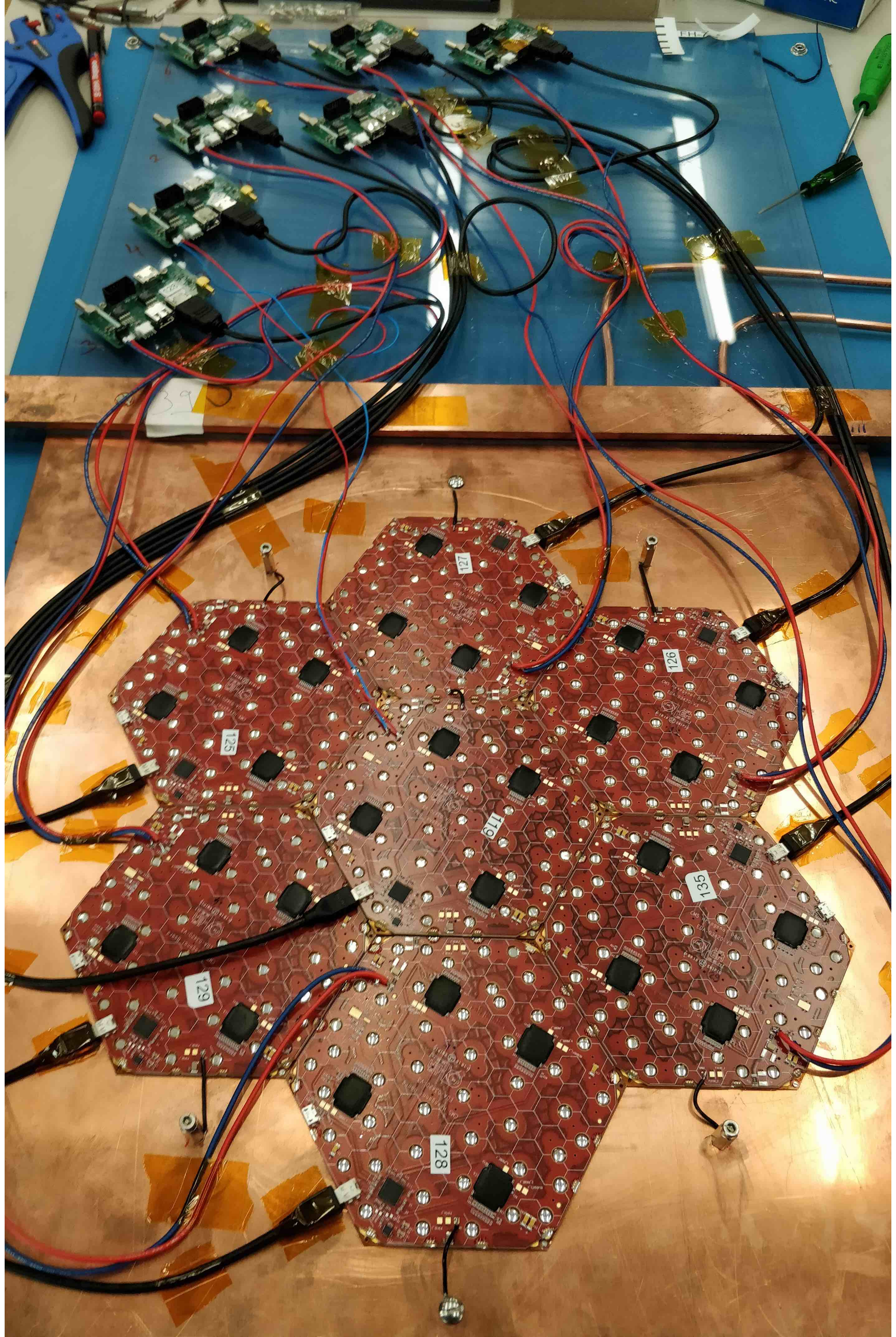
LLR Seminar
10/02/2020

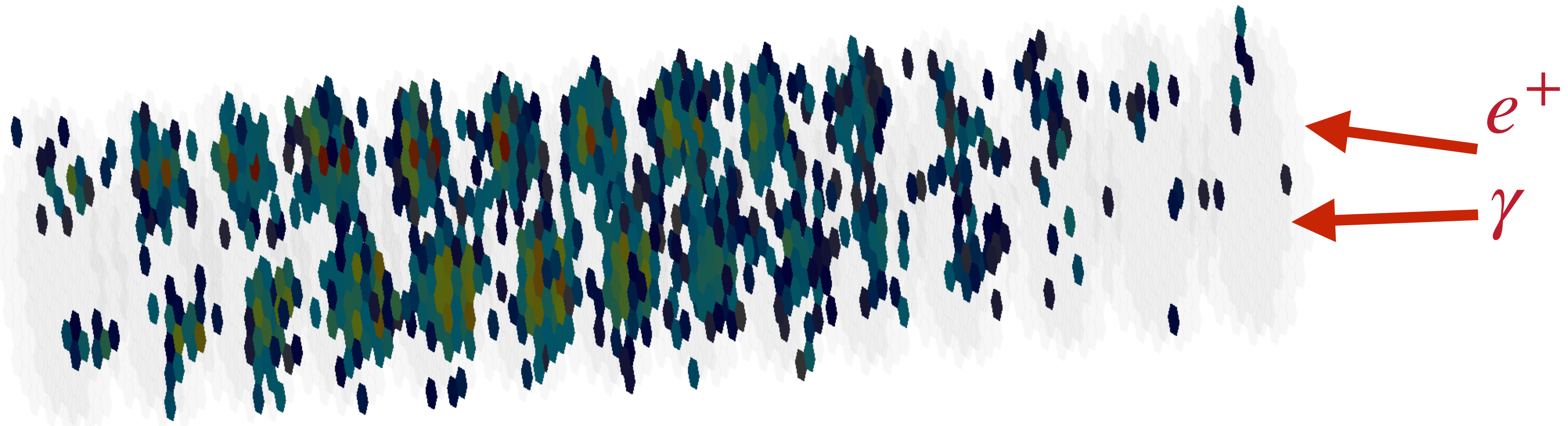
BEAM TESTS OF HGCAL PROTOTYPES AT CERN

Matteo Bonanomi
(LLR, CNRS, Ecole Polytechnique)
On behalf of the HGCAL Beam Tests group



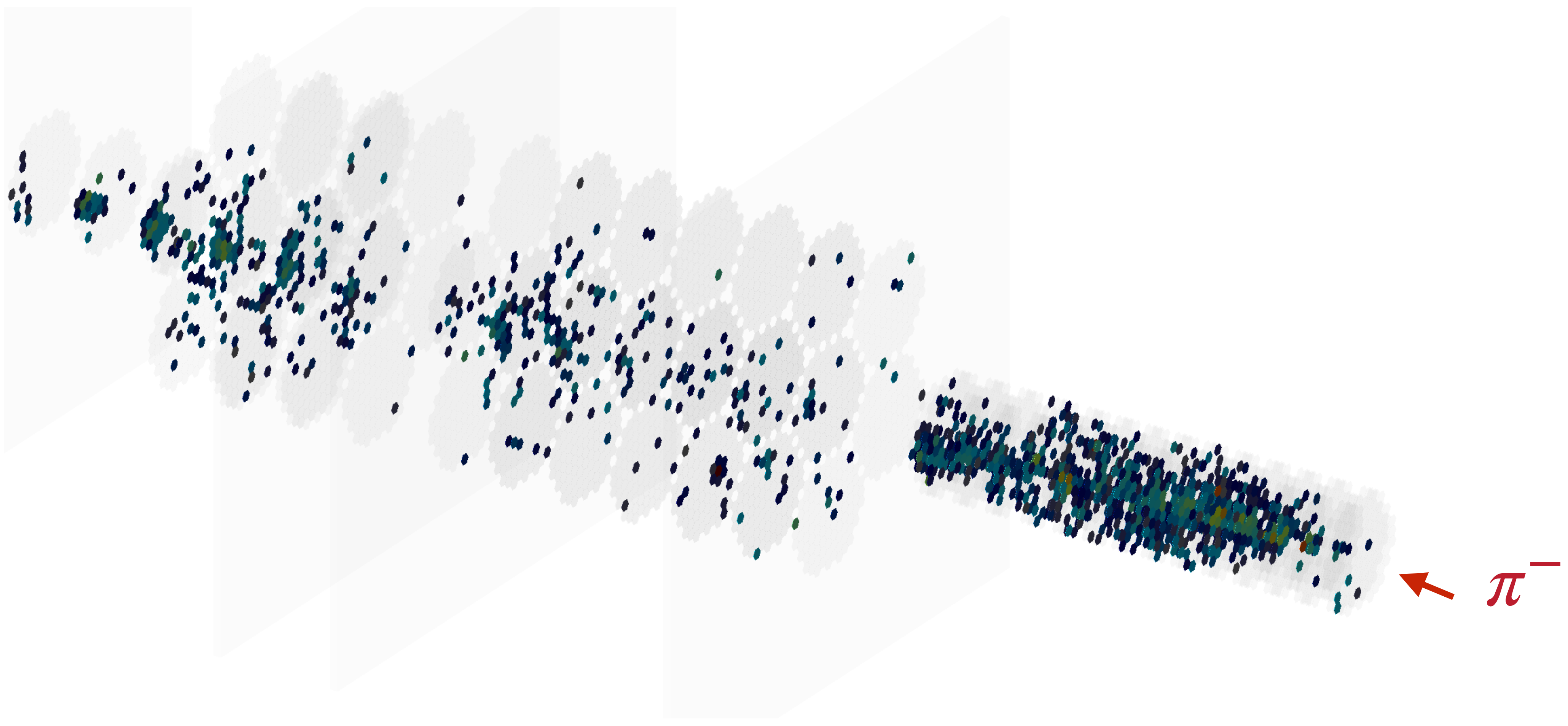
June 2018 run 407 - event 1

150 GeV/c e+



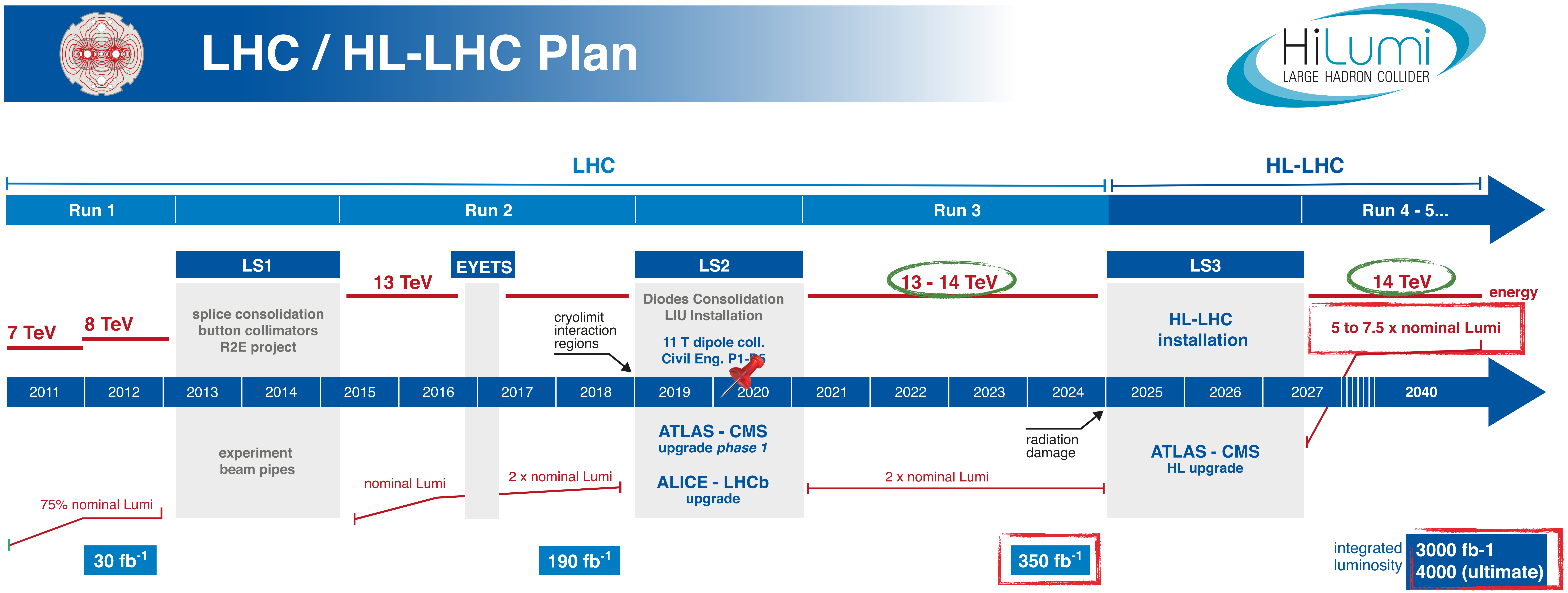
October 2018 run 517 - event 1

250 GeV/c π-



THE HIGH-LUMINOSITY LHC

- In 2027 CERN is intended to start the **H**igh-**L**uminosity **LHC** program:
- **HL-LHC** will integrate **5** (10) **times the instantaneous** (integrated) **luminosity** of LHC:
  - 🆙 **High pile-up rate**: evts/bunch-crossing from ~70 in LHC to O(140/200) in HL-LHC!
  - ☢️ **Unprecedented radiation levels**: doses up to 2 MGy and fluences up to 10^{16} n_{eq}/cm^2



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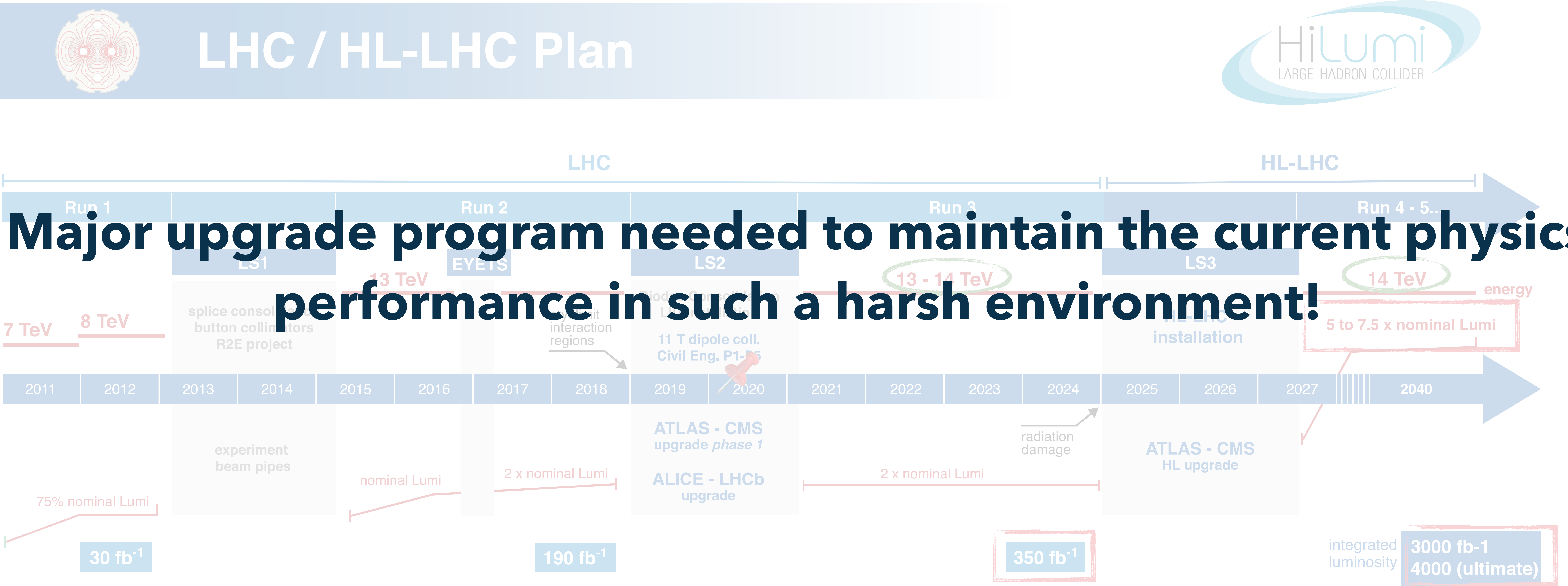
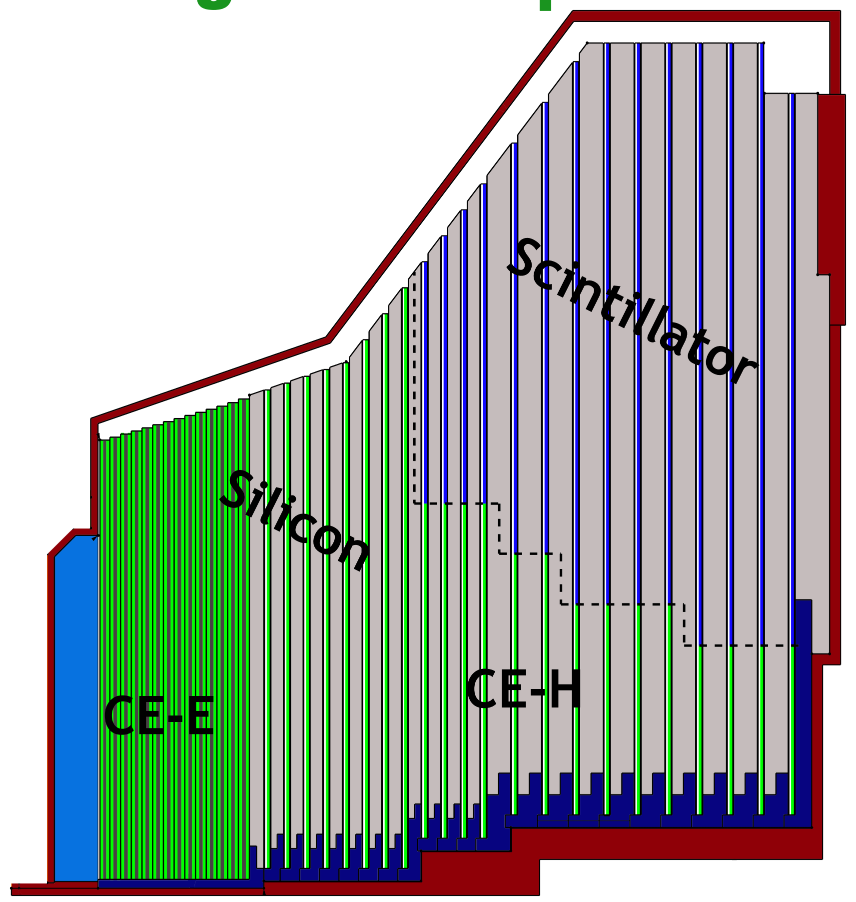


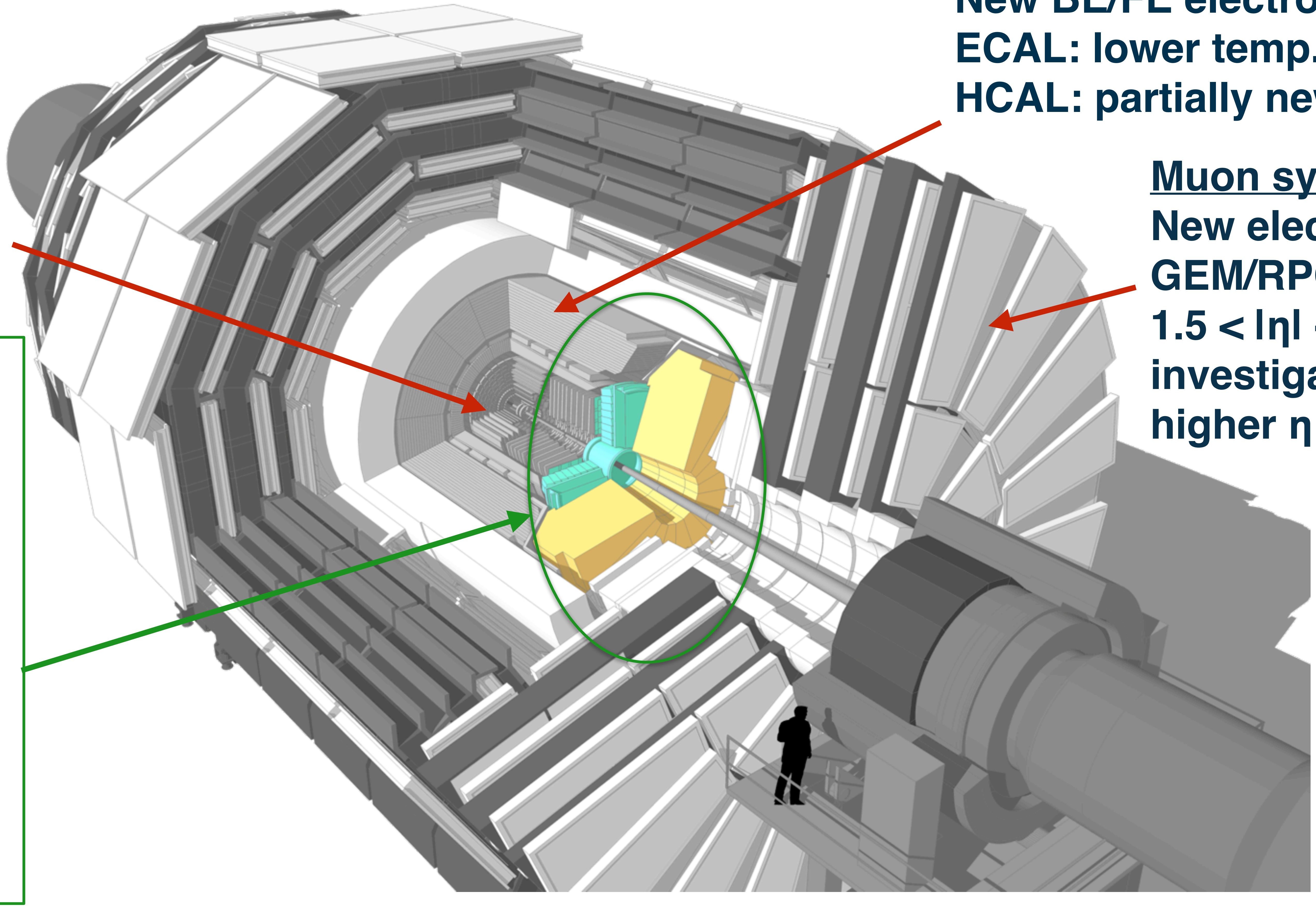
Major upgrade program needed to maintain the current physics performance in such a harsh environment!

THE CMS UPGRADES FOR HL-LHC

Tracker:
Radiation tolerant,
high granularity,
less materials, tracks in
hardware trigger (L1),
coverage up to |η| = 3.8

HGCAL:
Coverage 1.5 < |η| < 3.0





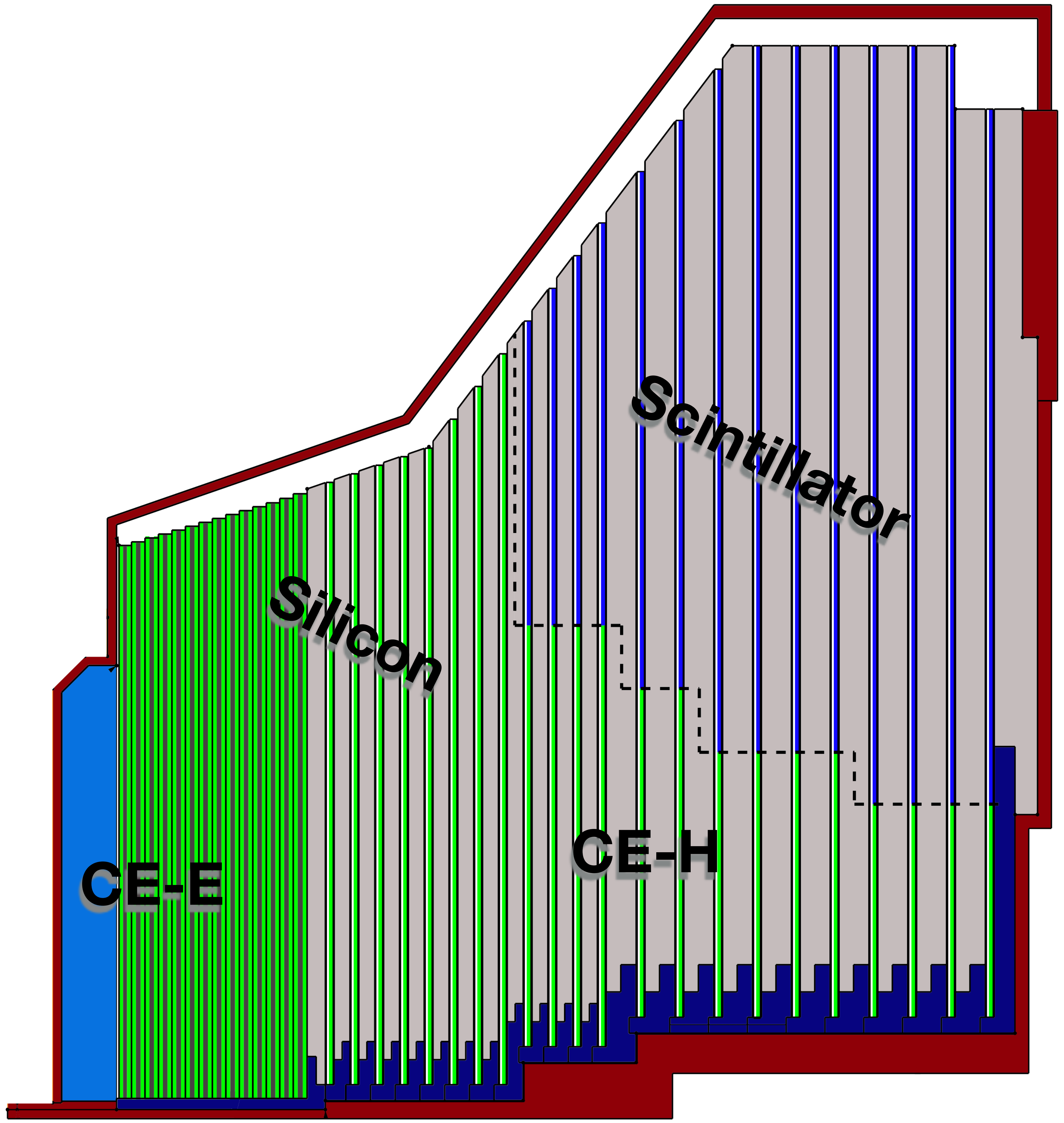
Barrel Calorimeter:
New BE/FE electronics,
ECAL: lower temp.,
HCAL: partially new scintillator

Muon system:
New electronics
GEM/RPC coverage in
1.5 < |η| < 2.4,
investigate muon tagging at
higher η

- 🆙 **High granularity and precise timing to mitigate pile-up**
- ☢️ **Radiation hard detector material to cope with large dose**

HGCAL: A NOVELTY IN CALORIMETRY

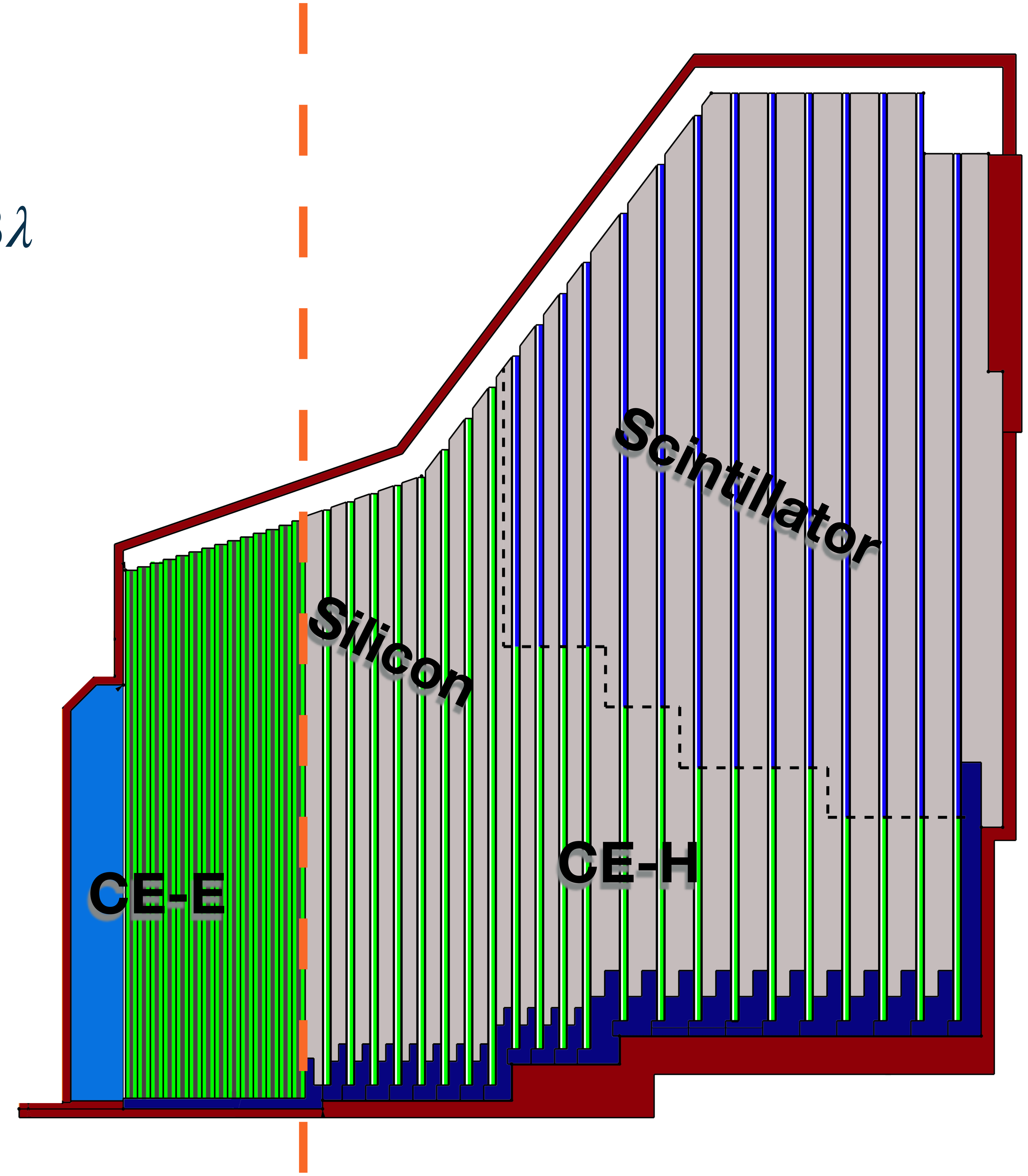
- New **endcap calorimeter** of CMS:
  - Need to replace **ECAL** crystals and **HCAL** scintillators as they were **designed for 500 fb^{-1}**
- **High precision energy measurements**:
  - Missing energy/precision resolution;
- Ideal detector for **Particle Flow**;
- **Particle ID**:
  - Important handle in software compensation;
- Fully utilise **timing** (real novelty in calorimetry!);
- **5D** (*imaging*) **calorimeter**:
  - Energy, time, x, y, z



