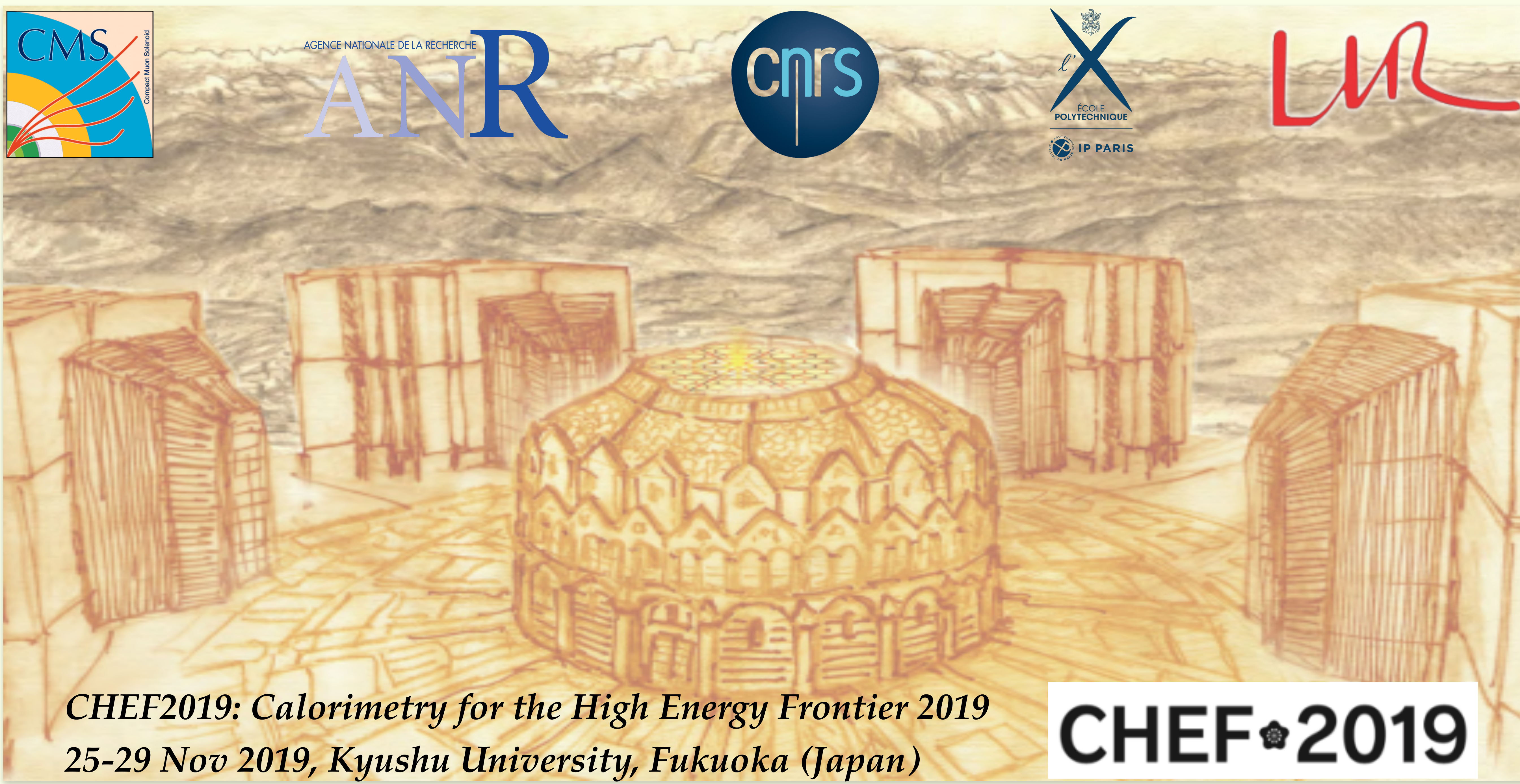

CHEF2019: Calorimetry for the High Energy Frontier 2019

25-29 Nov 2019, Kyushu University, Fukuoka (Japan)

CHEF 2019

Concepts and design of the CMS High Granularity Calorimeter Level 1 Trigger

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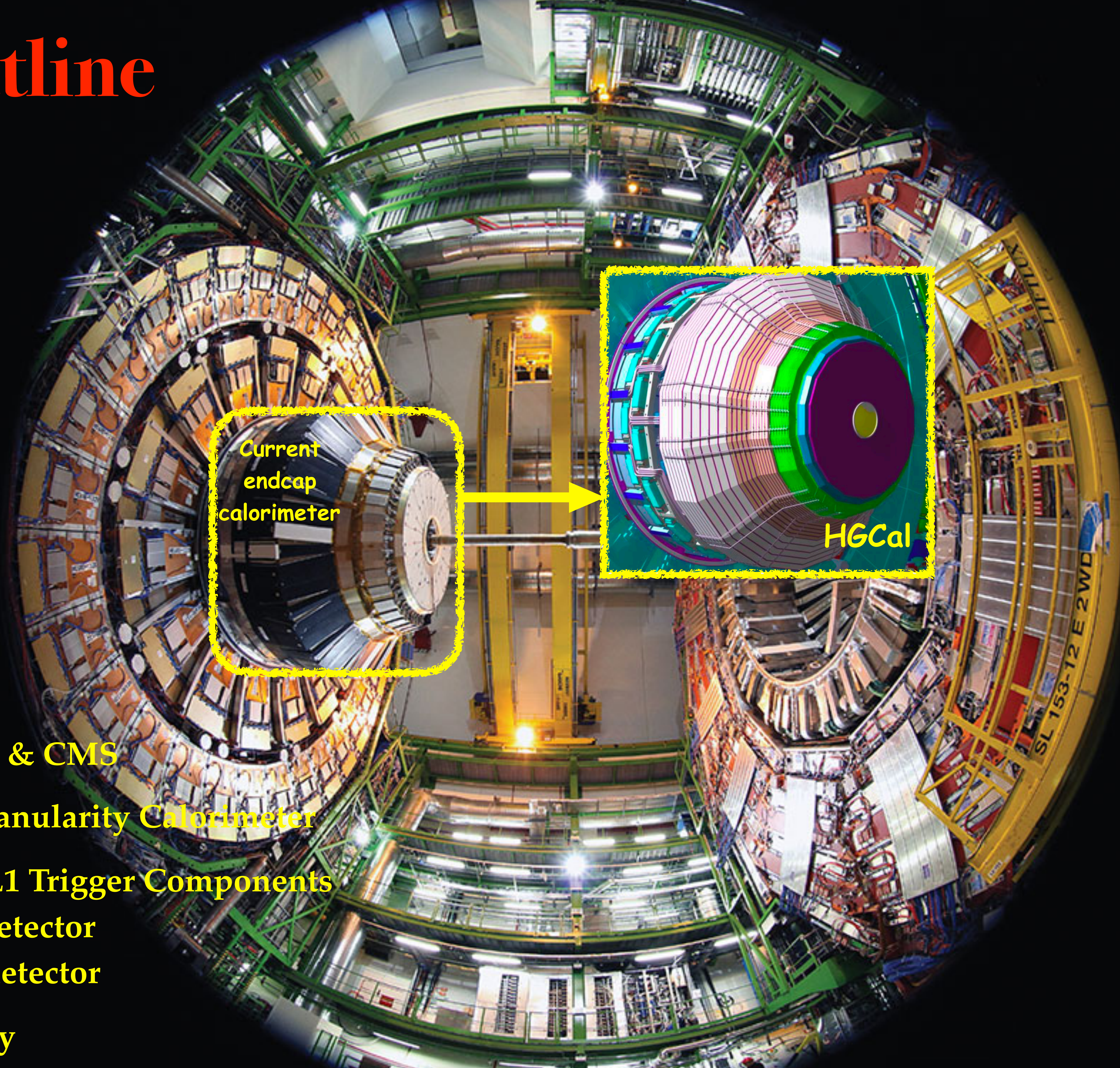
Ecole Polytechnique

