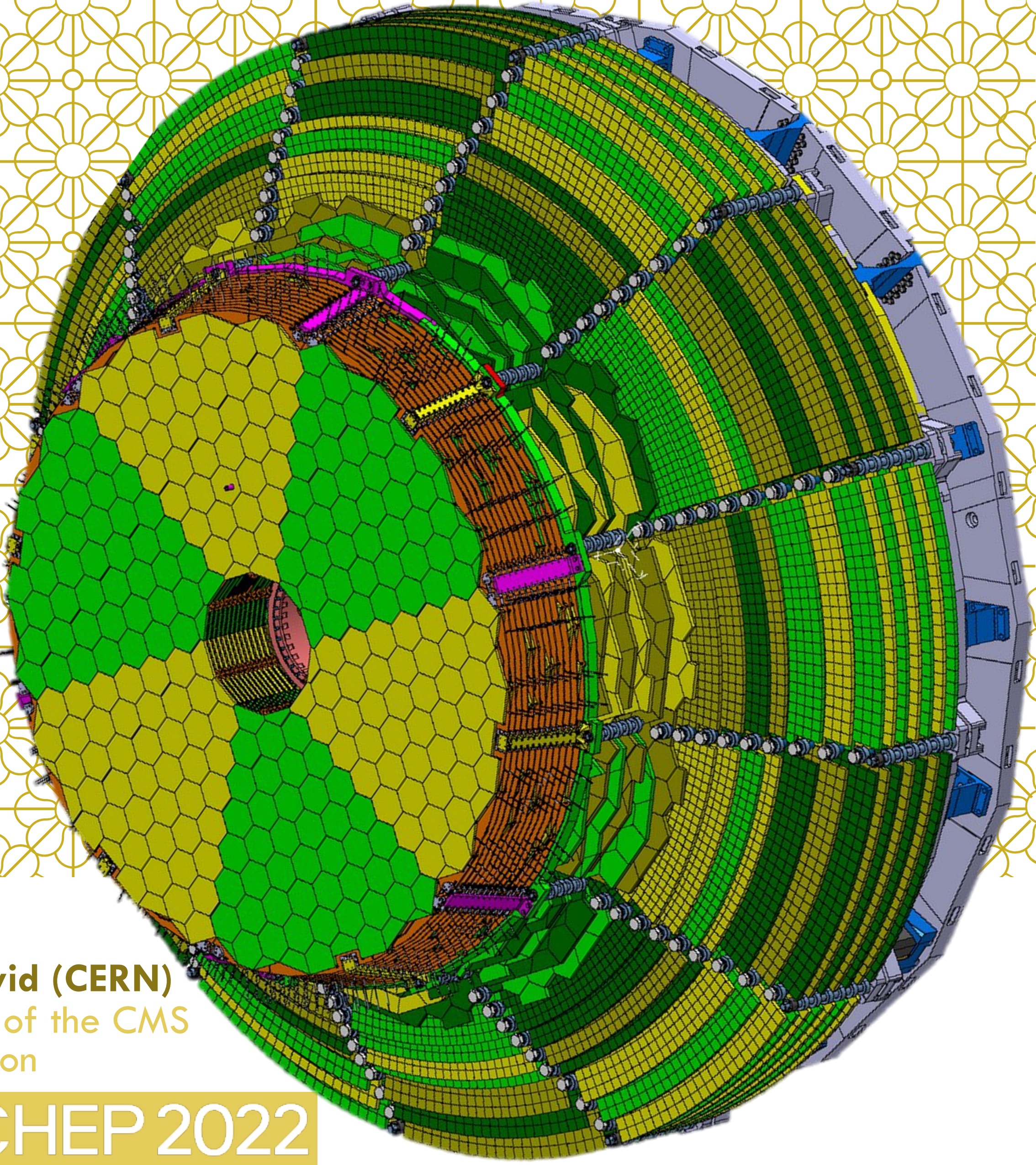
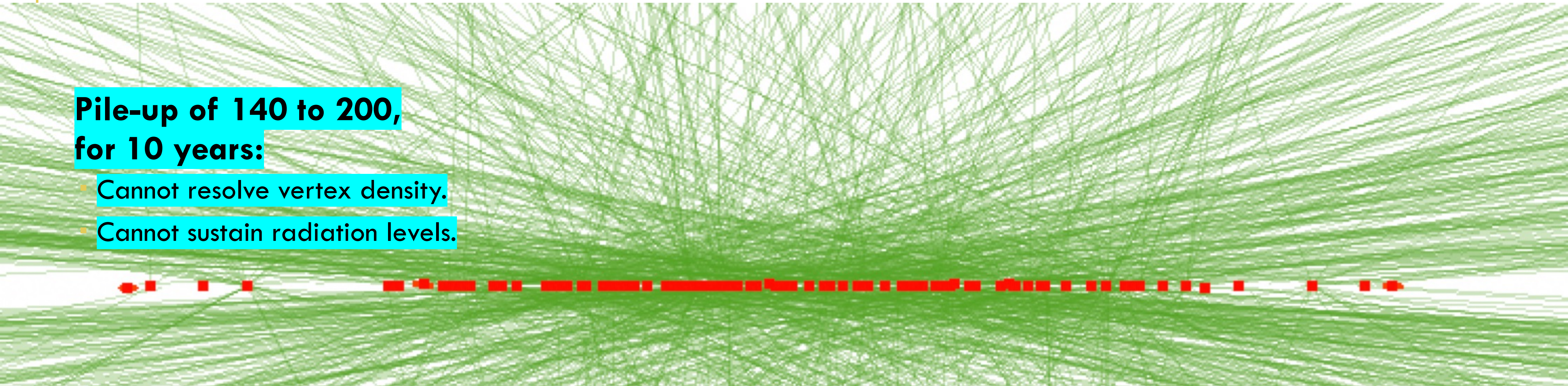


PERFORMANCE OF THE CMS HGCAL FOR LHC PHASE 2

André David (CERN)
On behalf of the CMS collaboration

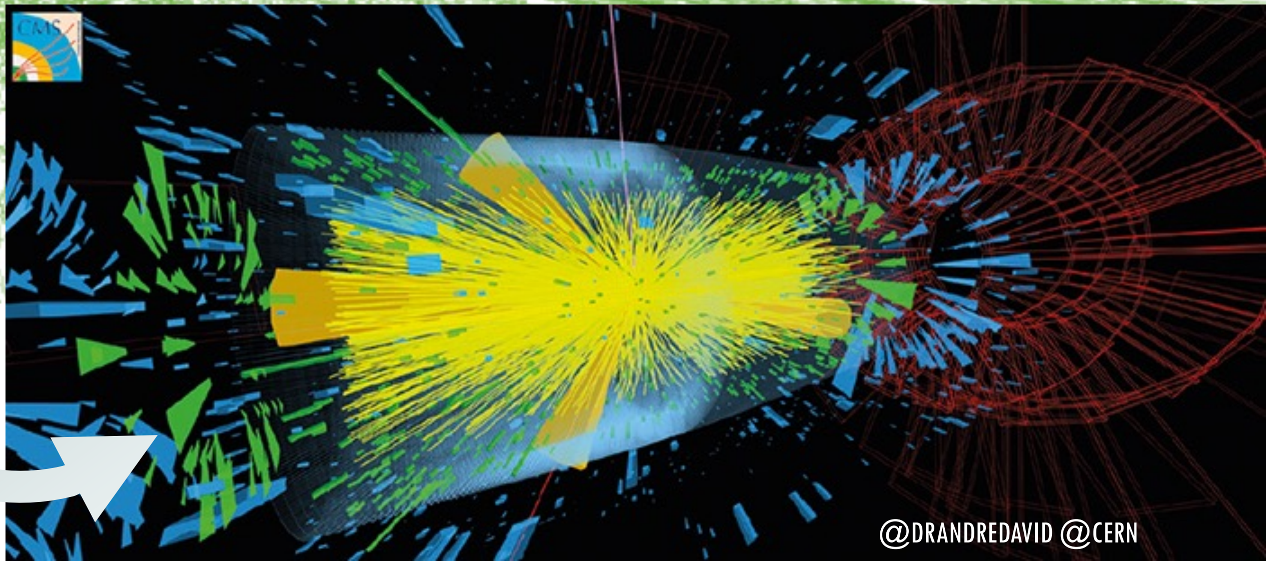
ICHEP 2022 BOLOGNA

HL-LHC: BEYOND PRESENT DETECTOR ABILITY



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

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



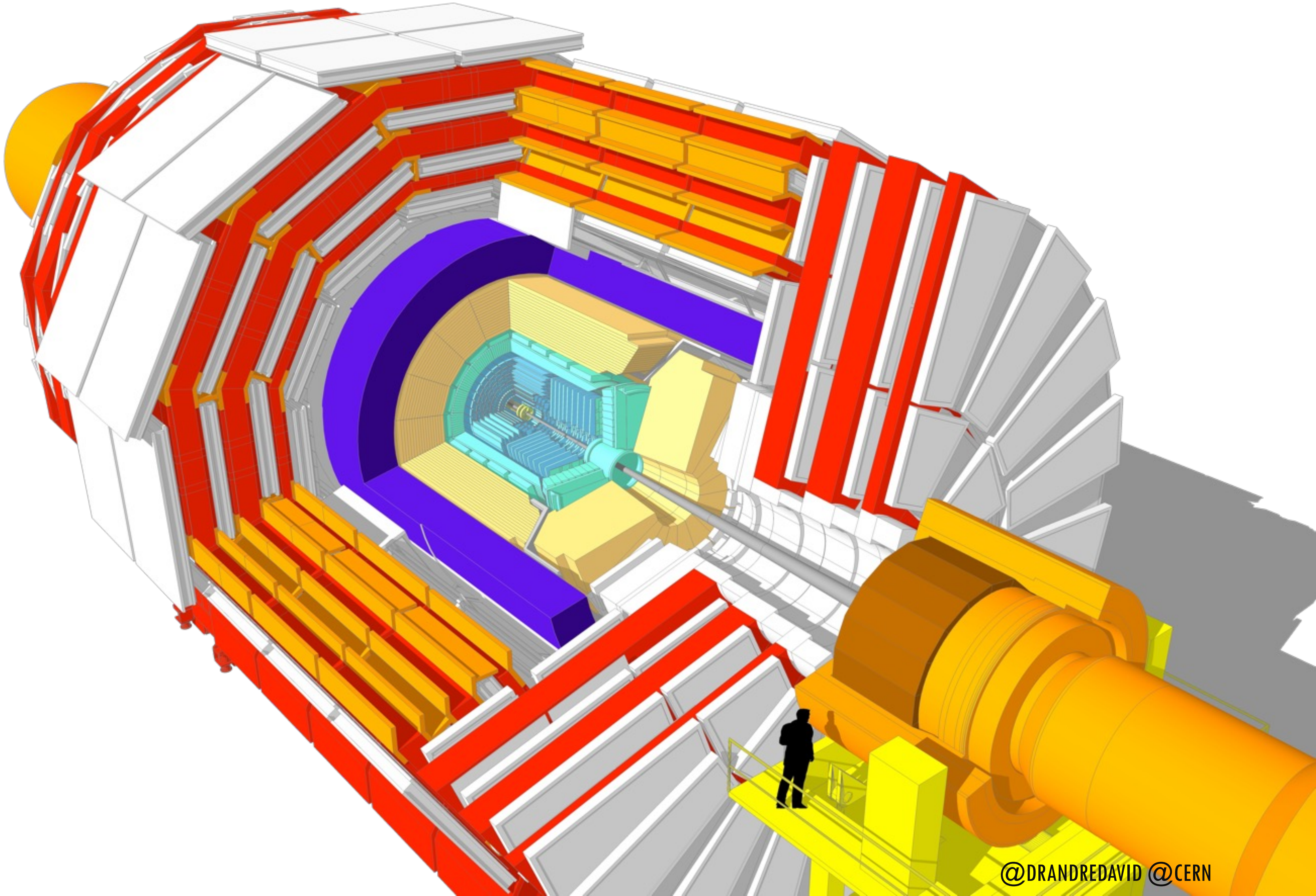
HL-LHC: BEYOND PRESENT DETECTOR ABILITY

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

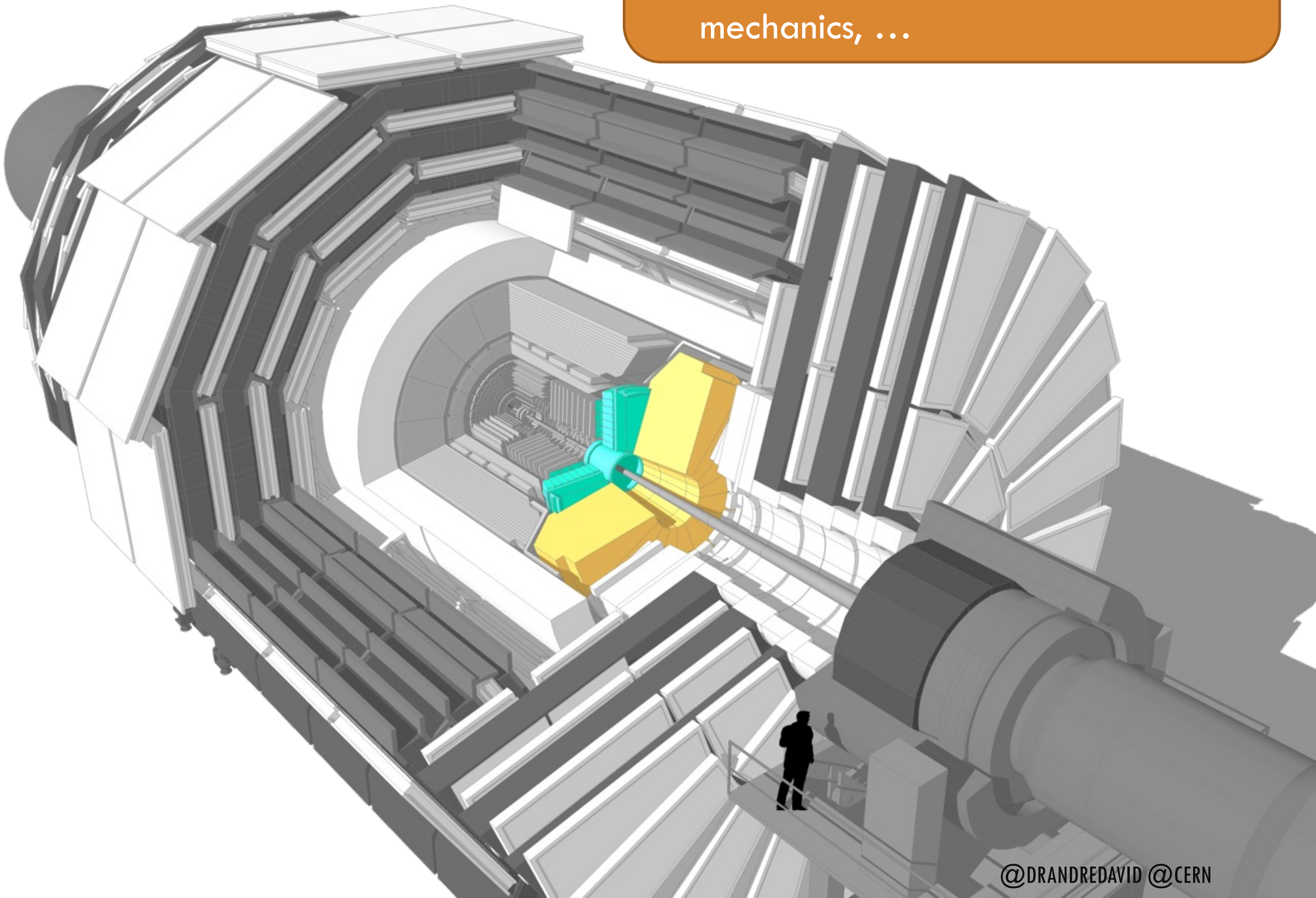
Key challenge:
- Channel density ⇒ ASIC design, power, services, connectivity, mechanics, …

Silicon imaging (EM) calorimeter.

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

Harsh radiation environment:
- Full volume operated at -35C.
- 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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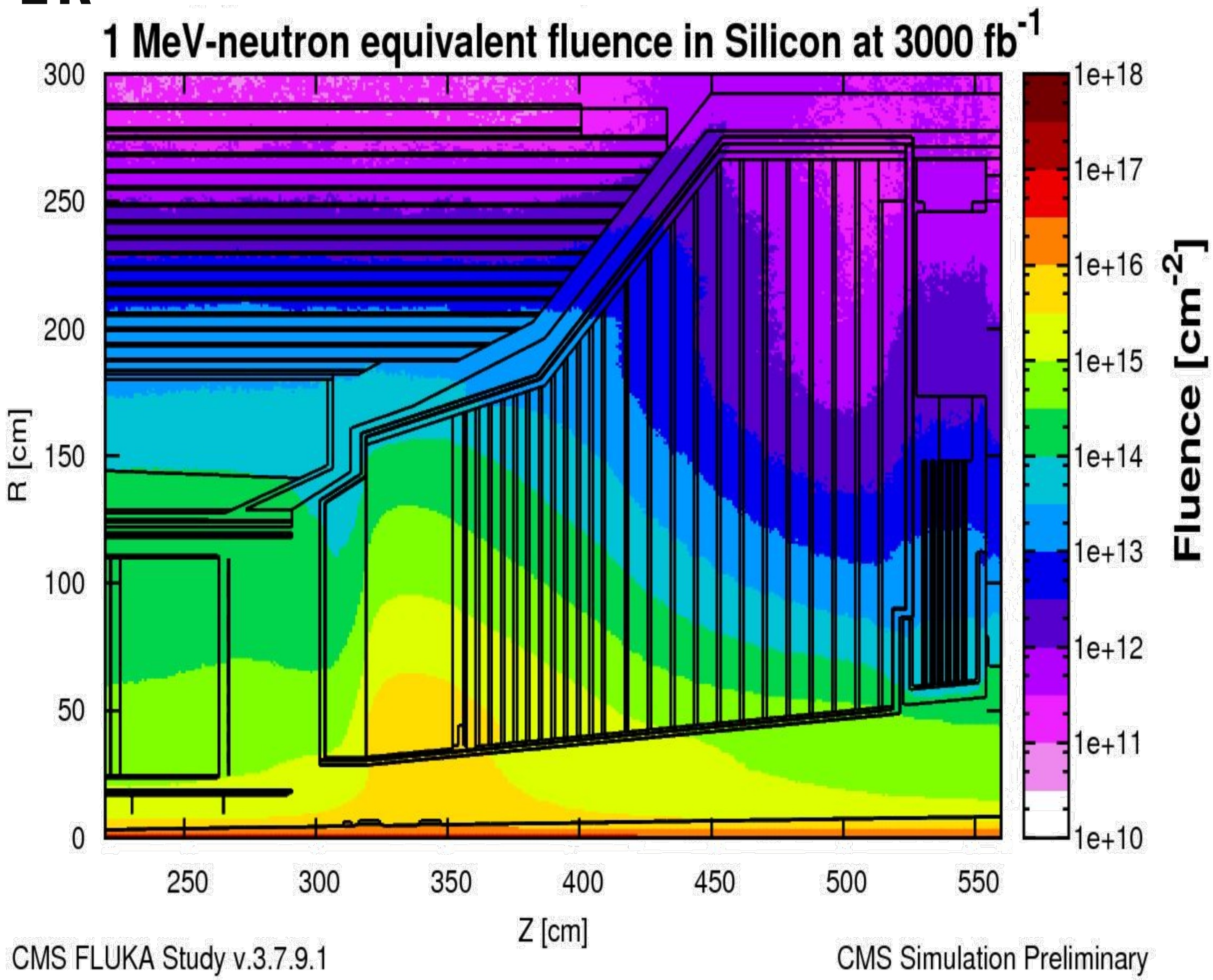