HGCAL IN NUMBERS

Sampling calorimeter consisting of:

- 28 layers **Si-based** EM compartment (CE-E), ~25X_0 and ~1.3λ
- 22 layers hadronic compartment (CE-H): **Si-based** + Scintillator tiles, ~8.5λ



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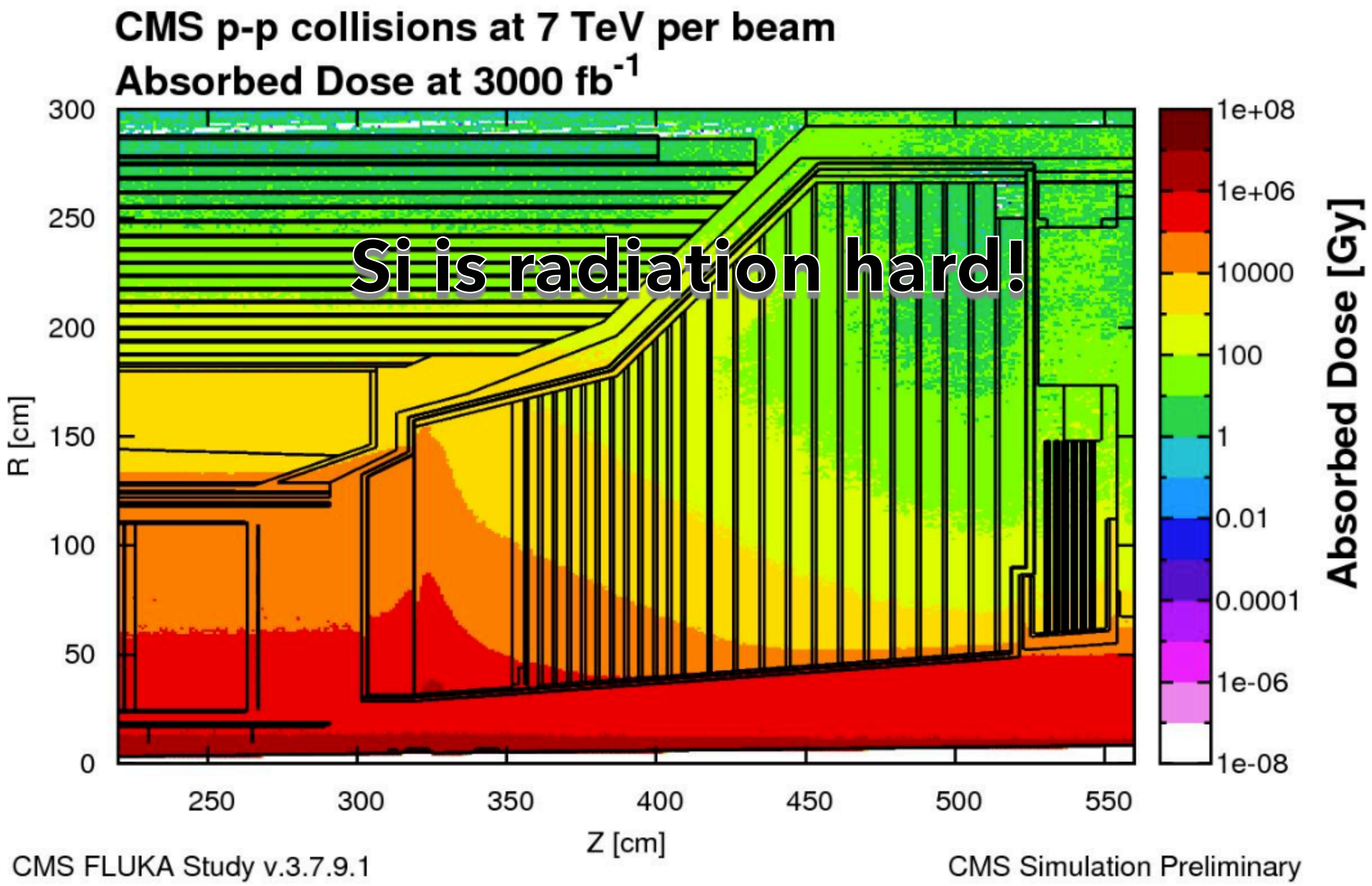

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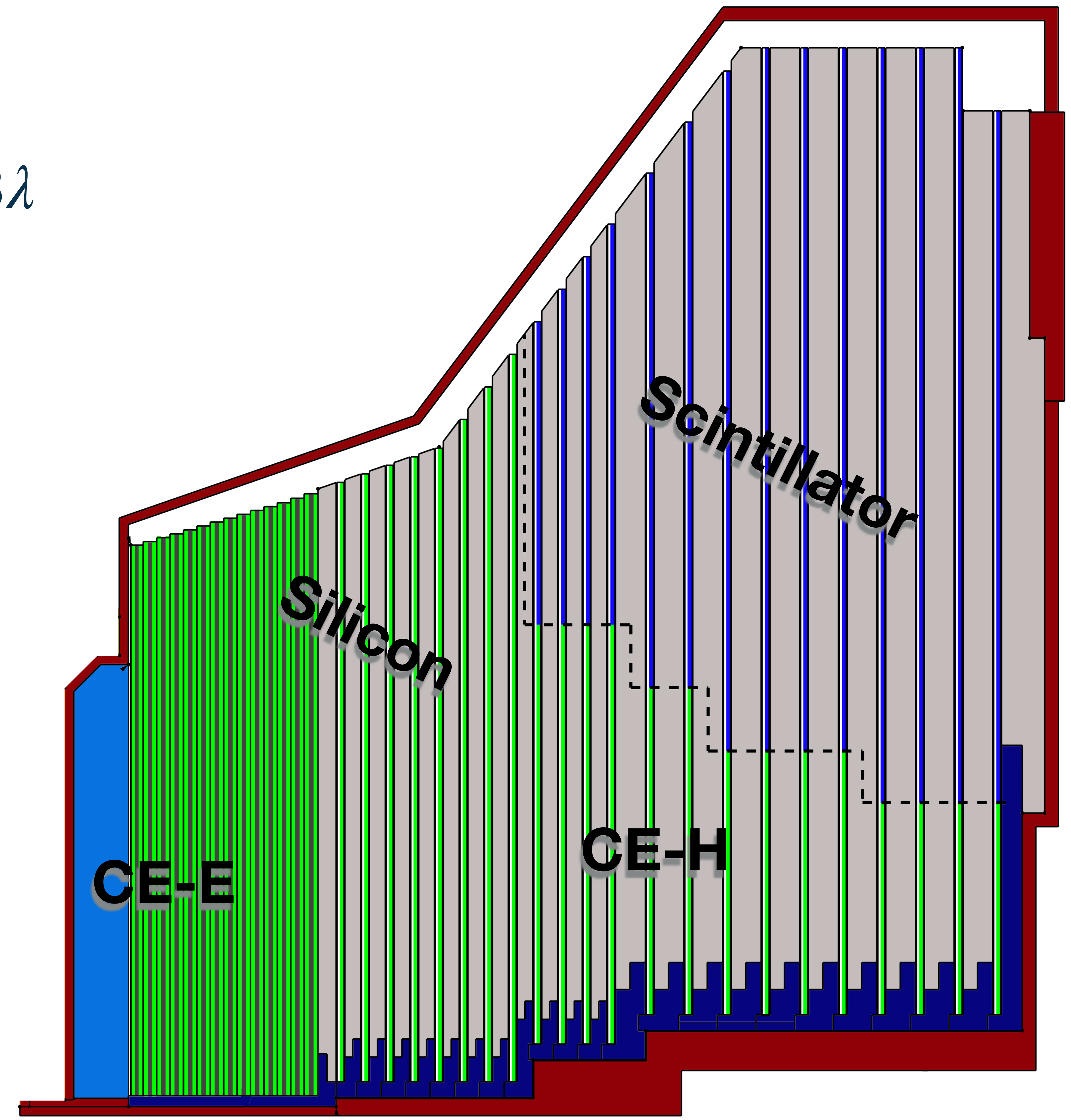
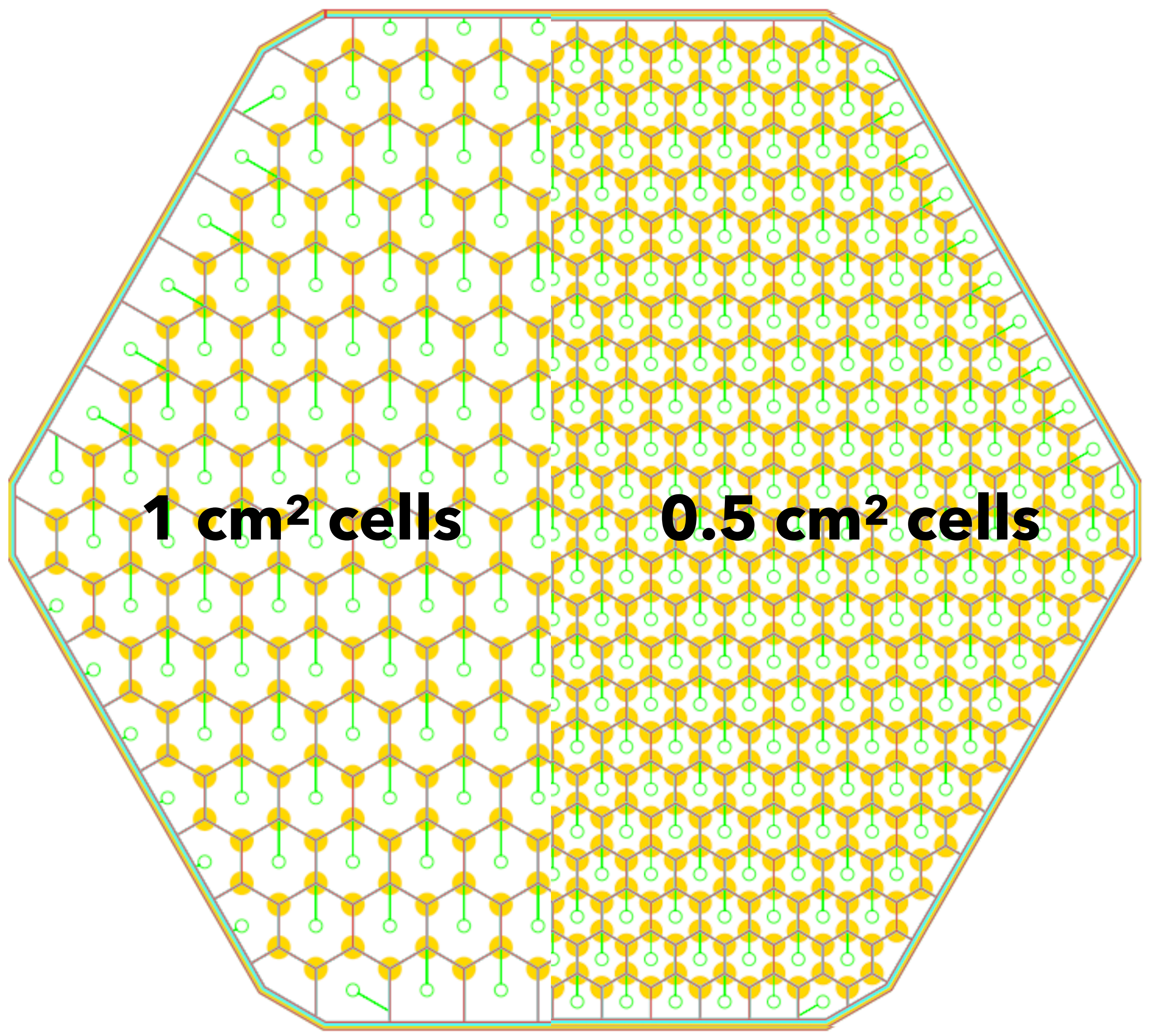
- 28 layers **Si-based** EM compartment (CE-E), ~25X_0 and ~1.3λ
- 22 layers hadronic compartment (CE-H):
  Si-based + Scintillator tiles, ~8.5λ
- Coverage: $1.5 < |\eta| < 3.0$
- **~620 m² Si** sensors in ~30k channels;
- **6M Si channels** of 0.5/1 cm² cell size;
- **~400 m²** of **scintillators** in 4k boards;
- ~240k scintillators channels, 4-30 cm² cell size;
- Operating temperature: -35 °C



HGCAL: THE SILICON MODULES

- **Hexagonal sensors on 8" wafers** for CE-E and CE-H: 300, 200, 120 μm
- **p-type sensors preferred** as more robust against non-Gaussian noise induced by radiation (n-type wafers used for the 300 μm sensors due to lower fluences)
- Sensor cells of **1**(0.5) **cm²** for **300, 200** (120) μm active thickness **silicons**



Active thickness (μm)	**300**	**200**	**120**
Area (m^2)	245	181	72
Largest lifetime dose (Mrad)	3	20	100
Largest lifetime fluence (n_{eq}/cm^2)	0.5×10^{15}	2.5×10^{15}	7×10^{15}
Largest outer radius (cm)	$\approx$180	$\approx$100	$\approx$70
Smallest inner radius (cm)	$\approx$100	$\approx$70	$\approx$35
Cell size (cm^2)	1.18	1.18	0.52
Initial S/N for MIP	11	6	4.5
Smallest S/N(MIP) after 3000 fb^{-1}	4.7	2.3	2.2

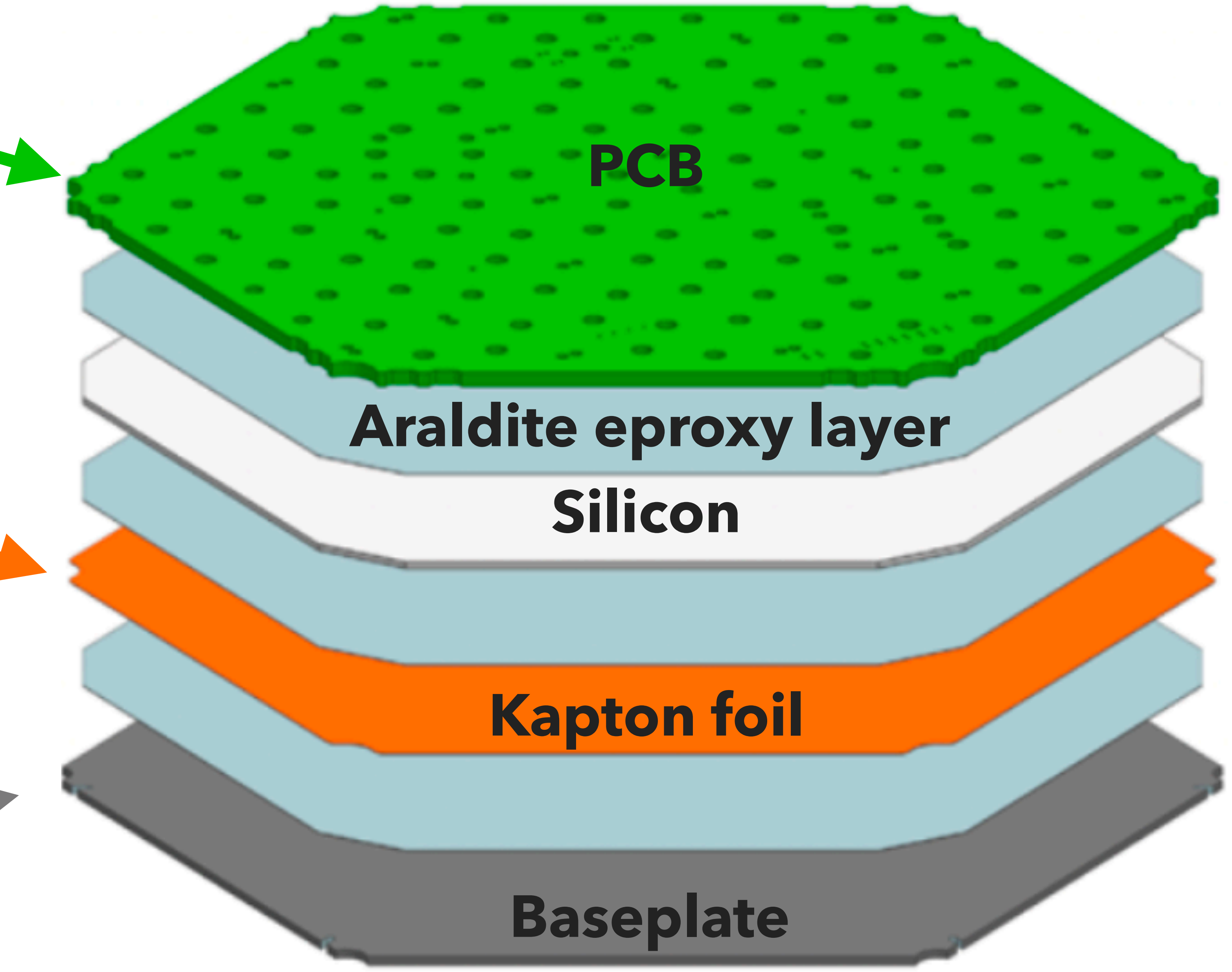
HGCAL: THE SILICON MODULES

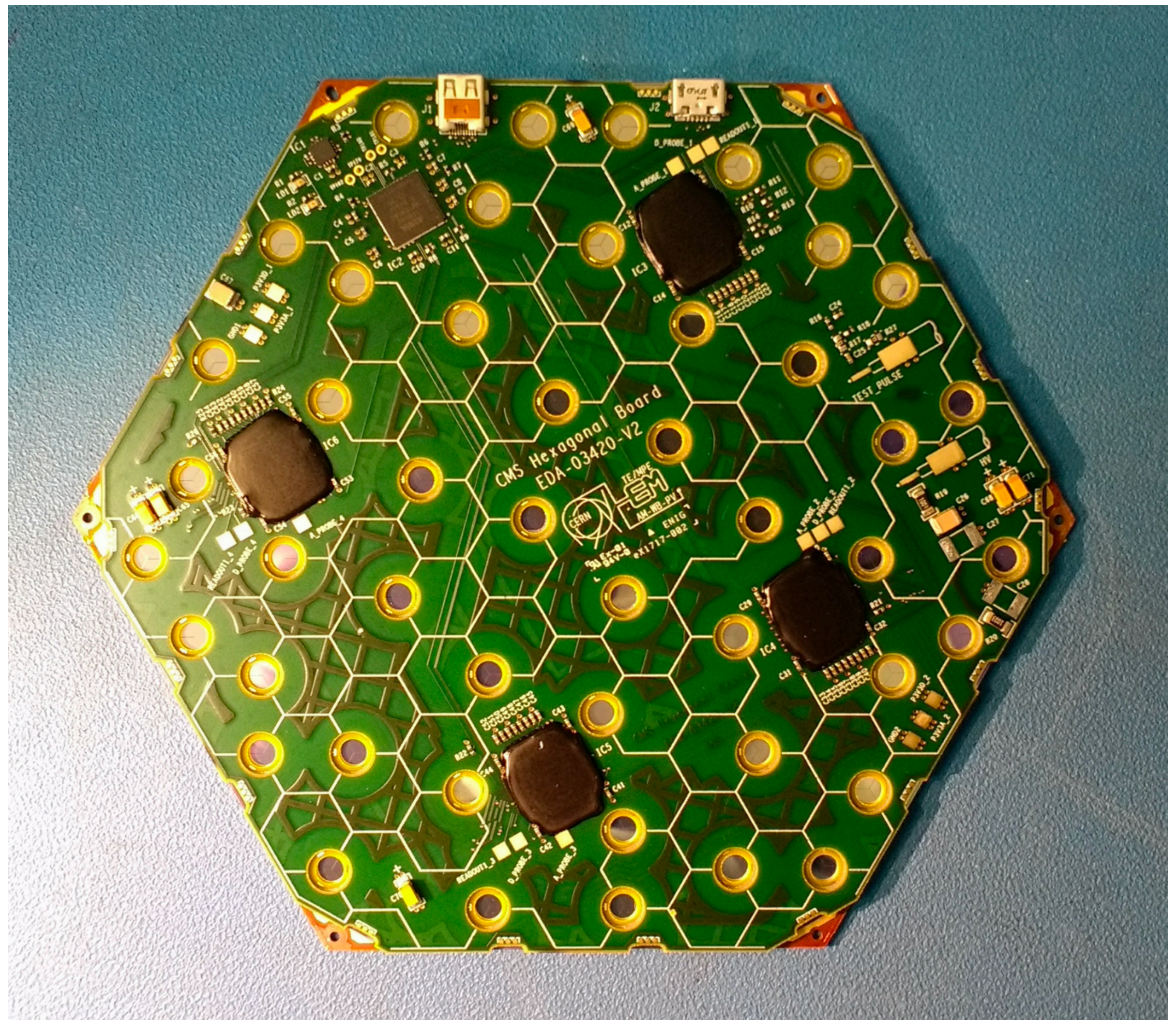
- **~27000 sensors** to be produced and installed in CE-E and CE-H
- **Stack of components**: baseplate (CuW or C fi bre), Kapton sheet, sensor, PCB
- **6" modules** assembled and **used in beam test campaigns**

Hexaboard (PCB)
HGCROC frontend readout ASIC

105 μm **Kapton sheet**
HV connection to sensor back-plane
Electrical insulation from baseplate

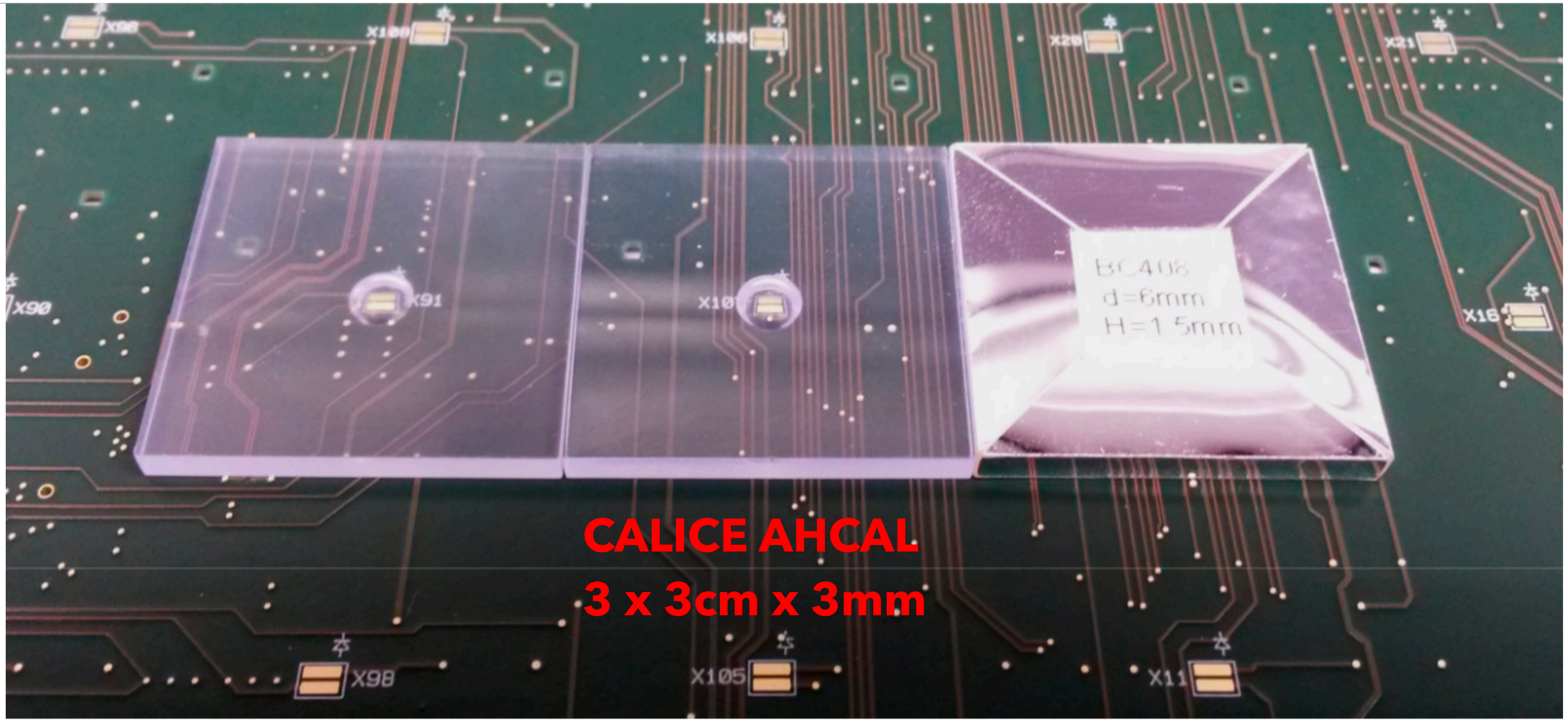
1.40 cm **CuW: Absorber**
Good thermal conductivity
Short radiation-length

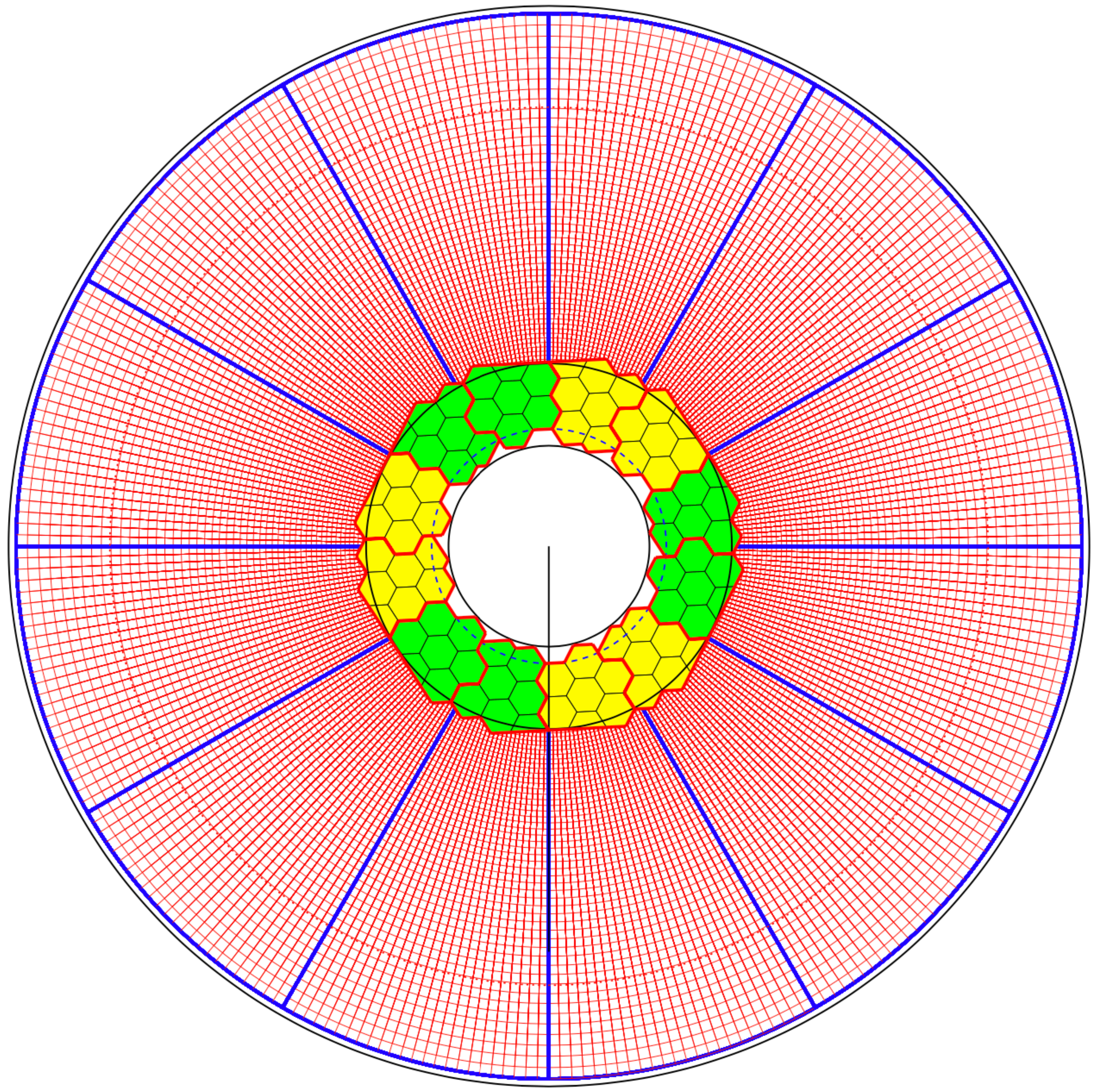




HGCAL: THE SCINTILLATOR TILES

- **Light** from the scintillation tiles **read** by **SiPM photodetectors**: high gain (>10^5) and excellent photodetection efficiency (>30%)
- **SiPM-on-tile geometry**: minimisation of non linearities by uniform light illumination
- Key point: **calibrate individual tiles using MIPs** ⟶ CALICE AHCAL technology





