Cluster reconstruction in the HGCAL @ Level 1 trigger

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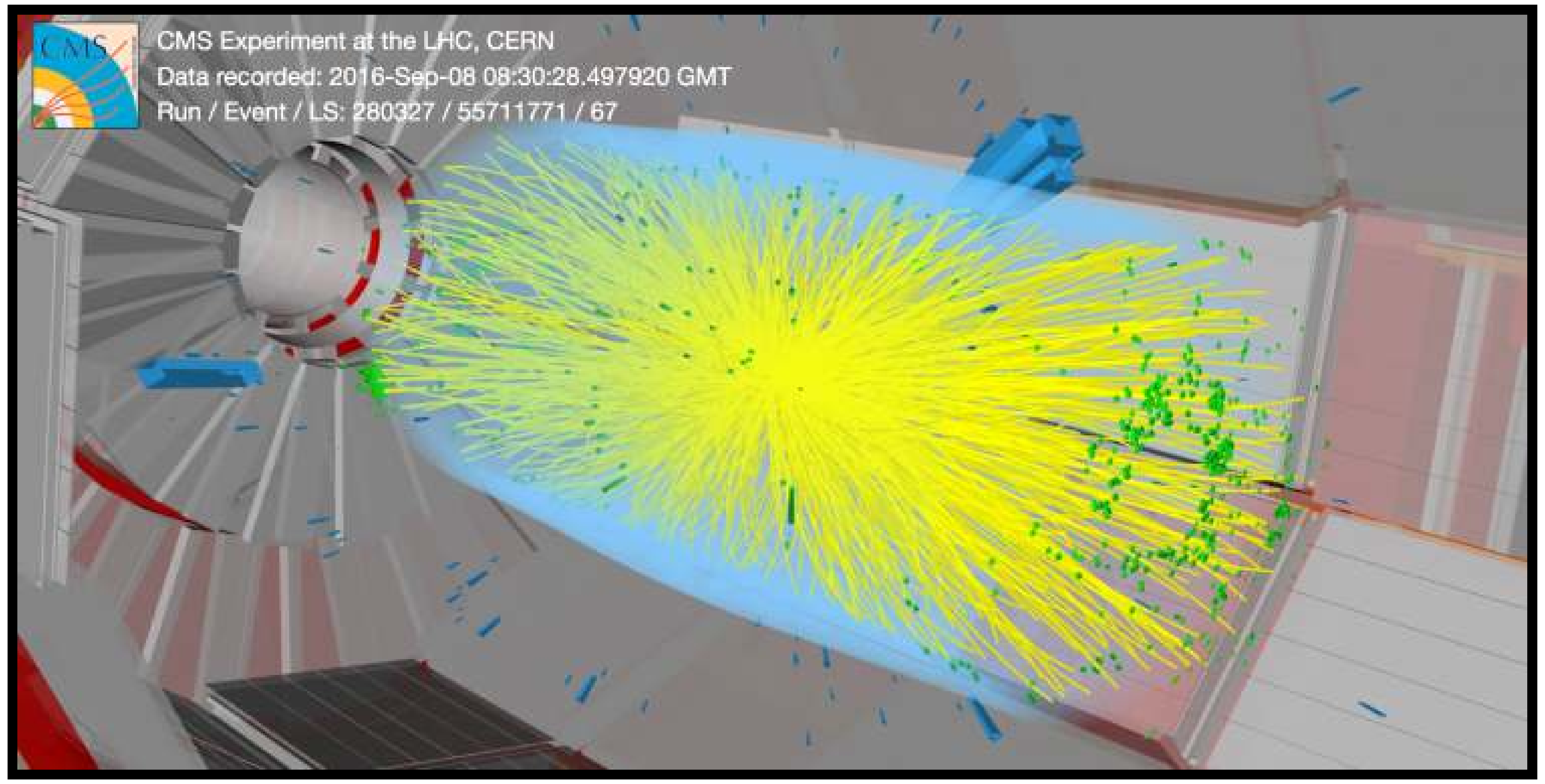
CHEP2023

8th May 2023

Indico

The High Luminosity Challenges

only 86 collisions/bunch...

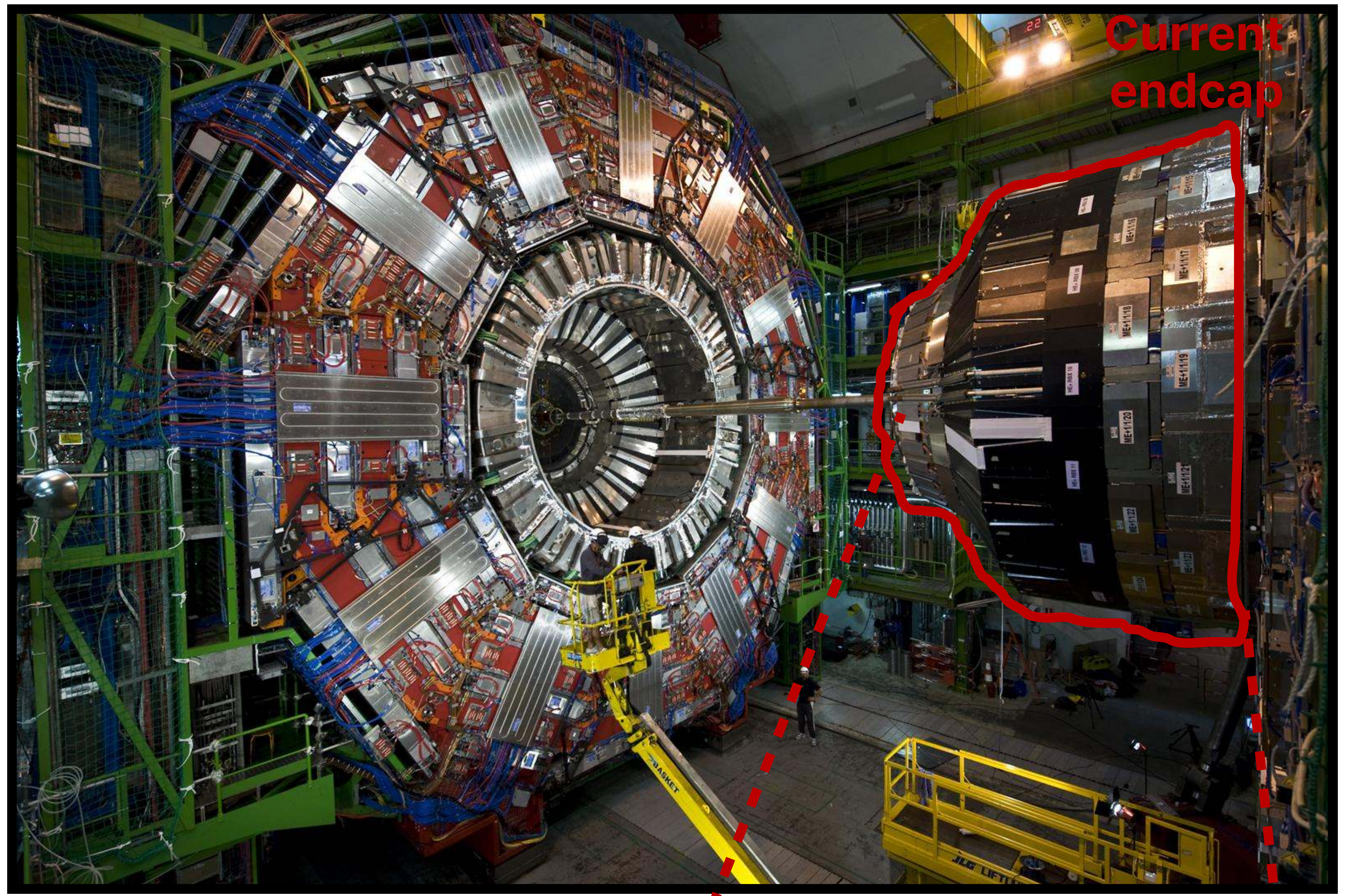


- ~4x more luminosity than the LHC (up to ~7.5 × 10^{34} cm^2/s)
- Up to 200 collisions per bunch crossing (1.6 vertices/mm)
- Harsh radiation environment (up to 10^{16} neq/cm^2)
- Enables full program of Precision and BSM Physics
  - Requires significant detectors upgrades
  - Challenging to maintain current trigger thresholds

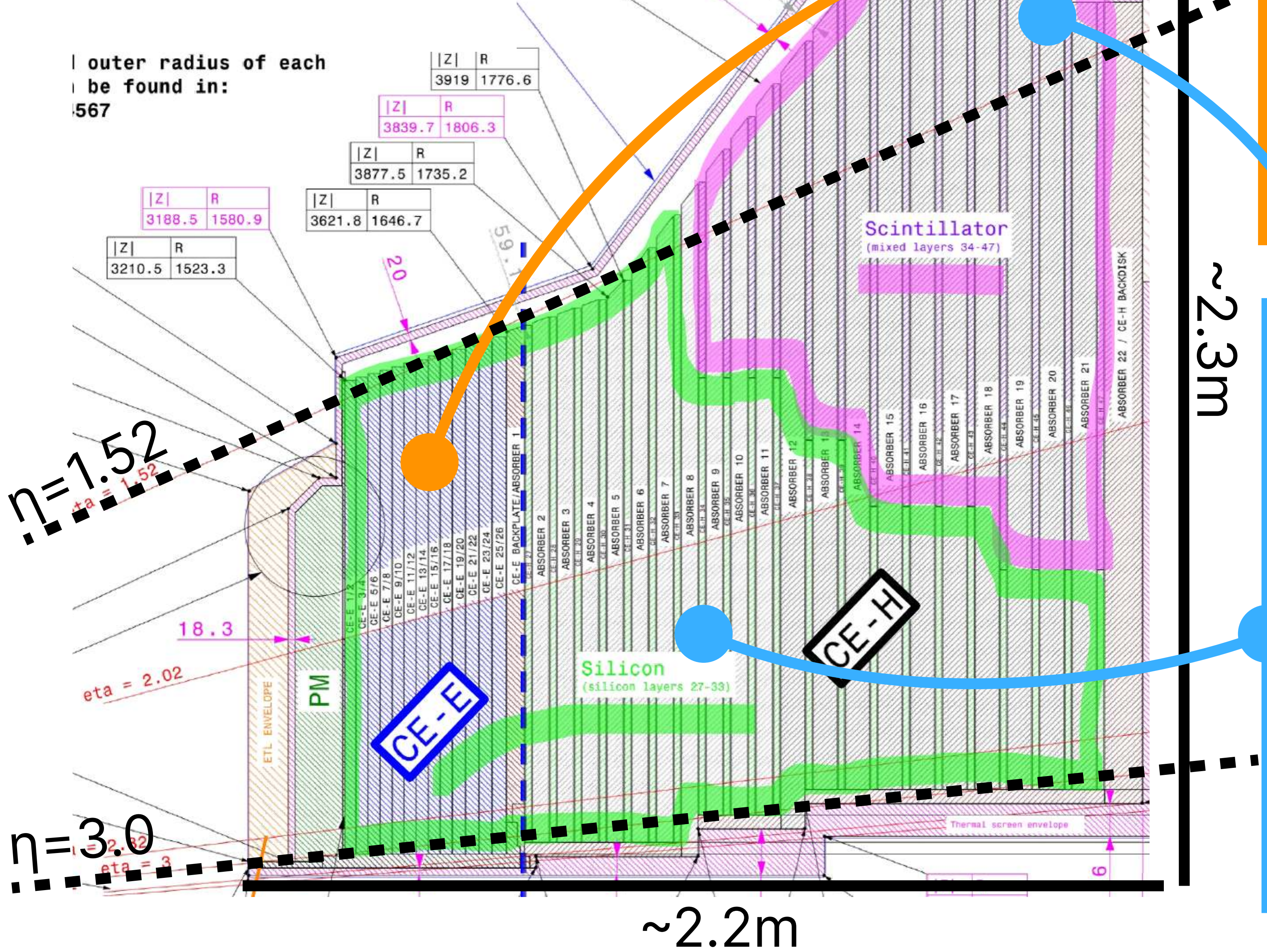
HL-LHC Timeline

High Granularity Calorimeter (HGCAL)

- Position, energy, timing (down to ~30ps): 5D imaging!
  - 620 m² silicon, 26K modules, 6M channels
  - 370 m² scintillator, 3.7K boards, 240K channels
- Higher granularity boosts particle flow reconstruction
  - tracking with the calorimeter!
- Processes 300Tb per second

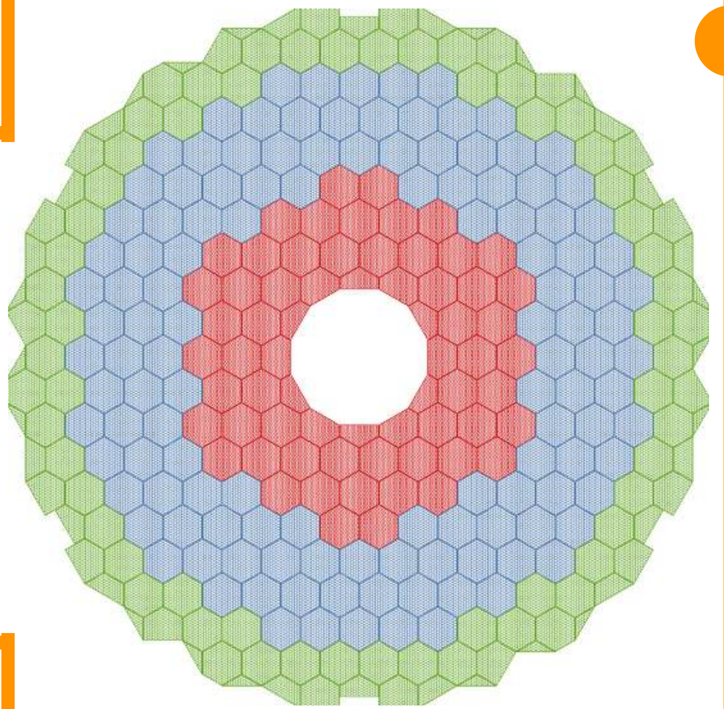


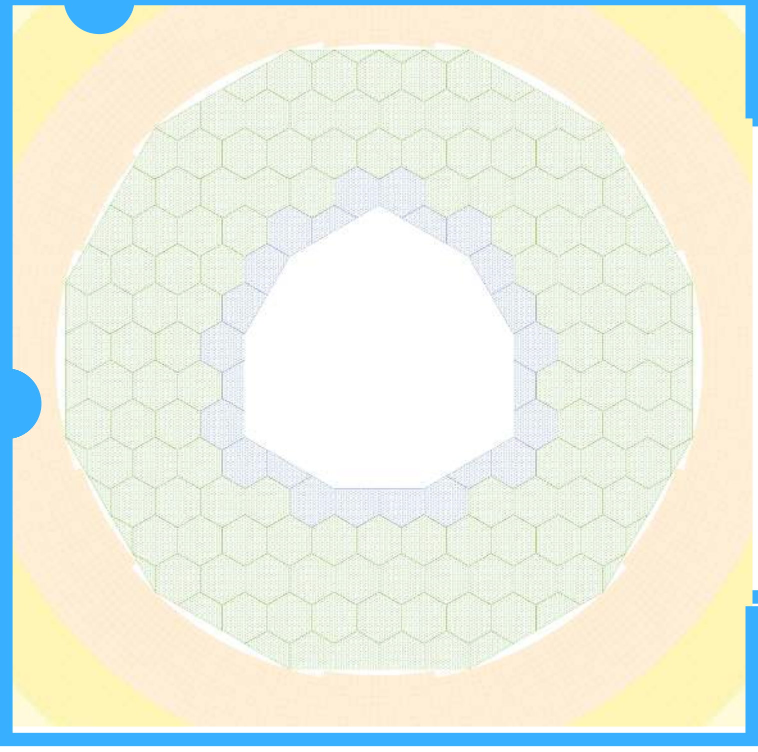
~215 tonnes x 2



EM silicon section

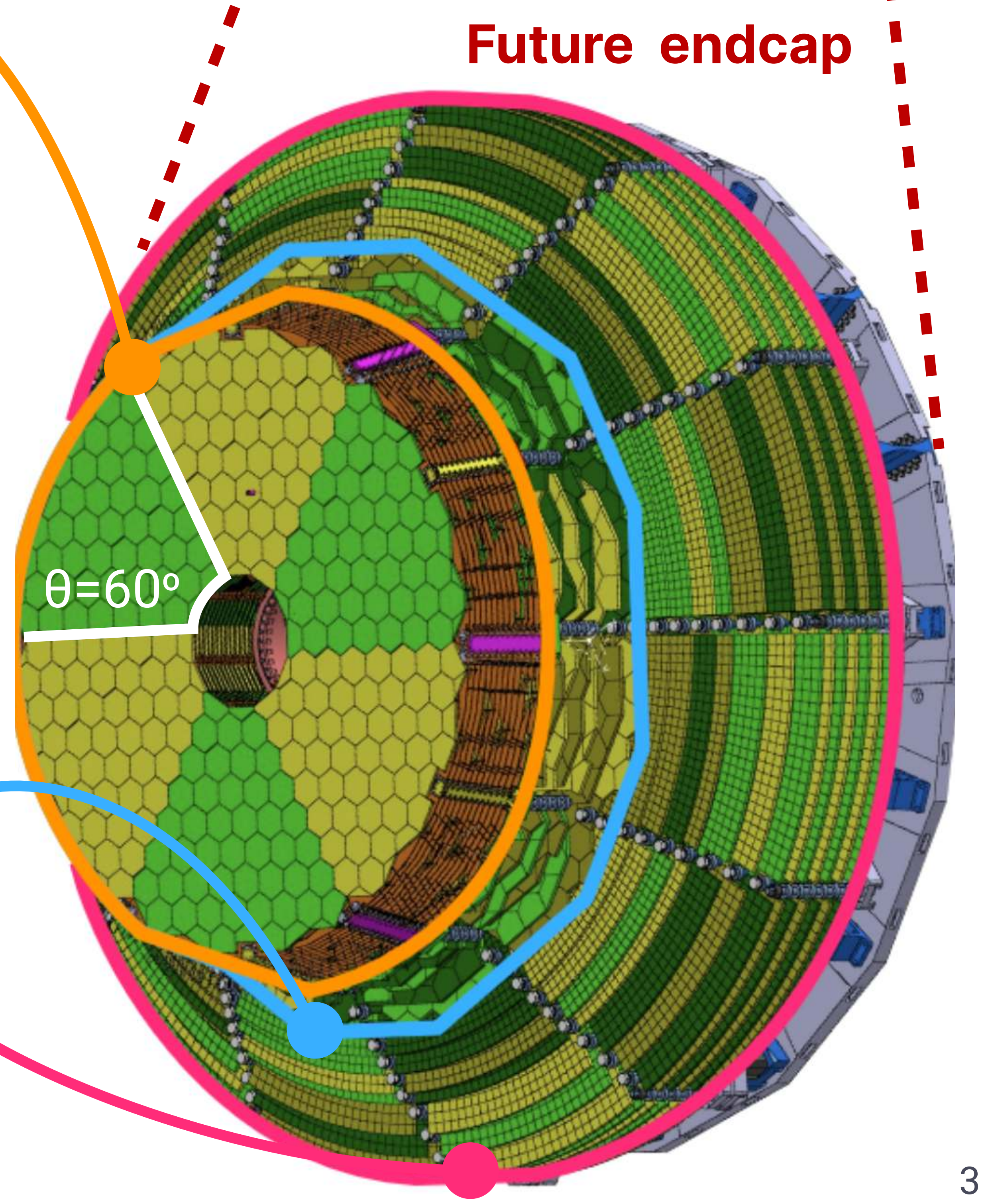
- 26 layers w/ 27.7X_0, ~1.5λ
- Absorber: CuW, Pb
- Sensors in hexagonal modules





Hadronic Si + Sci section

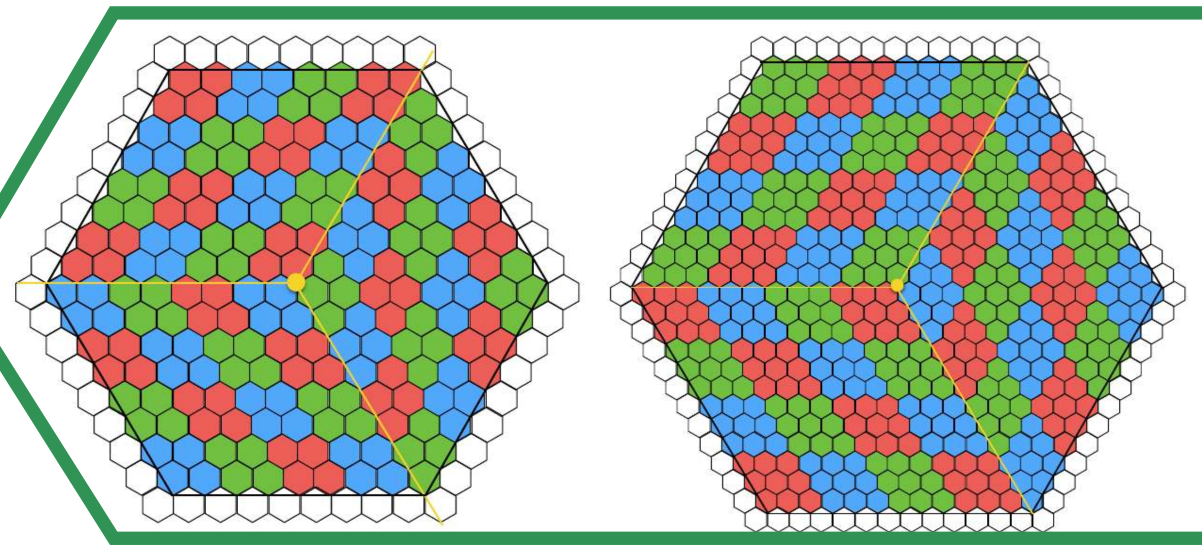
- 21 layers w/ ~8.5λ
- Absorber: Cu, stainless steel
- On-tile SiPM



Trigger Primitives’ Data Flow

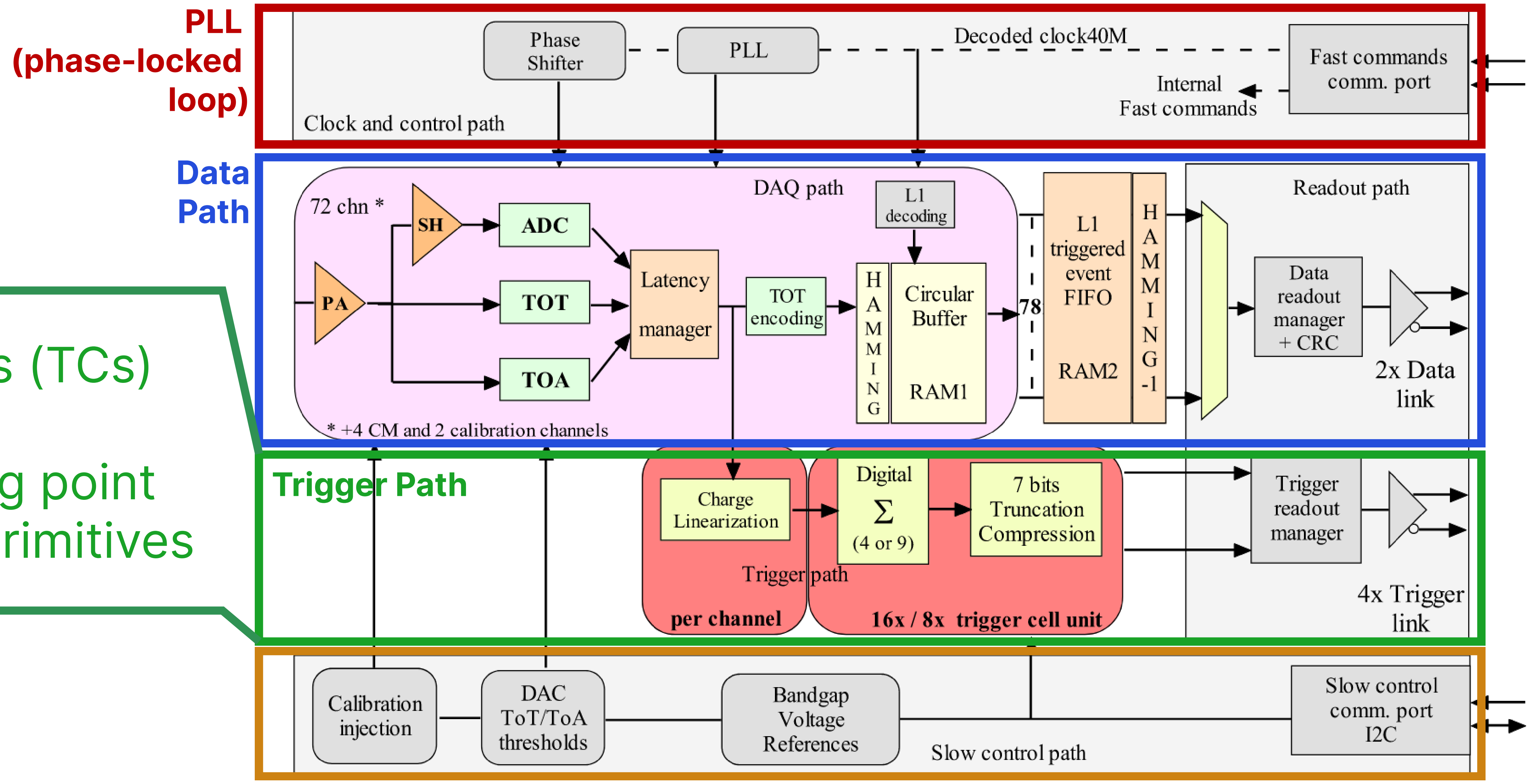
HGCROC

- HGCROC: Front-end read-out ASIC @ 40MHz, outputs 1.28 Gb/s w/ 12.5μs latency!