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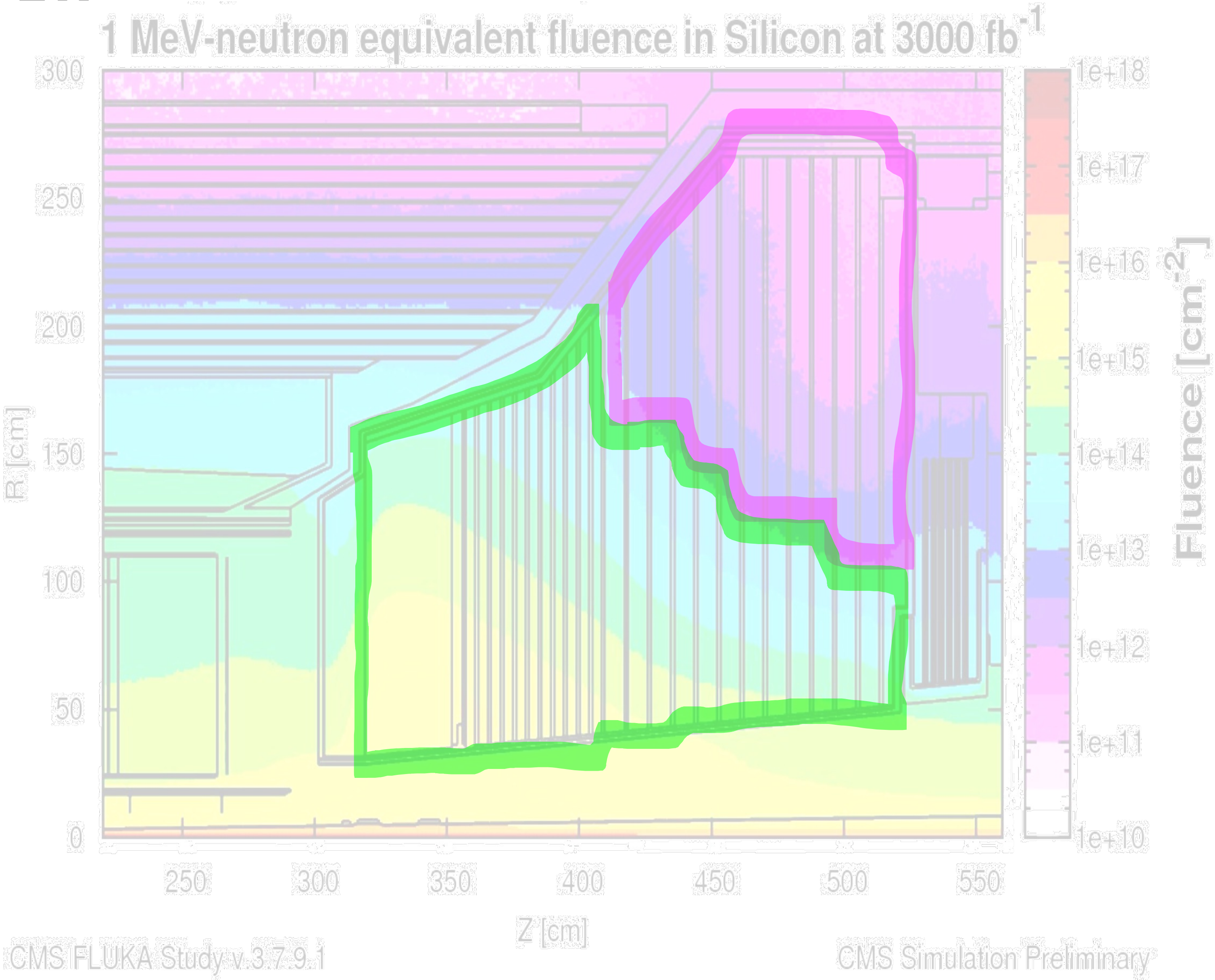

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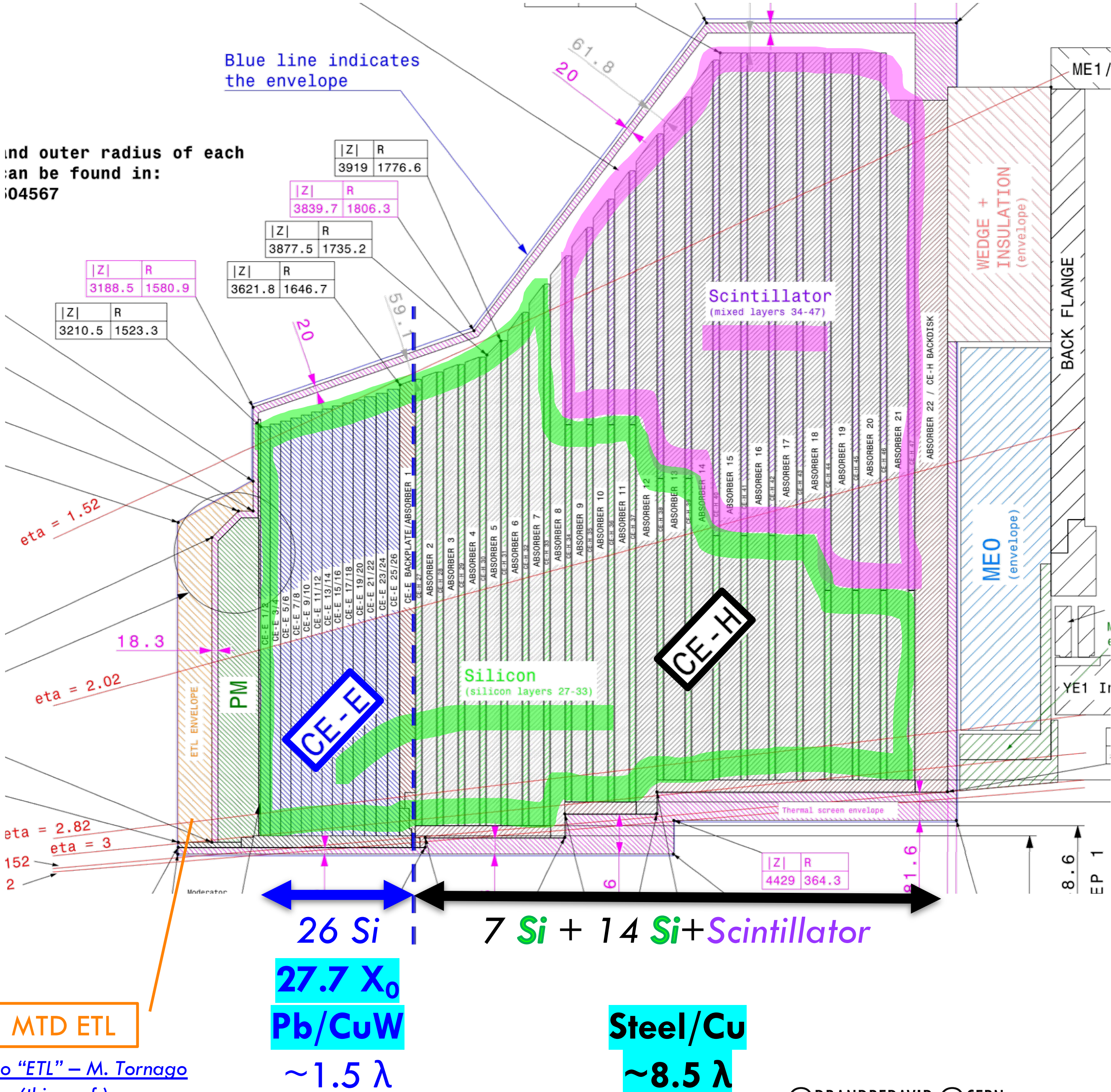


See also "ETL" – M. Tornago (this conf.)

HIGH-GRANULARITY IN 5D – CHALLENGES

Calorimetric **energy** measurement	Imaging **spatial** granularity	Precise **timing** for showers	Bringing all **5D** together

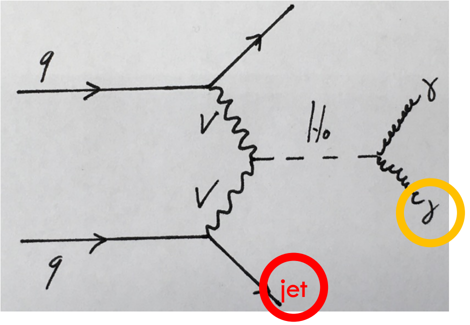
• ~50k dynamic range:
  • **Calibrate on single MIP.**
  • O(10k) MIP in particle showers.
	• 6M channels in ~40 m^3.
	  • **~10 channels per cell phone volume.**
	• Cell sizes from 0.6 to 30 cm^2.
		• **O(25 ps)** per channel energy above O(10) MIPs.	• Reconstruction **algorithms for a new era in calorimetry.**

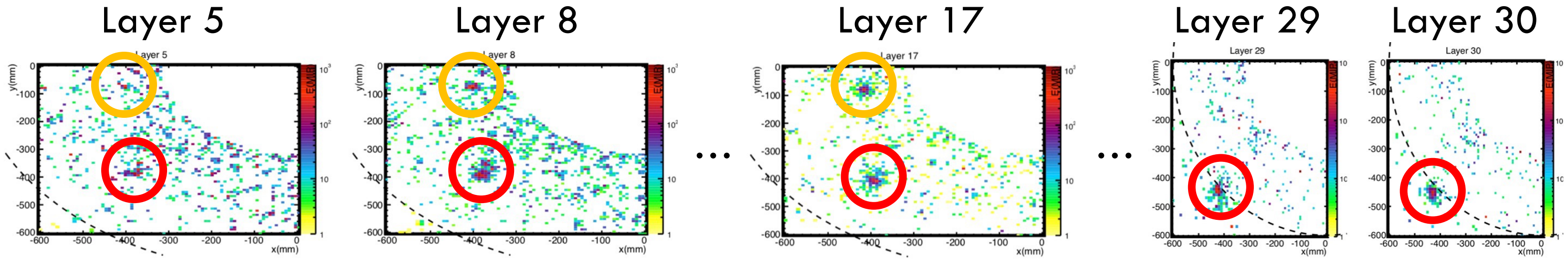
HE WANTS ALL INFINITY STONES...

...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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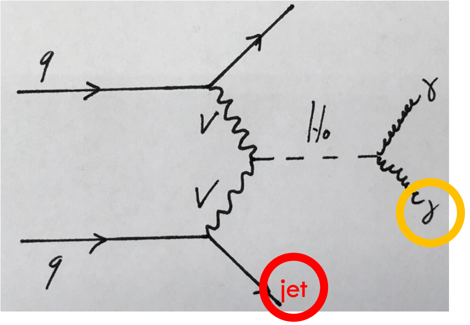

VBF H→γγ

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

Spatial granularity

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Timing resolution ↓

- Select hits in 90 ps window.
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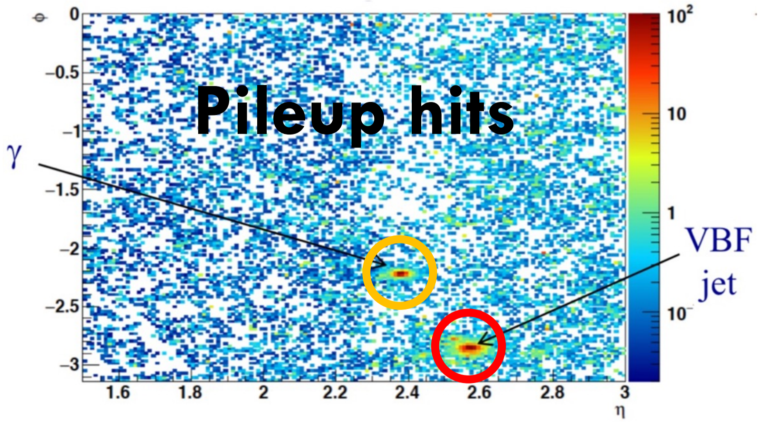
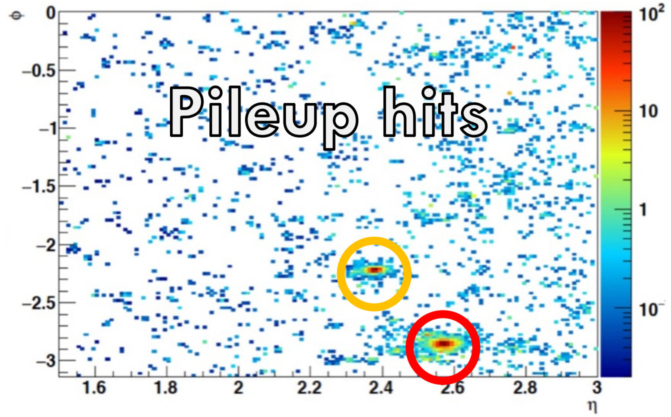


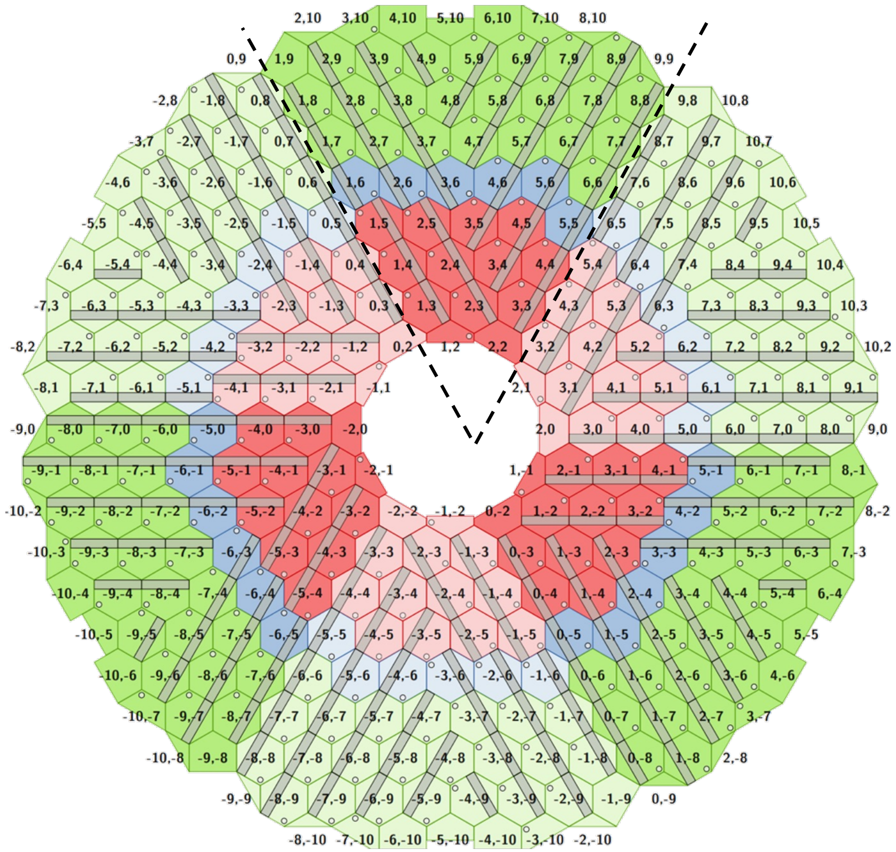


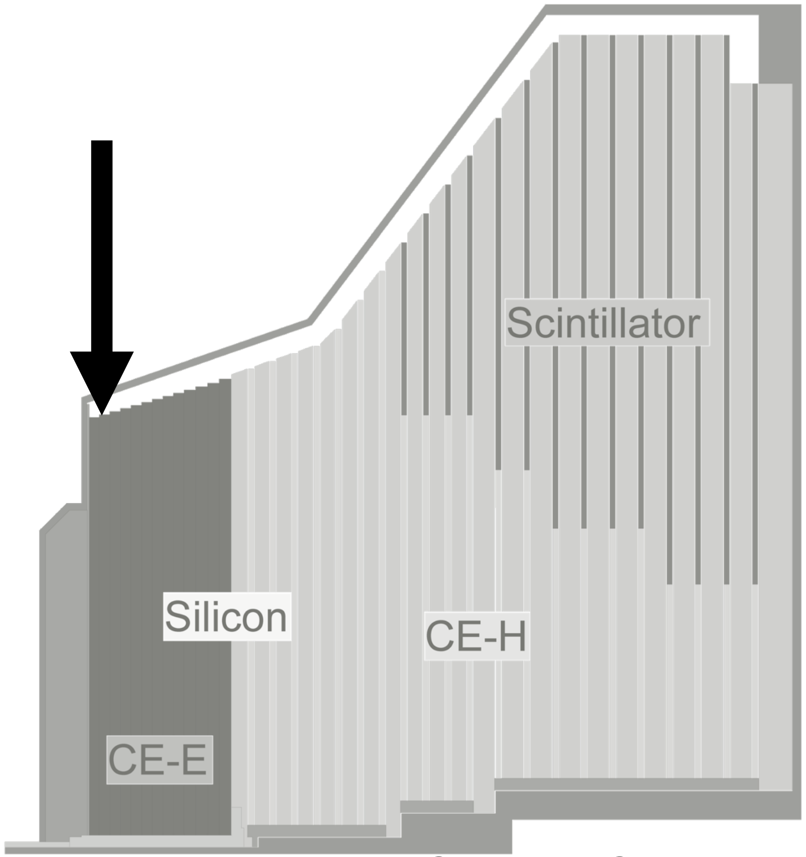
Hits from all layers projected to same depth.

