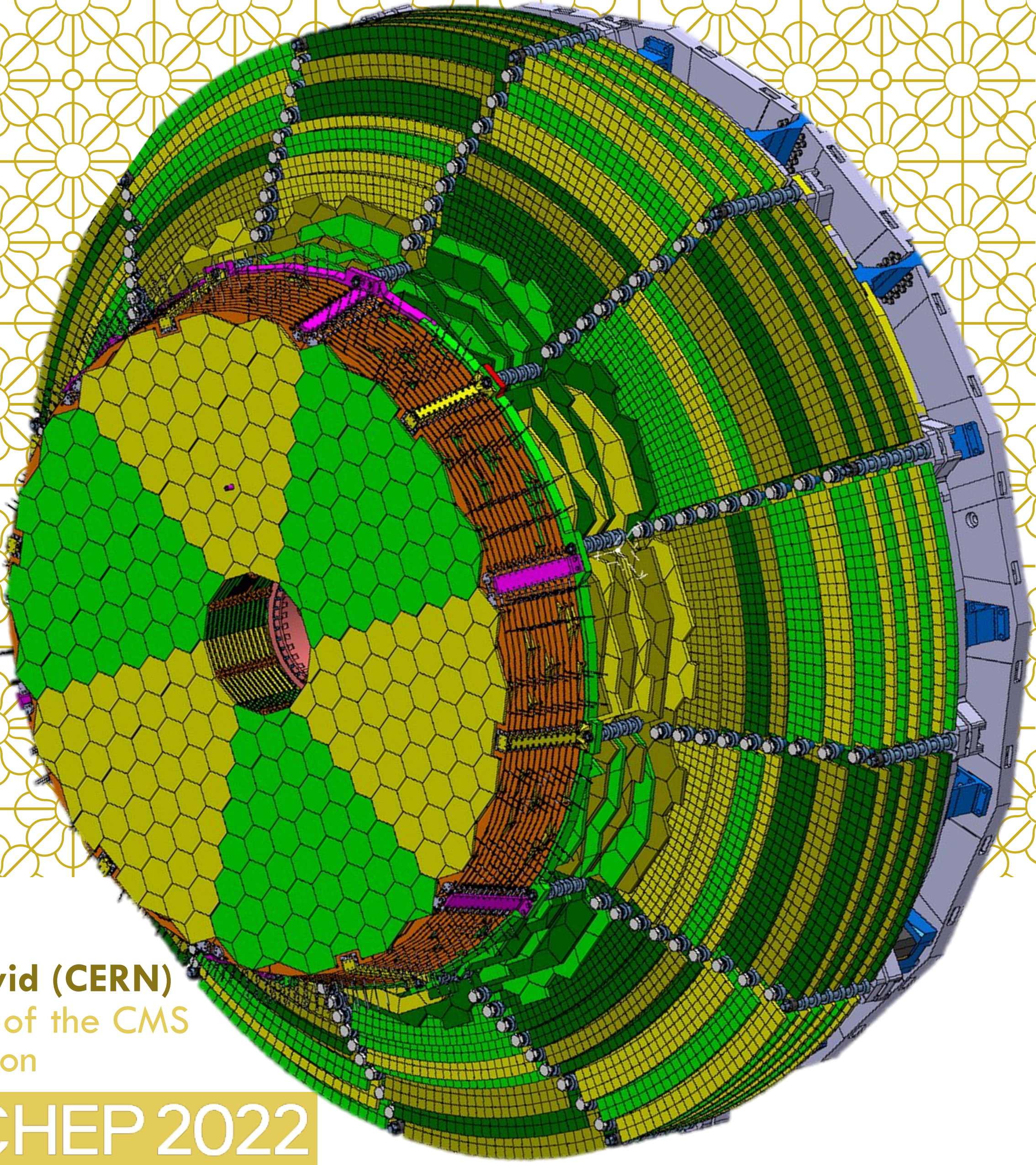
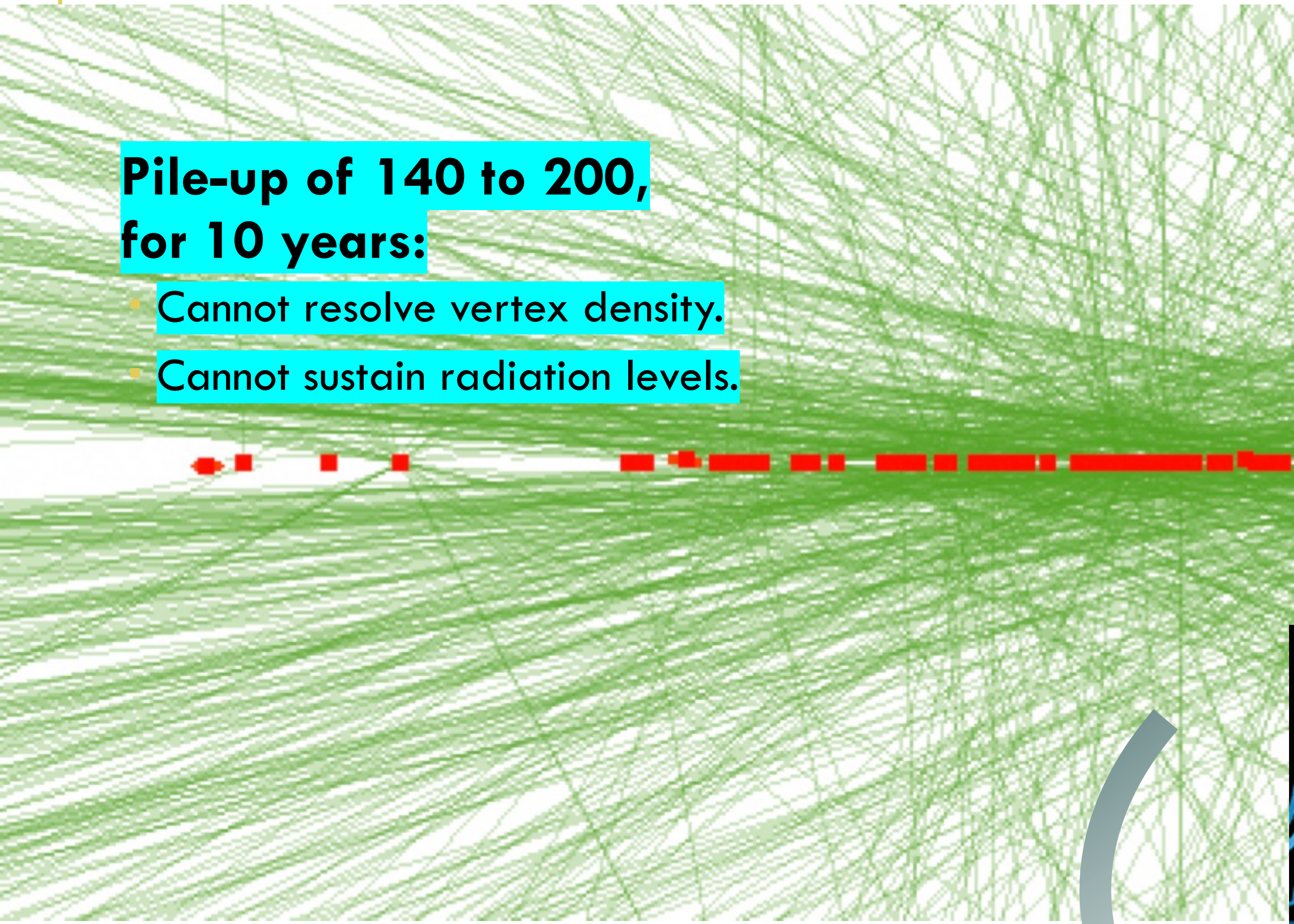


PERFORMANCE OF THE CMS **HGCAL** FOR LHC PHASE 2

André David (CERN)
On behalf of the CMS collaboration

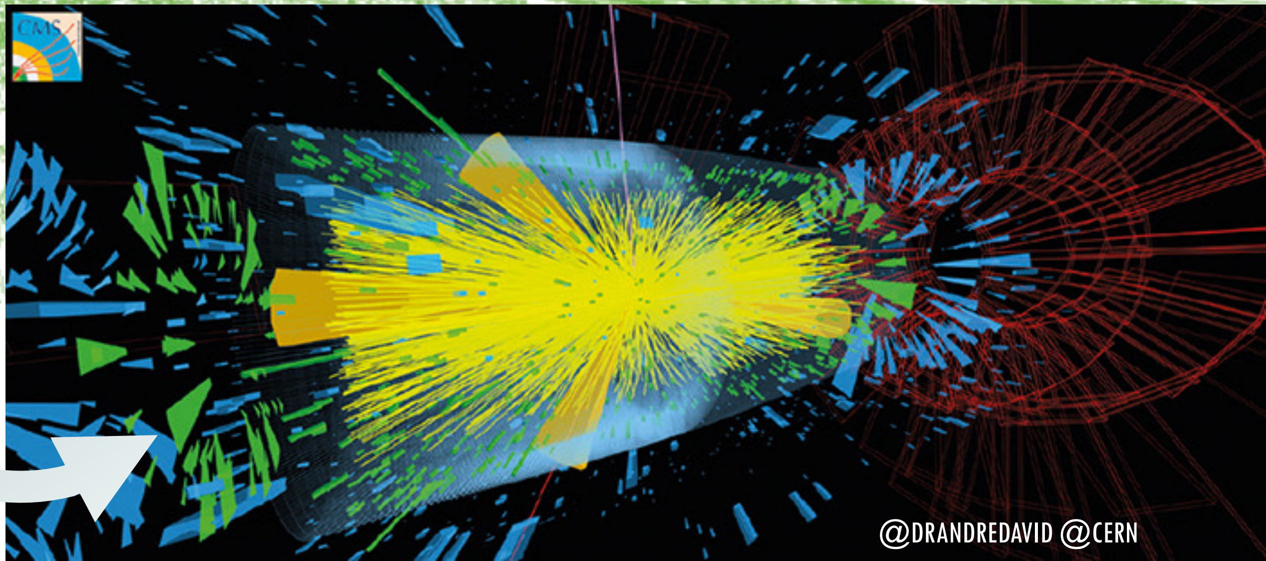
ICHEP 2022 BOLOGNA

HL-LHC: BEYOND PRESENT DETECTOR ABILITY



Pile-up of 140 to 200, for 10 years:

- Cannot resolve vertex density.
- Cannot sustain radiation levels.



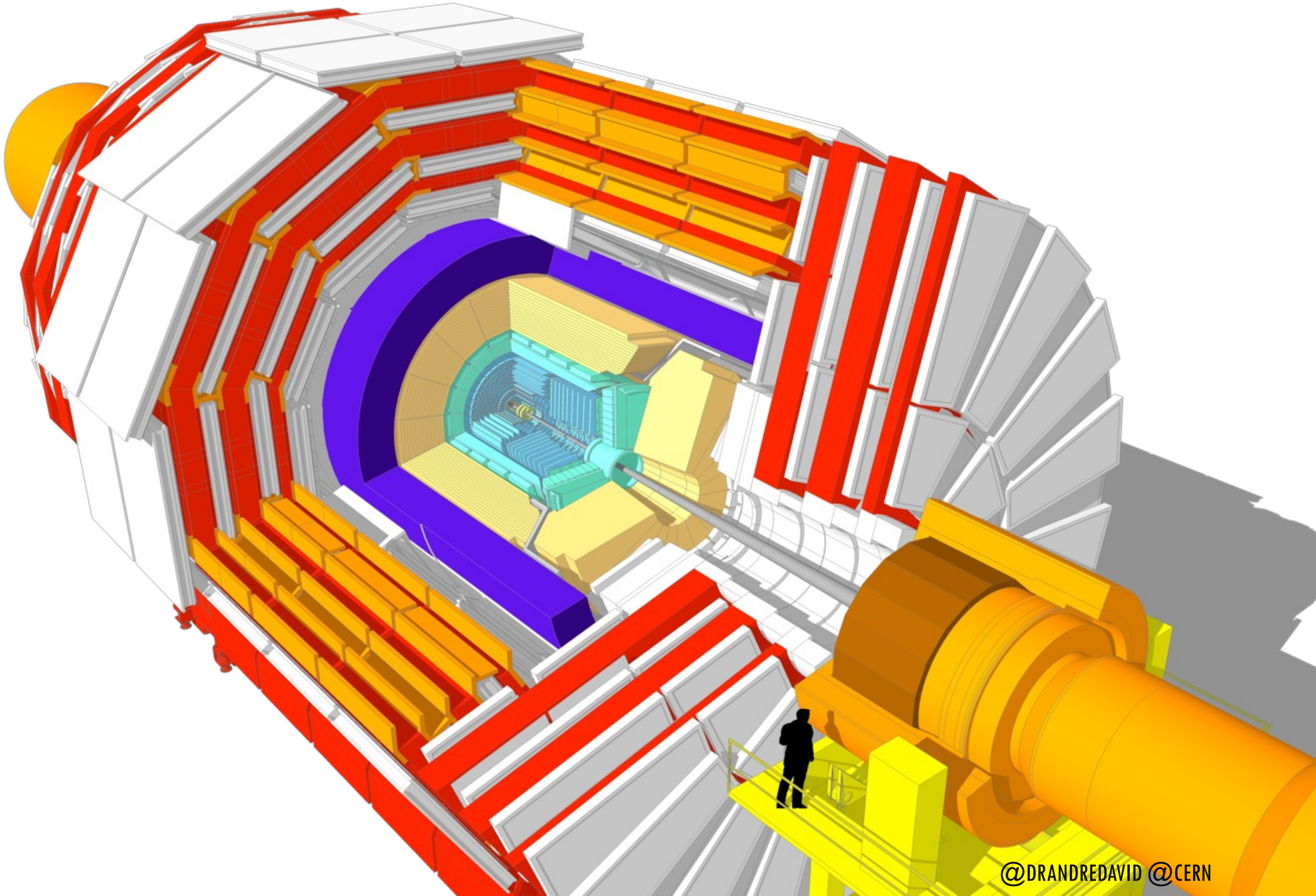
HL-LHC: BEYOND PRESENT DETECTOR ABILITY

Pile-up of 140 to 200,
for 10 years:

- Cannot resolve vertex density.
- Cannot sustain radiation levels.

Reined in through:

- **Higher radiation tolerance.**
- Better **3D granularity.**
- **Sub-100-ps** timing precision (3D → 4D).
- **More information at trigger level.**



NEW ENDCAP CALORIMETER

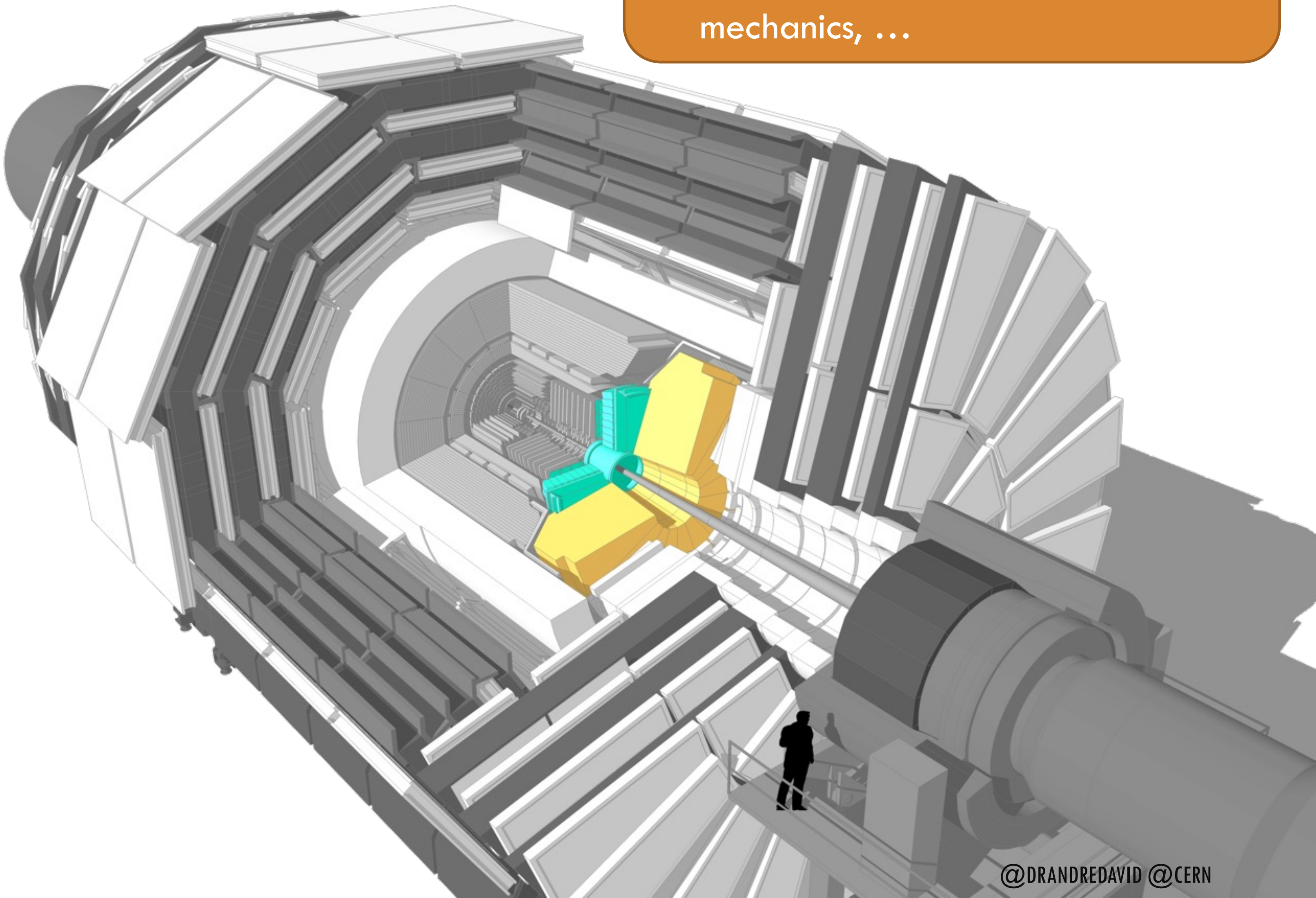
Key challenge:
- Channel density ⇒ ASIC design, power, services, connectivity, mechanics, …

Silicon imaging (EM) calorimeter.

Si and Si+Scintillator layers in back (hadronic) section.

Harsh radiation environment:
- Full volume operated at -30C.
- 215 t and up to 125 kW per endcap.

Overall:
- 6M silicon pads (620 m^2).
  - Cell size 0.6 or 1.2 cm^2.
  - Hexagonal silicon sensors.
    - 120/200/300-µm thick, 8” wafer process.
  - 26k modules.
- 240k plastic scintillator tiles (370 m^2).
  - Cell sizes from 4 to 30 cm^2.
  - SiPM-on-tile readout.
  - 3.7 k modules.