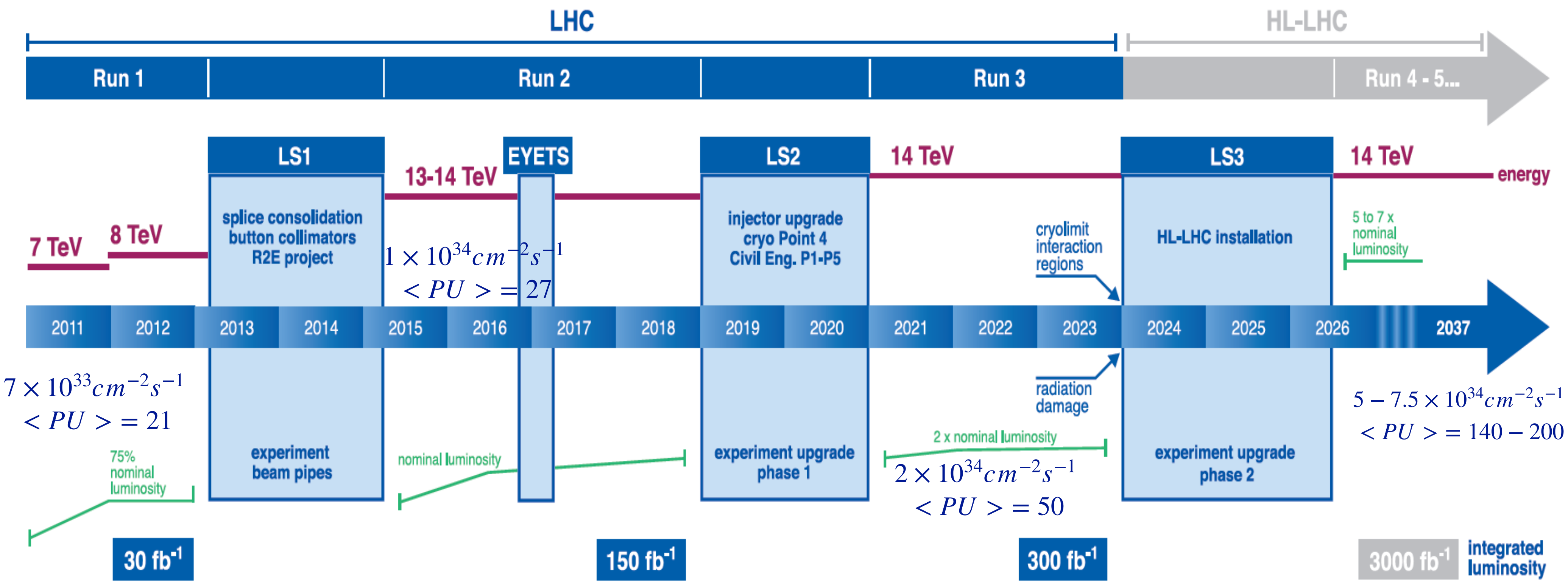
On behalf of the CMS Collaboration

Outline



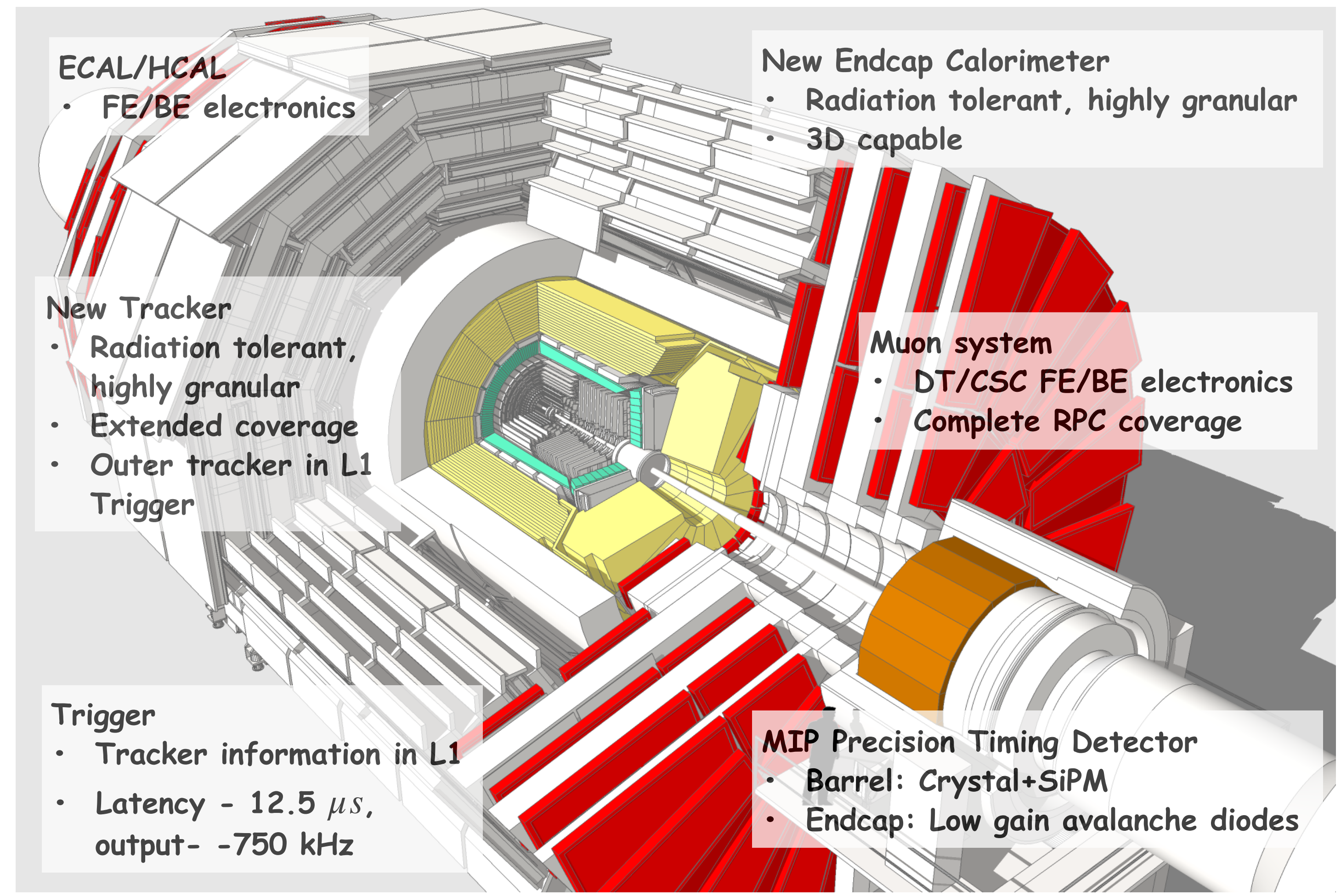
- HL-LHC & CMS
- High Granularity Calorimeter
- HGCal L1 Trigger Components
    - On detector
    - Off detector
- Summary

HL-LHC



With increased instantaneous luminosity & high levels of pile-up at the HL-LHC, CMS requires an upgrade of its endcap calorimeters