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

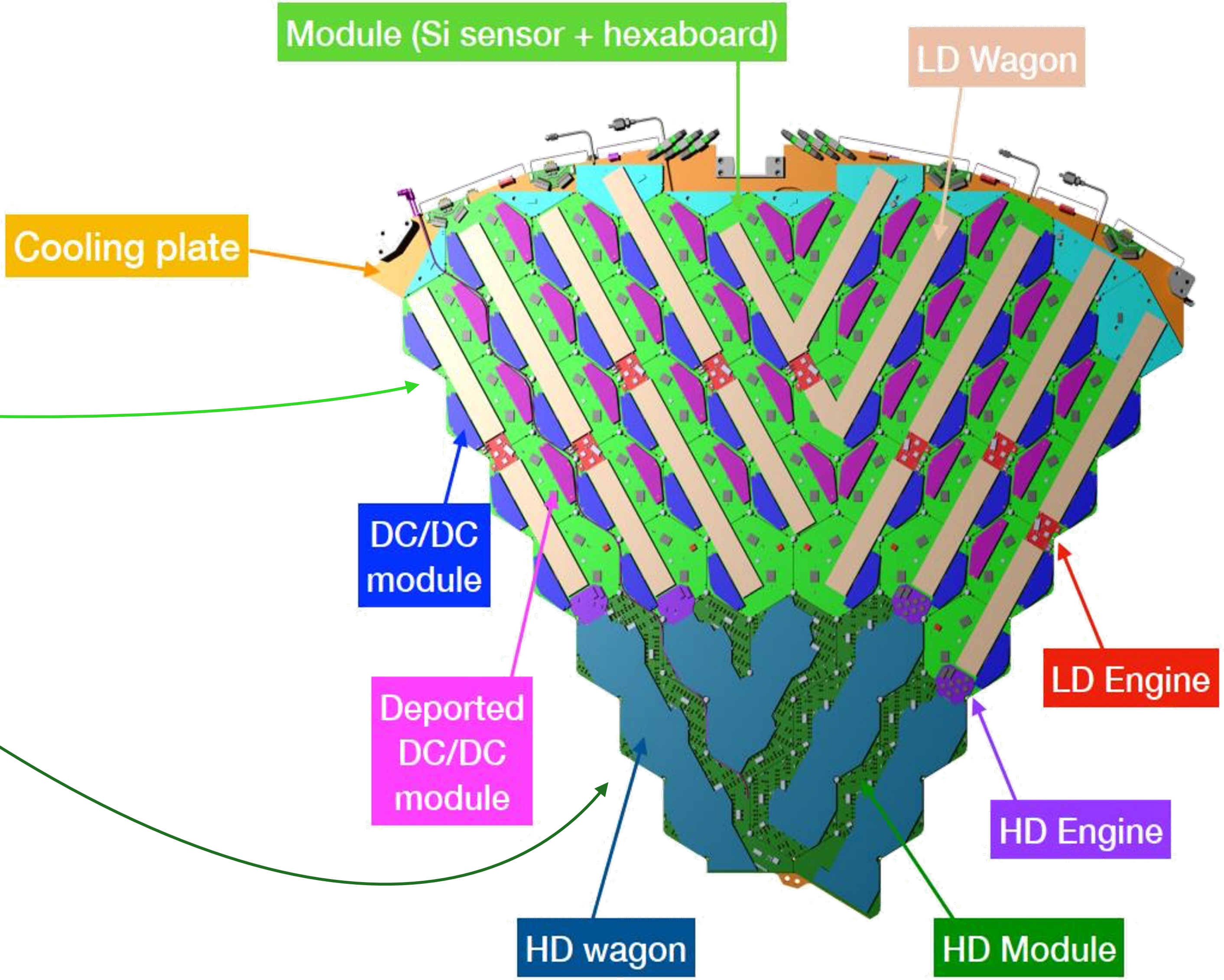




"MOBILE PHONE" INTEGRATION CHALLENGES

Layer 3

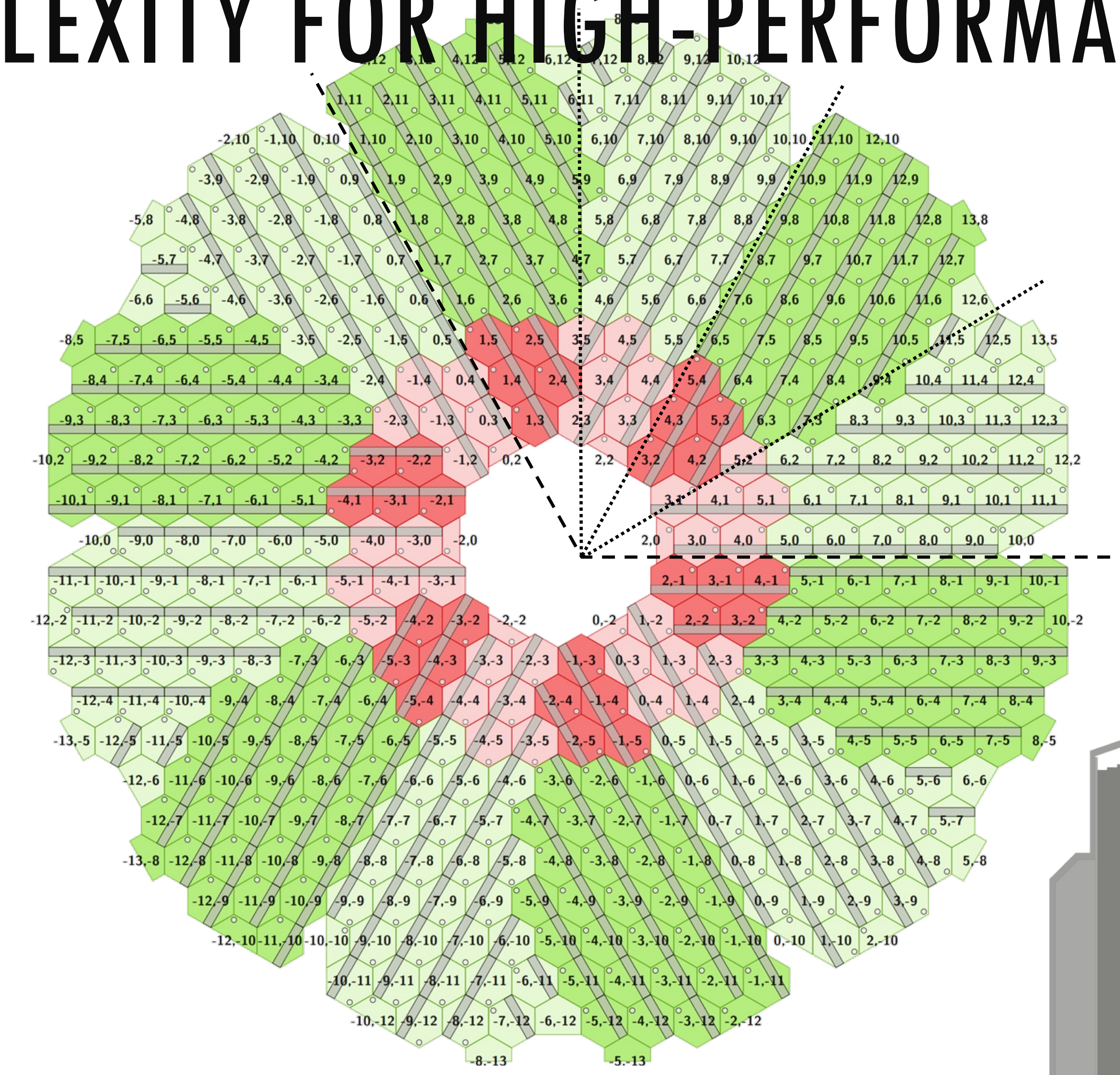
- 60-degree symmetry
  - **60-degree cassettes**
- **Low density silicon modules**
  - 300 μm thick
  - 200 μm thick
- **High-density silicon modules**
  - 120 μm thick

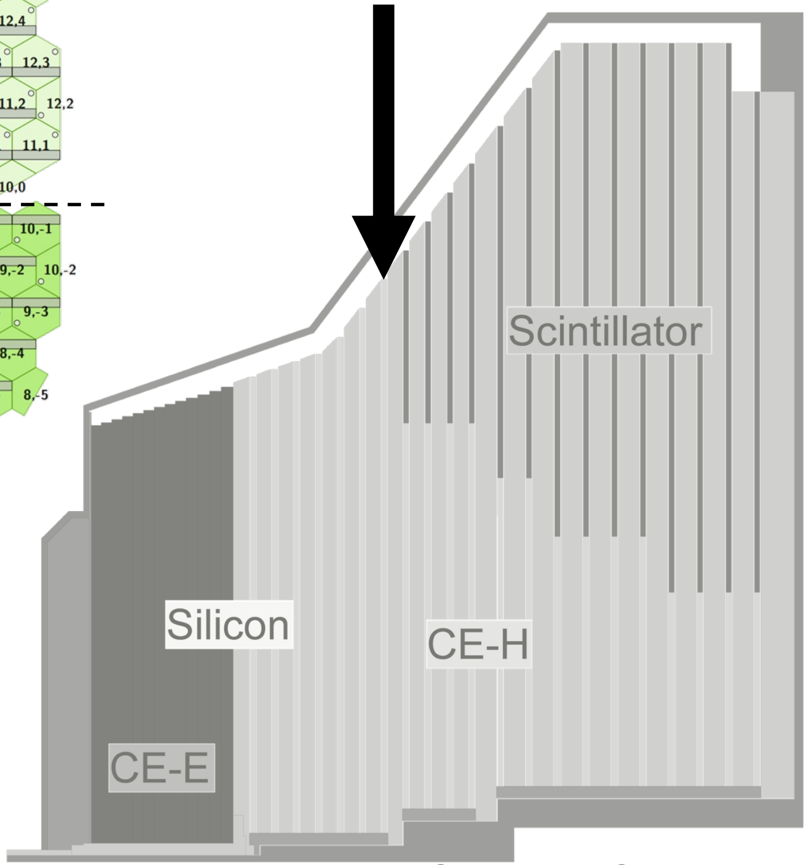


SPATIAL COMPLEXITY FOR HIGH-PERFORMANCE

Layer 33

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

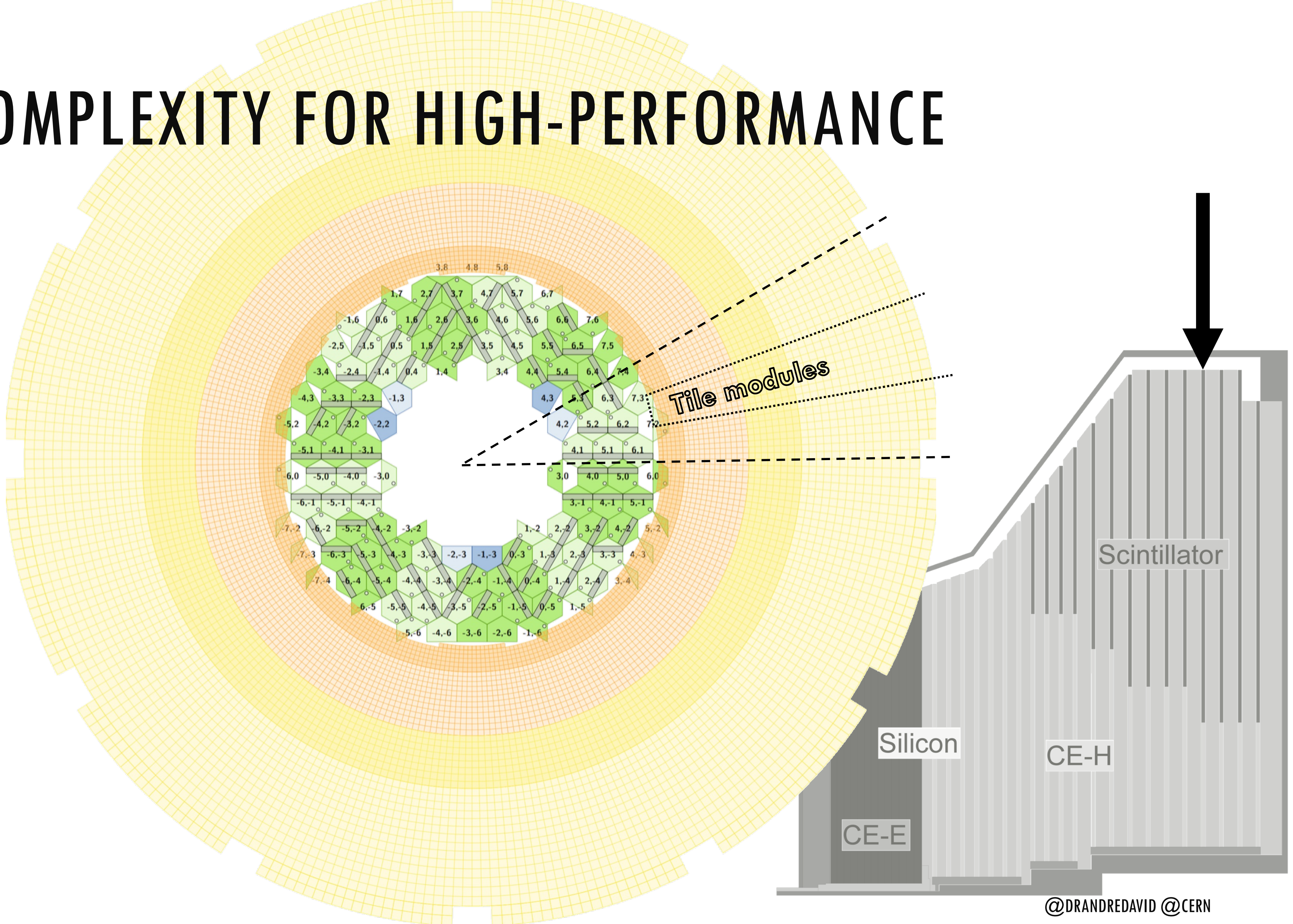




SPATIAL COMPLEXITY FOR HIGH-PERFORMANCE

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

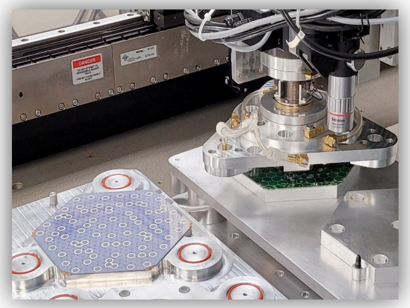
- New 8" process !

Metalized kapton sheet

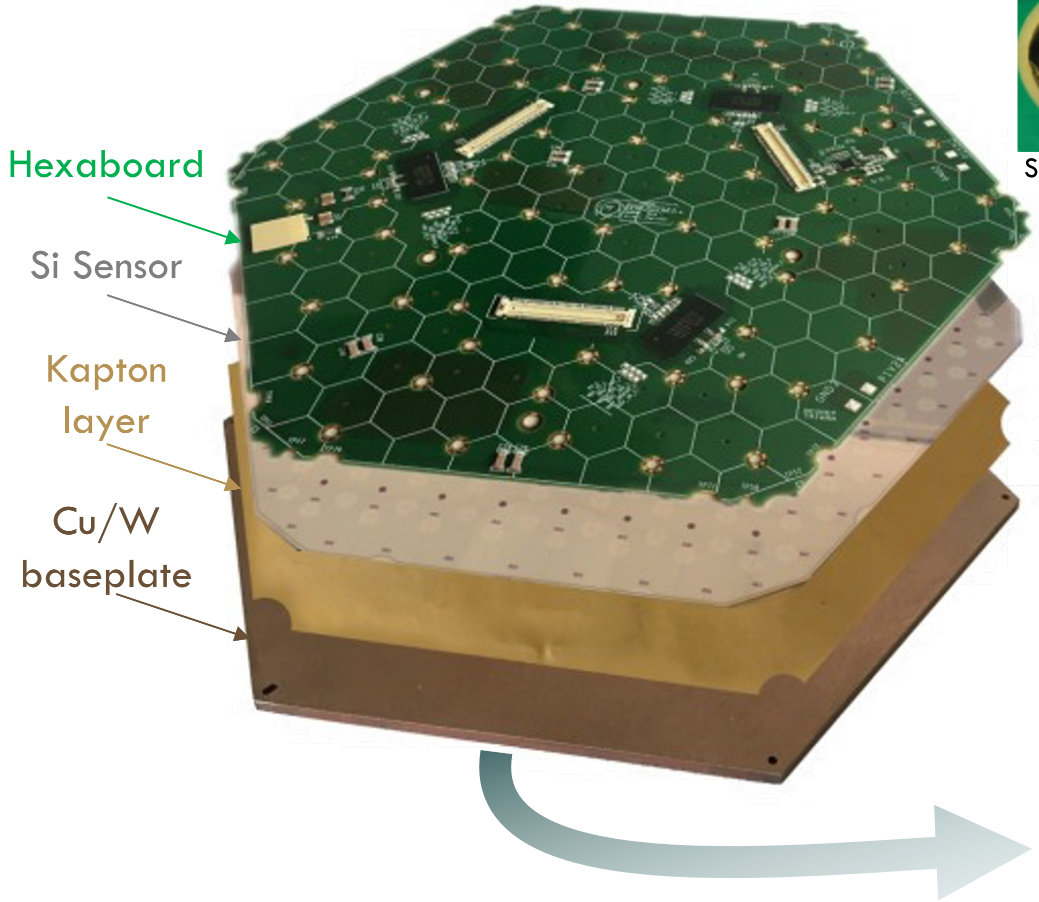
- Bias supply to sensor back side.
- Insulation from baseplate.

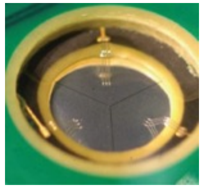
Copper-Tungsten baseplate

- Rigidity, contributes to absorber material.

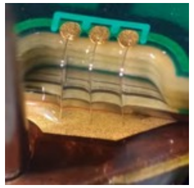


8-inch prototype module stack-up

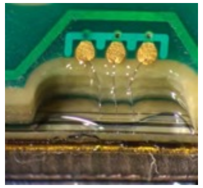




Si pads bonded to PCB

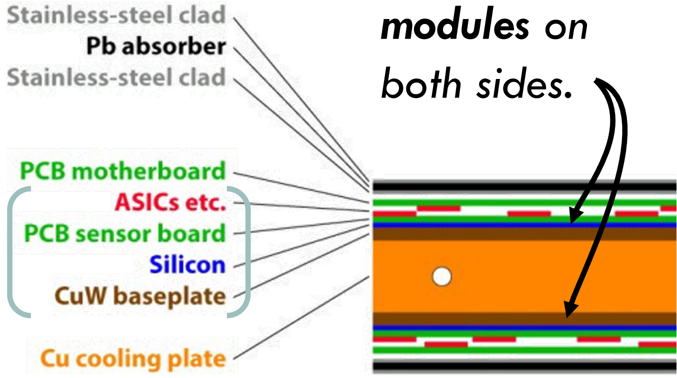


HV bias contacts



Guard ring contacts

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



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

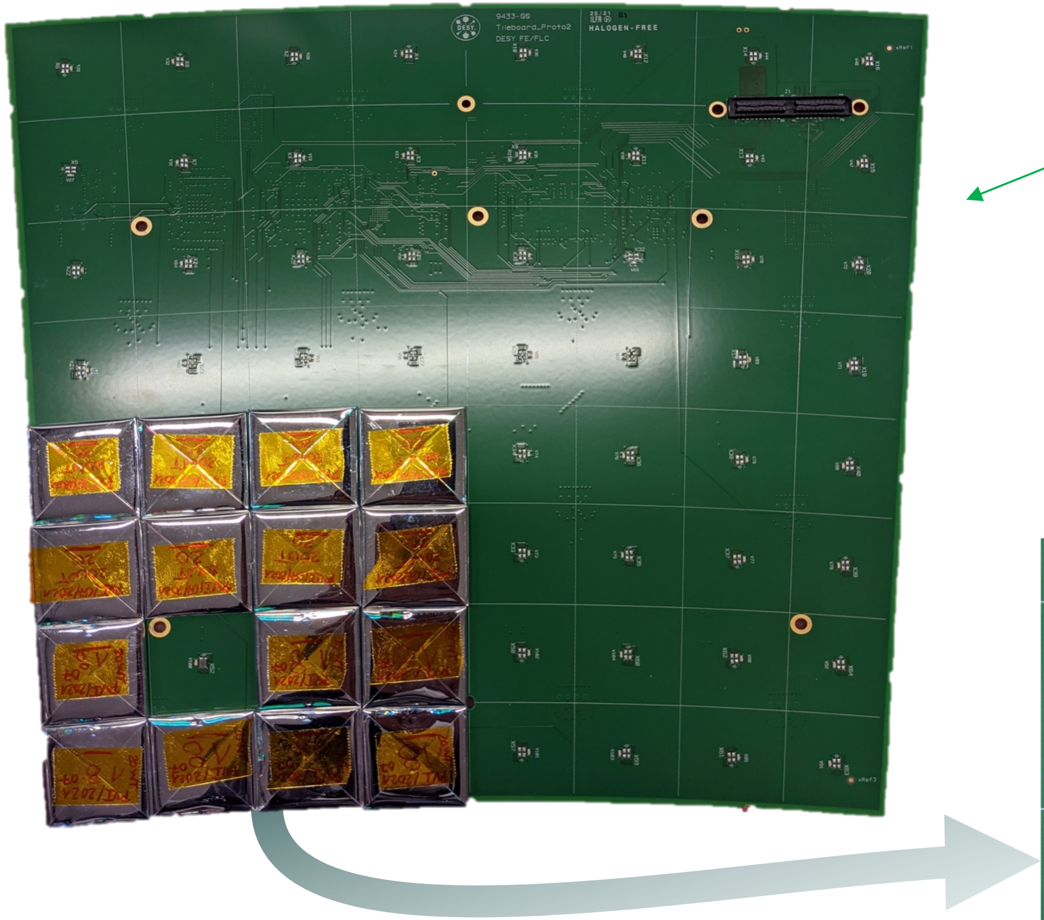
THE BUILDING BLOCKS – SCINTILLATING TILE MODULE

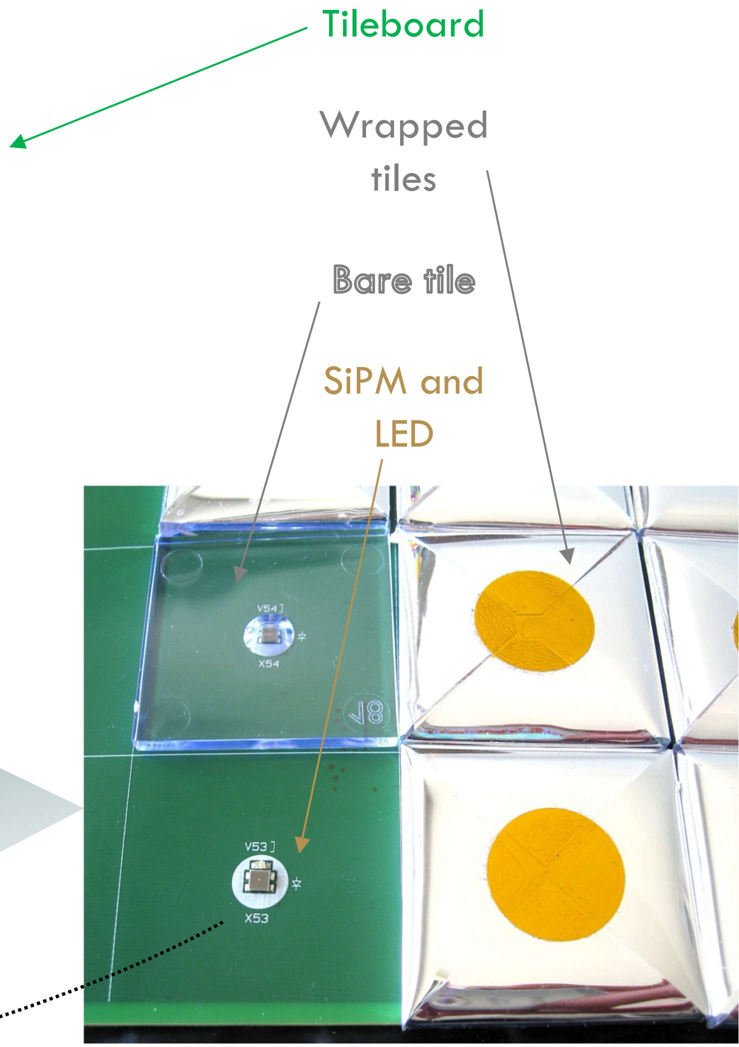
"Tile board" PCB

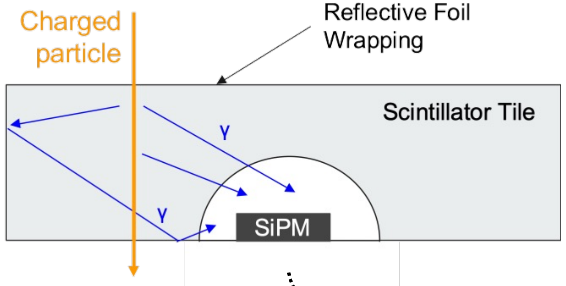
- Connects Silicon photo multipliers (SiPM) to HGCROC ASIC.
- Connects to motherboard for control and data transfer.