Sum channels into Trigger Cells (TCs)
- charge/energy linearization
- compression to 7-bit floating point
- starting point of L1 trigger primitives

HGCROC



I2C (inter-integrated circuit)

HGCROC + ECON-T

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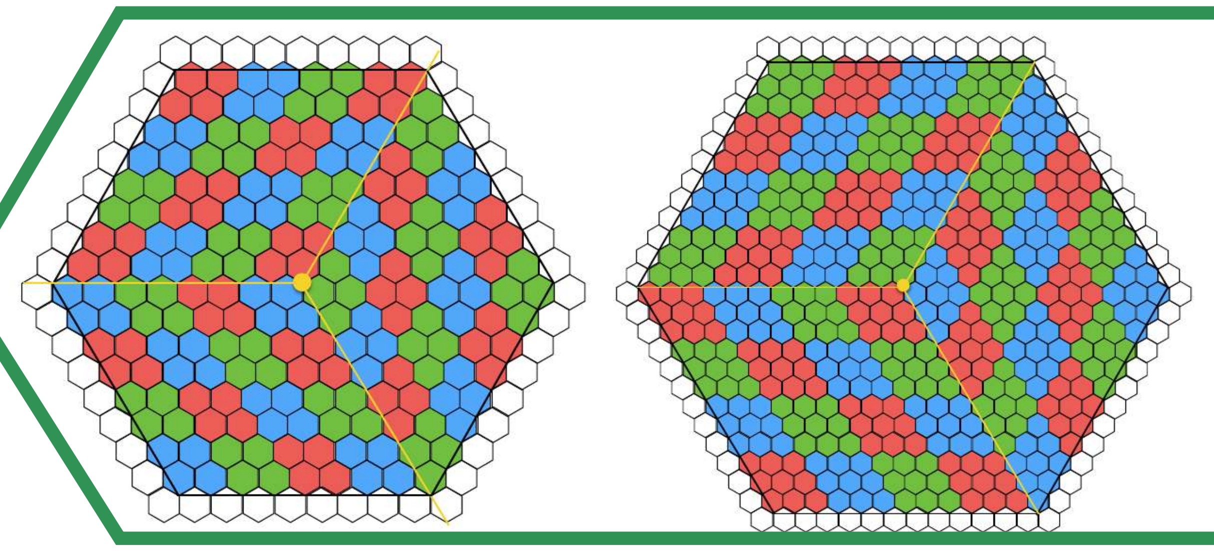

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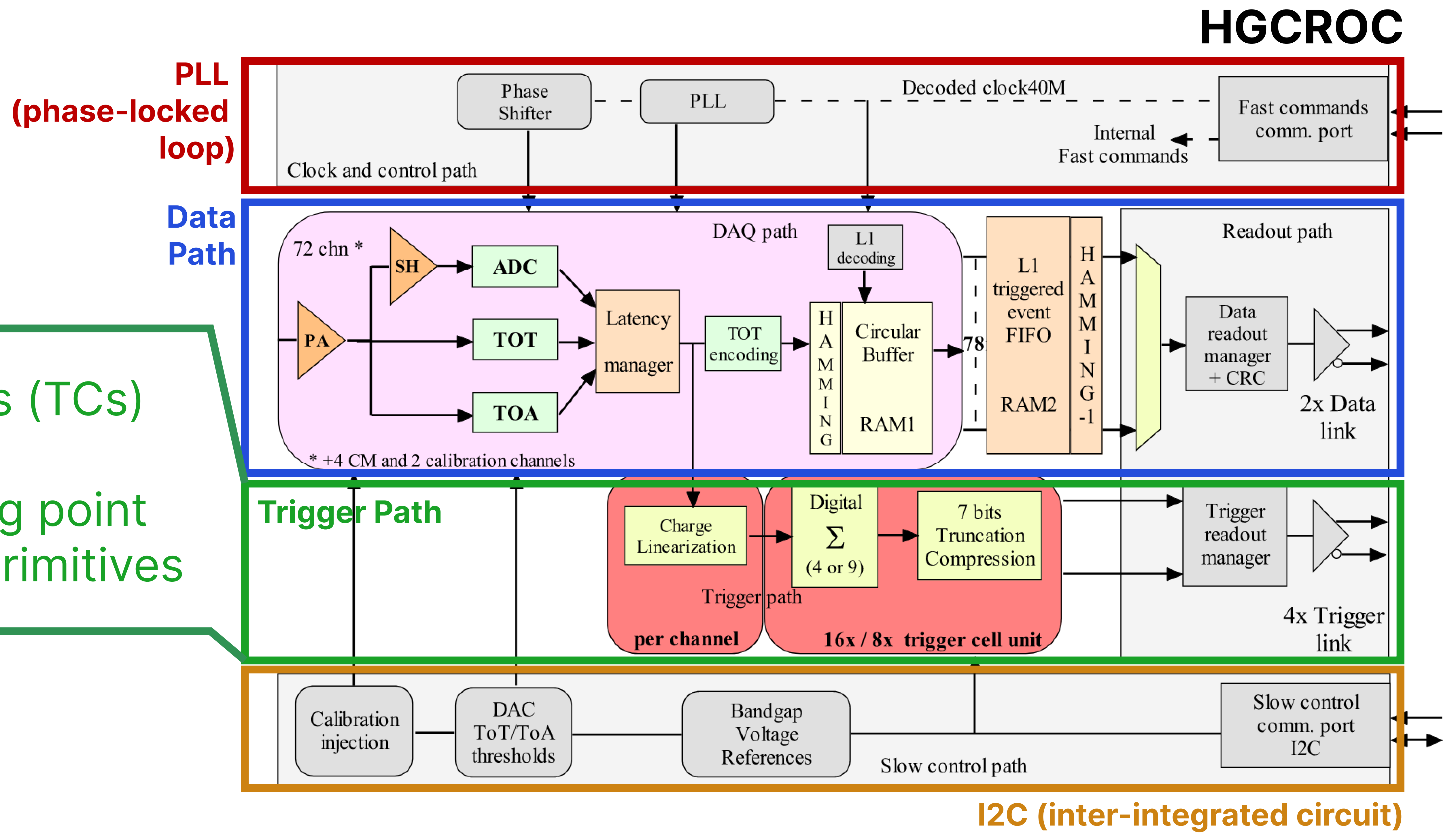
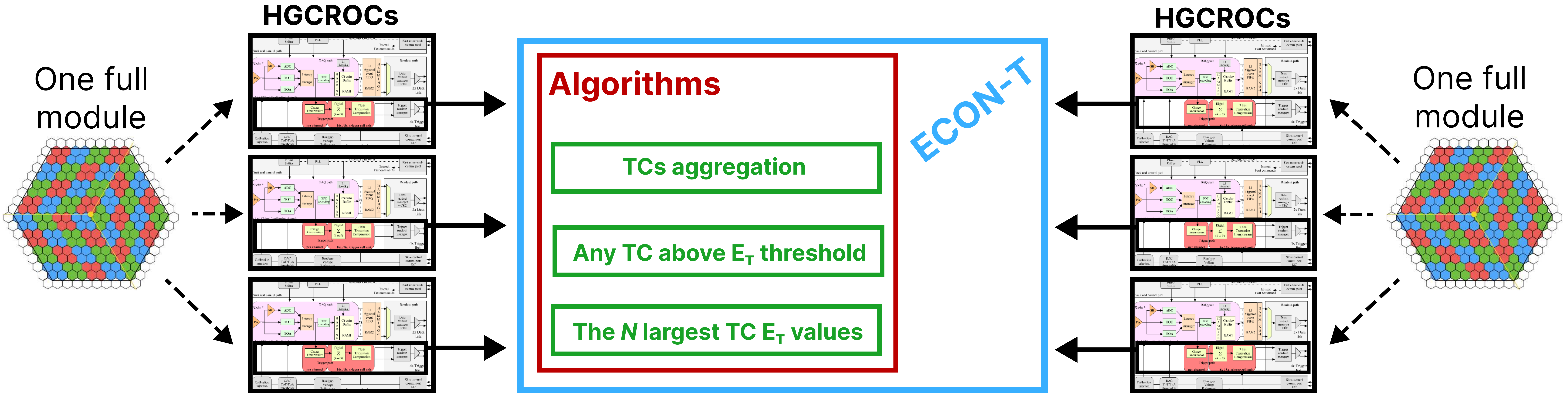


- ECON-T: concentrates HGCROC data w/ dedicated selection and aggregation algorithms
  - Timing cannot be used due to bandwidth constraints

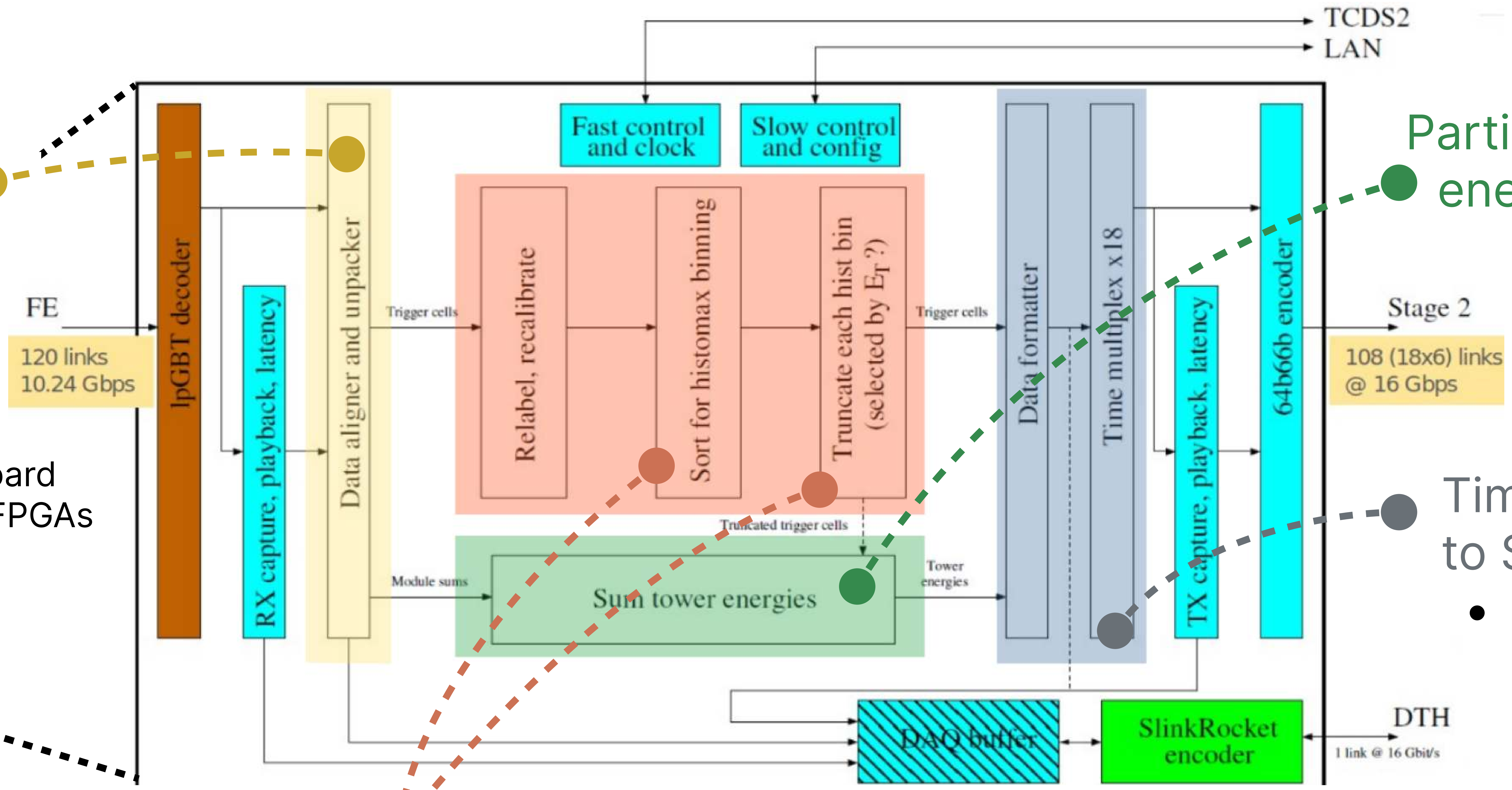


Backend Stage 1

Unpacks data from ECON-T

- Inputs grouped per bunch crossing

Serenity board w/ VU13P FPGAs (128 links)



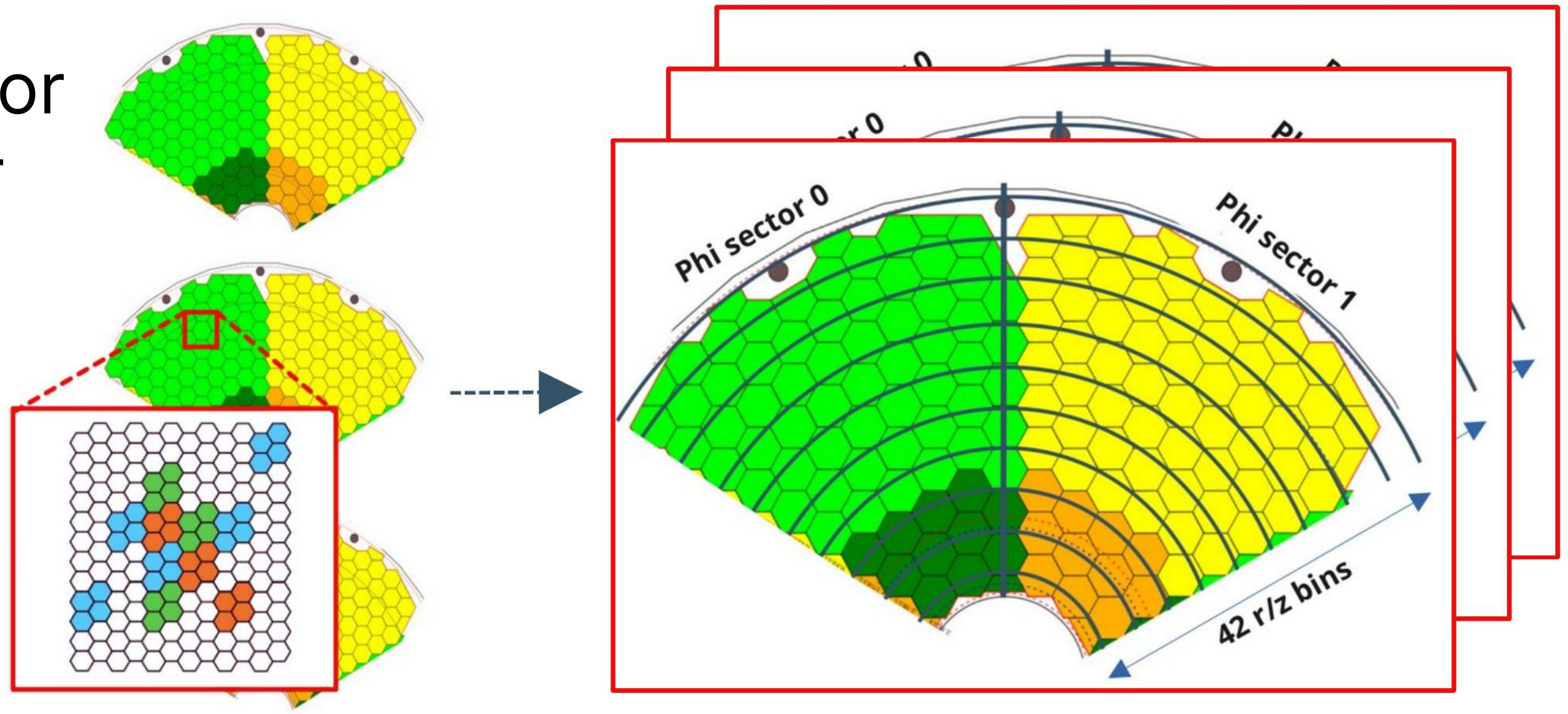
Partial sum of module energies into towers

Time multiplex data to Stage2

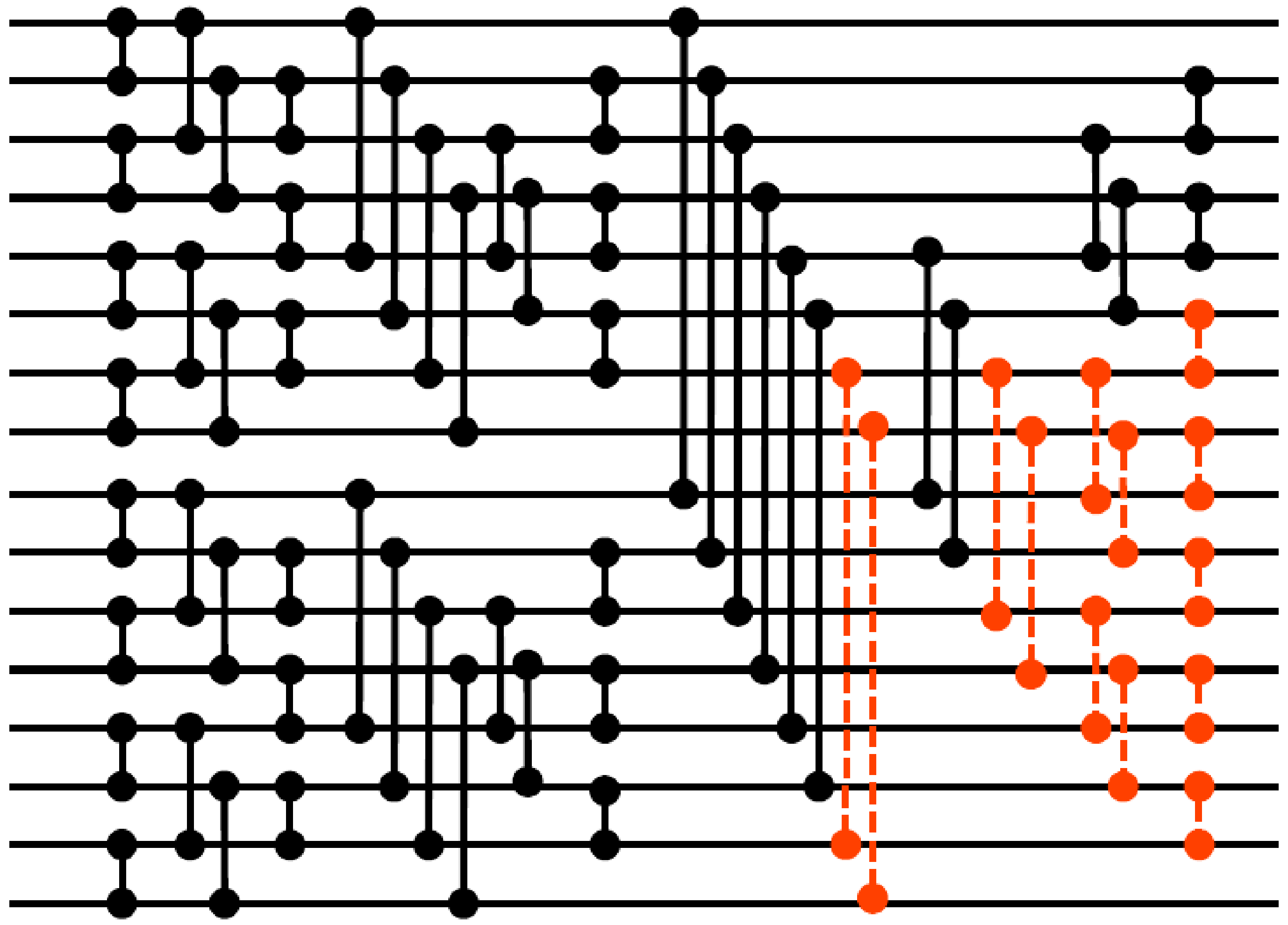
- 18 bunch cross.

Sort and truncate TCs in firmware

- TCs routed to bins
- 2(ϕ)x42(R/z) bins per 120º sector
- Energy sorting with the batcher odd-even sorting network
- On-the-fly truncation, fixed output bin size

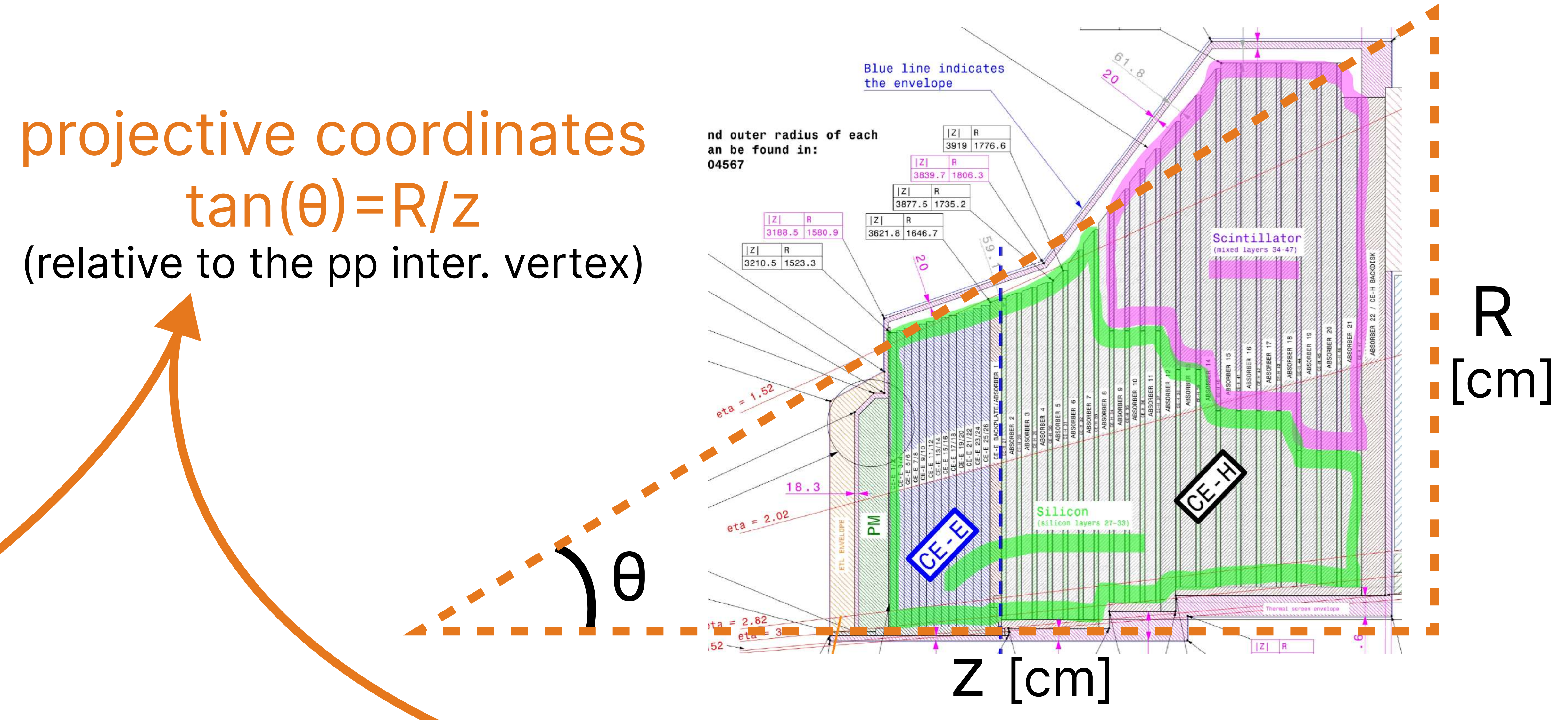


sort each bin independently



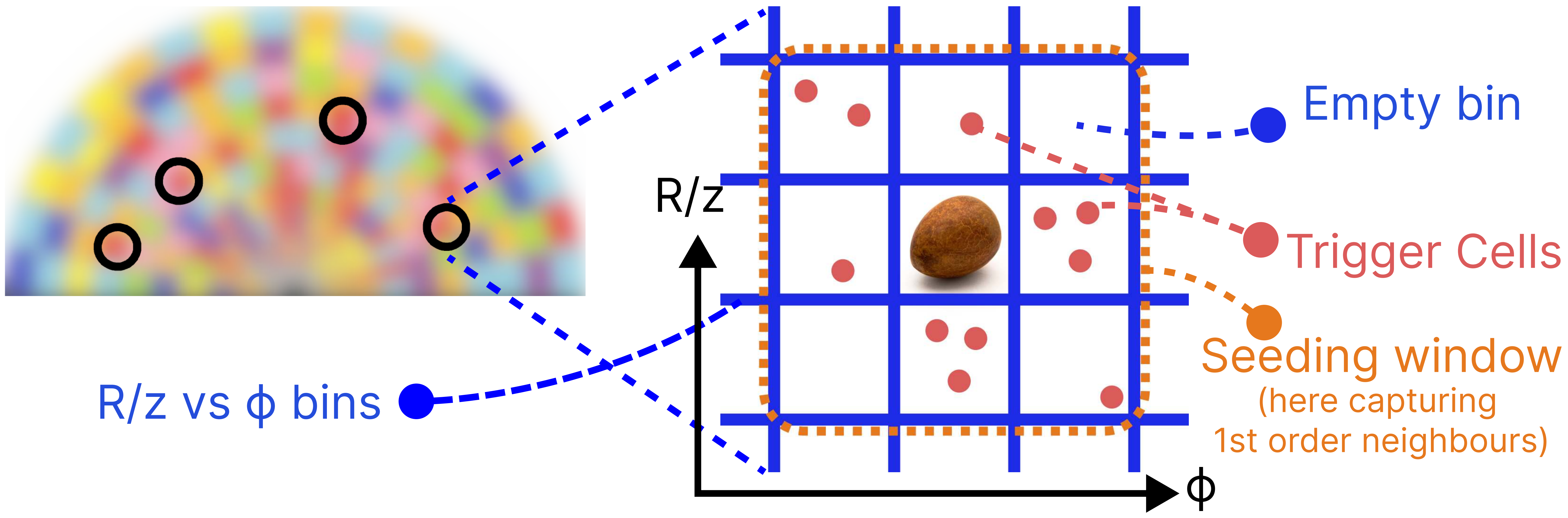
Backend Stage 2

- Finds and builds Trigger Towers + 3D clusters of TCs (positions, energies, shapes)
- Sends trigger primitives to L1 trigger



Seeding...