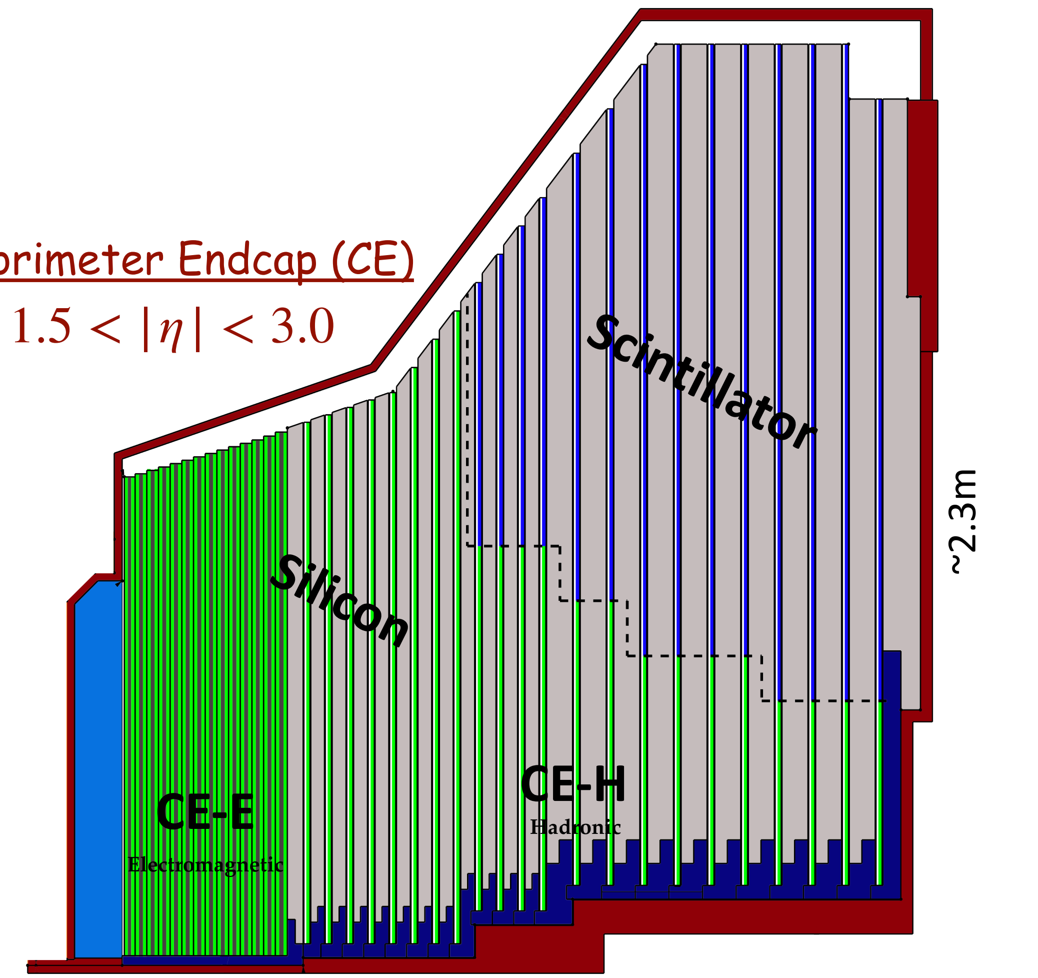
- Radiation dose in the current endcap calorimeters exceeds the design limit
- Increase in PU affects the background rejection performance



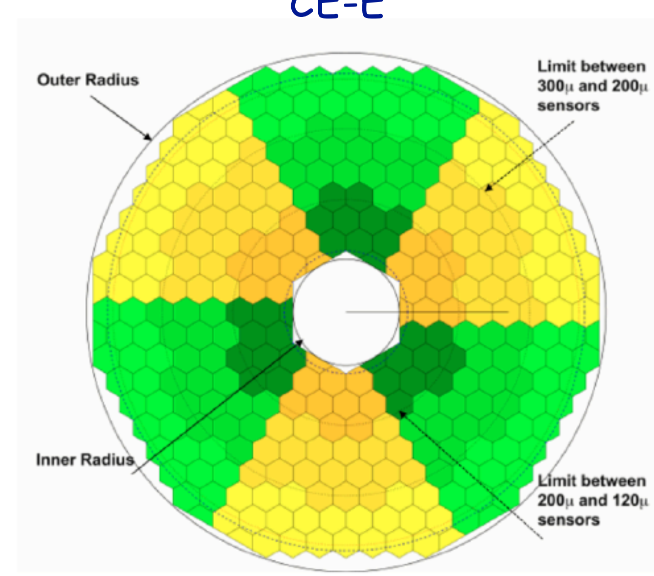
HGCAL for HL-LHC CMS

CMS endcap calorimeters will be replaced by a new **radiation hard** detector (High Granularity Calorimeter (HGCAL))

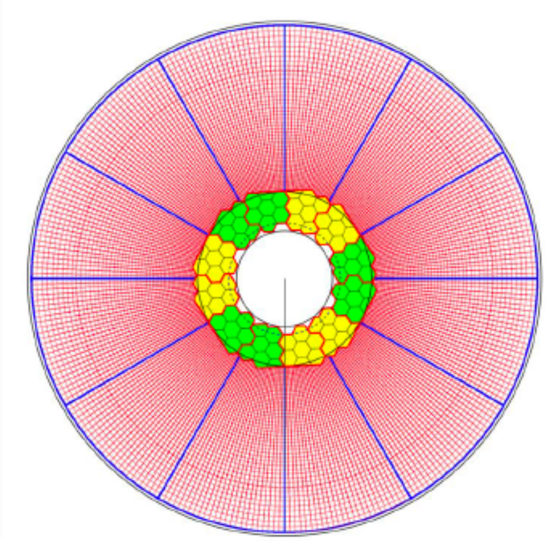
- **Silicon(Si)-only** hexagonal modules (high radiation region) & **Scintilator tiles+SiPM readout** (low radiation region)
  - CE-E: 28 layers (Si), CuW+Cu+Pb absorbers, 25.4X & 1.3λ
  - CE-H: 22 layers (Si+Si-Scint), Steel absorbers, 8.5λ
- 5D imaging calorimeter: energy, x, y, z, t
  - Dense absorbers: lateral shower confinement
  - Fine lateral granularity: two shower separation
  - Fine longitudinal granularity: PU rejection, PID & good energy resolution
  - Good timing resolution: PU energy rejection, vertex identification, particle flow
- HGCAL information to be used for L1 trigger decision



CE-E



CE-H



For details refer to the HGCAL General talk by Felix Sefkow

HGCAL Trigger

Harsh HL-LHC environment: <Pile-up> up to 200, very high occupancy & high radiation doses

Very high granularity: around 6 million Si channels

Upgraded CMS L1 Trigger: Event readout @ 750 kHz & maximum latency ~ 12.5 μs

Trigger capabilities in the forward region will be a key feature of the CMS detector during Phase-2

HGCAL Trigger Primitive Generator (TPG) will generate trigger primitives (TP) relying on its high granularity

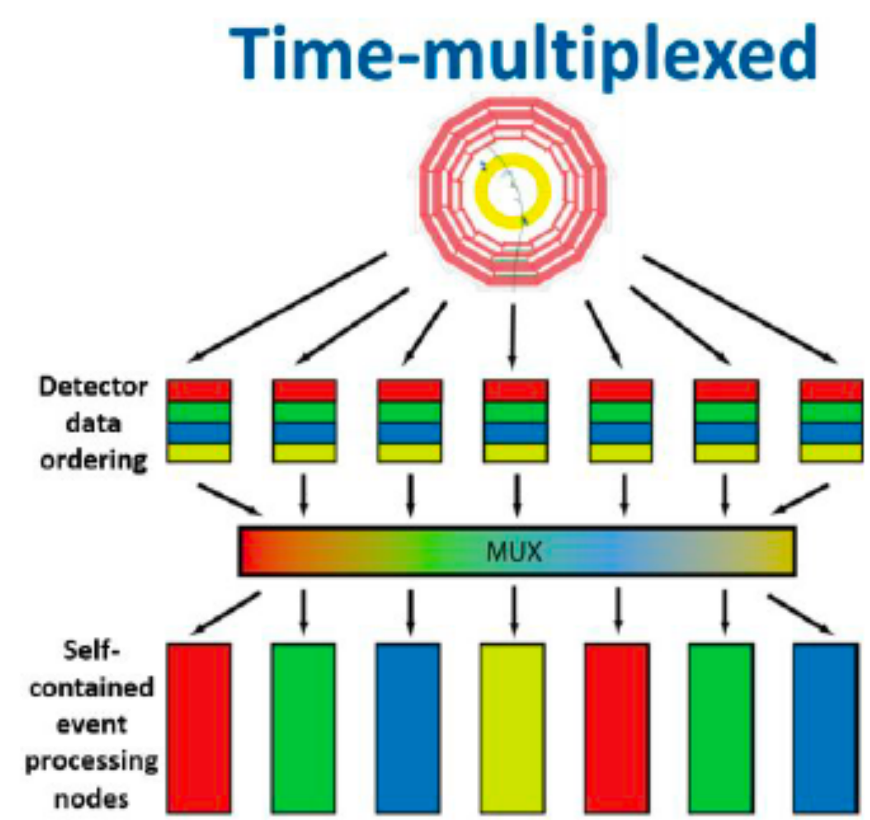
- TP will be a set of 3D clusters for each bunch crossing
- 3D clusters are combined with TPs from other detectors in the central Level 1 trigger to implement particle flow algorithms

