Vertex finding for pile-up mitigation in the Phase-2 upgrade of the Level-1 Trigger of CMS

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Outline

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Overview

1. Motivations for upgrading LHC and CMS
2. Opportunities and challenges of HL-LHC
3. Level-1 Trigger for Phase-2 CMS
4. Tracking for Level-1 Trigger
5. Vertex finding
6. Pile-up mitigation at Level-1 Trigger
7. Outlook

Upgrade Motivations

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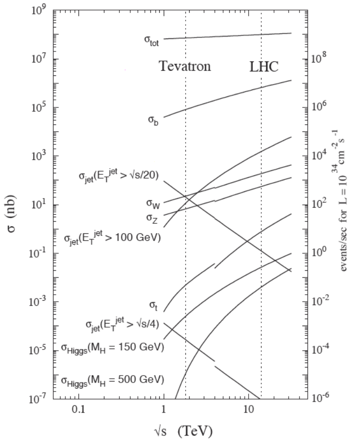

[ATLAS High-Level Trigger TDR, CERN-LHCC-2003-022]

Upgrading LHC: HL-LHC

- New physics lies orders of magnitude away from total interaction cross-section at LHC
- Precision measurements, rare process studies and new discoveries are dependent on large data-sets
- Luminosity upgrade to LHC is seen as effective means to speed up data collection significantly, thus expanding the physics reach of the experimental programme

Upgrading CMS

- Radiation damage would necessitate the replacement of detectors close to beam line and in forward region (i.e. Tracker and HGCAL)
- Upgrades will be necessary to maintain performance in increasingly challenging data-taking environment

Compact Muon Solenoid

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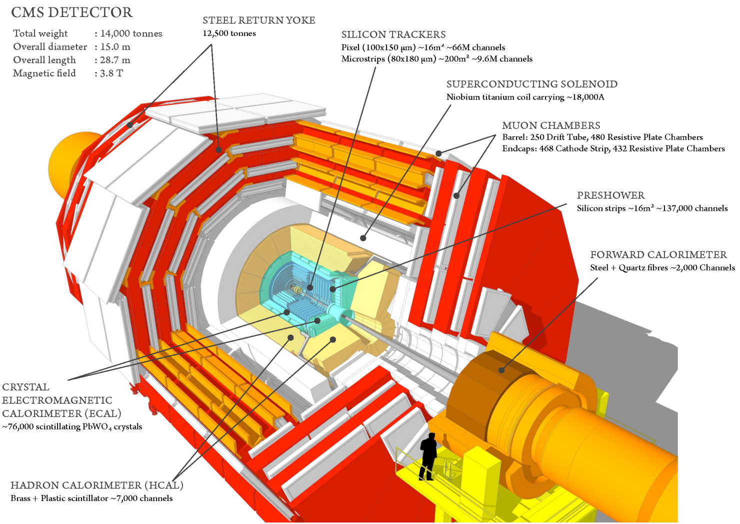

HL-LHC

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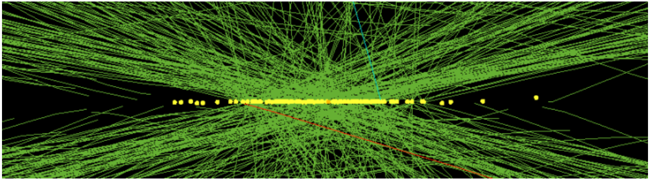
- High instantaneous luminosity will lead to high event multiplicity (pile-up) and will result in high occupancy in detectors
- Pile-up will complicate event reconstruction and in order to control data rates would drive the trigger thresholds up, leading to loss of physics acceptance
- Use of tracking at Level-1 Trigger is proposed to allow for sophisticated event reconstruction algorithms that can provide additional handles for controlling the trigger rates
- Increase in event complexity will require longer processing time to achieve reliable reconstruction (i.e. longer Level-1 latency)



An CMS event display from an event with 78 simultaneous interactions captured during data-taking in 2012

CMS Phase-2 Trigger

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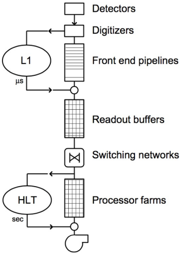
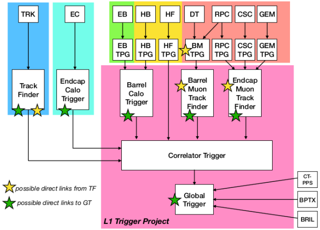
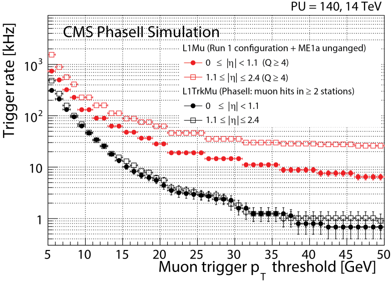
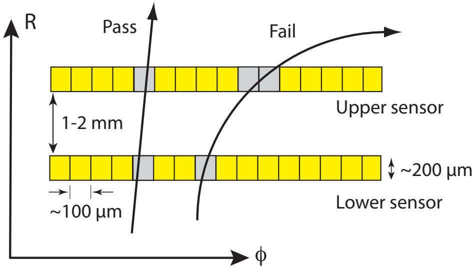