- Finds local maxima: seeds
- Seeds must also pass a p_T threshold selection
- Every seed creates a cluster



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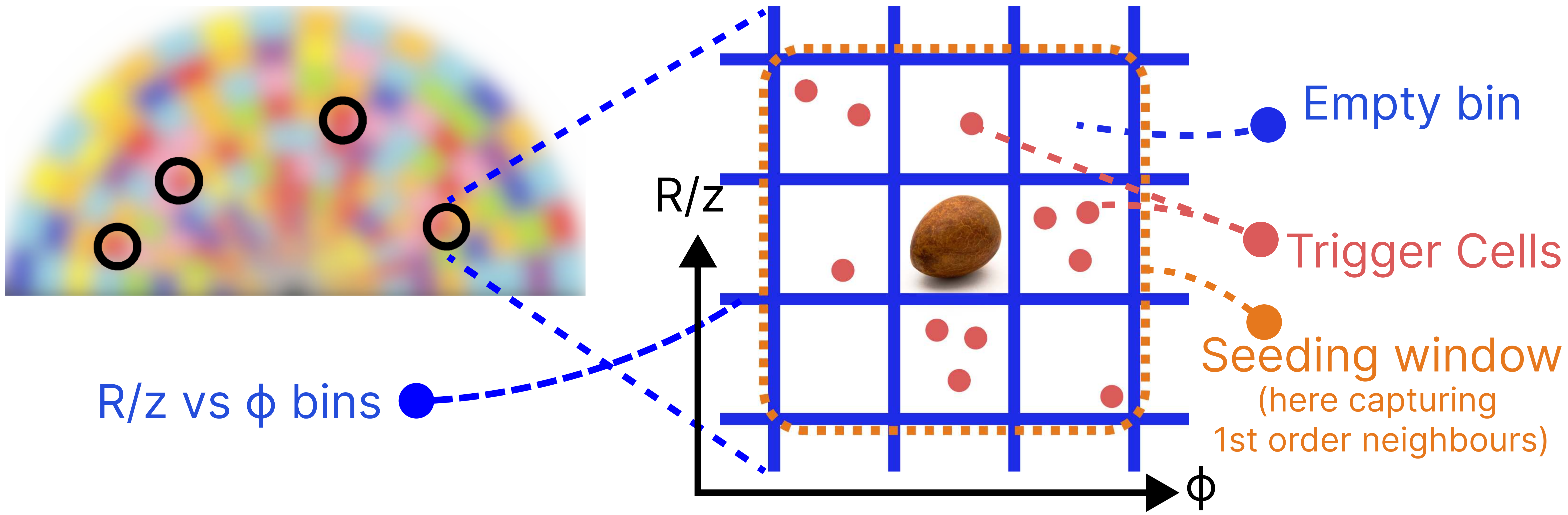
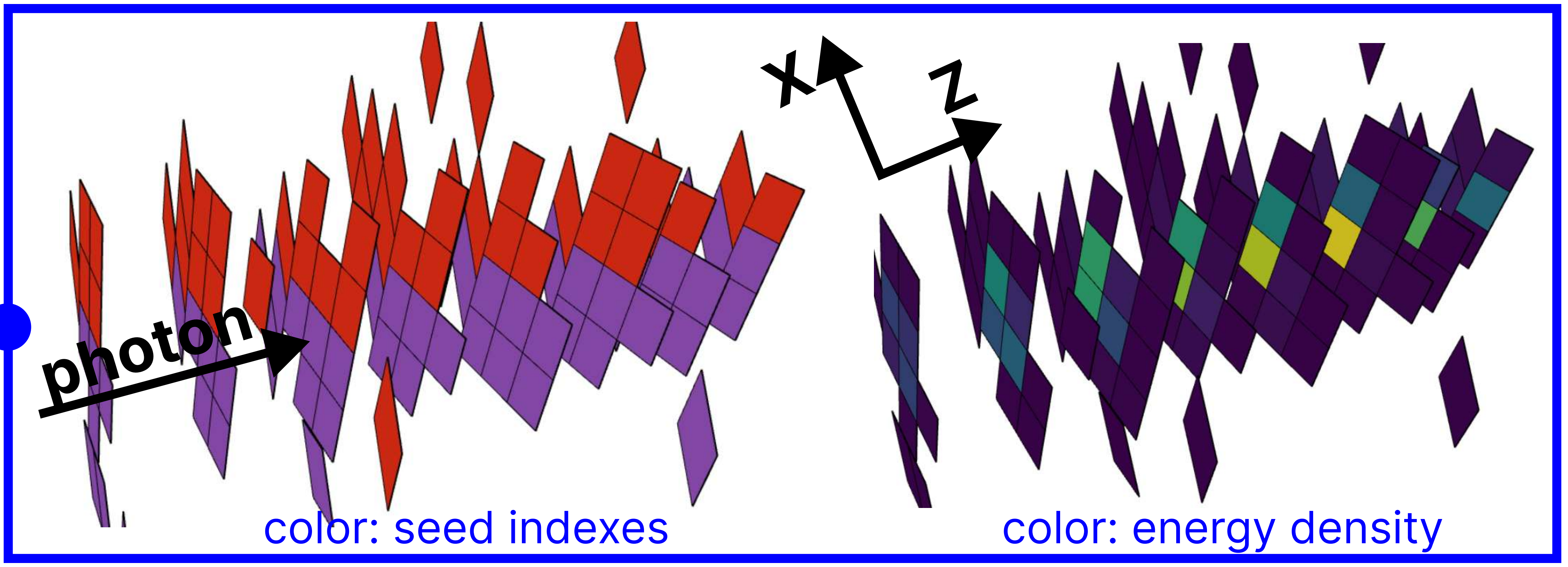


... but splitting

- Non-homogeneous distribution of TCs into bins
  - some bins have few cells, esp. close to the beam pipe
  - unphysical cluster splits!
- Study w/ single 0PU unconverted photon gun; $1.7<|\eta|<2.8$



“ByeSplits” Iterative Algorithm

- Optimizes the mapping of TCs to seeding bins, avoiding cluster splits
  - reduces variance of number of TCs/bin along ϕ
- The algorithm does not run on firmware
  - its output can be encoded as a TC-to-bin Lookup table (LUT)

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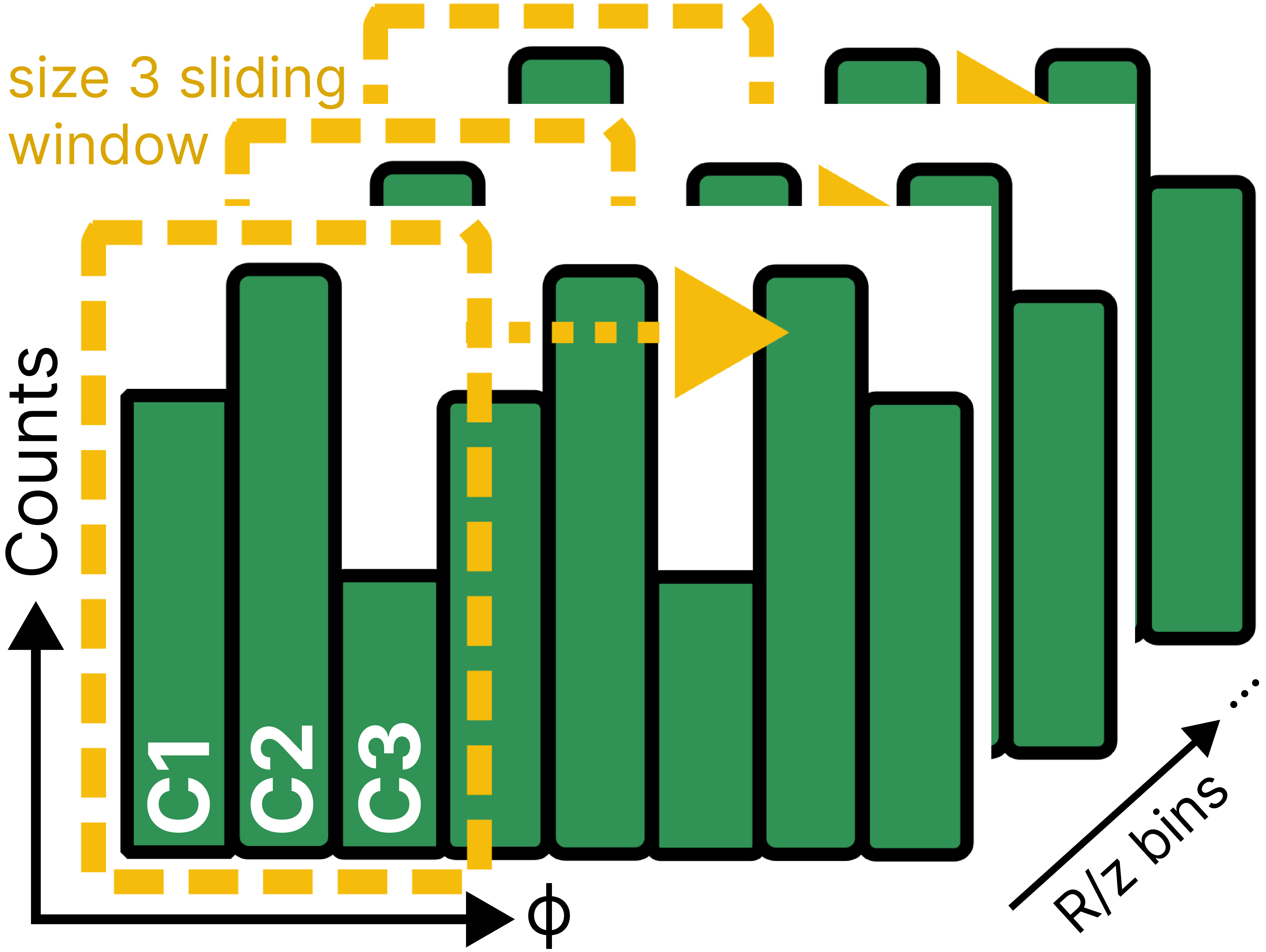

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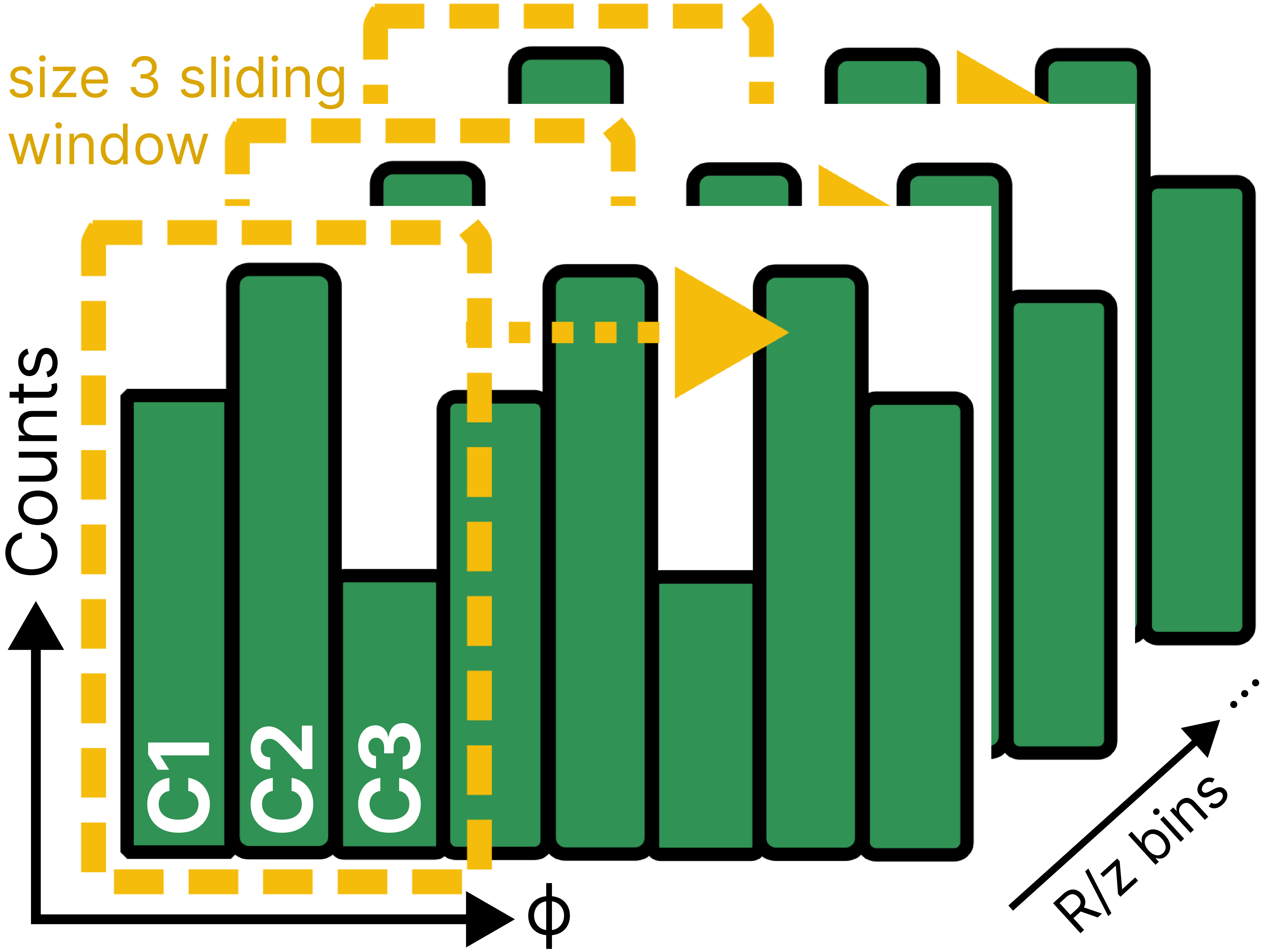


Calculate differences

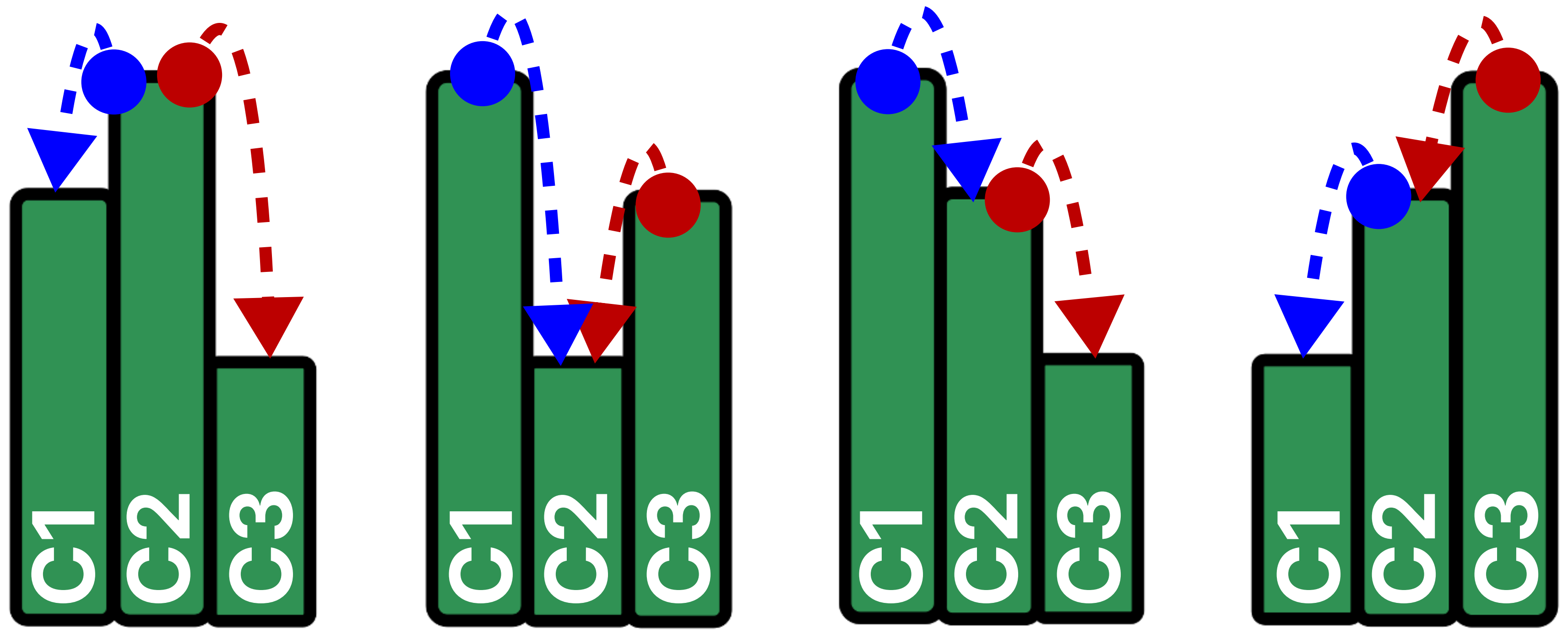
$$D_{\text{right}} = C_3 - C_2$$
$$D_{\text{left}} = C_2 - C_1$$

On which side should the TC shift be performed?

draw pseudo-random number *x* from uniform distribution

$$\text{Side} = \begin{cases} \text{left}, & \text{if } x \sim \mathcal{U}(0,1) < D_{\text{left}}/|D_{\text{left}} + D_{\text{right}}| \\ \text{right}, & \text{otherwise} \end{cases}$$

How to move TCs for the 4 high/low combinations?



Stopping criterion

must be true for all bins *i*

$$|D_{\text{left},i}| + |D_{\text{right},i}| \leq \max\{1, \lambda \times (|D^0_{\text{left},i}| + |D^0_{\text{right},i}|\}$$

tunable parameter $0 \leq \lambda \leq 1$

stabilisation for small λ

initial diffs. for bin *i*

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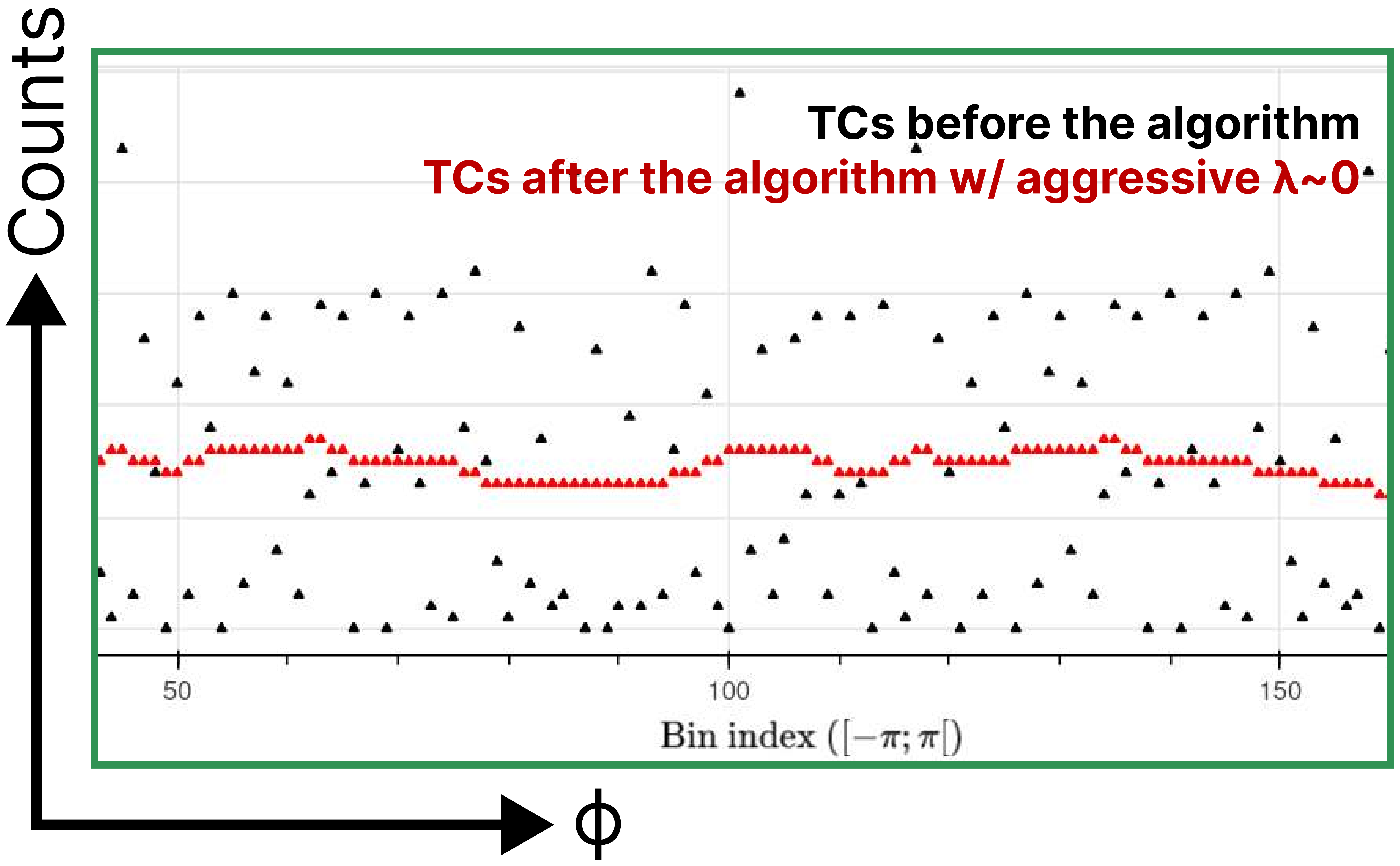

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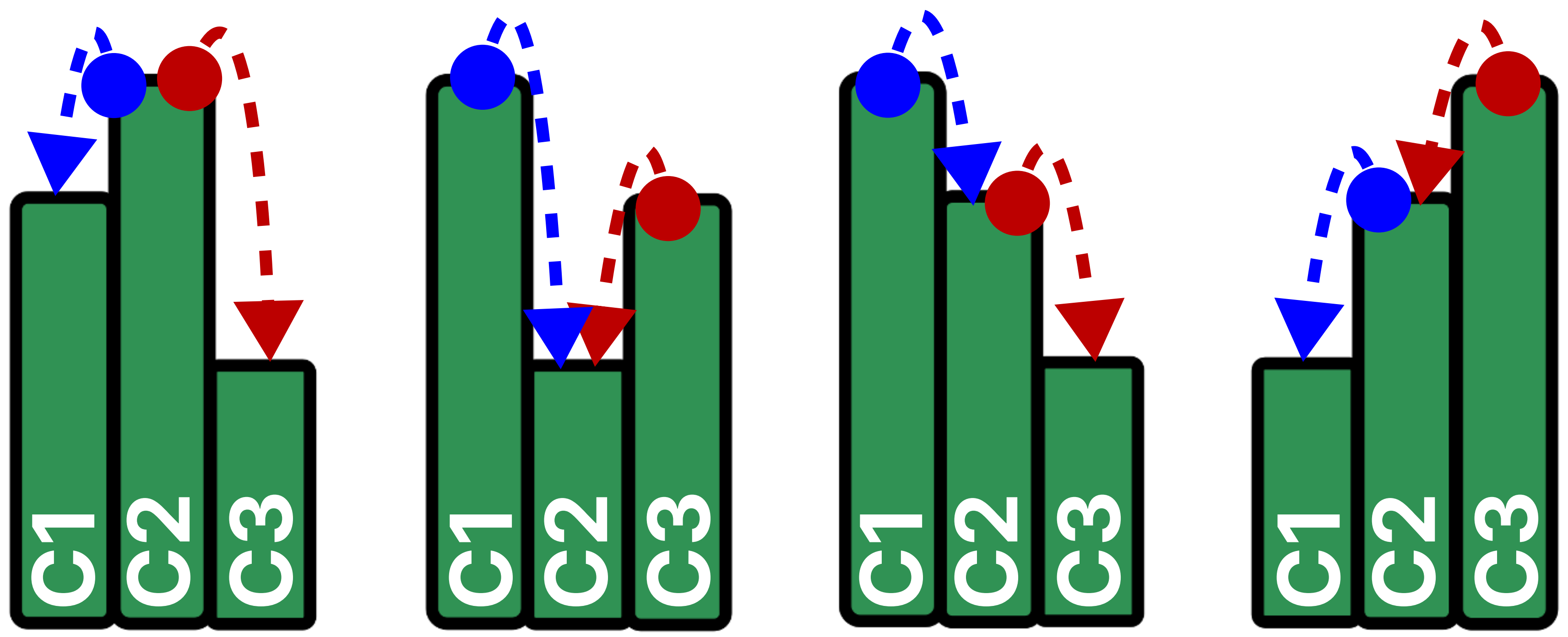

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tunable parameter 0≤λ≤1

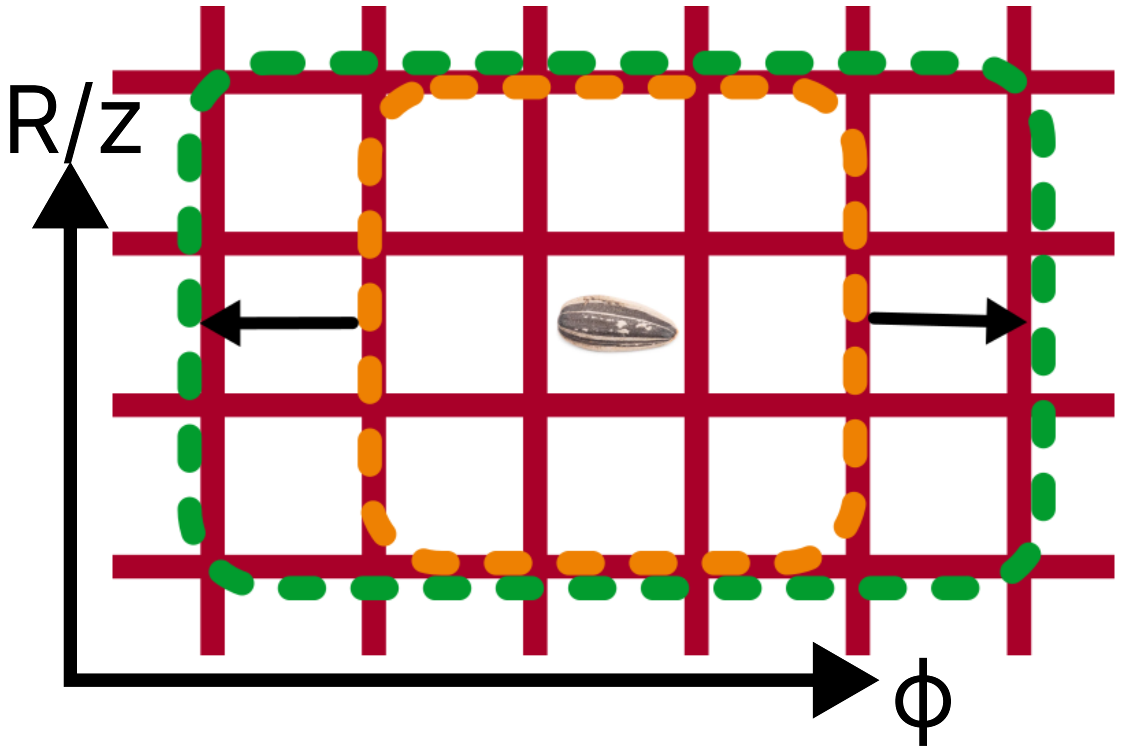
stabilisation for small λ

initial diffs. for bin *i*

Energy Density (before smoothing, before algo, phi seeding window = 1)
Bins before the algorithm
Gen Particle Position
CMSSW Cluster Position
Energy [mipPt]
R/z
ϕ
the split is gone!
Energy Density (before smoothing, after algo, , phi seeding window = 1)
Bins after the algorithm
Gen Particle Position
Custom Cluster Position
Energy [mipPt]
R/z
ϕ
Momentum Response
$p_{T,Reco}/p_{T,Gen}$
iterative algorithm
CMSSW
Custom
ideal
much better!
original reconstruction, no iterative algo
custom reconstruction w/ iterative algo
better position resolution, despite moving TCs!
Position Resolution
$\phi_{Reco}-\phi_{Gen}$, $\eta_{Reco}-\eta_{Gen}$
Phi Resolution: RecoPhi - GenPhi
CMSSW
Custom
improvement!
ideal
Eta Resolution: RecoEta - GenEta
CMSSW
Custom
improvement!
ideal
$\eta_{Reco} - \eta_{Gen}$
Note: resolutions showed for events with split clusters only

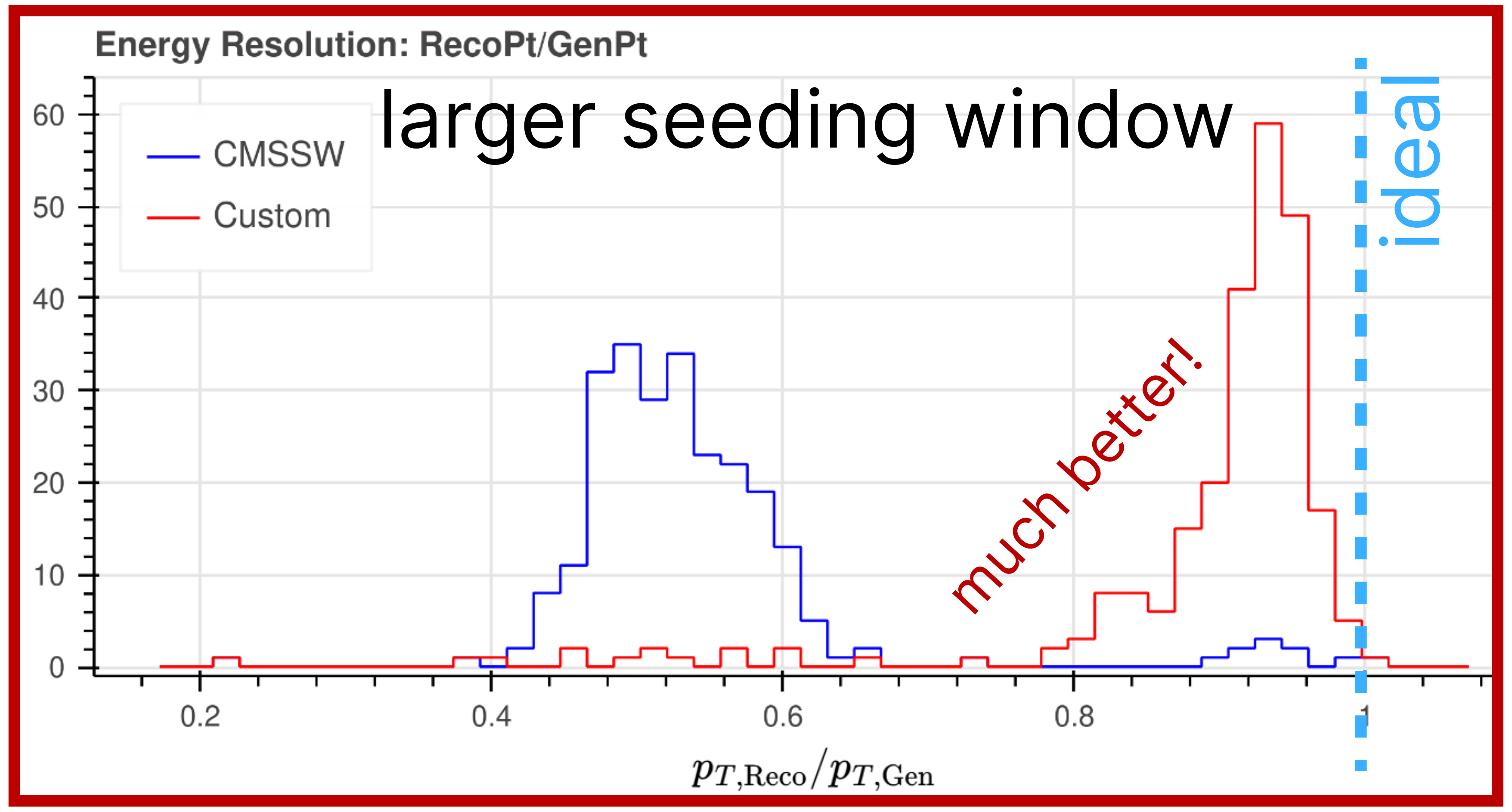
Other split-removal methods

- **Add “2nd order neighbors” in the seeding**
  - seeding window extended along ϕ
  - more FPGA resources required!
- **Modify the smoothing kernel along ϕ**
  - very similar results to method above
  - no additional resources!