HGCAL L1 trigger will have a time multiplexing architecture

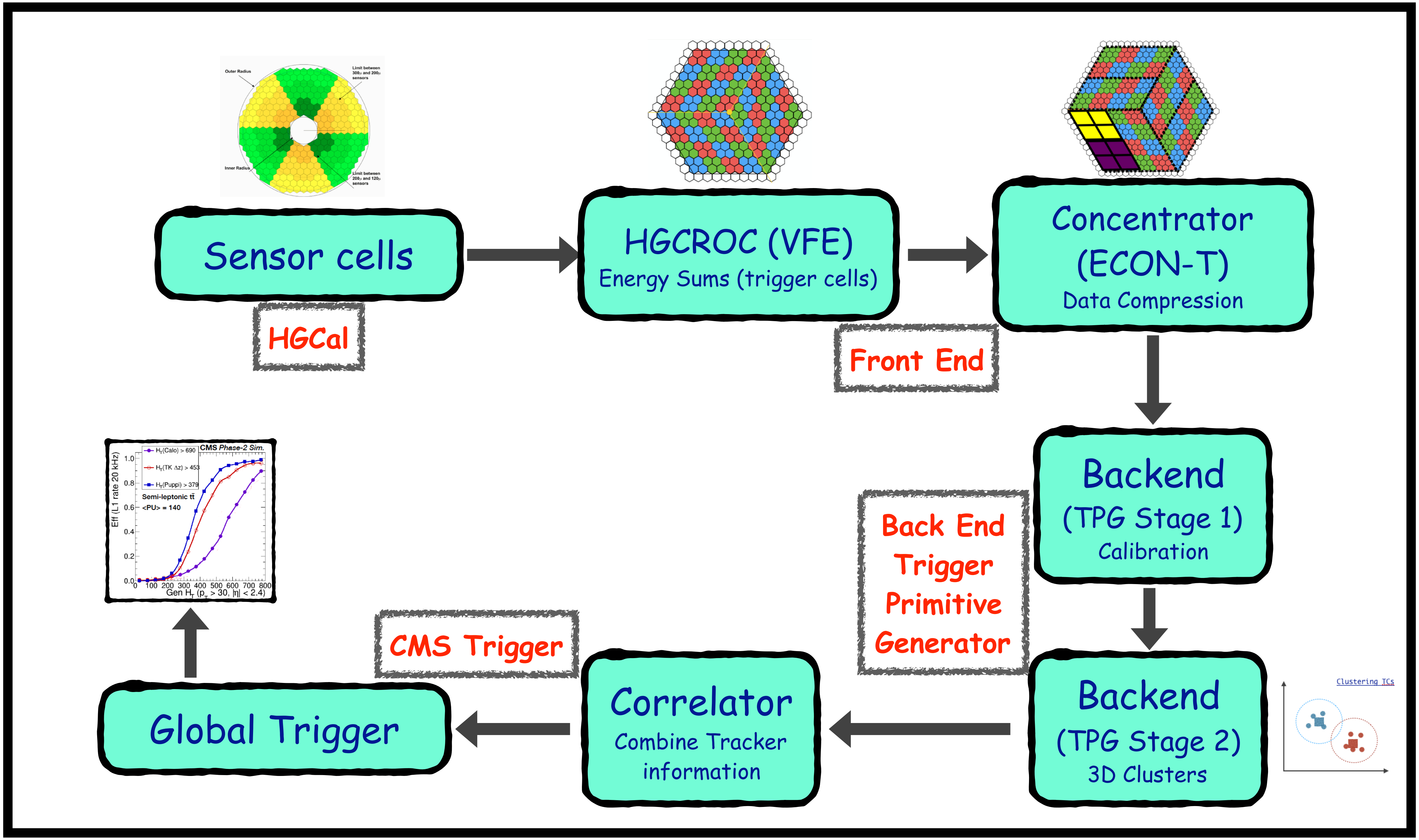
- Helps to collect data from a single bunch crossing into a single processing unit

Radiation hard electronics

- Radiation tolerance up to 2 MGy
  10^{16} 1MeV-equivalent neutrons/cm^2



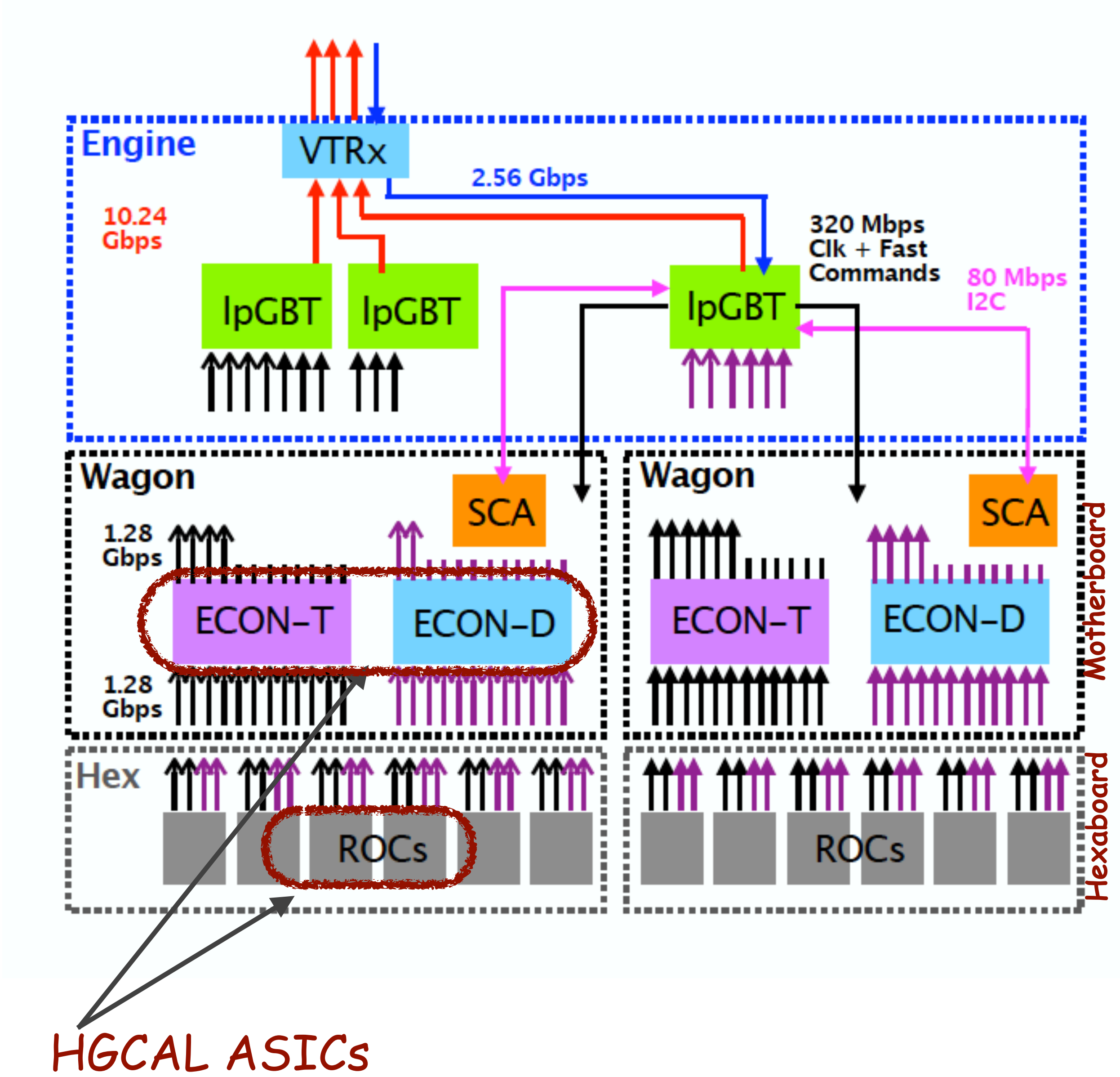
HGCAL Trigger Chain



On Detector Electronics

The front-end (FE)/ on detector electronics

- Measures & digitizes the charge from the Si sensor pads & the SiPMs
- Transmits digitized data to the off detector electronics (back-end (BE))
- Computes digital sums of neighbouring cells transmitted to the BE to build trigger cells
- Module PCBs (Hexaboard)
  - Very FE ASICs wirebonded to Si-sensors
  - Sends bunch crossing synchronous data to concentrator
- Motherboards host the concentrator ASICs & the transceivers to the off-detector electronics
  - Concentrator ASICs:
    - **ECON-T (trigger)**: selects trigger data before transmitting to the BE
    - **ECON-D (DAQ)**: sends zero suppressed fine granularity data to the DAQ
- Similar FE electronics for the readout of the SiPMs



