Operation of the CMS Level-1 calorimeter trigger in high pileup conditions & motivations for Phase 2

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In this talk:

1. Introduction
2. CMS Phase 1 calorimeter trigger upgrade
3. Run 2: operating in high pileup conditions
4. Phase 2: much higher pileup conditions
5. Summary
Introduction

- CMS Phase 1 calorimeter trigger running successfully since 2016
- μTCA time-multiplexed system with Virtex-7 FPGAs, 10Gb/s links
- Increase in calorimeter tower resolution by factor 4 in $\eta \times \varphi$
- More sophisticated algorithms $\rightarrow$ improved trigger performance
- Last few years challenging for L1: LHC delivering higher luminosity
  - increase in number interactions per bunch crossing (“pileup”)

- Some L1 algorithms exhibit non-linear dependence of rate with pileup, especially MET
- Flexibility of calorimeter trigger has enabled us to adapt quickly to changing beam conditions
- Lessons learned during from Phase 1 will inform design choices and algorithms for Phase 2
1. Introduction

2. CMS Phase 1 calorimeter trigger upgrade

3. Run 2: operating in high pileup conditions

4. Phase 2: much higher pileup conditions

5. Summary
L1 calorimeter trigger receives trigger primitives from ECAL, HCAL, and HF (forward calorimeter)

Layer 1 builds towers from TPs by adding ECAL+HCAL energies and setting feature bits

ECAL & HCAL TPs have particle response level calibrations applied at Layer 1 to account for losses

40 towers in $\pm \eta$ and 72 in $\phi$, with max. $E_T$ of 256 GeV

Layer 2 runs jet, egamma & tau algorithms, and constructs ETT, HTT, MET & MHT global energy sums

Pileup subtraction applied to jet, egamma, tau & MET

Object level energy calibrations applied at Layer 2, also egamma & tau isolation, shape ID

Layer 2 is then demultiplexed, with 12 highest energy objects + global energy sums sent to global trigger

Global trigger issues L1 accept if calorimeter objects (or muons) pass selection defined in the L1 menu

GT applies trigger rules and receives external conditions
18 × Layer 1 pre-processor CTP7 cards each receive a calorimeter region in $\phi$ for + or - $\eta$ and send data to Layer 2 via molex flexplane optical patch panel

- Input: 60 links/board @ ~6 Gb/s

9 × Layer 2 main processor MP7 cards receive data from full calorimeter: time multiplexed system

- Input: 72 links/board @ 10 Gb/s

- No need for overlap regions: no data sent between MPs

- Redundant nodes ready to receive and send data after central trigger reconfiguration if a board fails
CMS Level-1 calorimeter trigger

Layer 1 pre-processor cards

Layer 1 → Layer 2 patch panel

MP7 Rack

Layer 2 crate: MP7 main processor boards
Master Processor Virtex 7

- Main workhorse for L1 calorimeter trigger upgrade
- uTCA form factor
- Also used in BMTF, uGMT, uGT
- 1.5 Tb/s signal processor board Xilinx XC7VX690T FPGA
- 72 Tx + 72 Rx links @ 10 Gb/s Avago MiniPOD optics
- GbE, AMC13/TTC/TTS, PCIe, SAS, SATA, SRIO backplane links
- AVR UC3A3256 microcontroller
- MicroSD for FPGA booting, used as firmware repository
Modular firmware design, 240 MHz clock
- split into algorithm and infrastructure
- allows for independent development

High resource usage due to complex algorithms

Significant care required for timing constraints and clock distribution
Funky minibus provides firmware interface for run-time configuration of algorithm parameters

- Consists of clock line, data line, and instruction specifying what to do with data
- Bus is self-identifying: reports ordering, names and sizes of endpoints
- All data treated as BLOBs (LSB first): endpoint receives data, fills up, ignores remaining bits
- Endpoints joined together in daisy chain
- 6 types of instructions: ignore, data, read, write, lock, unlock
- Typical use case: send unlock instructions to all endpoints, send write instruction, send data for filling the first endpoint, send lock instruction \(\rightarrow\) loop until all endpoints have been written