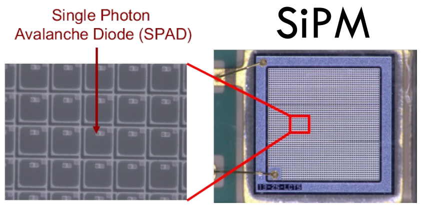
Wrapped scintillating tiles

- 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)

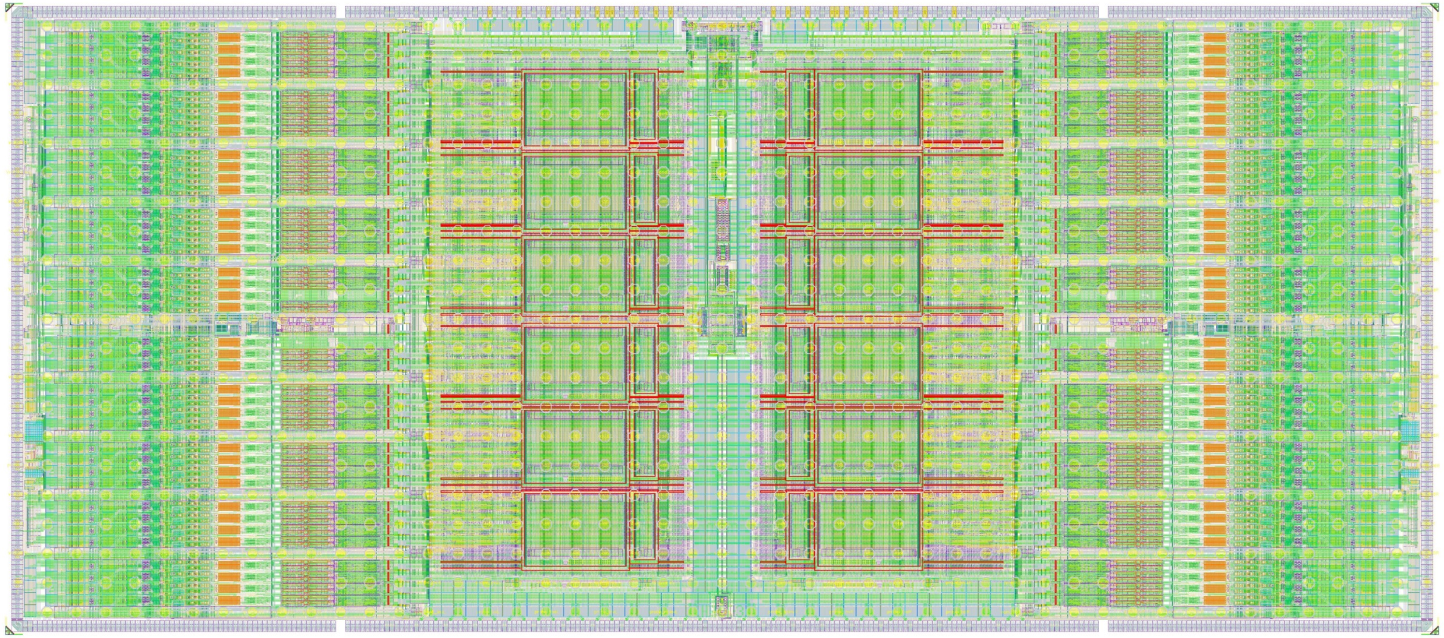
THE HGCROCV3 READOUT CHIP

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.



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- **4 common mode: ADC-only.**
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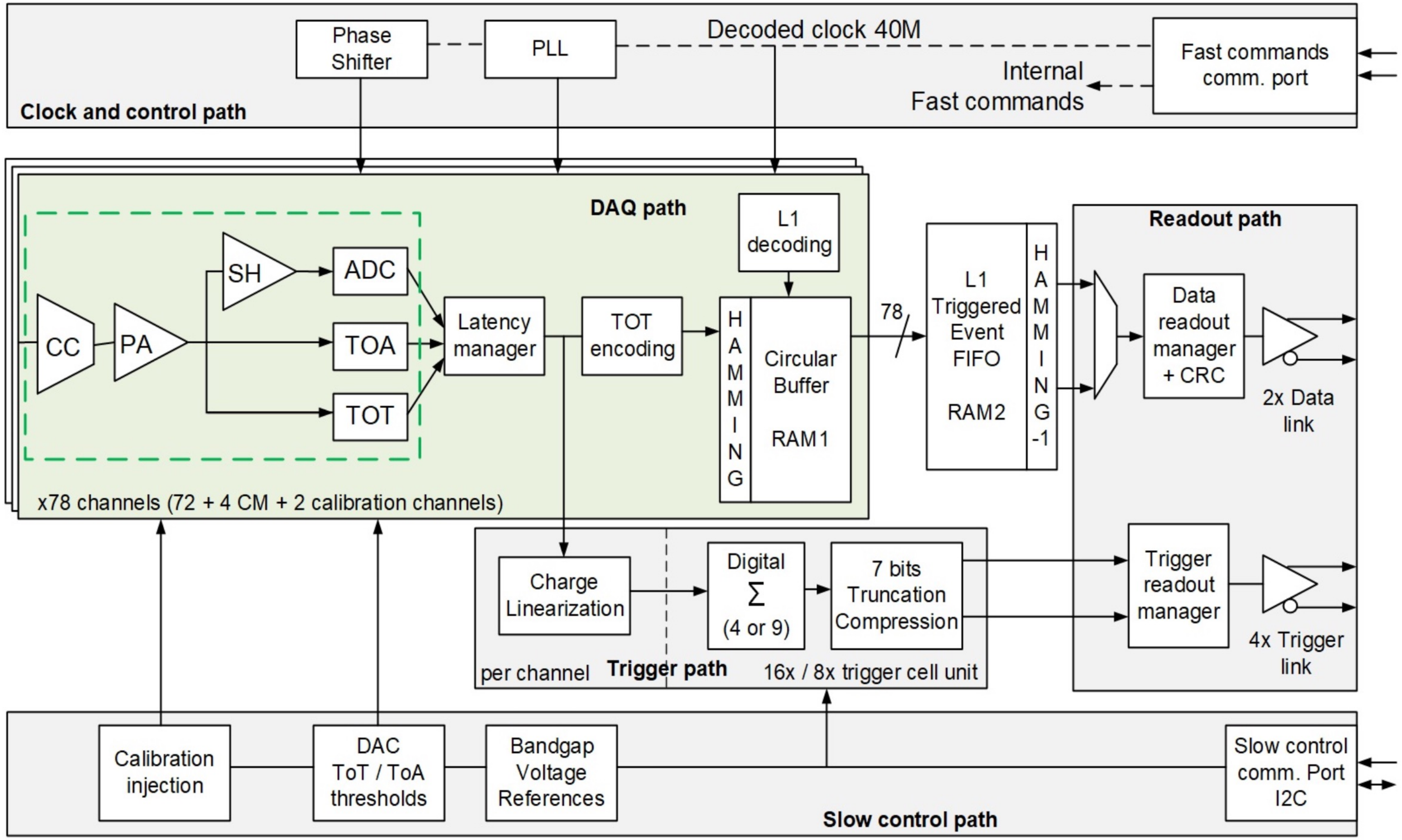

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Control:

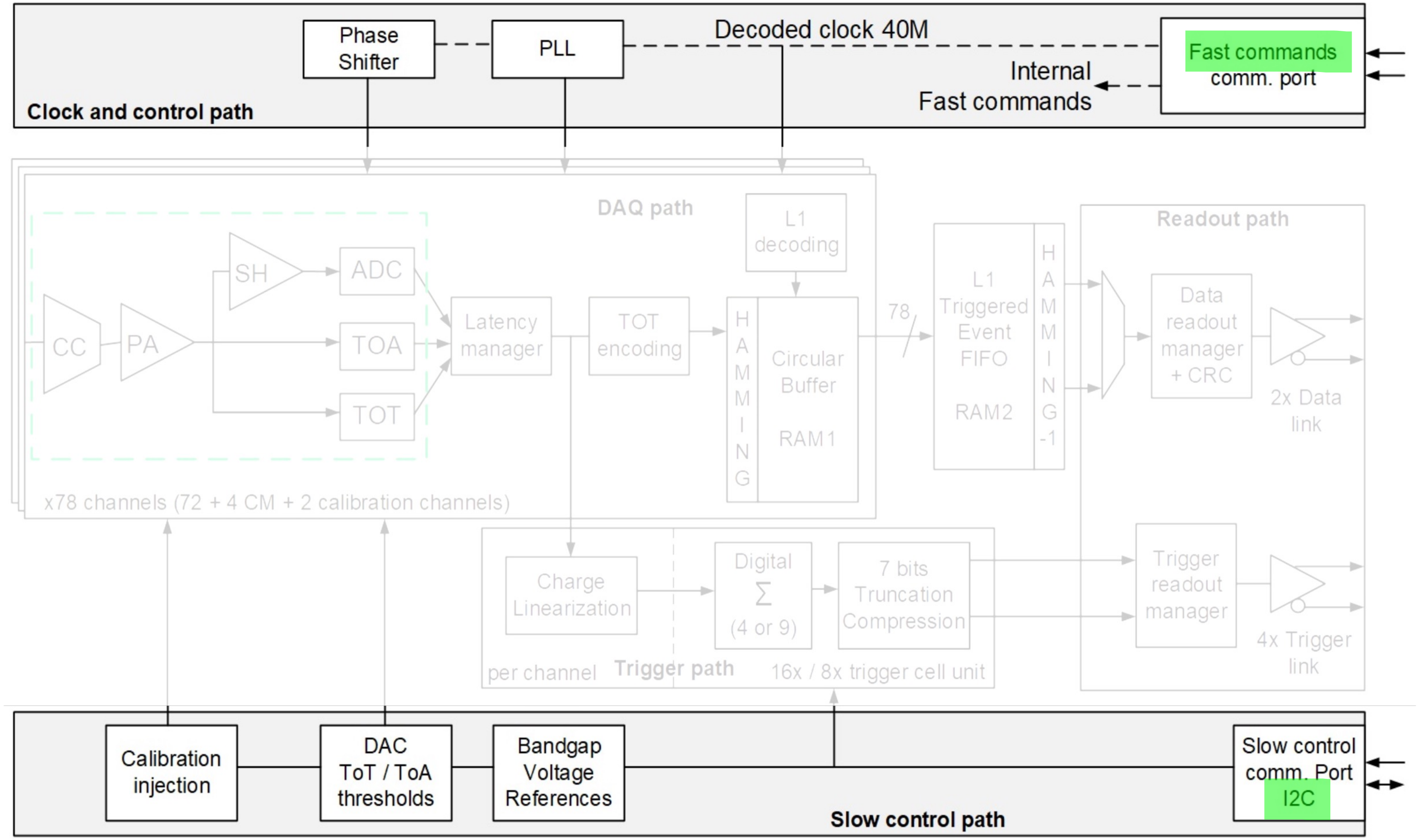
- **Synchronous fast control: custom 320 MHz (8 bit at 40 MHz).**
- **Asynchronous slow control: I2C.**

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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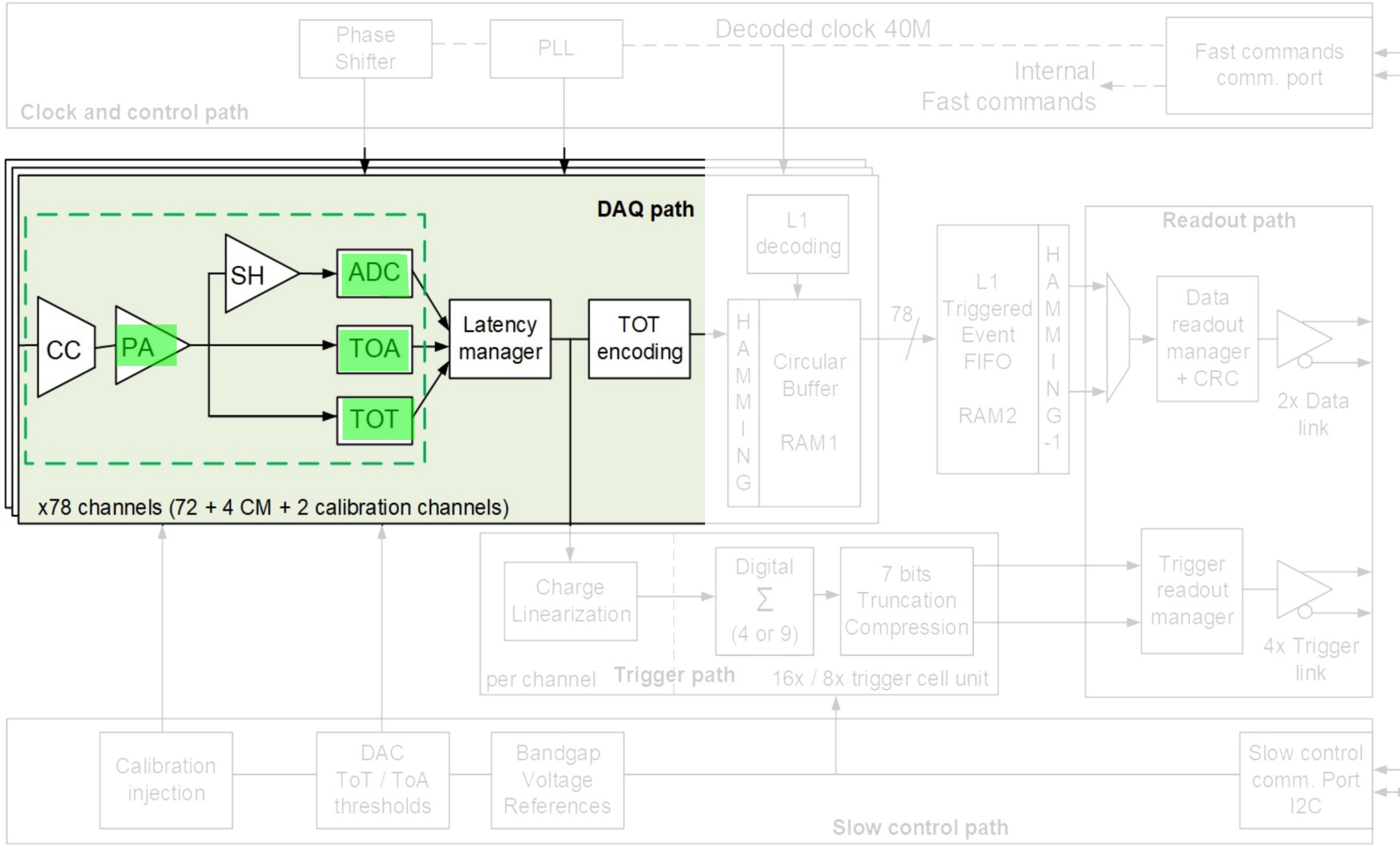

[J. D. Gonzalez Martinez (Pisa workshop 2022)]

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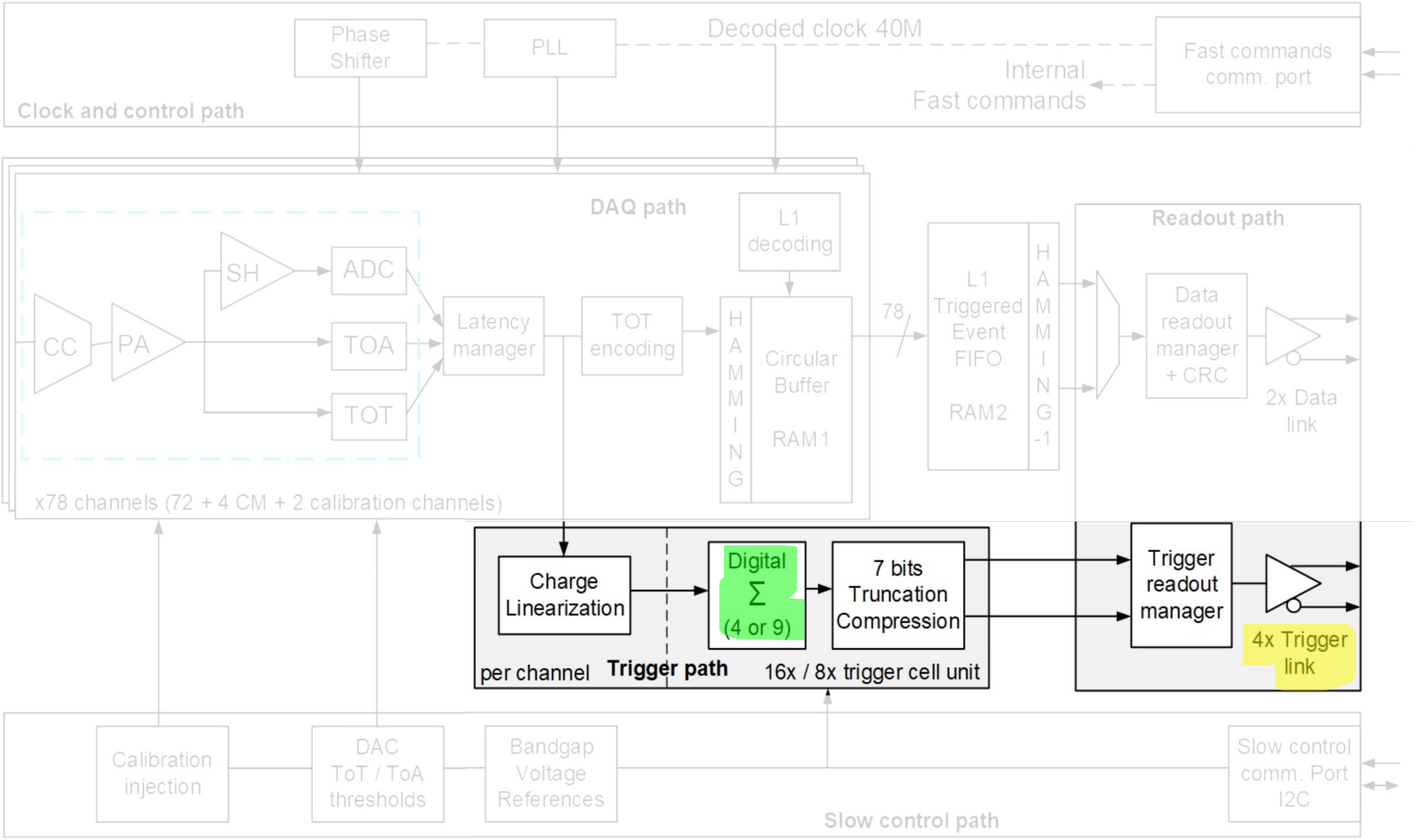