For details about HGCROC refer to talk by Damien Thienpont

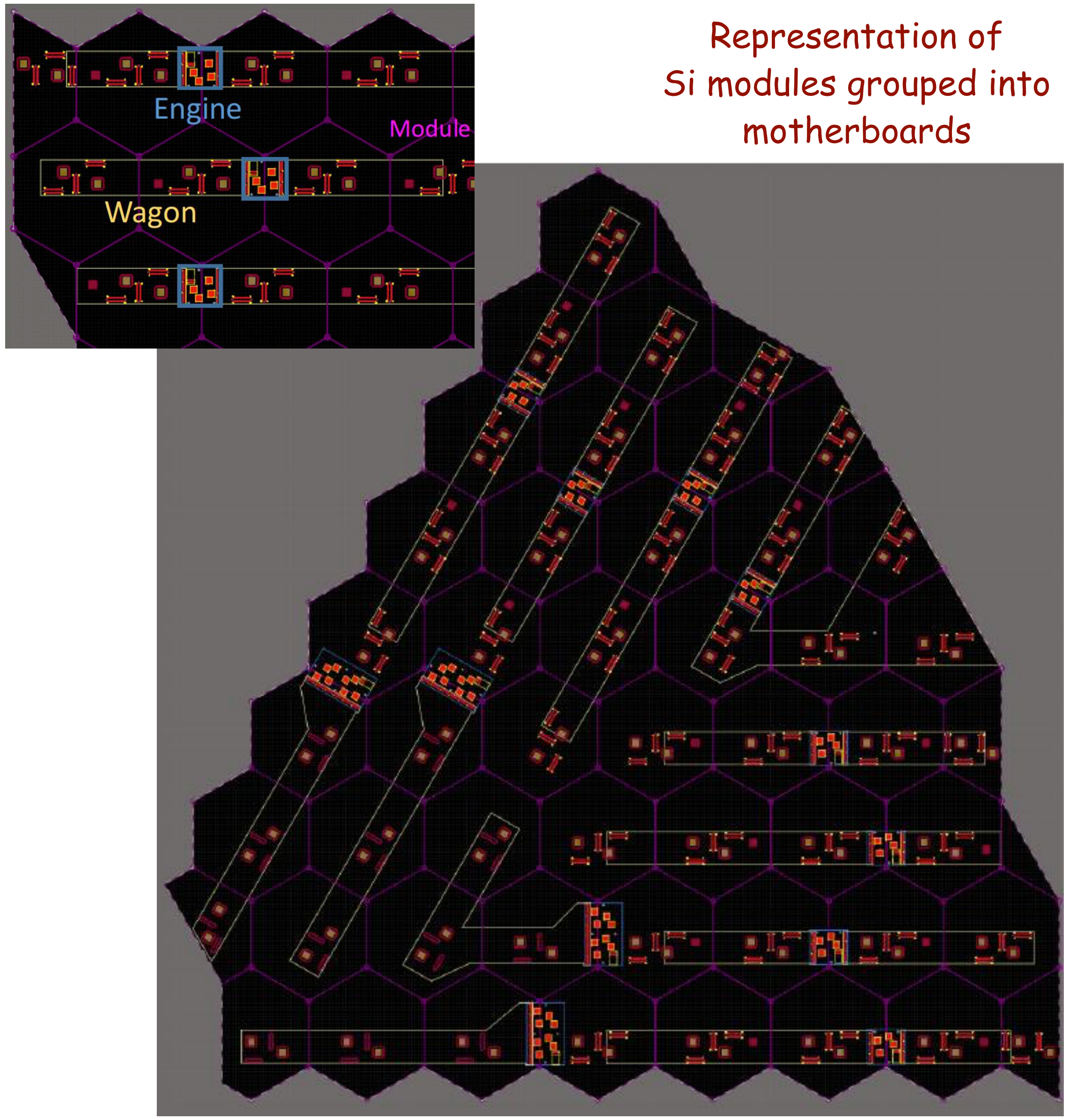
ECON-T

Concentrator reduces volume of trigger data to sent to off detector trigger electronics for clustering & further processing

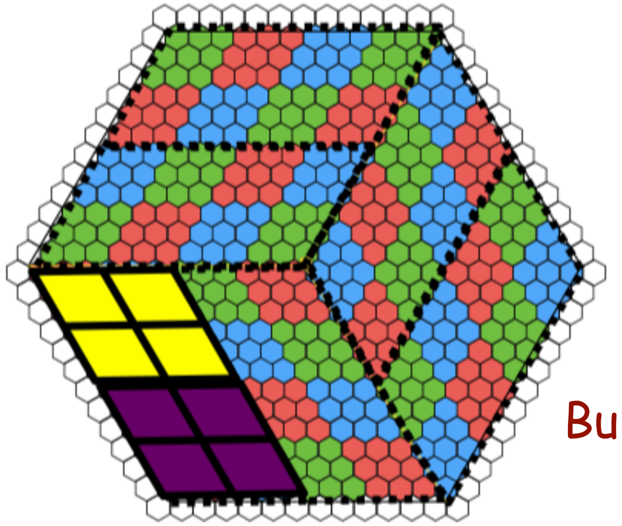
- Data rates: 40 MHz of selected/compressed data
- Basic architecture:
    - 12×1.28 Gpbs in & 14×1.28 Gbps out (for both ECON-T & ECON-D)
        - Replacing the 36×1.28 Gpbs in & 3×10.24 Gbps out architecture
    - Allows more unified ECON architectures, less design time & simpler

ECON-T Selection/Compression algorithms (programmable)

- Variable format:
    - **Threshold (Primary algorithm)** - selects trigger cells above a certain threshold (threshold defined in MIP_T)
- Fixed format:
    - **Best Choice** (sorted by p_T) - select N highest MIP_T trigger cells
    - **Super Trigger Cell** (STC) - readout large areas of trigger cells (super trigger cells (STC)) with reduced transverse granularity



