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Pileup Mitigation at CMS Level-1 Trigger for the HL-LHC

Abhijeet Ghodgaonkar[a], Pranav Keshav Govekar[a], Philip Coleman Harris[b], Kajari Mazumdar[a], Mandakini Ravindra Patil[a], Giovanni Petrucciani[c], Aravind Thacahayath Sugunan[a]

on behalf of

CMS Collaboration, CERN-LHC

[a] Tata Institute of Fundamental Research, Mumbai, [b] Massachusetts Institute of Technology. US, [c] CERN, Switzerland.

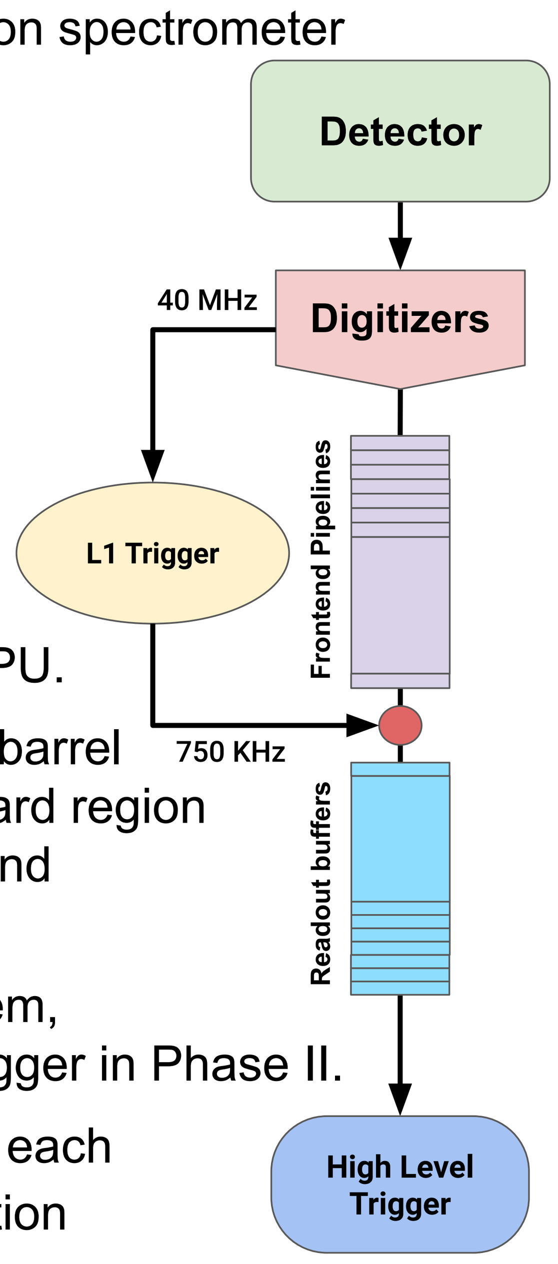
Abstract

The high luminosity operation of the LHC will deliver collisions with a flux of about 10 times higher than the original design value. This poses a big challenge for trigger and data acquisition in real-time due to nearly 200 overlapping collisions, called pile up. The CMS experiment will revamp its trigger structure as part of the required upgrade, to have the tracking information and more granular calorimeter data available for the first layer (Level 1, L1) of the trigger deployed in custom hardware including high-end FPGAs, SoM etc.. The correlator units at L1 will further process the information from each sub-detector to make a global event description through the particle flow (PF) approach. Disentanglement of the contributions from the pileup particles from those of interesting physics processes is achieved by implementing the Pile-Up Per Particle Identification (PUPPI) algorithm at L1. We present the strategy for implementation of PUPPI and PF at the L1, focusing on the Hadron Forward Calorimeter detector of CMS.