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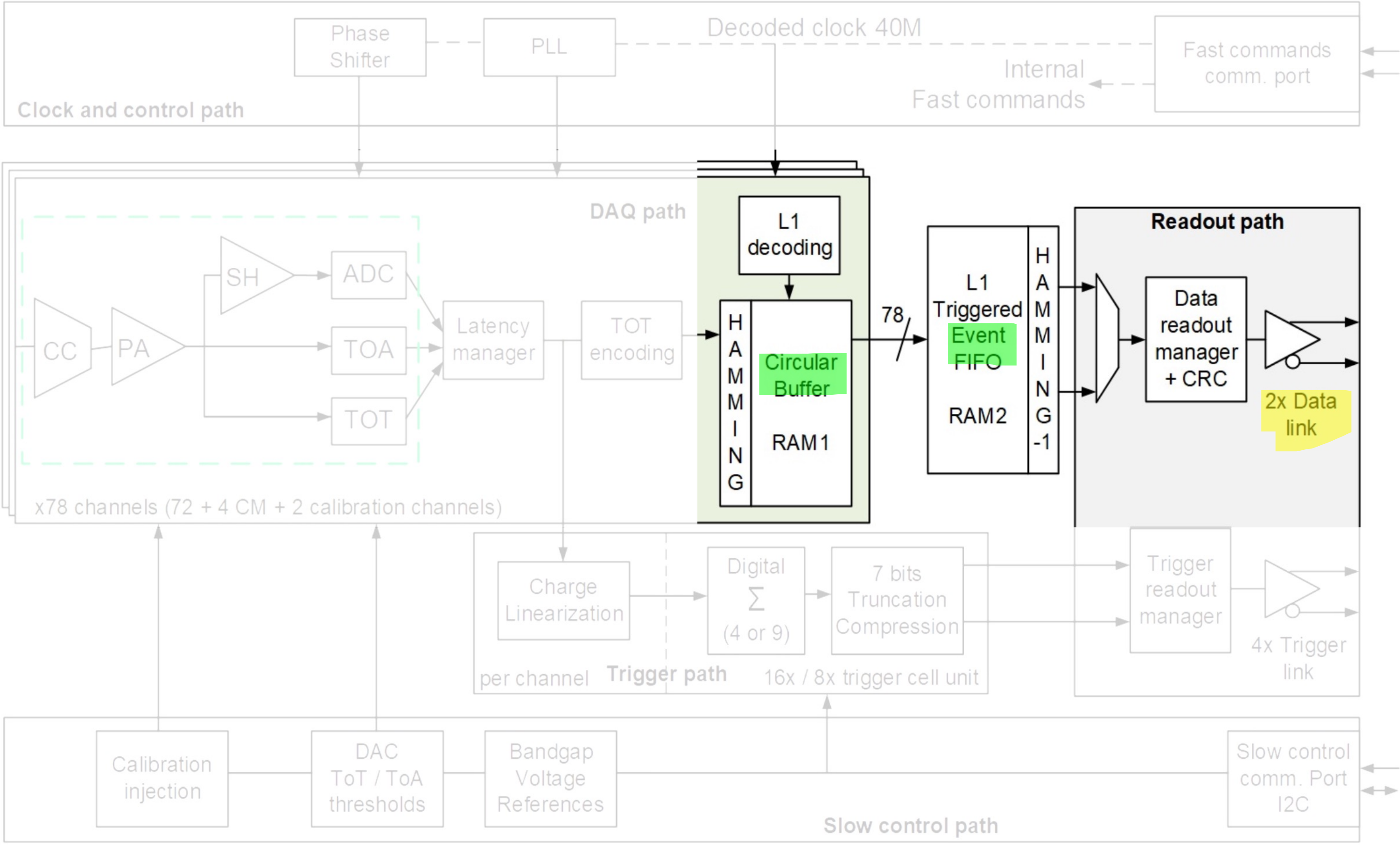


ELEMENTS OF THE PERFORMANCE CHAIN

Active material properties

Analogue and digital electronics performance

System integration aspects

Reconstruction algorithms

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

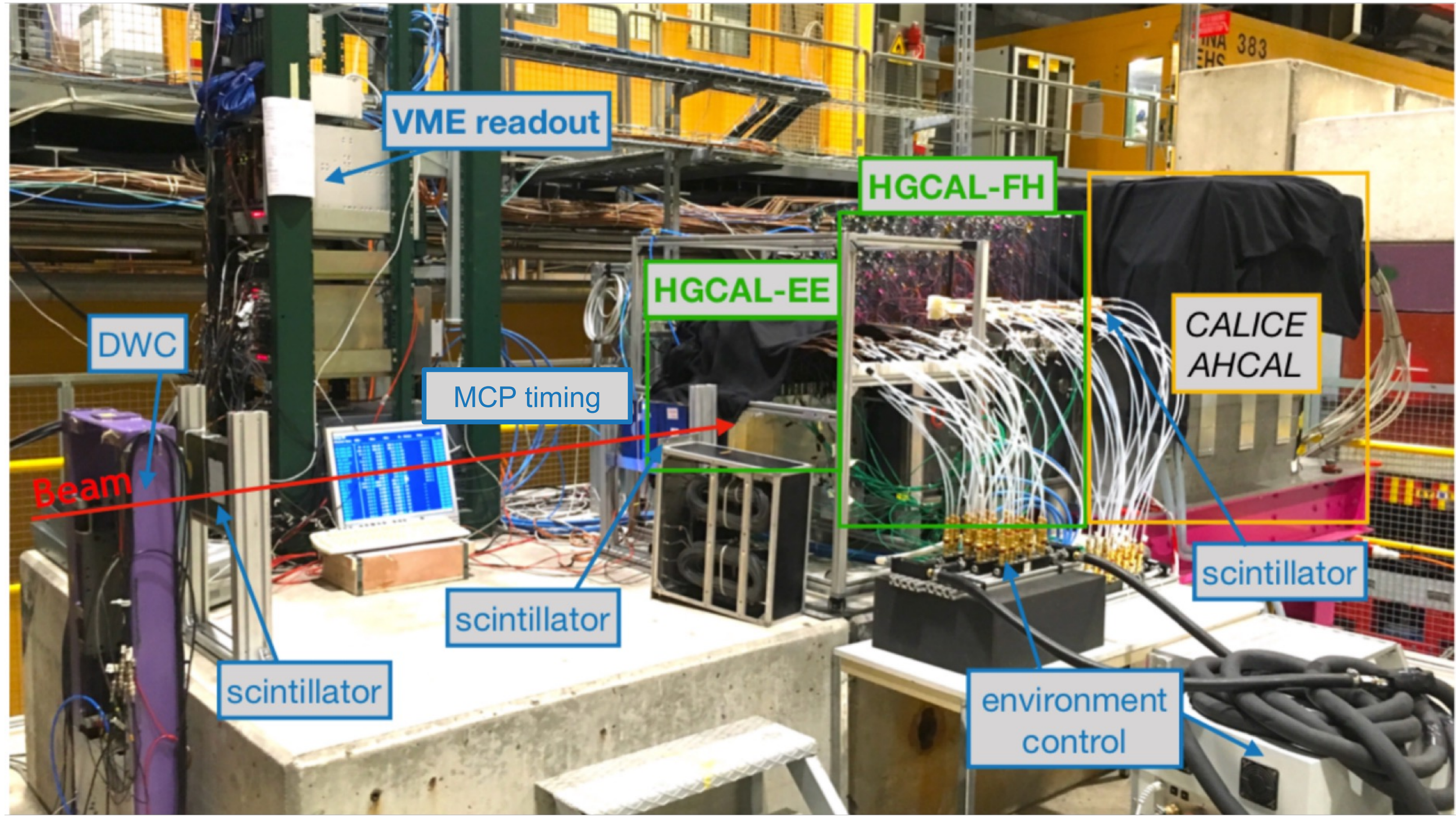
2018 PROTOTYPE

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)

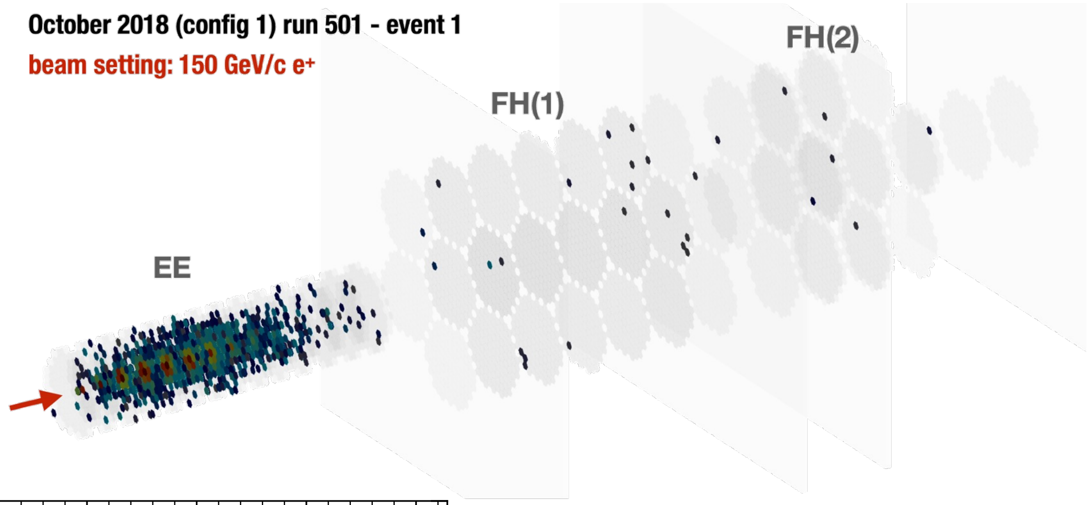
CERN-THESIS-2019-367
JINST 17 (2022) 05, P05022

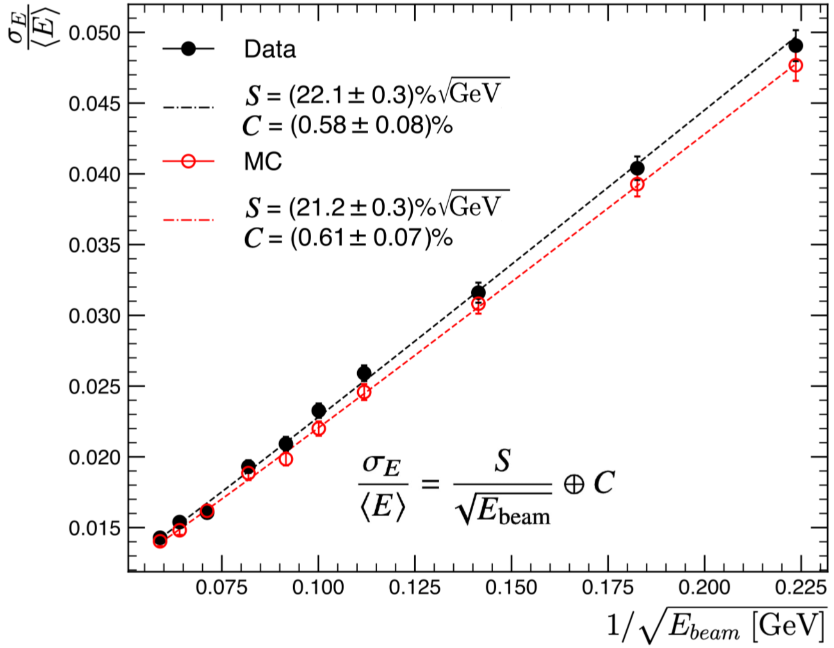
2018 PROTOTYPE ELECTROMAGNETIC PERFORMANCE

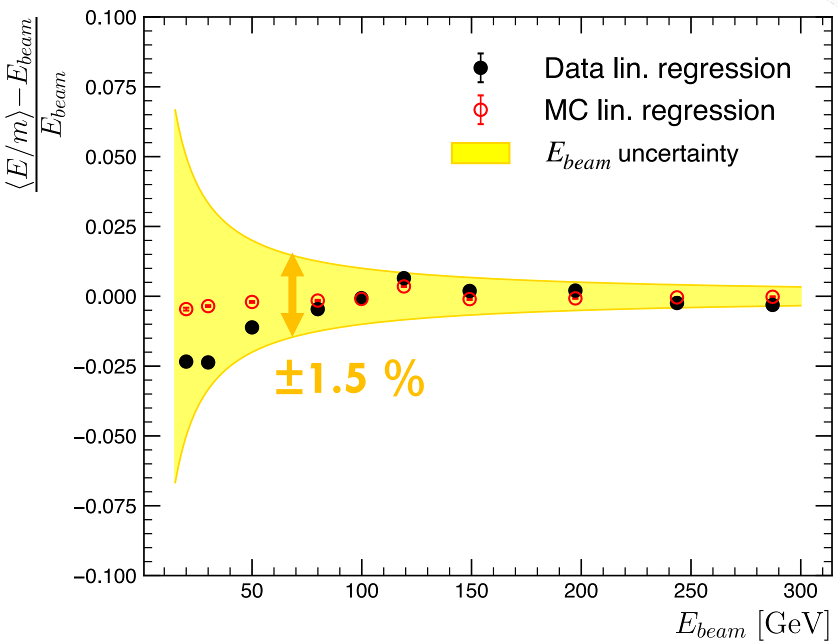
Good energy resolution
- 0.6% local constant term.
- 22% stochastic term.

Good linearity for E > ~50GeV.

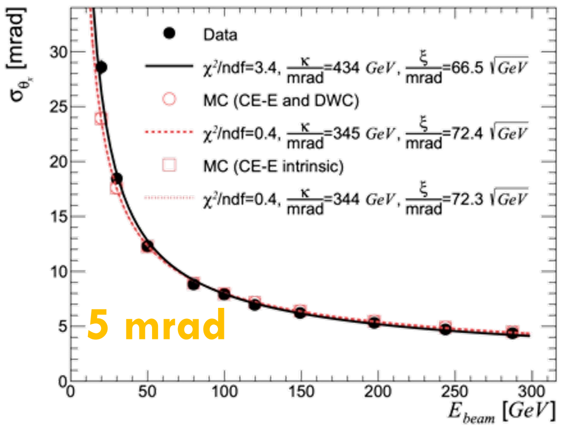
Good pointing resolution.





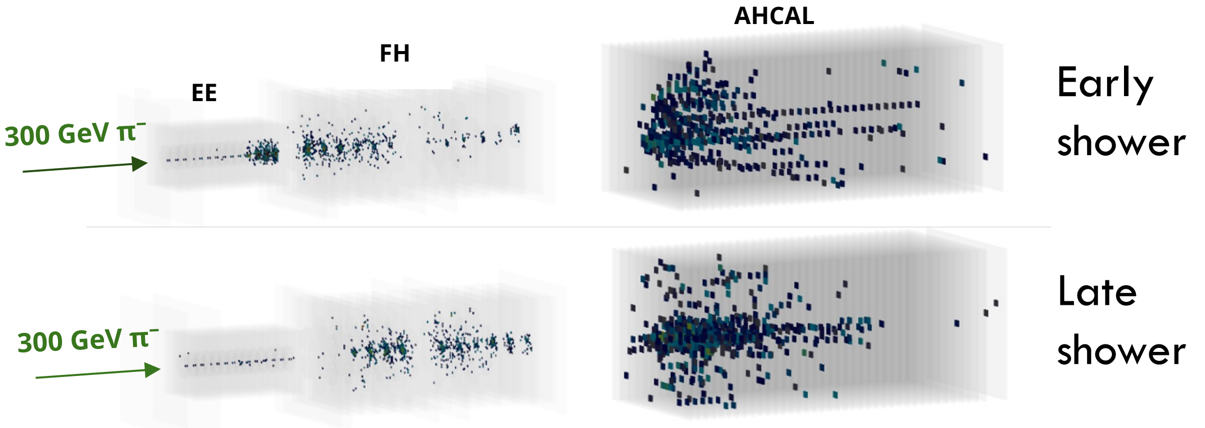


Shower axis angular resolution



A. Sirohi (BTTB 2022)

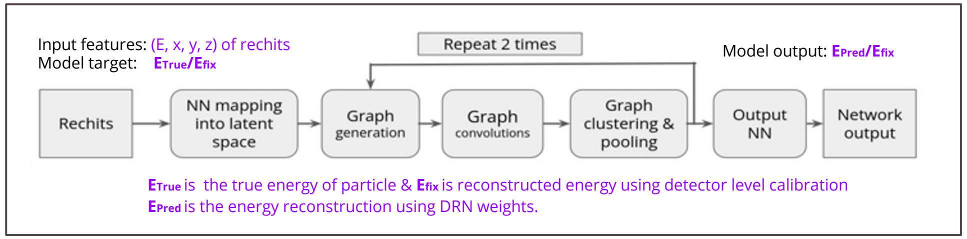
2018 PROTOTYPE HADRONIC PERFORMANCE

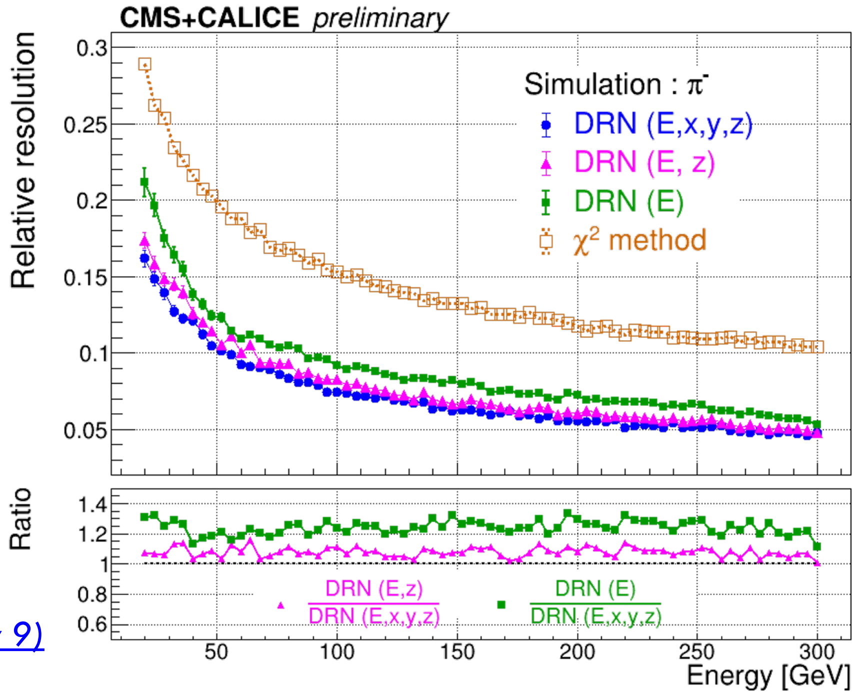


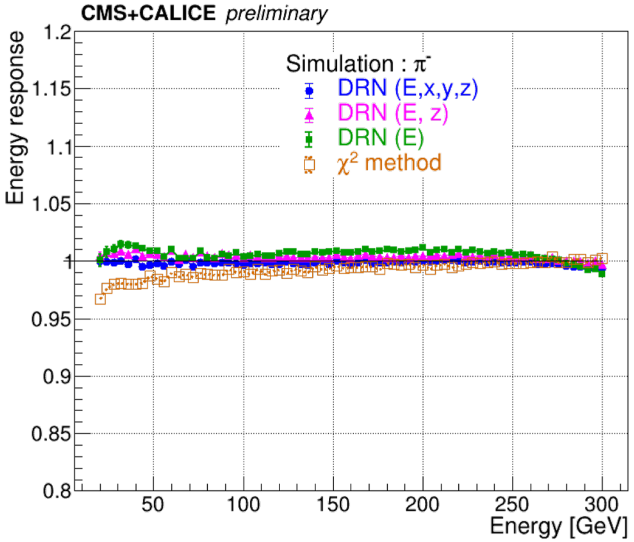
Hadronic showers have large variability.

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.







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

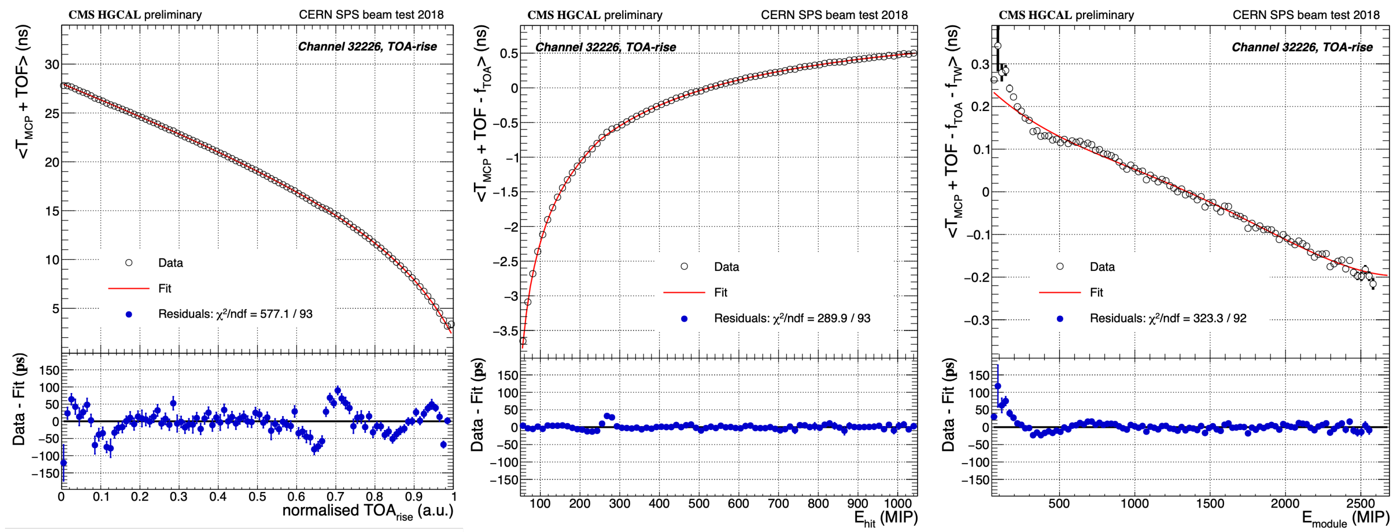
T. Quast (Pisa workshop 2022)

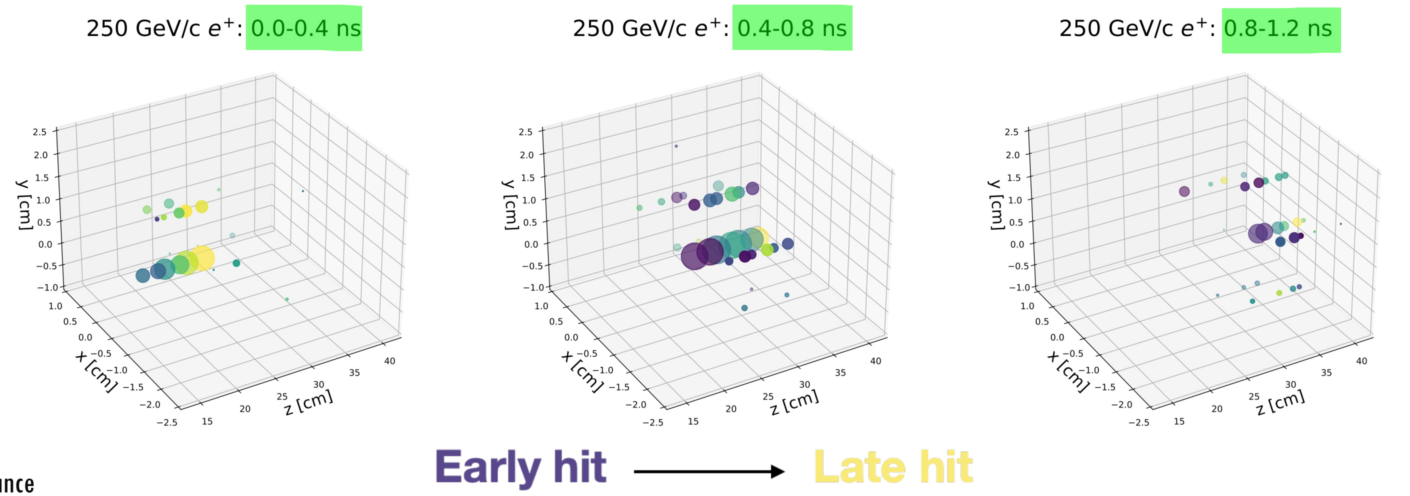
2018 PROTOTYPE TIMING PERFORMANCE

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 !