Representation of Si modules grouped into motherboards

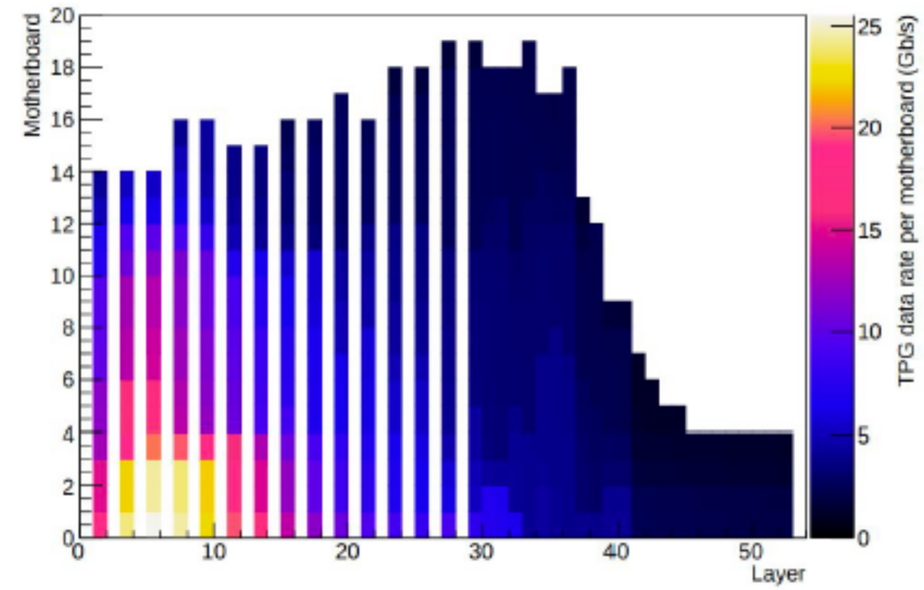


Building STCs

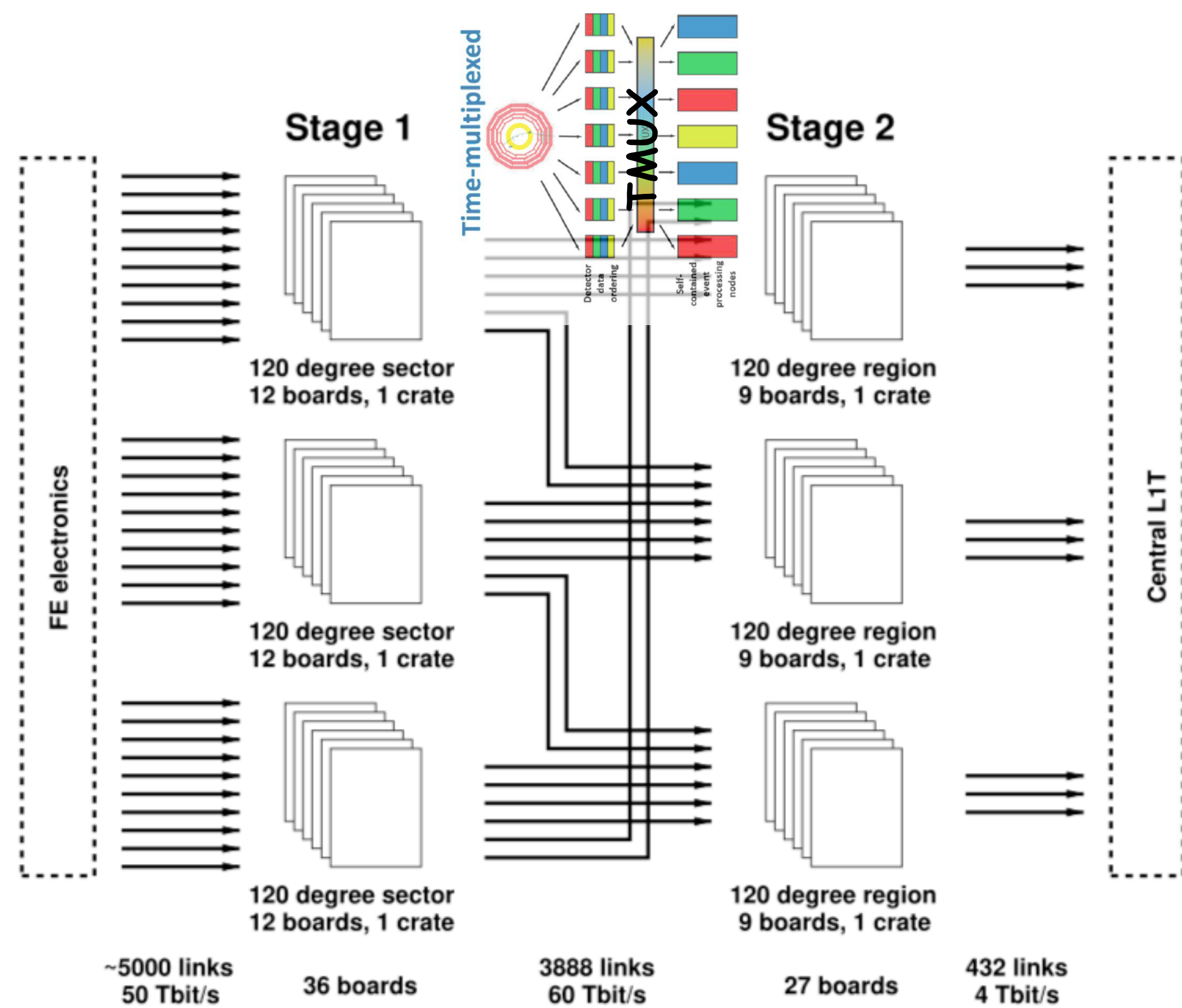
Off Detector Electronics

TPG receives FE data delivered on radiation hard low power gigabit transceiver (lpGBT) links

- O(10K) links @ 10Gbps from the FE to TPG
- Bandwidth challenge:
  - Financial allocation to trigger readout insufficient to read out all trigger cells, or even all hits
  - Need to cut down rate while retaining as much information as possible
    - Only half (alternate) electromagnetic layers have a trigger readout
    - Data readout at coarser granularity (trigger cells)
    - Threshold applied in FE to limit number of trigger cells
- Two Stage design
  - Time multiplexed architecture
  - Stage 2: every FPGA receives data from 120^o detector region (TMUX period = 18 BX)
  - Total latency ~ 5 μs
    - With ~ 2.3 μs needed for FE & transmission
    - Required latency of processing in 'Stages 1 + 2' $\leq$ 2.7 μs



Trigger raw data rates data rates (Gb/s) as function of layer and motherboard number

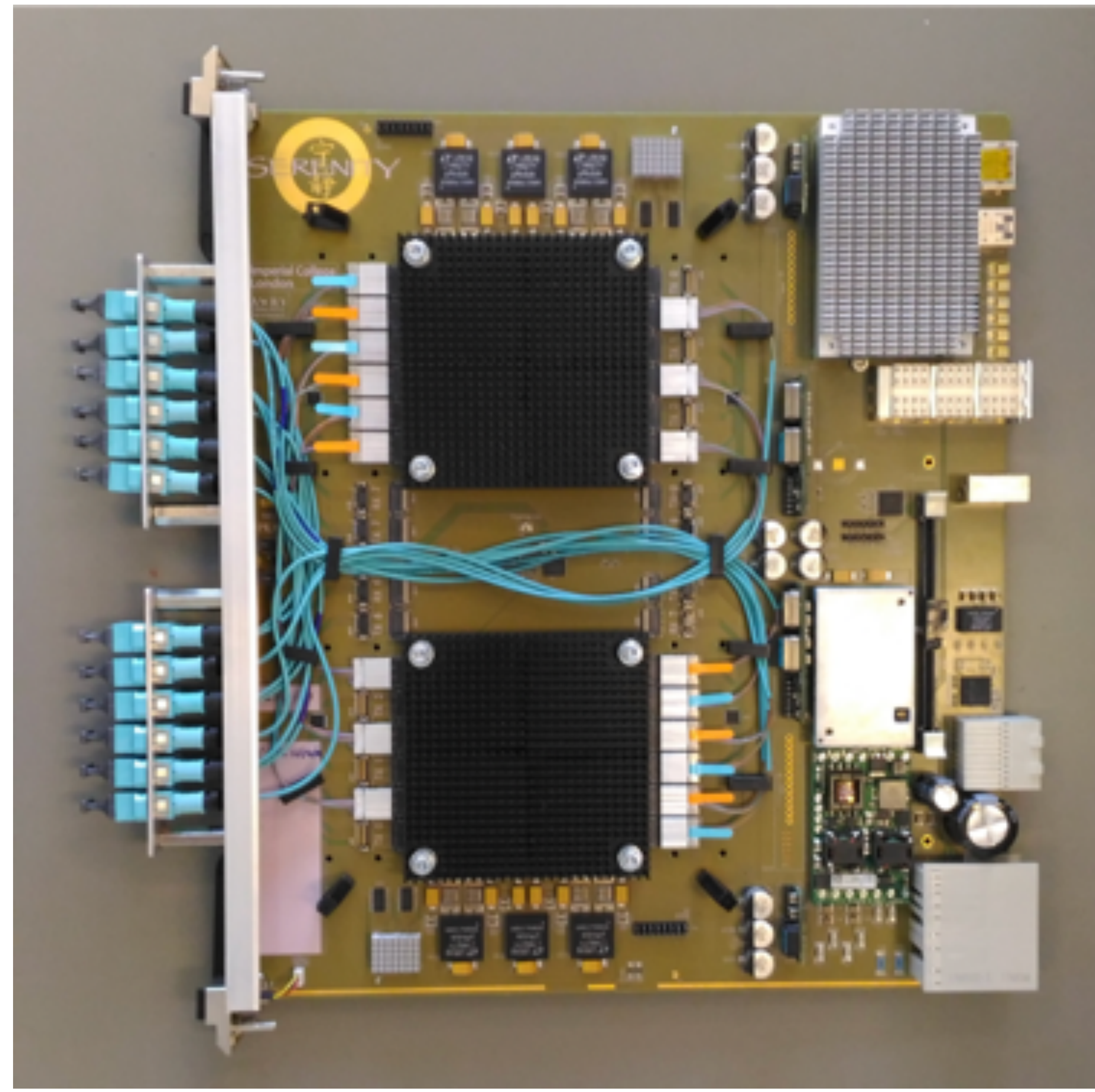


For one endcap side

Off Detector Hardware

General-purpose Serenity ATCA platform

- Generic motherboard common to other subsystems
- HGCAL specific exchangeable FPGAs on daughter boards (versatile)
- DAQ & TPG will use different FPGAs for each baseboard (cost efficient)
- Up to 72 in and 72 out links (link speed up to 25 Gbps)