CMS-TDR-019

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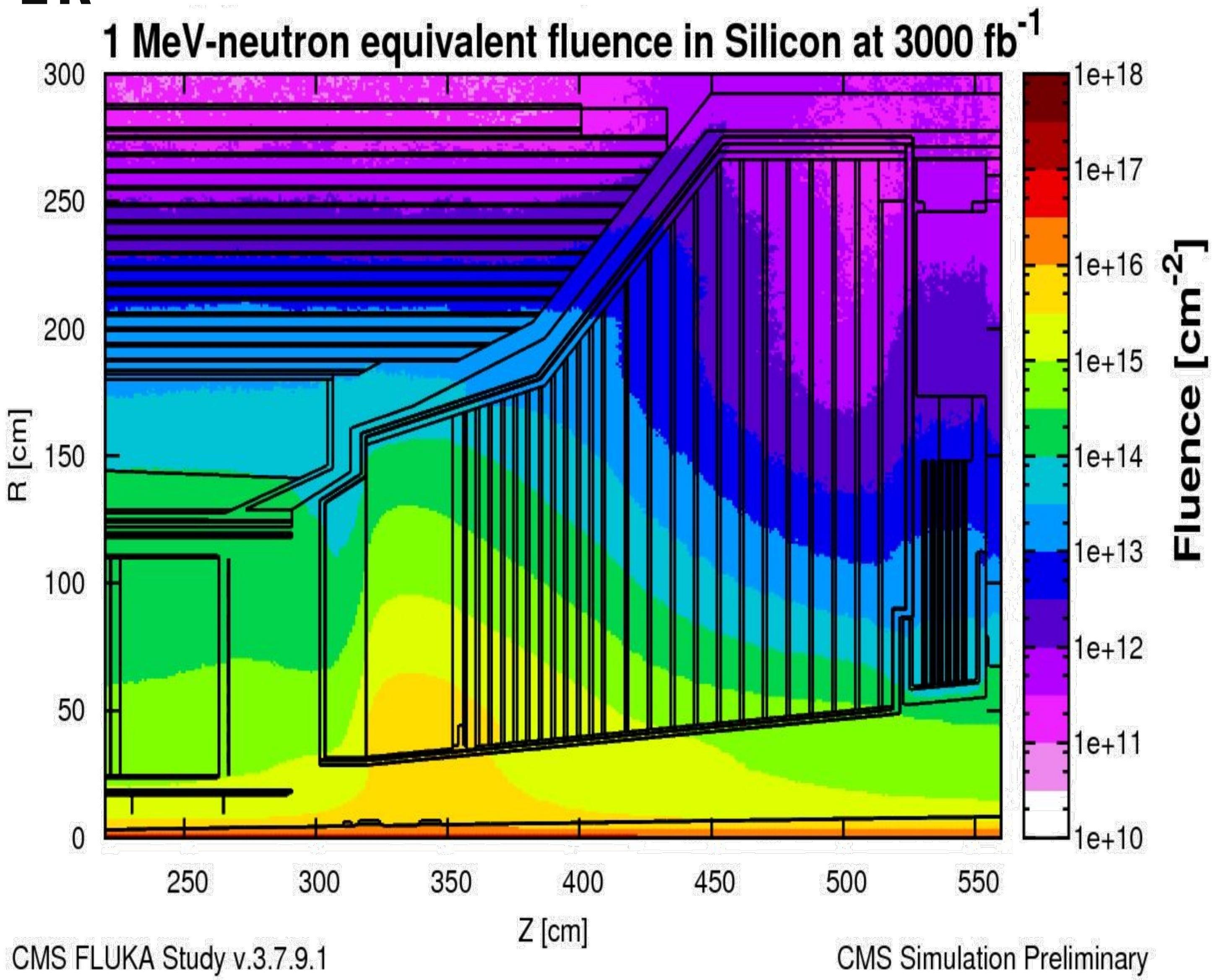

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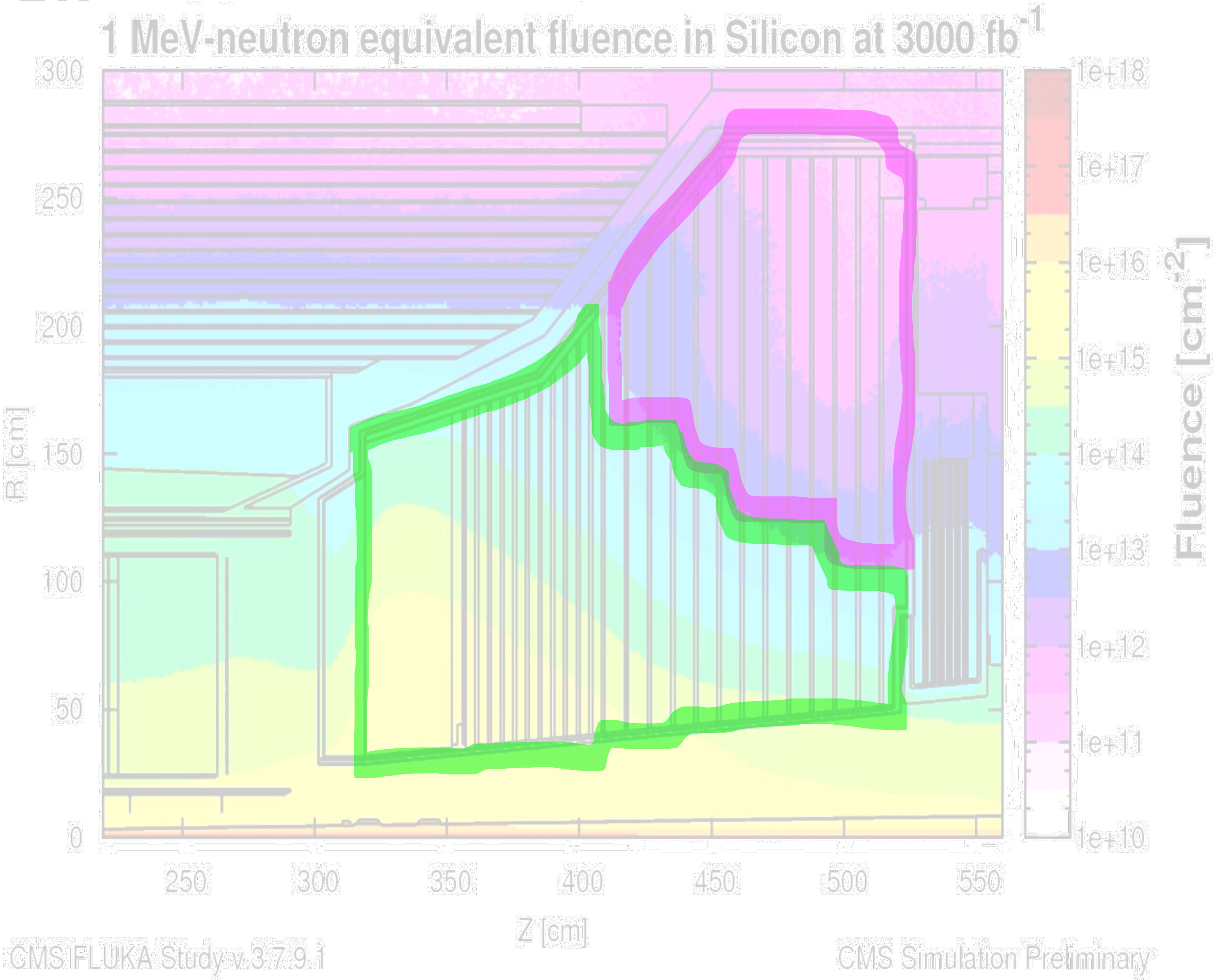

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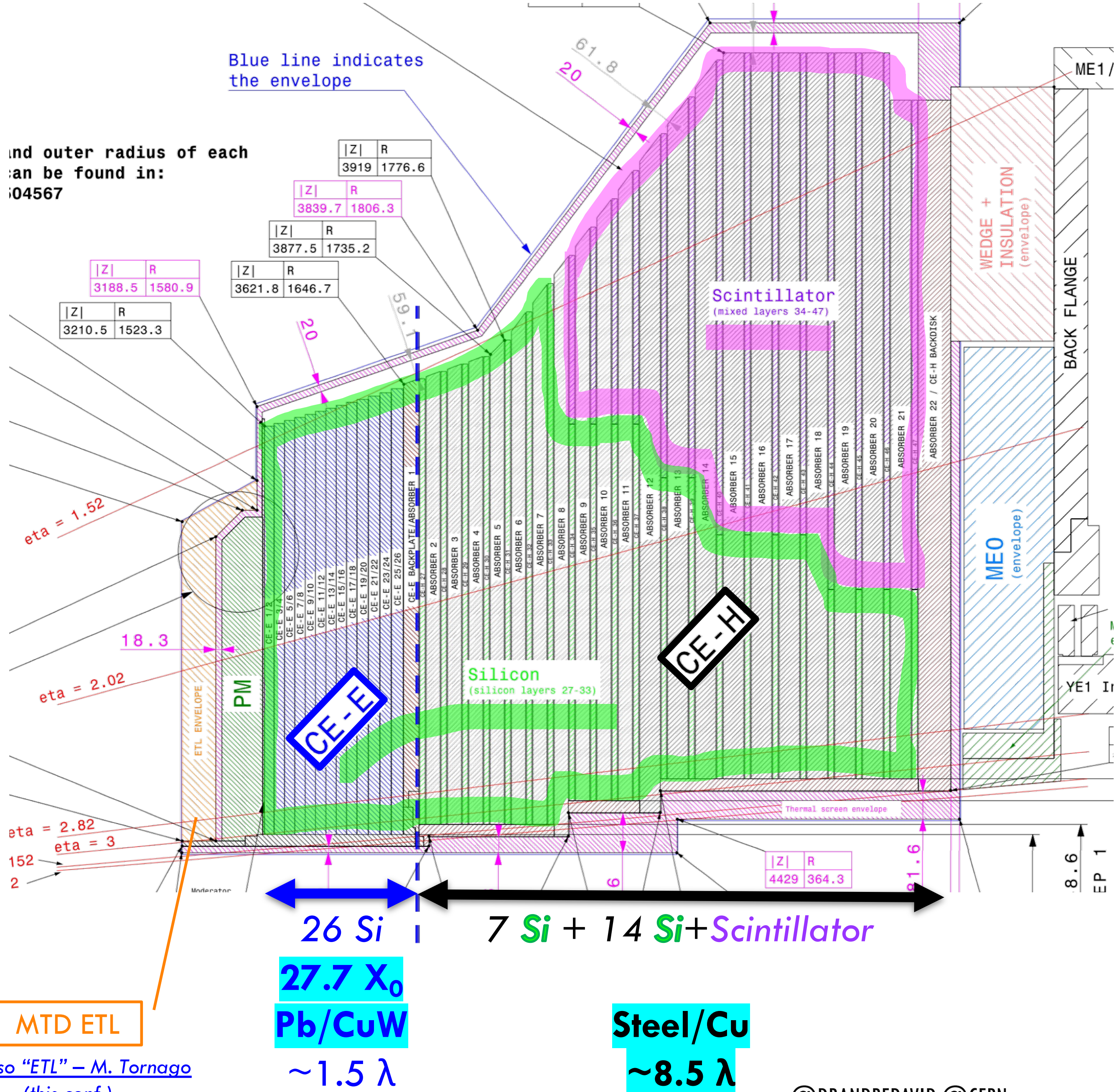


See also "ETL" – M. Tornago (this conf.)

HIGH-GRANULARITY IN 5D – CHALLENGES

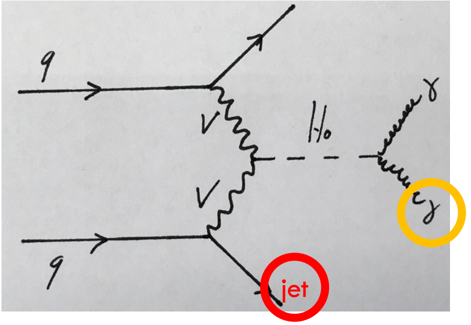
Calorimetric **energy** measurement	Imaging **spatial** granularity	Precise **timing** for showers	Bringing all **5D** together
• ~50k dynamic range: • **Calibrate on single MIP.** • O(10k) MIP in particle showers.	• 6M channels in ~40 m^3. • **~10 channels per cell phone volume.** • Cell sizes from 4 to 30 cm^2.	• **O(25 ps)** per channel energy above O(10) MIPs.	• Reconstruction **algorithms for a new era in calorimetry.**

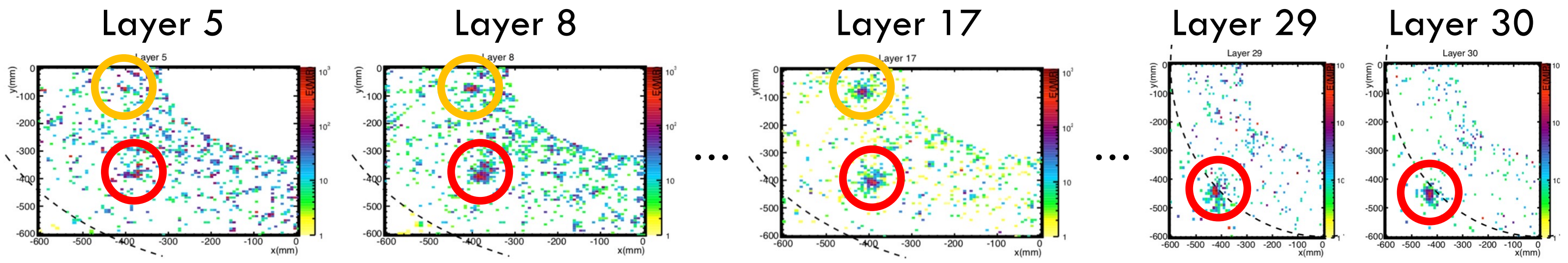
HE WANTS ALL INFINITY STONES...

...BUT HGCAL HAS THREE

T. Quast (Pisa workshop 2022)

THE NEED FOR SPACE-TIME PRECISION





VBF H→γγ

- Turn LHC into a VV collider !
- Forward jet signatures.

Spatial granularity ↑

- Clearly separated objects…
- …but pileup hits clobber interesting objects.

Timing resolution

- Select hits in 90 ps window.
- Pileup hits cleaned up !

Hits from all layers projected to same depth.

[T. Quast (Pisa workshop 2022)]

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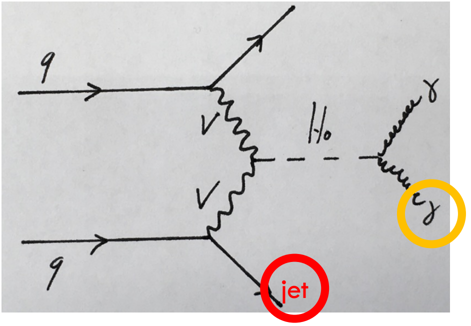

VBF H→γγ

- Make LHC a VV collider !
- Forward jet signatures.

Spatial granularity

- Clearly separated objects…
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Timing resolution ↓

- Select hits in 90 ps window.
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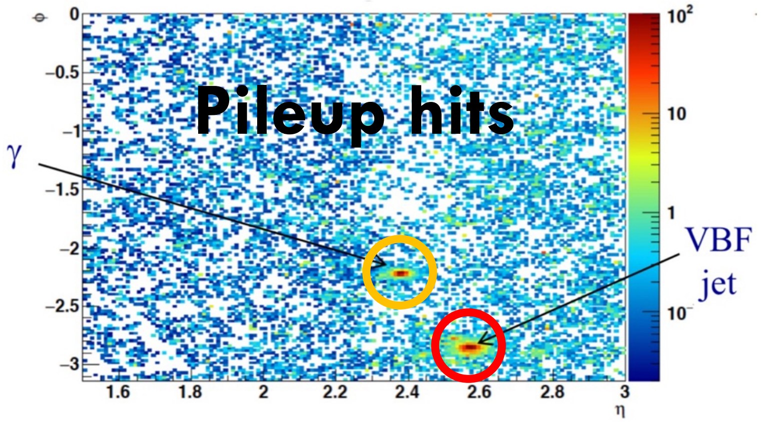
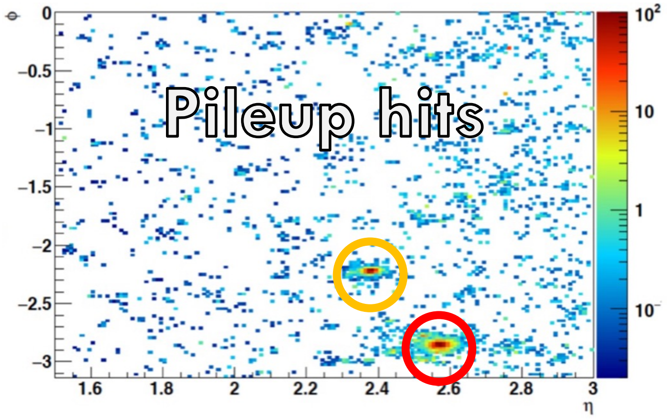


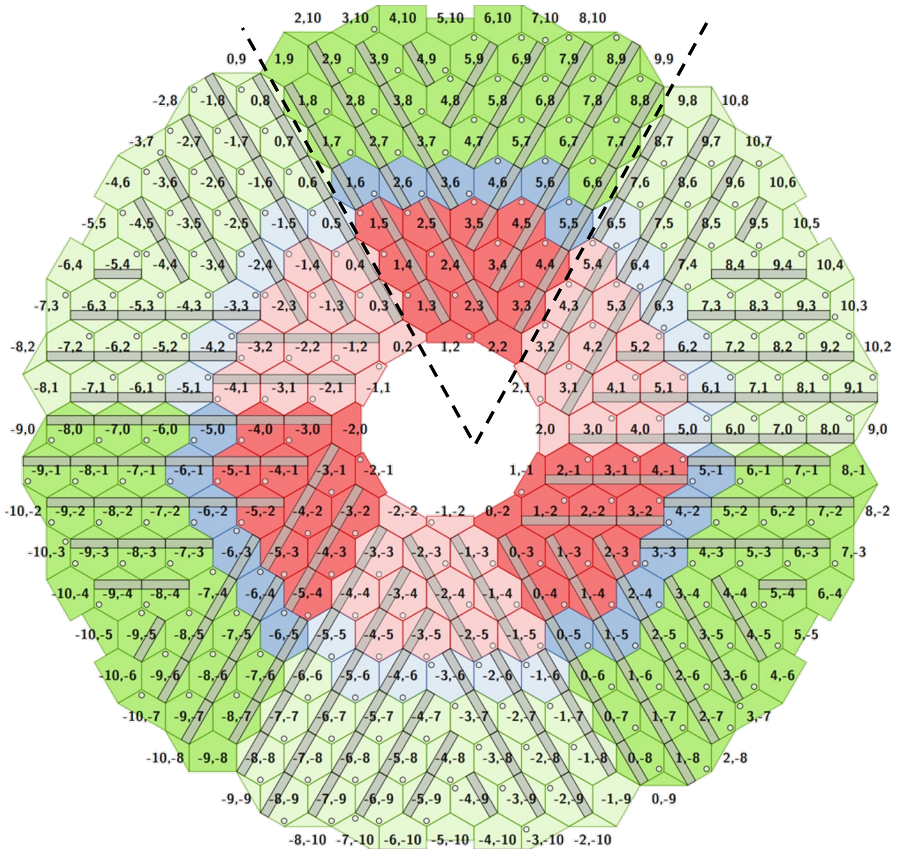


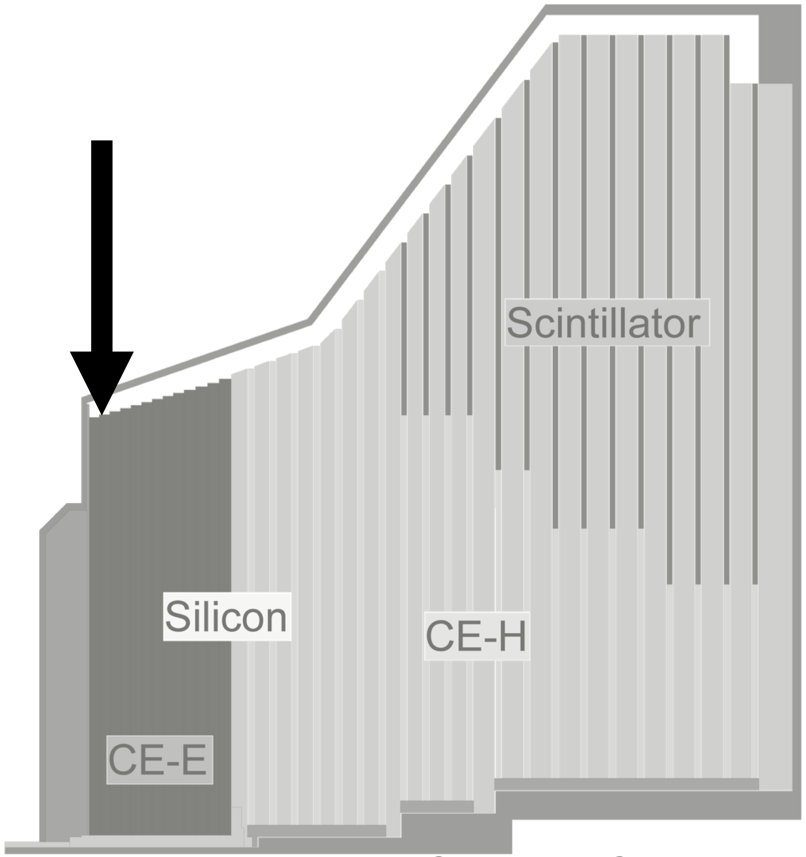
Hits from all layers projected to same depth.