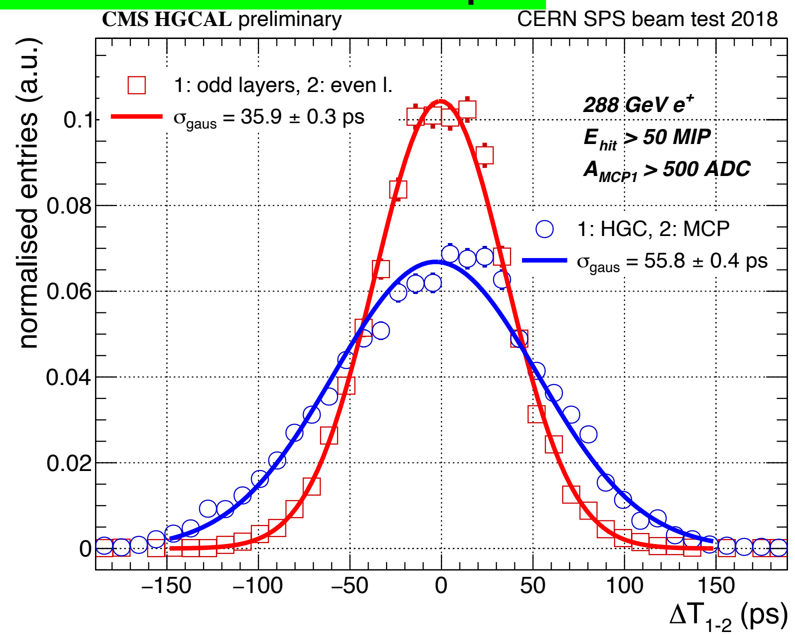
T. Quast (Pisa workshop 2022)

2018 PROTOTYPE TIMING PERFORMANCE

Complex set of measurements

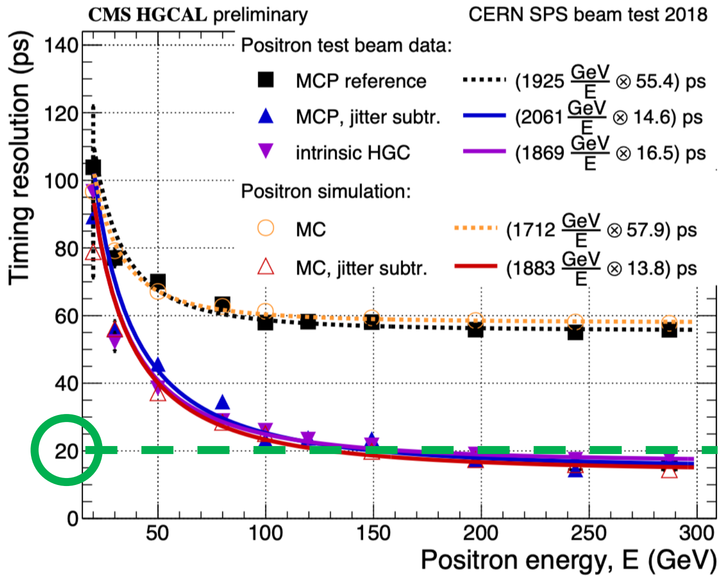
- Cross-checks with MCP detector reference.
- Est. MCP-HGCAL correlated jitter O(50 ps).

High-energy shower time resolution < 20 ps !

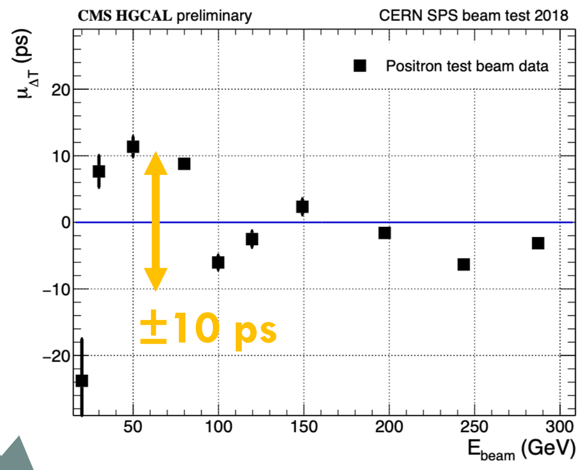


HGCAL odd vs even layers: **~36 ps**

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

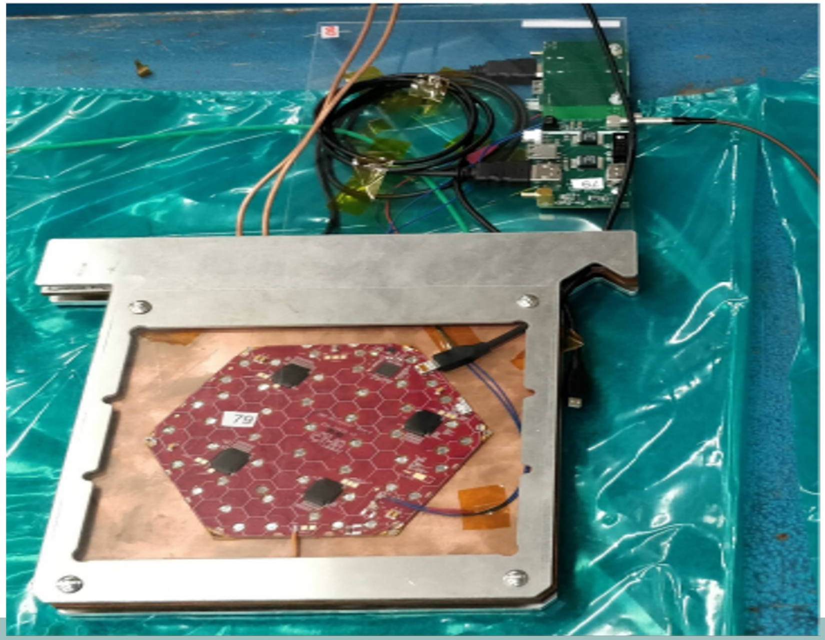


Resolution-weighed average of timing of shower hits: **< 20 ps** for **E > 200 GeV**.



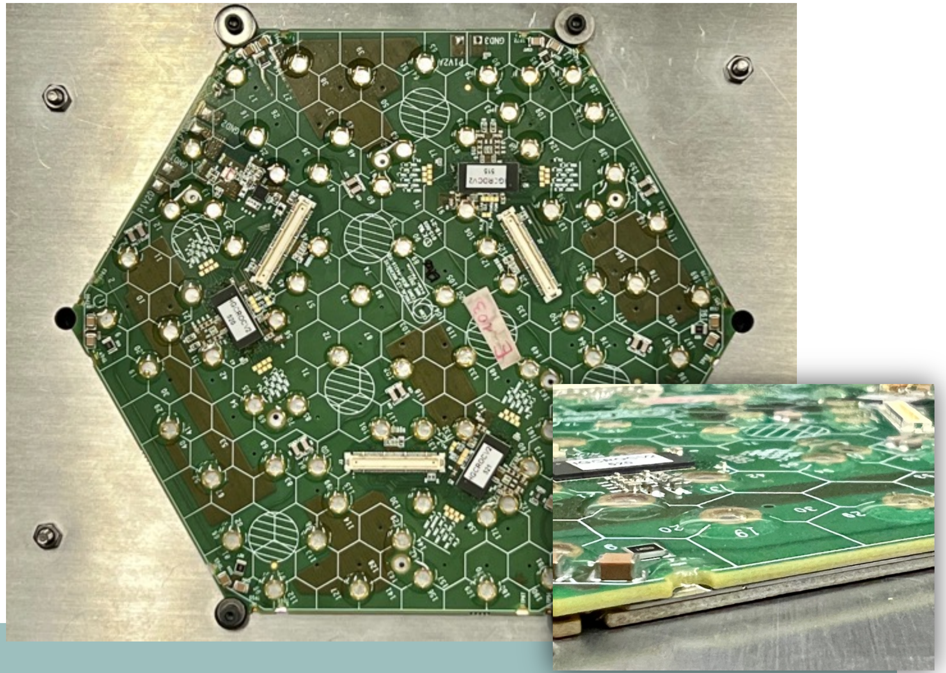
Accuracy w.r.t. MCP reference within **±10 ps** for **E > 50 GeV**.

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

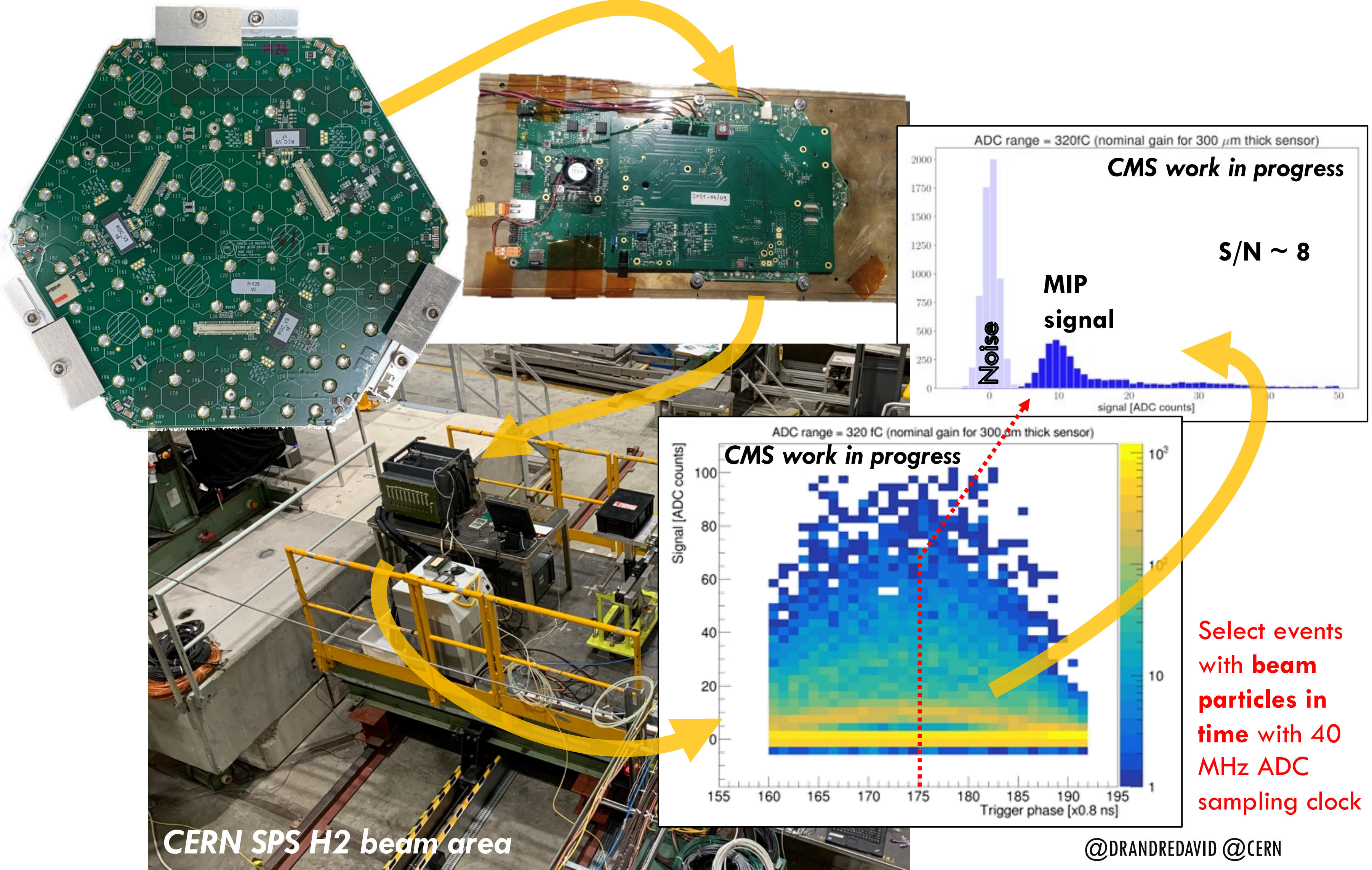
Very fast turnaround:

- 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

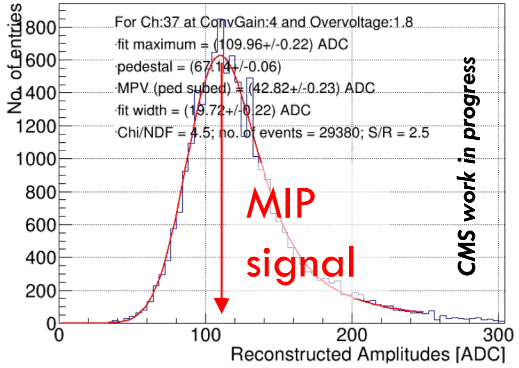
Performance of irradiated SiPMs

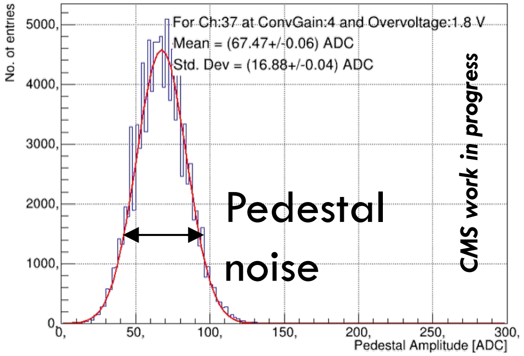
- Irradiated to 2×10^{12} n_{eq}/cm^2.
- Beam tests at DESY II in April 2022.
- Shared readout system with Silicon module.

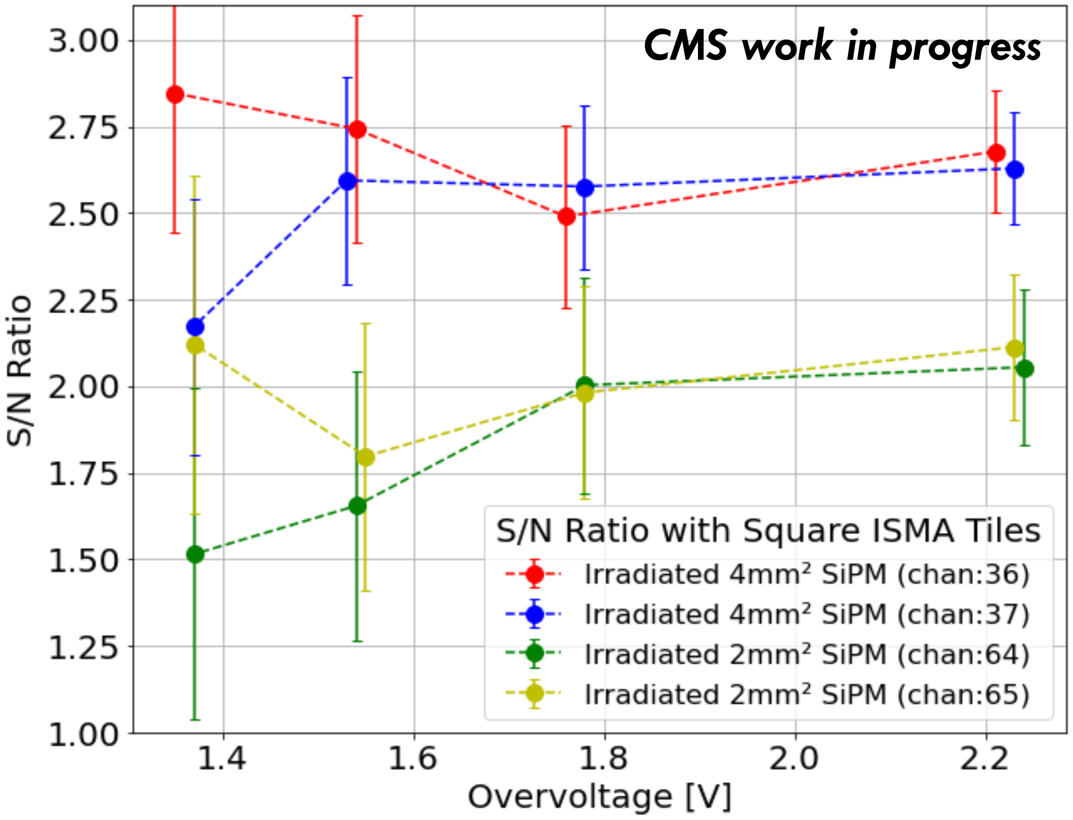
S/N ratio relatively independent from overvoltage.

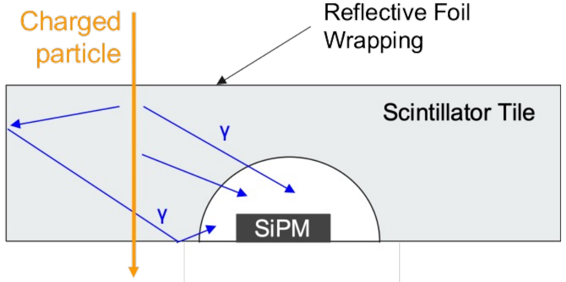
Confirms end-of-life S/N performance with final SiPMs.