TPG Hardware

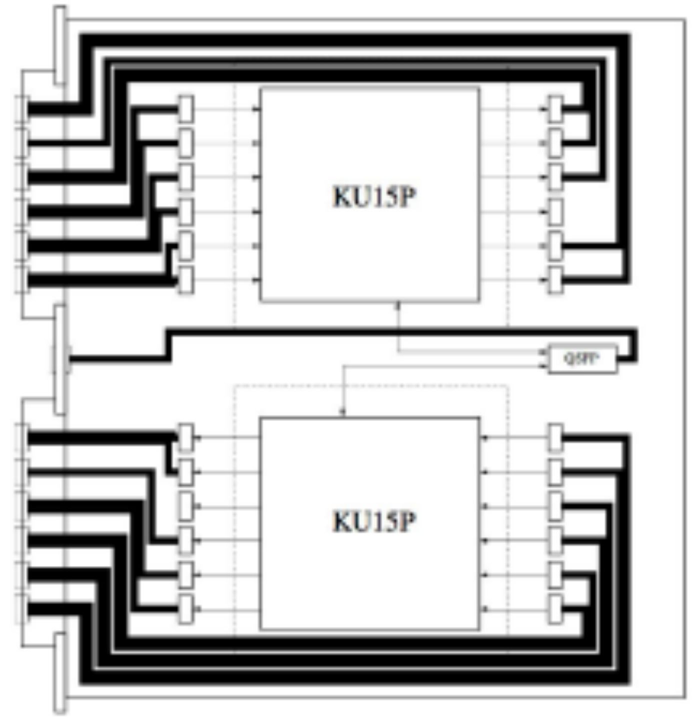
Different flavours of 'Serenity boards' planned for each TPG stage:

TPG Stage 1

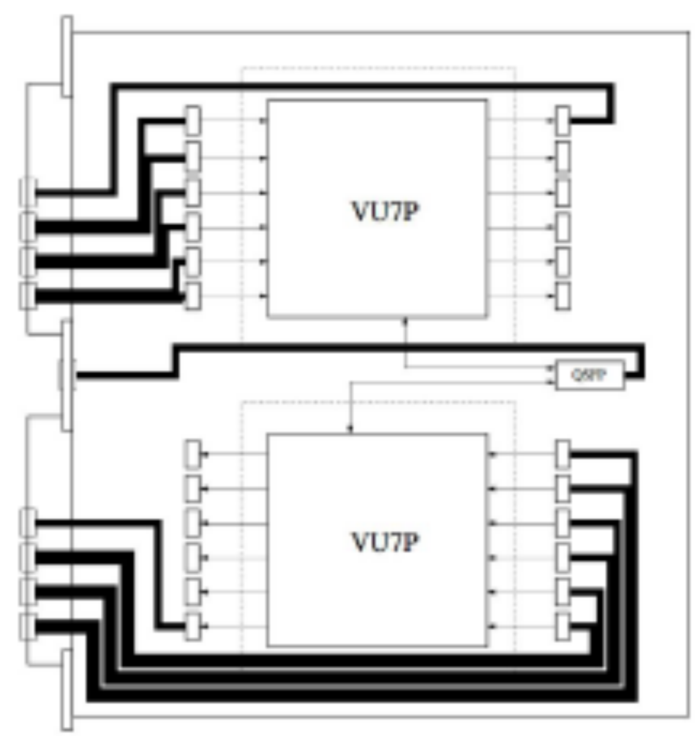
- Receives data from FE using lpGBT links
- Xilinx KU15P FPGAs daughter cards (DC)
- Calibration is applied
- TMUX is implemented (x18 BX)

TPG Stage 2

- Xilinx VU7P FPGAs DC
- Each FPGA collects and processes data from a 120° detector sector for every layer.
- Each processing FPGA deals with data from the same BX for the whole TMUX period of 18 BX (450 ns)
- Collecting all the data into a single FPGA is a design choice made in order to keep the system flexible for possible future algorithm evolution
- Main goal is to generate the trigger primitives from the calibrated high granularity trigger cells



Stage 1



Stage 2

TPG: Current Baseline Algorithm

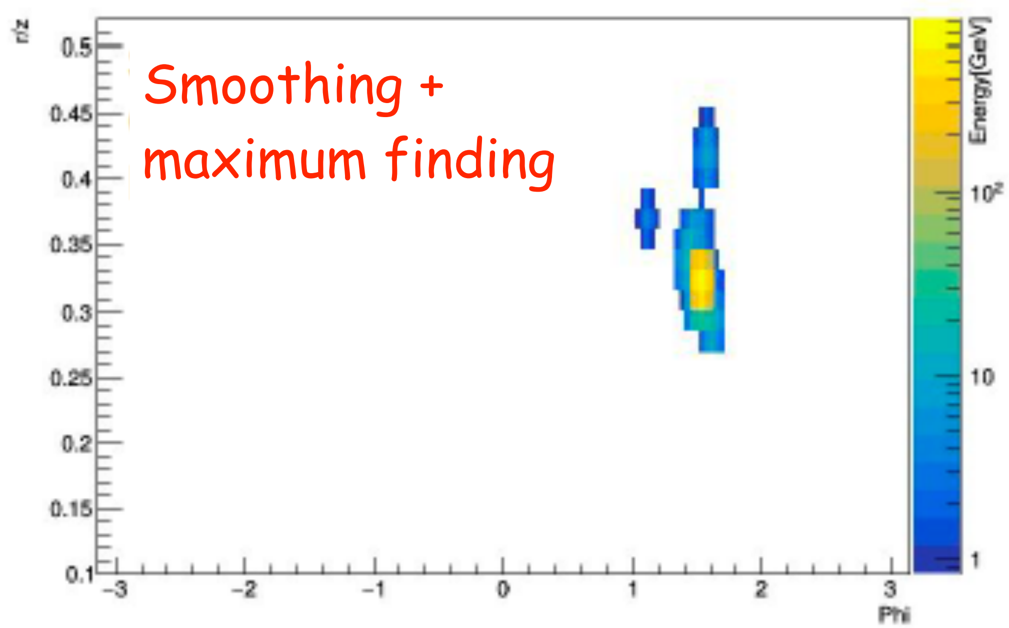
Stage 1:

- Implement energy calibration & convert to transverse energy units

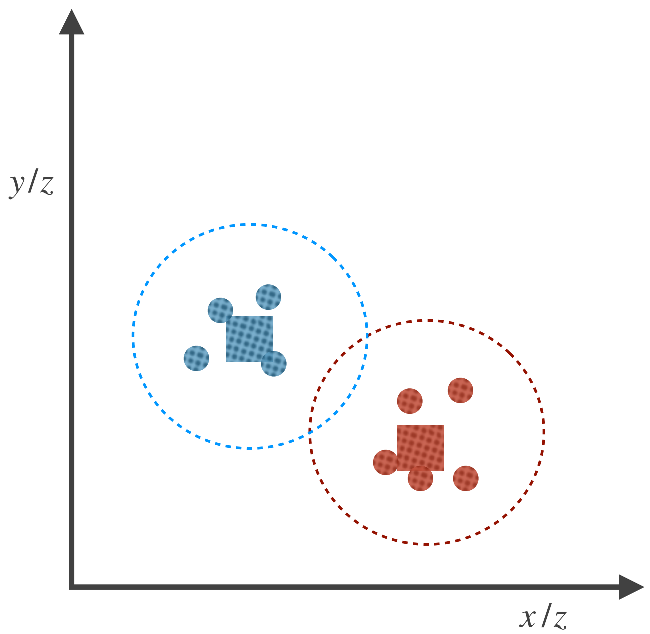
Stage 2: (3D clustering)

- Seeding: Find energy weighted maxima from a 2D histogram (binned in $r/z, \phi$ coordinates) (with seed above a certain threshold)
- 3D clustering: Cluster triggers cells around each seed within a maximum scaled distance (programmable) & use it to determine properties of the 3D cluster (position, energy & shape variables)

