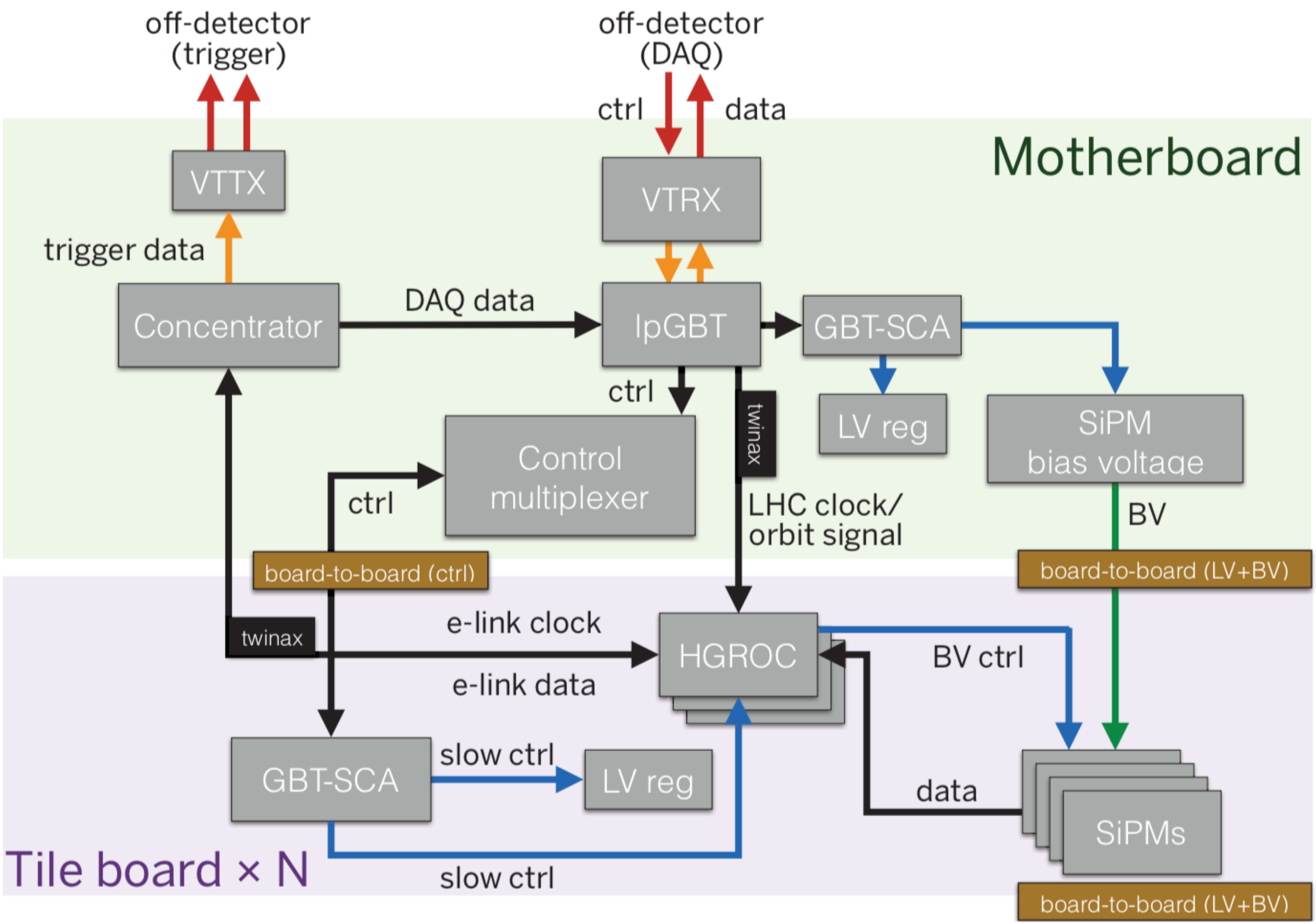
Rotation of the entire HGCal to vertical position





Lowering of one HGCal into the experimental cavern and connection onto YE1

Scintillator Tile-boards Read-out Chain

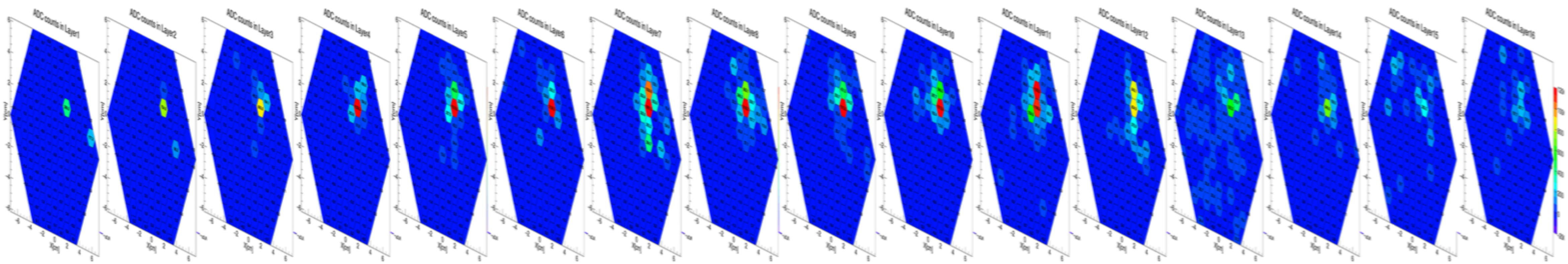


Shower Development

- Event displays of the energy seen in each cell of consecutive silicon layers due to electron-induced electromagnetic showers.

Fermilab
16 layers

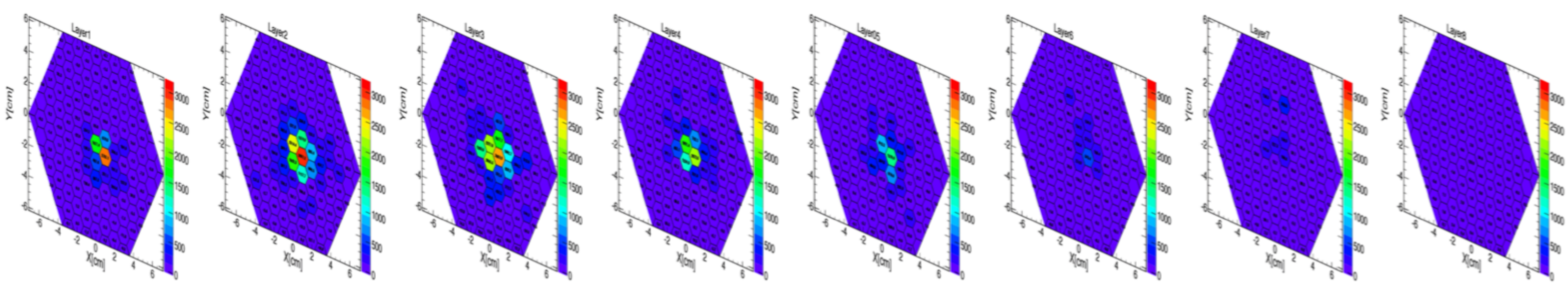
32 GeV electron



$1\ X_0$ $5\ X_0$ $10\ X_0$ $15\ X_0$

Cern
8 layers

250 GeV electron



$5\ X_0$ $15\ X_0$ $21\ X_0$ $27\ X_0$