Momentum Response

$p_{T,Reco}/p_{T,Gen}$



… 1/8 | 1/4 | 1/2 | **1** | 1/2 | 1/4 | 1/8 … → ϕ

new kernel →

… 1/4 | 1/2 | **1** | **1** | **1** | 1/2 | 1/4 … → ϕ

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Momentum Response

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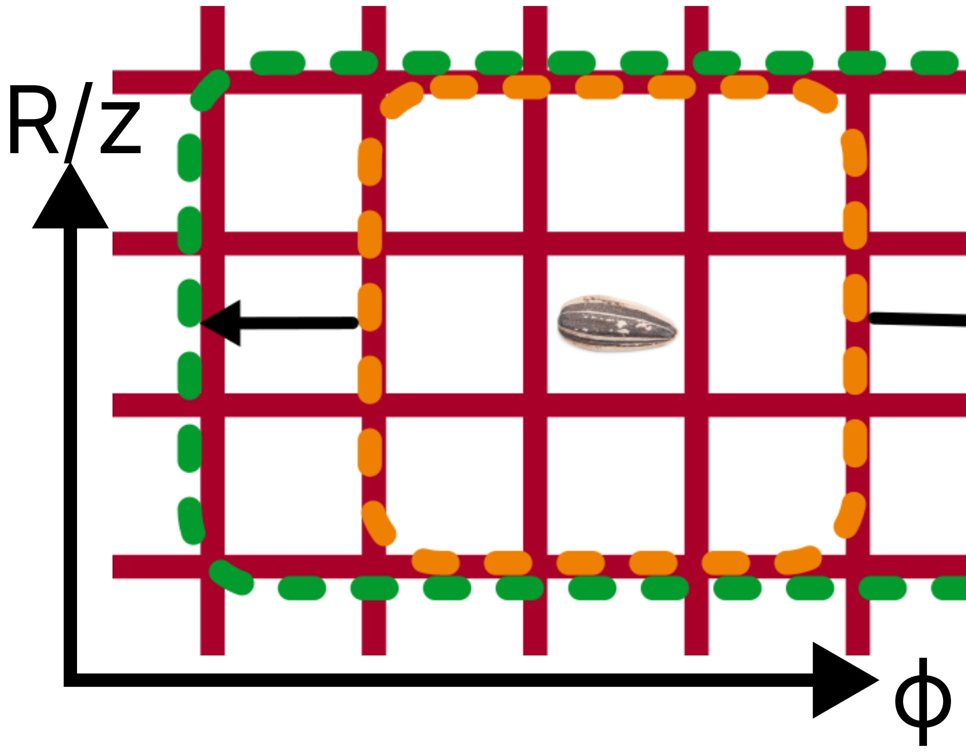
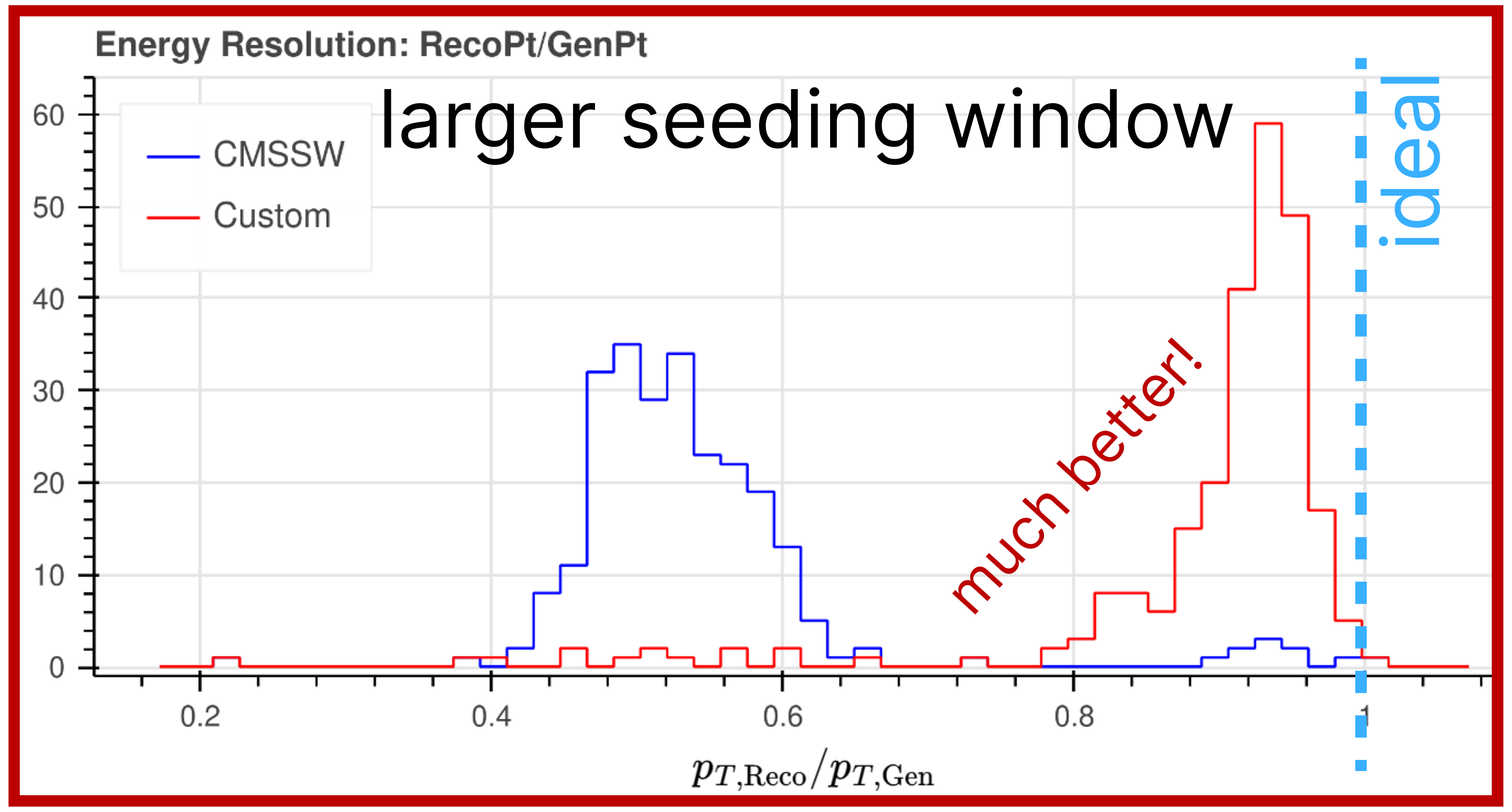
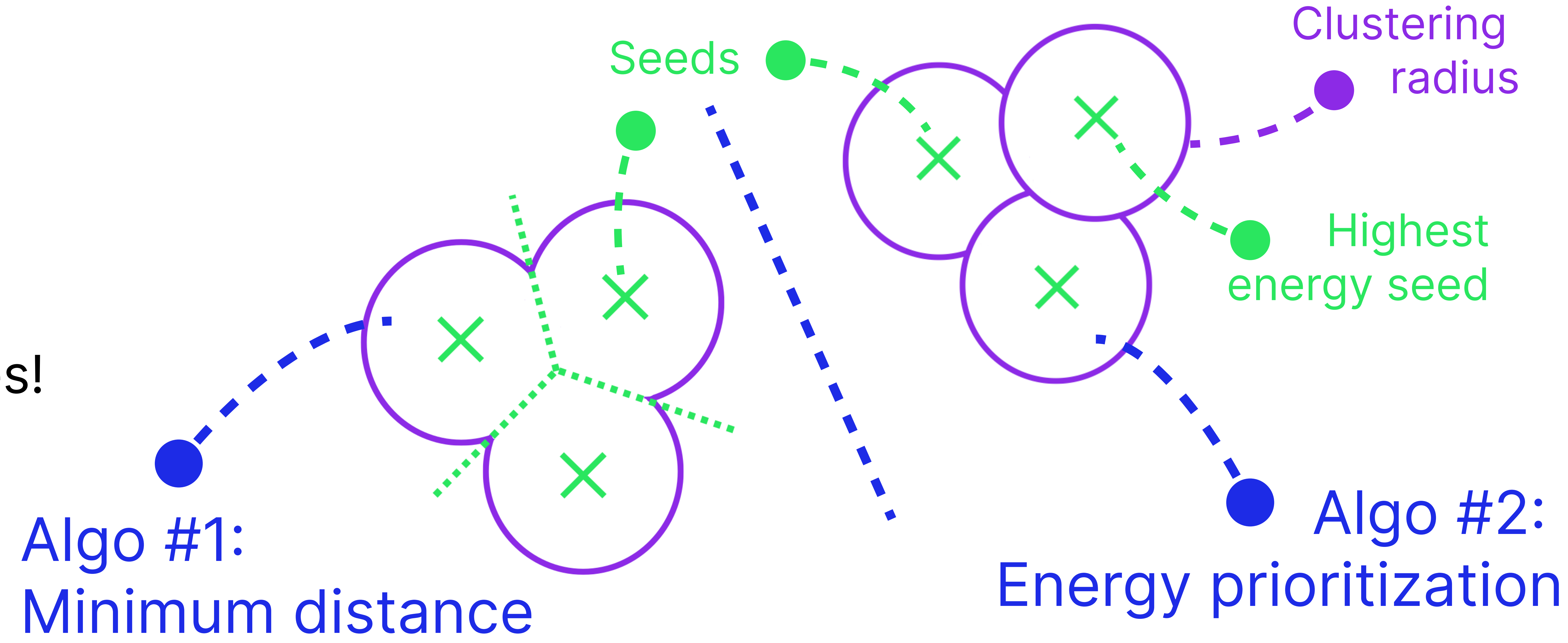




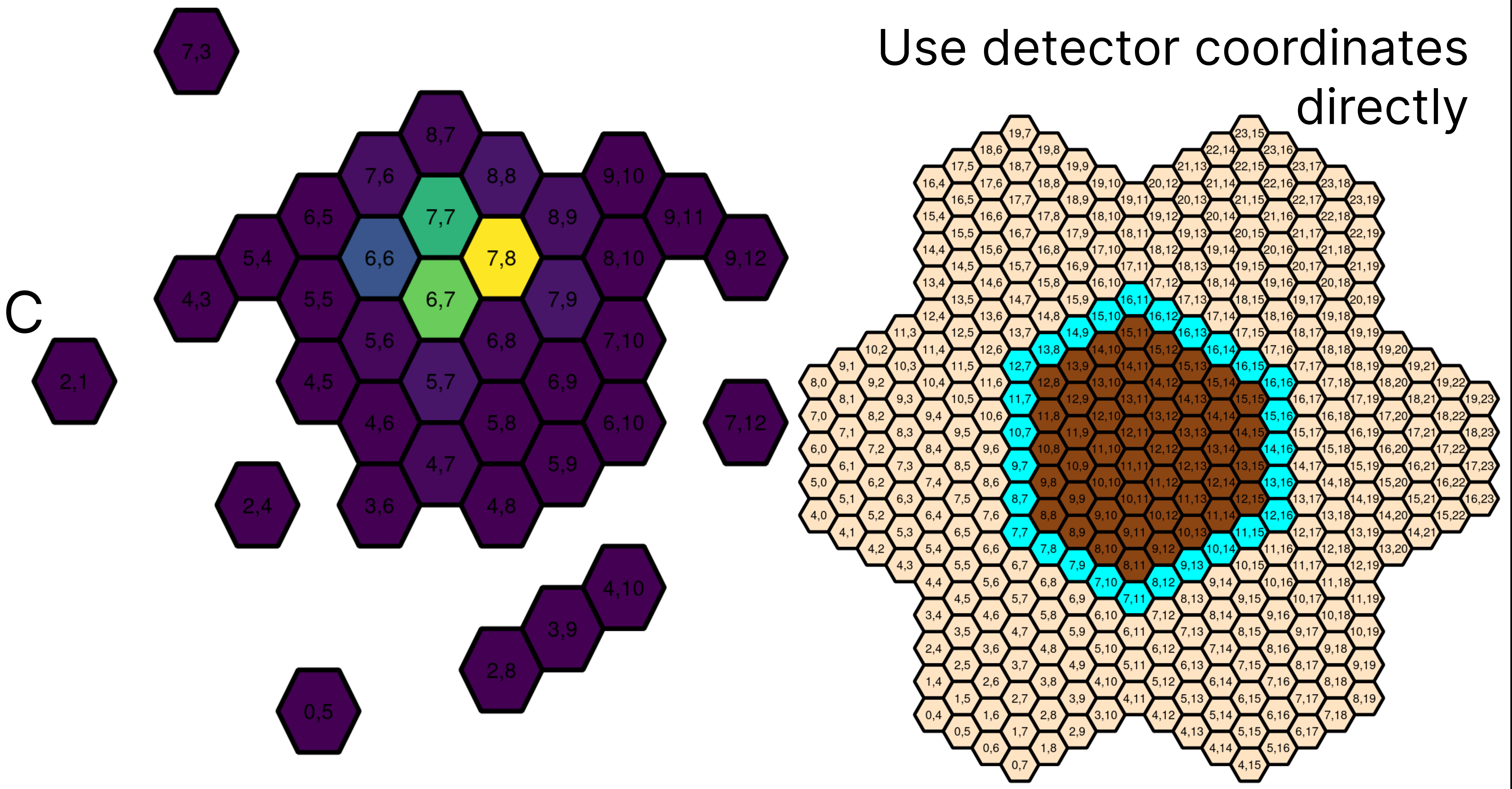
Clustering

- Associates TCs to seeds and calculates cluster properties
  - Energy, position, …
  - Used for the previous resolution studies!
- Uses different projective coordinates
  - x/z, y/z
- Two algorithms currently defined



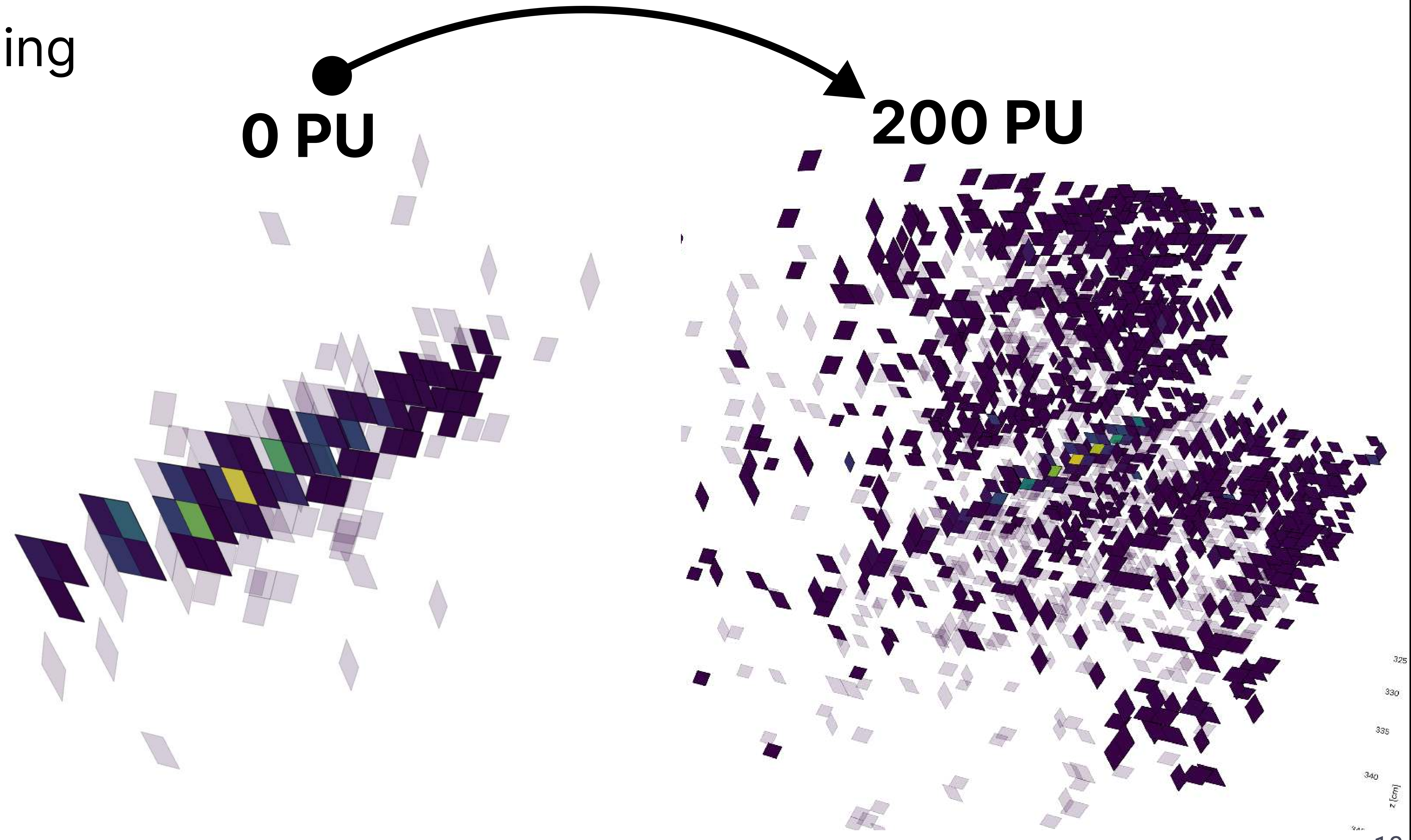
Conclusions & Next Steps

- HGCAL is a very significant CMS upgrade for the HL-LHC
- HGCAL trigger primitives for the L1 trigger are the final product of a complex processing chain
  - robust on- and off-detector electronics
  - resource-constrained algorithms perform computations on multiple ASICs and FPGAs
- A complete reconstruction chain is available in simulation, from hits to cluster-related variables
  - algos implemented in firmware, optimization on-going



Can we do better? Yes! Current work:

- Explore more detector-like coordinate systems to remove TC-bins routing complexity
- Focus on specific regions in the detector to further decrease the amount of data processed
- Assess the performance of new algorithms with 200PU
- Develop 2D and 3D event displays for quick inspection



Backup

Indico

References

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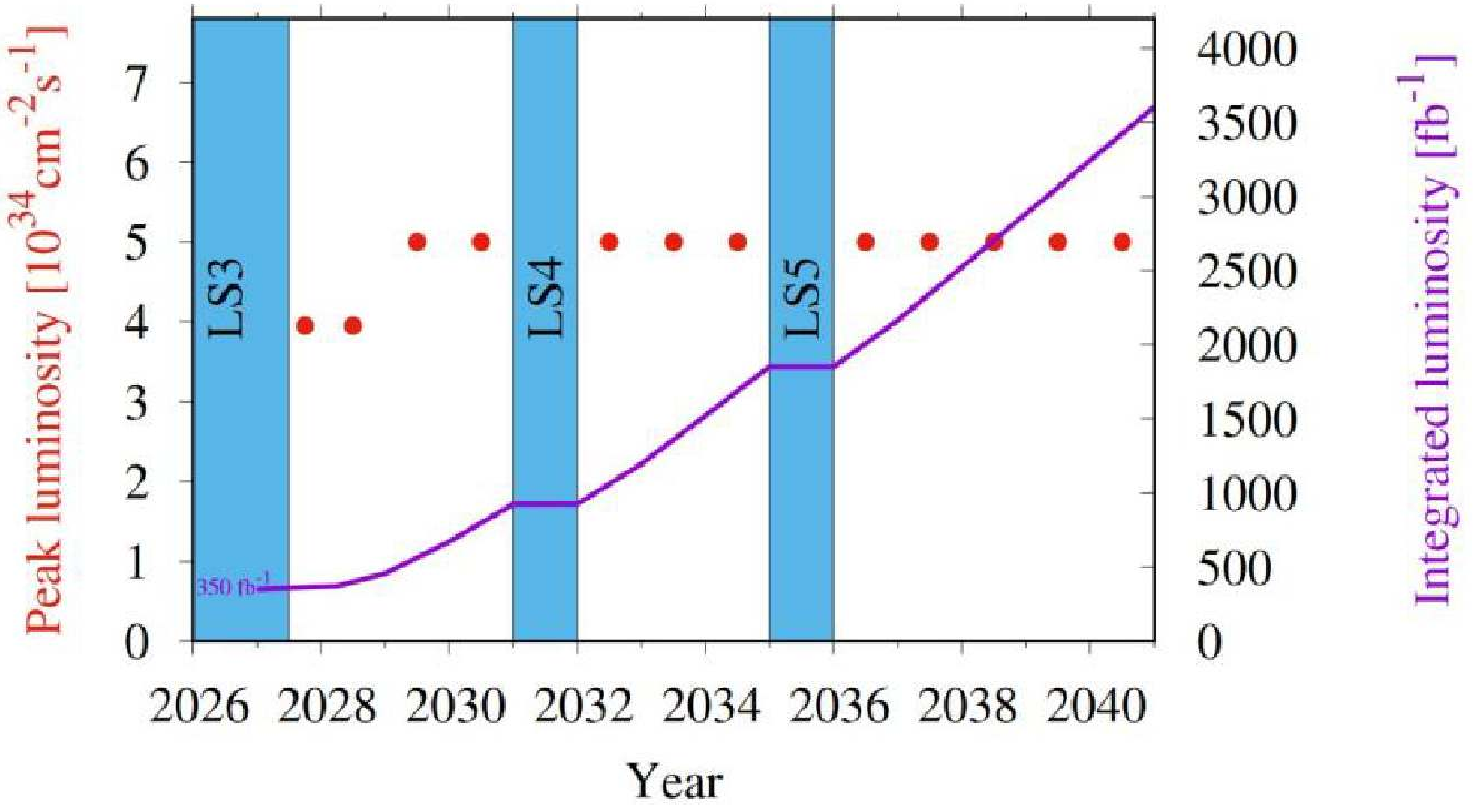
- N. Strobbe, The overall electronics chain (powering and readout) of the CMS HGCAL, CALOR 2022
- T. Kolberg, The SiPM-on-Tile Section of theCMS High Granularity Calorimeter, CALOR 2022
- [Cover lower background image] An aperiodic monotile, arXiv2303.10798

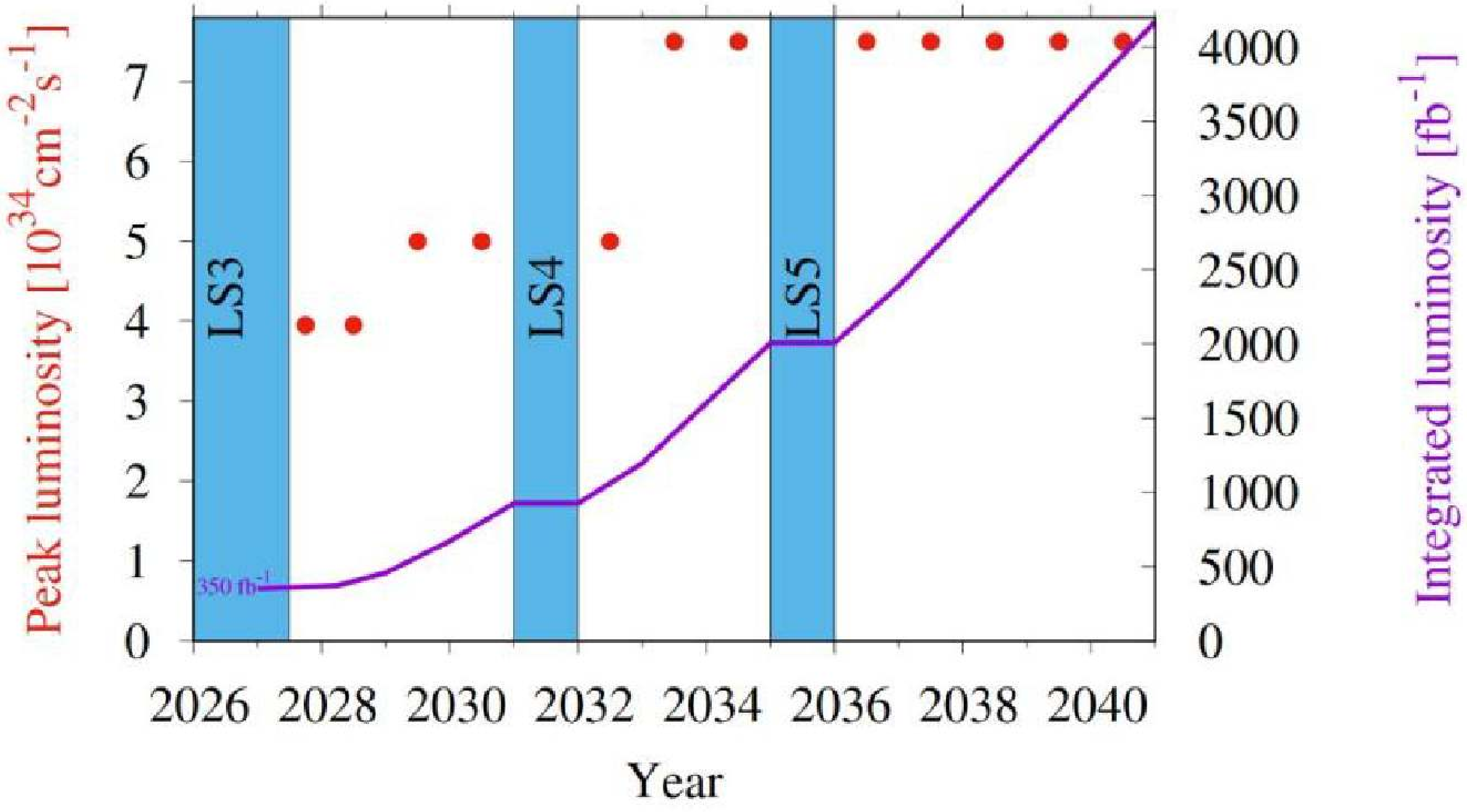
Many thanks to:
- J-B. Sauvan for reviewing and providing his own yet unpublished references.
- M. Chiusi for the help provided to produce 3d event displays