Seeding



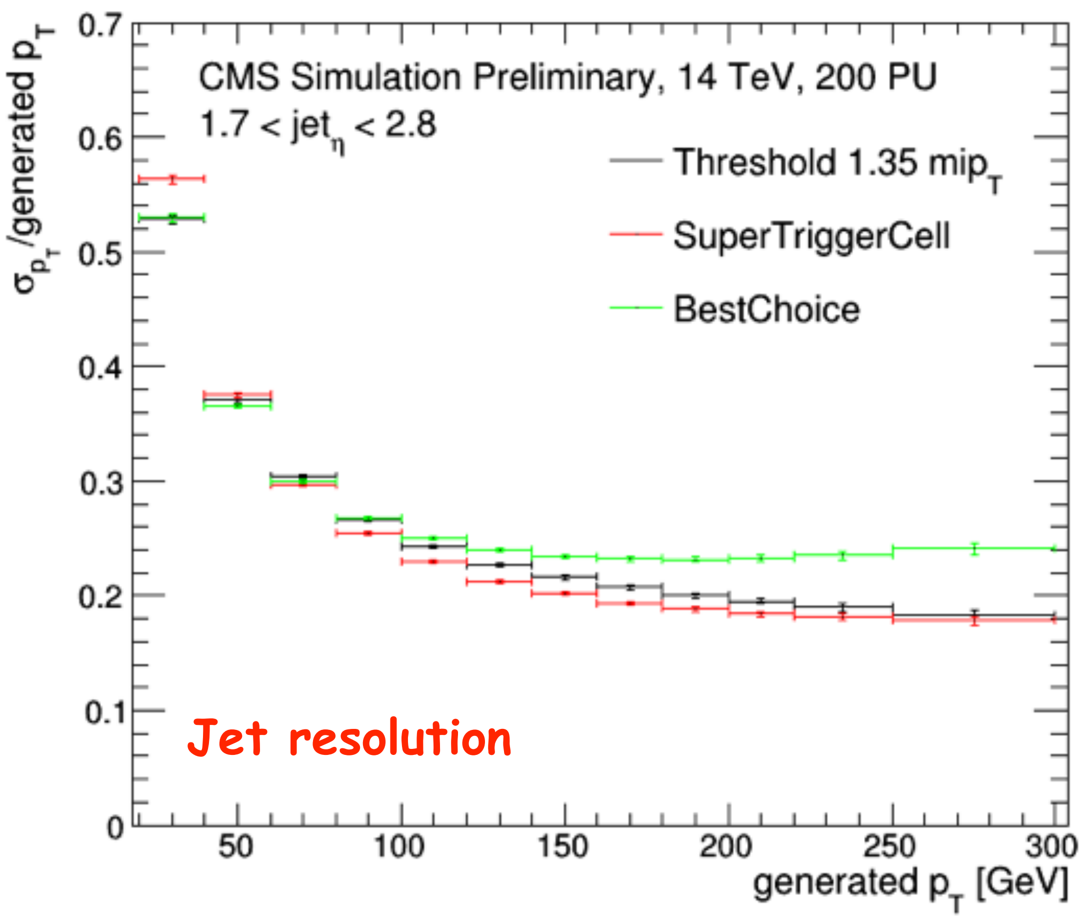
Clustering TCs

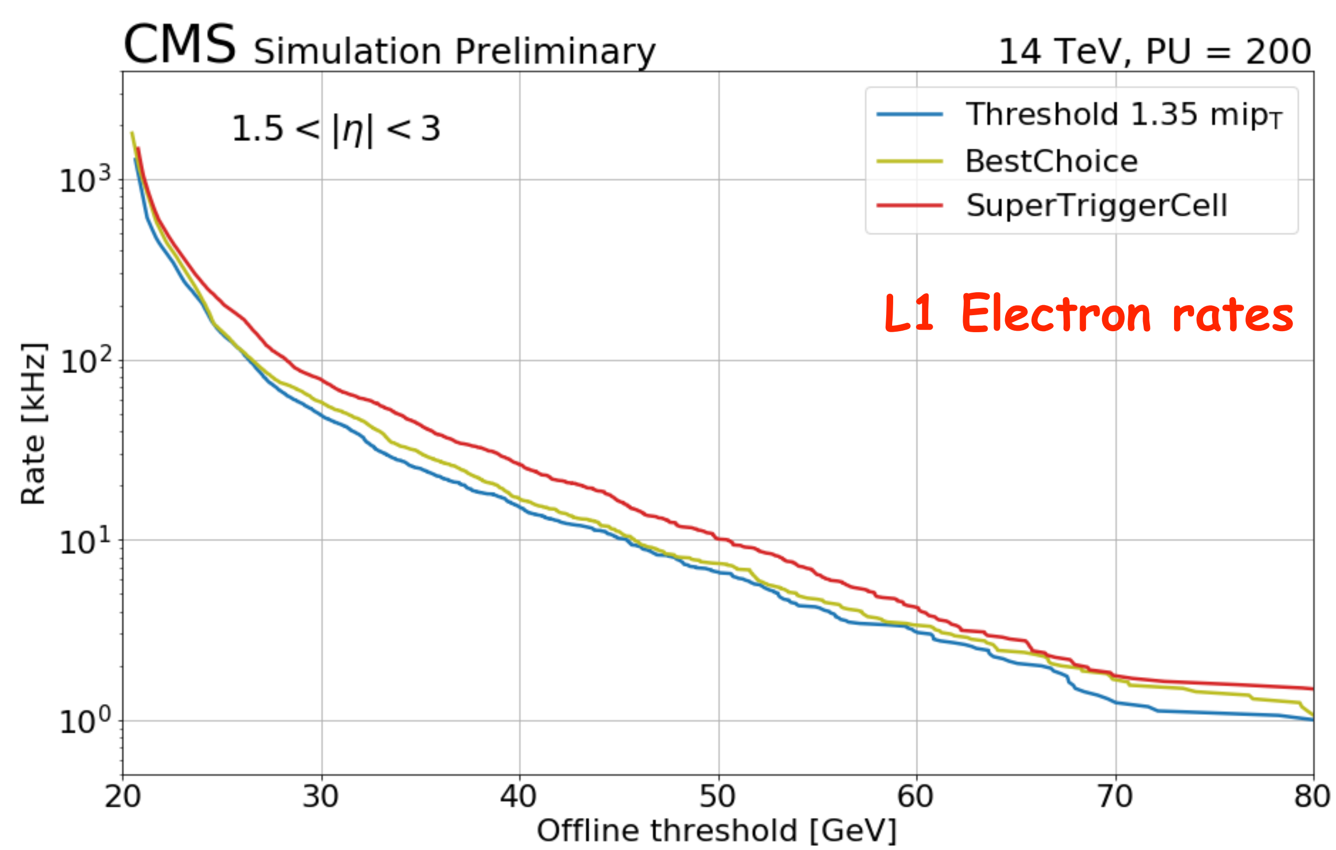


Physics Object Performance

Impact of FE data selection algorithms on the performance of physics objects (with 3D clustering optimized according to the FE option)

- Choice of FE algorithm affects jet resolution performance at higher p_T values
- Threshold option tends to give the lowest egamma L1 rates at 200 PU





Since TDR

	TDR	*Present*
ECON-T Architecture	36 x 1.28 Gbps in 10 x 10.24 Gbps out	12 x 1.28 Gbps in 14 x 1.28 Gbps out
ECON-T Algorithm	Not well defined	Well defined selection algorithms (Threshold (primary))
TPG Hardware	Generic ATCA based platform (conceptual)	Hardware well defined ATCA based Serenity boards
TPG Algorithm	Stage 1 - 2D clusters (per layer) Stage 2 - 3D clusters	Stage 1 - Calibration + TMUX Stage 2 - 3D Clustering

Summary

Lots of developments for HGCAL level-1 trigger since the release of the TDR in 2017

CMS HGCAL trigger is a challenging task:

- Due to high luminosity, high radiation doses & pileup, increase in detector granularity & a very high number of channels

Immense studies for the trigger path & algorithms are being performed

- Performance of physics objects (energy resolution, shower shapes, discrimination, rates, etc.) based on each of the concentrator algorithms & clustering algorithm
- Requires balance between performance & usage of resources

Back Up