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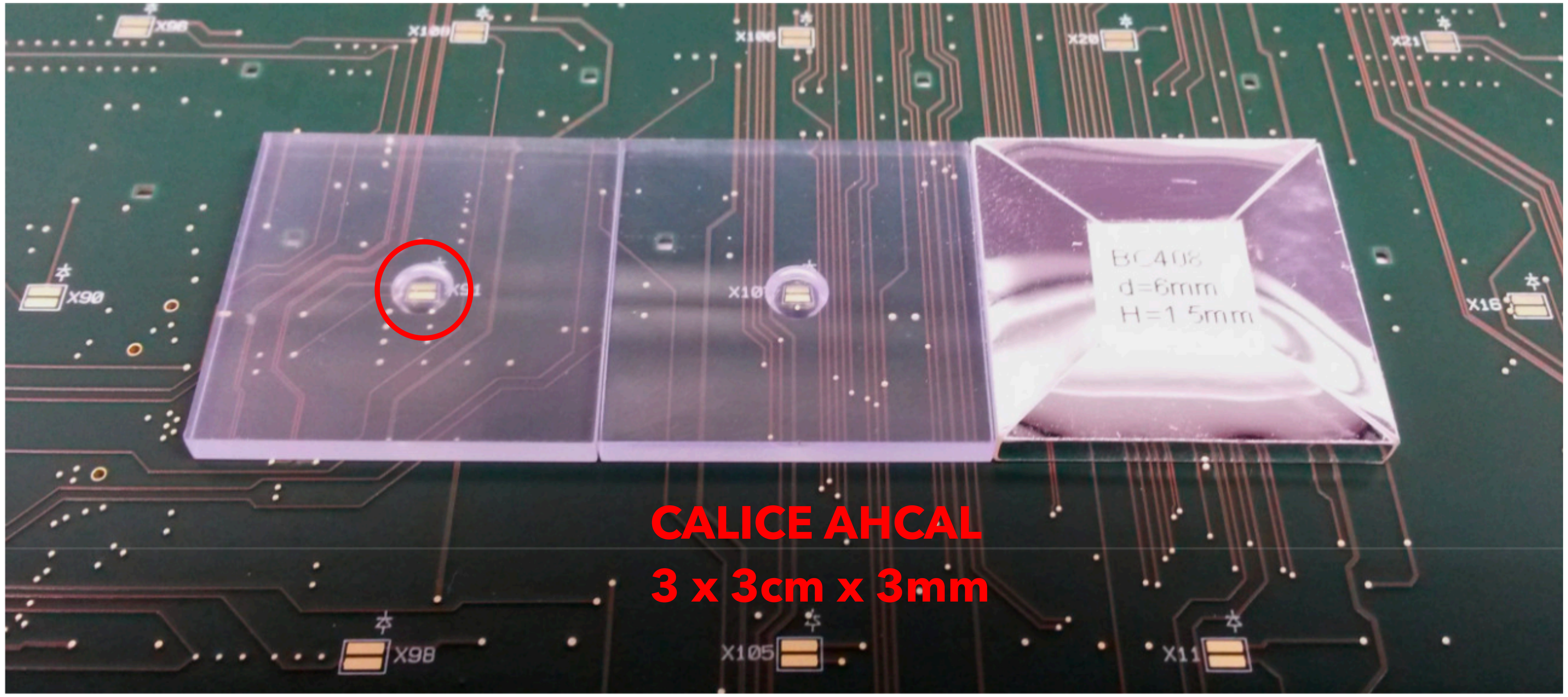

- Direct readout of light from the scintillator tile;
- MIP signal $\propto 1/\sqrt{A_{tile}}$
- Si-Scintillator boundary dictated by **MIP S/N** ≥ 5

FRONT-END (FE) ELECTRONICS: THE HGCROC ASIC

"***Precision measurement of time of high energy showers***: to obtain precise timing from each cell with a significant amount of deposited energy, aiding **rejection of energy from pileup**" [1]

[1] From HGCAL TDR, "Requirements of the HGCAL upgrade"

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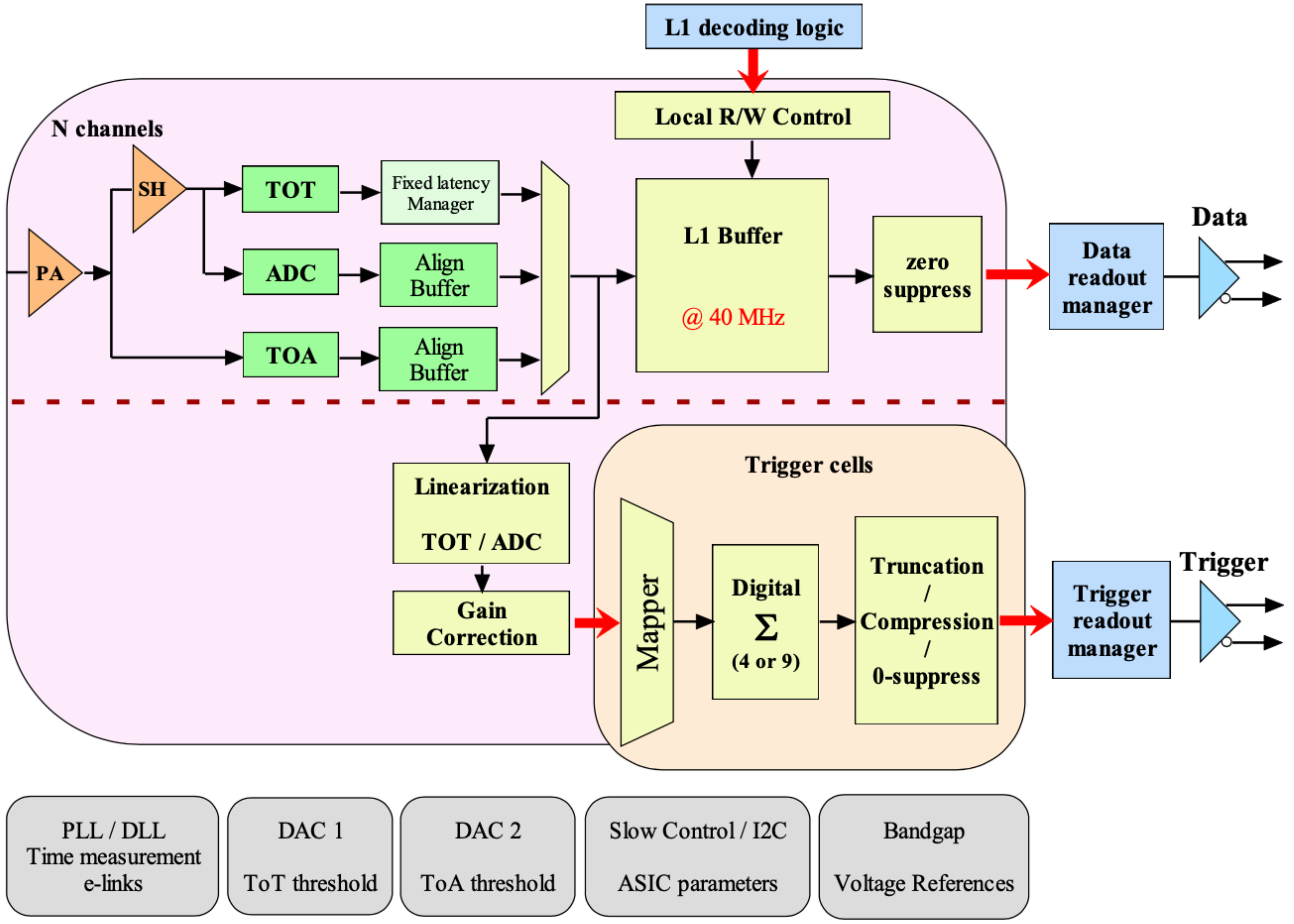
"***Precision measurement of time of high energy showers***: to obtain precise timing from each cell with a significant amount of deposited energy, aiding **rejection of energy from pileup**" [1]

- Expected **timing resolution** of **O(20) ps** for an energy deposit equivalent to 50 fC (12 MIPs)
- **Stringent requirements** on the FE electronics: low noise, large dynamic range, fast shaping time, compatibility with pos/neg pulses …
- Measurement of Time-over-threshold (**TOT**) , Time-of-arrival (**TOA**) and **ADC** (low/high gains) stored at **40 MHz** (+ possible acceptance by L1 trigger)
- **HGCROC** comprises **78 channels** and it is designed in a **radiation-hard 130 nm CMOS technology**



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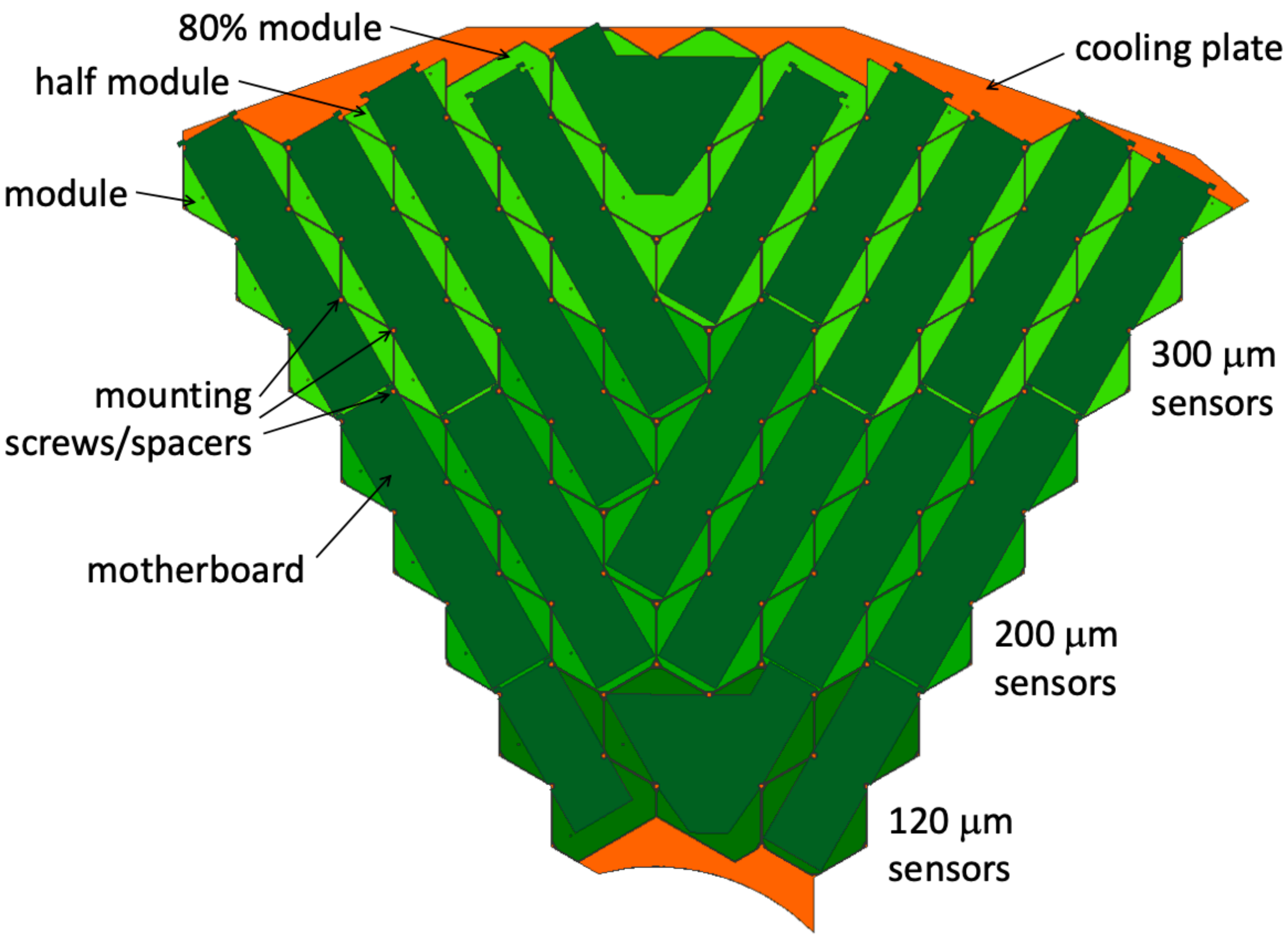
MECHANICS: THE CE-E CASSETTES

- **Wedges 60° wide** provide the support of the electromagnetic compartment modules;
- **Silicon detectors** on both sides of **central copper cooling** (CO_2) **plate** and incorporate **stainless steel-clad lead absorbers** layers into the covers of the two sides;
- HGCAL is a sampling calorimeter: cooling plate + CuW baseplates form one absorber layer, while stainless steel-clad lead plates form the other;
- Each endcap contains 84 cassettes.



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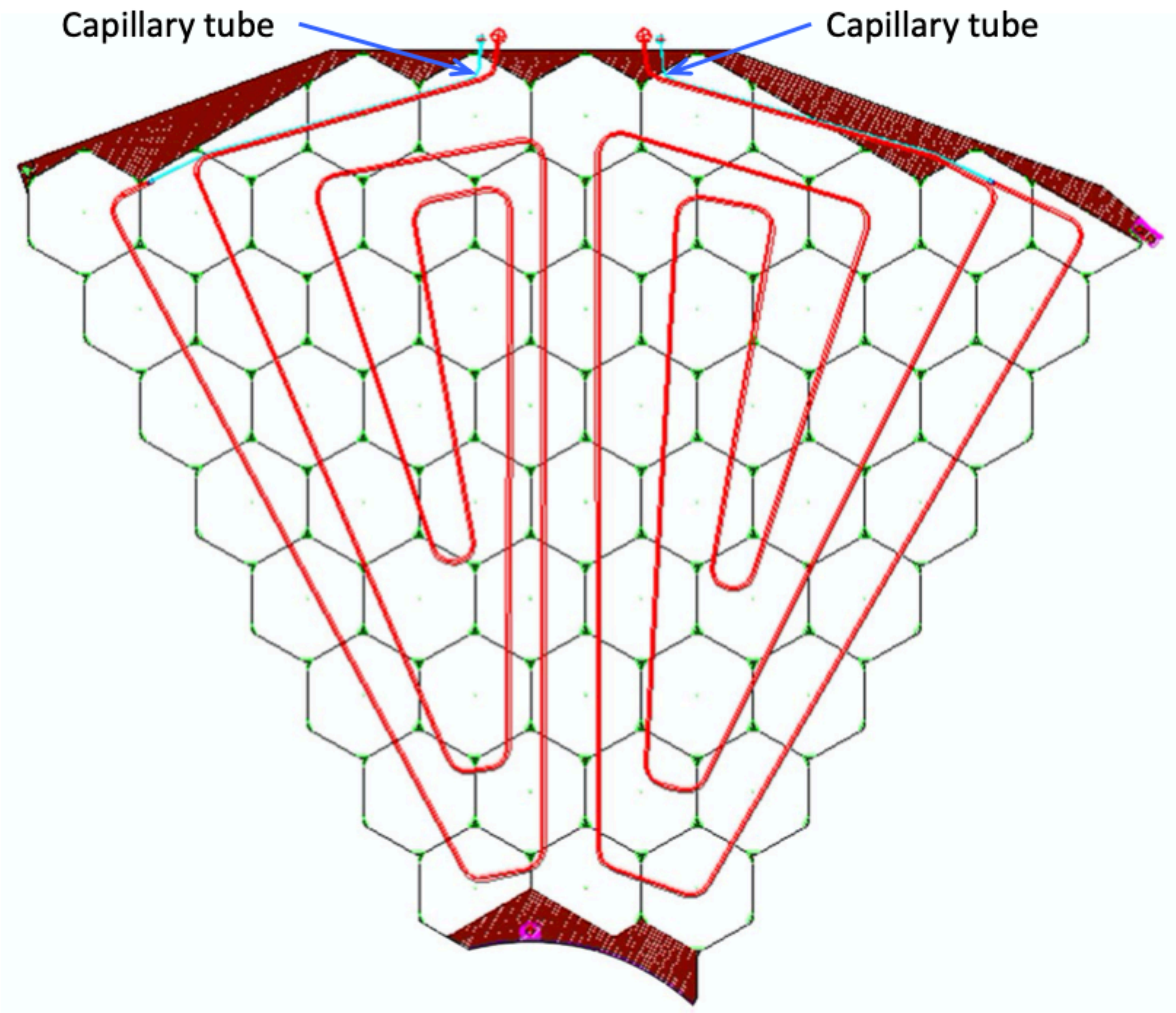
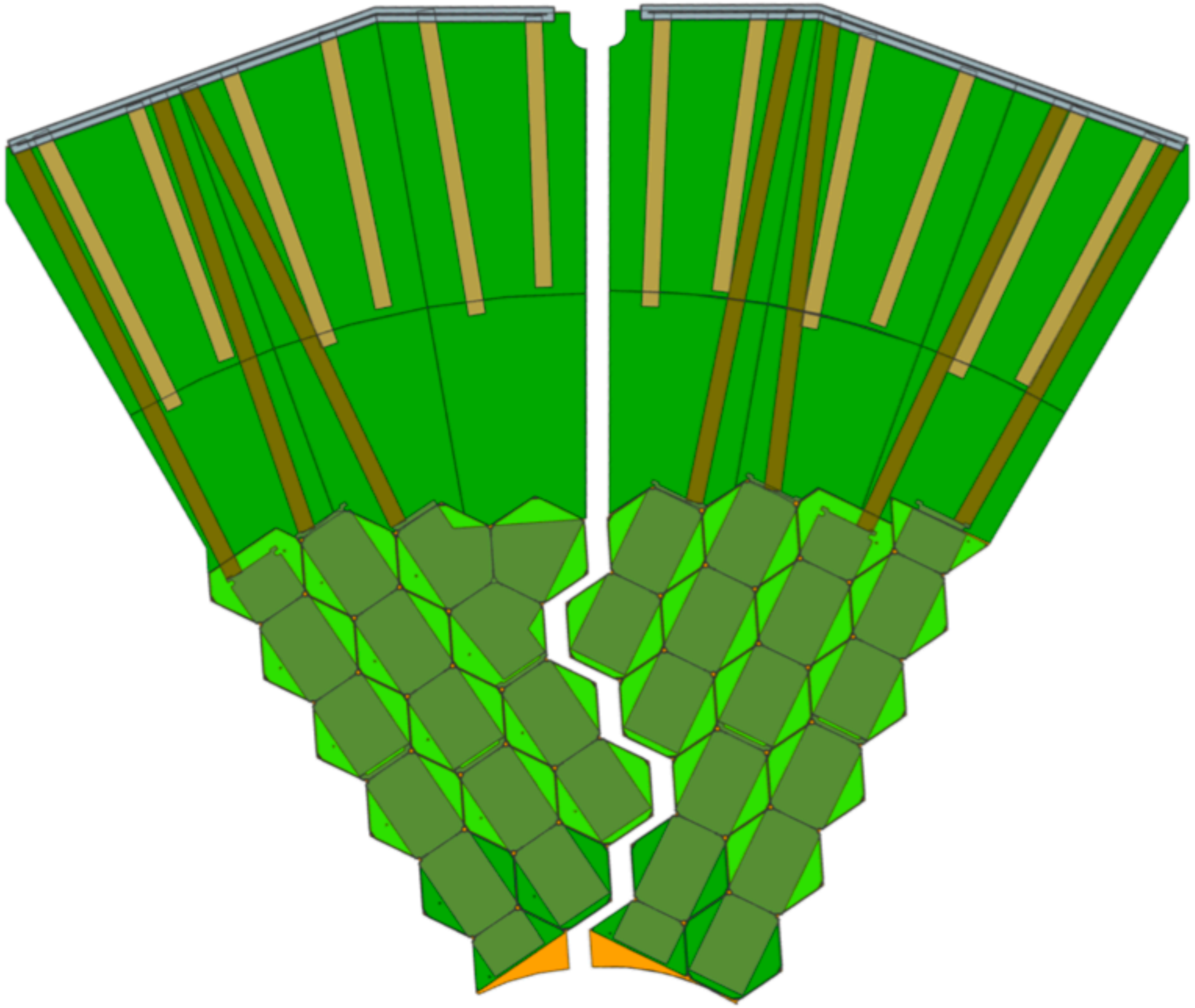


Cooling system on CE-E cassette

MECHANICS: THE CE-H CASSETTES

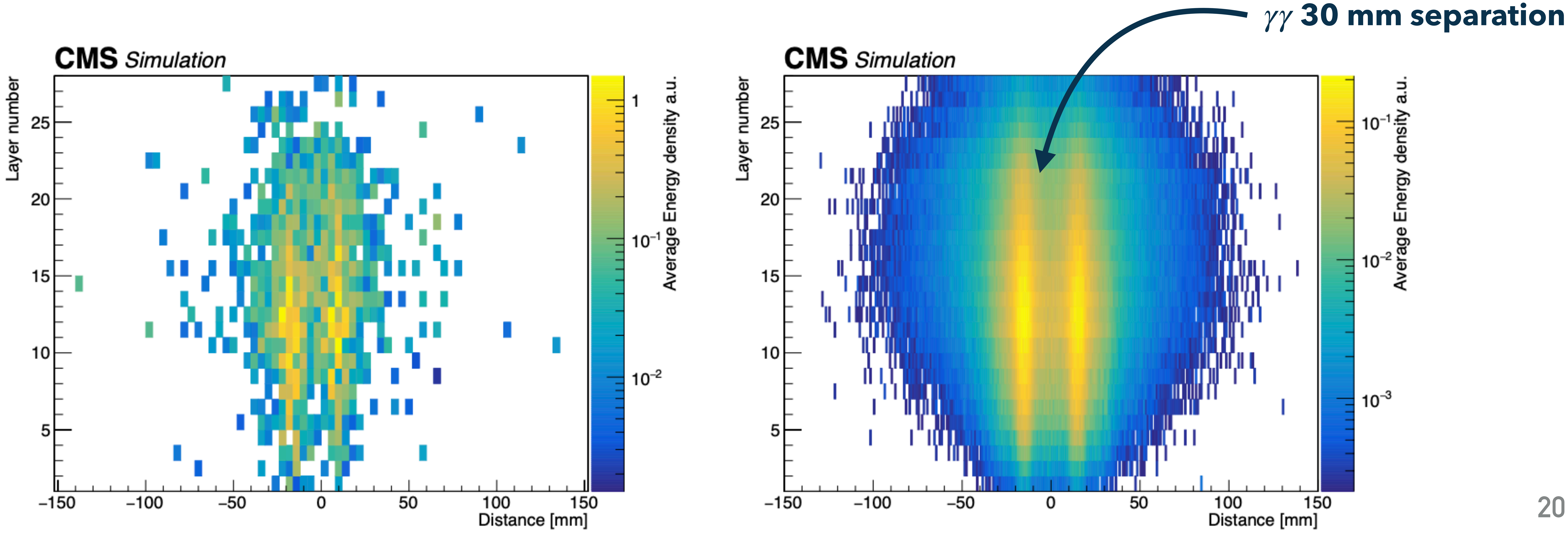
- **Wedges 30° wide** provide the support of the hadronic compartment modules;
- **Active elements** only **on one side** of the copper cooling plate;
- **Independent of the absorber** and the mechanical structure;
- Two different varieties:
  - All-silicon;
  - Mixed with Si-modules and scintillators/SiPM tiles;
- First 8 layers of CE-H with similar structure to CE-E cassettes. From layer 9 to 24, 40% to 90% scintillator fraction.



PHYSICS PERFORMANCE

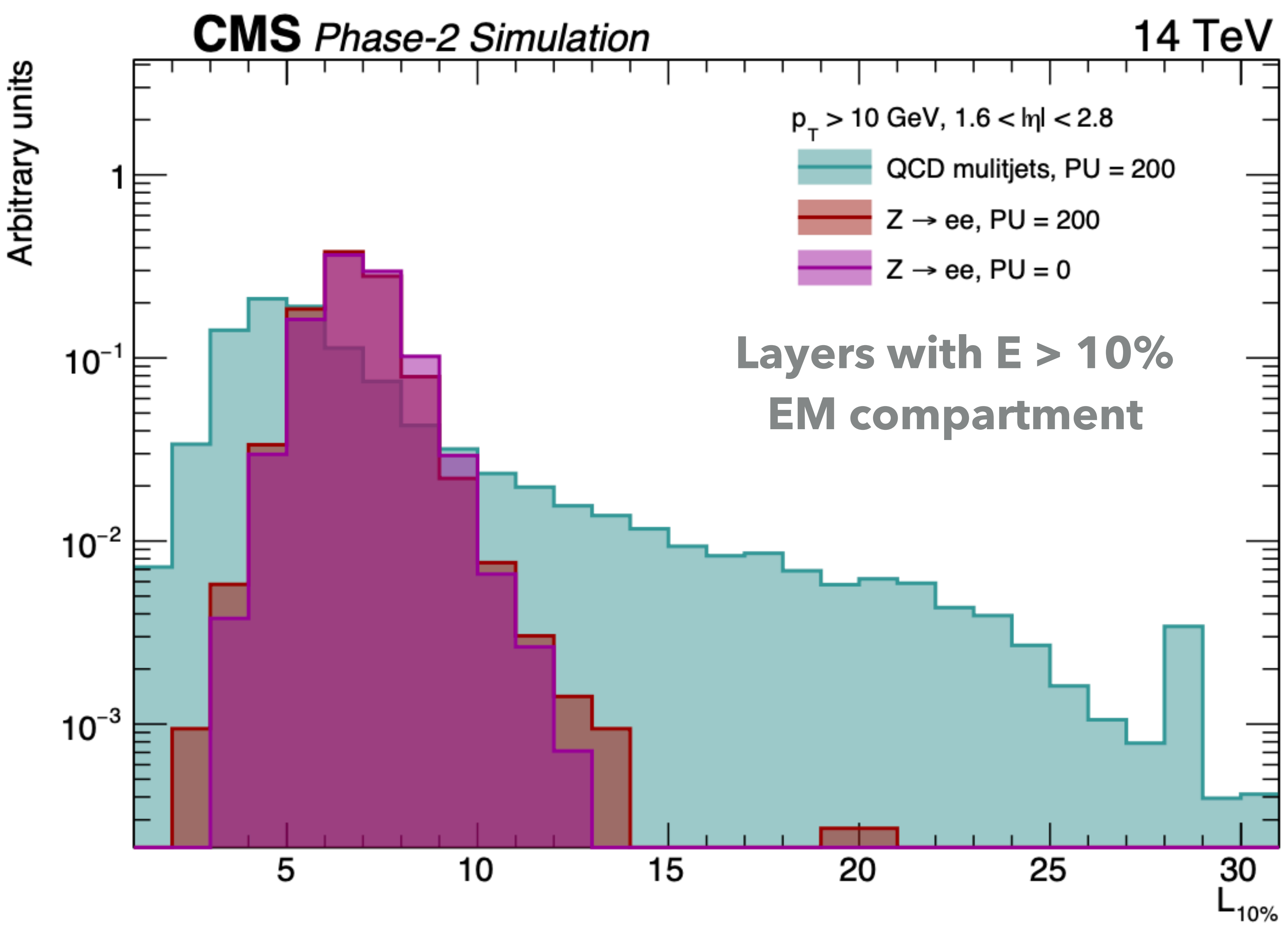
HGCAL: A PARTICLE-FLOW DETECTOR

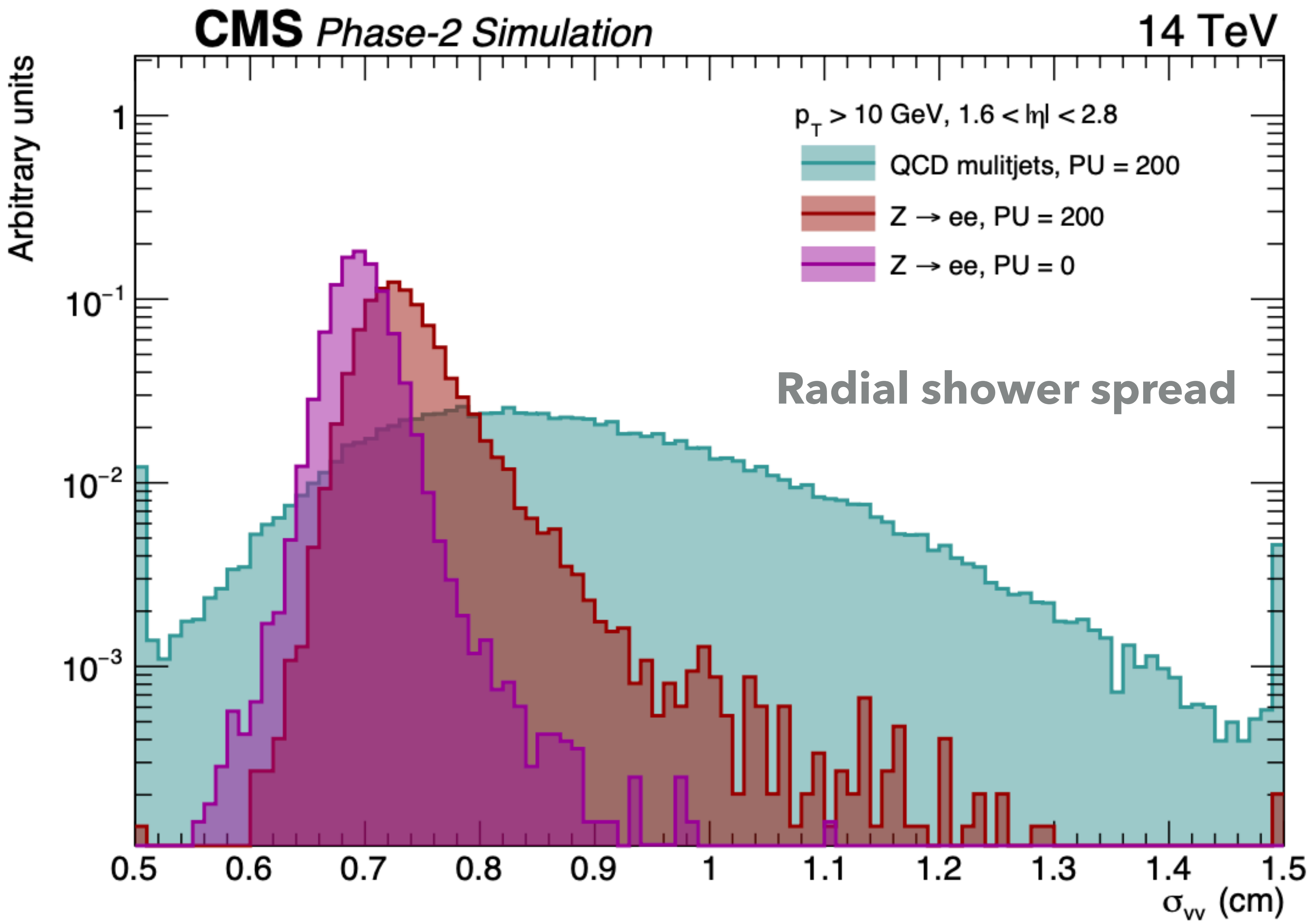
- The fine granularity (longitudinal and transversal) and the timing information (**5D/imaging detector**) make **HGCAL** an **ideal detector for PF**
- The first step in reconstruction is **clustering** of the hits:
    - Reconstruct **2D clusters** in **each layer** exploiting energy density;
    - **Collect** them into **3D cluster** (*multicluster*).