Projected Luminosity

Nominal HL-LHC parameters



Ultimate HL-LHC parameters

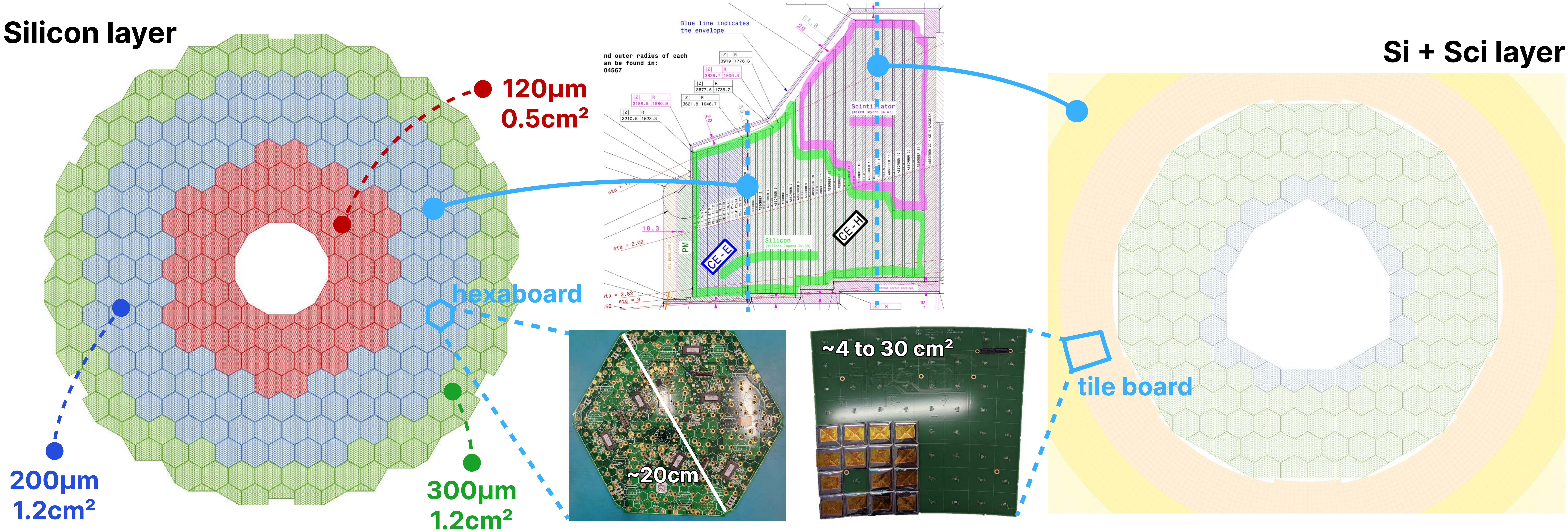


Silicon section

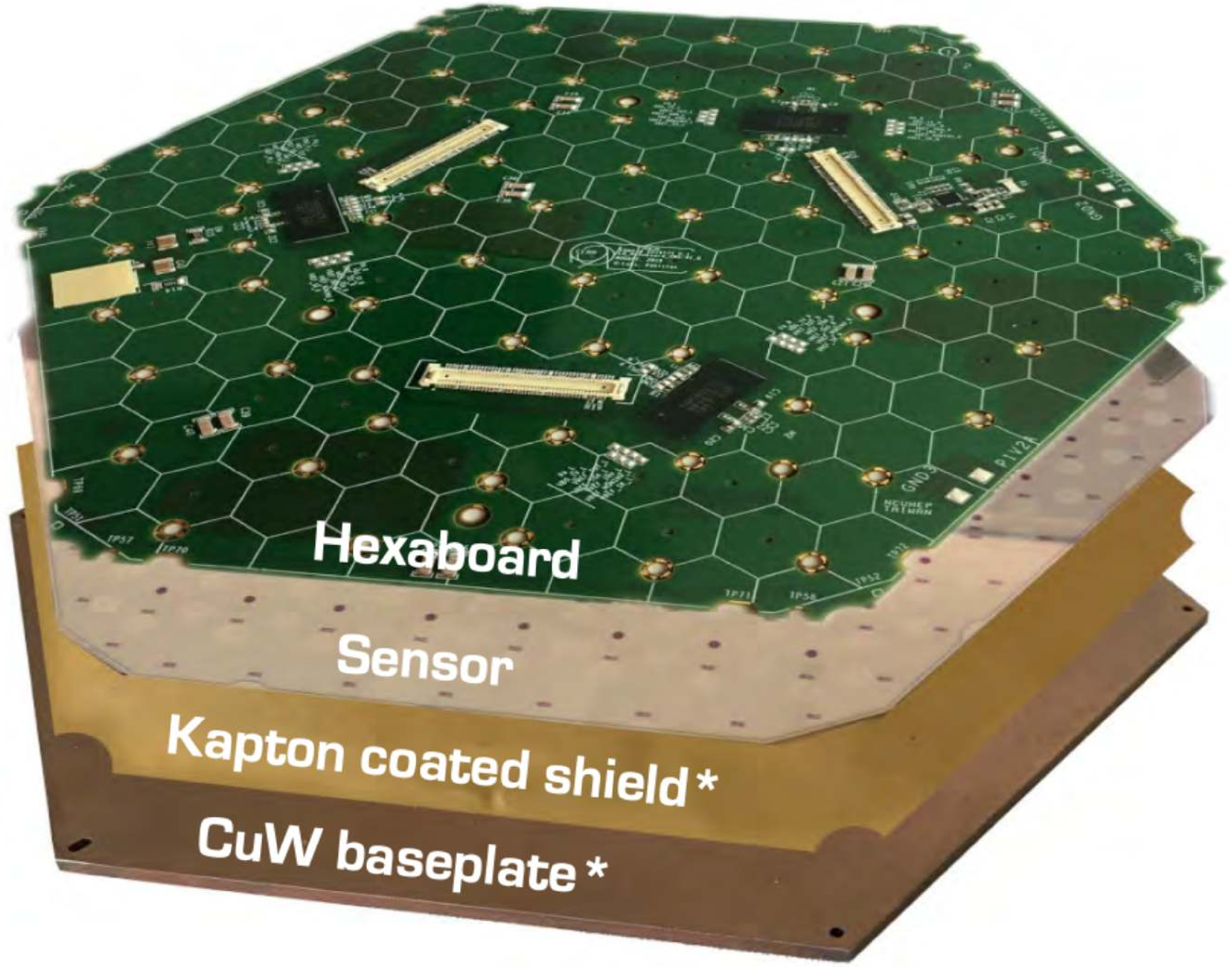
- Fine segmentation in the transversal direction
- Located in regions of high radiation (higher |η|)
- Silicon cells within hexagonal modules
- Low and high density: 192 or 492 sensors
  - translates to 48 trigger cells, w/ 4 or 9 sensors each
  - different cell thicknesses and sizes to improve S/N

Scintillator section

- Cheaper, but low radiation only
  - radiation goes down almost three orders of magnitude in the si/sci interface
- Direct on-tile SiPM collect light
- TCs groups of 2×2 tiles

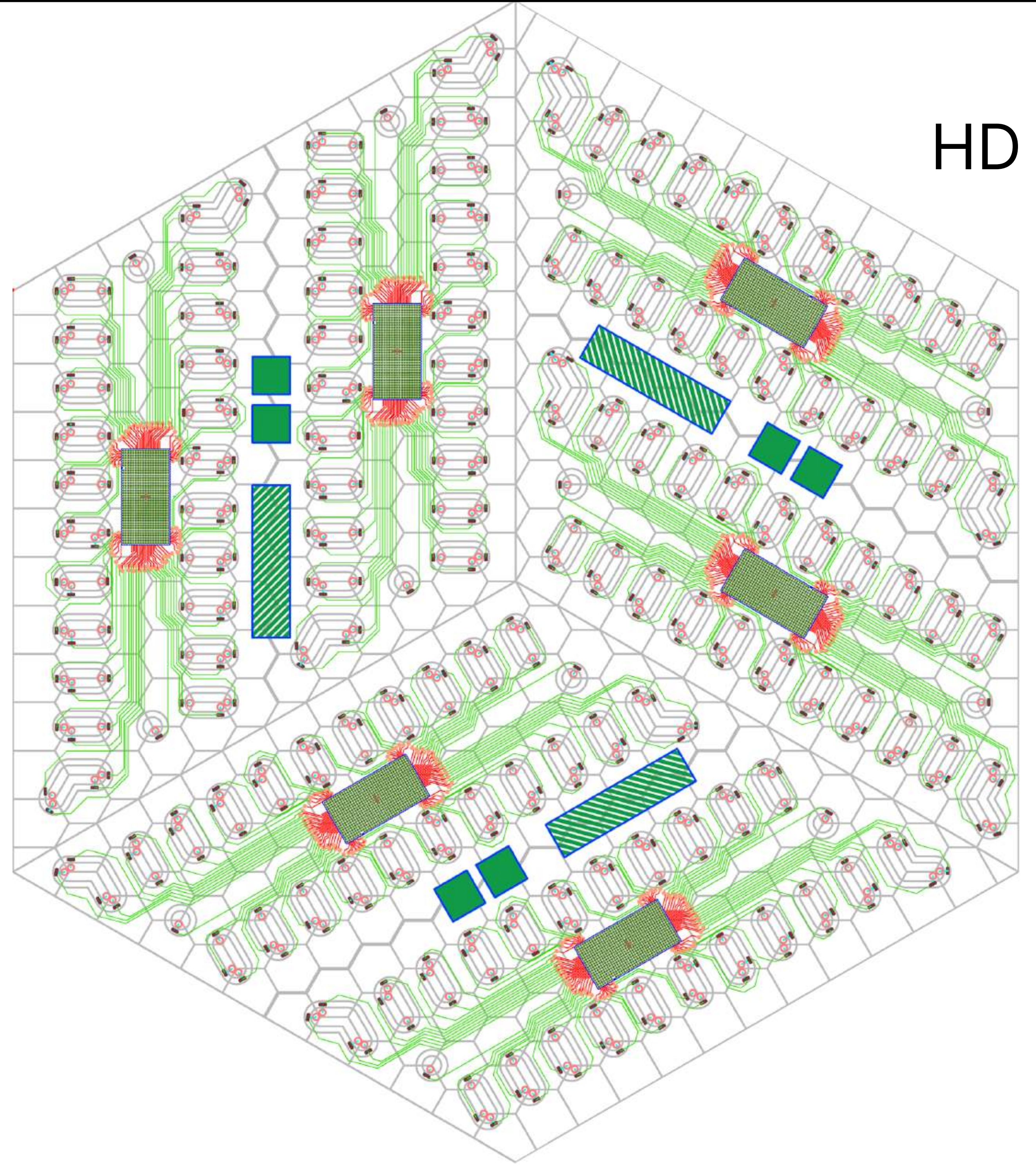


Module properties

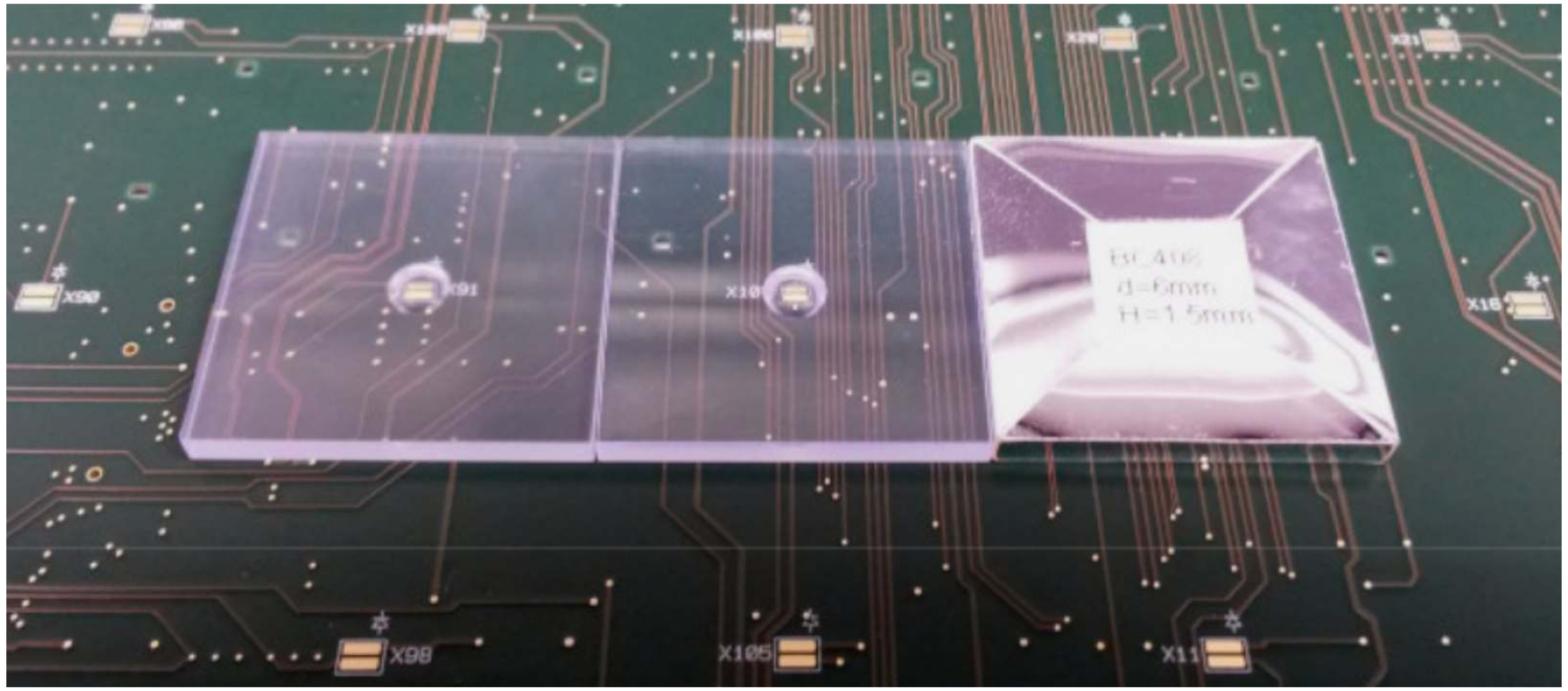


Module structure

HD module schematic
w/ 6 HGCROCs



Scintillator tiles w/ SiPM



HGCROC

- Front-end read-out ASIC @ 40MHz, outputs 1.28 Gb/s w/ 12.5µs latency!
- Low noise (<2500 electrons) and high dynamic range (0.2fC-10pC)
- Fast shaping time: <20% of the signal in other bunch crossings
- Timing information (ToA) down to 25ps
- Low power consumption: less than 20mW per channel
- Radiation tolerance: 200Mrad

Digitise collected charge:

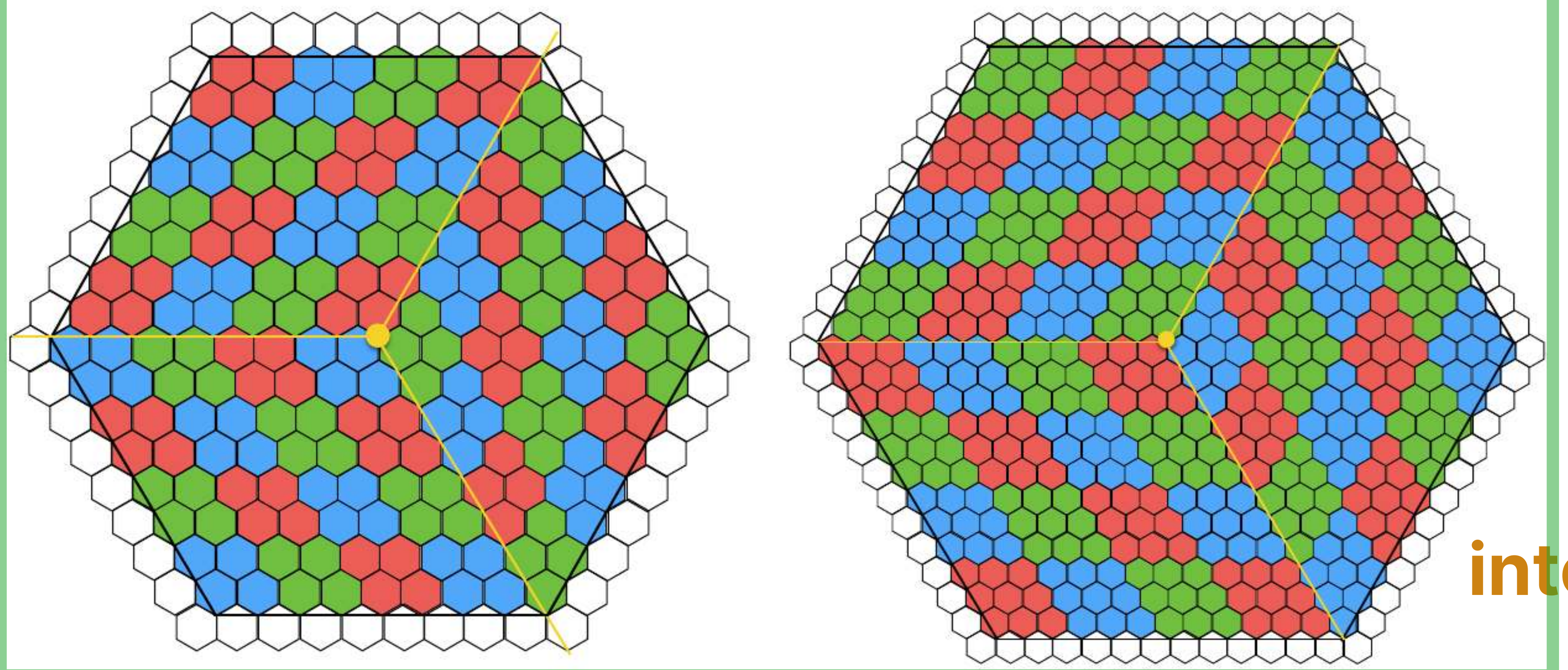
- <~100fC: 10bit ADC
- >~100fC: 12bit TDC ToT (up to 200ns)

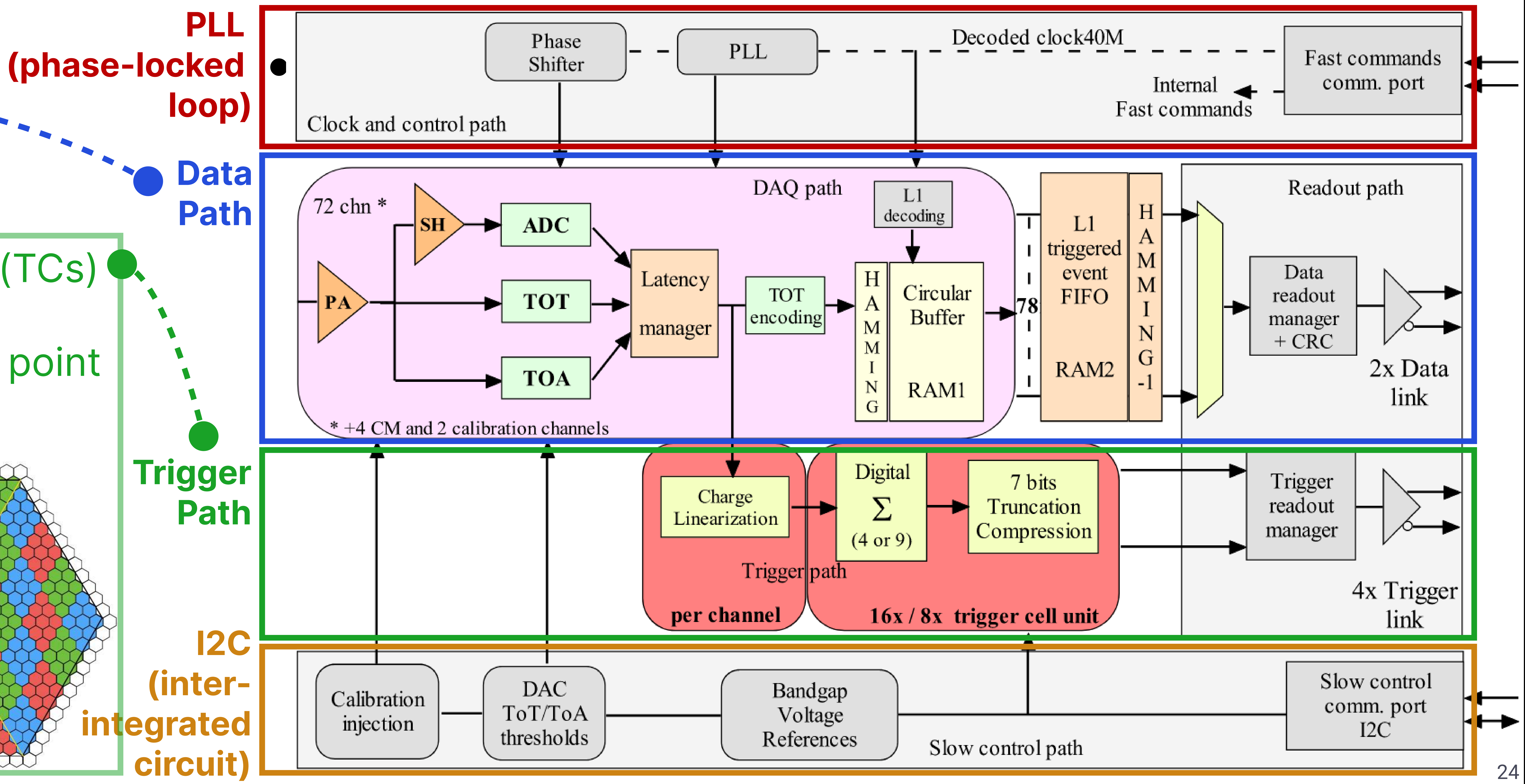
Channels:

- 72 for energy and time measurements
- 2 for calibration
- 4 common mode

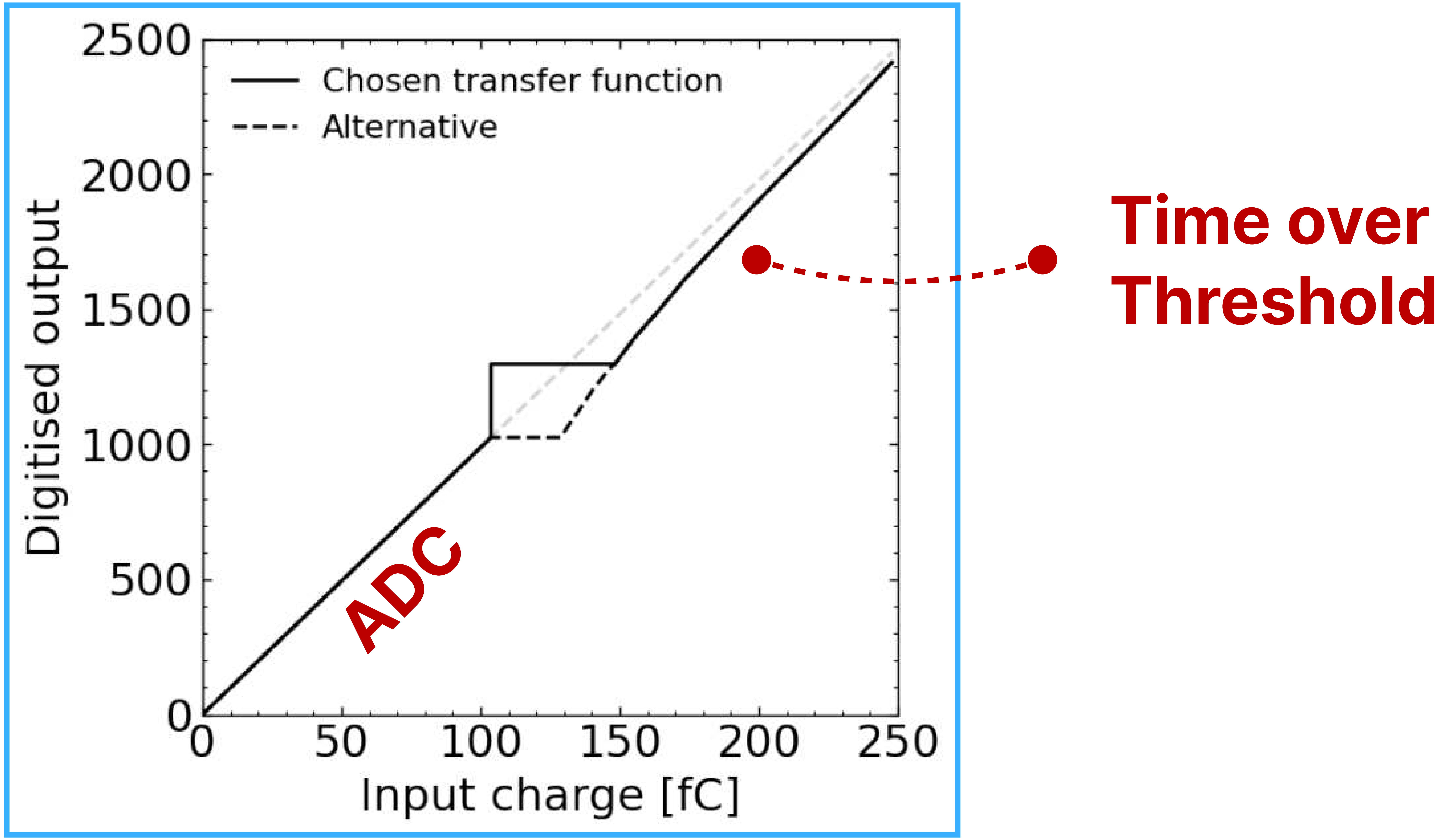
Sum channels into Trigger Cells (TCs)

- charge linearization
- compression to 7-bit floating point
- input to L1 trigger primitives