SPATIAL COMPLEXITY FOR HIGH-PERFORMANCE

Layer 3

- 60-degree symmetry
  - 60-degree cassettes
- Low density silicon modules
  - 300 µm thick
  - 200 µm thick
- High-density silicon modules
  - 120 µm thick

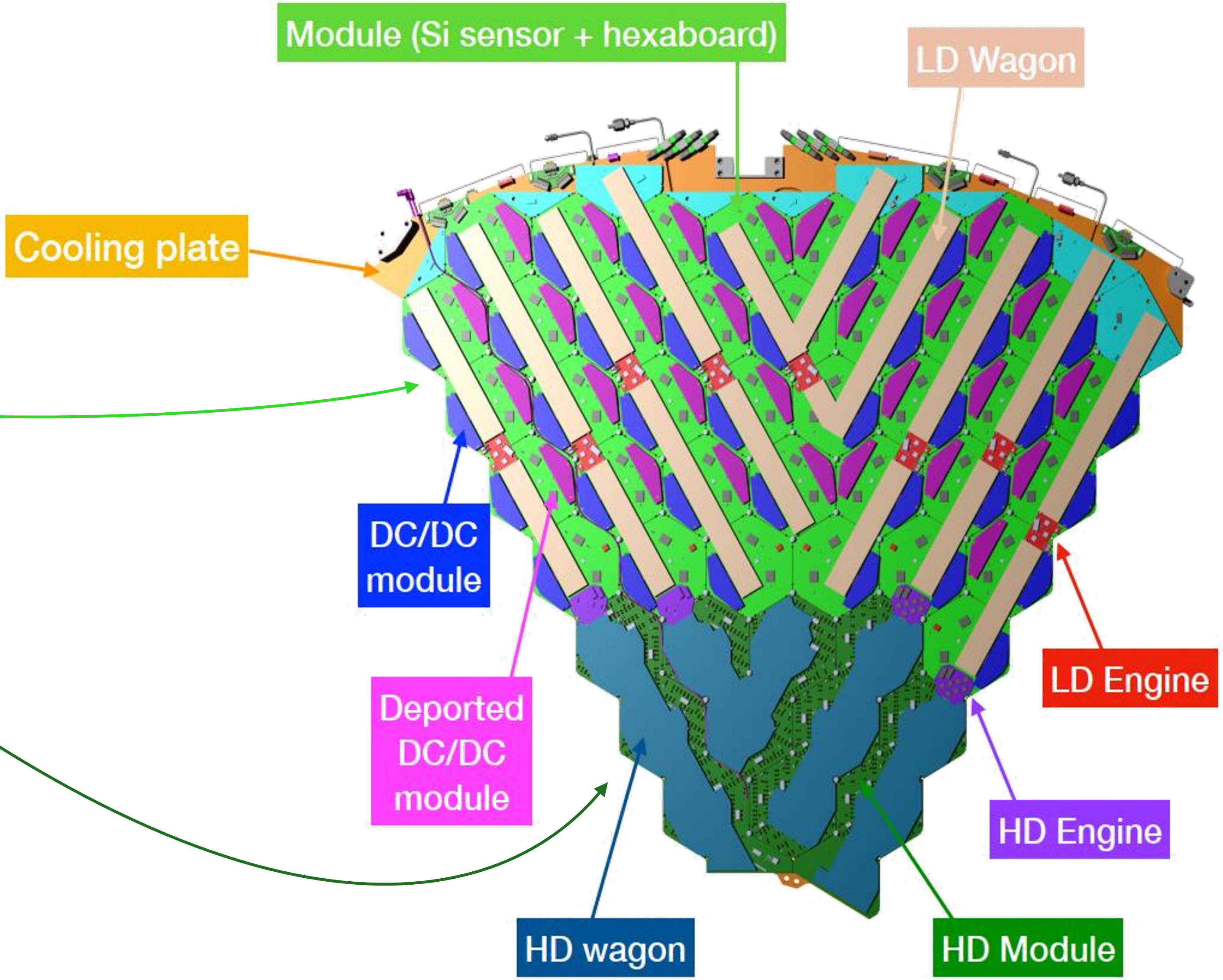




"MOBILE PHONE" INTEGRATION CHALLENGES

Layer 3

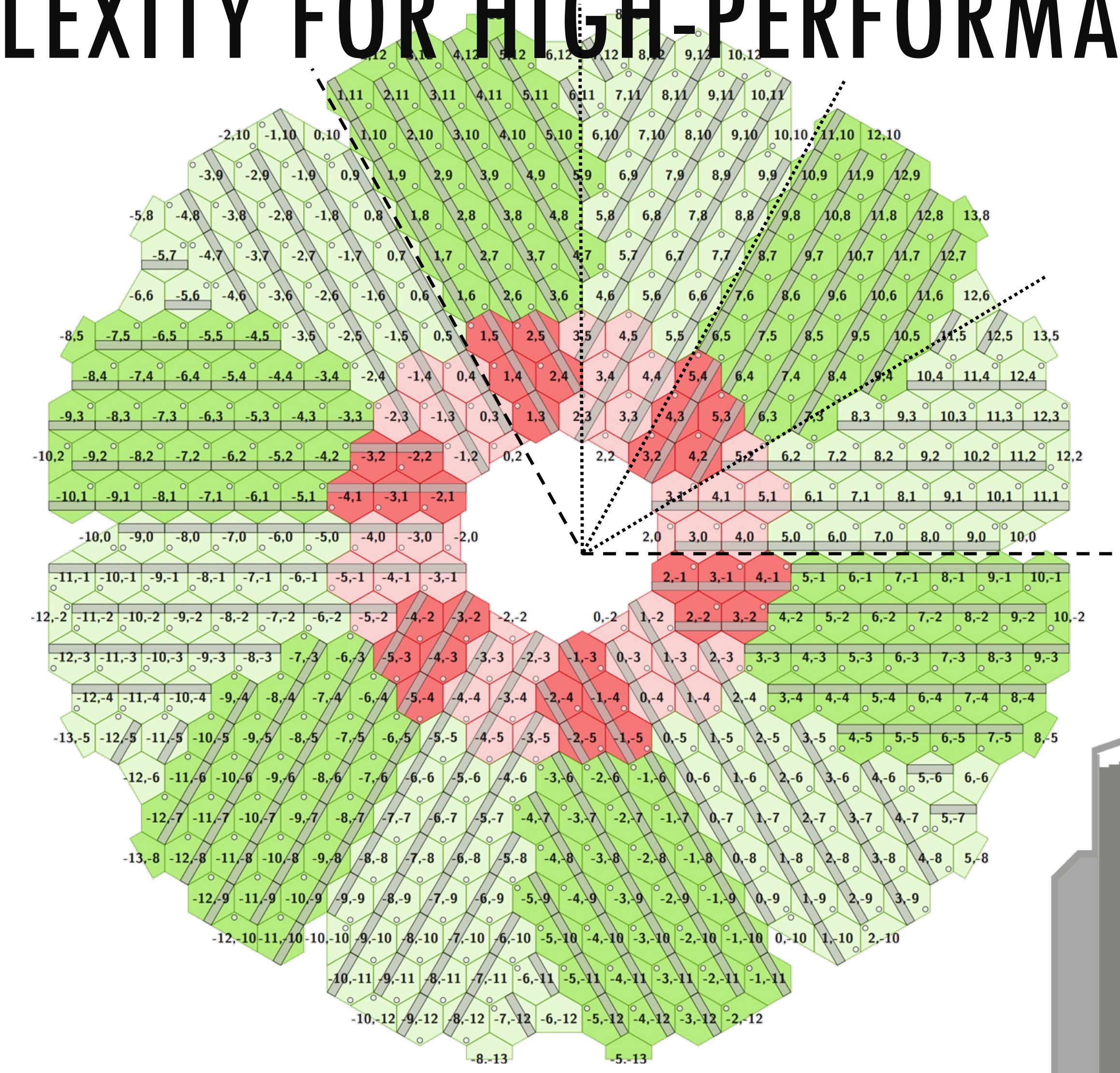
- 60-degree symmetry
  - **60-degree cassettes**
- **Low density silicon modules**
  - 300 µm thick
  - 200 µm thick
- **High-density silicon modules**
  - 120 µm thick

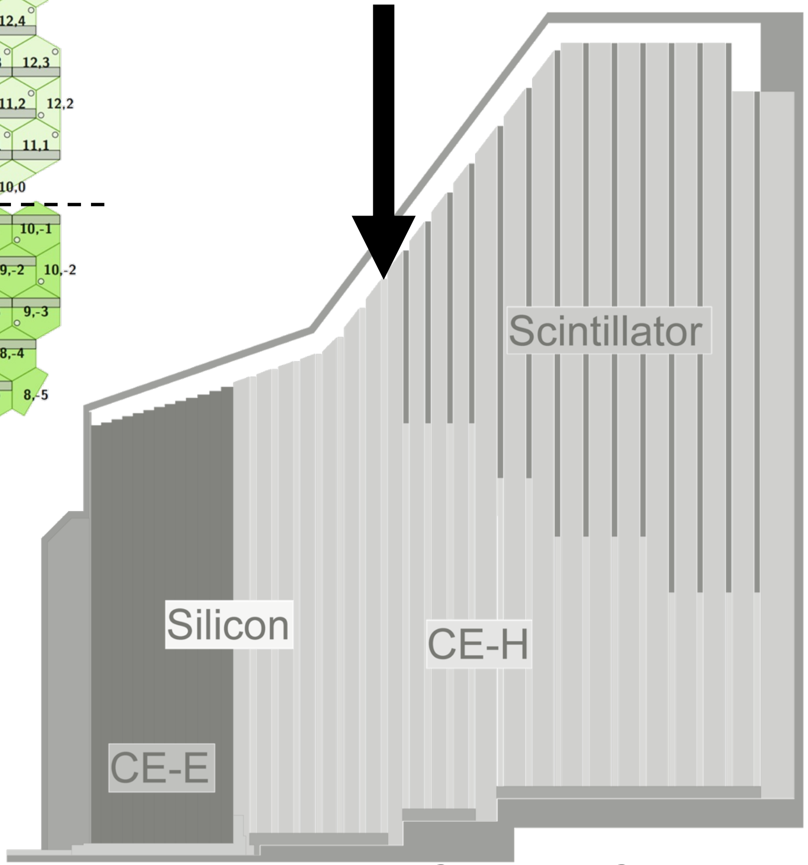


SPATIAL COMPLEXITY FOR HIGH-PERFORMANCE

Layer 33

- 120-degree symmetry
  - 30-degree cassettes
- Low density silicon modules
  - 300 μm thick
- High-density silicon modules
  - 120 μm thick

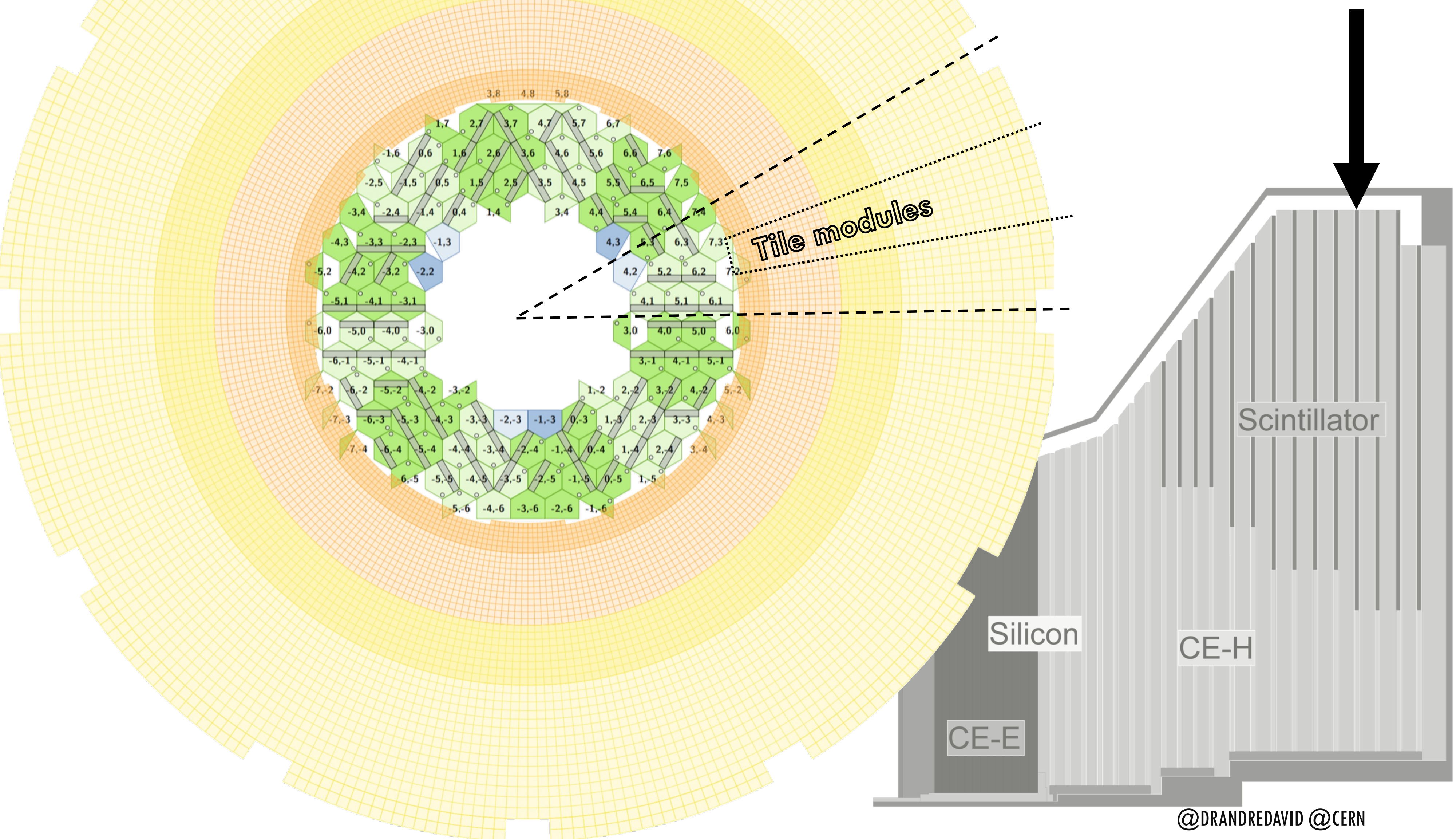




SPATIAL COMPLEXITY FOR HIGH-PERFORMANCE

Layer 44

- 120-degree symmetry
  - **30-degree cassettes**
- Low density silicon modules
  - **300 µm thick**
  - **200 µm thick**
- **Scintillating-tile modules**
  - **10-degree cassettes**



ELEMENTS OF THE PERFORMANCE CHAIN

Active **material** properties

Analogue and digital electronics performance

System integration aspects

Reconstruction algorithms

THE BUILDING BLOCKS – SILICON MODULE

"Hexaboard" PCB

- Connects sensor to readout ASIC (HGCROC).
- Connects to motherboard for control and data transfer.

Silicon sensor

- New 8" process !

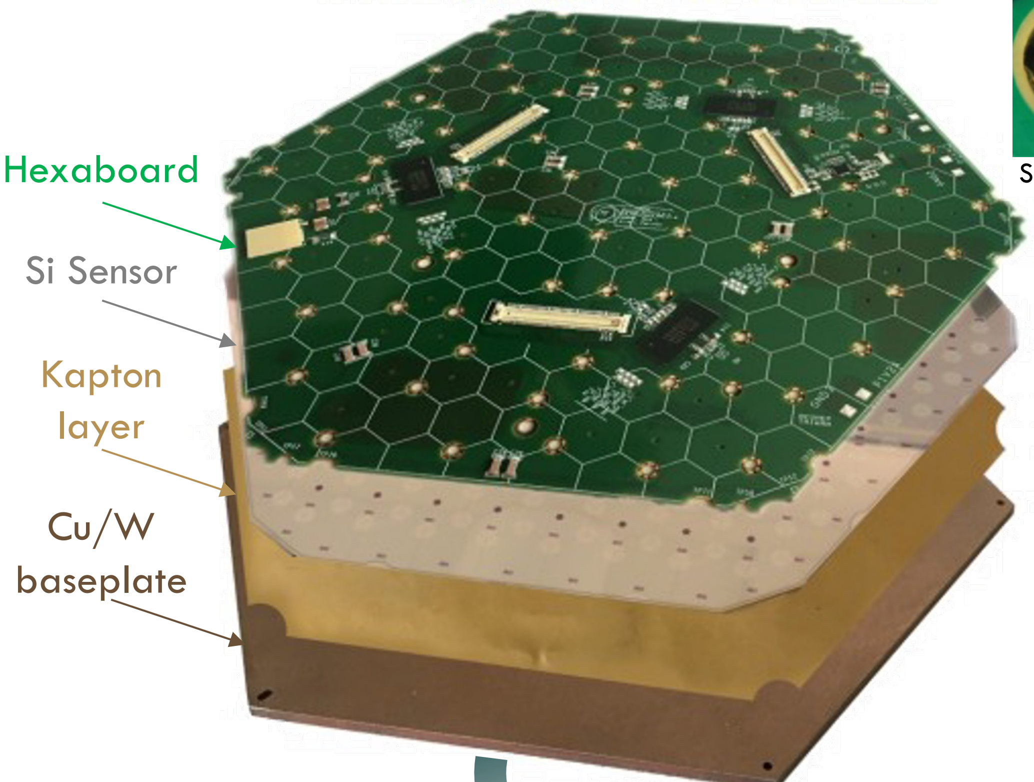
Metalized kapton sheet

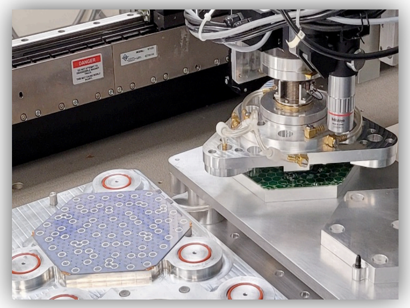
- Bias supply to sensor back side.
- Insulation from baseplate.

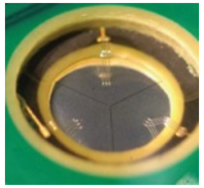
Copper-Tungsten baseplate

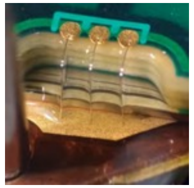
- Rigidity, contributes to absorber material.

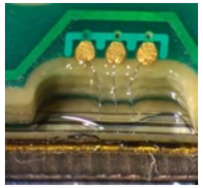
8-inch prototype module stack-up



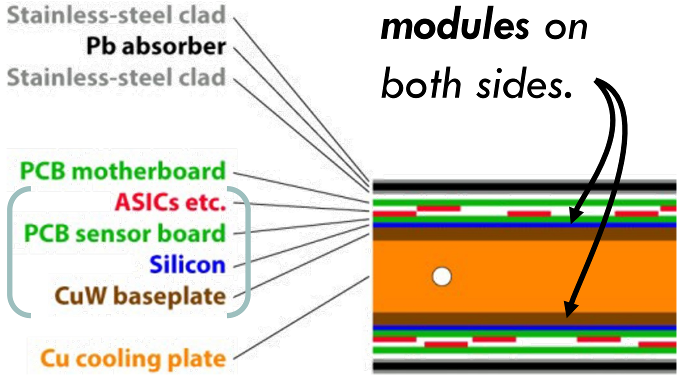



Si pads bonded to PCB


HV bias contacts


Guard ring contacts

*EM section layers have **modules** on both sides.*



Don't miss "Si sensors" – C. Yuan (tomorrow)

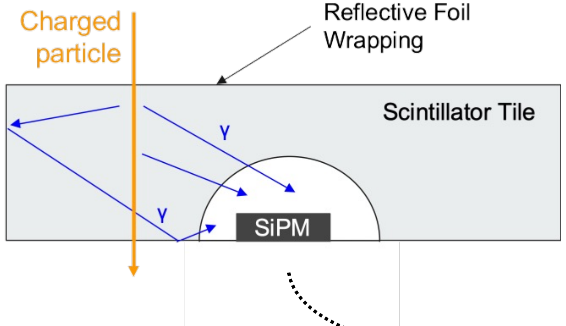
THE BUILDING BLOCKS – SCINTILLATING TILE MODULE

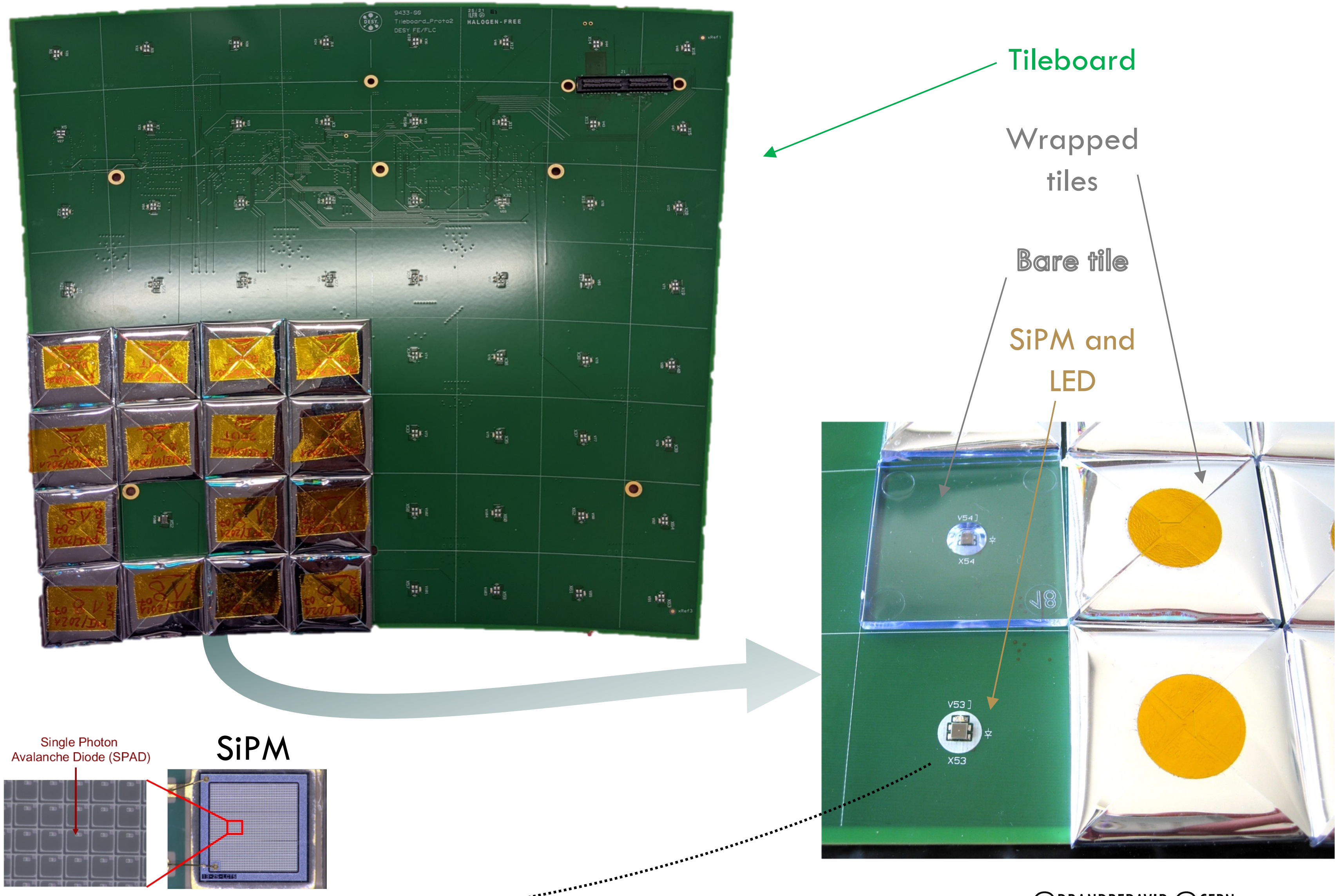
"Tile board" PCB

- Connects Silicon photo multipliers (SiPM) to HGCROC ASIC.
- Connects to motherboard for control and data transfer.

Wrapped scintillating tiles

- Reflective foil wrapping.
- Light collected by SiPM.
- Light injection LED.