HGCAL: A PARTICLE-FLOW DETECTOR

- Principal component analysis (**PCA**) to **identify** the **main shower axis**;
- Identification of **variables** with **high discriminating power** also in presence of large PU;
- **Electrons ID using BDT** trained with $Z \rightarrow e^+e^-$ as signal, to discriminate against jets





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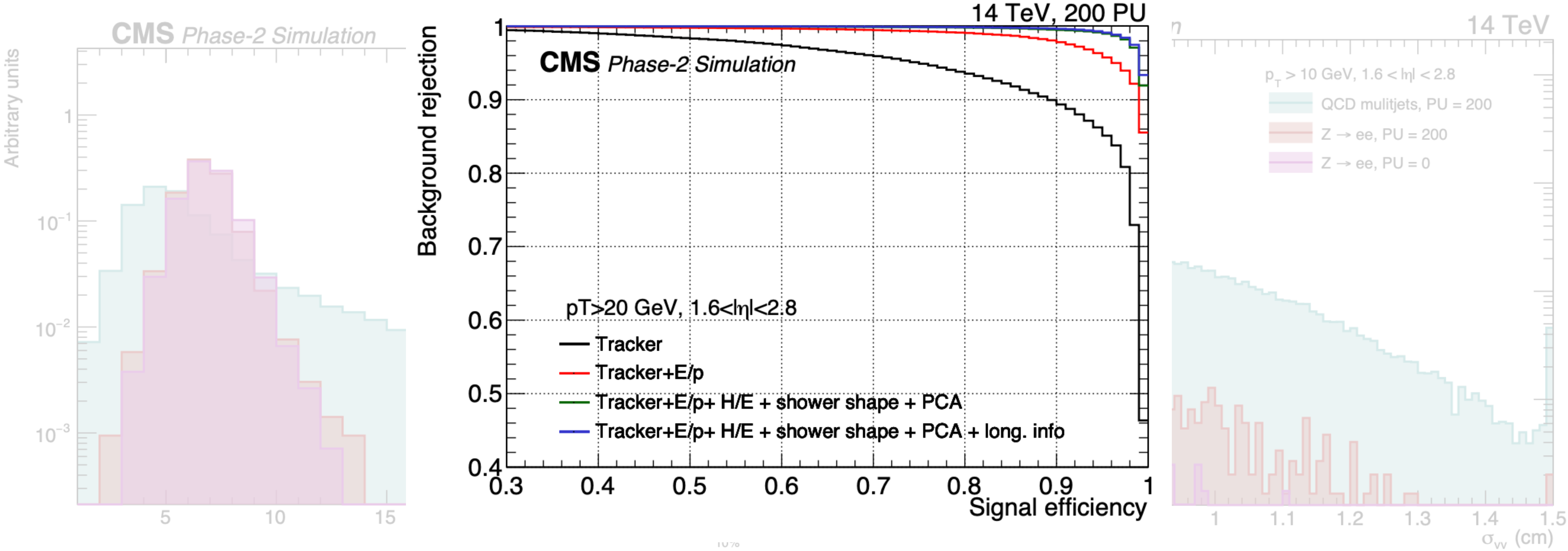
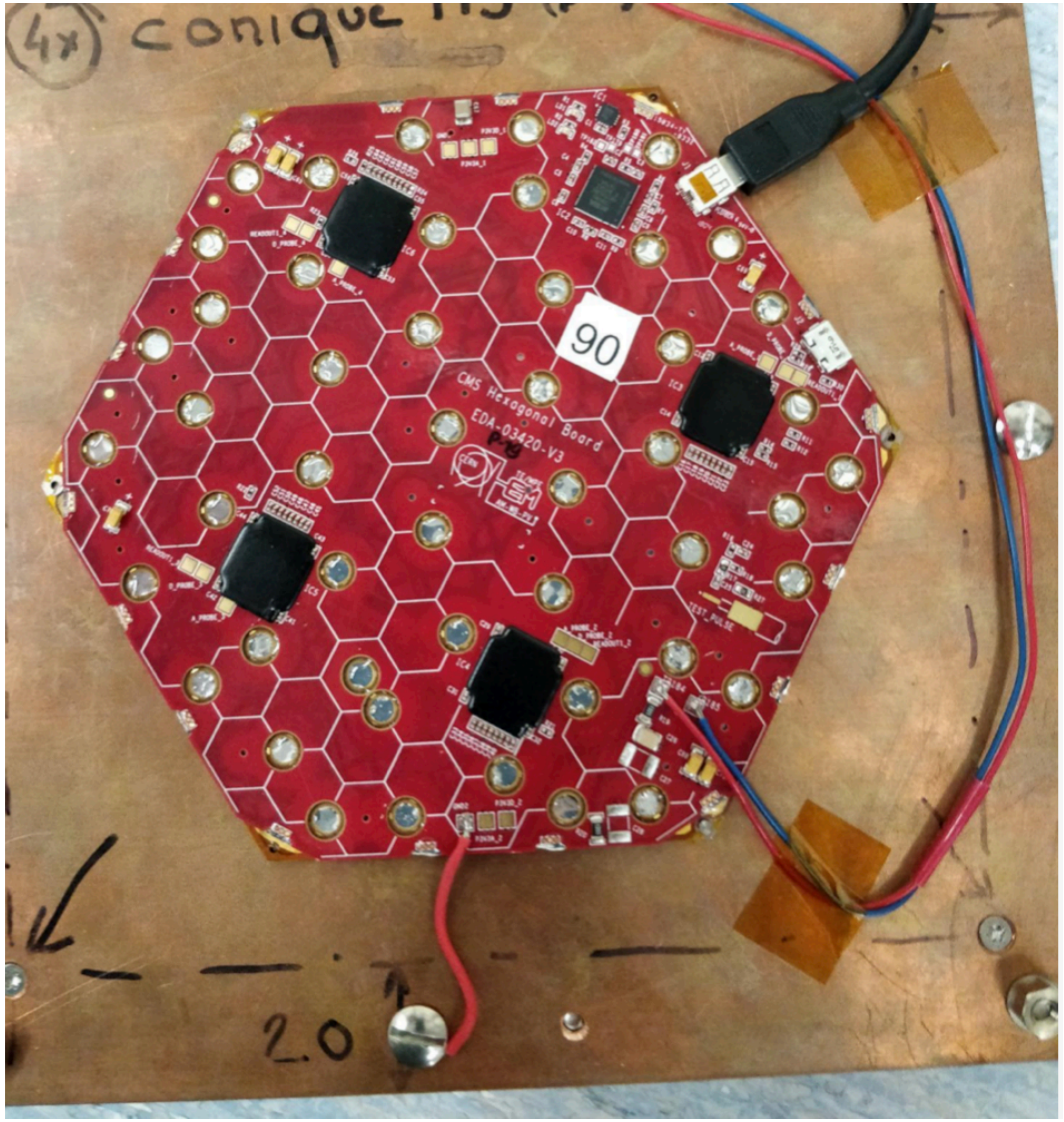


BEAM TESTS

BEAM TESTS OF HGCAL

- **Validation** of the **detector design** and study of the **physics performance**;
- **Detailed comparisons with MC simulation**;
- For beam tests, **6" modules** were used;
- 300 and 200 μm sensors tested;
- **SKIROC2-CMS ASIC**:
  - Validated by CALICE collaboration;
  - **TOT** and **TOA** information;
  - ADC with high/low gains;



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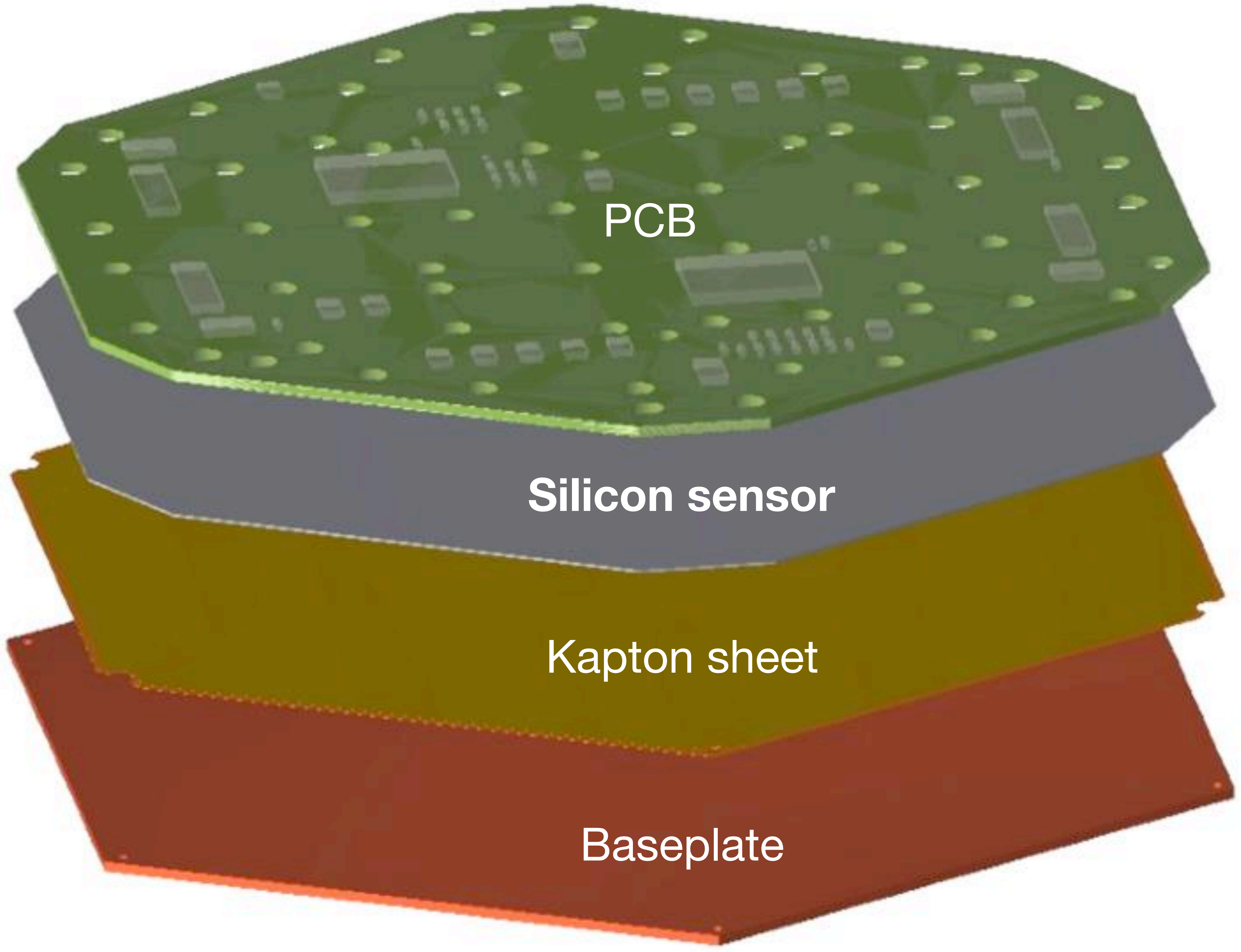
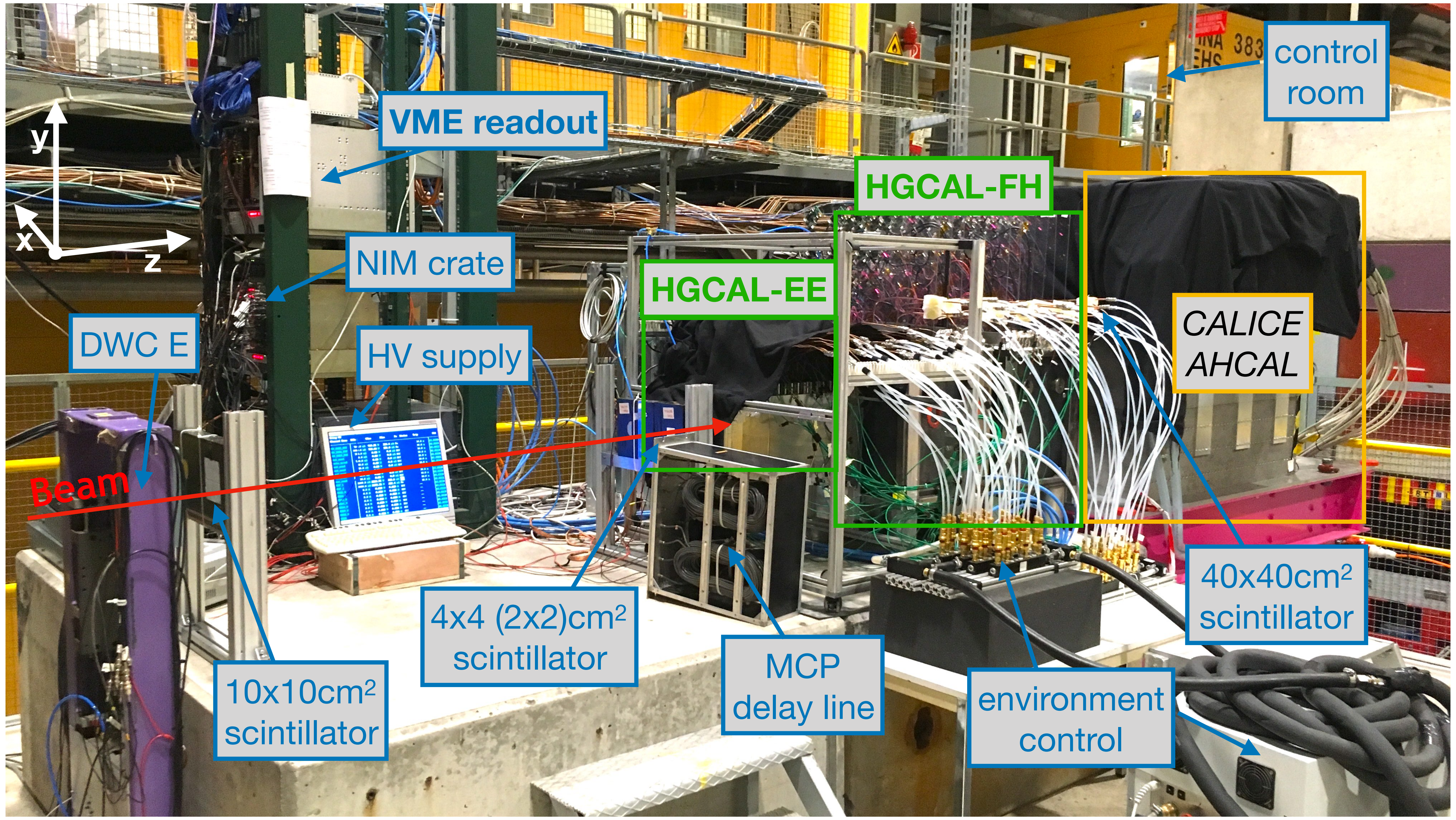


OCTOBER 2018: BEAM TEST @CERN-SPS

🎖 LHCC milestone

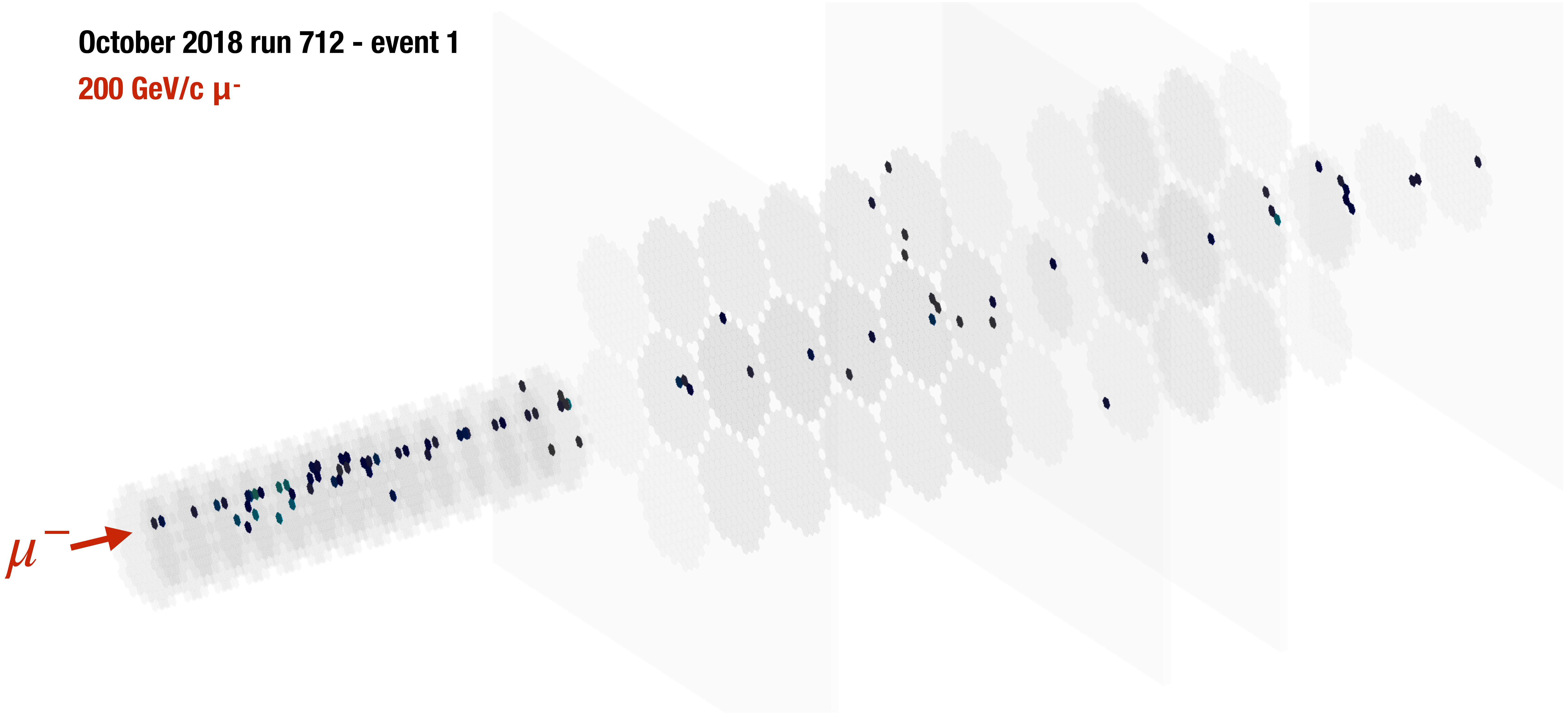
- **First large scale prototype**
  - 28 layers CE-E
  - 12 layers CE-H
  - 39 layers CALICE AHCAL
- **Calibration** of the detector **with MIPs** and showers;
- **Physics performance** : e^+ **and** π^- over a wide energy range (20-300 GeV);
- **Timing performance** from TOA.



O(10^6) events collected!

CALIBRATION WITH MIPs

Due to their **negligible energy loss** compared to particles of initial momenta of multiple GeV/c, the *amount of energy deposit per distance* can be regarded as *independent on the calorimeter depth*. Hence MIPs are suitable to **equalise the electric response throughout the detector.**



CALIBRATION WITH MIPs

The primary method of establishing the sensor inter calibration *and maintaining it over time, following the slow changes in charge collection efficiency over the duration of the HL-LHC,* ***will use signals from minimum-ionizing particles.*** [1]

[1] From HGCAL TDR, "Calibration and Monitoring"

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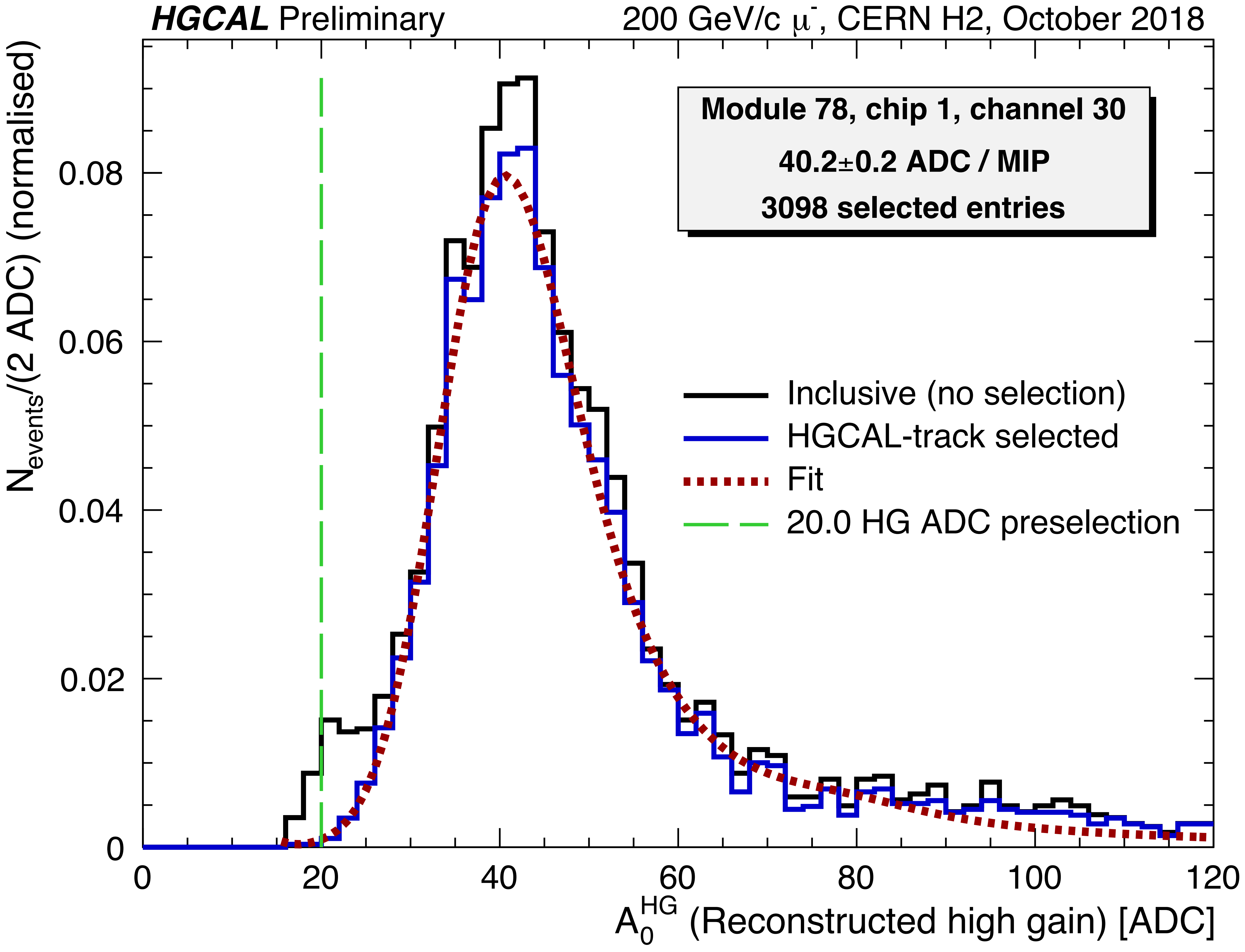
- **HGCAL prototype used for tracking** of MIPs and consequent reconstruction;
- Retrieve the MPV of the MIP signals from Landau x Gauss fit of the distributions;
- In October **85% of the cells** were calibrated;
- **S/N = 8** for high-gain in **300 μm sensors** and S/N = 5 for high gain in 200 μm sensors.