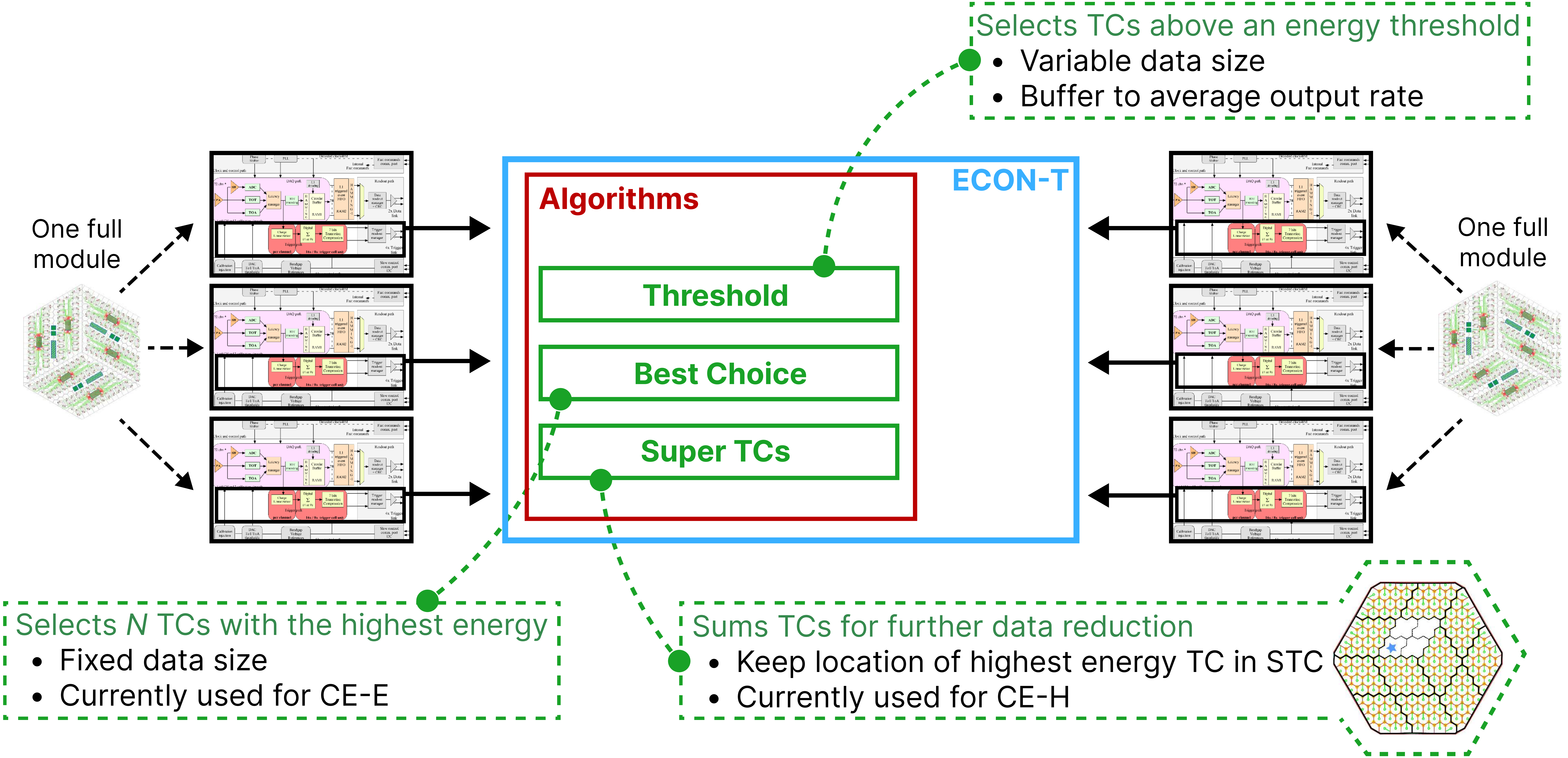


HGCROC Charge Linearization



ECON-T

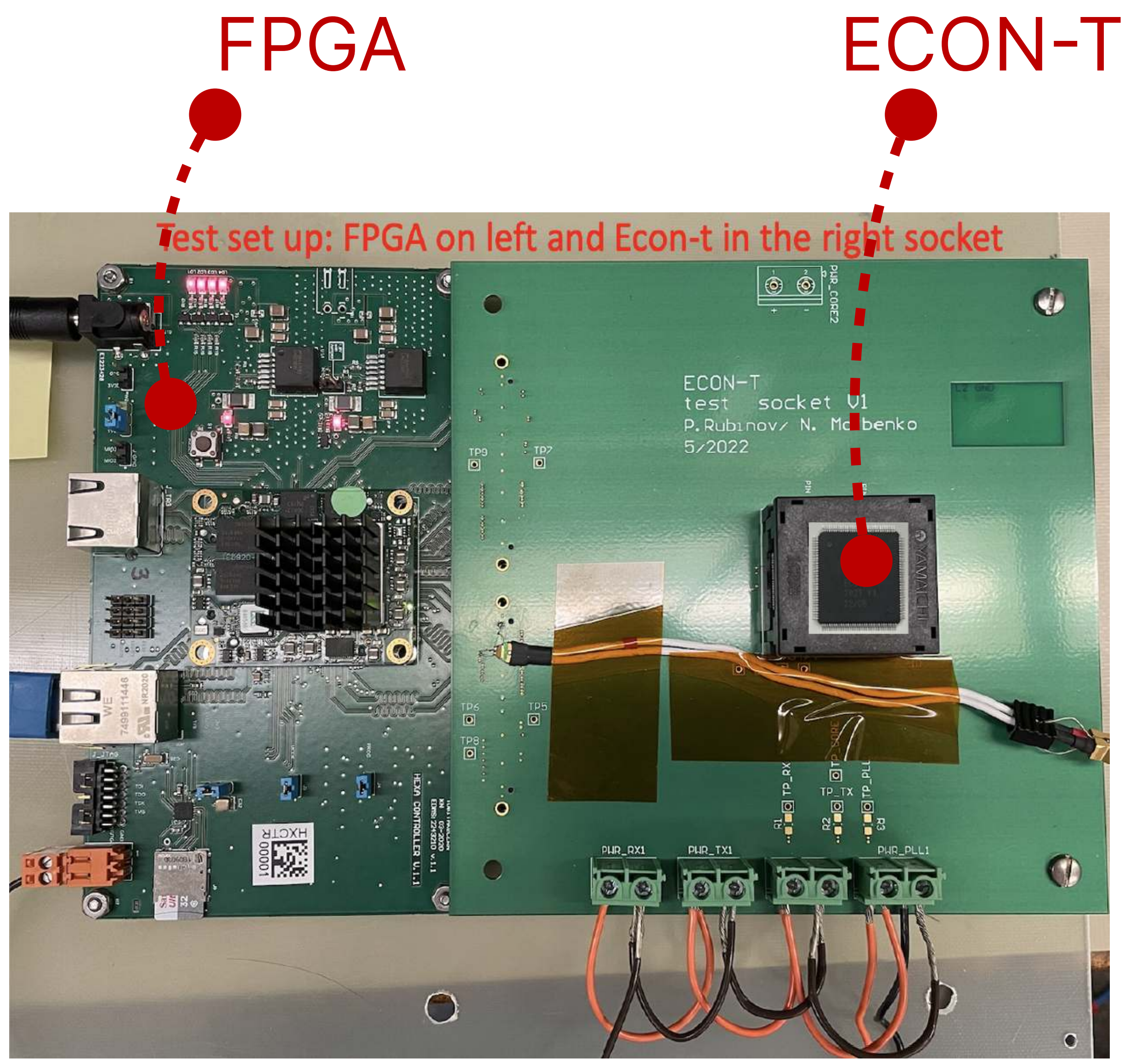
- Frontend chip: concentrates data w/ dedicated algorithms
- Selects or compresses HGCROC trigger data for transmission off-detector



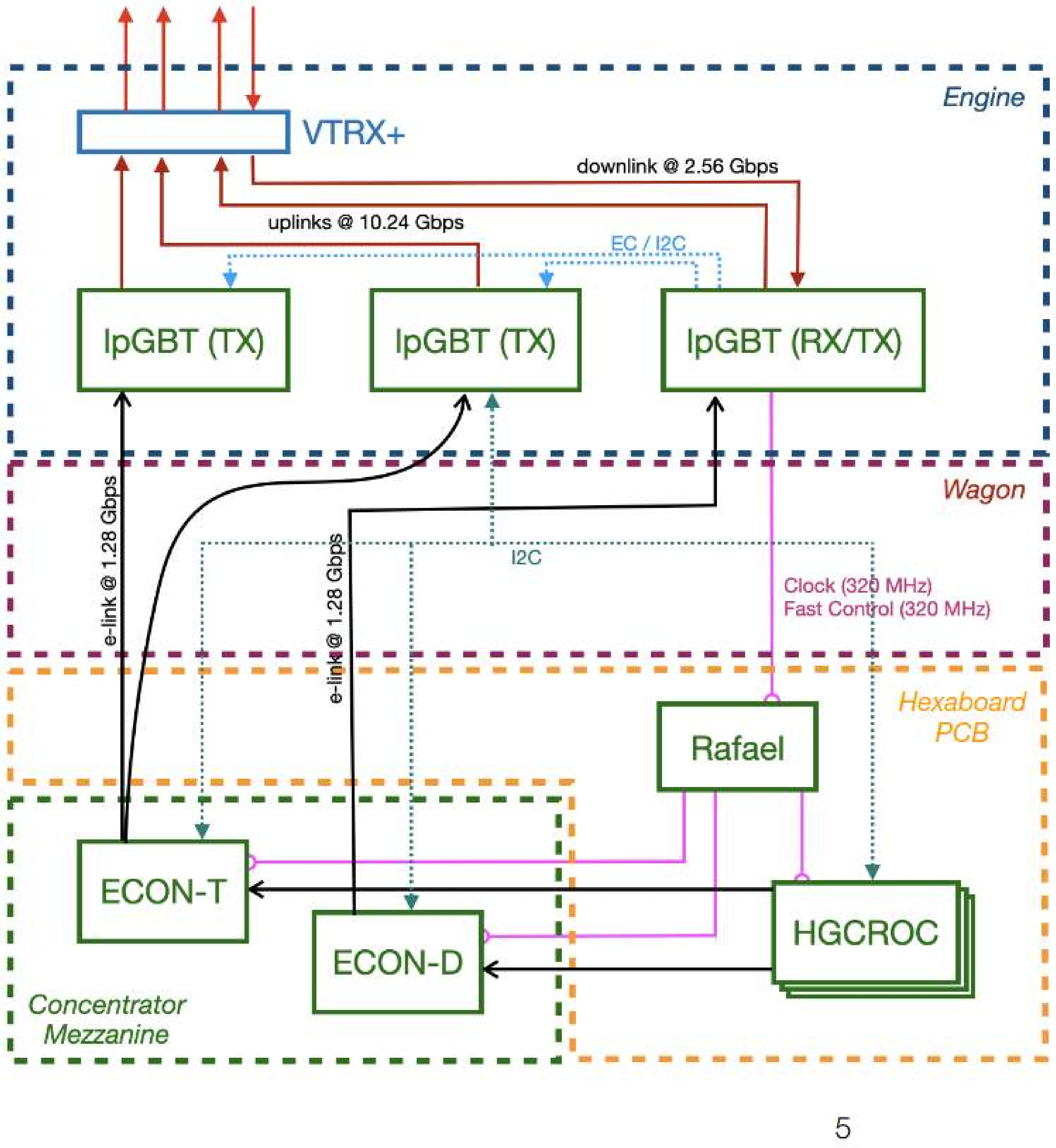
Frontend architecture

- ECON-T: frontend concentrator chip for trigger path, concentrates trigger data via one of 4 trigger algorithms
- ECON-D: frontend concentrator chip for DAQ path, performs channel alignment and zero suppression after L1 Accept
- Rafael: clock and fast control fanout
- lpGBT: for sending/receiving data/clk/control signals via optical link (and VTRX+)

credit to N. Strobbe



Test setup



Engine board is connected to 2 Wagon boards

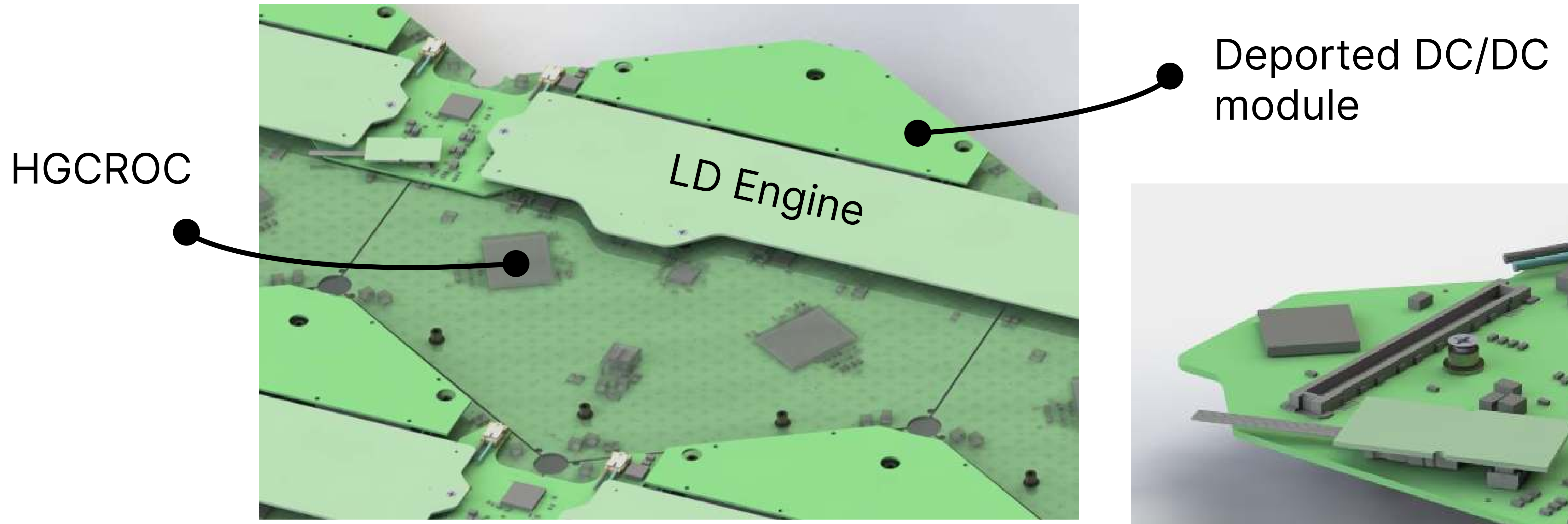
Passive Wagon board is connected to 1—3 Modules

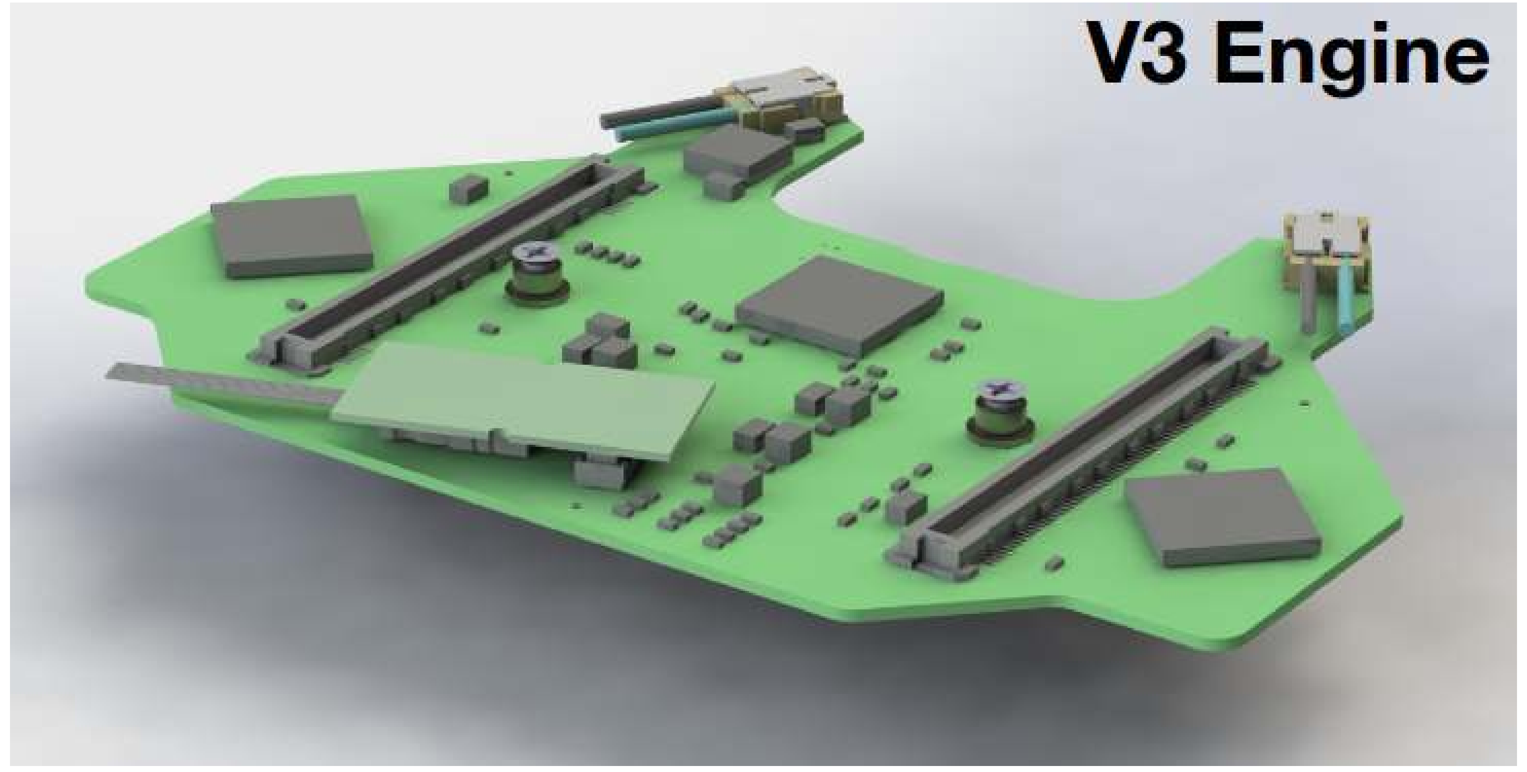
Module is composed of the Si sensor and hexaboard PCB

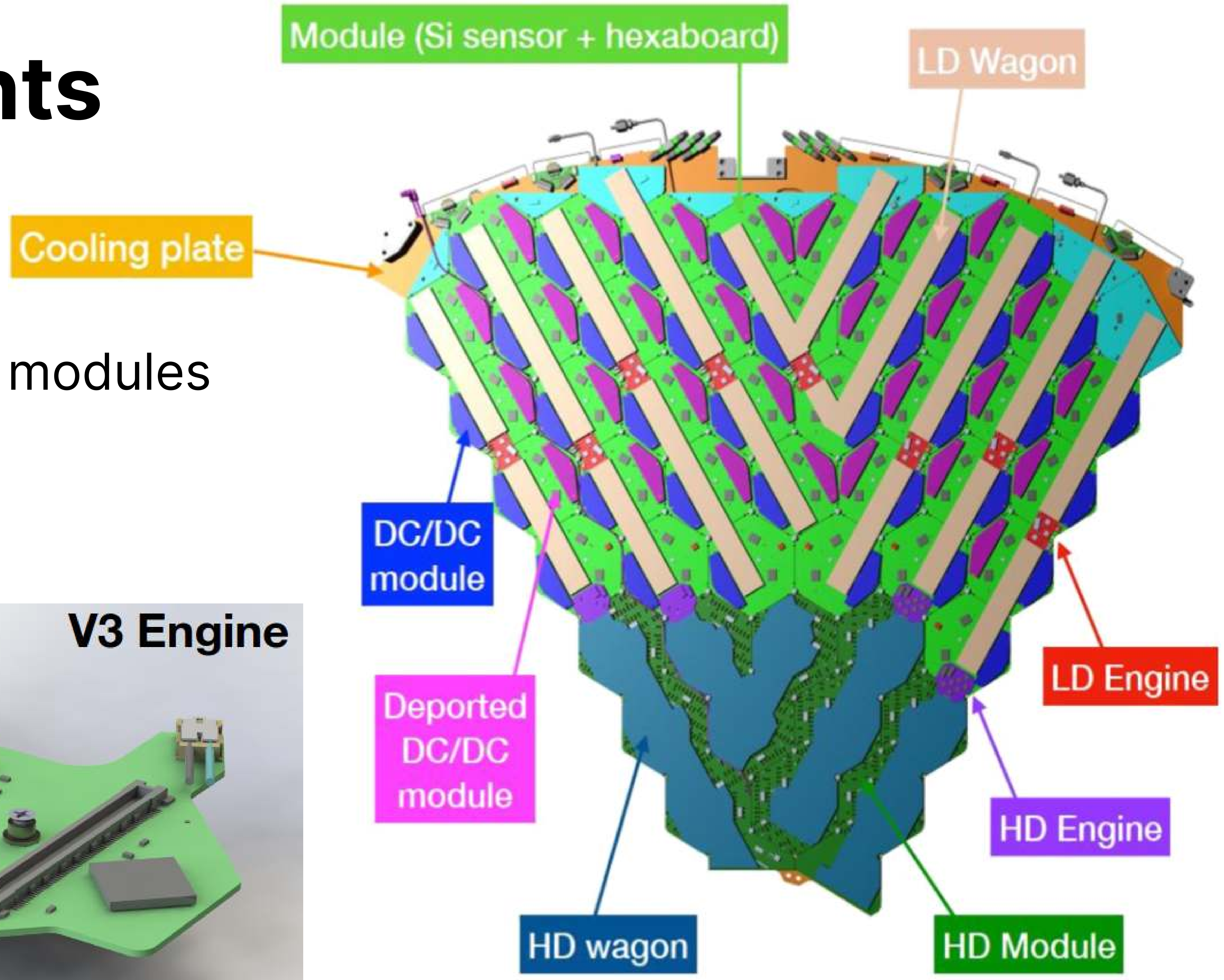
HGCROC and ECON are custom for this project, all other chips and components are common developments!

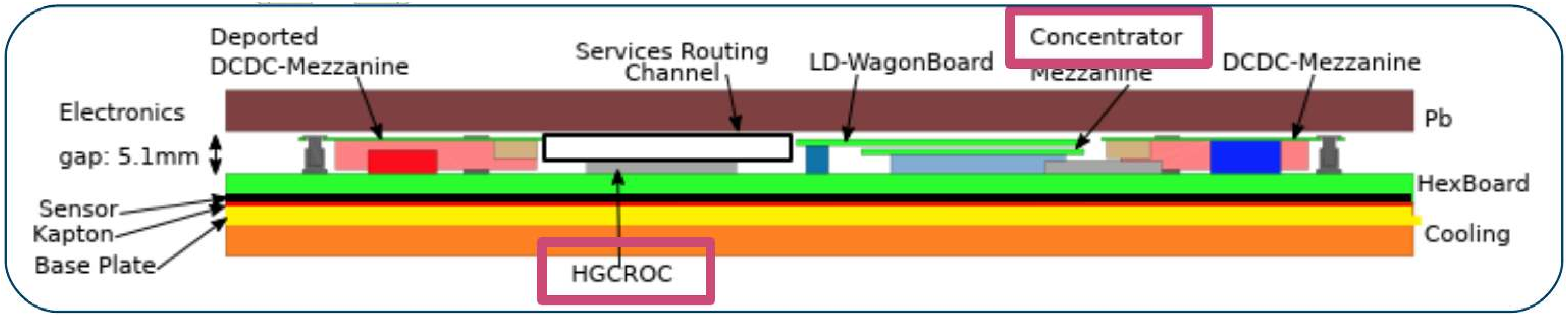
Hardware / Mechanical Components

- 60 degree symmetry for the cassettes
- Wagons are passive boards (many shapes and lengths)
- Engine is always the same and supports up to 6 LD (3 HD) modules