ELEMENTS OF THE PERFORMANCE CHAIN

Active material properties

Analogue and digital **electronics** performance

System integration aspects

Reconstruction algorithms

J. D. Gonzalez Martinez (Pisa workshop 2022)

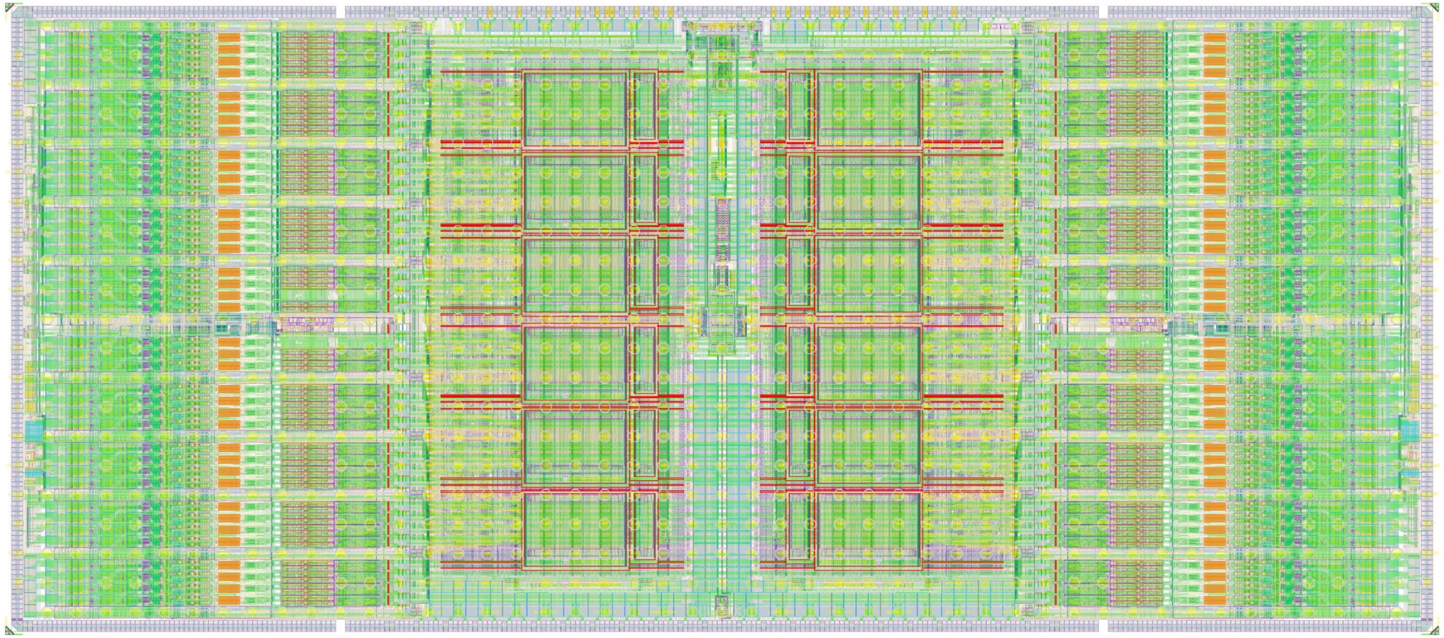
THE HGCROCV3 READOUT CHIP

Covers full dynamic range of HGCAL: silicon and scintillator with small adaptations.

Radiation-tolerant TSMC 130nm CMOS process.

Channels:

- 74 regular.
- 4 common mode:
  - AC-coupled to bias voltage.



J. D. Gonzalez Martinez (Pisa workshop 2022)

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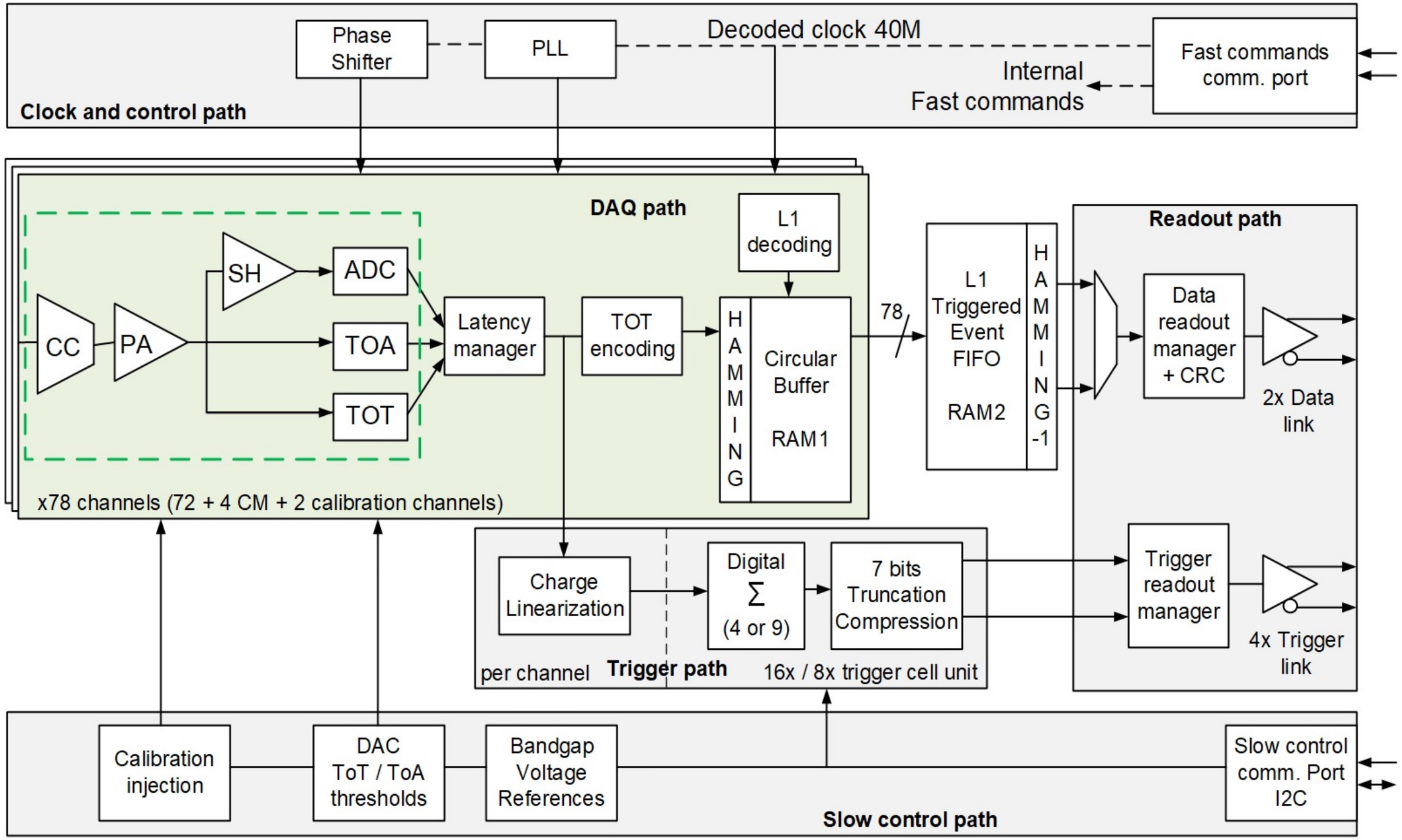
- **4 common mode: ADC-only.**
  - **AC-coupled to bias voltage.**



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Control:

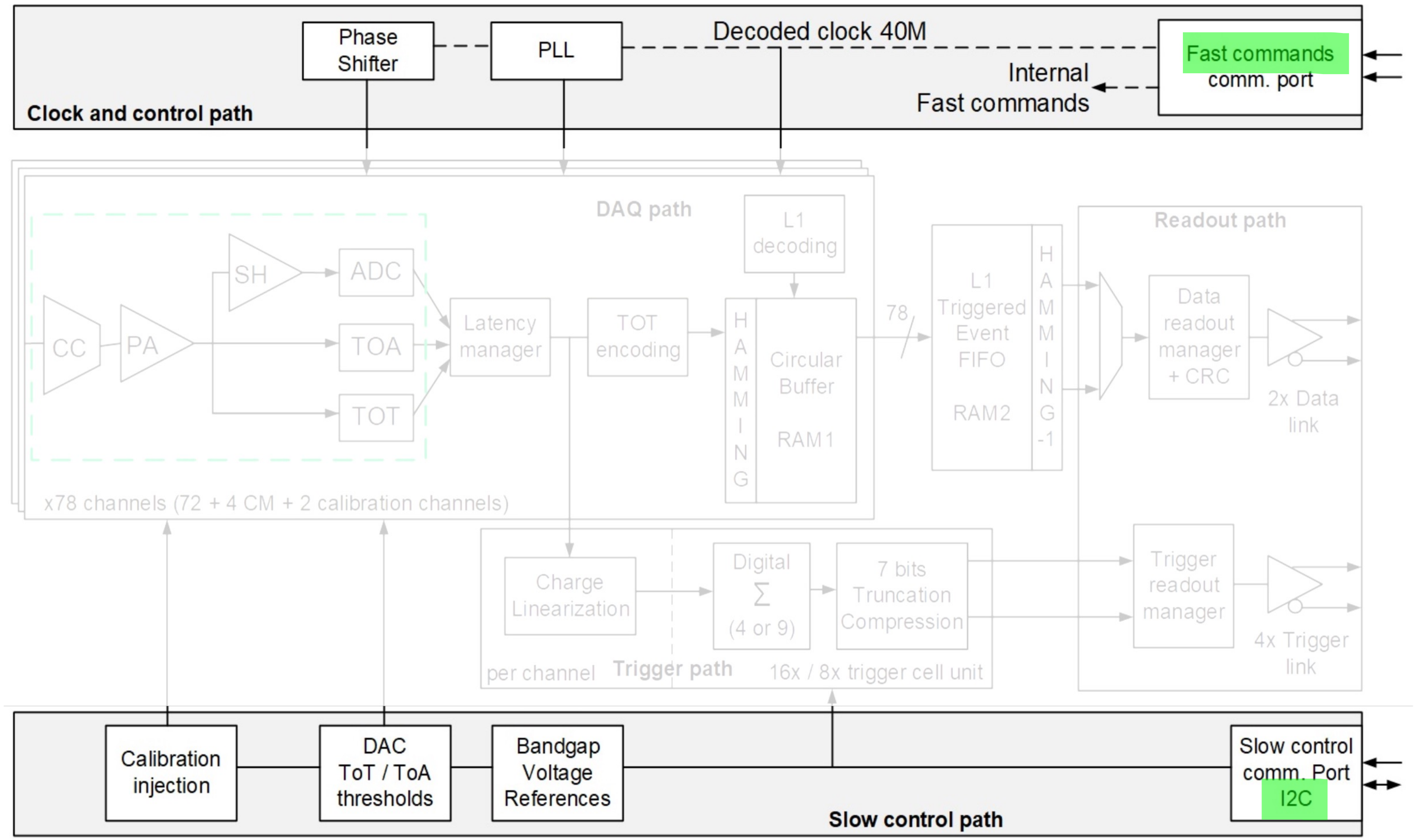
- **Synchronous fast control: custom 320 MHz (8 bit at 40 MHz).**
- **Asynchronous slow control: I2C.**

Measurements

- Programmable pre-amplifier gain.
- Charge/energy:
  - ADC for small values: 10-bit 40 MHz SAR.
  - TOT TDC after preamplifier saturates: 12-bit with 50 ps LSB.
- Timing: TOA TDC 10-bit and 25 ps LSB.

1.28 Gb/s outputs

- Trigger primitive data
  - Sum of 4 (9) channels, linearization, compression to 7-bit floating point format.
- DAQ event data
  - 12.5 µs latency buffer (500-deep) for ADC/TOT/TOA.
  - 32-event derandomizer buffer (750 kHz av. trigger rate).



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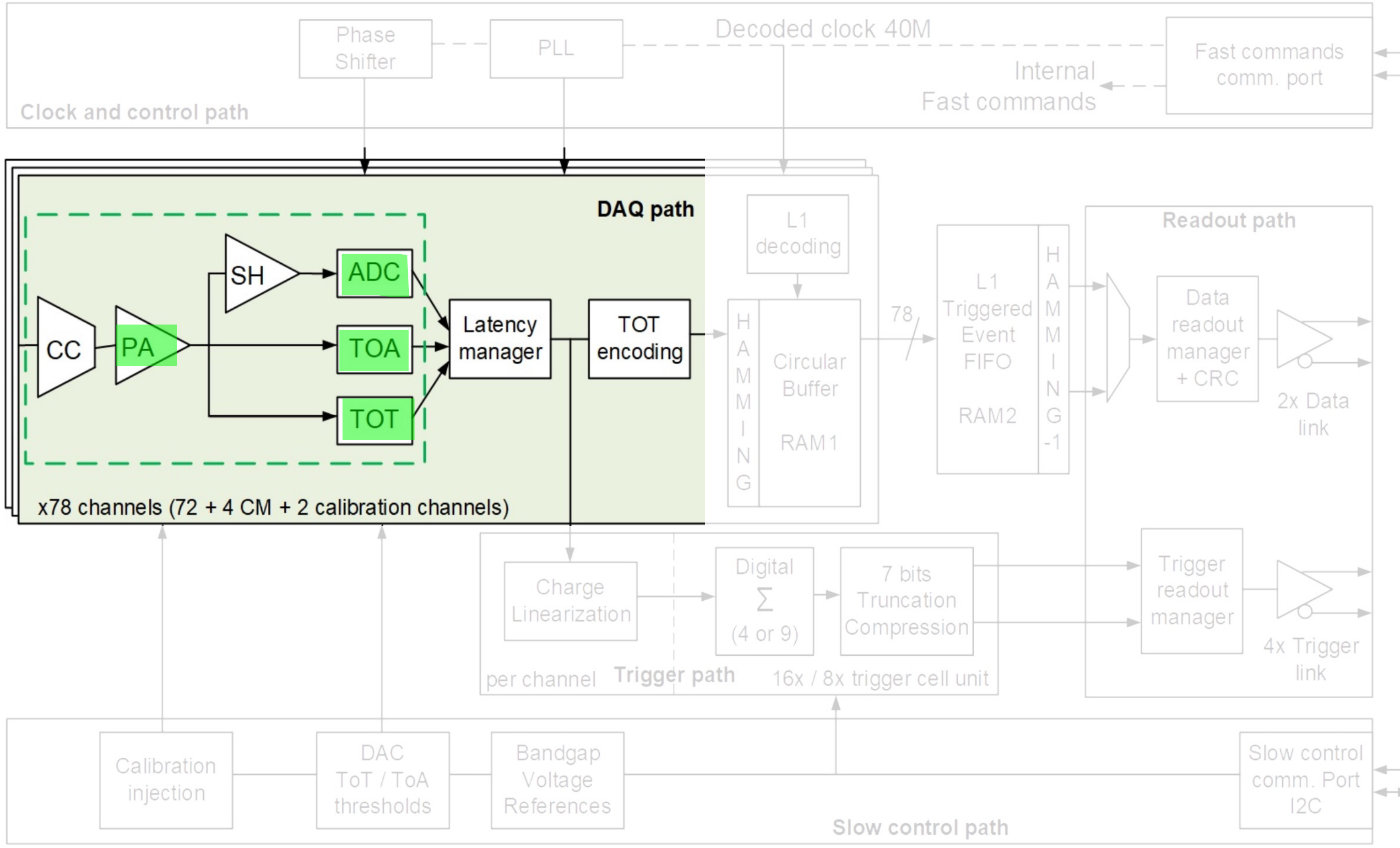

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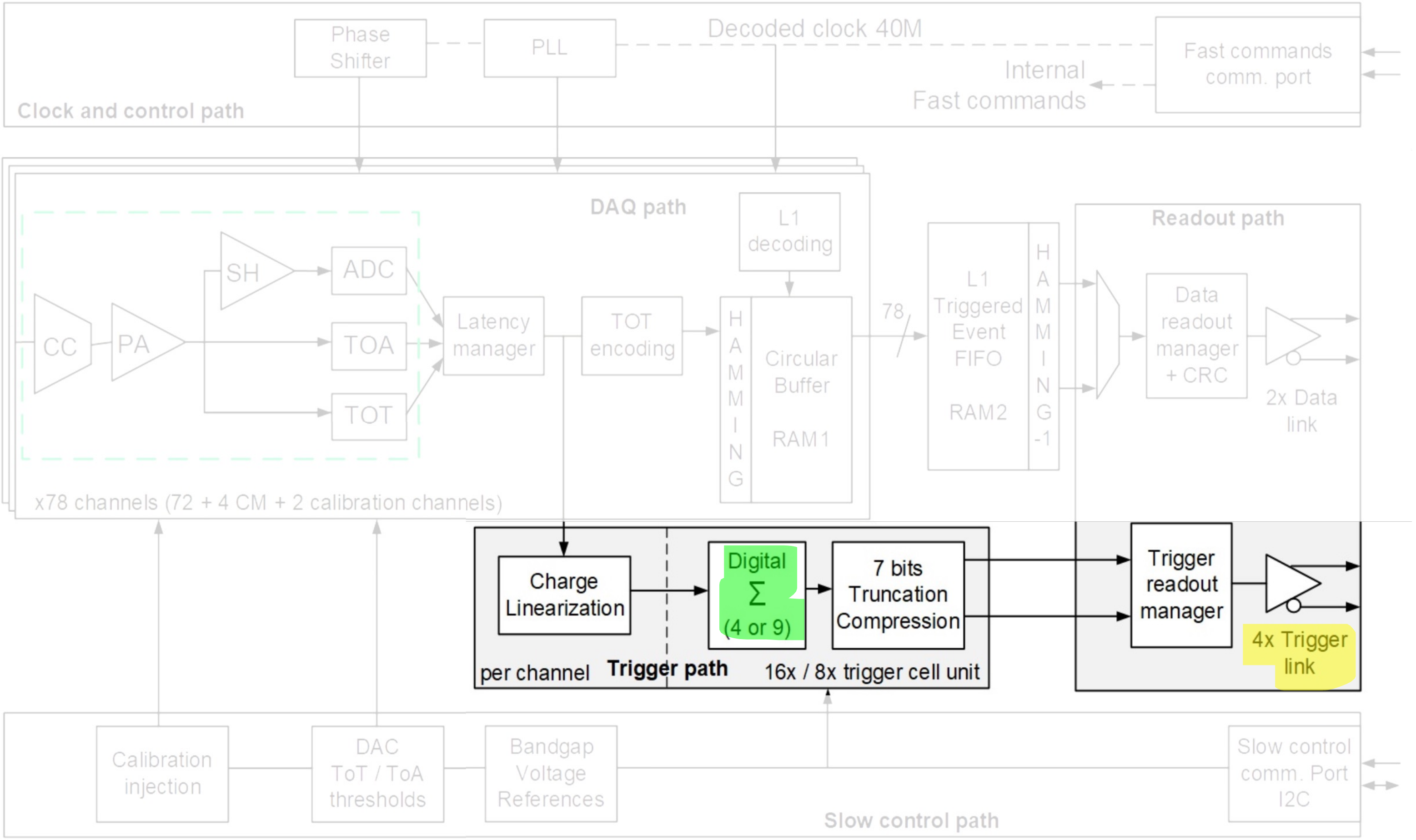

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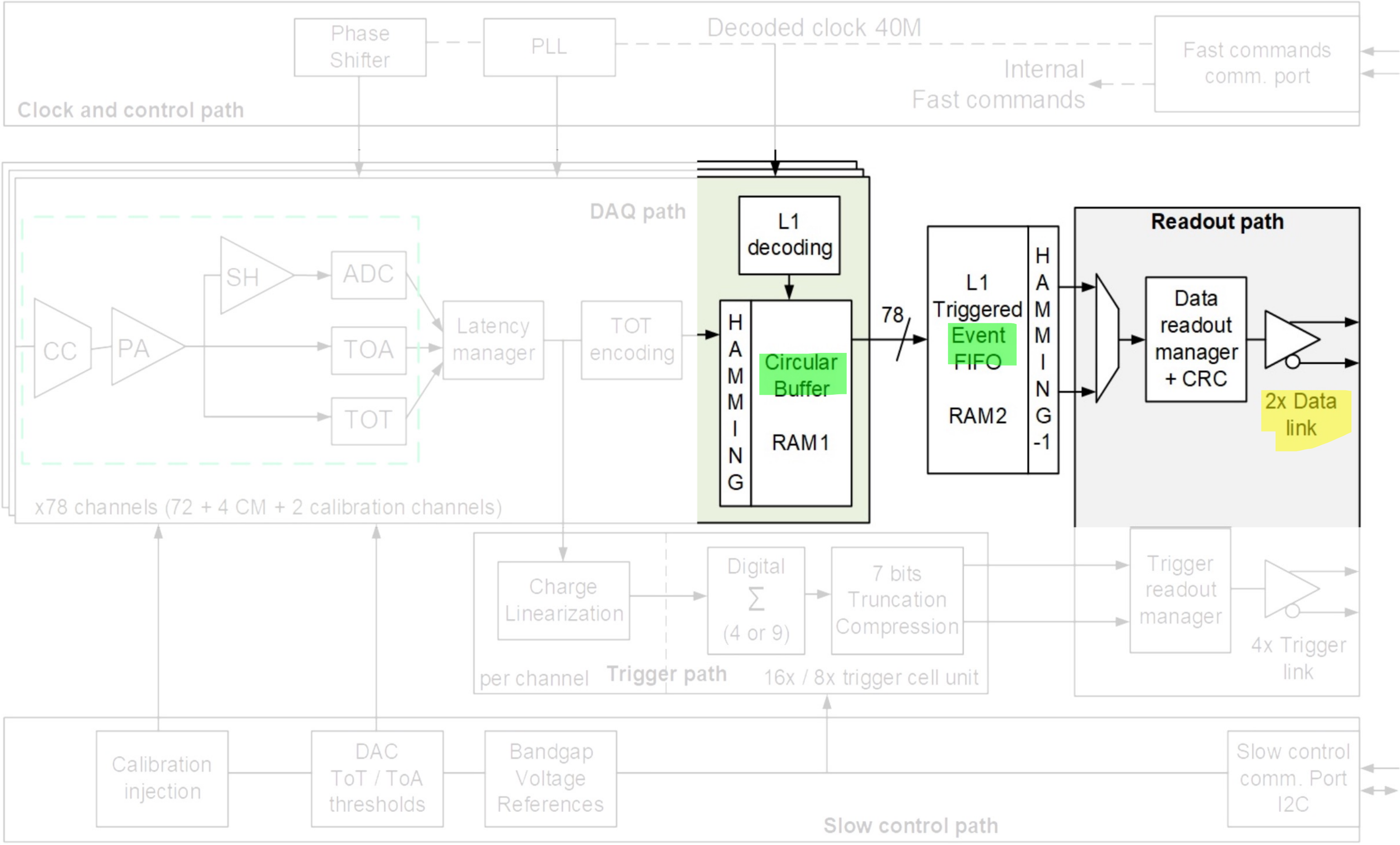