HL-LHC Challenges

- Upto about 200 inelastic p-p collisions within a single bunch crossing.
- Interesting scattering information recorded in the detector along with these less energetic, unwanted, secondary collisions → **pile up (PU).**
- Extensive upgrade of the experiments for HL-LHC operation essential for maximising physics potential and sensitivity → **Phase 2 upgrade.**
- Challenge of event selection in real time : maximal mitigation of **PU** contribution for **efficient *Trigger*** decision.
- CMS Trigger architecture: 2-tier system to reject or accept event information for further scrutiny at a later stage.

Level 1 Trigger at HL-LHC

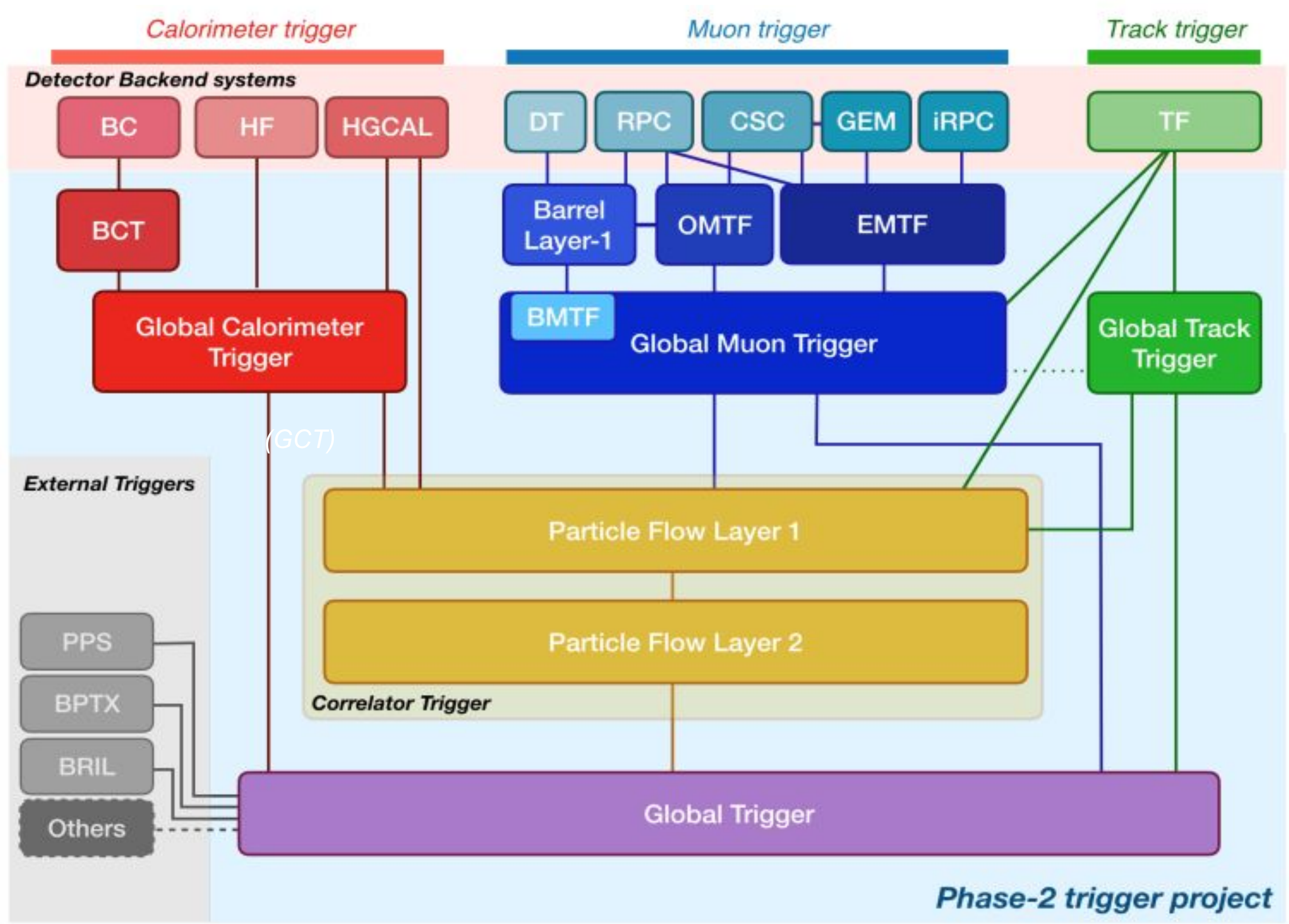


- Uses information from Tracker, Calorimeter, Muon spectrometer subsystems of CMS detector.
- Trigger rate reduction: 40 MHz → 750 kHz.
- Custom hardware with high end FPGAs, SoMs
  - Processing latency 12.5 μs .
- **L1 trigger architecture:**
  - **Tracker:** Utilises track stubs for $p_T > 2$ GeV and $|\eta| < 2.4$.
    - Provides vertexing capability.
    - Helps to identify charged particles from PU.