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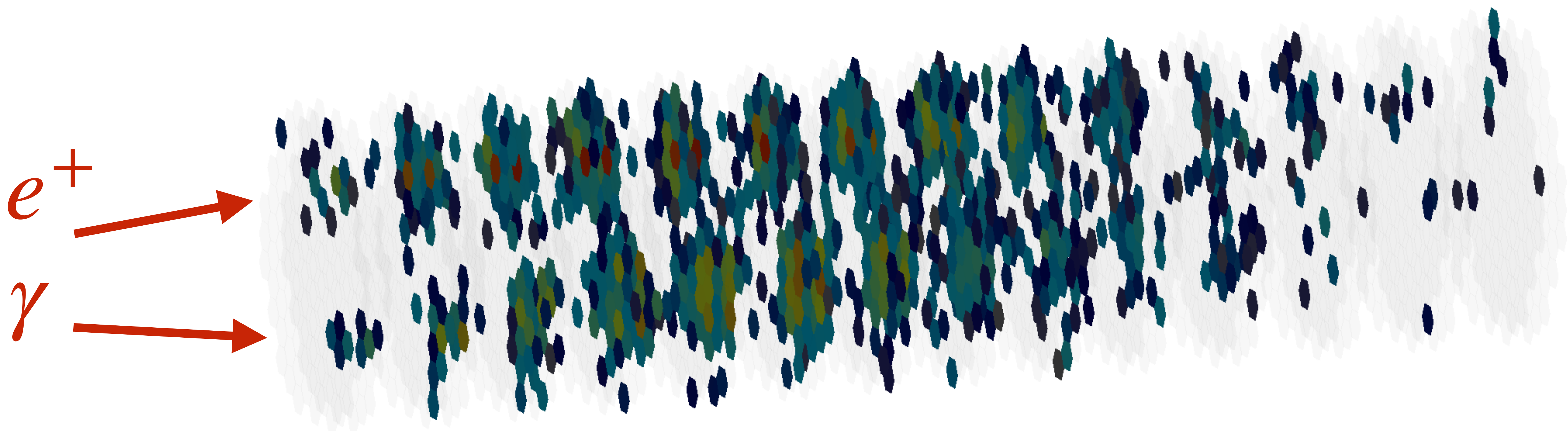
PHYSICS PERFORMANCE: ELECTRONS IN CE-E

June 2018 run 407 - event 1

150 GeV/c e+

Single electron + brem. photon

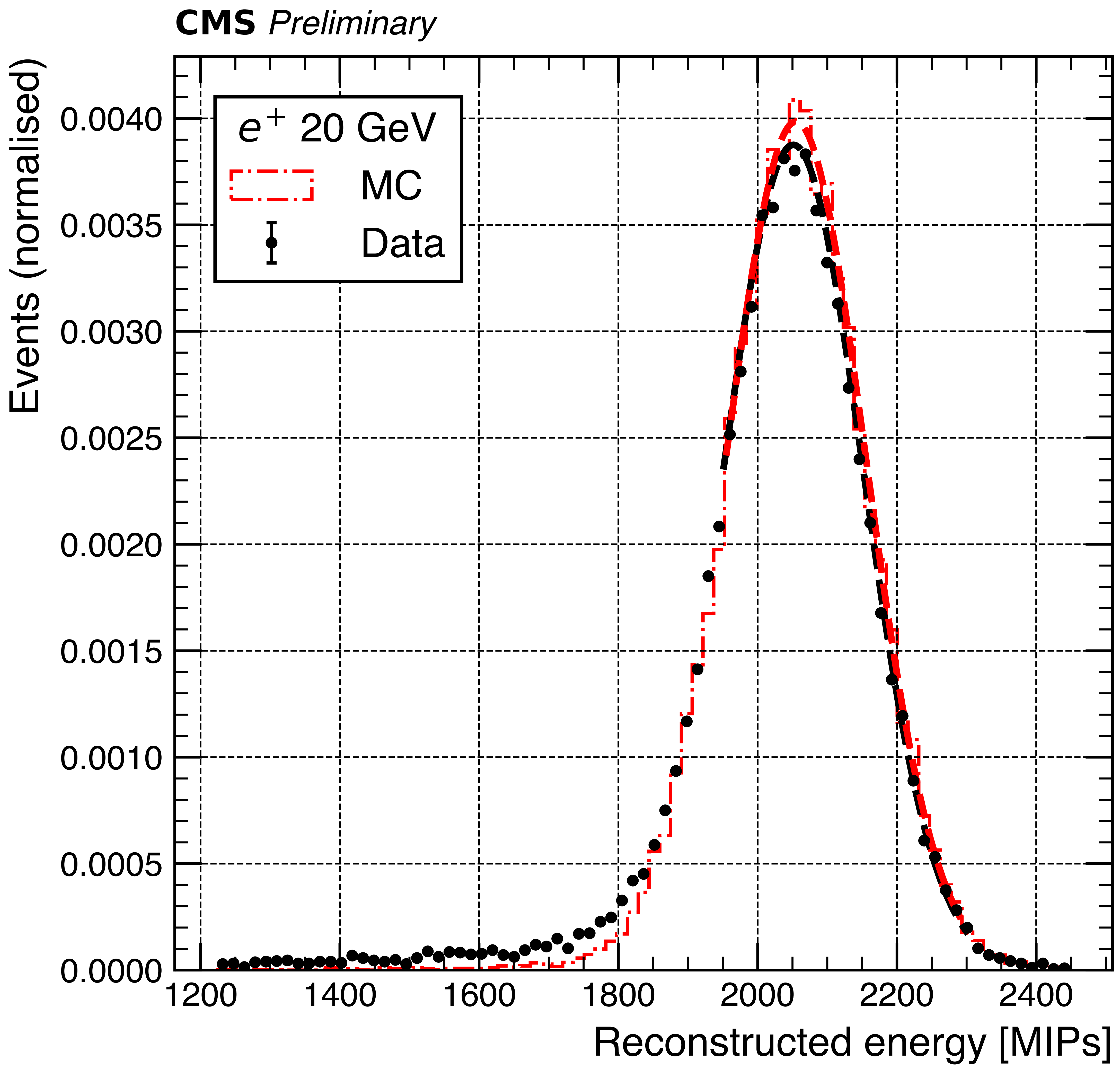


Fine longitudinal and transverse granularity make HGCAL an **imaging calorimeter**

It has a **great separation power** allowing the identification of multiple tracks, e.g. **showering electron**(s) **accompanied** by a hard **bremsstrahlung photon**.

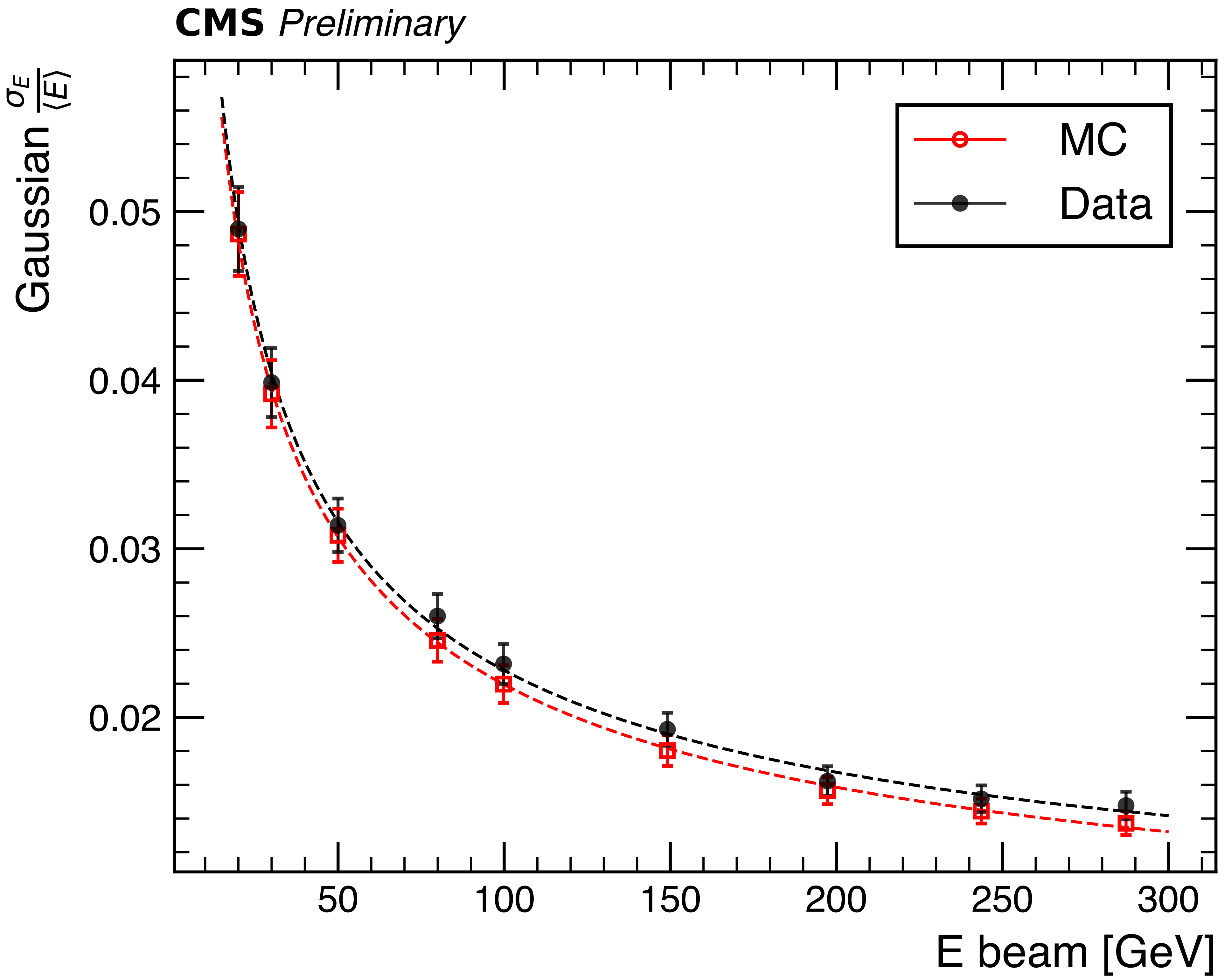
PHYSICS PERFORMANCE: ELECTRONS IN CE-E

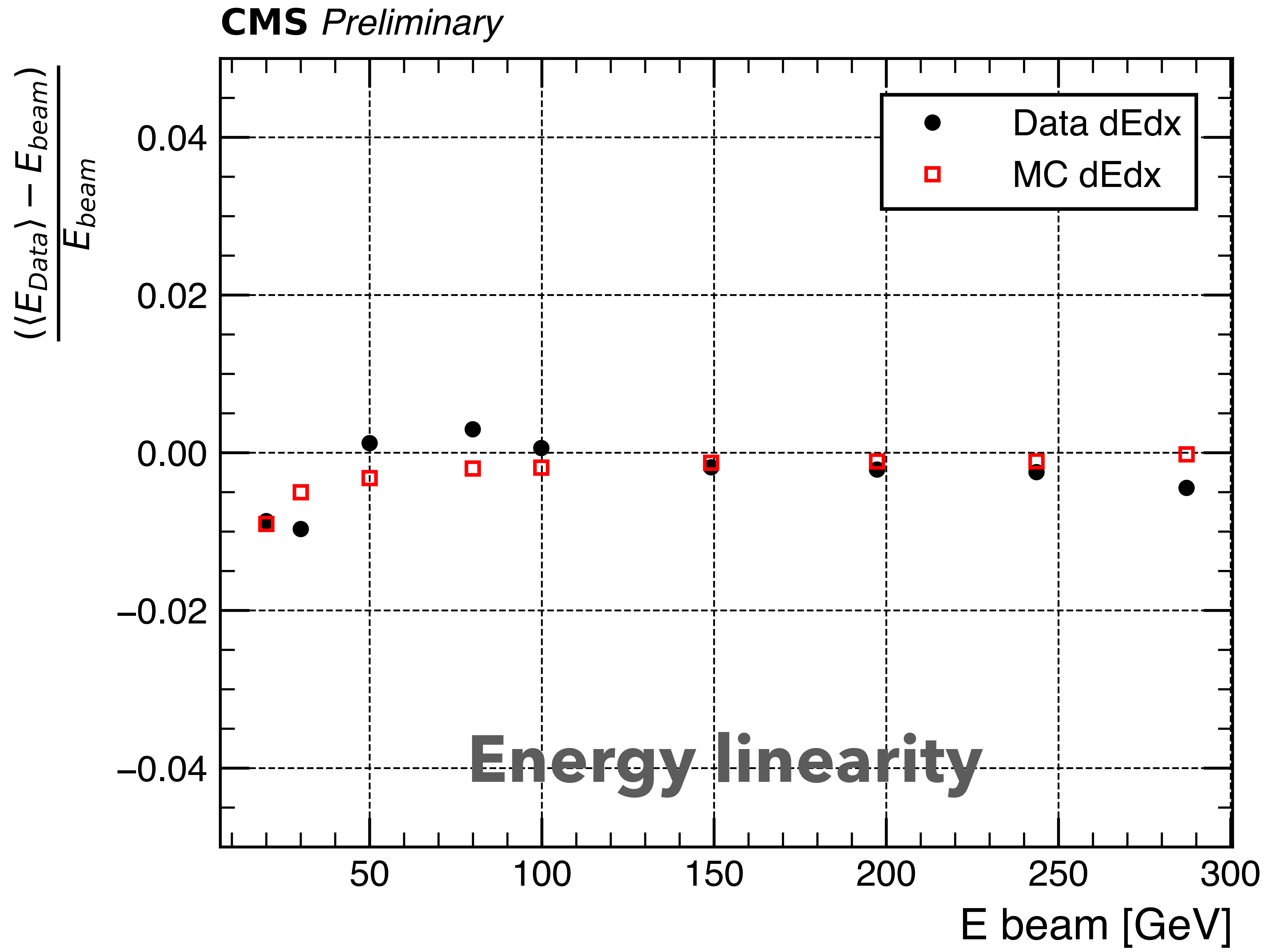
- **Different reconstructions** studied: **MIPs** inter-calibration, **dE/dx weights**, sampling fraction method (**SF**);
- **Energy distribution as** unclustered energy **sum** of the deposit **in all Si-pads**;
- **Gaussian fit** around the core region to retrieve the MPV and the σ of the distribution, used **to determine the energy resolution** $\sigma_E / \langle E \rangle$
- **Good Data/MC agreement** throughout the full energy range;



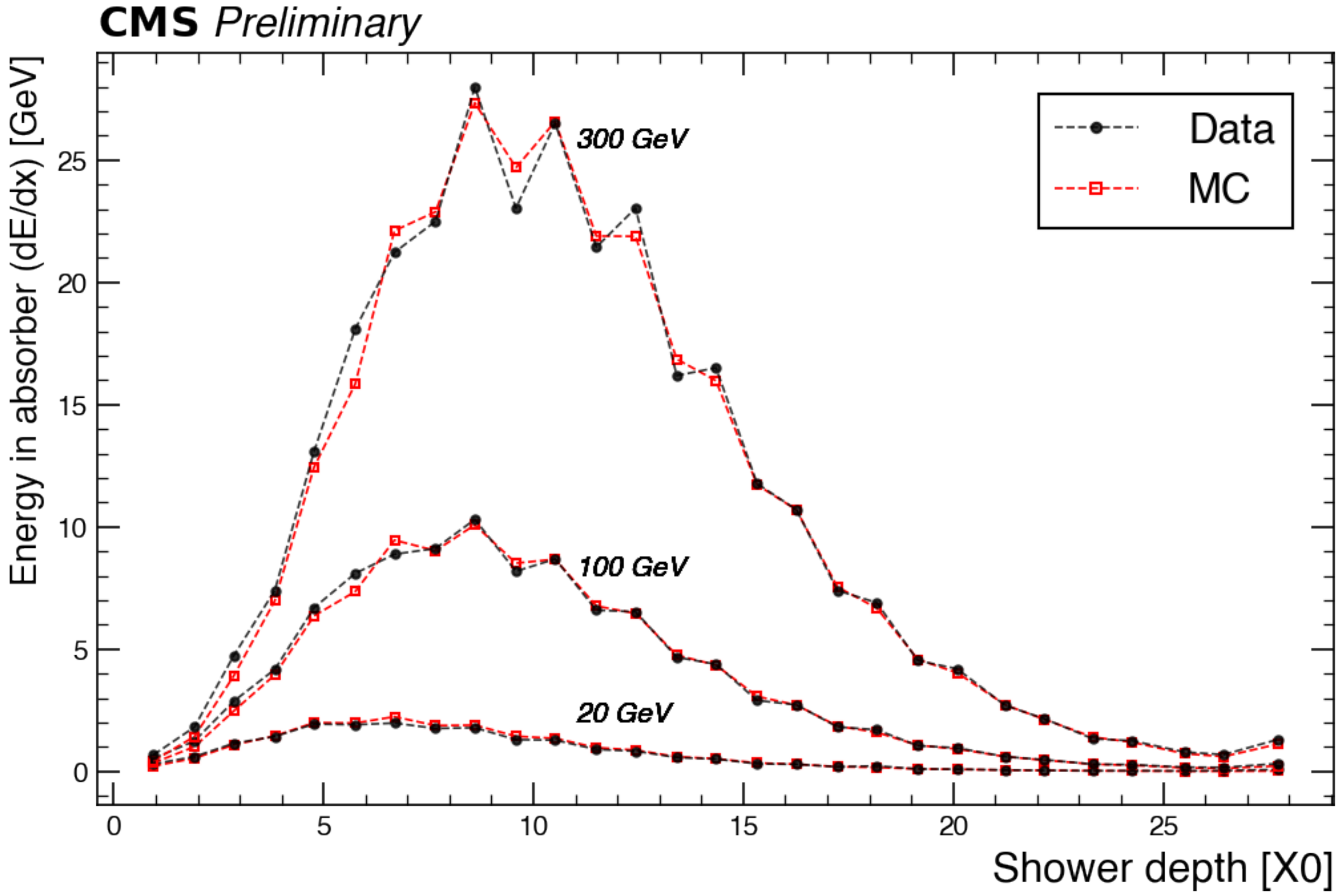
PHYSICS PERFORMANCE: ELECTRONS IN CE-E

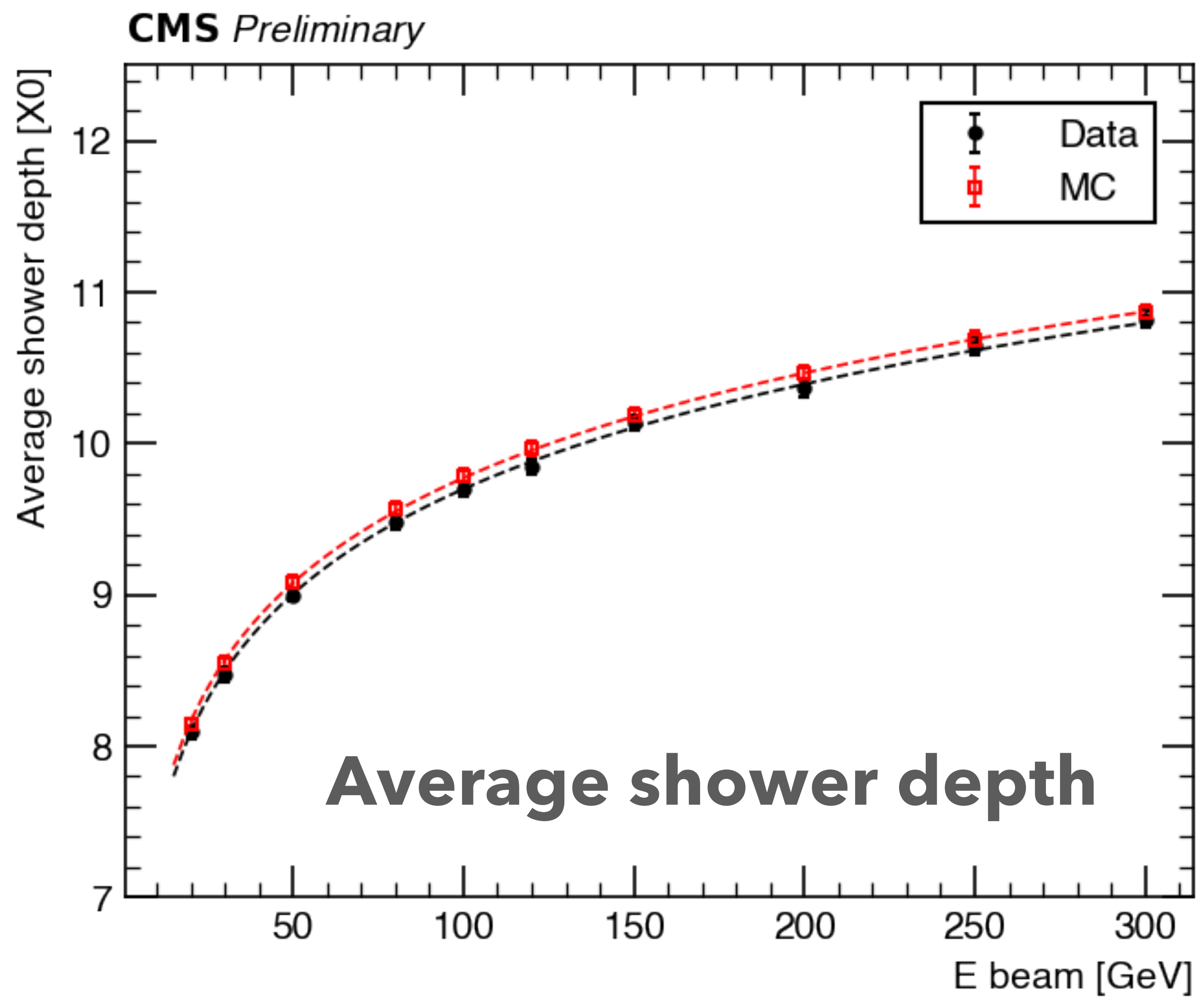
- Measurement of **electromagnetic resolution and linearity;**
- **Validation of** the dedicated GEANT4 **simulation**;
- Good Data/MC agreement and values within expectations;

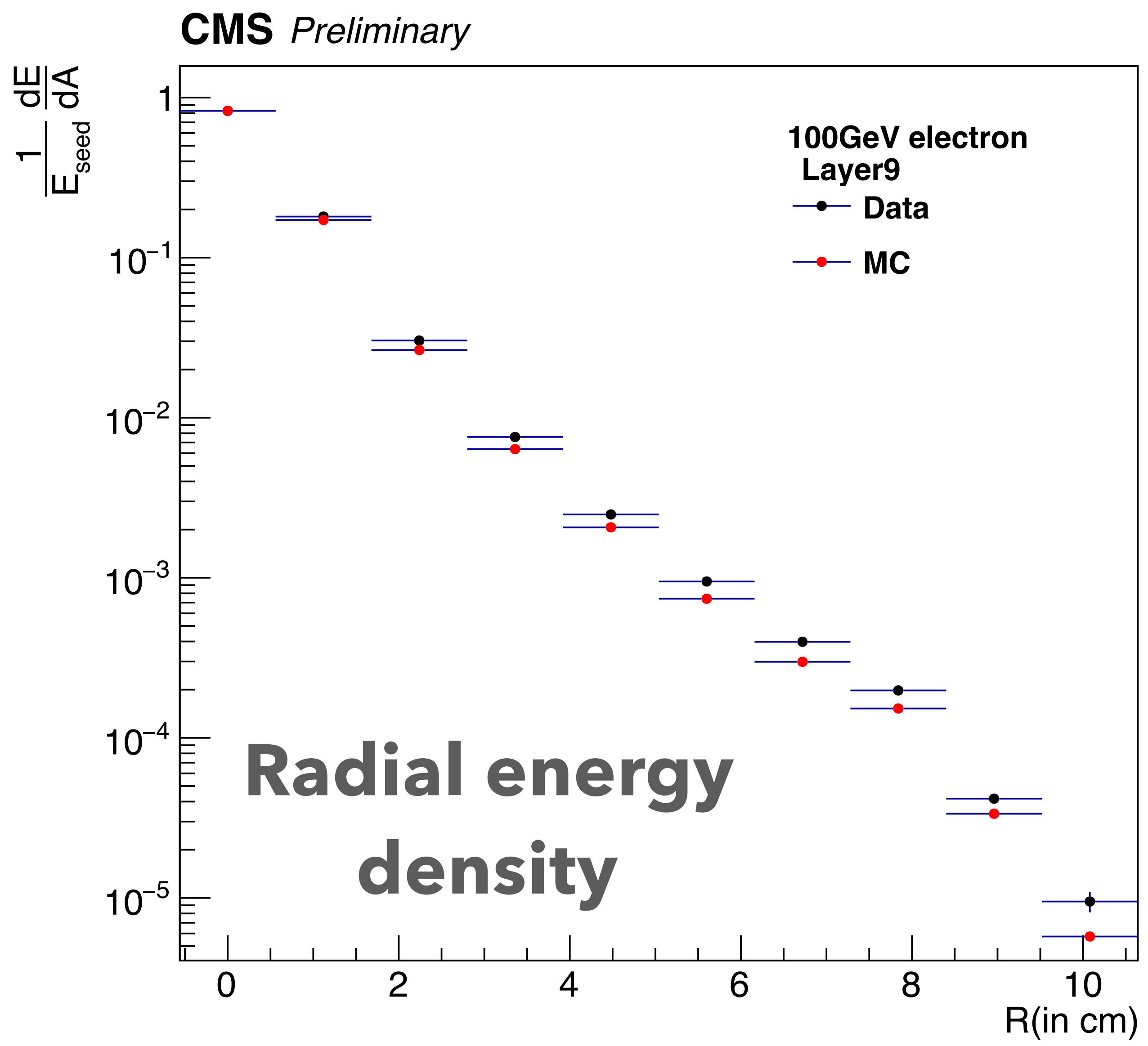


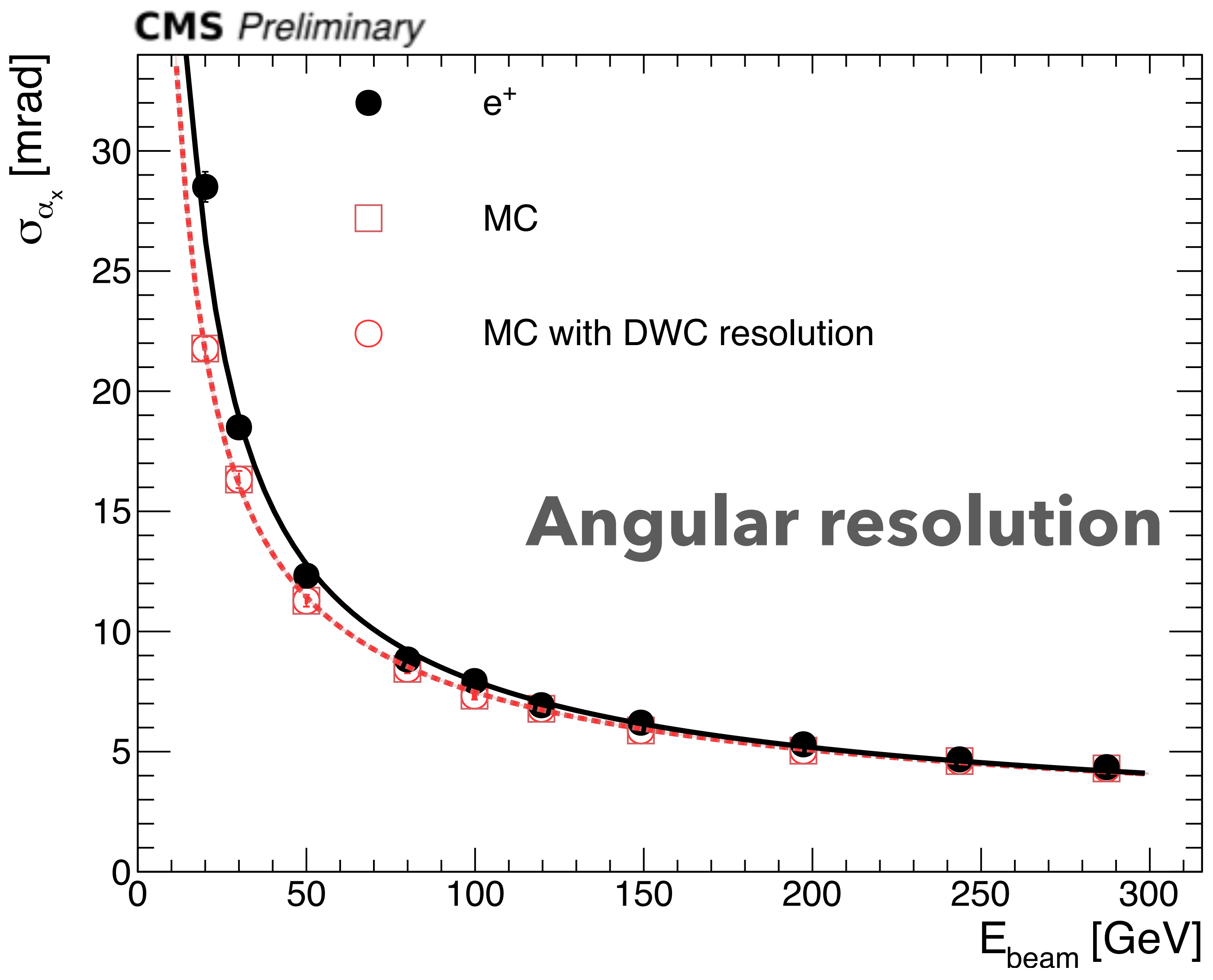


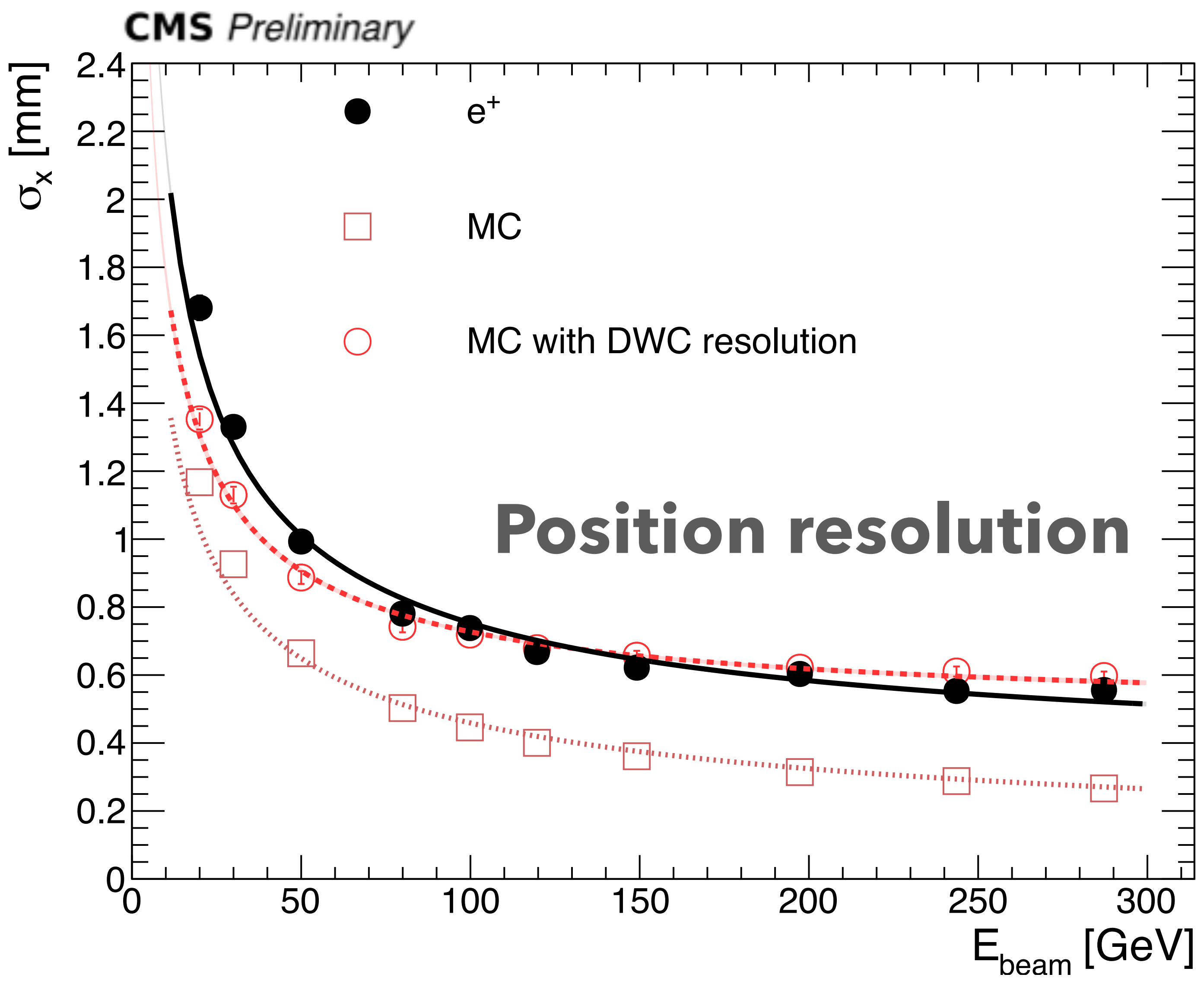
ELECTRONS IN CE-E: FULL CHARACTERIZATION OF EM SHOWERS