ELEMENTS OF THE PERFORMANCE CHAIN

- Active material properties
- Analogue and digital electronics performance
- **System** integration aspects
- Reconstruction algorithms

JINST 16 (2021) 04, T04002
JINST 16 (2021) 04, T04001

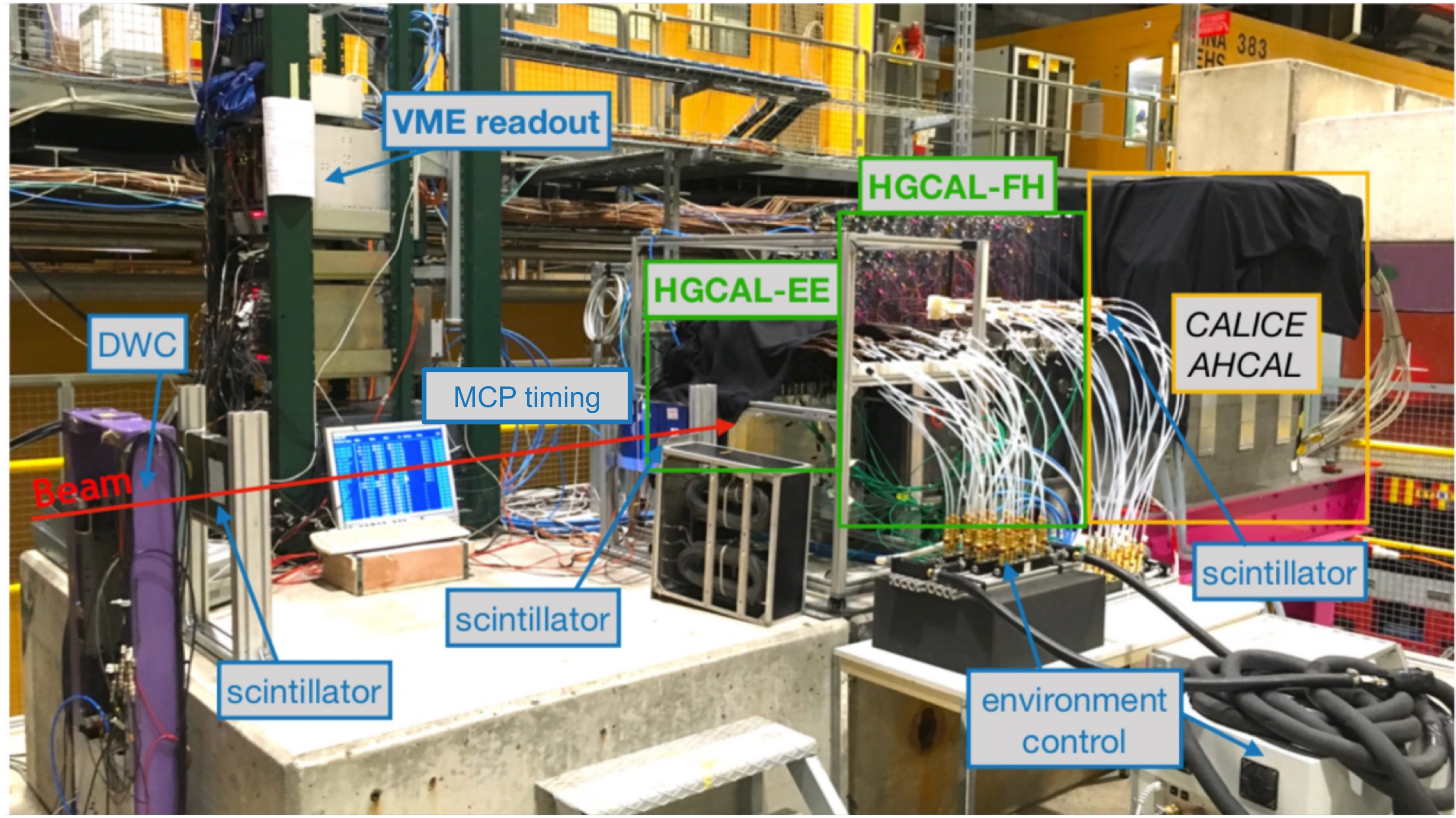
2018 PROTOTYPE

Large-scale prototype in SPS H2

- HGCAL EM and Hadronic sections:
  - 94 prototype 6” silicon modules.
  - 12’000 silicon pad channels.
- CALICE AHCAL scintillator section.

Beams: e^+, μ^-, π^- up to 300 GeV/c.

- Full in-situ MIP and timing calibration.
- Performance comparison to GEANT4 simulation.



See also “CALICE AHCAL” – A. Irles (tomorrow)

CERN-THESIS-2019-367
JINST 17 (2022) 05, P05022

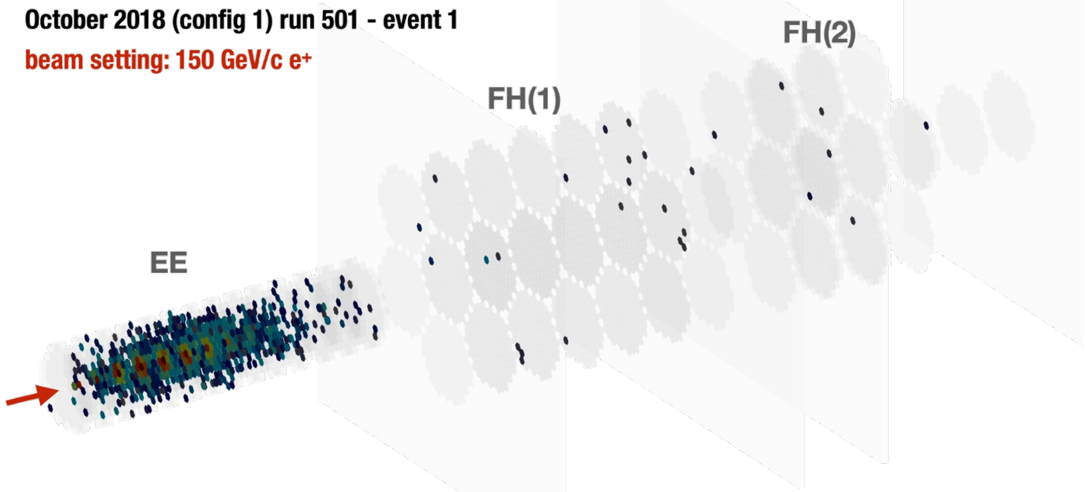
2018 PROTOTYPE ELECTROMAGNETIC PERFORMANCE

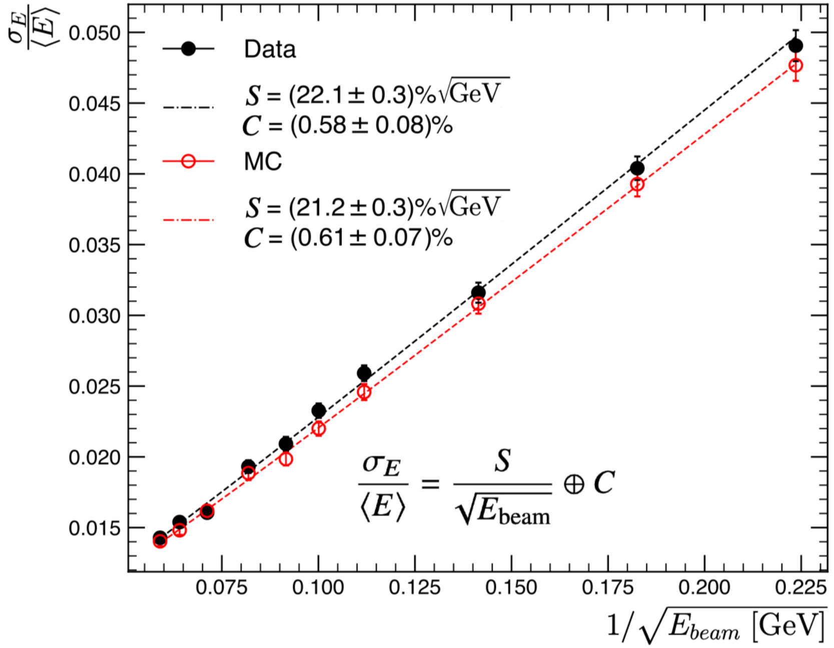
Good energy resolution

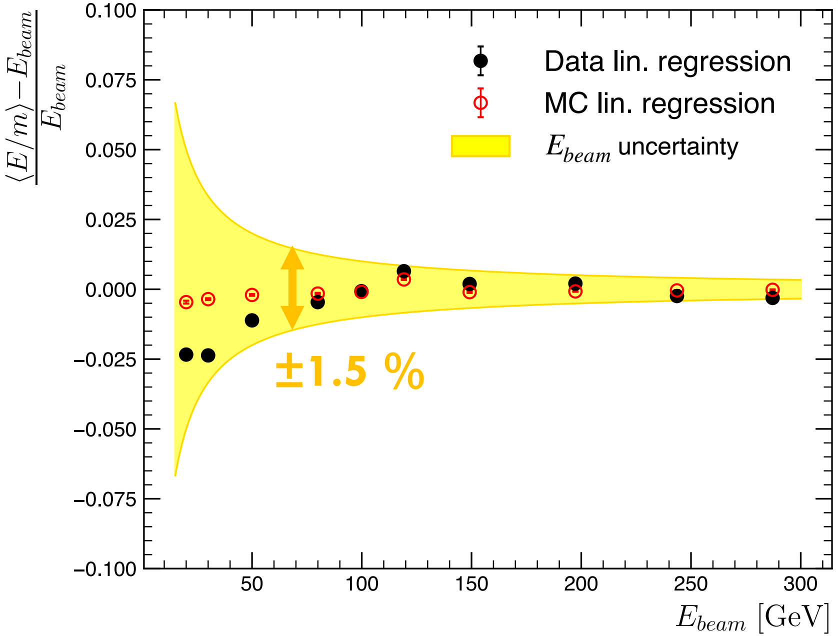
- 0.6% local constant term.
- 22% stochastic term.

Good linearity for E > ~50GeV.

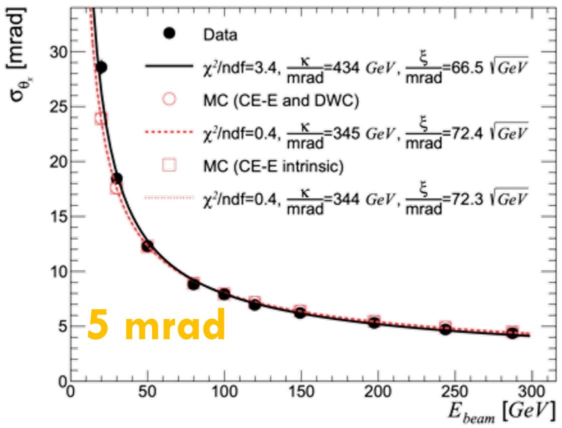
Good pointing resolution.







Shower axis angular resolution



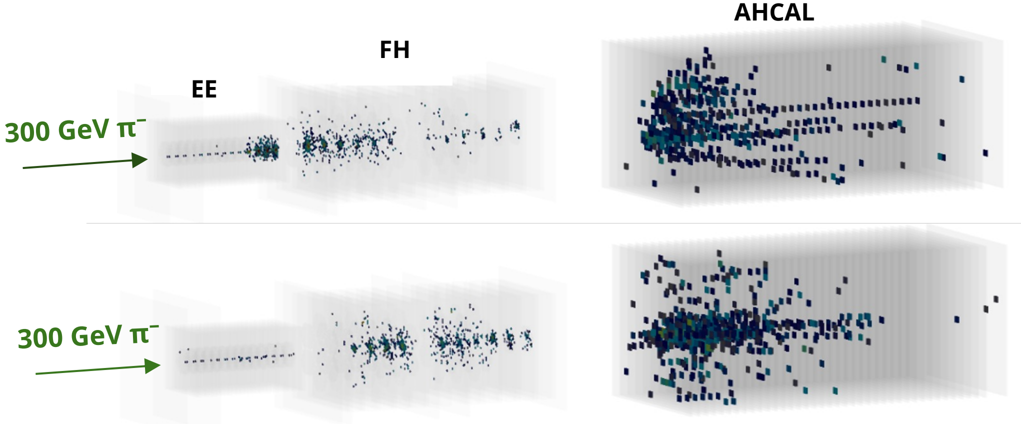
A. Sirohi (BTTB 2022)

2018 PROTOTYPE HADRONIC PERFORMANCE

Hadronic showers have large variability.

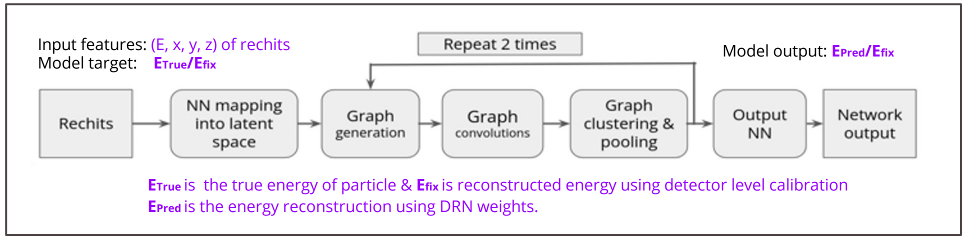
Exploratory work on energy regression

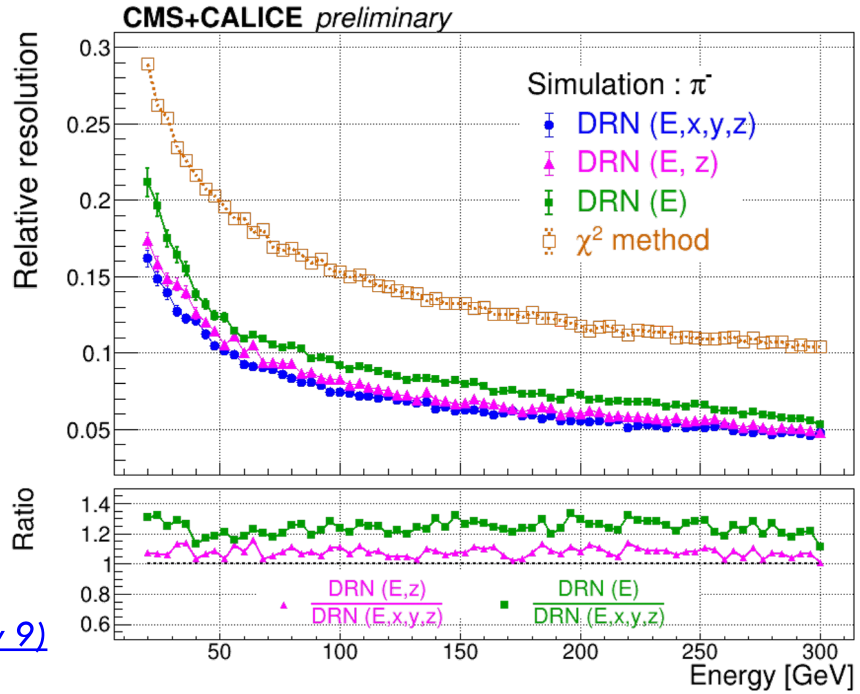
- Dynamic Reduction Network (DRN).
- Comparison with per-layer weighted energy.
  - Good data-simulation agreement.
  - Promising resolution and linearity performance.
  - Developing understanding of performance.

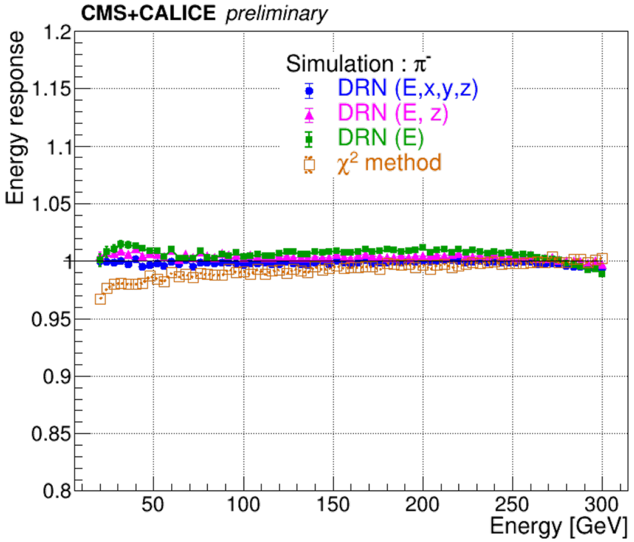


Early shower

Late shower







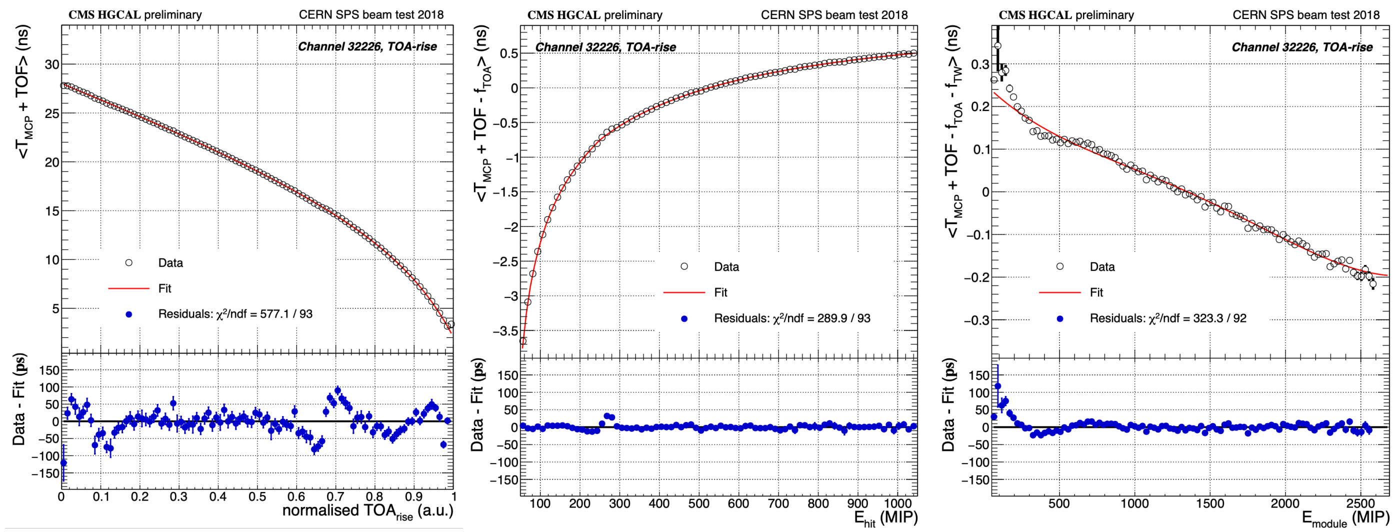
Don't miss "GNN reconstruction" – S. Rothman (July 9)

T. Quast (Pisa workshop 2022)

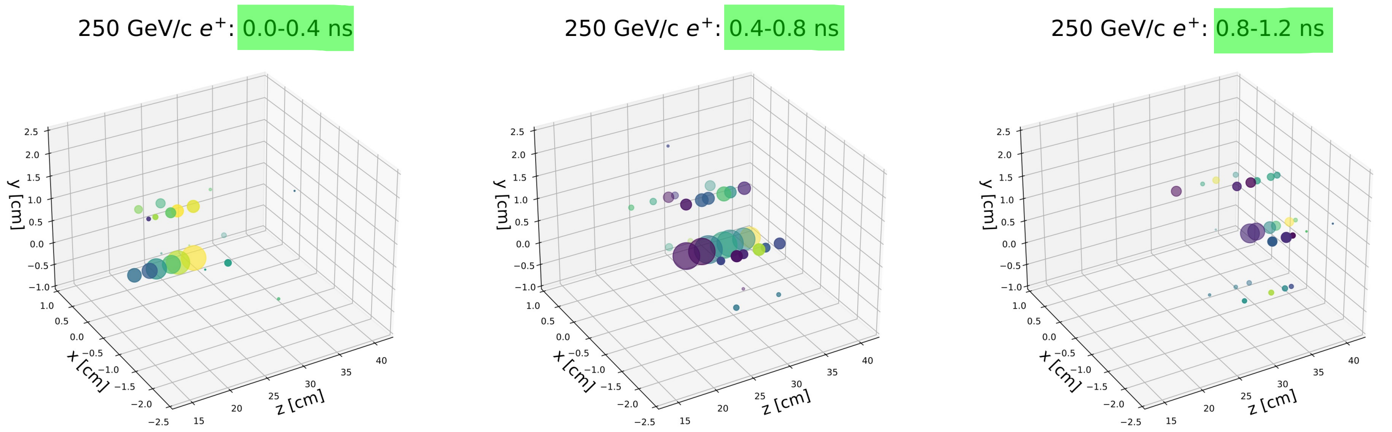
2018 PROTOTYPE TIMING PERFORMANCE

Calibration[3]

- Response non-linearity: ~10 ns
- Discriminator time-walk: ~ 1 ns
- Module-energy corrections: ~ 0.1 ns



Resolved the time development of real particle showers !