- 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

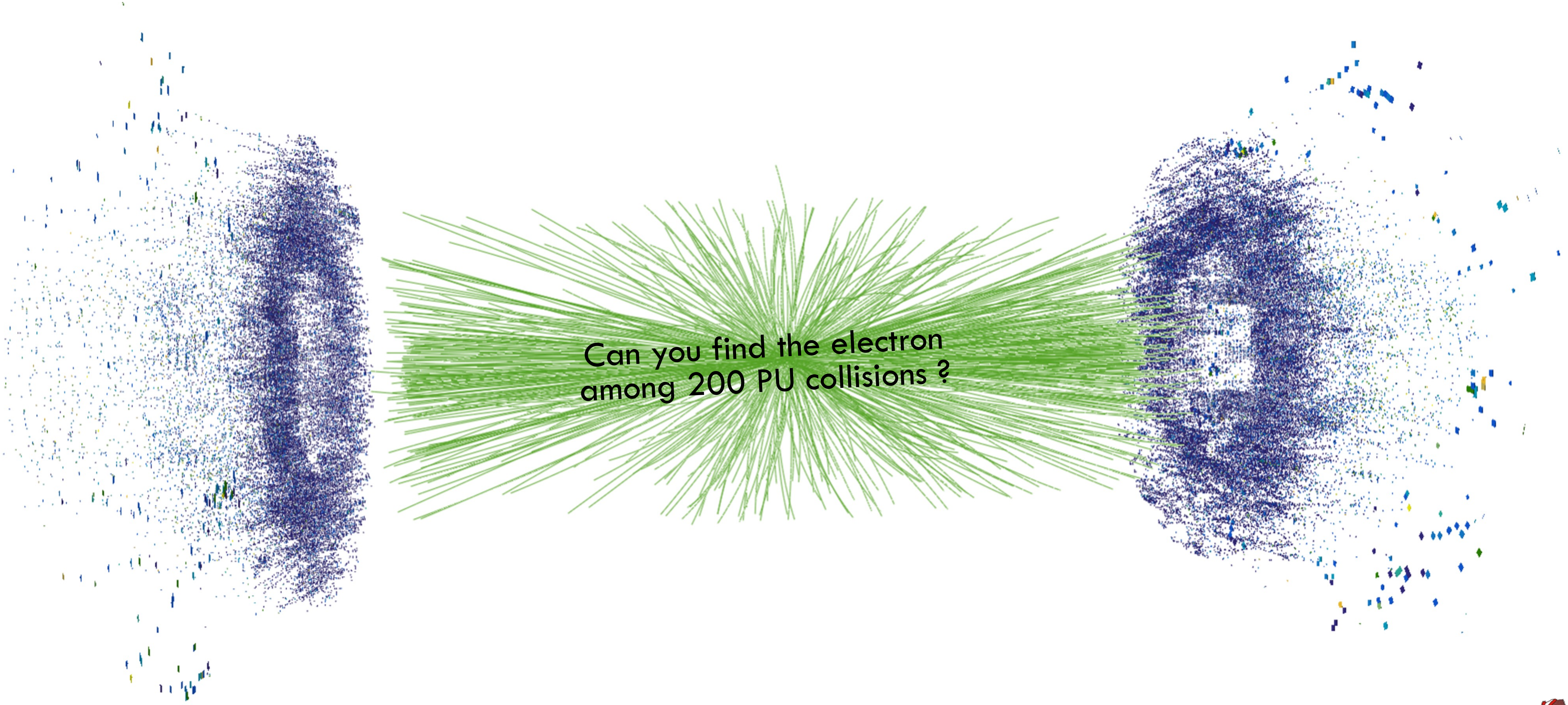
Active material properties

Analogue and digital electronics performance

System integration aspects

Reconstruction **algorithms**

BRINGING THE 5D PERFORMANCE TO FRUITION

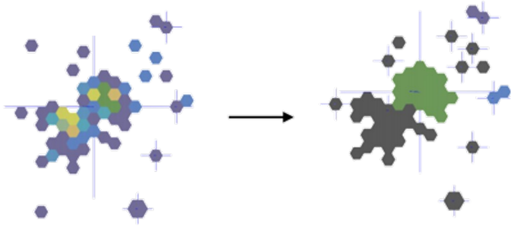


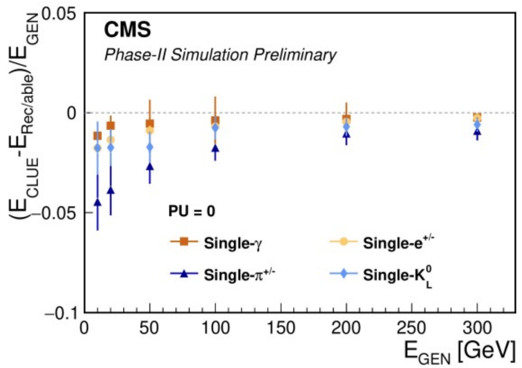
F. Pantaleo (ACAT 2021)
E. Brondolin (ACAT 2021)
B. Alves (ACAT 2021)

CLUSTERING-BASED RECONSTRUCTION

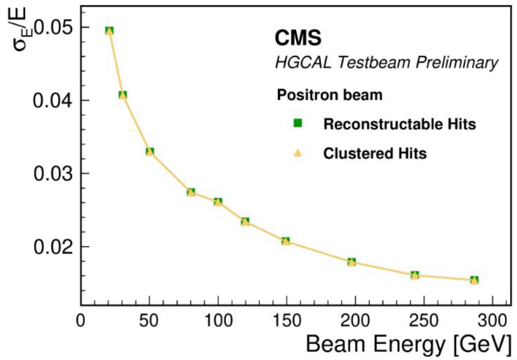
CLUE – algorithm for energy clustering

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





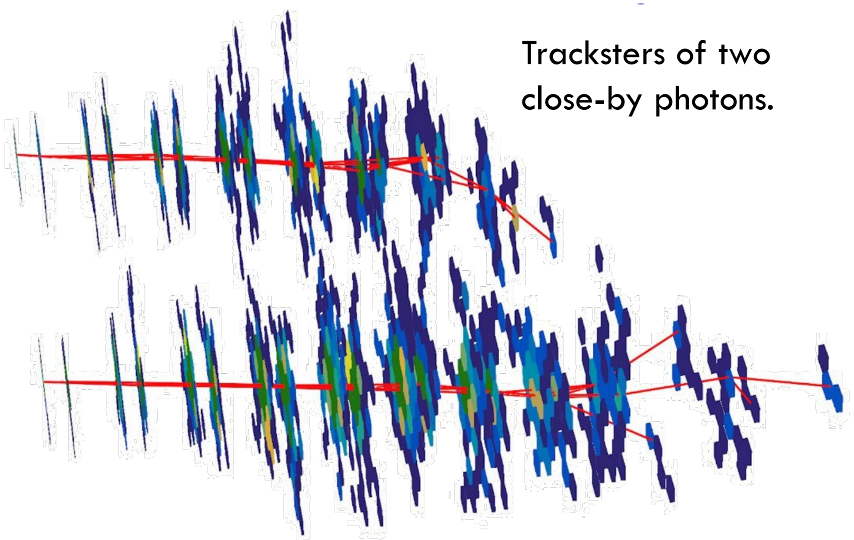
CLUE loses O(1%) energy



CLUE in beam test data

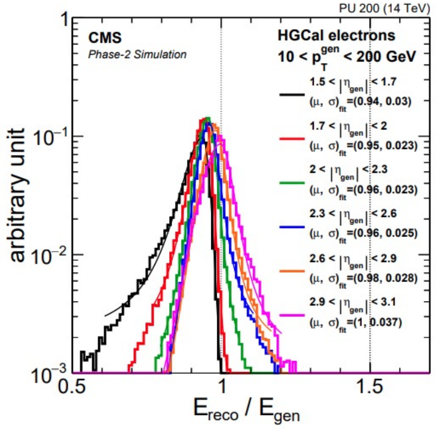
TICL – The Iterative Clustering

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

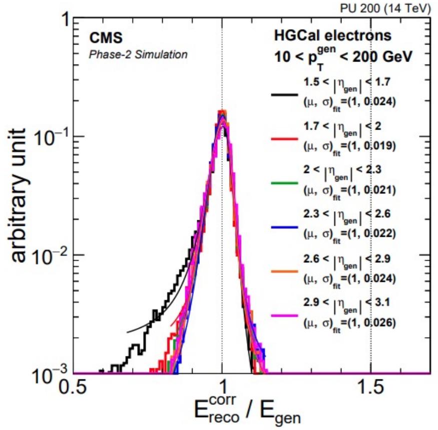


Tracksters of two close-by photons.

Uncorrected energy



DNN-regressed energy



T. Klijnsma (ACAT 2021)

END-TO-END MACHINE LEARNING RECONSTRUCTION

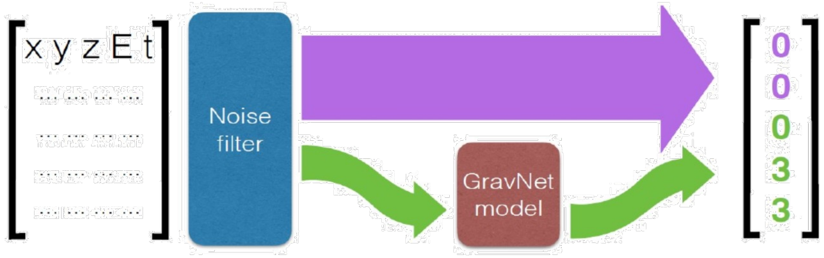
Directly use Rechits.

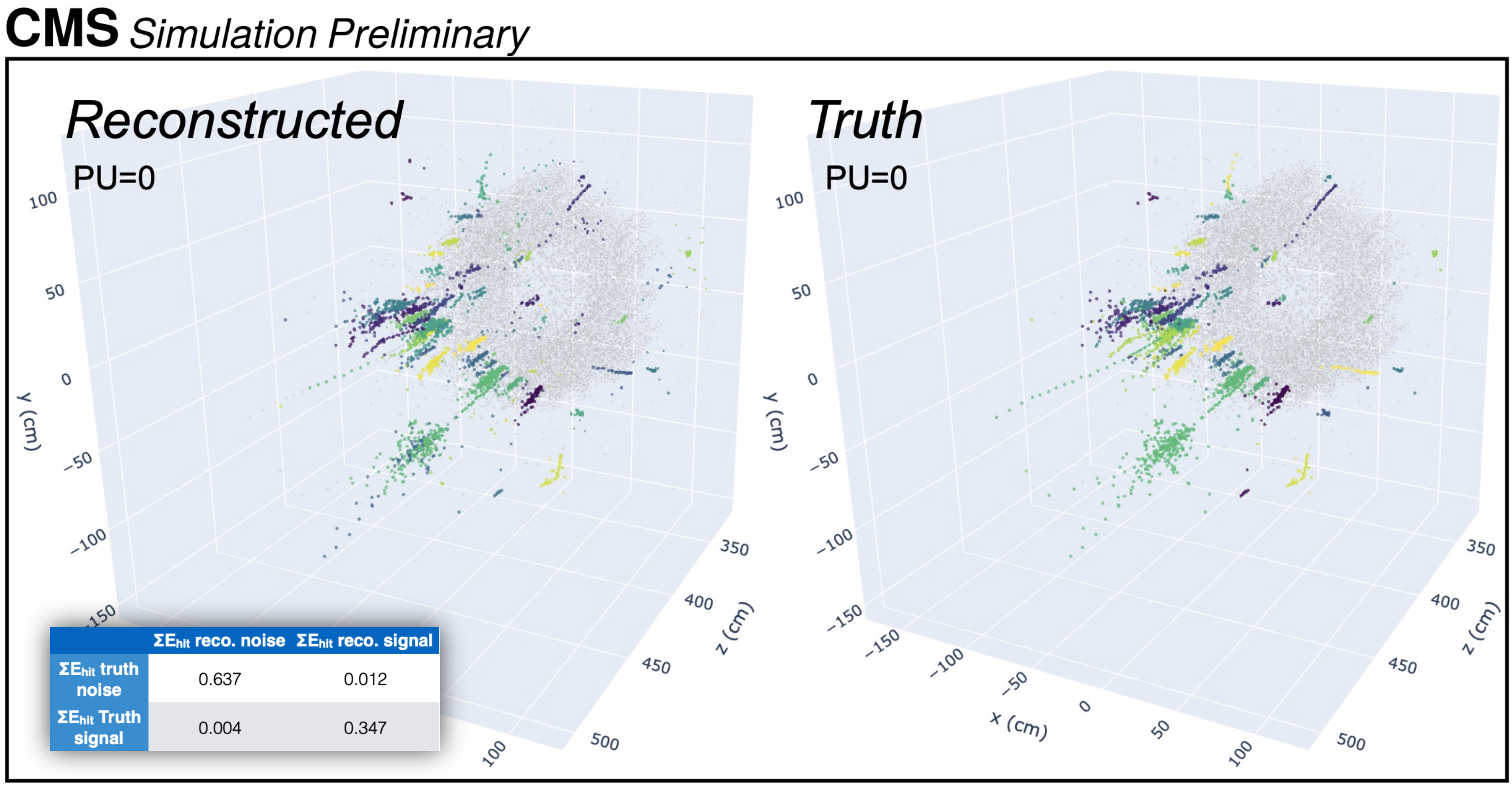
Two-stage model with:

- **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**

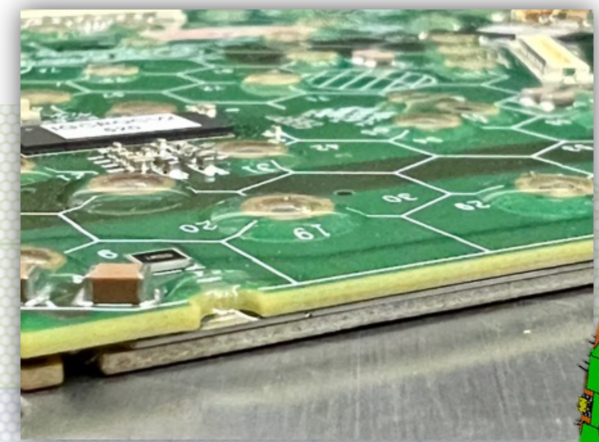
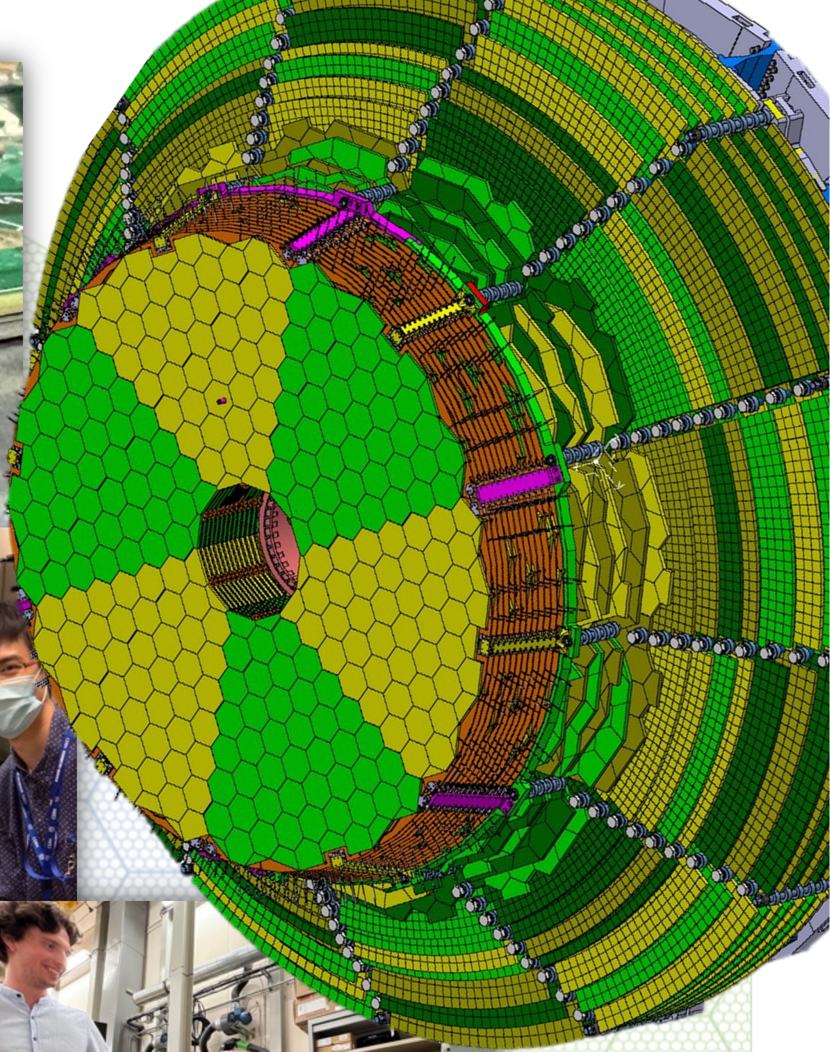
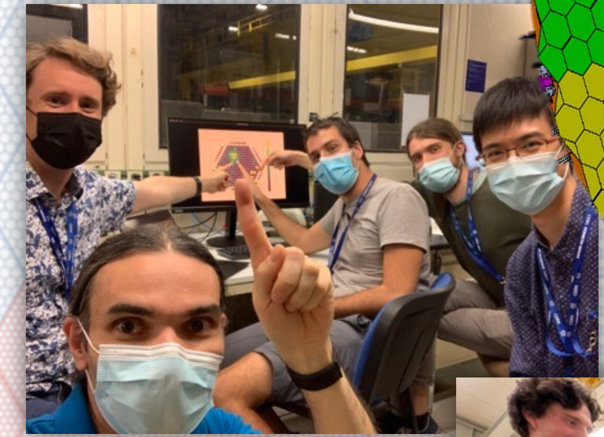
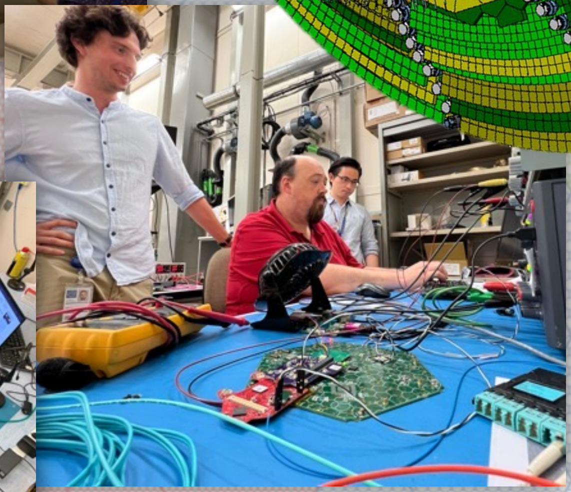
- **Spatial** integration in small volume.
- 20-ps **timing** precision over 600 m^2 of detector.
- **Energy** linearity from single MIP to showers.

Online and offline challenges

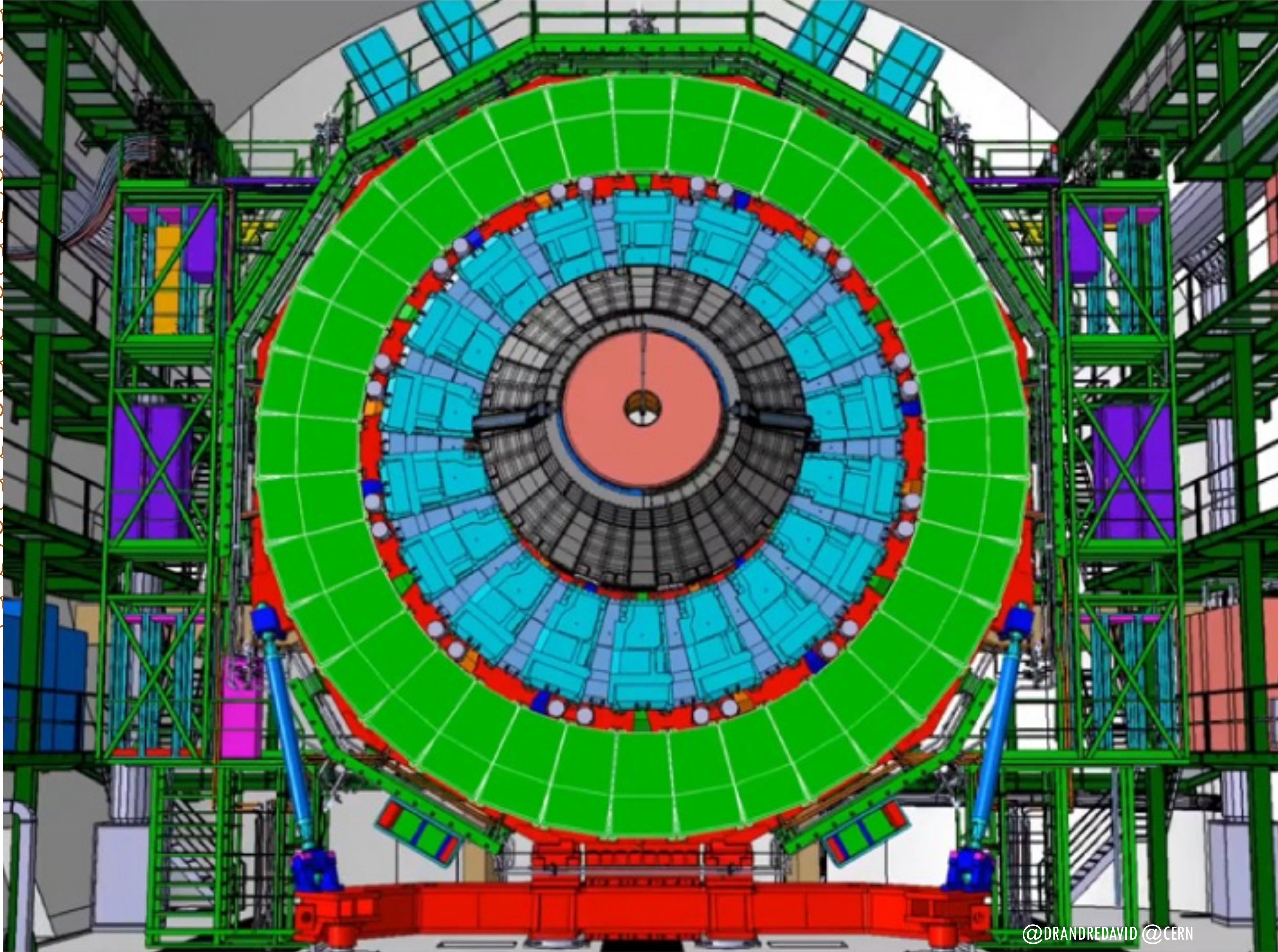
- Full system integration under way.
- Next-generation reconstruction algorithms.