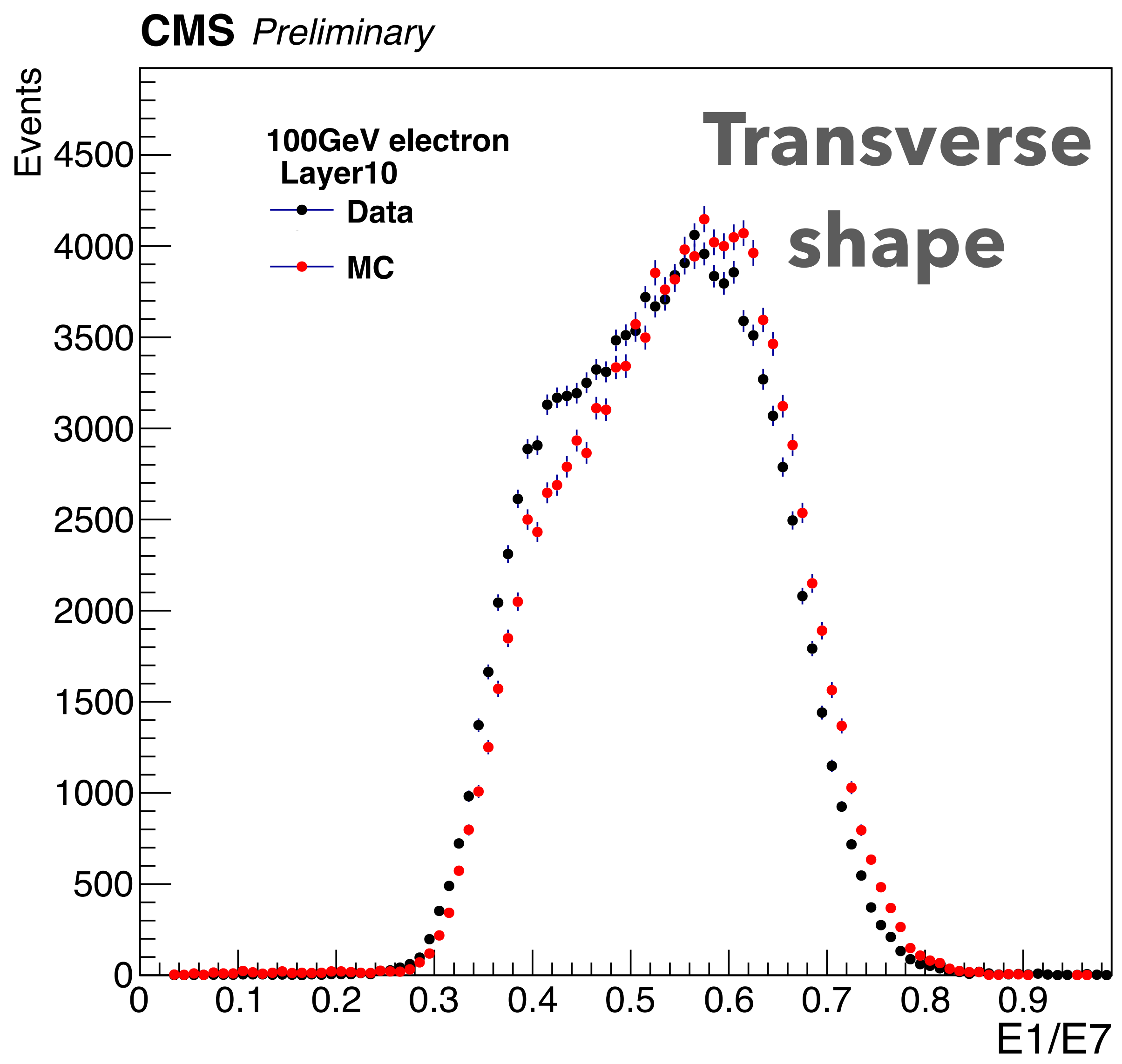




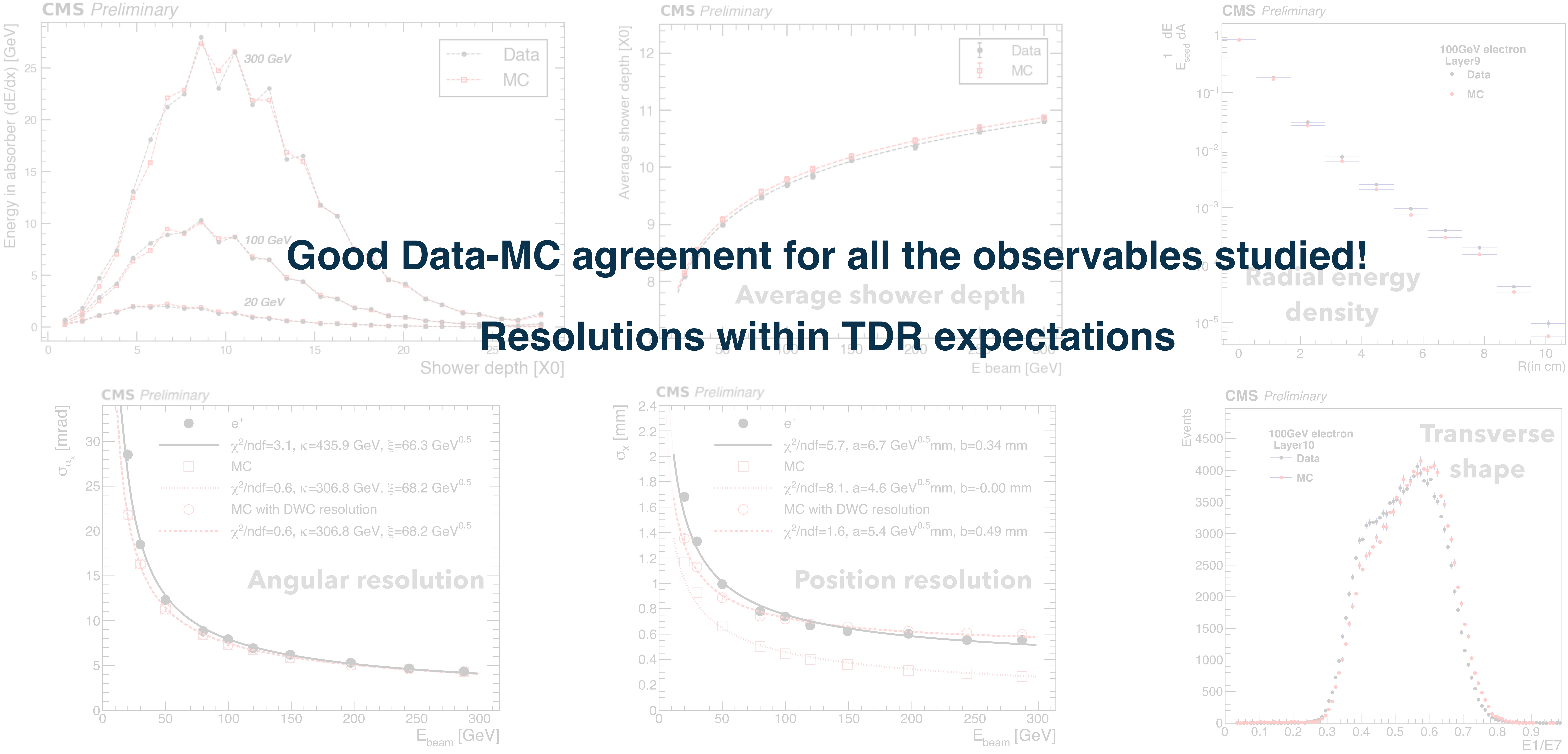








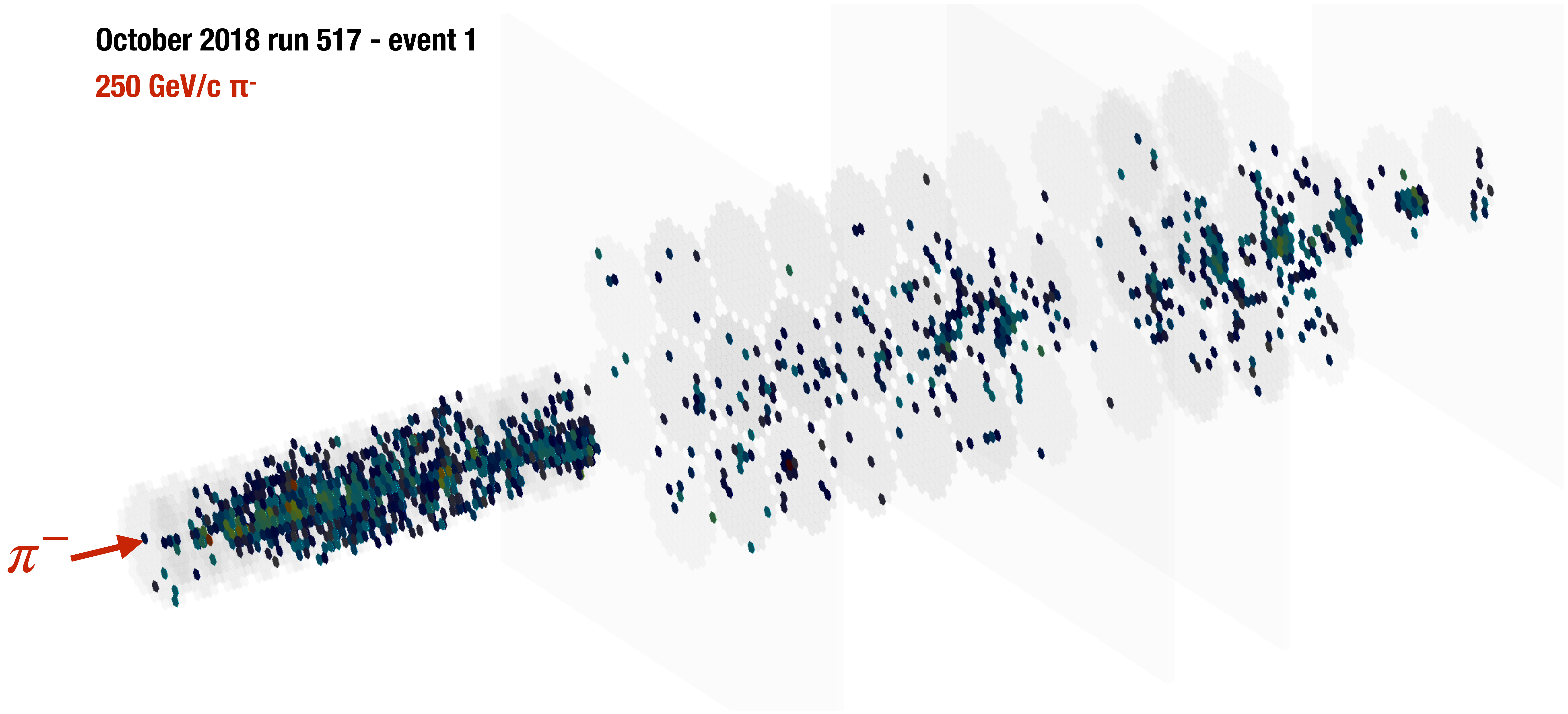
ELECTRONS IN CE-E: FULL CHARACTERIZATION OF EM SHOWERS



Good Data-MC agreement for all the observables studied!

Resolutions within TDR expectations

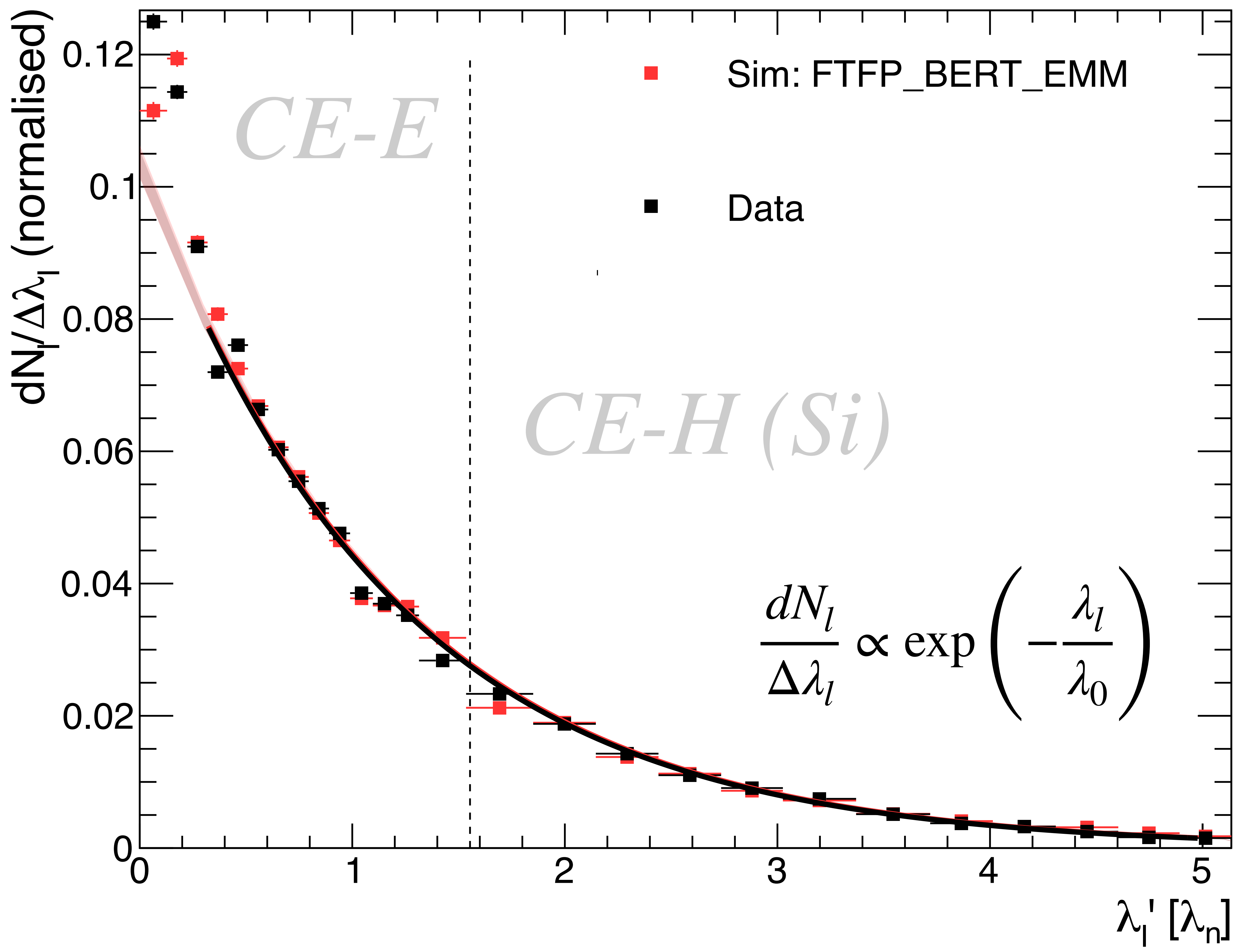
PHYSICS PERFORMANCE: PIONS



Hadrons showers are initiated by a nuclear interaction at a random depth in the calorimeter. The following cascade includes a variety of electromagnetically and hadronically interacting components.

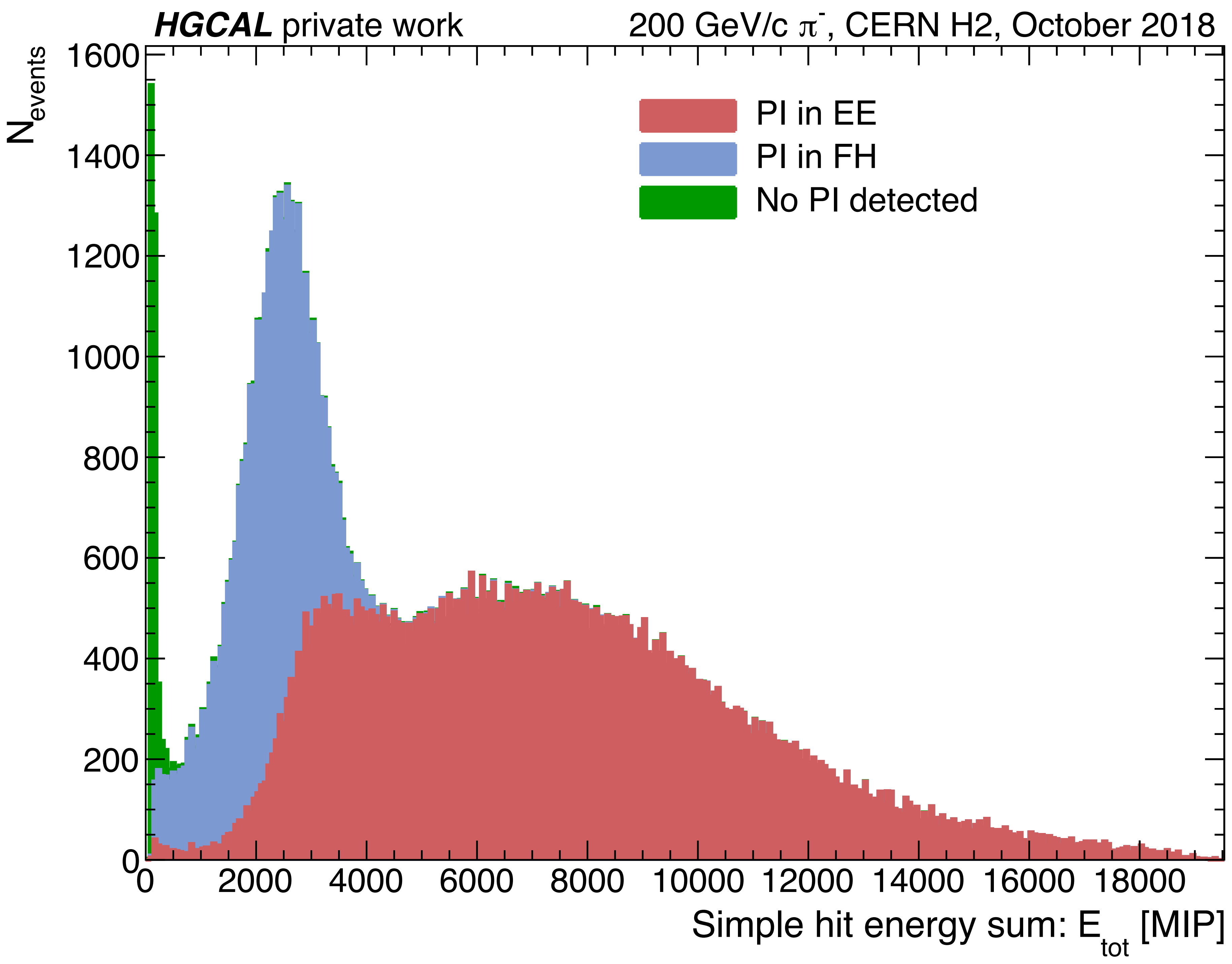
PHYSICS PERFORMANCE: PIONS

- Complete validation of the HGCAL prototype physics performance using pions;
- Test the **capability** of the detector **to identify the Primary Interaction layer** (PI) for hadrons induced showers;
- Good Data/MC agreement and qualitative validation of the expected exponential law for the PI



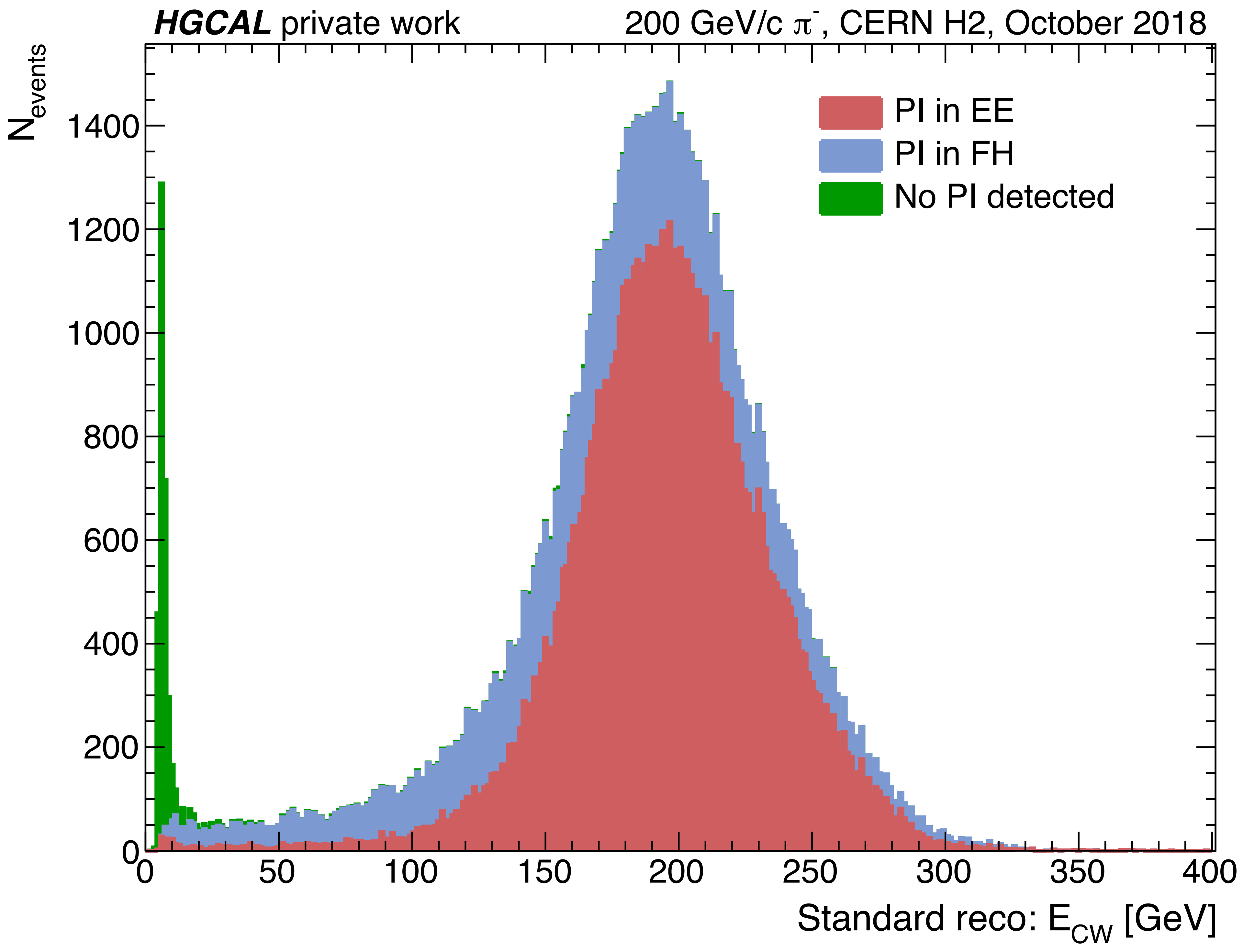
PHYSICS PERFORMANCE: PIONS

- **CE-E** and **CE-H** have **different sampling** frequencies:
  - Dedicated **weighting algorithm** necessary **to reconstruct the shower energy** distribution;
- Final energy distribution reconstructed as $E_{Tot} = w_{CE-E} \cdot E_{CE-E} + w_{CE-H} \cdot E_{CE-H}$
- **Work ongoing to include** also **AHCAL** in the reconstruction.



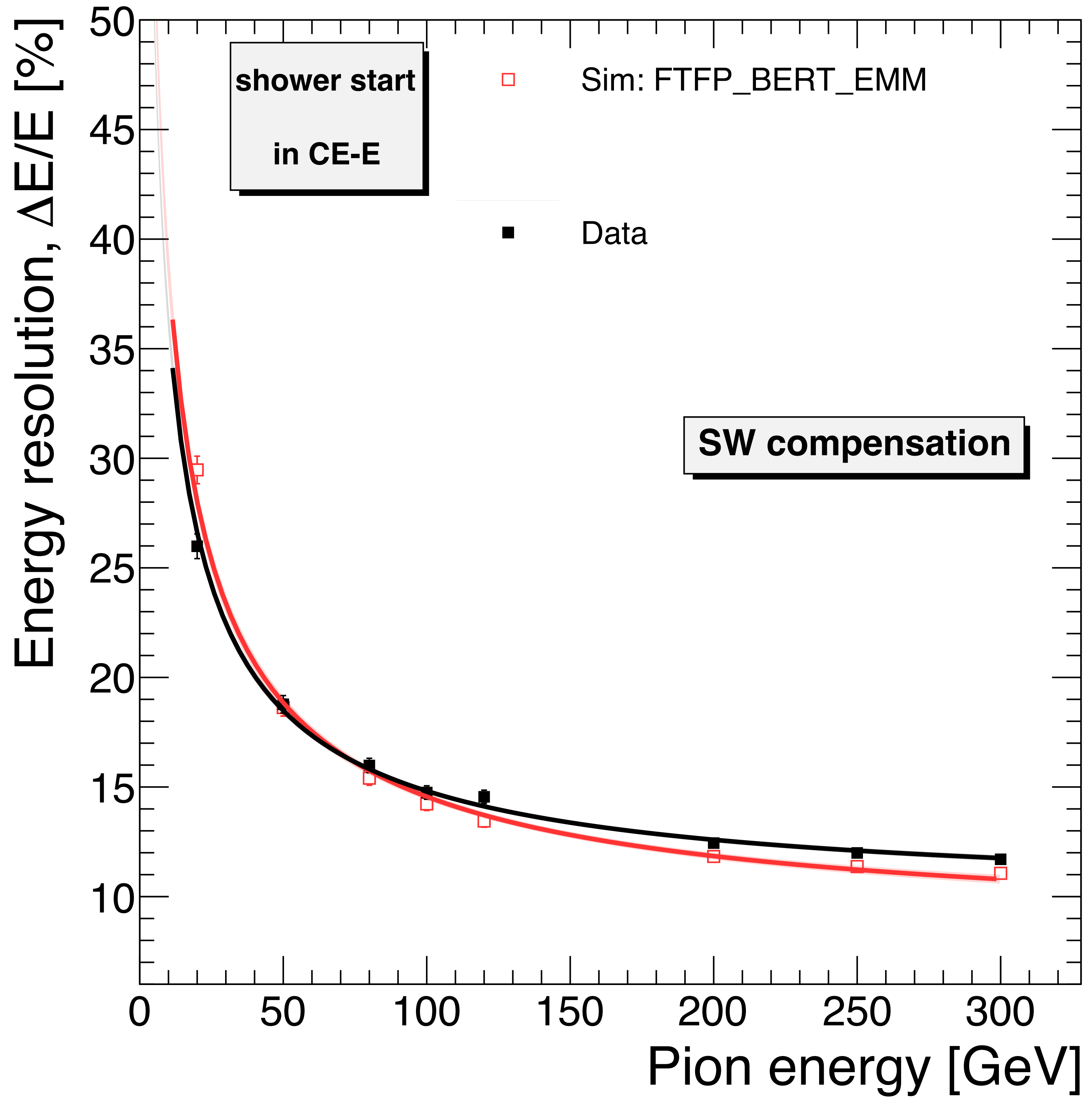
COMPARTMENT

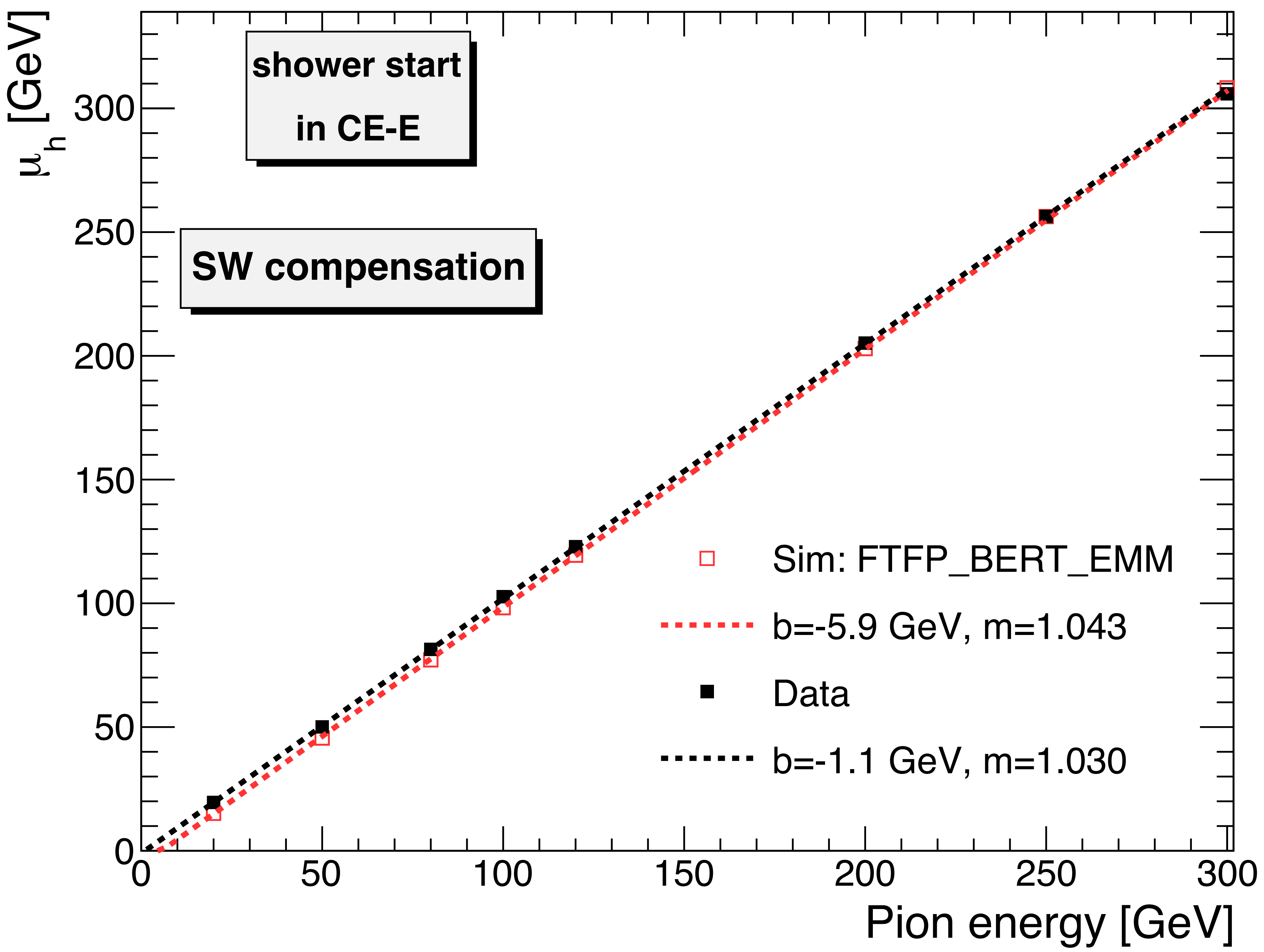
WEIGHTING



PHYSICS PERFORMANCE: PIONS

- **Energy resolution** and **linearity** measured for pions showering in CE-E;
- **Promising** Data/MC **agreement** from these preliminary results;
- **Different reconstruction methods** (SW compensation, compartments weighting …)