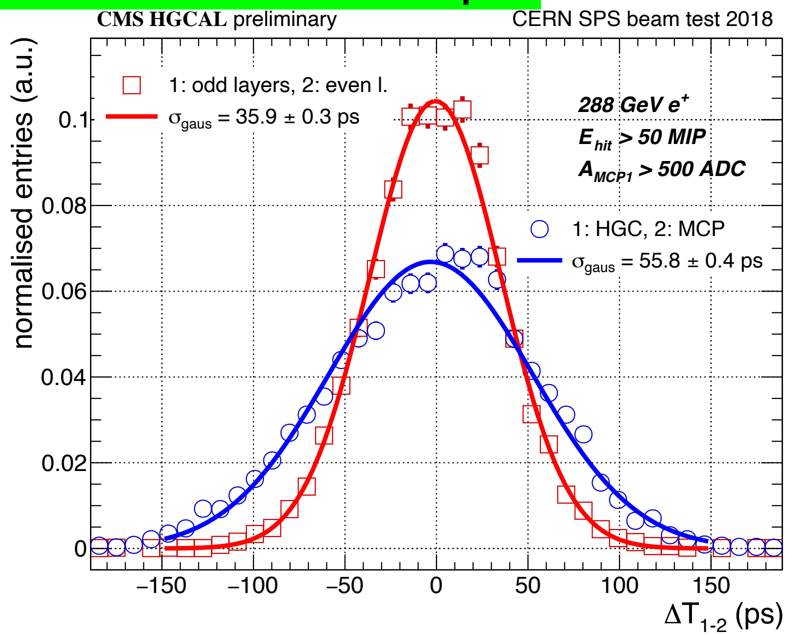
Early hit → Late hit

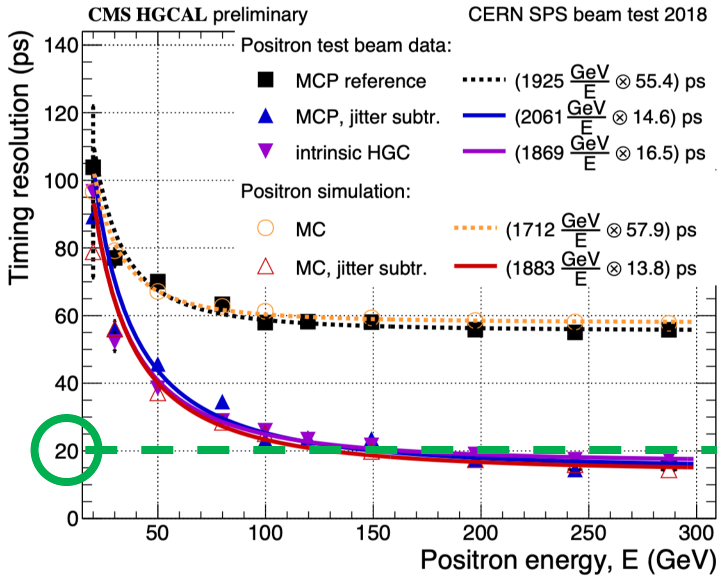
2018 PROTOTYPE TIMING PERFORMANCE

Complex set of measurements

- Cross-checks with MCP detector reference.
- Est. MCP-HGCAL correlated jitter O(50 ps).

High-energy shower time resolution < 20 ps !

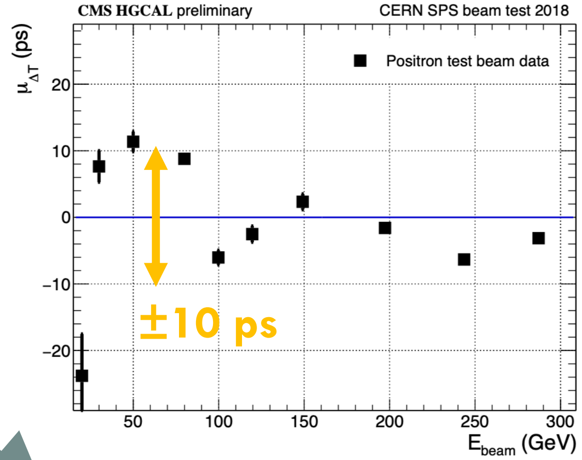




Resolution-weighed average of timing of shower hits: **< 20 ps** for **E > 200 GeV**.

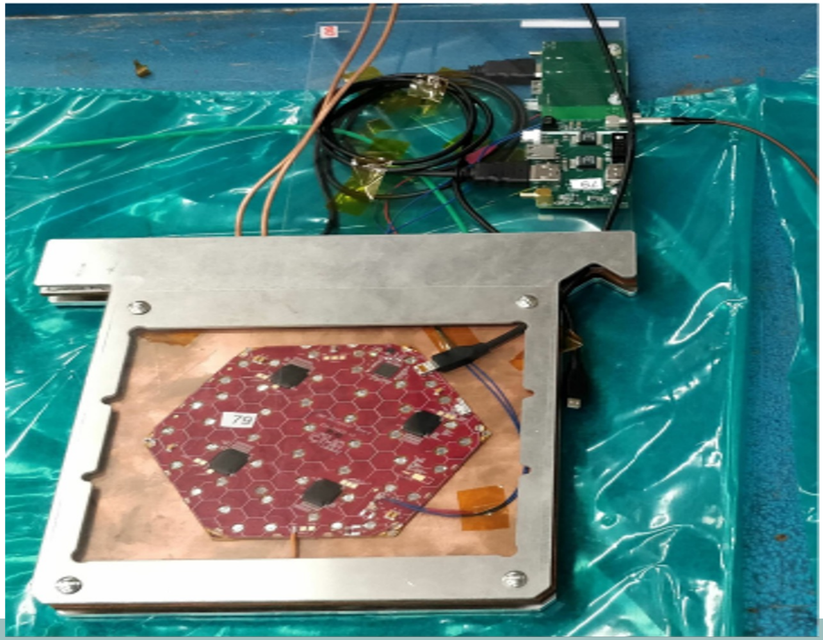
HGCAL odd vs even layers: **~36 ps**

HGCAL-MCP: **~56 ps** (incl. global jitter)



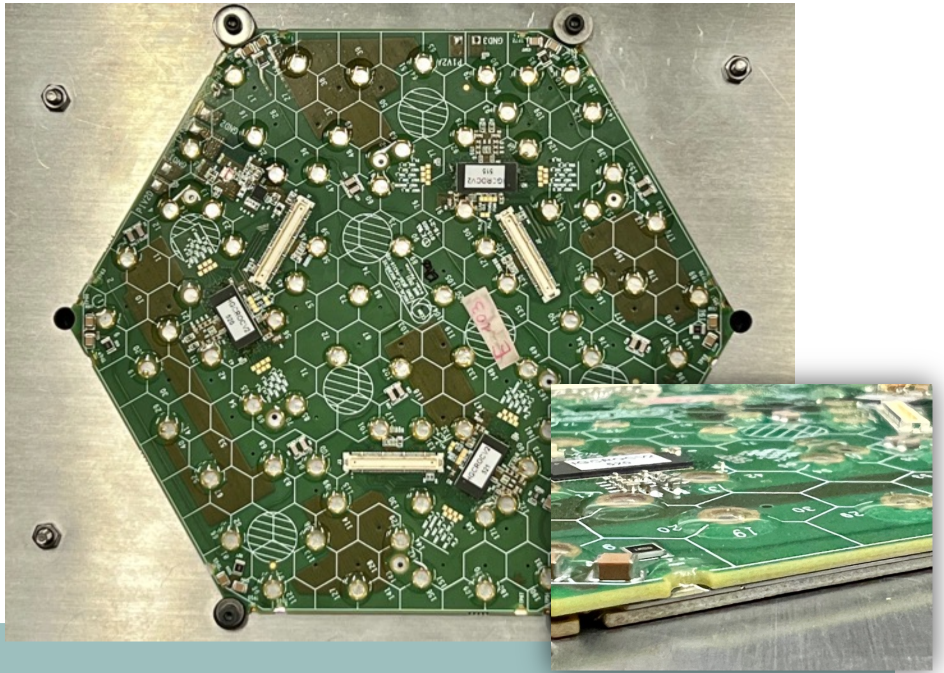
Accuracy w.r.t. MCP reference within **±10 ps** for **E > 50 GeV**.

PERFORMANCE IN MORE RECENT SYSTEMS



2018 prototype

- 6" sensor and module
- SKIROC2-CMS ASIC



2021 prototype

- 8" sensor and module
- HGCROCv3 ASIC

A. Becker (BTTB 2022)

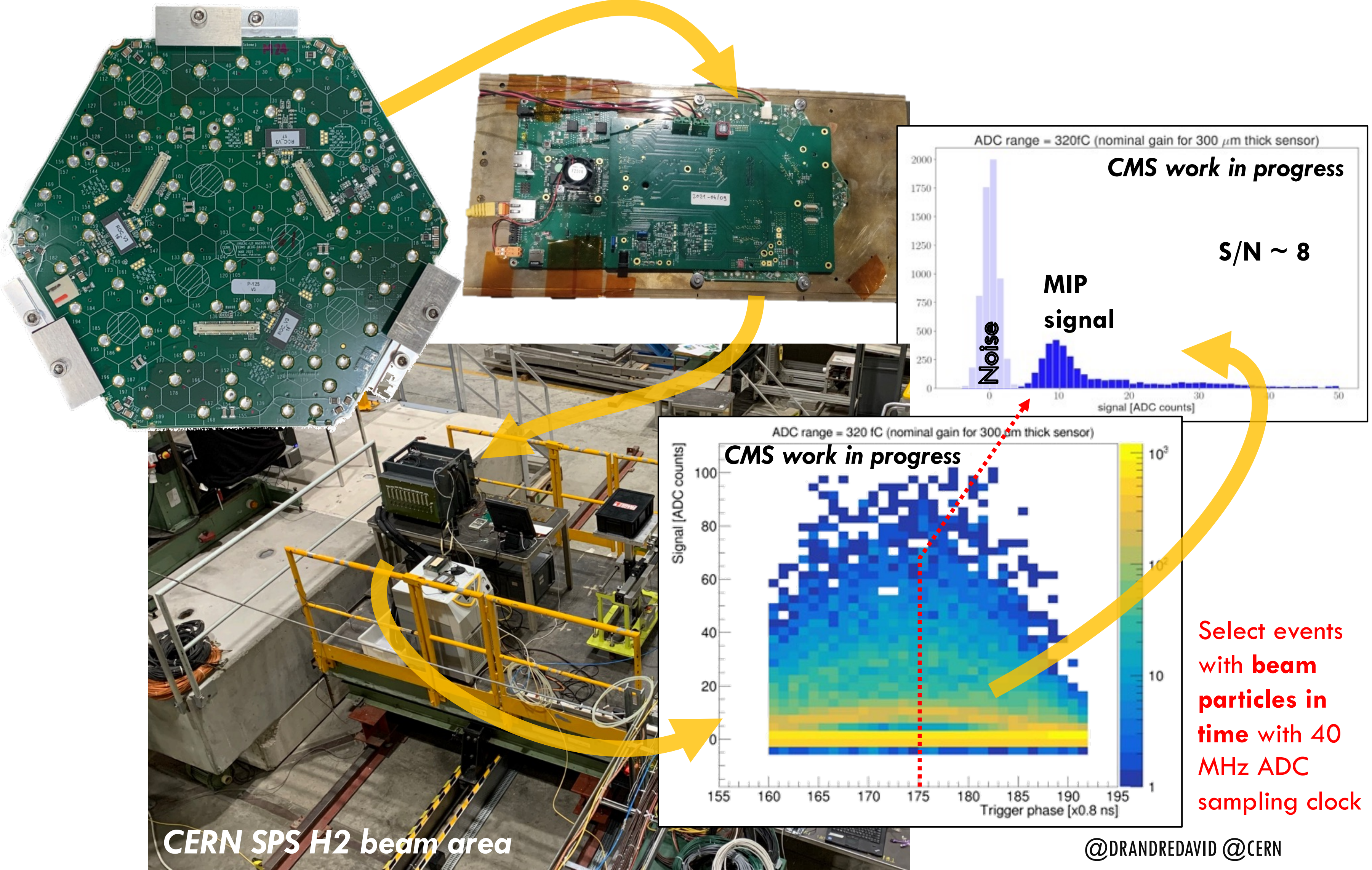
2021 SILICON MODULE PERFORMANCE

300 µm silicon sensor module with latest components
- HGCROCv3
- Hexaboard PCB

Very fast turnaround:
- Jul. 2021: ROC ASICs received.
- *(debug, fix, assemble)*$^{\sim 3}$
- Oct. 2021: module in beam.

Asynchronous beam trigger
- Trigger phase resolution ~ 0.8 ns.

Clear MIP signal peak with almost-final components !



Select events with **beam particles in time** with 40 MHz ADC sampling clock

M. De Silva (BTTB 2022)

2022 SIPM-ON-TILE PERFORMANCE

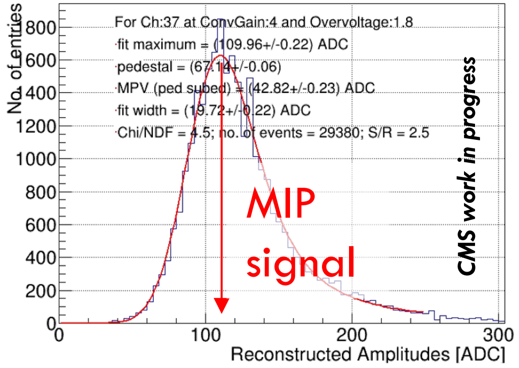
Performance of irradiated SiPMs

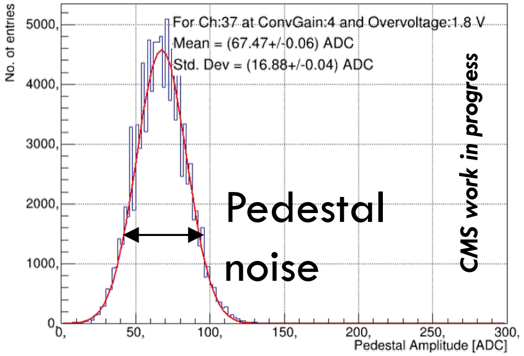
- Irradiated to $2\times10^{12}\ n_{eq}/cm^2$.
- Beam tests at DESY II in April 2022.
- Shared readout system with Silicon module.

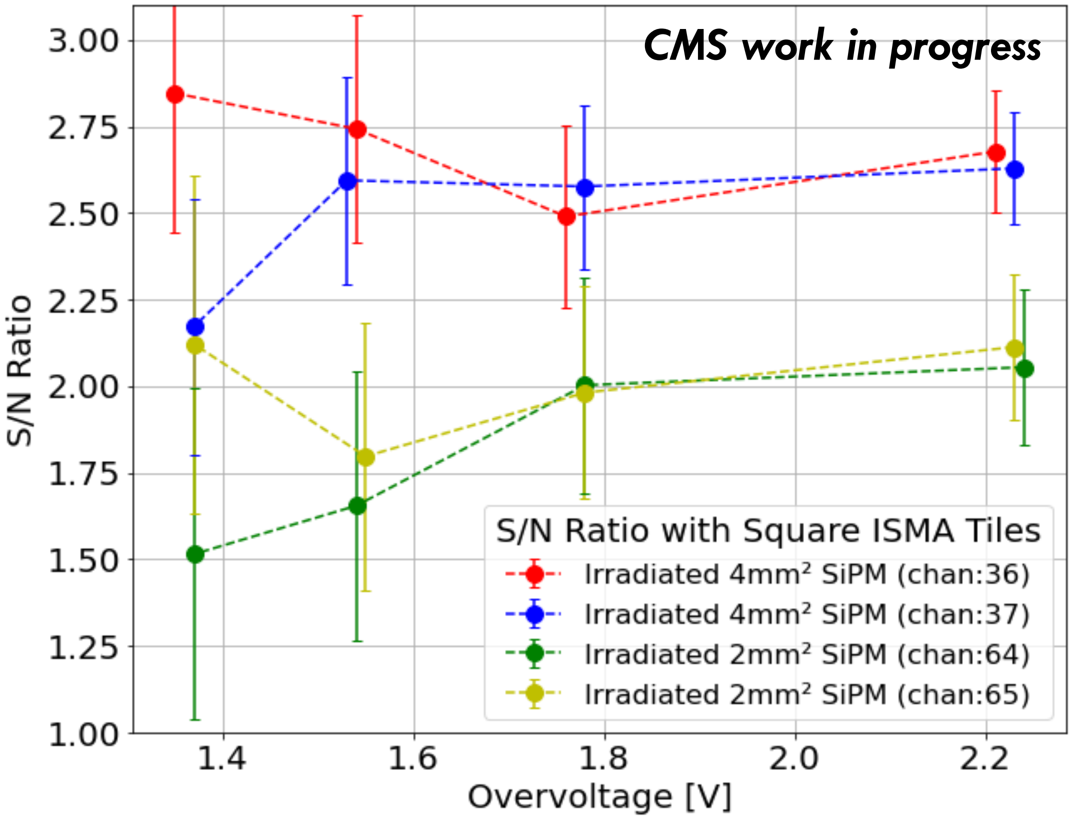
S/N ratio relatively independent from overvoltage.

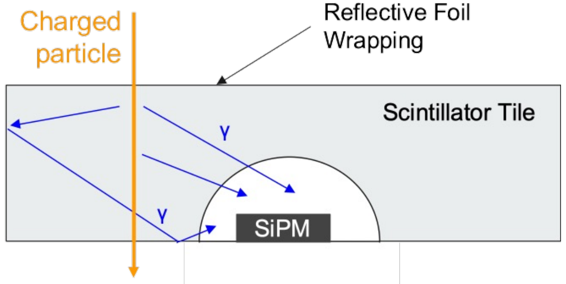
Confirms end-of-life S/N performance with final SiPMs.

- S/N ~ 2.0 for 2 mm² SiPMs, and
- S/N ~ 2.5 for 4 mm² SiPMs.







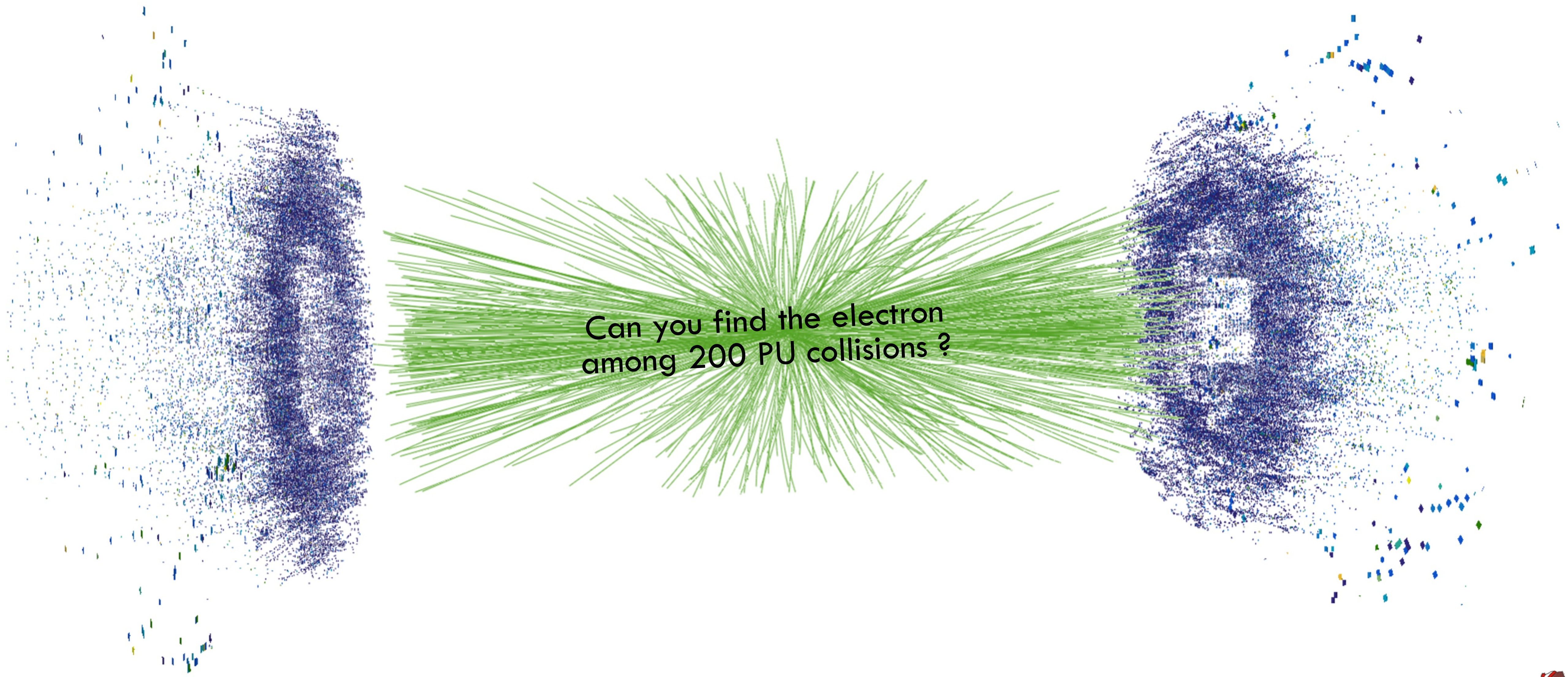


4 irradiated SiPMs

ELEMENTS OF THE PERFORMANCE CHAIN

- Active material properties
- Analogue and digital electronics performance
- System integration aspects
- Reconstruction **algorithms**

BRINGING THE 5D PERFORMANCE TO FRUITION

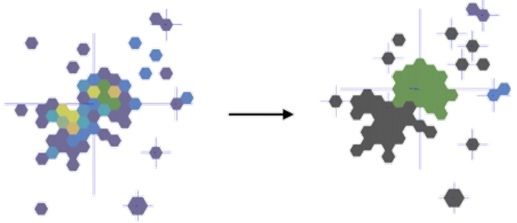


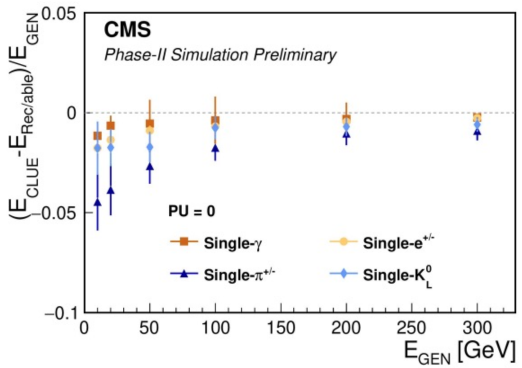
[F. Pantaleo (ACAT 2021)](#)
[E. Brondolin (ACAT 2021)](#)
[B. Alves (ACAT 2021)](#)

CLUSTERING-BASED RECONSTRUCTION

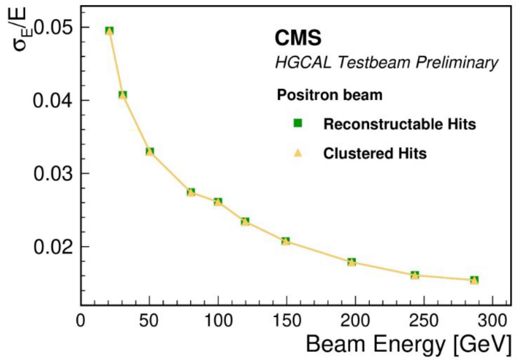
CLUE – algorithm for energy clustering

- Combinatorics reduced 10× by making 2D energy clusters.
- Parallelized, runs on GPUs.
- Tested with testbeam data.