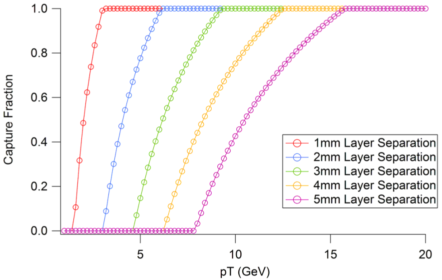




- Level-1 latency is constrained by size of front-end buffers in tracking detector which will be increased in size for the Phase-2 upgrade giving projected latency of 12.5 µs.
- Matching deposits between different detector systems in a Level-1 Trigger Correlator can significantly improve the energy resolution of reconstructed objects

CMS Track-Trigger





- Upgraded tracker is to include stacked sensor modules that feature local p_T discrimination based on track bend in solenoid field
- Rough p_T cut achieved by forming pair of hits (stubs) adjacent sensors under condition of separation within a sliding window
- Resulting data-rate reductions make it feasible to perform fast track reconstruction suitable for uses in Level-1 trigger
- Availability of tracking can significantly improve the energy resolution of objects reconstructed at Level-1 allowing to lower the trigger thresholds

Algorithm Overview

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- Finding the hard interaction vertex is a requirement for rejecting objects in event coming from pile-up interactions
- Current track-fitting is constrained to the beamline which means that vertexing is reduced to 1-D clustering along z
- Two example algorithms presented: simple binning tracks along z and Density Based Spatial Clustering with Noise (DBSCAN)

Binning

- Tracks are binned according to their z_0 and are weighted by their p_T
- Highest p_T bin is chosen as hard primary vertex
- Ideally suited to hardware implementation as histogram maps directly onto BRAMs

DBSCAN

- Forms clusters of objects based on the density in the vicinity of a point
- Resulting clusters can interpreted as separate primary vertices
- Algorithm is a good candidate for use in hardware as previous firmware implementations exist

Performance

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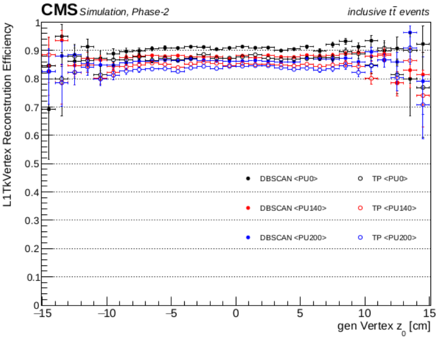

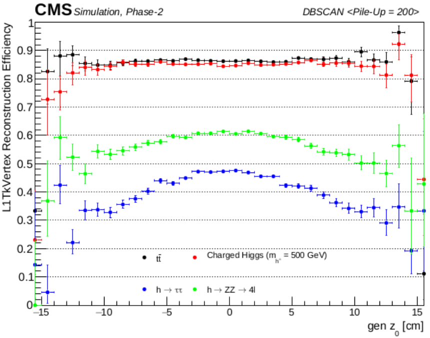

- Both algorithms show similar performance with high reconstruction efficiency (fraction of vertices found within 1 mm of truth) in ttbar and z_0 resolution around 0.3 mm
- Performance is found to be strongly dependent on the physics process involved and less so on the amount of pile-up in the event
- Biggest driver of performance was found to be the presence of well fit high-p_T tracks

Particle Flow and PUPPI

Particle Flow

- An event reconstruction technique that matches deposits in calorimeters with information from tracker in order to improve the energy resolution of reconstructed objects
- For offline reconstruction, it has been proven and is now widely used due to its ability to shift reliance for energy measurement from HCAL onto the more precise ECAL and tracker.

Pile-Up Per-Particle Identification (aka PUPPI)

- A technique for estimating the backgrounds in event due to charged and neutral hadrons from pile-up interactions
- Requires information about hard interaction vertex which then can be used to identify, via reconstructed tracks, energy deposits from pile-up charged hadrons.
- Charged hardron distribution is then used as an estimate of the energy density due to neutral hadrons.
- The pile-up energy distributions are then used to perform energy corrections to reconstructed objects in event depending on amount of pile-up in its vicinity

PUPPI at Level-1 (aka FastPUPPI)