4 IPbus endpoints:
- register for sending instruction down bus
- register for loading data for sending down bus
- register reporting bus size
- RAM containing list of endpoints ("infospace")

All calorimeter trigger object level calibrations and algorithm parameters use this bus
- Has been critical part of flexibility of calorimeter trigger firmware to adapt quickly
1. Introduction
2. CMS Phase 1 calorimeter trigger upgrade
3. Run 2: operating in high pileup conditions
4. Phase 2: much higher pileup conditions
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Towards end of 2016 pp running, LHC raised instantaneous luminosity by increasing number of protons per bunch → significant increase in number of interactions per crossing

This increase in pileup led to (very!) non-linear increase in rates for some trigger algorithms

- particularly MET and multi-jet triggers

Significant contribution to this pileup dependence driven by larger towers at high $\eta$ in endcap

- For HTT, simply $\eta$-restricted to same as offline

For MET solution was not so simple, need full calorimeter

- required event level pileup mitigation

Flexibility of calorimeter trigger system allowed implementation of run-time configurable LUT

- excludes towers from MET calculation below $E_T$ threshold determined from $\eta$ of tower & estimation of event pileup

Significantly reduced pileup dependence of MET triggers

- kept rates manageable in high pileup conditions
- maintained low thresholds and high trigger efficiencies
During 2017 running, a problem in one of the LHC sectors produced frequent beam dumps due to gas contamination around pumping port. Beam interaction with gas produces electron clouds, which cause beam dump. Most of these issues were fixed by warming to 90K and pumping out, resulting in only a few 16L2 beam dumps this year.
2017 p-p running: a challenge for L1T

- Mitigated by changing fill scheme: 48 bunch trains $\rightarrow$ 8b4e (8 filled, 4 empty)
- To maintain instantaneous luminosity, bunch intensity increased
- Increased overall level of out of time pileup, which is larger for first few bunches of train
- Calorimeter front end dynamic pedestal subtraction not as effective for first 2 filled bunches
  - need to measure pedestal to subtract over first few bunches in train
- Leads to further increase in the pileup dependence various L1 algorithm rates
- Mitigated by tuning the MET pileup subtraction LUT to increase tower thresholds
- Important to consider how changes in fill scheme can affect TPs and trigger rates for Phase 2
Responding to changes in detector response

- Electromagnetic & hadronic calorimeter response changes significantly over various timescales.
- Generally response degrades as it is irradiated → increase channel gains.
- ECAL exhibits significant recovery during technical stops / shutdown (even inter-fill!).

- Heavily irradiated high $\eta$ towers in endcap suffer significant loss of transparency, do not recover well:
  - need to amplify channels by up to $50 \times$
  - noise floor raised above minimum tower $E_T$
- For some towers in $\eta$-$\varphi$

- To avoid including ECAL noise in L1T algorithms, implemented $\eta$-dependent zero suppression.
- Possible using ECAL TP calibration LUTs: scale factors applied for given $\eta$ and $E_T$
- Significantly reduced rate for algorithms using towers at high $\eta$, particularly jets & MET.
Measuring the trigger latency

- Measuring latency of various trigger subsystems not necessary for legacy trigger
  - just needed to time in final L1 accept decision with detector

- Phase 1 trigger upgrade much more complex: improved algorithms & additional stages → latency increased

- Now important to understand every BX of latency in system, all the way from trigger primitives to TCDS, including fibre lengths, serialisation/de-serialisation etc.