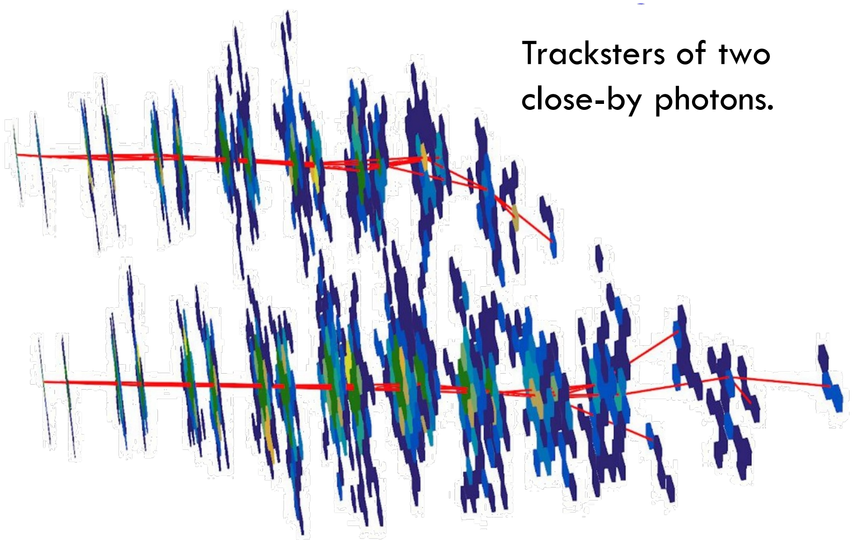
CLUE loses O(1%) energy



CLUE in beam test data

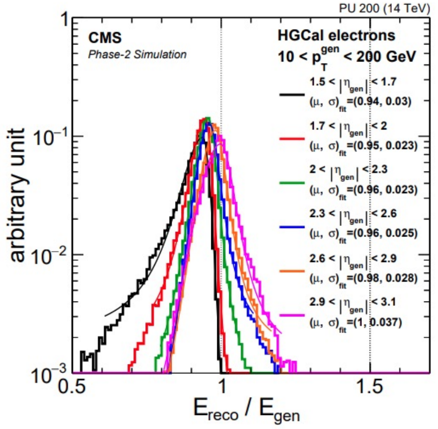
TICL – The Iterative Clustering

- Interacting particles create "Rechits".
- CLUE: Rechits → 2D LayerClusters.
- Link LayerClusters across layers into Tracksters (showers/particles).
- Trackster information regressed with ML techniques.

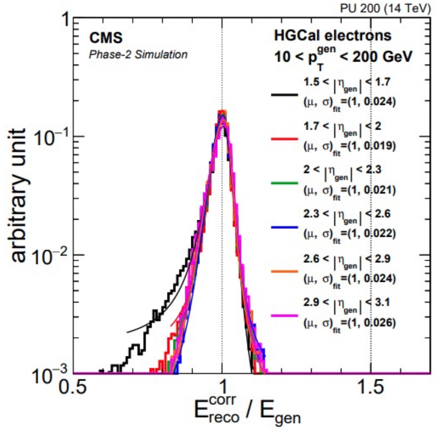


Tracksters of two close-by photons.

Uncorrected energy



DNN-regressed energy



T. Klijnsma (ACAT 2021)

END-TO-END MACHINE LEARNING RECONSTRUCTION

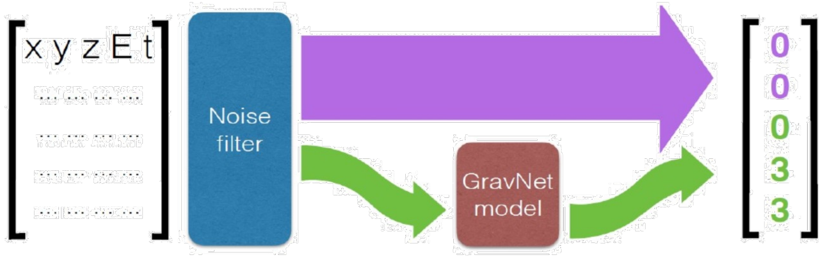
Directly use Rechits.

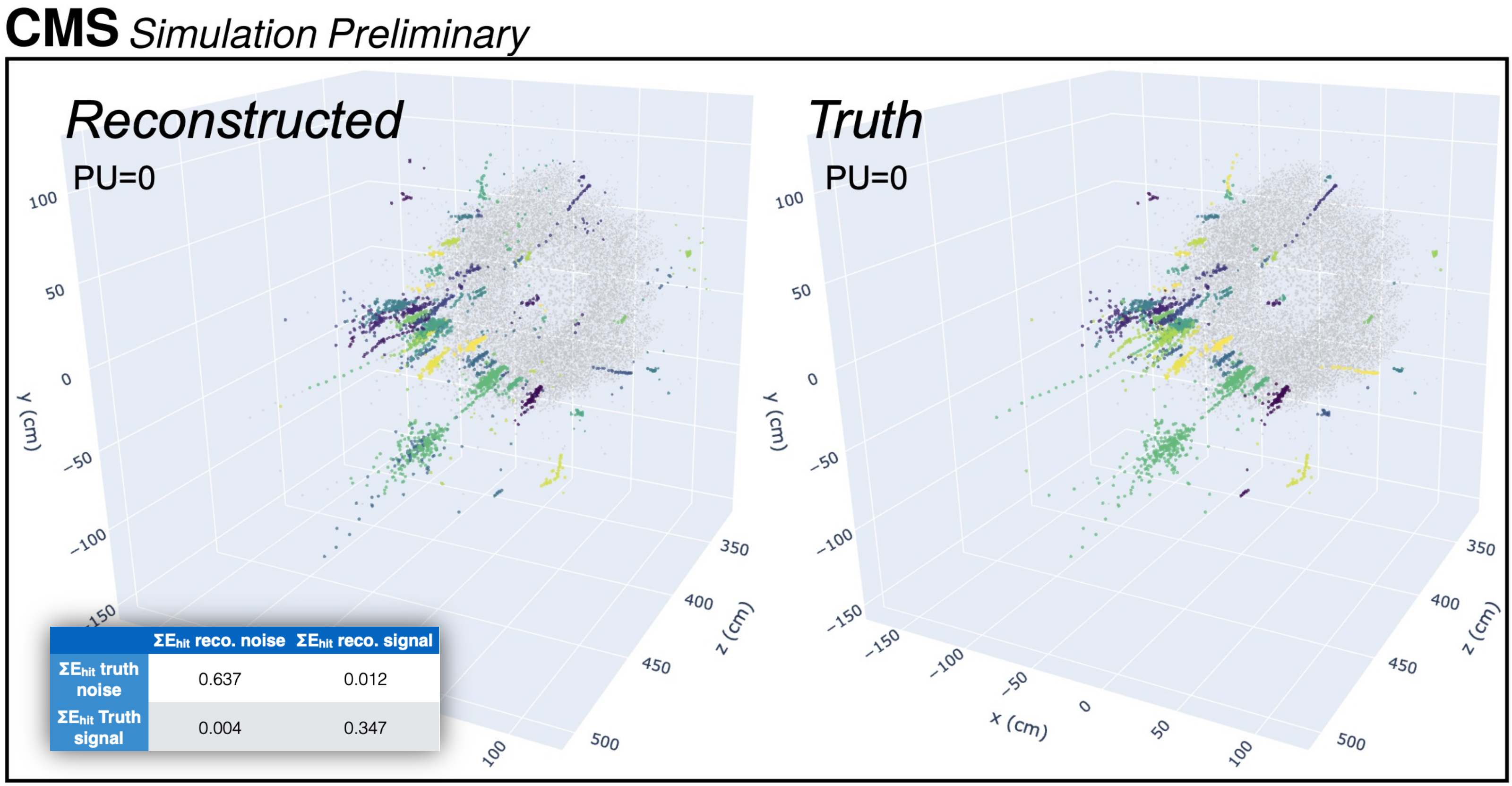
Two-stage model with:

- **Noise filter** to identify bulk of (uninteresting) hits.
- **GravNet** graph neural network performs clustering on cleaned data.

Promising performance

- Studying physics performance on single particles.



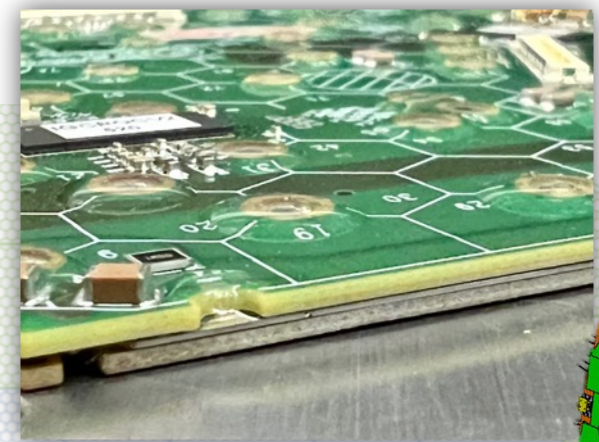


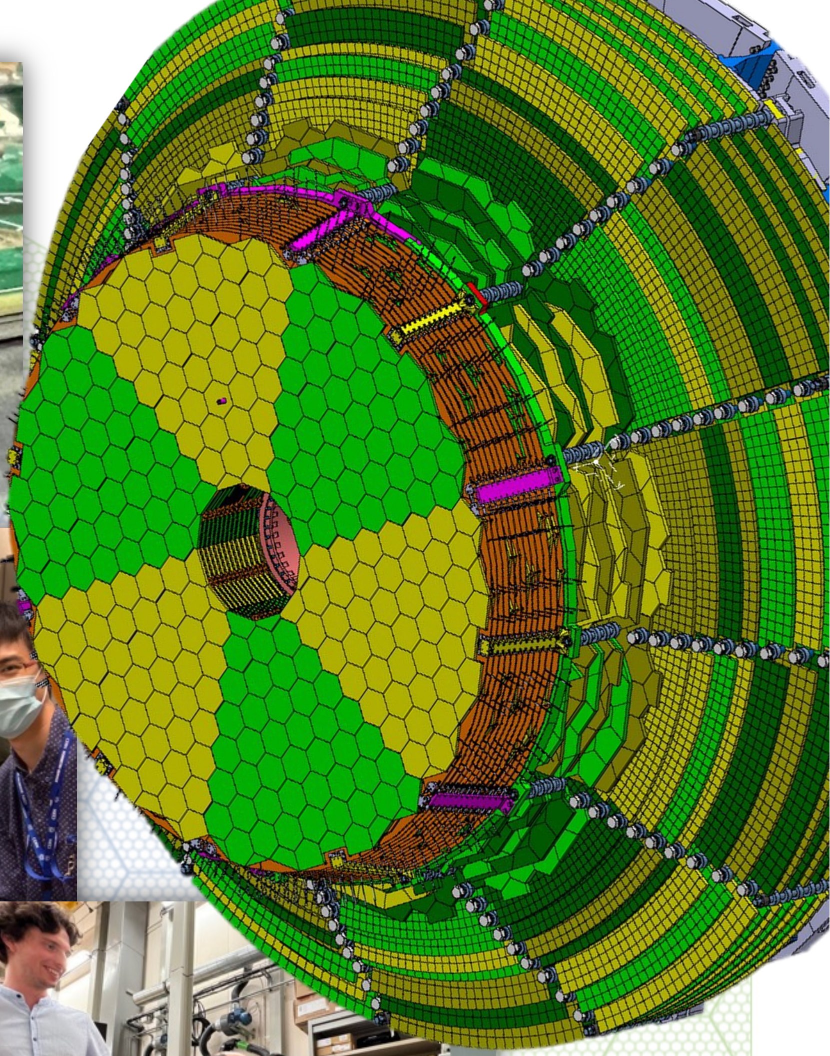
	ΣE_{hit} reco. noise	ΣE_{hit} reco. signal
ΣE_{hit} truth noise	0.637	0.012
ΣE_{hit} Truth signal	0.004	0.347

A zero pileup example with two tau leptons decaying hadronically (to 3π, and π+π^0, respectively) in one HGCAL endcap.

Don't miss GNN reconstruction – S. Rothman (July 9)

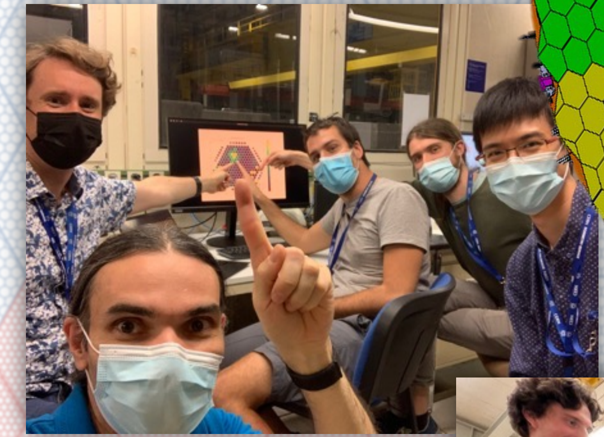
OUTLOOK





On the way to **excellent 5D performance**

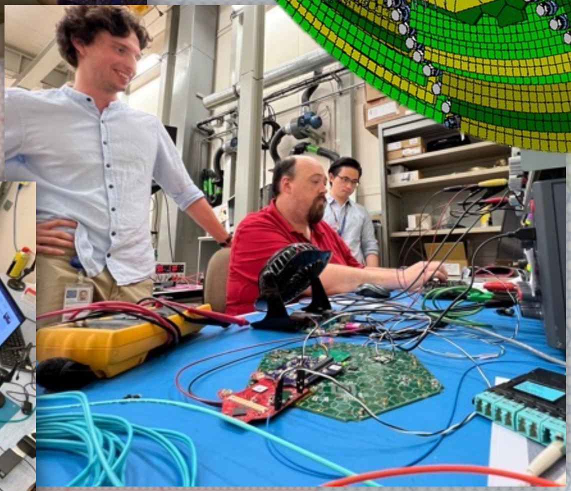
- **Spatial** integration in small volume.
- 20-ps **timing** precision over 600 m^2 of detector.
- **Energy** linearity from single MIP to showers.



Online and offline challenges

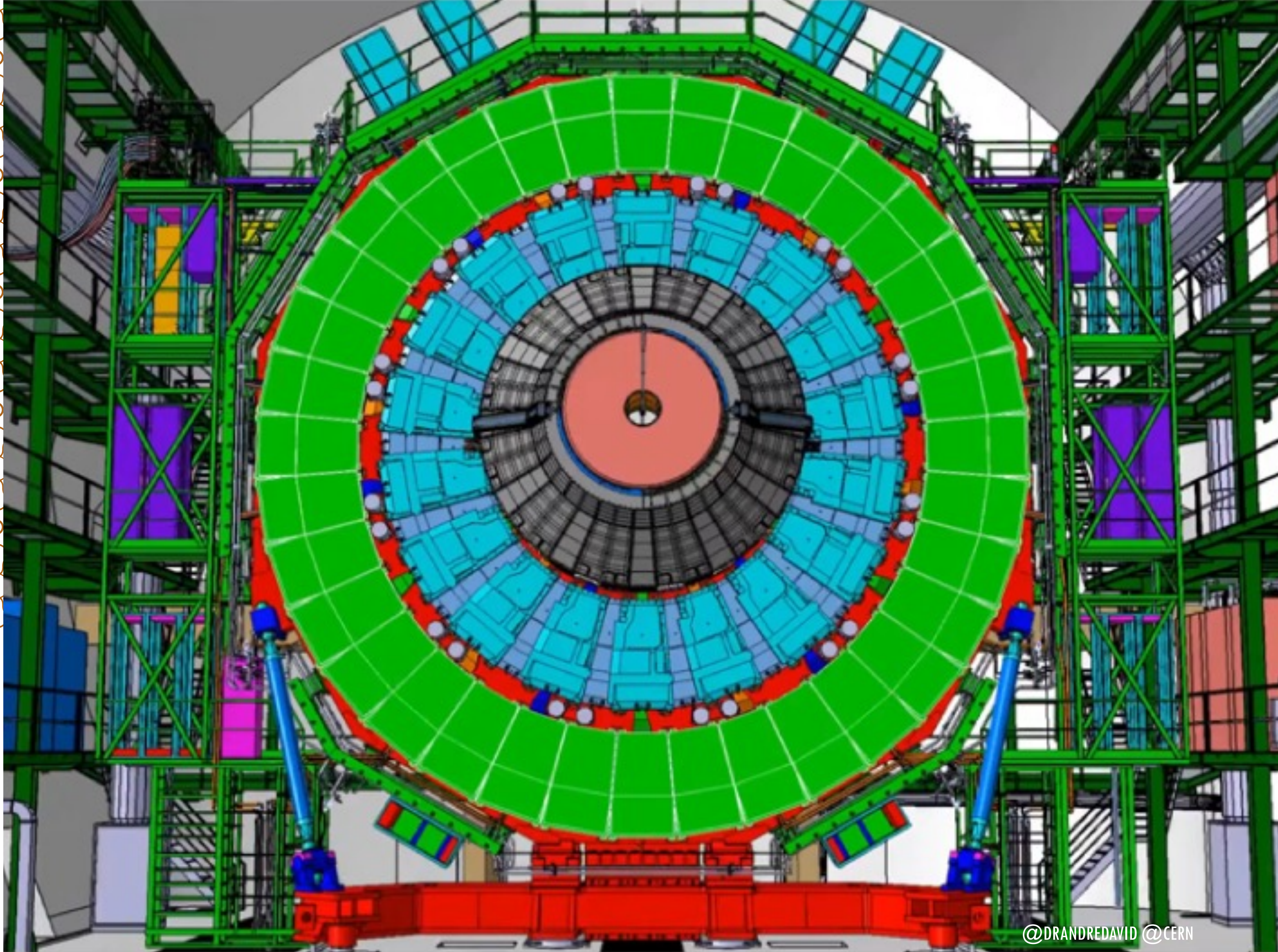
- Full system integration under way.
- Next-generation reconstruction algorithms.

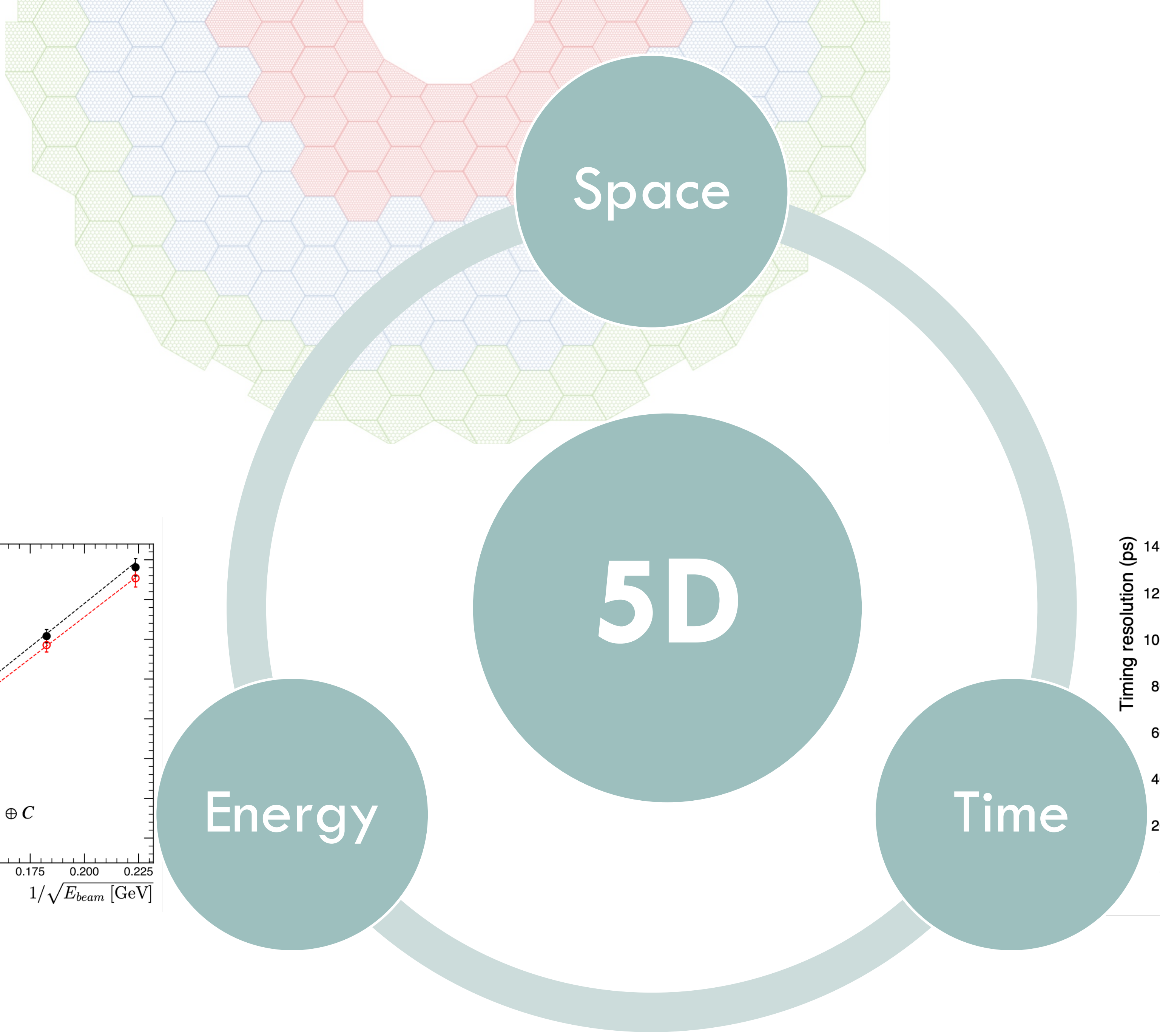
All are welcome to join in the fun !