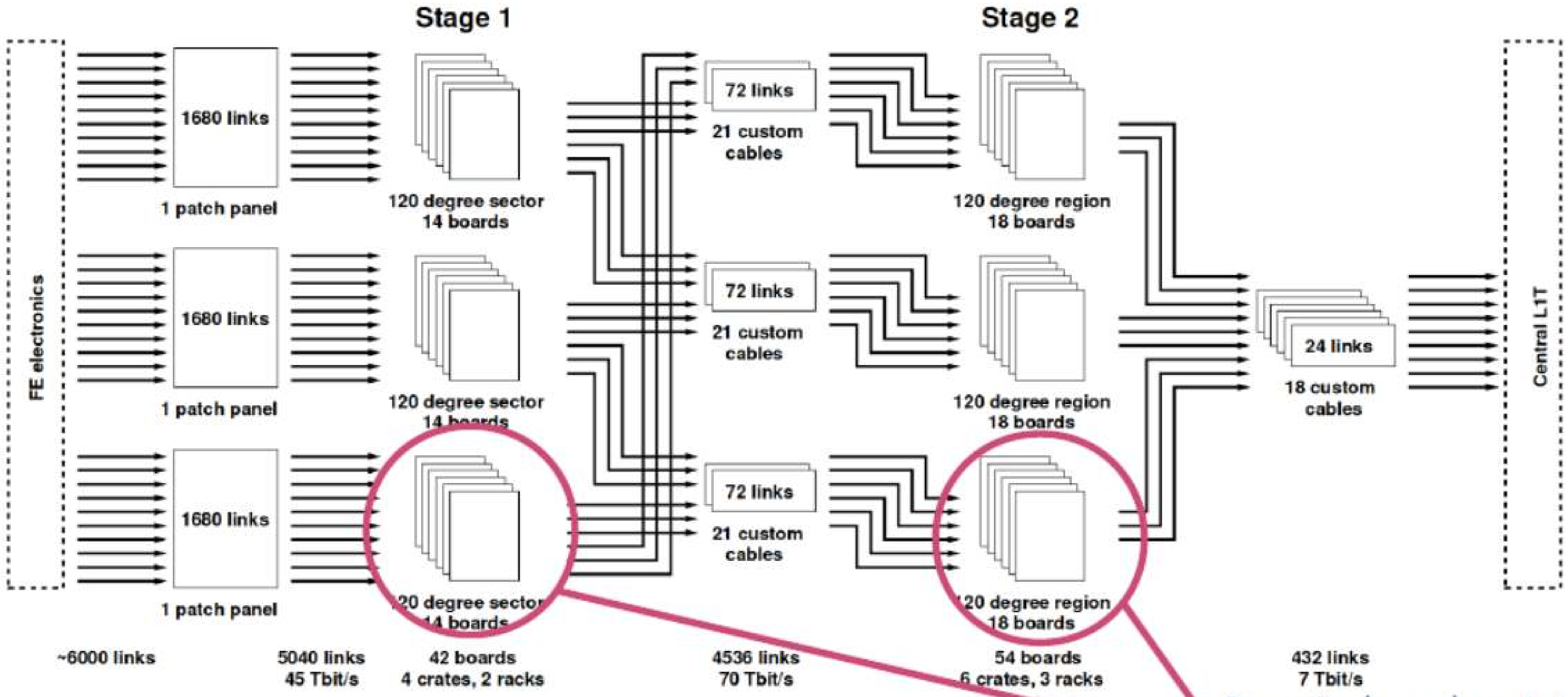




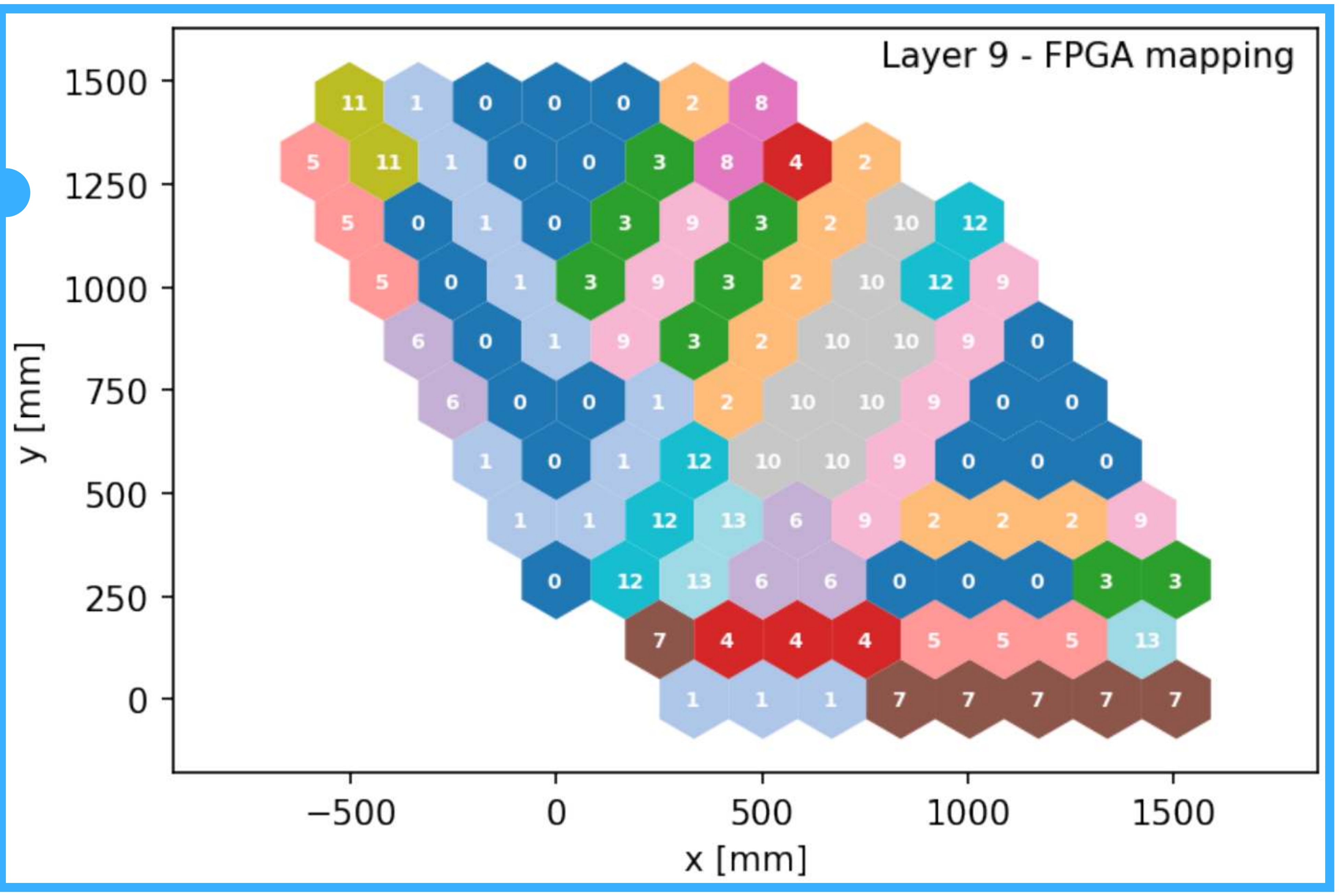




Frontend mapping to Backend

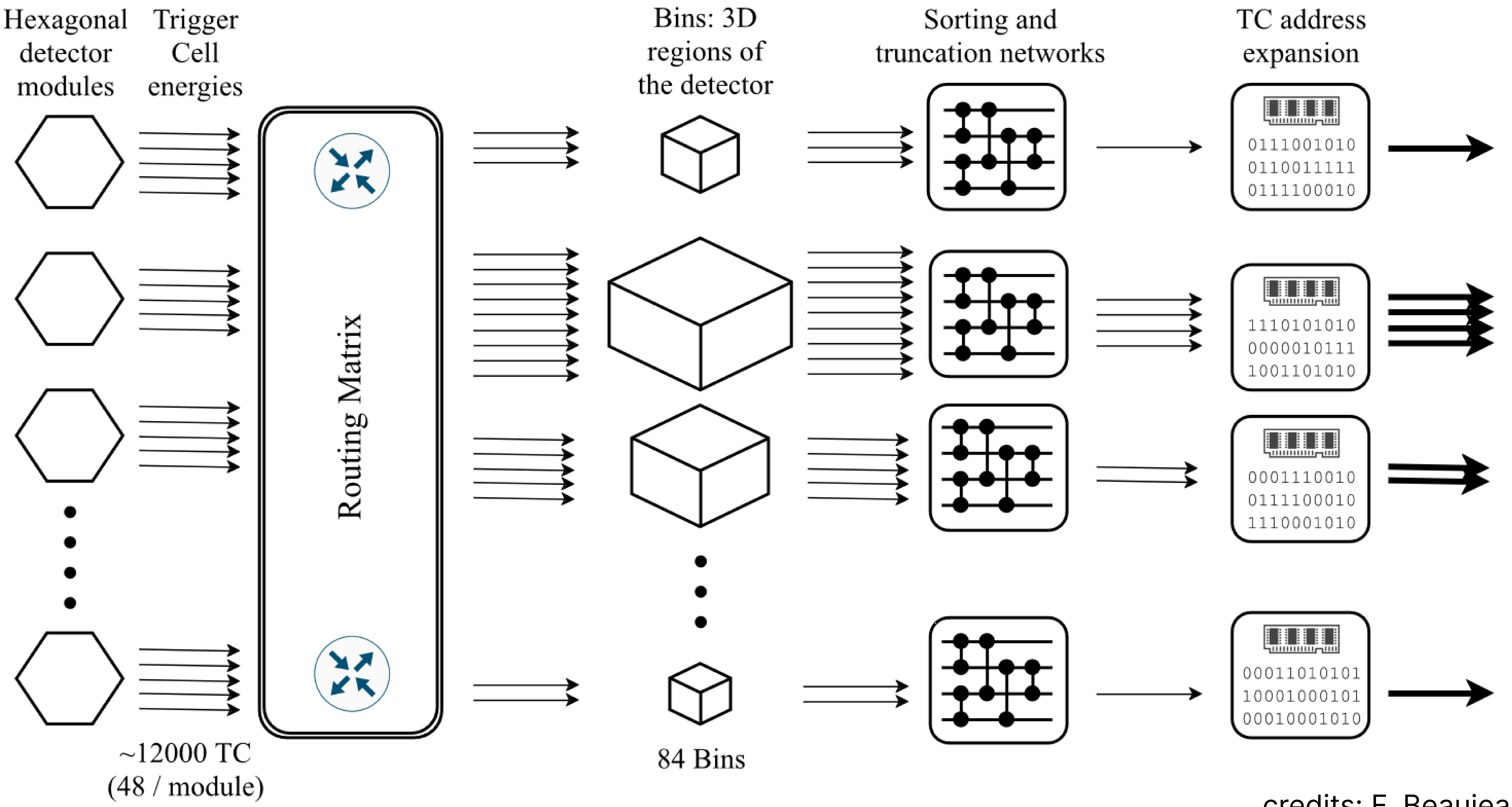


Serenity board prototype



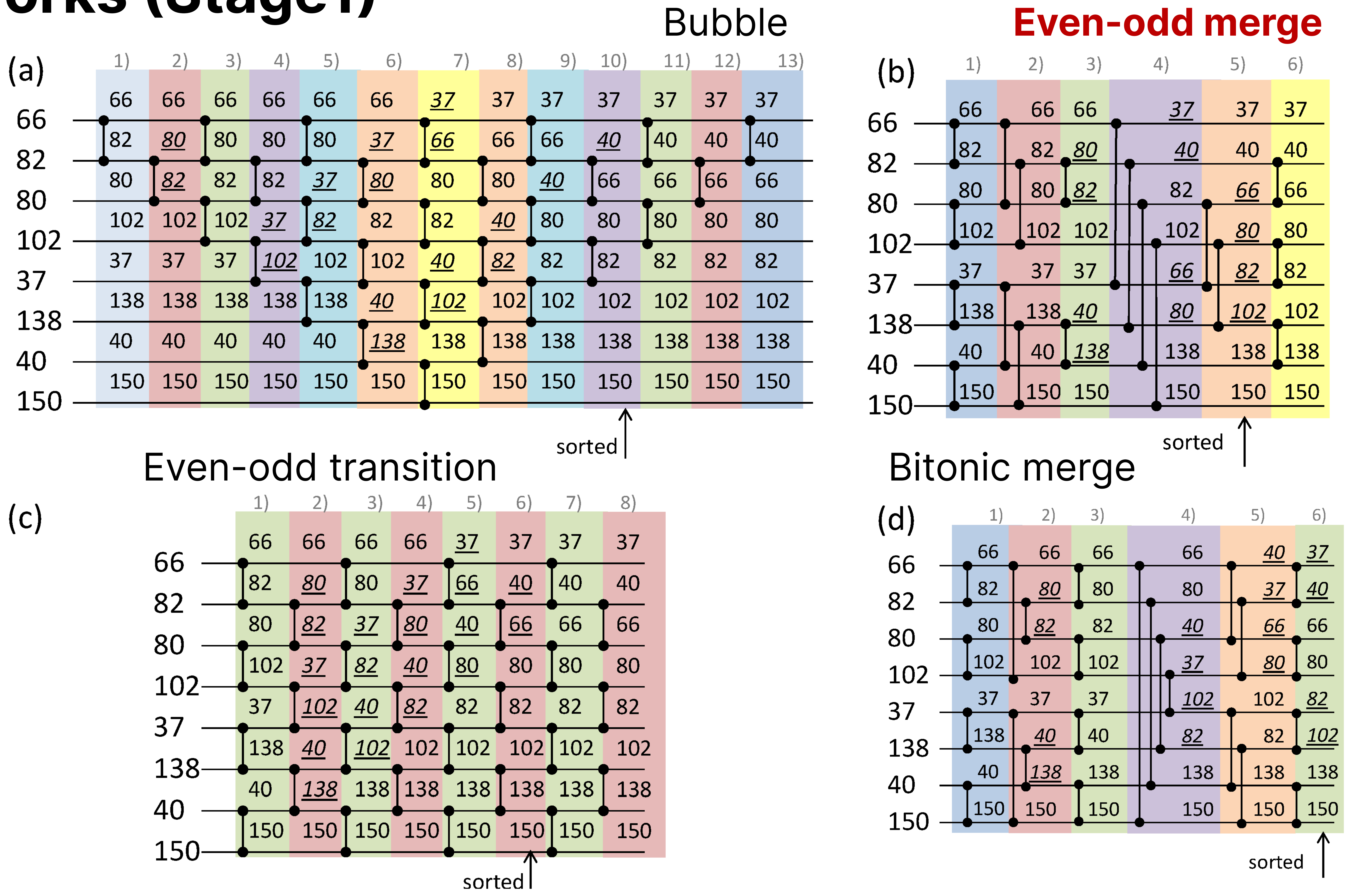
Mapping of modules
to FPGAs in a 120º sector
(stochastic Hill Climbing algorithm)

Backend Stage1



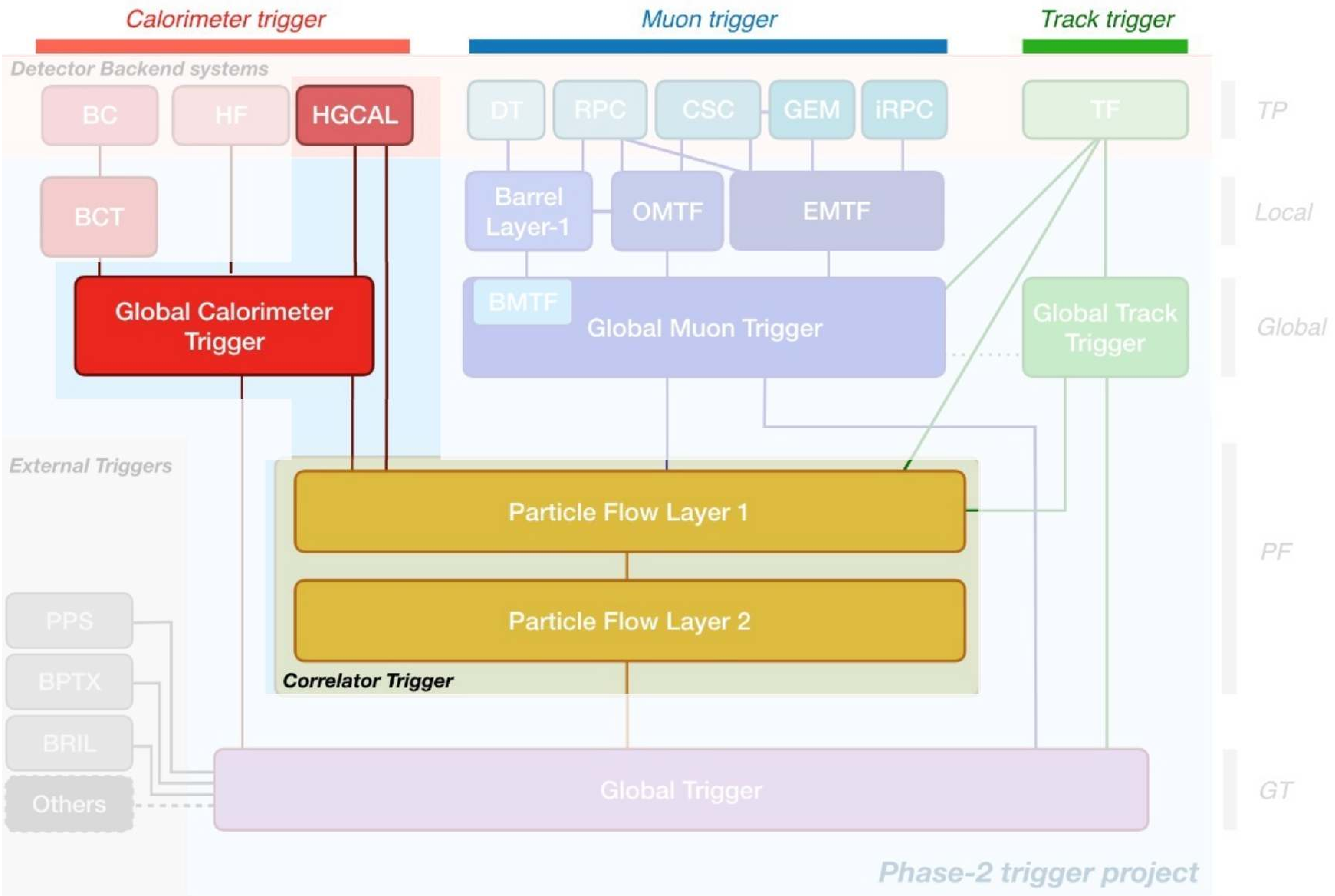
credits: F. Beaujean *et al.*

Sorting networks (Stage1)