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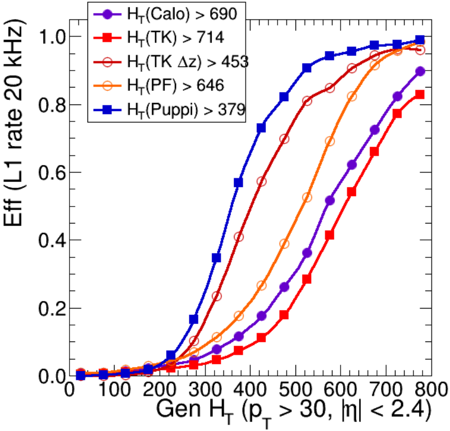

- FastPUPPI is an implementation of Particle Flow and PUPPI for use in Level-1 Trigger
- Currently implemented in software and hardware via Vivado HLS
- Hardware implementation has been tested on Virtex-7 and VU9P based boards
- For H_T, FastPUPPI (PF+PUPPI) shows significantly better performance than reconstruction with PF, Calorimeters or tracker objects alone.
- A good example of a trigger algorithm that would use the reconstructed primary vertex from L1 tracks

References

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- The Phase-2 Upgrade of the CMS L1 Trigger Interim Technical Design Report, CERN-LHCC-2017-013 / CMS-TDR-017
- Technical Proposal for the Phase-II Upgrade of the CMS Detector, CERN-LHCC-2015-010 / LHCC-P-008 / CMS-TDR-15-02
- The Phase-2 Upgrade of the CMS Tracker, CERN-LHCC-2017-009 / CMS-TDR-014
- Particle-flow reconstruction and global event description with the CMS detector, JINST 12 (2017) P10003 (CERN-EP-2017-110)
- Pileup Per Particle Identification, JHEP 10 (2014) 59

Summary

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- In order to enable the unprecedented study of rare and Standard Model processes the HL-LHC will deliver 3000 fb^{-1} of integrated luminosity
- Increased backgrounds associated with higher luminosity will put particular strain on TDAQ systems of ATLAS and CMS
- To assist the event reconstruction at Level-1 Trigger, CMS tracker will upgraded to perform fast track reconstruction which would enable novel reconstruction algorithms to be performed at Level-1
- Vertex finding using the Level-1 tracks is an enabler for a set of new Level-1 algorithms and different vertexing algorithms are being investigated
- Investigations of the use of quality information about the reconstructed tracks have only recently started but could make the problem suitable for Machine Learning based algorithms

CMS Phase-2 Tracker

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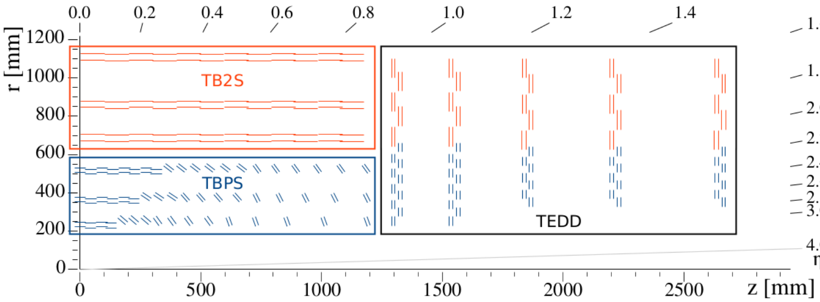
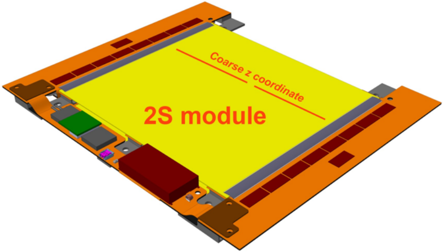
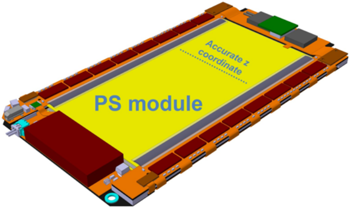
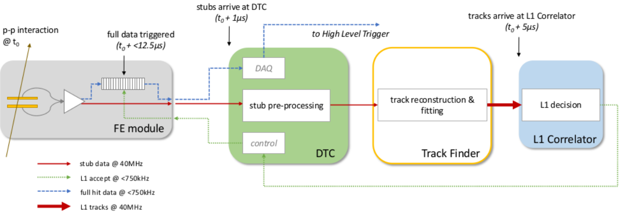
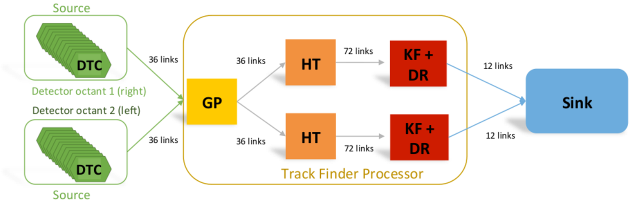






Time-Multiplexed Track-Trigger





- A track-trigger system using Hough Transform for object finding and Kalman Filter for track fitting, capable of reconstructing the output of ttbar PU 200 event in under 5 μs was designed and demonstrated in physical hardware