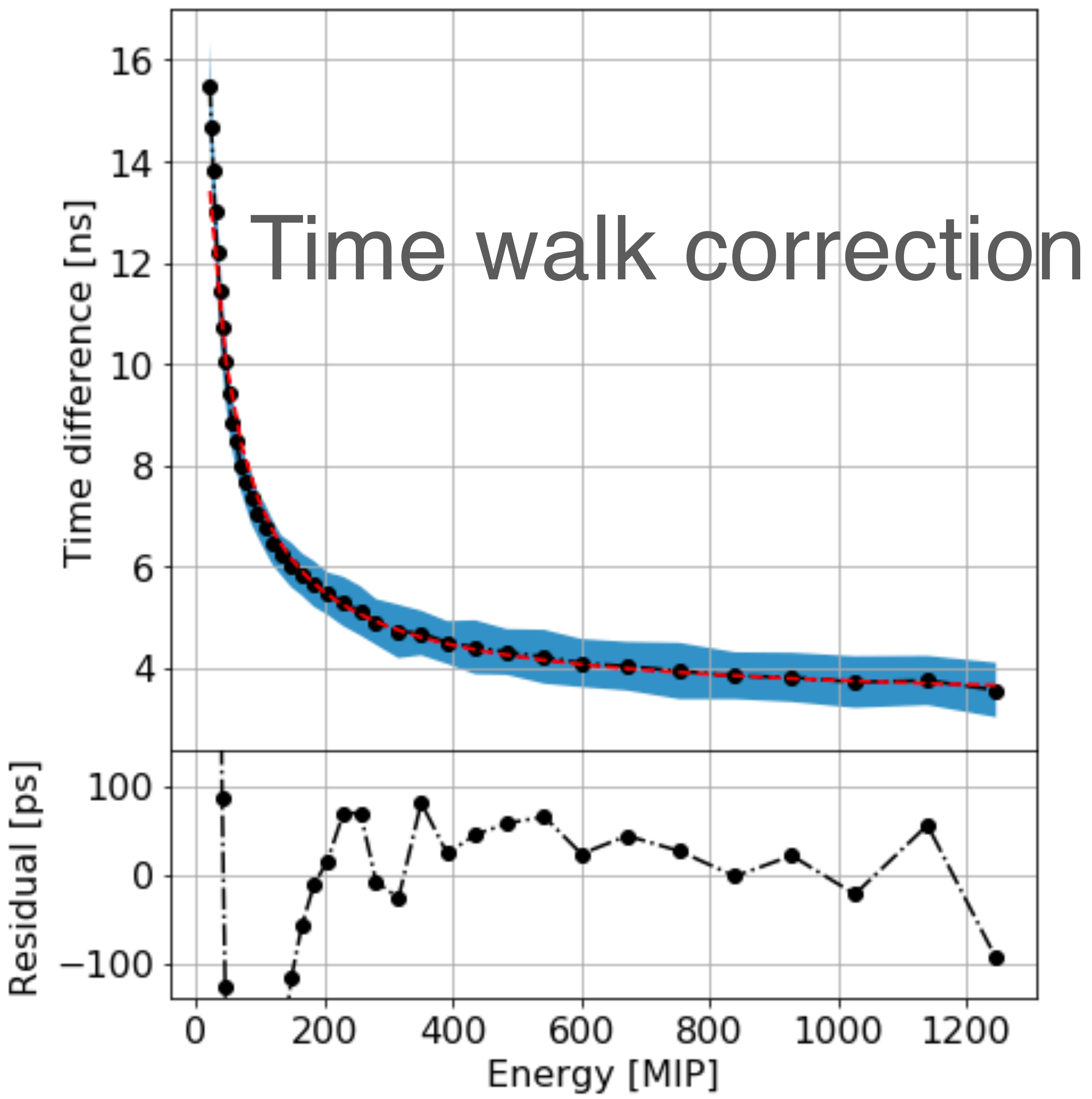


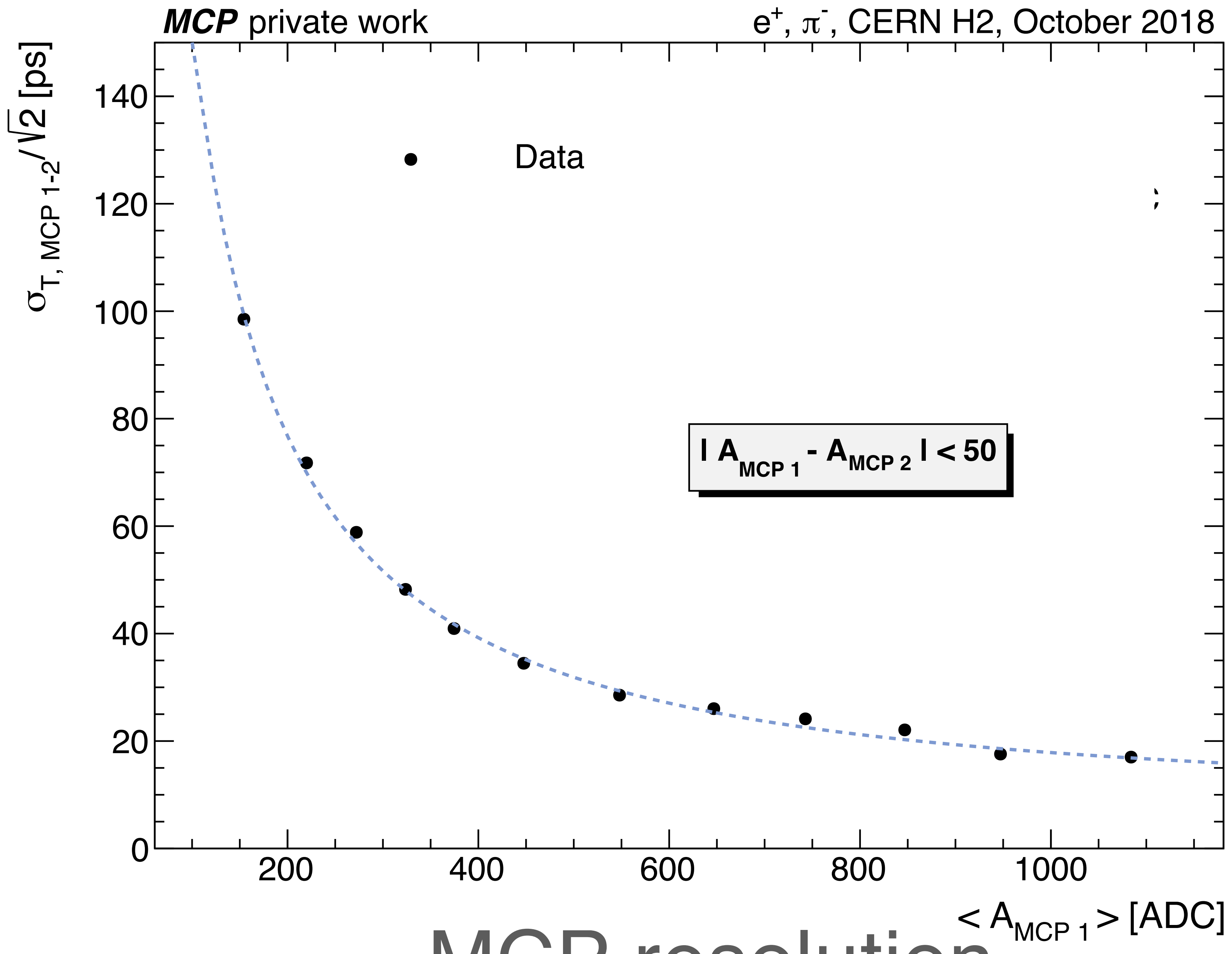


TIMING PERFORMANCE

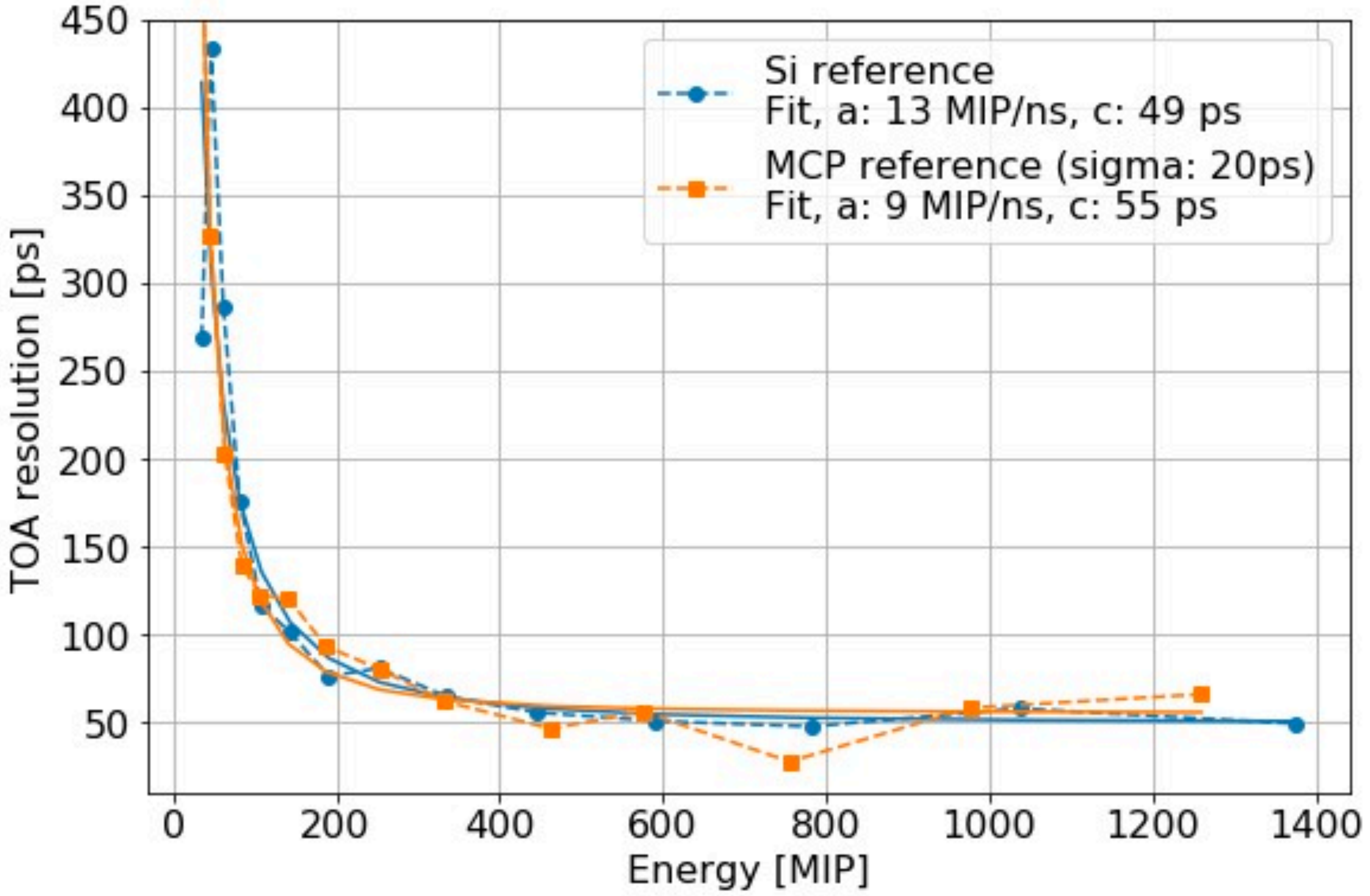
- **Timing measurement with Time-of-Arrival (TOA)** circuit integrated in ASIC: 25 ns range, ~25 ps binning, resolution constant term ~50 ps
- **Sophisticated calibration required:**
  - TOA pedestals (upper and lower limits)
  - TOA response correction (unfolding TOA from asynchronous beam)
  - Time walk correction using **external time reference** (MCP-PMT, sigma ~20 ps)

- **TOA offsets follow time-of-flight** for pions (over CE-E and CE-H for central modules)
- Time **resolution: reaching ~50 ps** constant term —> within ASIC specification!





MCP resolution



Single-channel time resolution

A SUCCESSFUL TEST BEAM: 6 PAPERS BEING WRITTEN!

6 papers are being prepared, targeting submission to JINST

★ **H1:** DAQ system for detector readout of HGCAL prototypes

★ **H2:** Commissioning and calibration of HGCAL prototypes

- **H3:** Electrons performance
- **H4:** DESY beam test
- **H5:** Timing performance
- **C1:** Pion performance (with CALICE AHCAL)

OUTLOOK AND SUMMARY

For the **HL-LHC upgrade CMS** is planning to replace endcaps calorimeter with **HGCAL**.

Detector development has to face **many challenges** due to the **harsh environment**:

- **High pile-up rate**: O(200) evts per bunch crossing!
- **Unprecedented radiation levels**: doses up to 2 May and fluences up to 10^{16} n_{eq}/cm^2!

HGCAL: finely segmented sampling calorimeter

- **5D** (Imaging) **calorimeter** ideal for **particle flow:** optimal particle ID
- **Radiation hard detector with Si-based modules (novelty in calorimetry)**
- **Precision timing measurement (novelty in calorimetry)**

OUTLOOK AND SUMMARY

Beam tests are fundamental to **validate detector design and physics performance**

In October 2018 the first **large scale prototype** of HGCAL was tested

- **Calibration** of the detector **with MIPs**: foreseen for the final detector
- **Measurement** of the electromagnetic and hadronic **physics performance**:
  - **Good Data/MC agreement** for all the observables studied;
  - **EM resolutions in agreement with TDR expectations**;
- **Timing resolution** measured **agrees with expected** one for **SKIROC2-CMS TOA**

Gain expertise with analysis methodologies, tune MC simulation and very good performance already with this preliminary HGCAL prototype!

There is no such thing as a "typical hadronic shower profile"

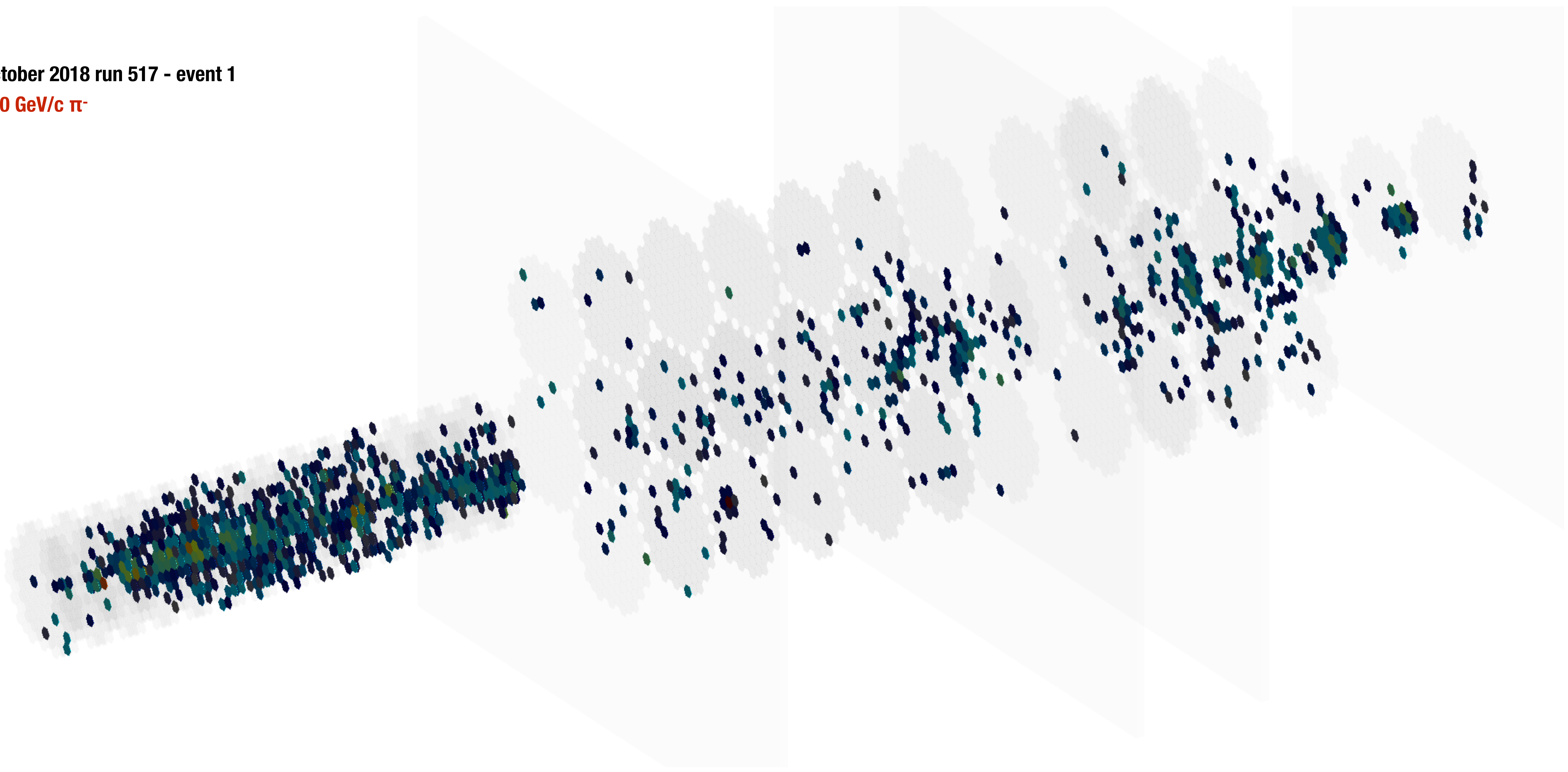
\- R. Wigmans

There is ~~no~~ such thing as a "typical hadronic shower profile"

- HGCAL, 2018 TB

October 2018 run 517 - event 1

250 GeV/c π^-

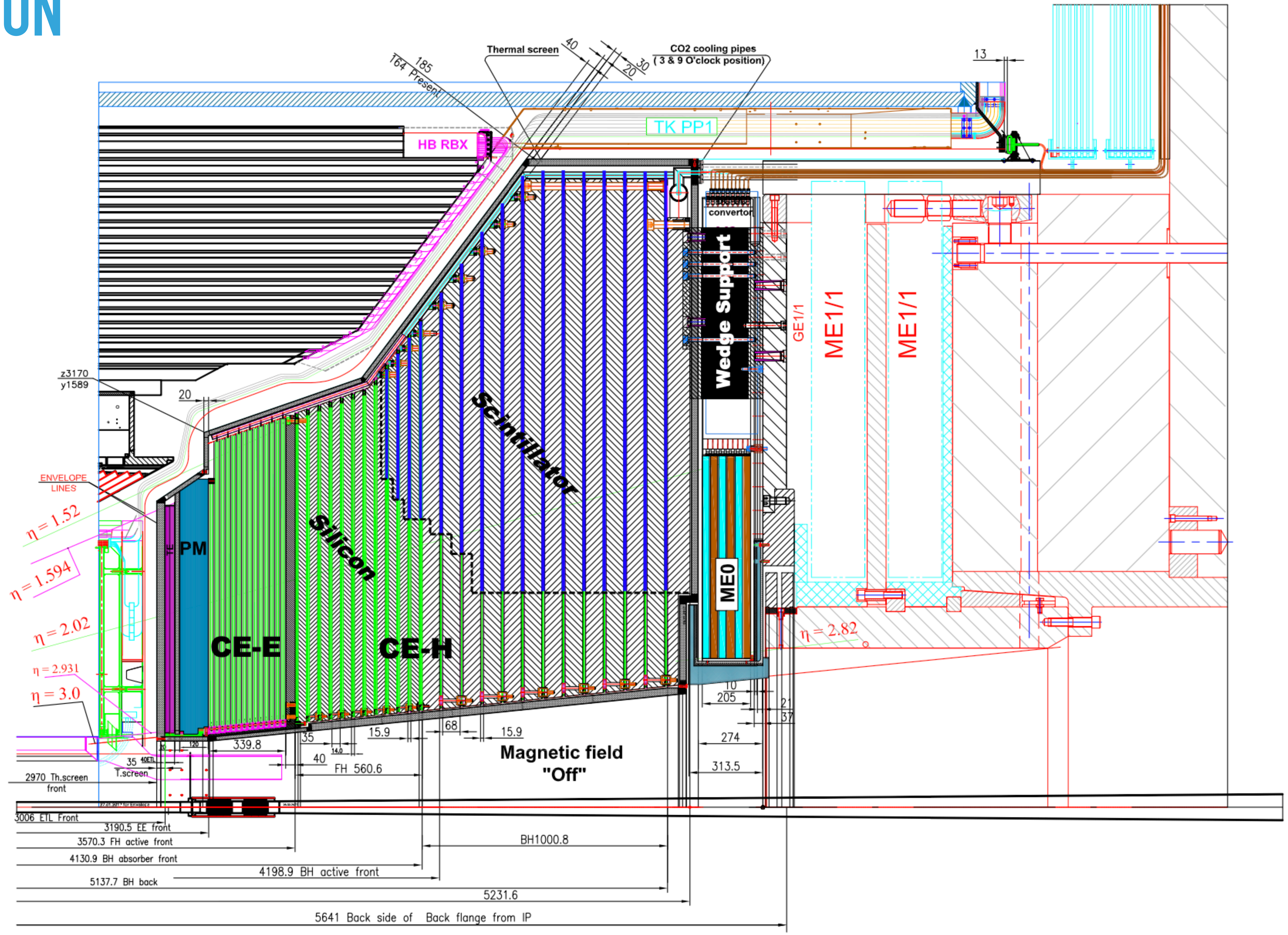


ADDITIONAL MATERIAL

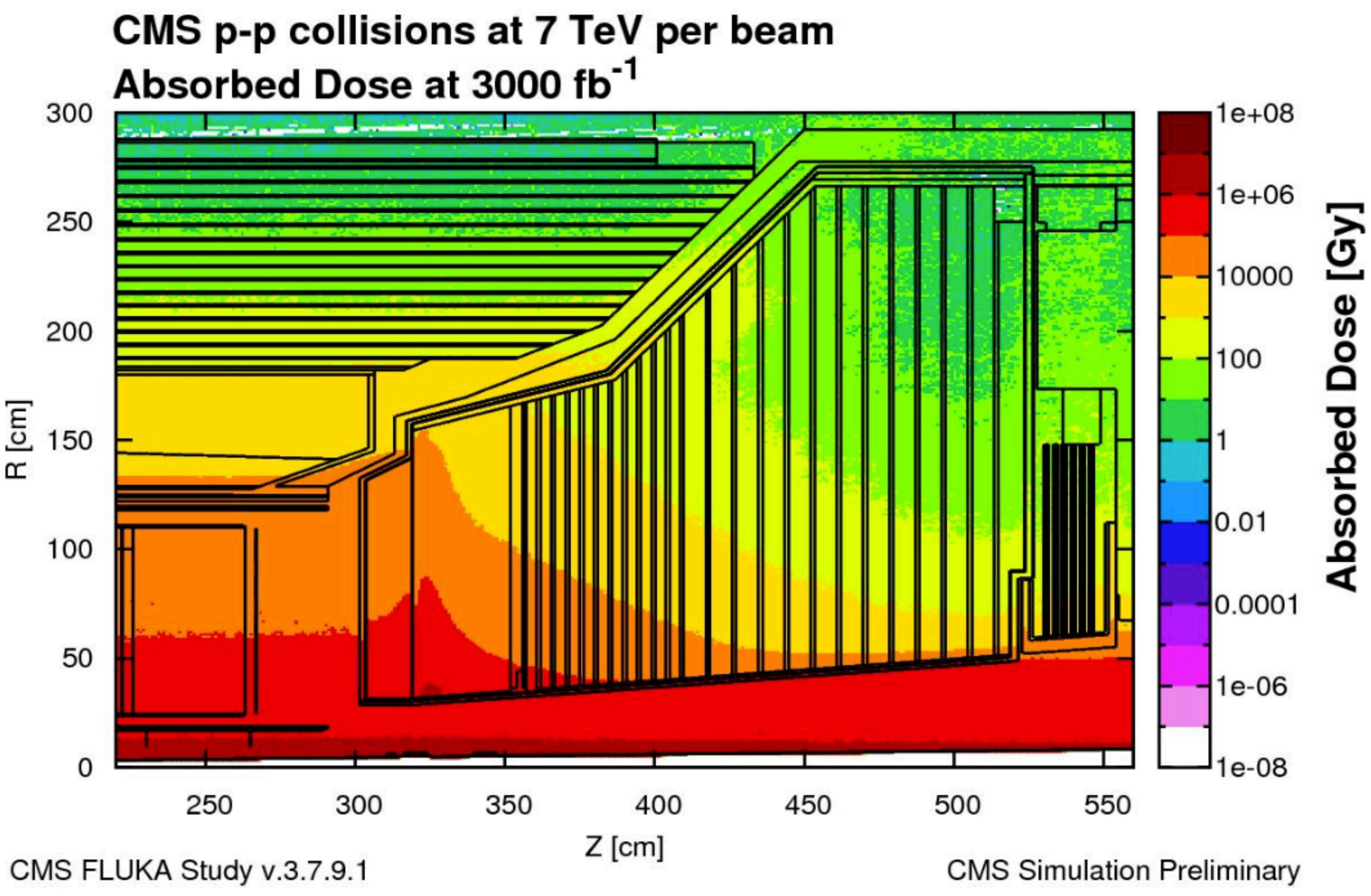
THE TRAKER AND HGCAL

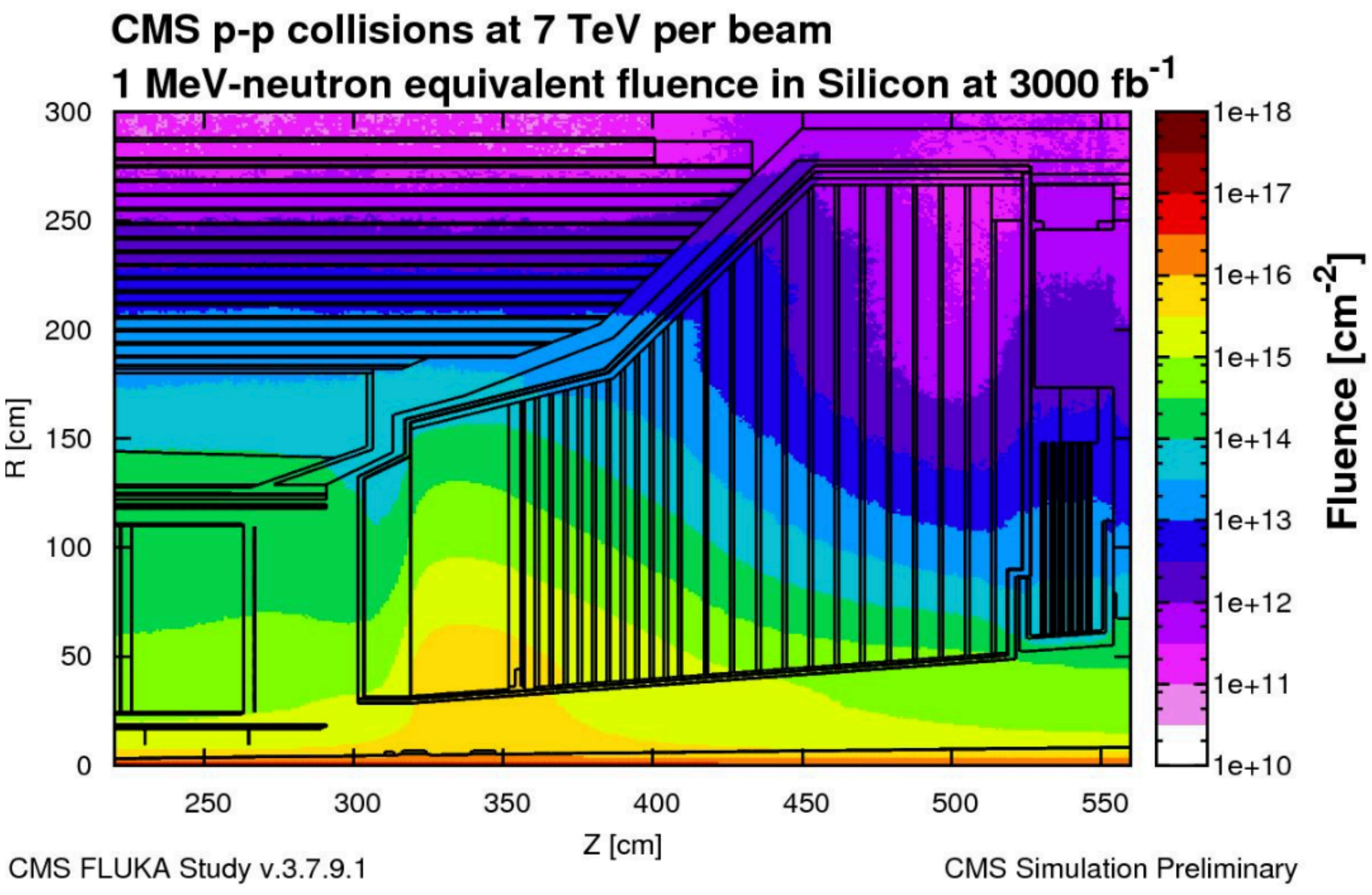
The main differences between the tracker and the HGCAL are that the ***HGCAL will use large area pads*** *(≈1cm^2)* ***rather than finely segmented strips*** *(≈90µm pitch), and that whereas* ***in*** *the* ***tracker*** *case the* ***fluence is dominated by charged hadrons***, ***in*** *the case of the* ***HGCAL the neutrons dominate.***