- Find out where latency can be saved → any algorithm or system improvements that require additional latency can be implemented if/when necessary

- For Phase 1 far from a trivial process: no “standard” method built into system to measure latency of various trigger sub-components
  - took a lot of time and effort to understand and measure trigger subsystem latencies

- For Phase 2, an order of magnitude more complex than Phase 1, extremely useful to have built-in ability to accurately measure latency at each subsystem

- In addition to easily determining where latency can be saved for more important uses, will facilitate timing in different trigger paths that arrive at a common subsystem, e.g. correlator
Some lessons from Phase 1

- Always prepare for LHC to deliver more than expected
  - has sometimes been difficult to maintain rates within the L1 bandwidth
  - either due to increase in instantaneous luminosity, increase in pileup, or both
  - rates can sometimes behave unpredictably with changes in beam conditions

- Make algorithms as flexible and configurable as possible
  - ability to update and tune algorithms easily has enabled us to maintain stability in the L1 trigger throughout many changes in the LHC beam conditions

- Understand calibrations well
  - complex detector and sophisticated algorithms require significant care with calibrations
  - small change in calibrations can have large effect on rates and efficiencies
  - must maintain consistency from detector → trigger primitives → towers → algorithms
  - wherever possible use data driven calibrations, try not to rely on MC, or at least cross-check with data
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Phase 2 L1T: architecture (WIP!)

- BE+L1 System: 40,000 kHz event data processing

**Track trigger**

**Correlator**

**Global Trigger**

- 750 kHz To HLT
- 7.5 kHz To Offline

**Endcap Calorimeters**

- CE BE

**Outer Tracker Detector**

- DTC: Outer Tracker BE

**Barrel Calorimeters**

- EB/HB/HF BE

**Barrel Calo Trigger**

- Trigger GCT

**Endcap Muon System**

- EMU BE

**Overlap Muon Track Finder**

**Barrel Muon Track Finder**

**Barrel Muon Track Finder**

**Endcap Muon Track Finder**

**Correlator Trigger Layer-1**

**Correlator Trigger Layer-2**

**Global Trigger**

- 750 kHz To HLT

**DAQ/HLT System**

**Pixel Tracker**

**MIP Timing Detector**

**Correlator Trigger Layer-1**

**Correlator Trigger Layer-2**

**Barrel Calo Trigger RCT**

**BE+L1 System**

- 40,000 kHz event data processing
Phase 2 pileup mitigation: HGCAL

- Current ECAL + HCAL calorimeter endcaps will be replaced during Phase 2 upgrade [1]
- High granularity calorimeter endcap will measure electromagnetic + hadronic components
- Built to facilitate particle flow: 3D separation of individual particle showers
- Fine lateral granularity limits energy measurement region → minimise inclusion of pileup energy
- Fine sampling of longitudinal shower development: good energy resolution
  - significantly improve ability to discriminate against pileup jets
- Precision time measurement of high energy showers
  - helps with rejection of energy from pileup
- Fast shaping time: peaking-time 20ns
  - minimise out-of-time pileup

Phase 2 pileup mitigation: Track Trigger

- For Phase 2 CMS will have a track trigger
  - provide tracks to the L1 trigger algorithms
- Crucial in mitigating high pileup of HL-LHC
  - up to 200 interactions per bunch
- Run vertex finding and associate L1 objects to primary vertex
- Run Particle Flow and PUPPI (Pileup Per Particle Identification) as is currently done offline
- Will still of course need robust standalone calorimeter and track only algorithms

- Ongoing work to characterise vertex finding with L1 tracks
  - provide necessary info to PF and PUPPI algorithms
- Eventually train machine learning algorithm
  - identify leading vertices in the event
  - utilise HLS4ML resources
Summary

- Many lessons learned from Phase 1 upgrade that will inform design choices for Phase 2
- Up to 200 pileup from HL-LHC: need to be prepared for this at L1 trigger
- Build system that can maintain high trigger efficiencies whilst keeping rates within bandwidth
- Need as much flexibility as possible to allow L1 to respond effectively to beam conditions
- Important for L1 to be able to deal with fluctuations in the response of the detectors
- Require both robust standalone calorimeter & track algorithms in addition to complex high performance algorithms that use particle flow, PUPPI, machine learning etc.