  - **Calorimeter :** Single crystal readout for the barrel calorimeter and enhanced coverage of forward region by the HGCAL looking for electromagnetic and hadronic energy deposits.
  - **Muon :** charged track in outermost subsystem,
    - single hit information available for the trigger in Phase II.
  - **Correlator Layer:** Collects information from each subsystems and builds global event description
    - Links tracks to calorimeter clusters.
    - Implements Particle Flow reconstruction.
    - Applies the **Pile-Up Per Particle Identification (PUPPI)** algorithm to mitigate pile-up effects.

High Level Trigger (HLT): CPU farms + GPUs

- Full reconstruction of events à la offline.
- Rate reduction: 750 kHz → 7 kHz.

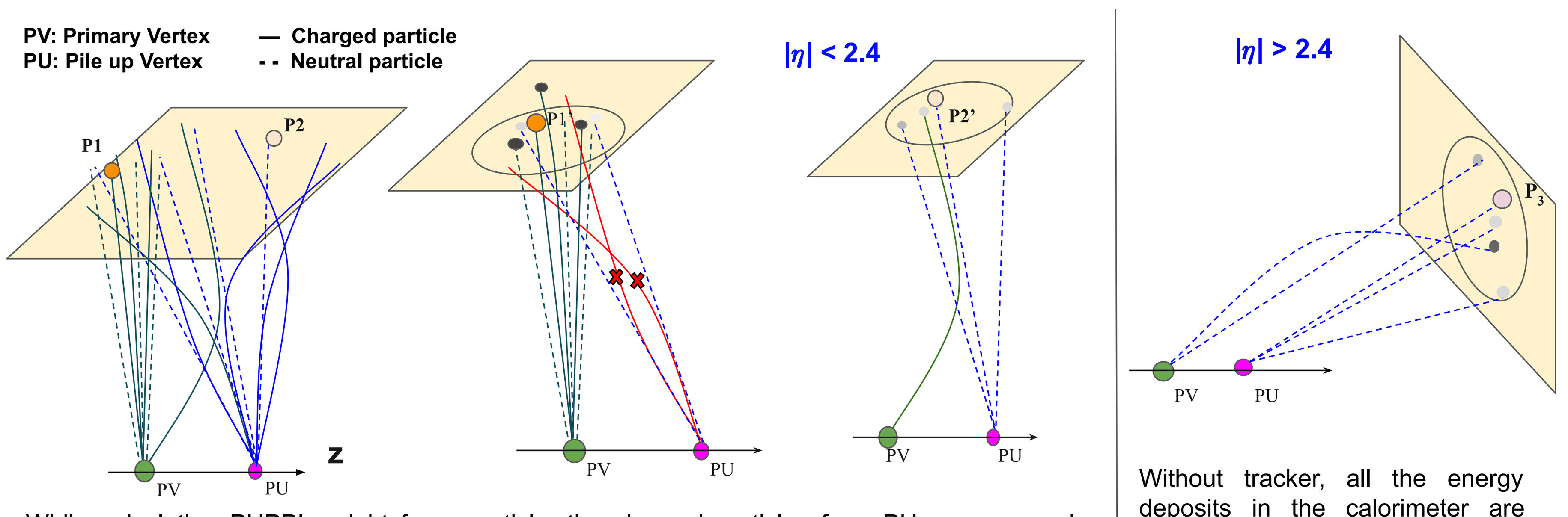
Schematic overview of CMS L1 Trigger at HL-LHC



The Tracker and HGCAL subsystems are new addition to the inputs of Level 1 Trigger of CMS at HL-LHC. The Correlator layer collects and links the processed information form each subsystem to make a global description of each detected particles.