HGCAL XSECTION



ABSORBED DOSE AND FLUENCY AT 3000FB^{-1}





WIRE BONDING

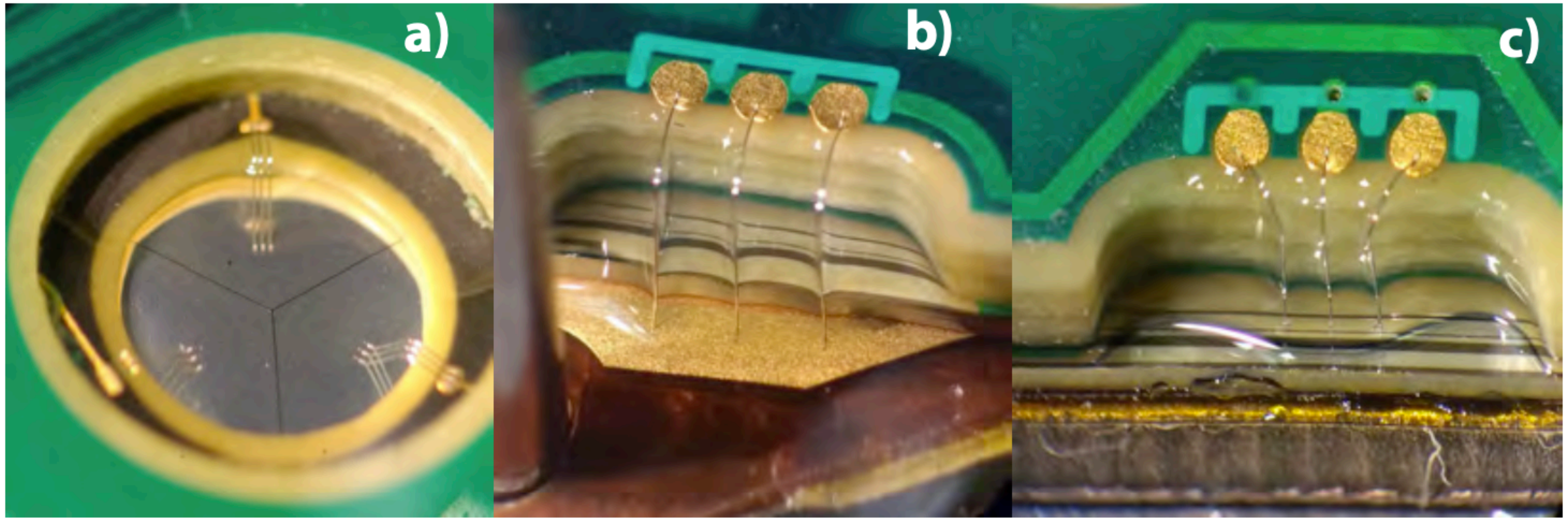


Figure 2.9: From left to right: a) wirebonds for three sensor pads at a stepped hole in the hexaboard used for test beam modules in 2017; b) wirebond to the Au-Kapton layer to provide back-plane biasing of the sensor; and c) wirebonds at the edge of the module to the sensor guard rings.

HGCAL REQUIREMENTS FROM TDR

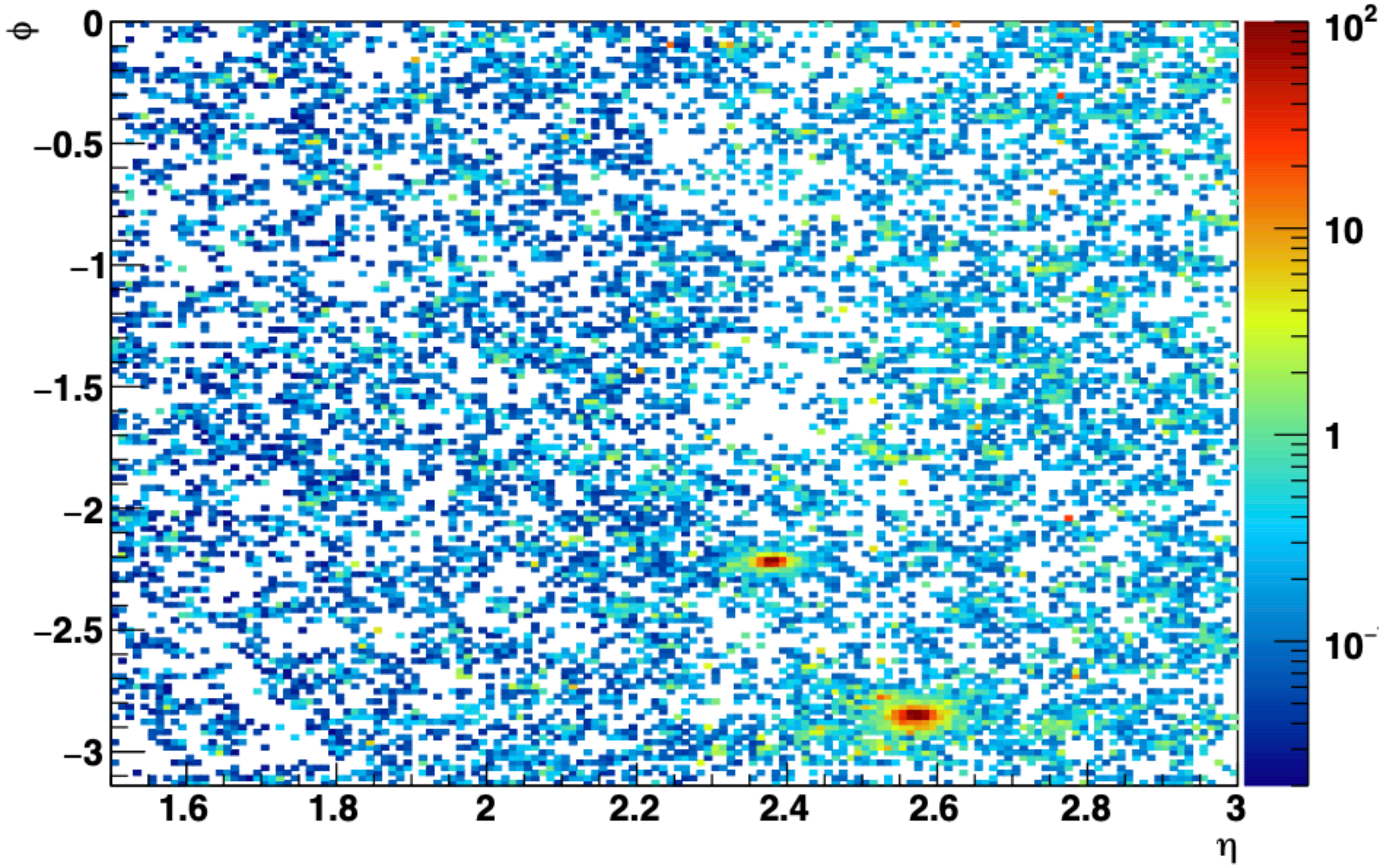
1.2 Requirements for the HGCAL upgrade

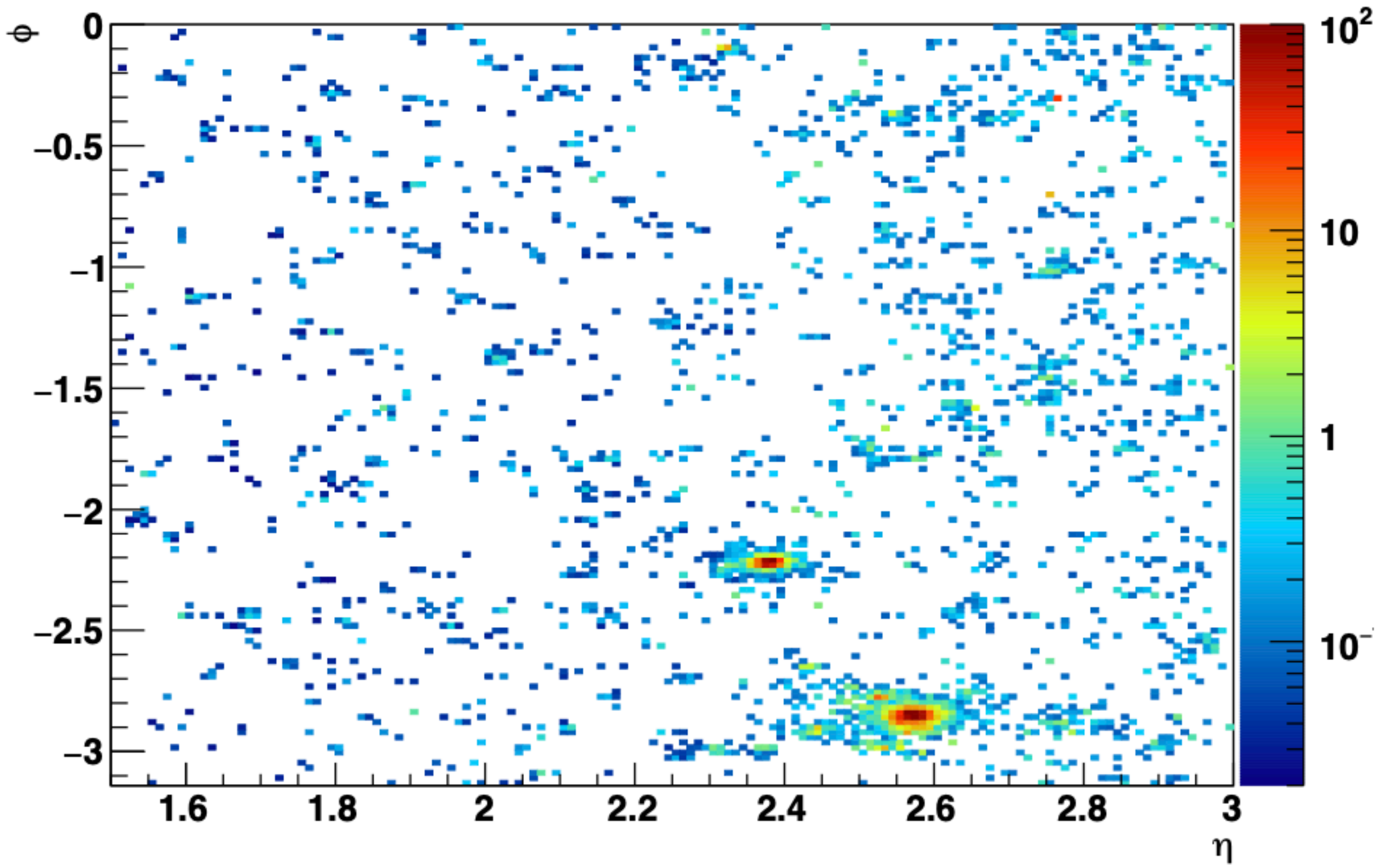
Preserving good performance over the full lifetime will require good (at the level of a few percent) inter-cell calibration. Adequate calibration accuracy can best be achieved if minimum-ionizing particles (MIPs) can be cleanly detected in each cell. This requires a good signal-to-noise ratio (S/N) for MIPs after 3000 fb^{-1}, necessitating the use of low-capacitance silicon cells, of a small size (≈0.5–1 cm^2), and scintillator cells of a small enough size for high light collection efficiency and S/N, resulting in a high lateral granularity. Fine longitudinal sampling is needed to provide good energy resolution, especially when using thin active layers (100–300 μm thick Si sensors). The fine lateral and longitudinal granularity leads to a high cell count. The main requirements for the HGCAL upgrade can be summarized as follows:

- *radiation tolerance:* fully preserve the energy resolution after 3000 fb^{-1}, requiring good inter-cell calibration (≈3%) using minimum-ionizing particles,
- *dense calorimeter:* to preserve lateral compactness of showers,
- *fine lateral granularity:* for low energy equivalent of electronics noise so as to give a high enough S/N to allow MIP calibration, to help with two shower separation and the observation of narrow jets, as well as limiting the region used for energy measurement to minimize the inclusion of energy from particles originating in pileup interactions,
- *fine longitudinal granularity:* enabling fine sampling of the longitudinal development of showers, providing good electromagnetic energy resolution (e.g. for $H \to \gamma\gamma$), pattern recognition, and discrimination against pileup,
- *precision measurement of the time of high energy showers:* to obtain precise timing from each cell with a significant amount of deposited energy, aiding rejection of energy from pileup, and the identification of the vertex of the triggering interaction,
- *ability to contribute to the level-1 trigger decision.*

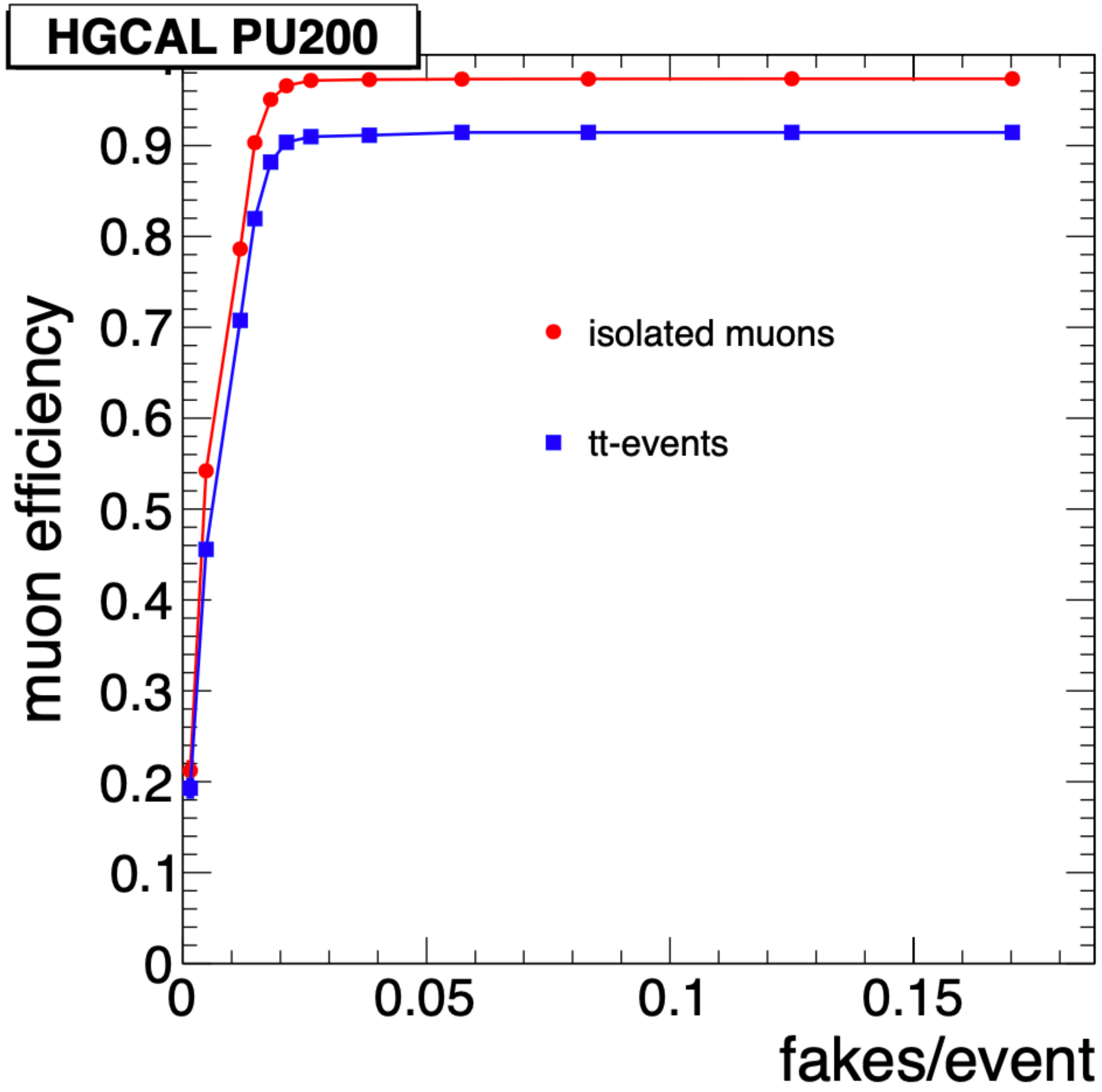
TIMING POWER OF HGCAL: PILEUP MITIGATION

VBF H—>$\gamma\gamma$ without and with requirement on timing for hits above 12 fC with $|\Delta t| \geq 90$ *ps*

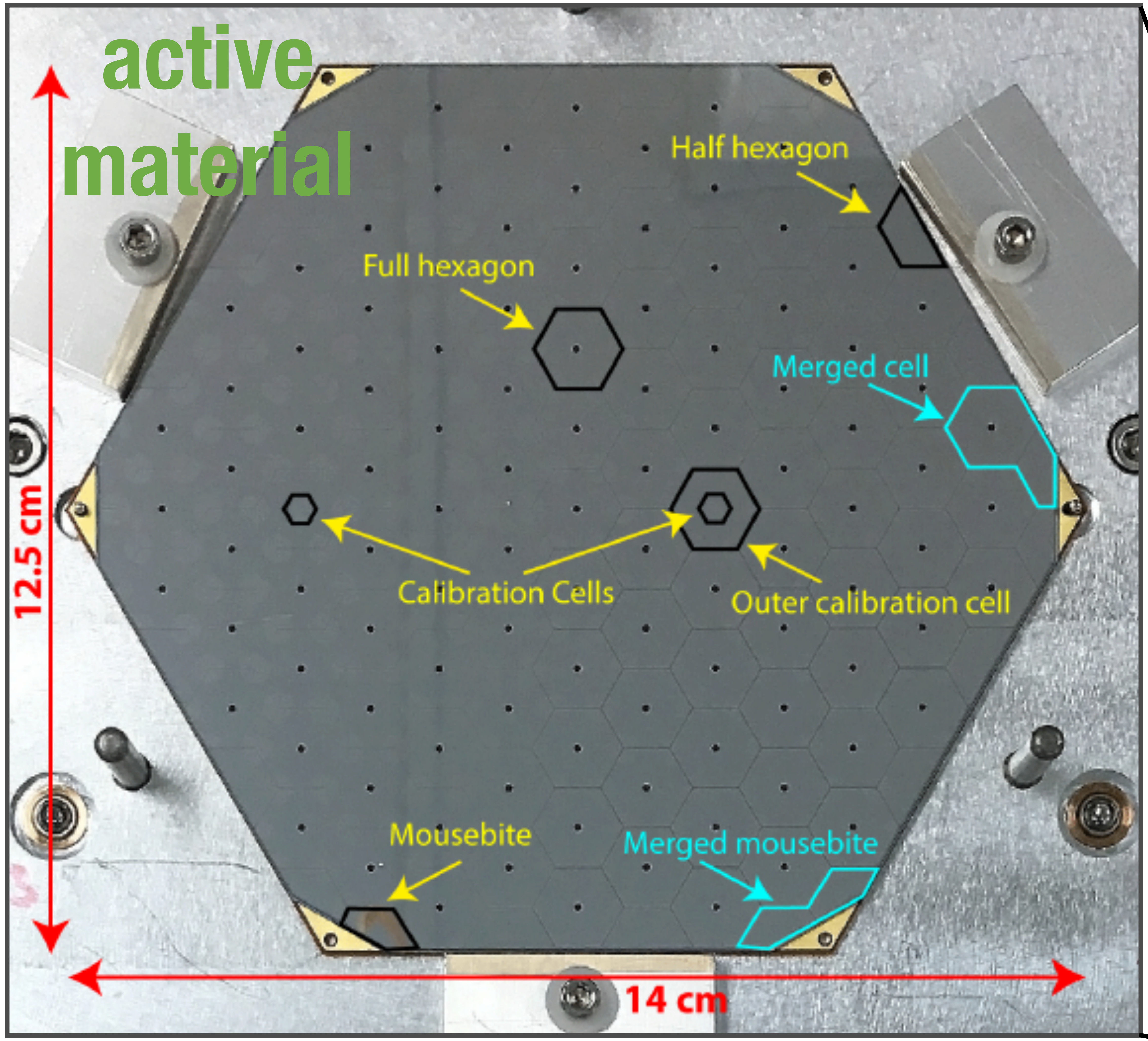




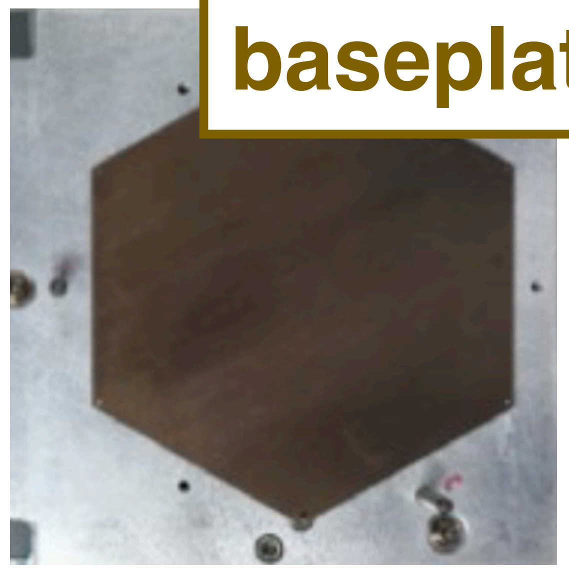
MUONS DETECTION EFFICIENCY



MODULES FOR THE 2018 BEAM TESTS



baseplate



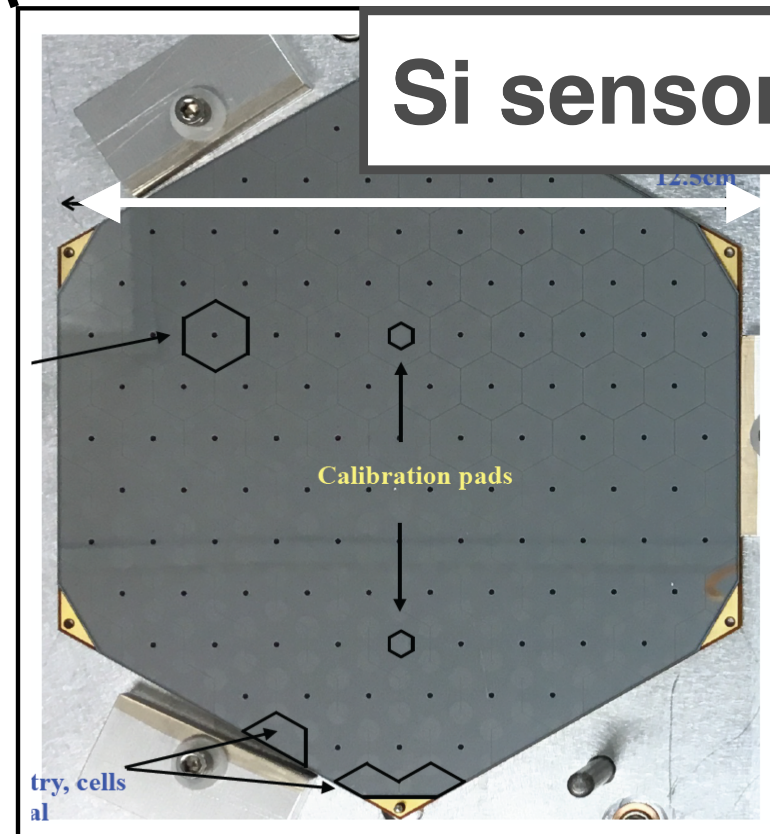
- CuW
- Cu

Kapton®

- Gold plated

+

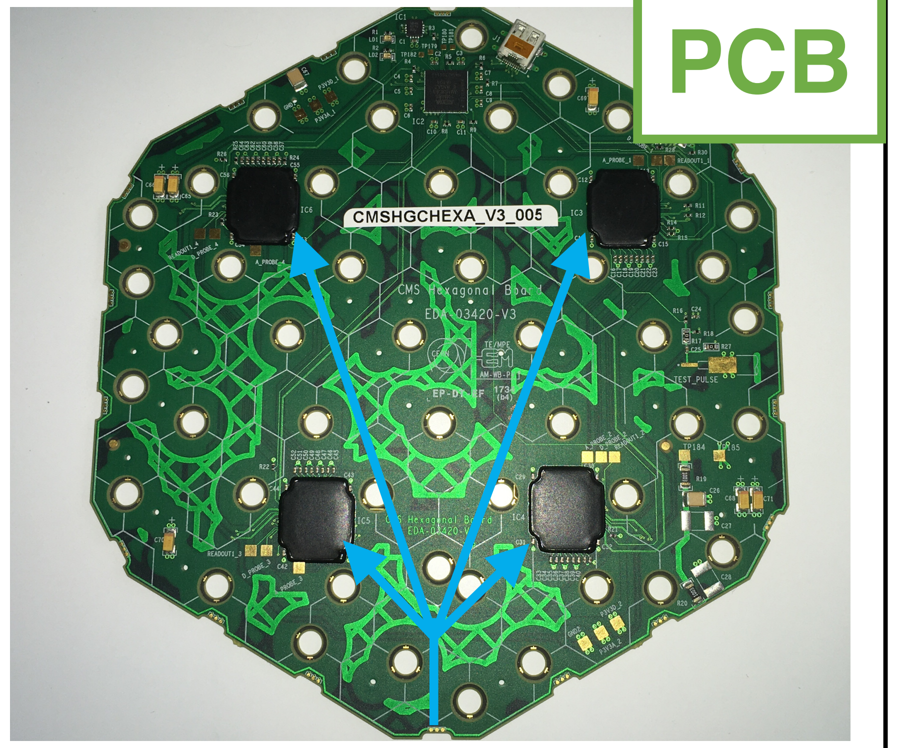
Si sensor



6" silicon sensors:

- n-type, 128 cells
- 1 cm^2 cell-size
- depletion: 200 & 300μm

PCB



- SKIROC2-CMS ASIC, 64 ch., 4 chips/module
- Developed for CALICE (Skiroc2) & adjusted for HGCAL requirements

TB2018 MIP CALIBRATION