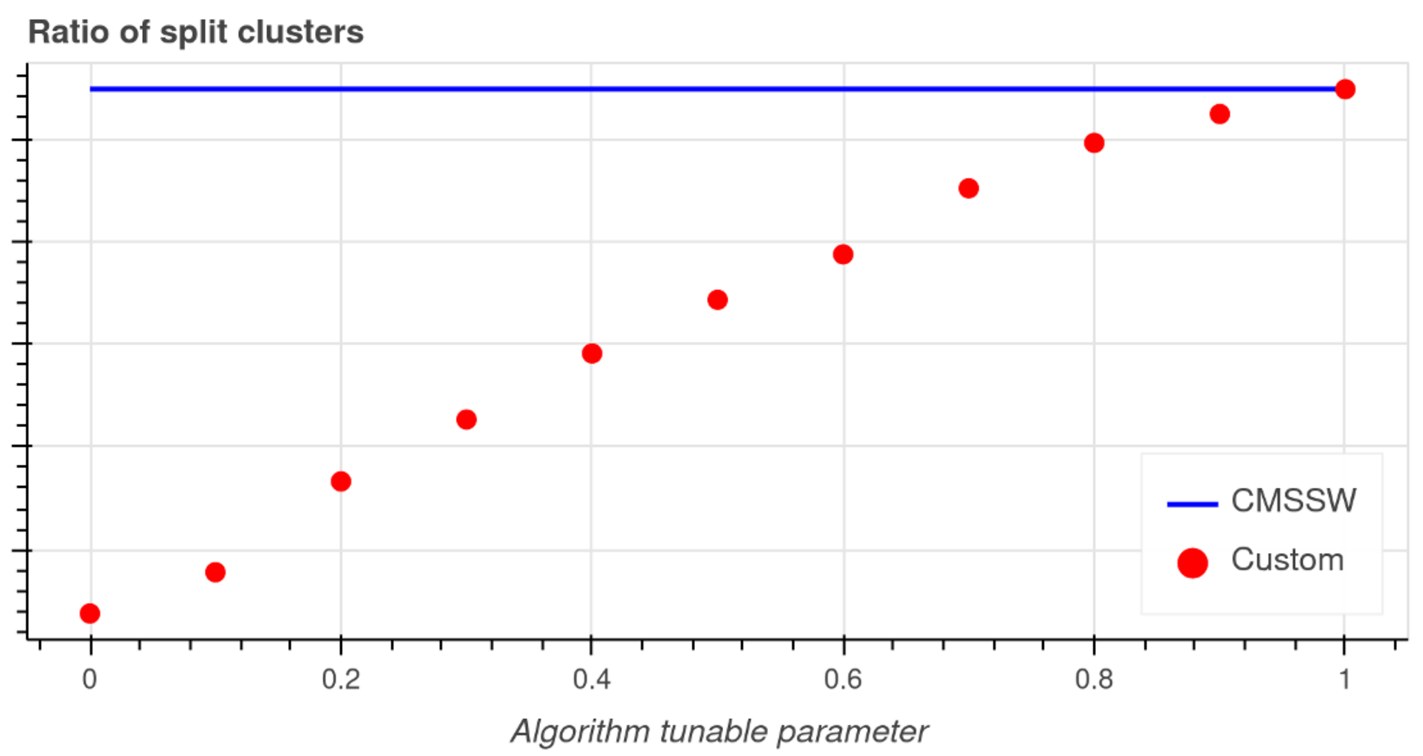
credits: I. Skliarova

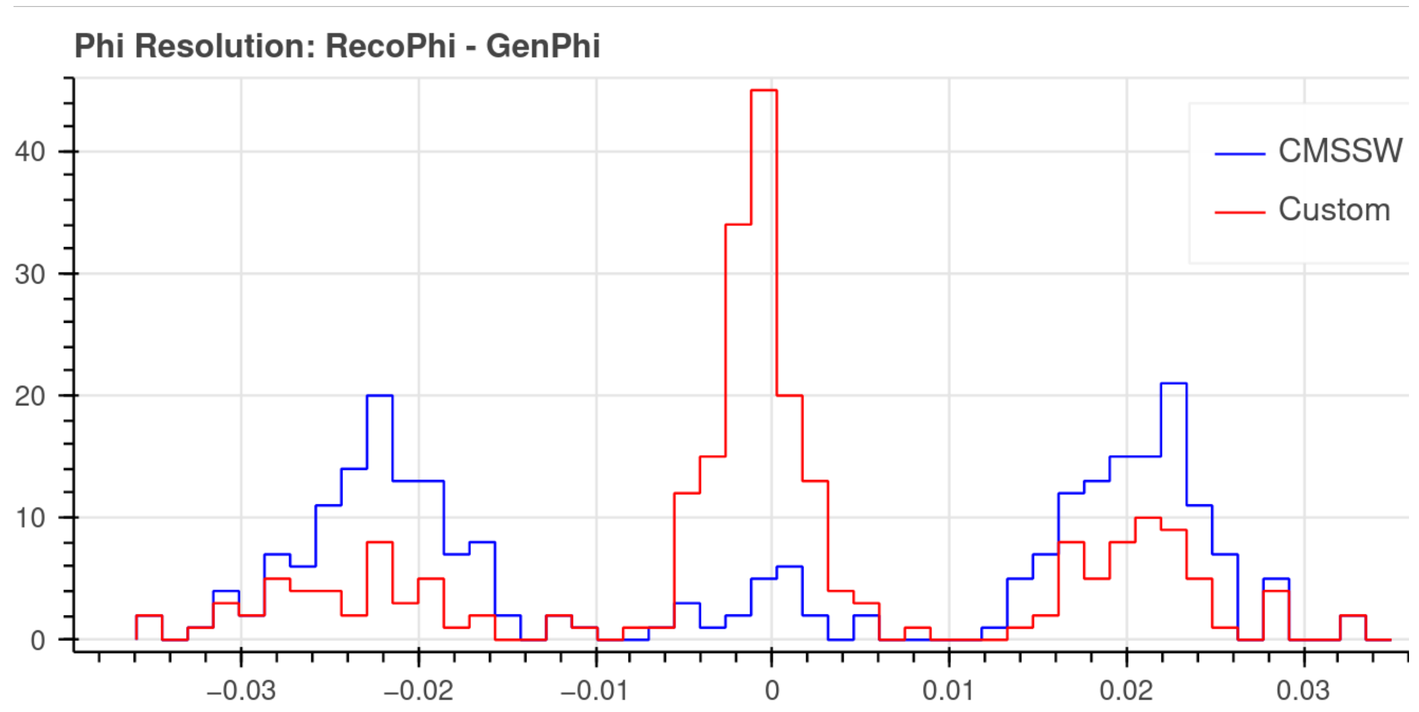
HGCAL TPG as part of the L1 trigger

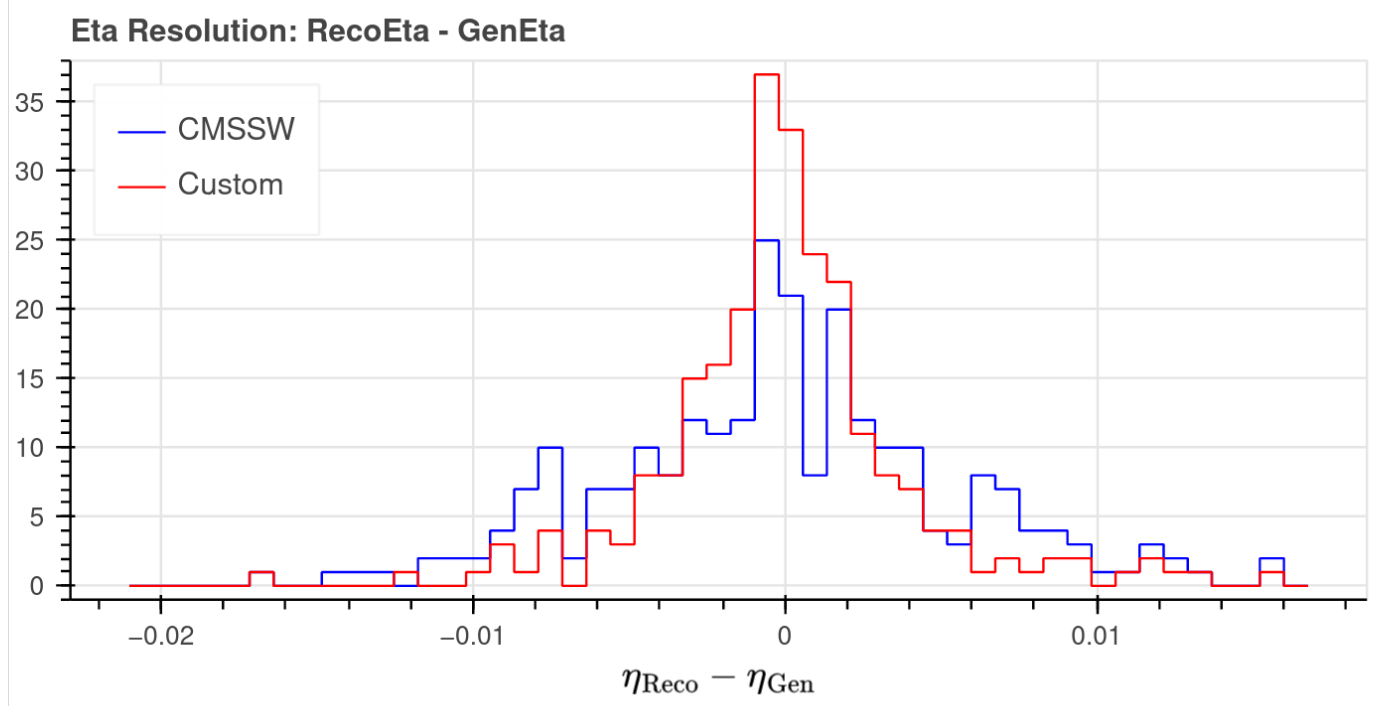


Cluster Splitting: Resolutions

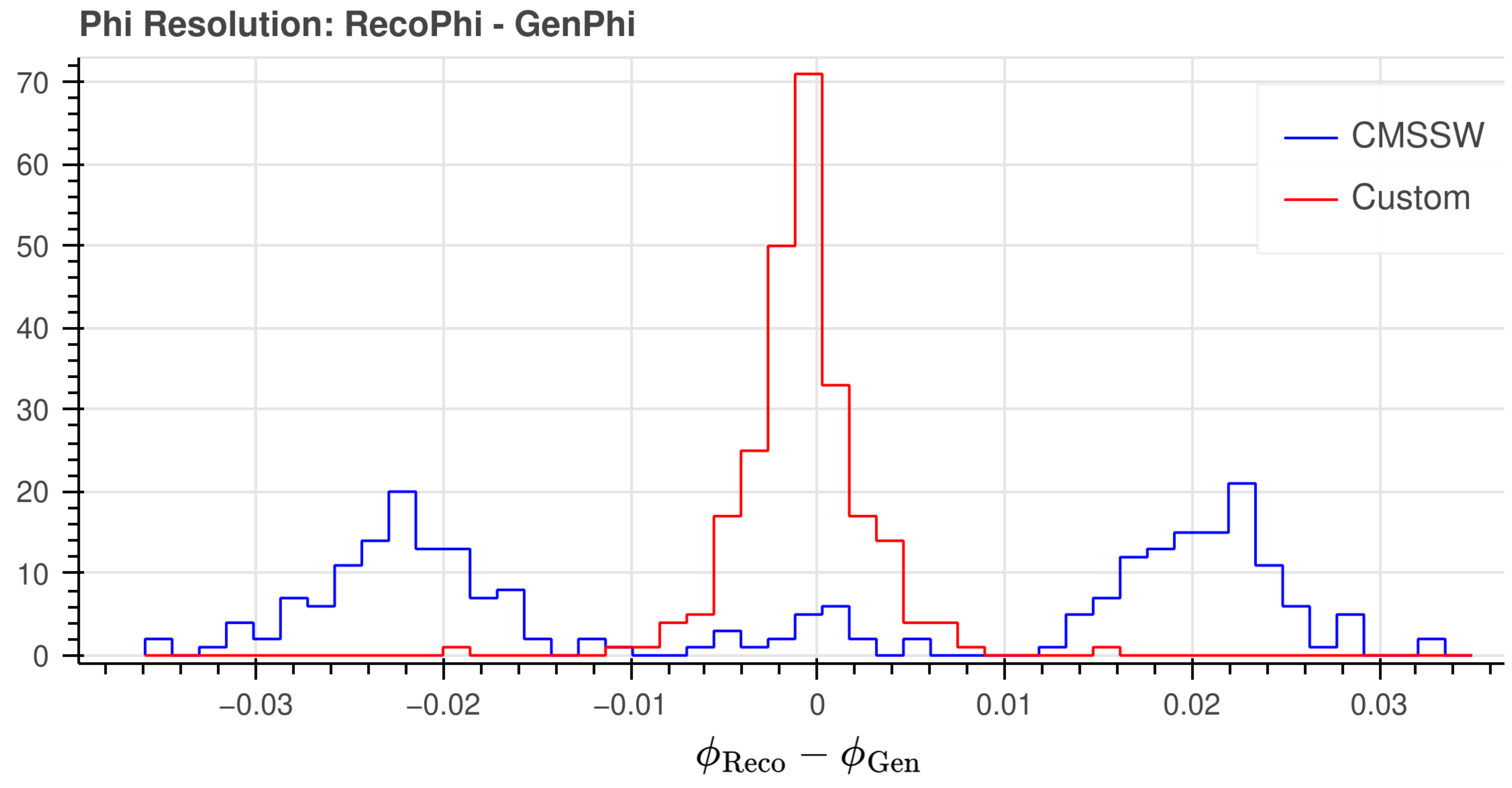
- **"ByeSplits" algorithm:**

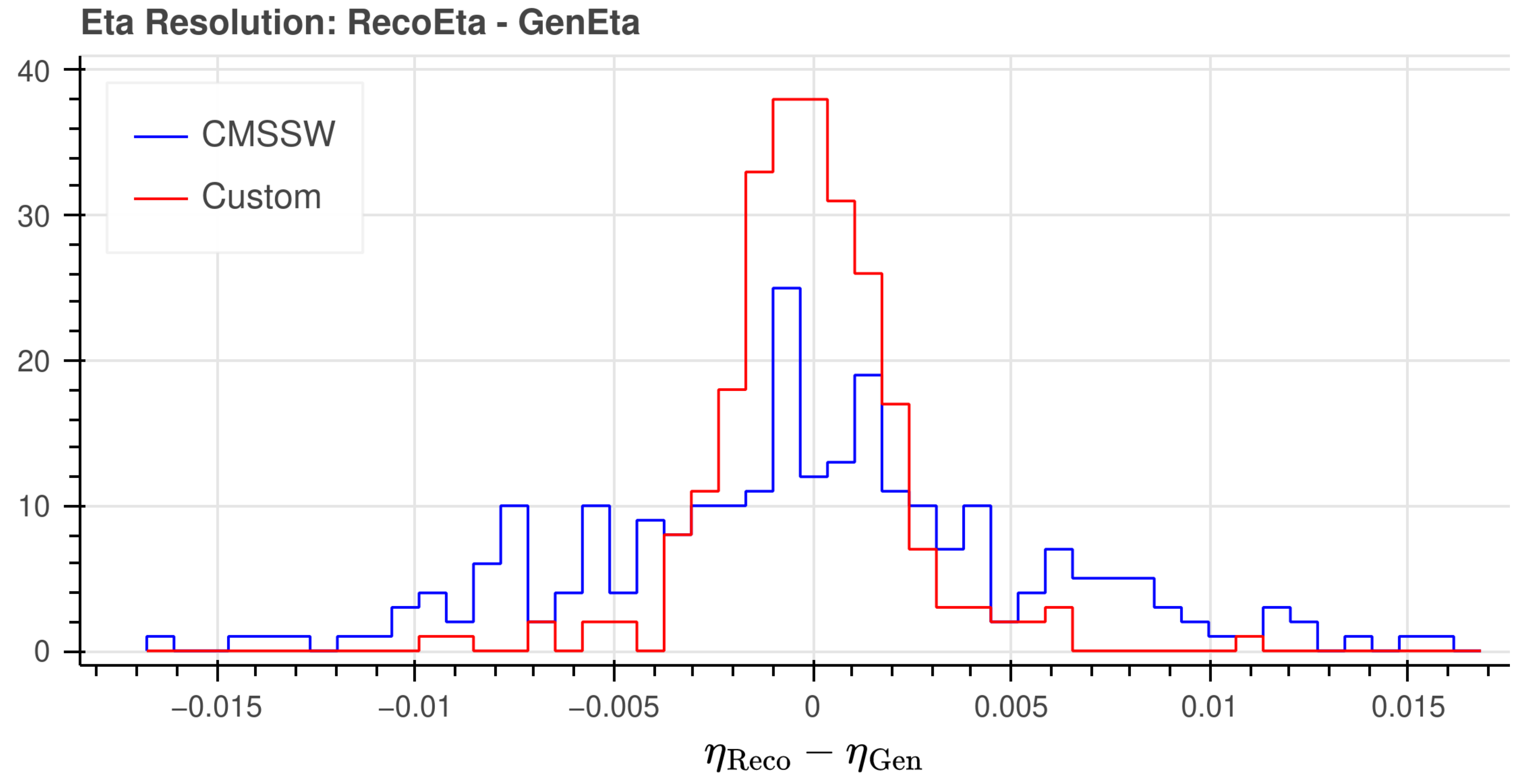






- **Add "2nd order neighbors" in the seeding:**



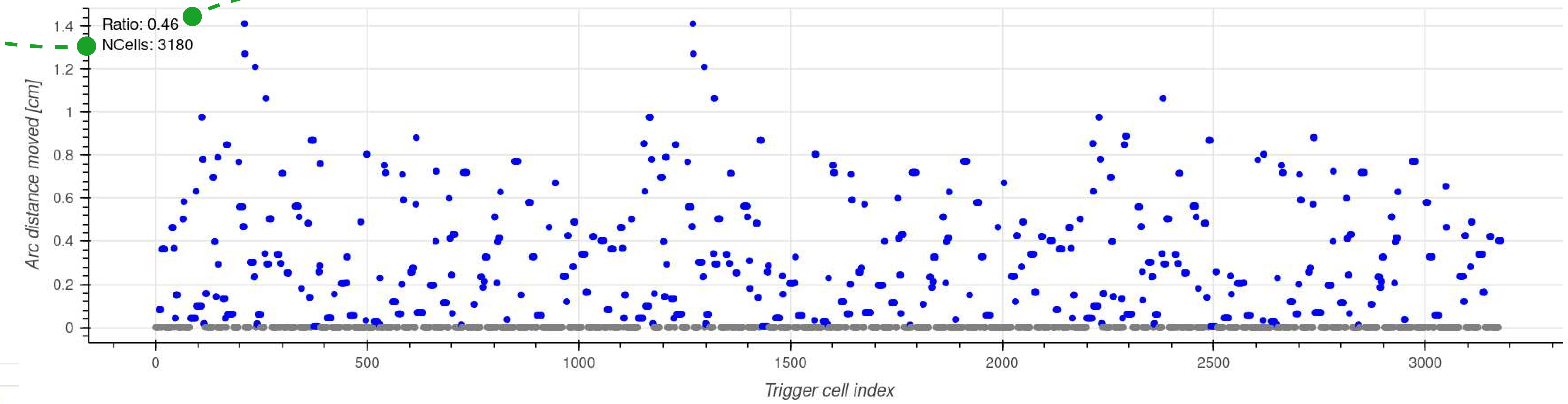


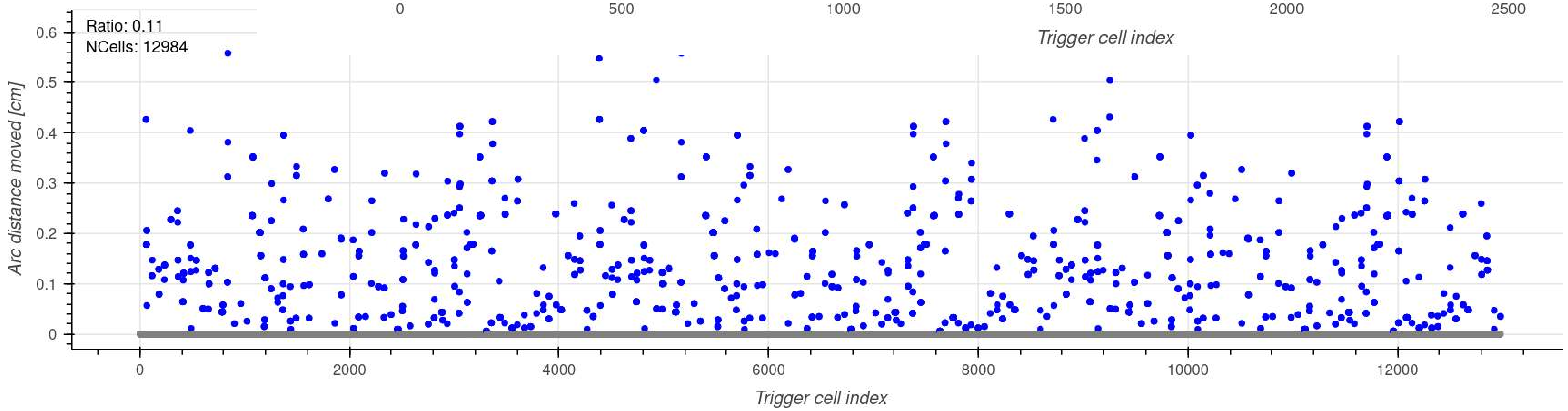
ByeSplits algorithm: TC arc distance moved along ϕ

total number of TCs in a R/z slice

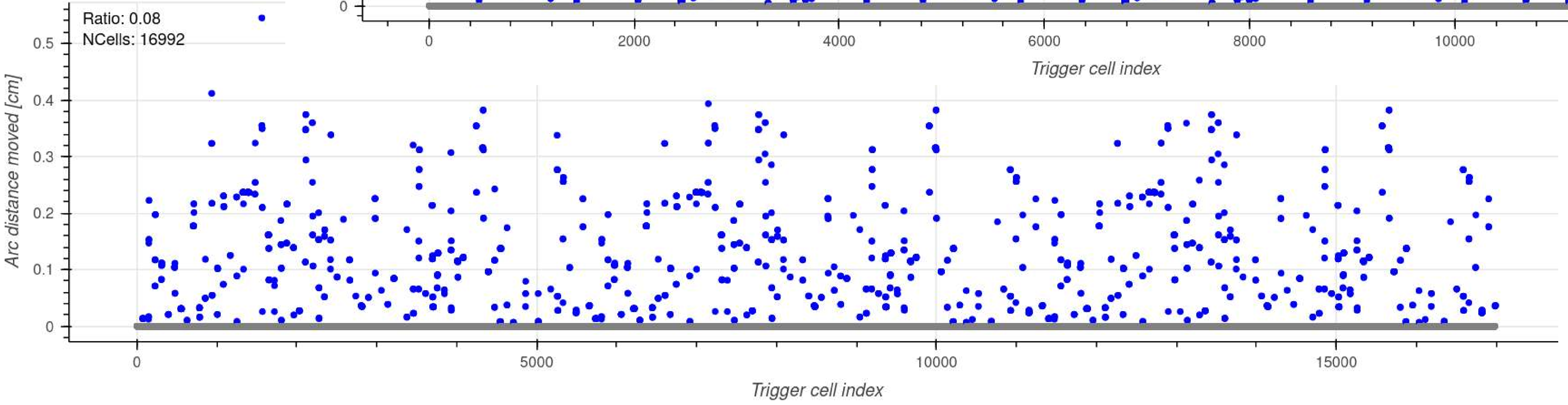
fraction of TCs that moved

R/z slice 0 (lower η)





R/z slice 3



R/z slice 6

(there are 42 slices in total)

Software developments

- The reconstruction chain of the HGCAL TPGs was fully ported to Python. This enables:
  - quick prototyping of new ideas
  - quick testing of those ideas
  - easy parameter optimization studies
  - conveniently debug the original chain

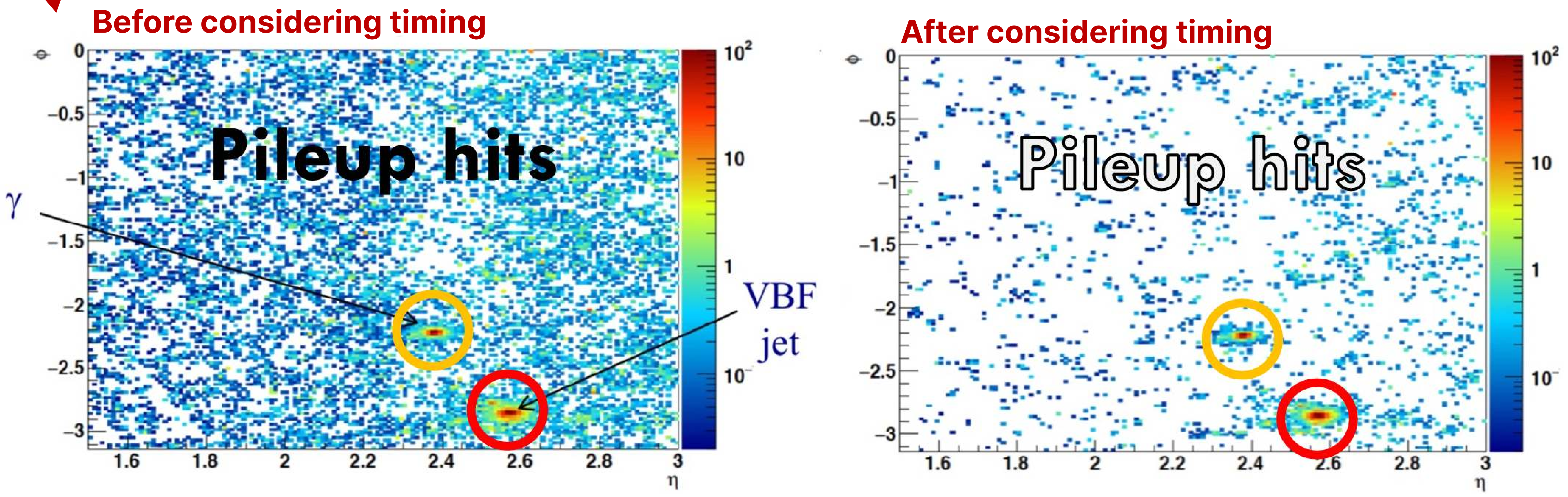
- A simplified version of the HGCAL geometry was developed in Python. Benefits:
  - event displays
  - debugging the original geometry (some bugs already found!)

- The two above, when used together, make possible the visualization of specific events after running custom algorithm, for real-time inspection

- The framework is available here.

HGCAL Physics Motivation

- Extend Particle Flow measurements from the tracker into the calorimeter
- Subtract pileup energy leading to a good energy resolution even w/ high pileup
  - good time resolution is essential
- Merged jets can be reconstructed with higher efficiency and better energy resolution improving the boosted object reconstruction performance
- The high lateral granularity allows tagging of narrow jets originating from VBF-produced Higgses and jets from VBS.
- High granularity also allows efficient e/γ reconstruction/PID in the forward region w/ pileup
- Small expected energy resolution constant term (typically dominates the energy resolution at high energies) will lead to an EM resolution similar to the current one

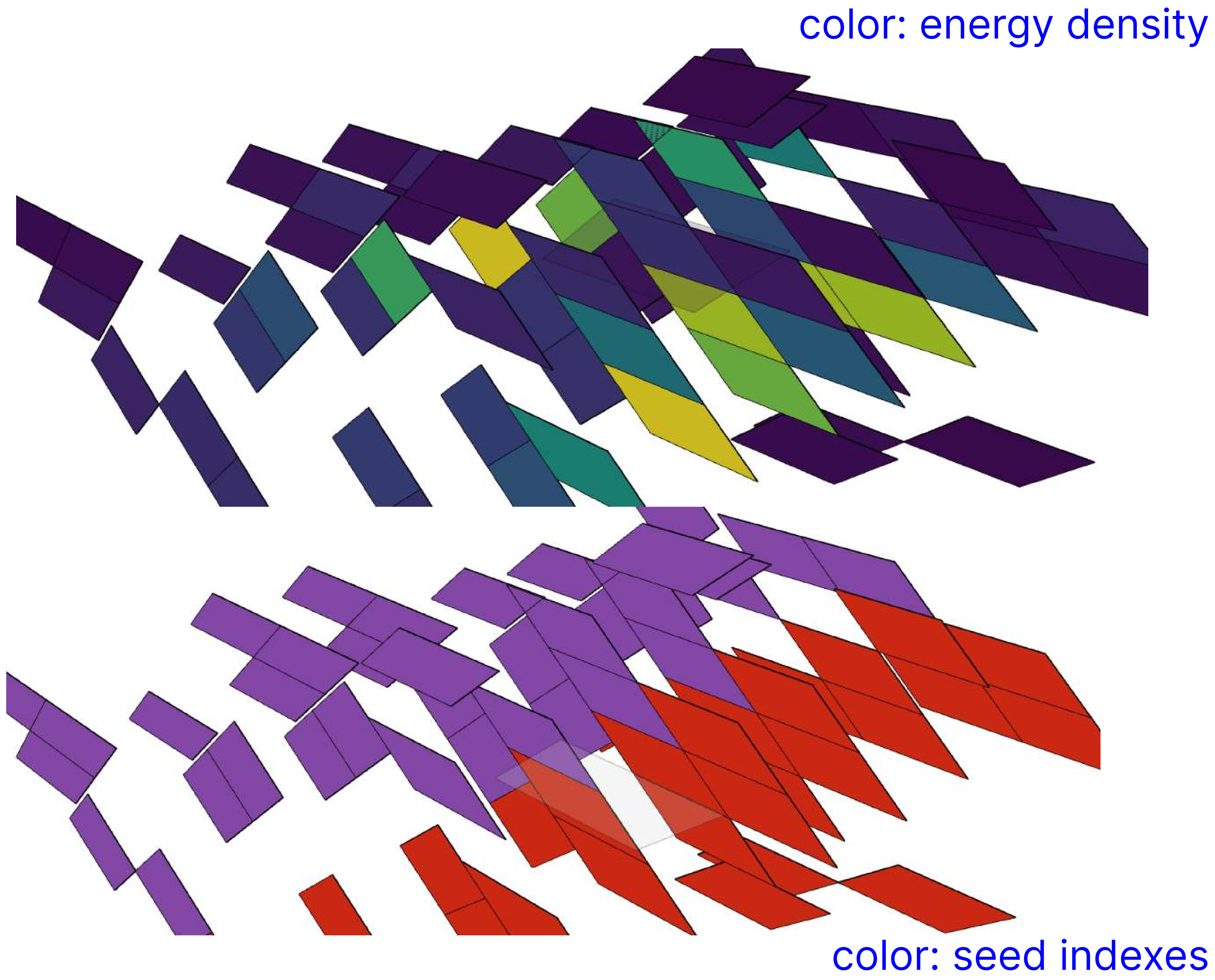


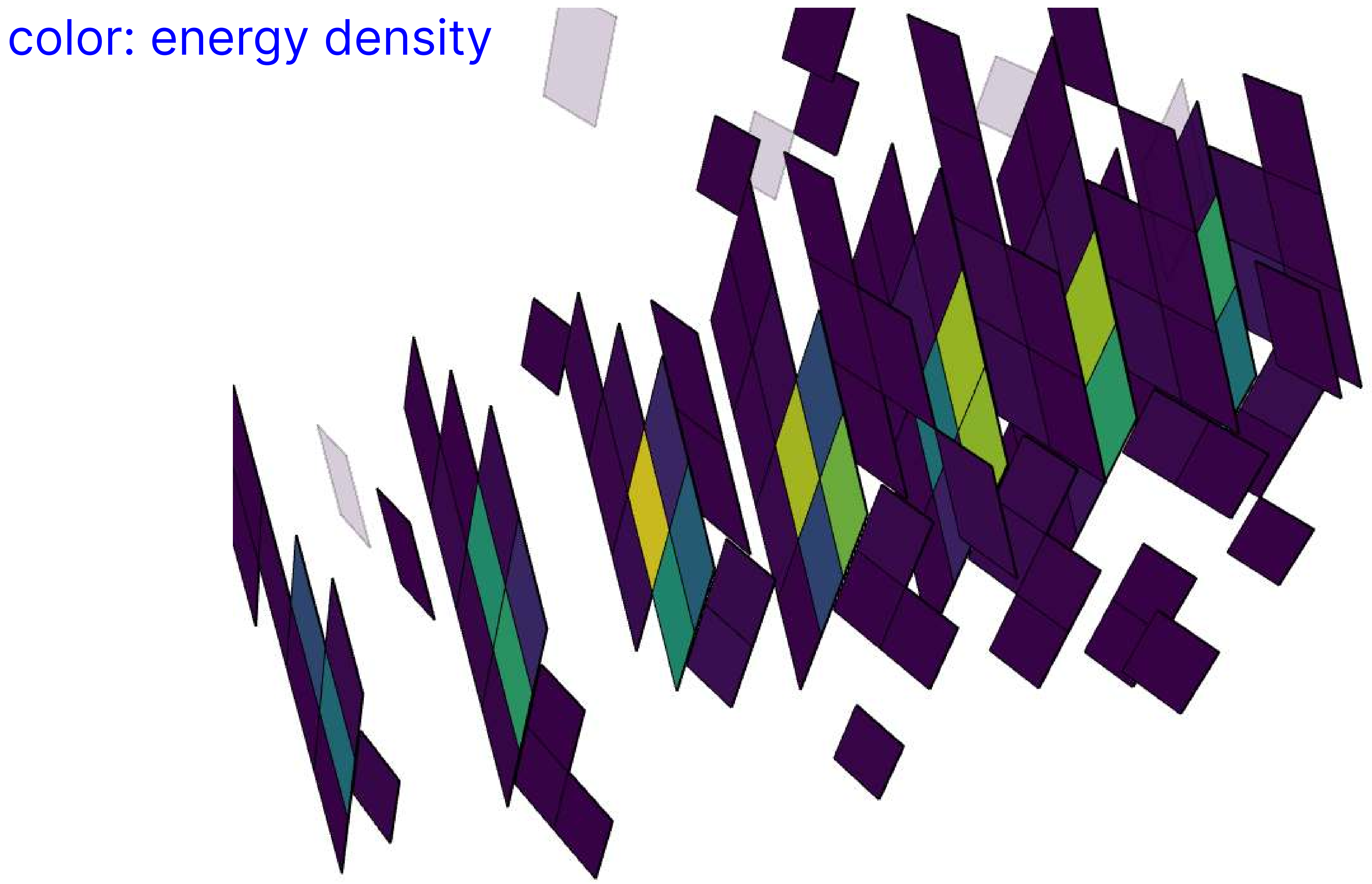
VBF H→γγ, Hits from all layers projected to the same depth

Typical jet:
- ~ 62% charged particles
- ~ 27% photons
- ~ 10% neutral hadrons
- ~ 1% neutrinos

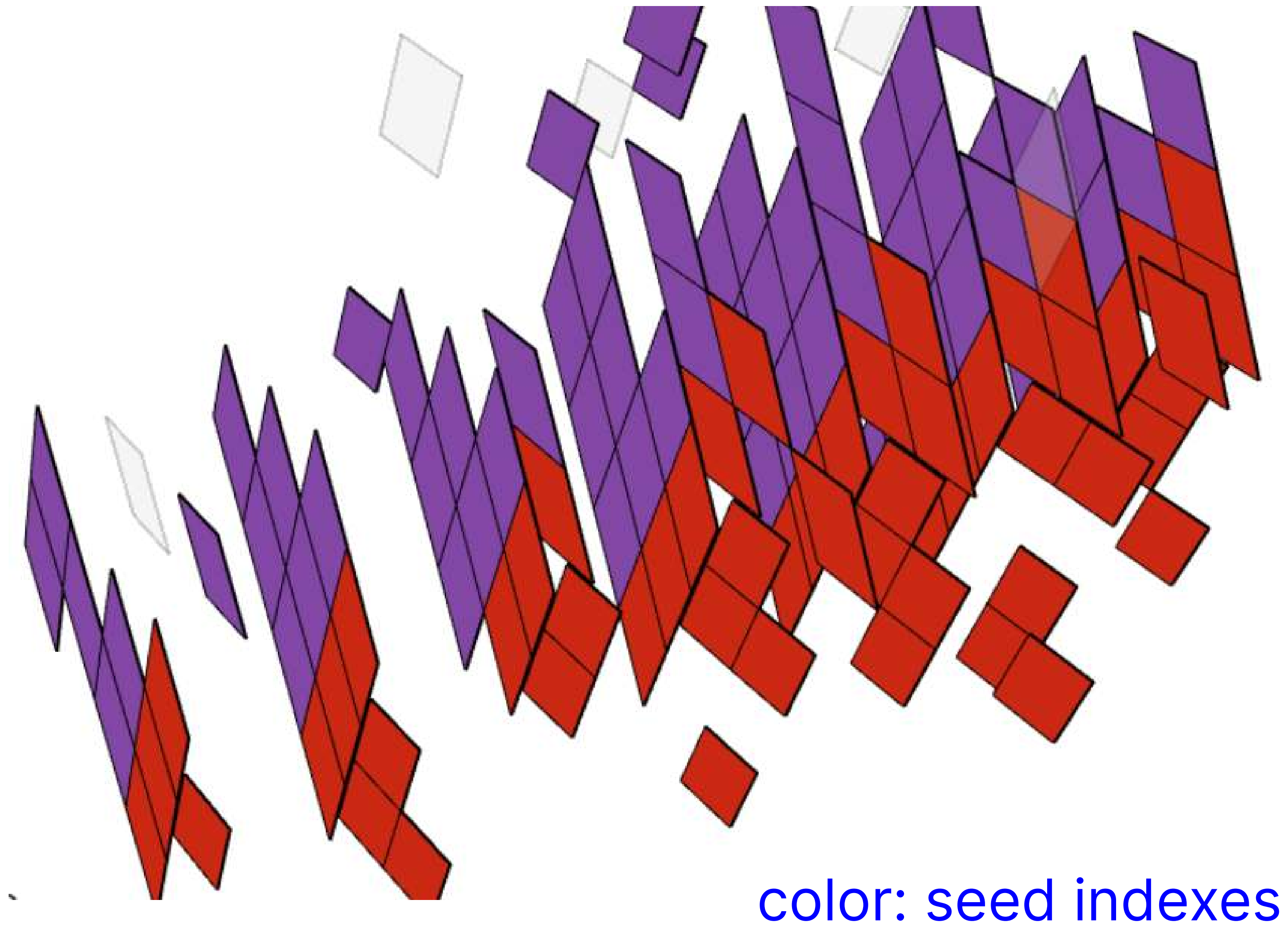
3D Event Displays which originated cluster splits (0PU photons)

this one really has two “peaks”!





most showers are standard, where the split clearly is artificial



Event Displays for 200PU single pion guns