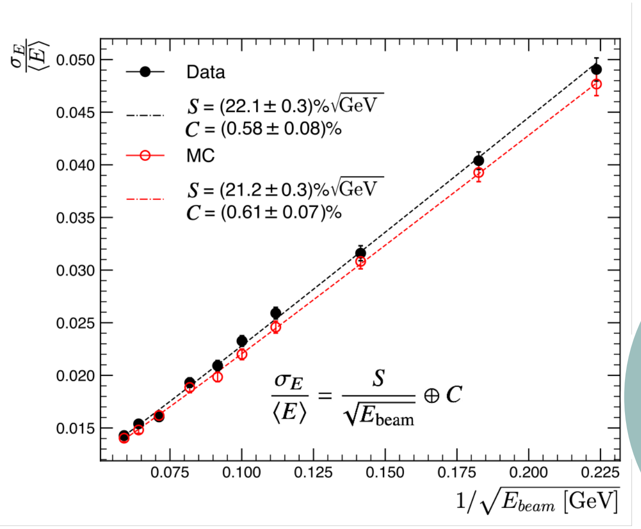
#LifeWithHexagons in HGCAL is creating the blueprints for future detectors.

THANK YOU!

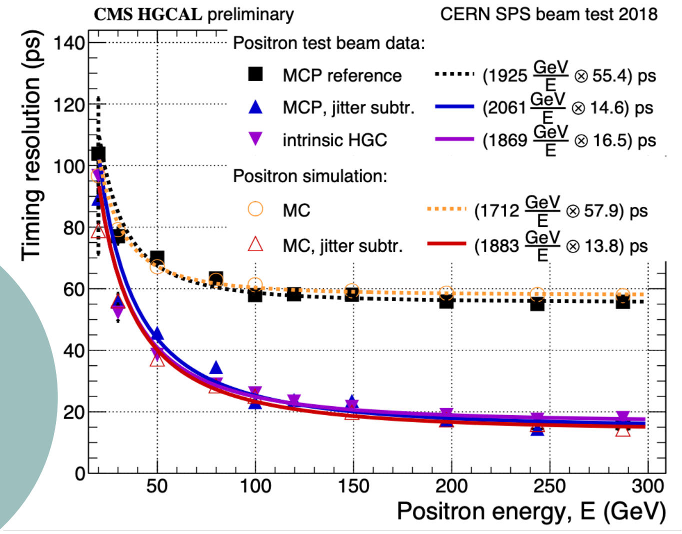




Space
5D
Energy
Time



$\frac{\sigma_E}{\langle E \rangle}$
Data
$S = (22.1 \pm 0.3)\% \sqrt{\mathrm{GeV}}$
$C = (0.58 \pm 0.08)\%$
MC
$S = (21.2 \pm 0.3)\% \sqrt{\mathrm{GeV}}$
$C = (0.61 \pm 0.07)\%$
$\frac{\sigma_E}{\langle E \rangle} = \frac{S}{\sqrt{E_{\mathrm{beam}}}} \oplus C$
$1/\sqrt{E_{beam}}$ [GeV]



CMS HGCAL preliminary
CERN SPS beam test 2018
Positron test beam data:
MCP reference
(1925 GeV/E ⊗ 55.4) ps
MCP, jitter subtr.
(2061 GeV/E ⊗ 14.6) ps
intrinsic HGC
(1869 GeV/E ⊗ 16.5) ps
Positron simulation:
MC
(1712 GeV/E ⊗ 57.9) ps
MC, jitter subtr.
(1883 GeV/E ⊗ 13.8) ps
Timing resolution (ps)
Positron energy, E (GeV)

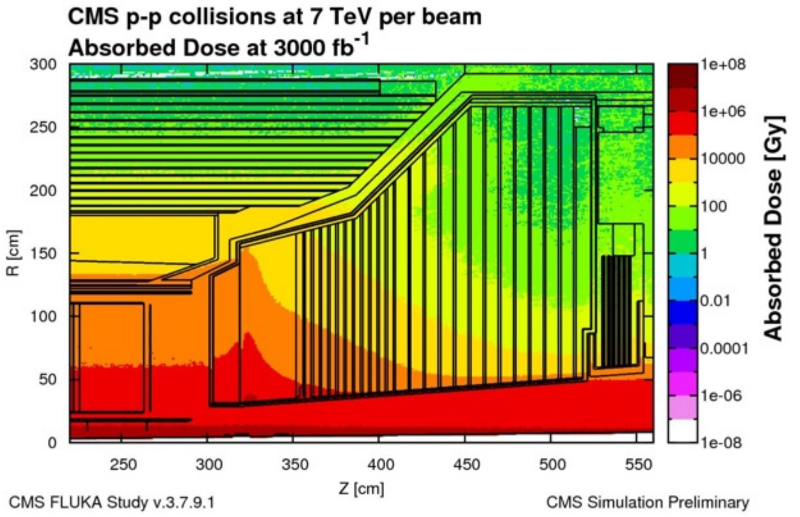
REQUIREMENTS

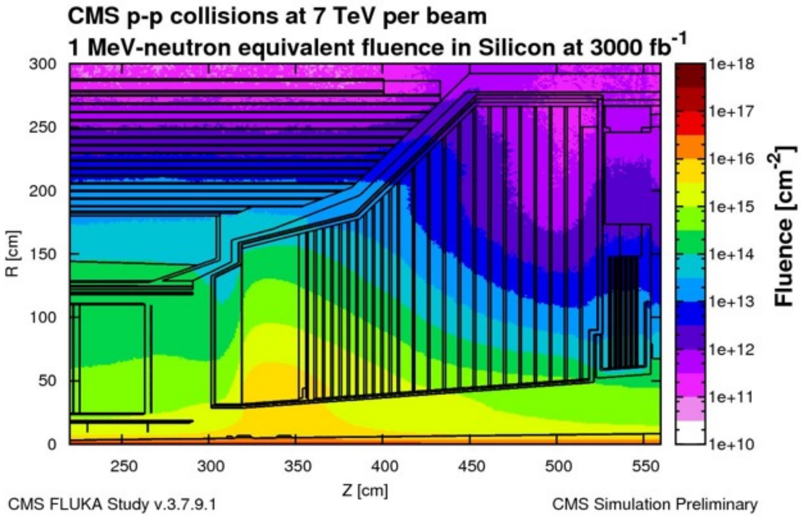
Radiation hardness

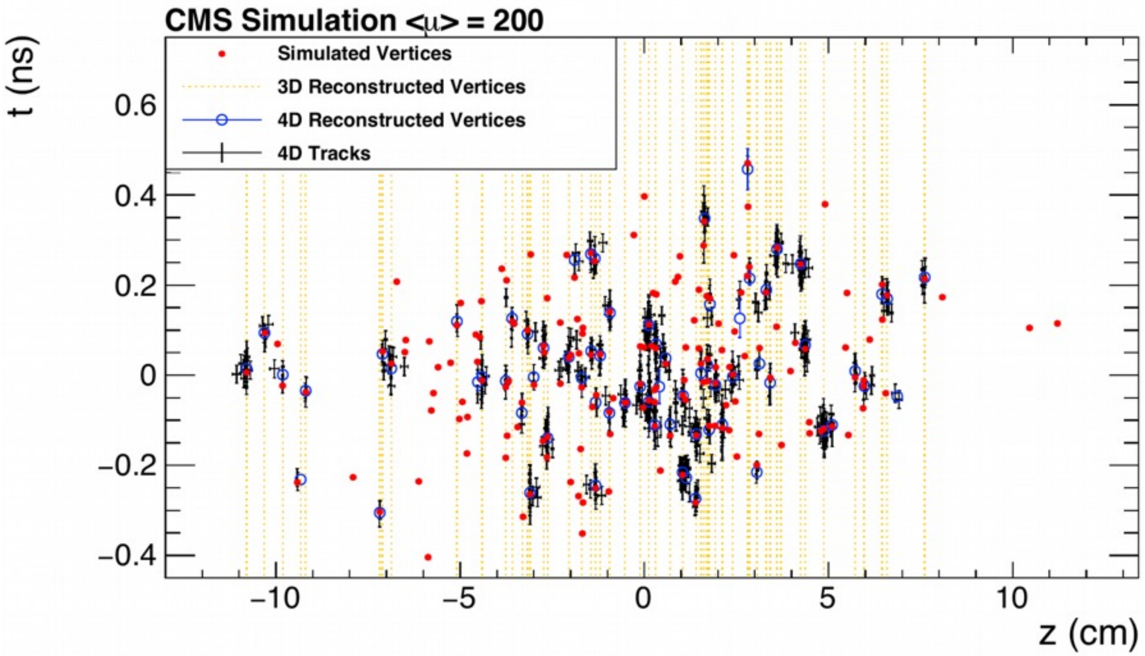
- Fluences from 1×10^{12} n_{eq}/cm^2…
- … to 1×10^{16} n_{eq}/cm^2.
- Dose from 10 Gy to 1 MGy.

Spatial and time resolution

- Resolve energy deposits originating from pile-up vertices spread over O(10 cm) and O(100 ps).

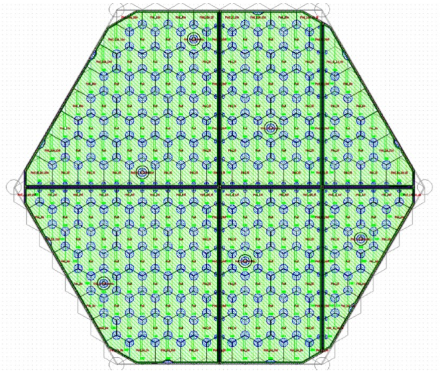




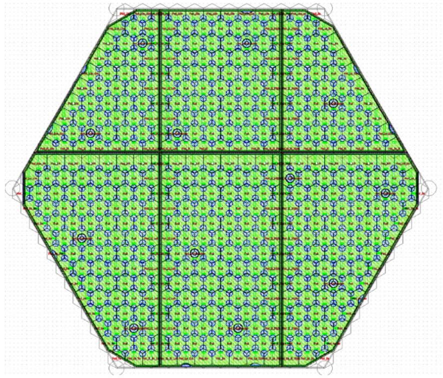


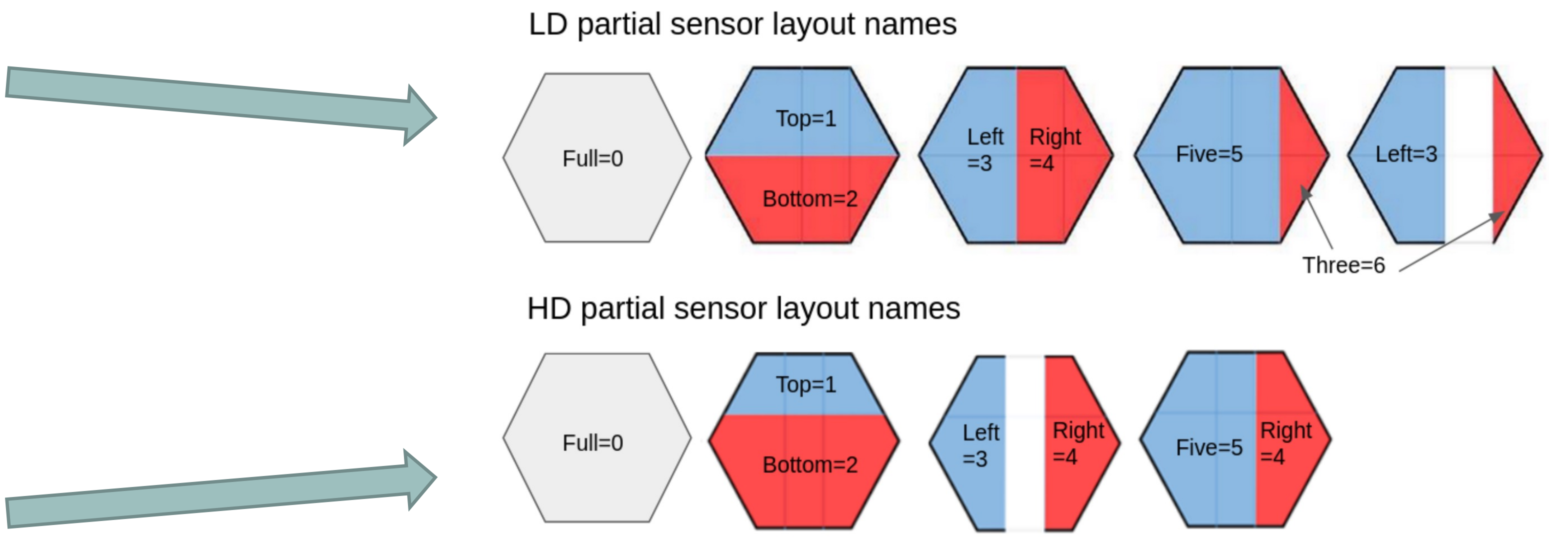
"HEXAGONATURE" OF THE CIRCLE

Low Density
Multi-Geometry Wafer



High Density
Multi-Geometry Wafer





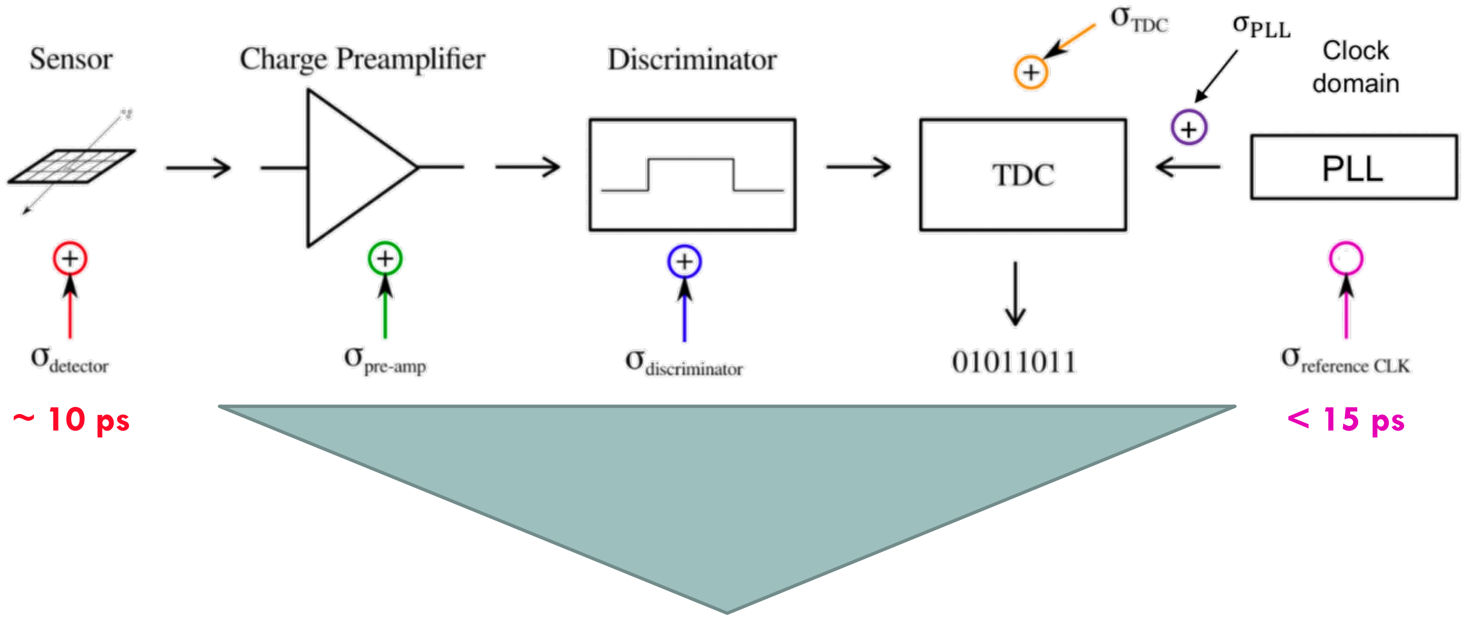
T. Quast (Pisa workshop 2022)

TIMING PERFORMANCE

Many contributions.

Crucial aspects:

- Front-end readout ASIC performance.
- Calibration procedure.



$$\sigma_t^2 = \left(\frac{t_{rise}}{S/N}\right)^2 + \left(\left[\frac{t_{rise}V_{th}}{S}\right]_{RMS}\right)^2 + \left(\frac{TDC_{bin}}{\sqrt{12}}\right)^2 + ([TDC]_{RMS})^2 +$$

Preamplifier Time walk TDC quantization noise and linearity

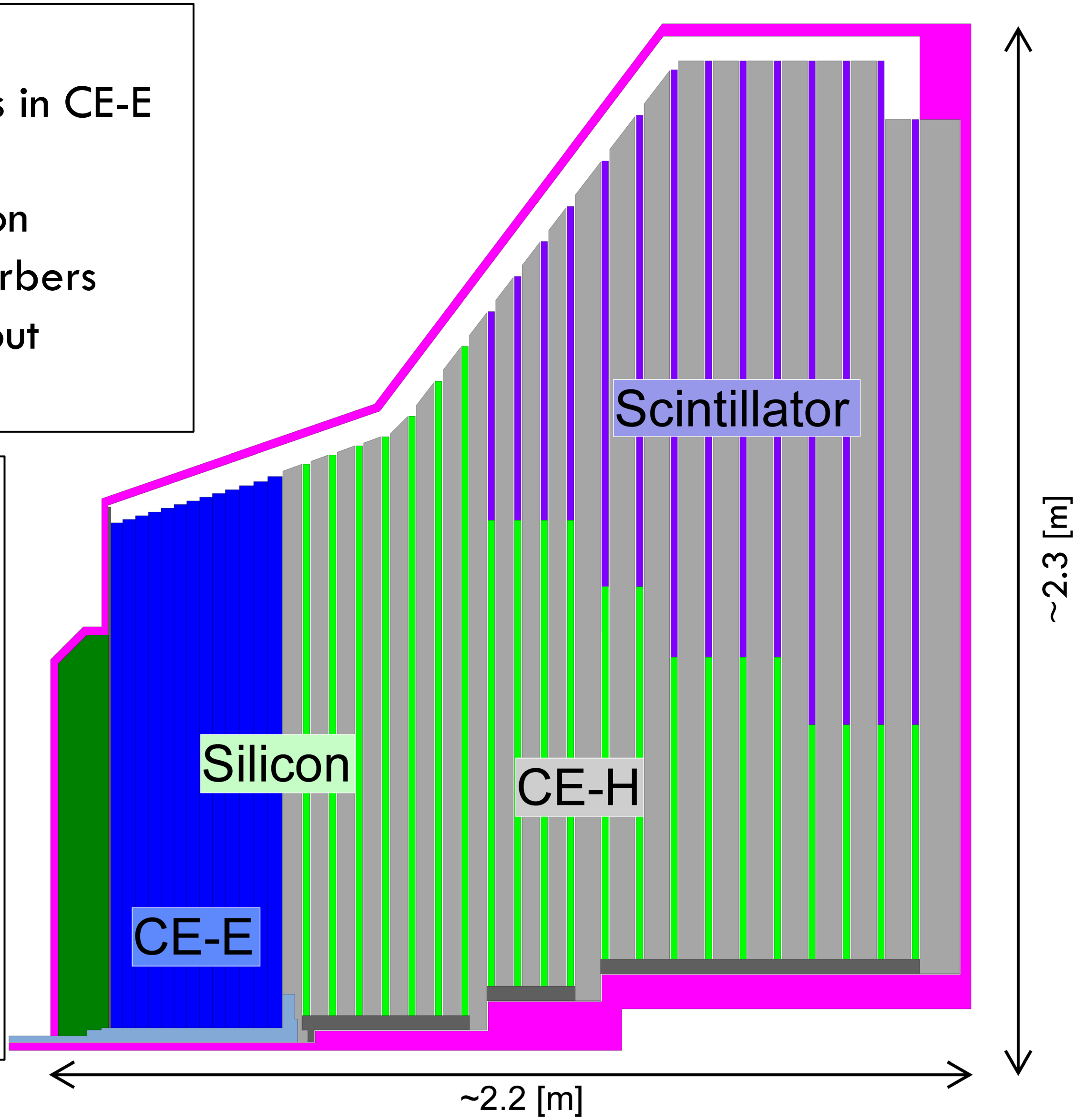
HGCAL

Active Elements:

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

Key Parameters:

Coverage: $1.5 < |\eta| < 3.0$
~215 tonnes per endcap
Full system maintained at -30°C
~620m² Si sensors in ~26000 modules
~6M Si channels, 0.6 or 1.2cm² cell size
~370m² of scintillators in ~3700 boards
~240k scint. channels, 4-30cm² cell size
Power at end of HL-LHC:
~125 kW per endcap



Electromagnetic calorimeter (**CE-E**): **Si**, Cu & CuW & Pb absorbers, 26 layers, 27.7 X_0 & ~1.5λ
Hadronic calorimeter (**CE-H**): **Si** & **scintillator**, steel absorbers, 21 layers, ~8.5λ