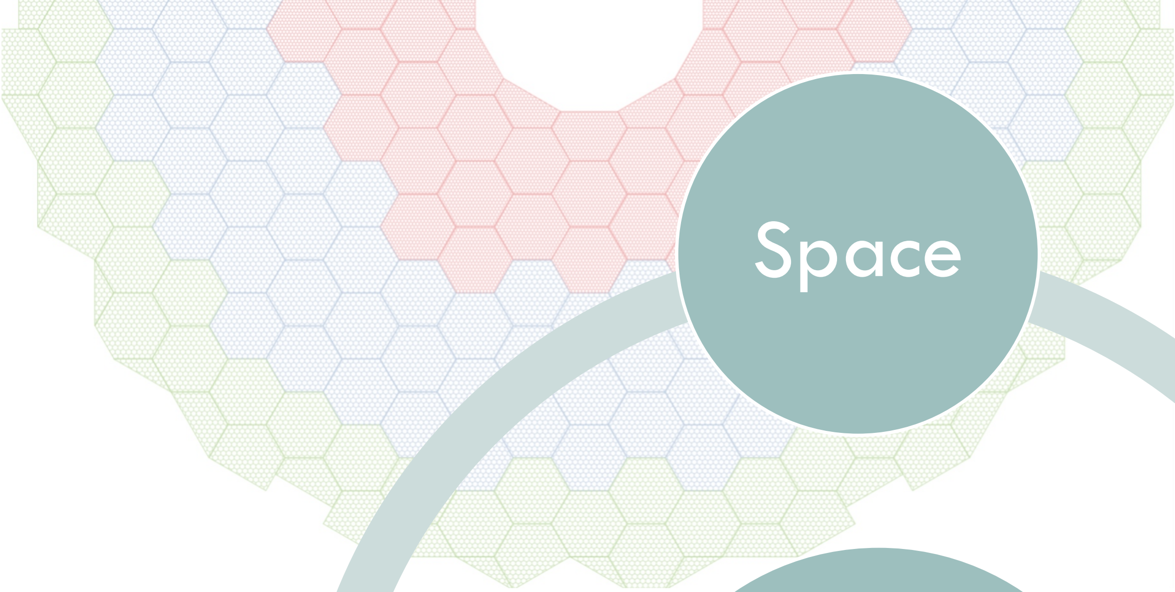
All are welcome to join in the fun !

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

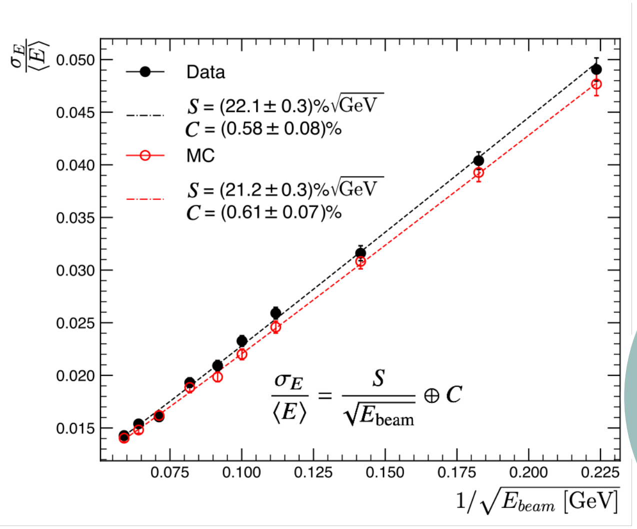

THANK YOU!





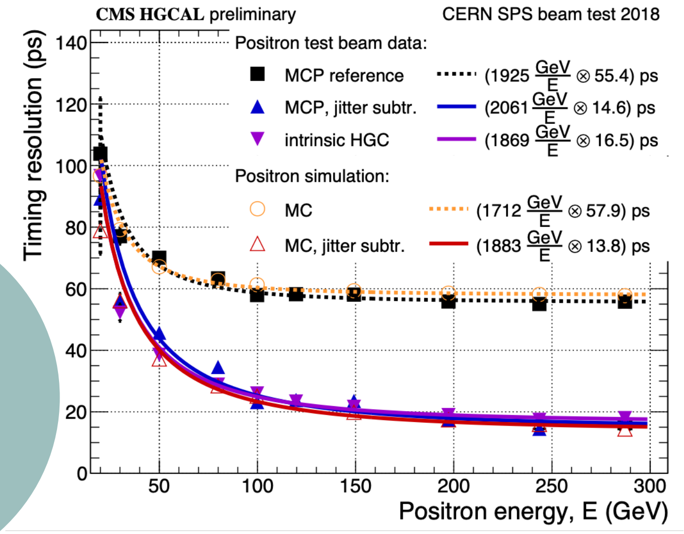
Space

5D



Energy

Time



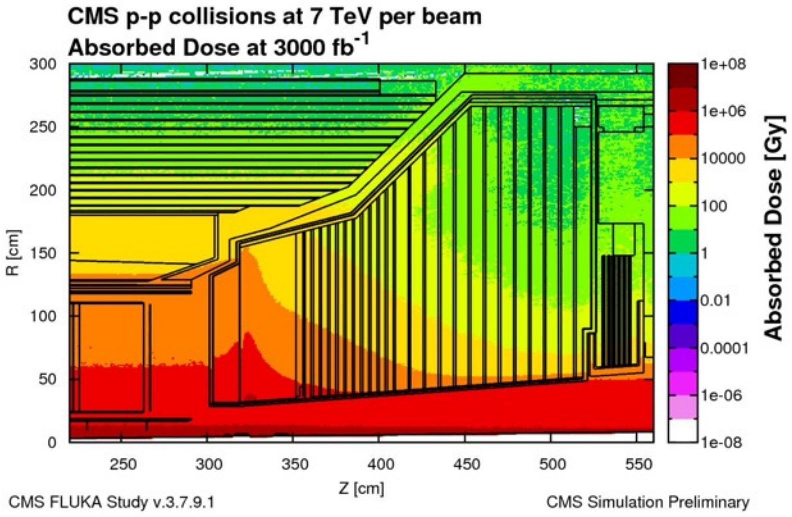
REQUIREMENTS

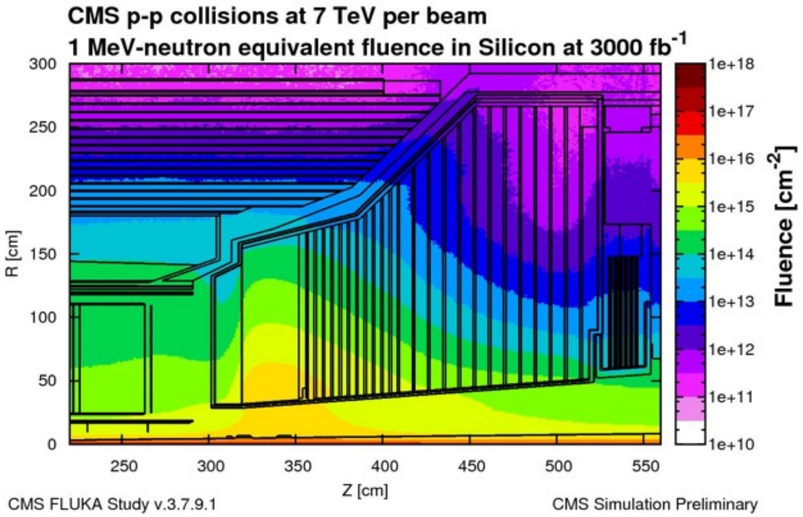
Radiation hardness

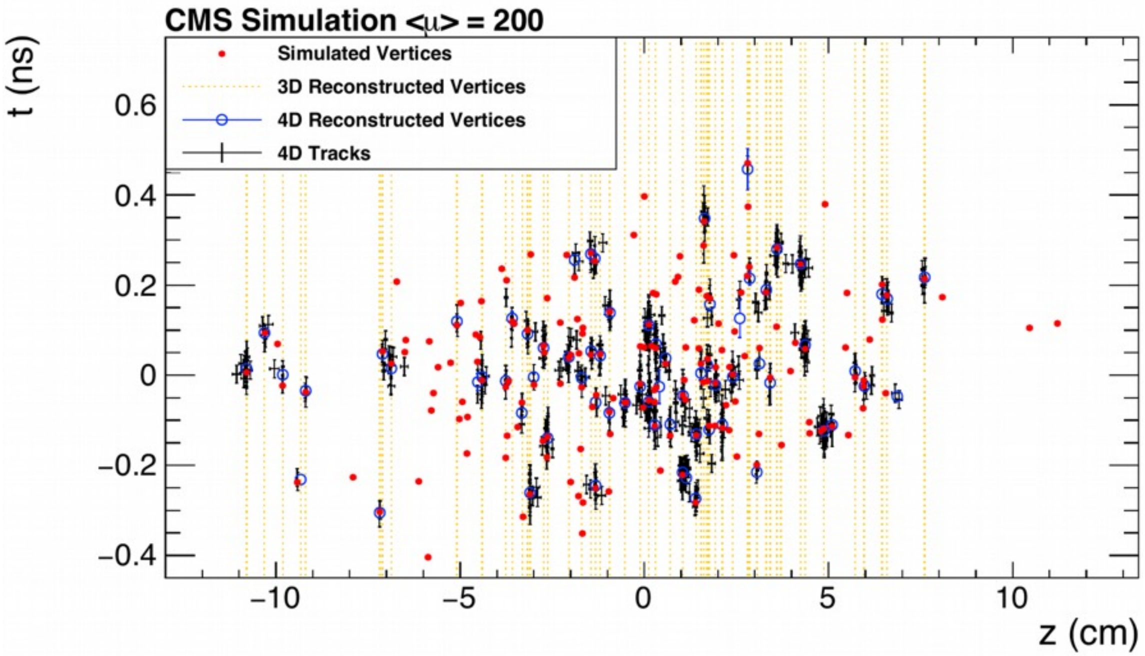
- Fluences from 1×10^{12} n_{eq}/cm^2…
- … to 1×10^{16} n_{eq}/cm^2.
- Dose from 10 Gy to 1 MGy.

Spatial and time resolution

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

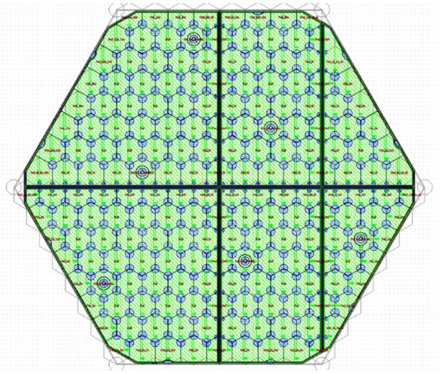




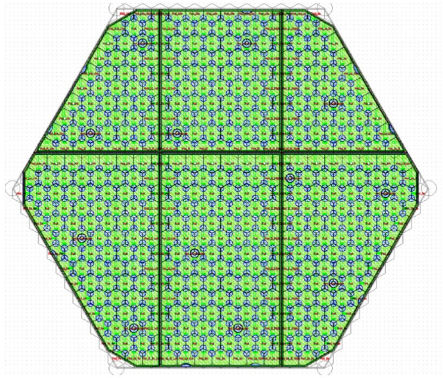


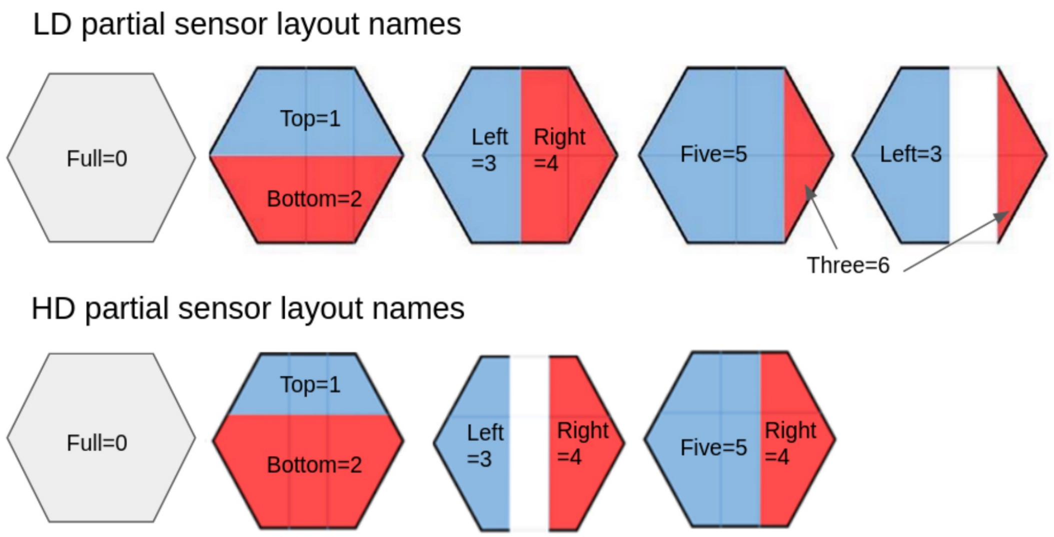
"HEXAGONATURE" OF THE CIRCLE

Low Density Multi-Geometry Wafer



High Density Multi-Geometry Wafer





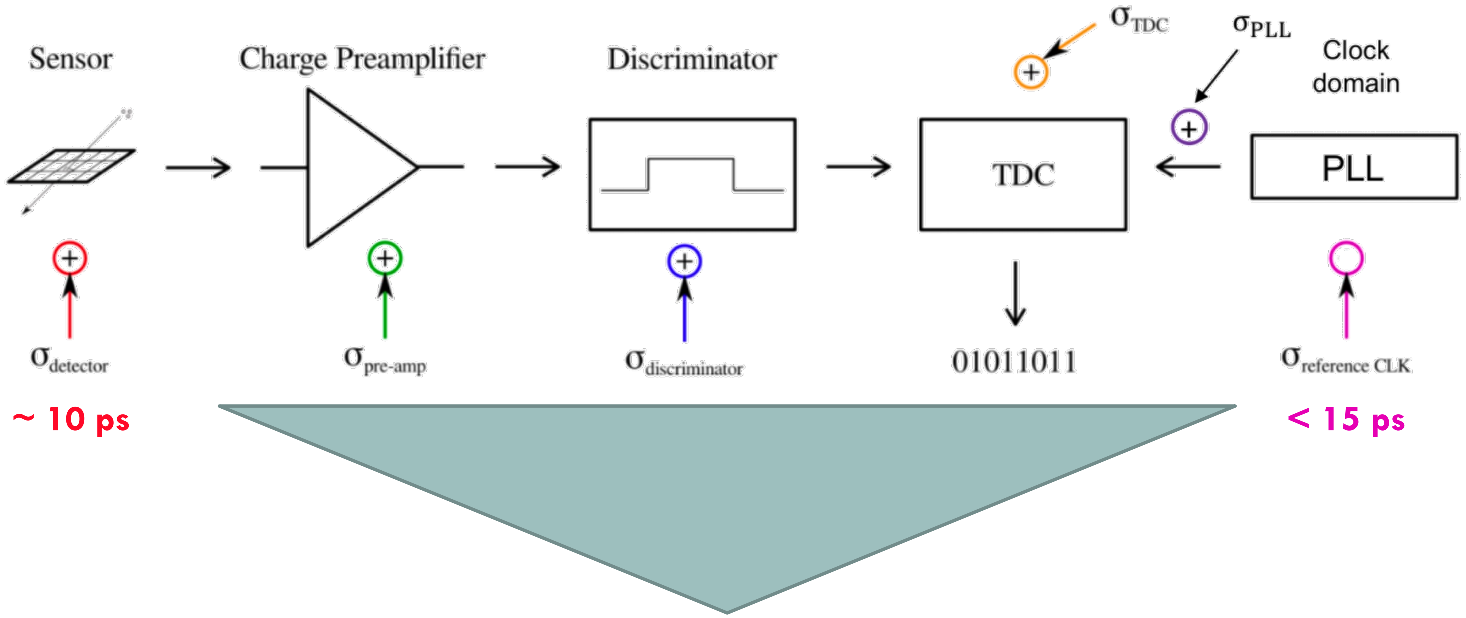
T. Quast (Pisa workshop 2022)

TIMING PERFORMANCE

Many contributions.

Crucial aspects:

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



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

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 -35°C

~620m^2 Si sensors in ~26000 modules

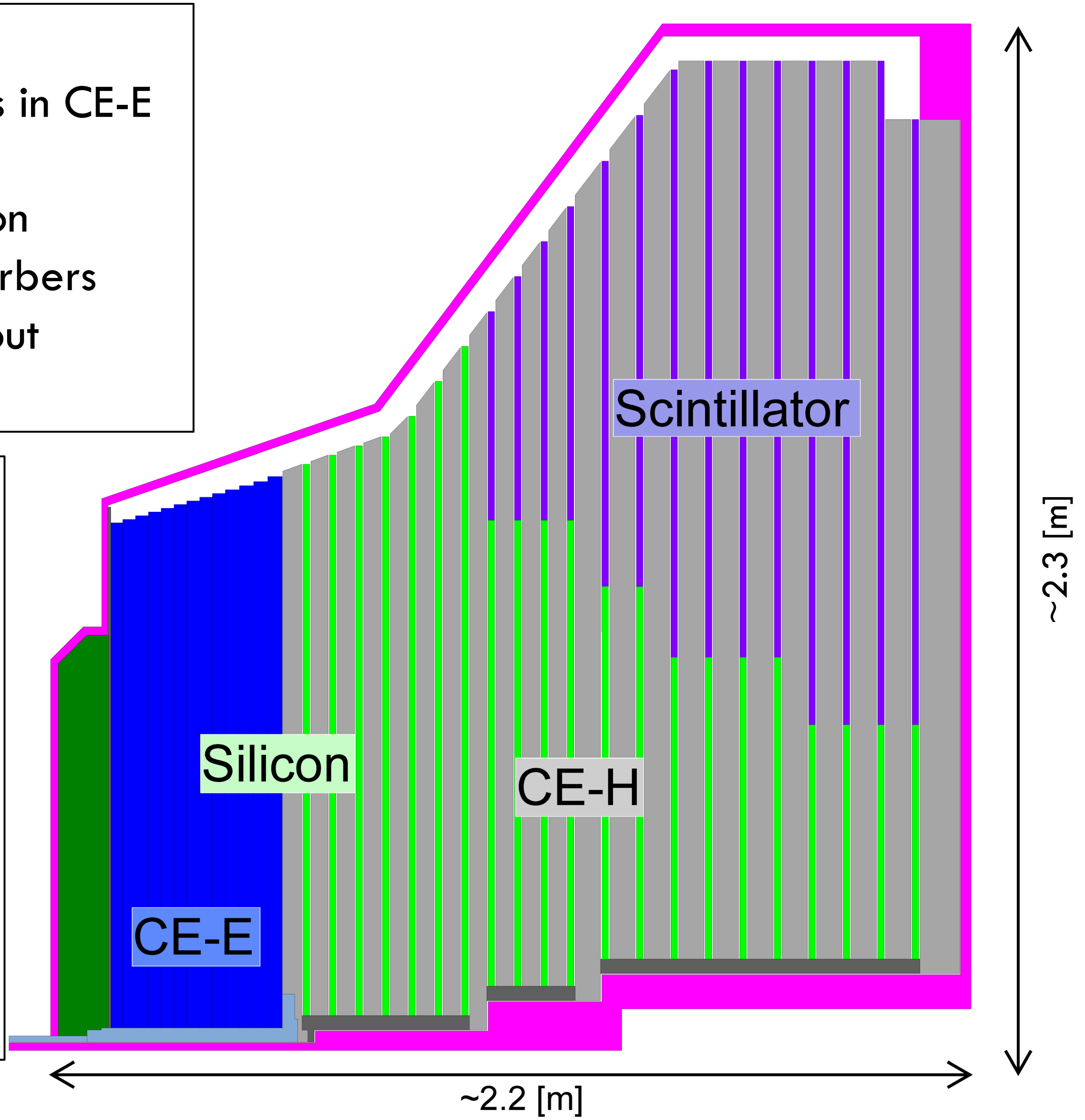
~6M Si channels, 0.6 or 1.2cm^2 cell size

~370m^2 of scintillators in ~3700 boards

~240k scint. channels, 4-30cm^2 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