PUPPI Algorithm

- Utilizes both global and local information in the event before clustering.
- Each particle (charged and neutral) assigned a weight dependent on the density of other particles in its neighbourhood defined by a distance in η-ϕ space, $\Delta R < 0.3$.
- Contribution of a neighbouring particle of transverse momentum p_T to the weight roughly proportional to $p_T^2/(\Delta R)^2$.
- Parameters for the PUPPI algorithm are also optimized as a function of η .

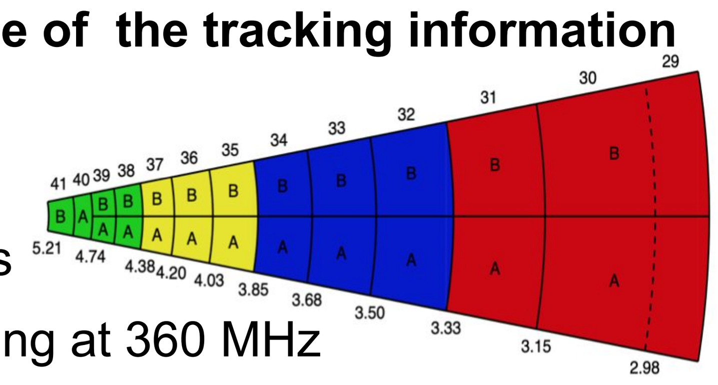


While calculating PUPPI weight for a particle, the charged particles from PU are removed (using vertexing information). Particles from PU generally has lower p_T and have a diffused profile, making their PUPPI weights smaller.

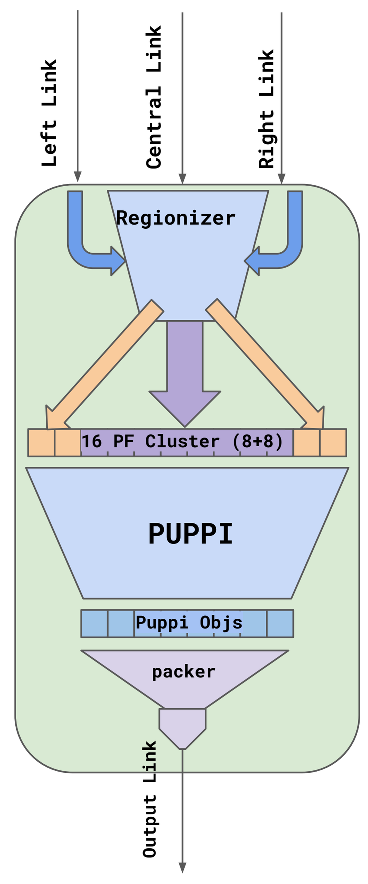
Without tracker, all the energy deposits in the calorimeter are treated as neutral particles and the PUPPI weights are calculated.

PUPPI *for* Hadron Forward (HF) Calorimeter

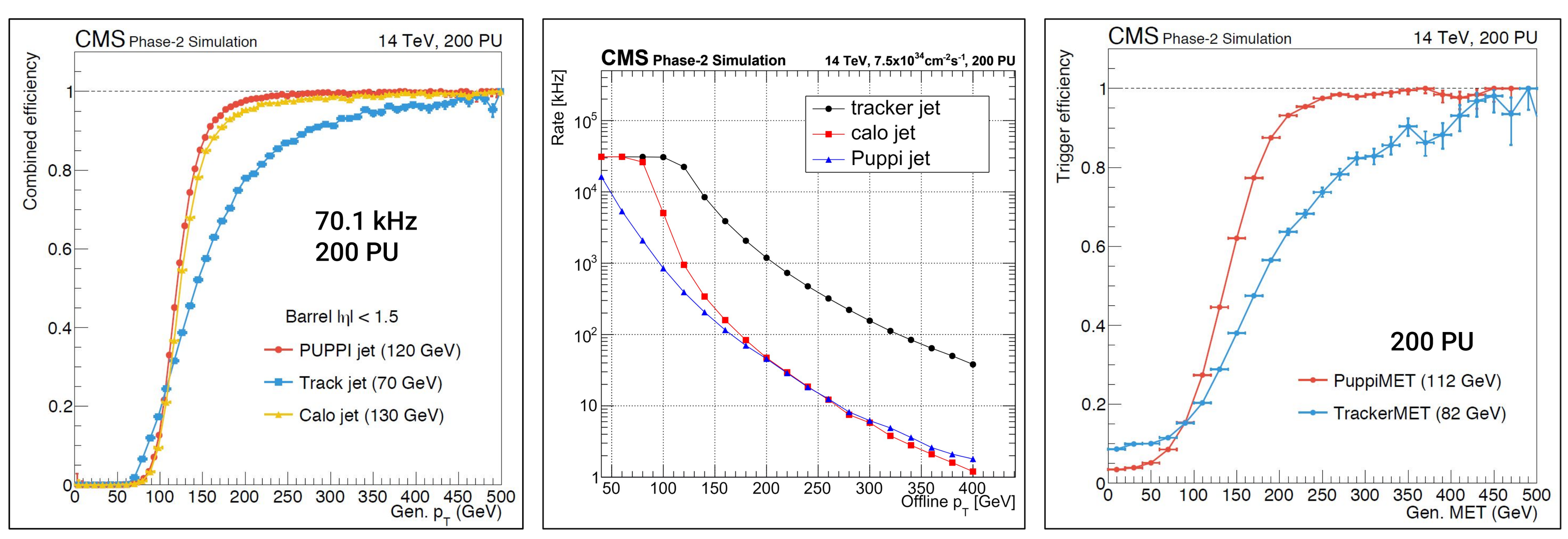
- **PUPPI algorithm implemented in absence of the tracking information**
- Data from each HF ($3 < |\eta| < 5$) read out in 20^0 azimuthal angle (ϕ) wedges.
- Processed in custom-designed *APx* boards
  - Xilinx-VU13P FPGA based design running at 360 MHz on *GCT Boards.*
  - Processes events at 40 MHz throughput.



- 48 clusters from each HF passed through 6 links for further processing.
- **Challenges tackled** in firmware implementation due to limited resources available on the FPGA after handling information from barrel calorimeter.
  - ***Regionized approach with reduced complexity.***
  - Divides each HF into 6 sectors along ϕ direction.
  - Implements 2 copies of PUPPI firmware to achieve a reduced latency of 255 ns and fitting in 1 *SLR of FPGA.*
- PUPPI-based physics objects (eg., p_T of reconstructed jet, missing transverse energy) lead to reduced trigger rates and better efficiencies.
- Calorimeter based trigger decision can <u>now</u> use reliable information from the HF+ and HF- regions of the detector.



Expected Performance at L1T for PUPPI based Phase II objects



L1 Trigger efficiency (L) and rate (M) for jet triggers based on 3 methods of jet reconstruction.
(R) Efficiency of trigger based on missing transverse energy: huge improvement after mitigating pile up.

Conclusion

Implementation of Particle Flow reconstruction and PUPPI algorithm for pile up mitigation at Level 1 Trigger enhances the reach of the CMS physics programme at HL-LHC.

References:
1. The Phase-2 Upgrade of the CMS Level-1 Trigger, *CERN 2020, CERN-LHCC-2020-004*
2. Pileup per particle identification, *Bertolini, D., Harris, P., Low, M., & Tran, N. (2014).JHEP, 2014(10).*