Trigger (CMS)

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Introduction

• The LHC is world’s largest and most powerful particle collider in discovery mode

• Main physics goals:
  ‣ Discover the Higgs boson to establish its role in EWSB
  ‣ Search for beyond SM phenomena at TeV energy scale

During Run-2:
  ‣ 2556 bunches, \( \sim 2.5 \times 10^{11} \) protons per bunch
  ‣ Instantaneous luminosity reached \( 2.5 \times 10^{34} \) cm\(^{-2}\) s\(^{-1}\)
  ‣ A total of \( \sim 10^{16} \) proton-proton collision events out of which \( \sim 10^{4} \) produce the Higgs boson
Rates of Physics Processes

June 2021

CMS Preliminary

- New physics processes like Supersymmetry, dark matter etc predicted to have even lower cross sections
- Benefit-cost analysis between keeping large amount of data and storage capacity

All results at: http://cern.ch/go/pNj7
The CMS Trigger System

- CMS is one of the two general purpose detectors at the LHC, built around a superconducting solenoid.
- Dedicated sub-detectors to identify different particles, combined information to reconstruct collision event.
- Decision to store interesting events taken by the online Trigger system at real time.

Trigger system provides first decision to accept/reject events based on the topology.

- Selection performed in stages:
  - **Level-1 (L1):** hardware driven, based on fast detector readout, custom electronics, limited granularity.
  - **High Level Trigger (HLT):** software based, commercial PCs, improved object reconstruction comparable to offline.
- Once rejected by trigger, event is lost forever.
**Trigger Design**

- Challenges of hadron collider machine: high rejection of physics events
- Reconstruct physics objects and event variables online with available granularity
- At L1 each sub-detector provides a sub-trigger, logical OR of which is the global trigger (exploit trigger redundancy)
- At HLT sophisticated algorithms (*paths*) look for specific event signatures
- As a complement, also select minimum bias events to study unknown event signatures
  
  \[ \rightarrow 1 \text{ out of } 10^6 \text{ events selected} \]

- Each reconstructed event takes \(~1\) MB of storage space
- Data acquisition constraint of \(~1000\) events per second
- Event prescaling: one event picked at random from several similar events to save storage
  
  \[ \rightarrow \text{still producing up to } ~1 \text{ PB data per day} \]
Level-1 Trigger Implementation

Calorimeter trigger

- ECAL TPs (energy)
- HCAL TPs (energy)
- HF TPs (energy)

Calo Layer-1 (pre-processor)

Calo Layer-2 (main processor)

De-multiplexing

Global trigger (decision)

Muon trigger

- DT TPs (segments)
- RPC TPs (hits)
- CSC TPs (segments)

Concentrator (pre-processor)

Track finder (main processor)

Global muon trigger (decision)

Level-1 Accept

Decision takes typically ~1 µs, coupled with propagation delay the latency is ~4 µs
Level-1 Trigger Algorithms

- **Electrons/photons:**
  - Cluster shape and electromagnetic energy fractions to discriminate against jets
  - Use of energy weighted position measurement, cluster energy calibration and isolation measurement

- **Taus:**
  - Similar to electrons/photons, shape discrimination optimised separately

- **Jets:**
  - Sliding window algorithm looking for trigger tower seeds over a given energy threshold
  - Sum of 9x9 trigger towers to match jet radius of 0.4 at offline
  - Pileup subtraction and calibration

- **Energy sums:**
  - Sum of jet energies with a restriction in energy and pseudorapidity

- **Muons:**
  - Extrapolation based track finding in barrel, pattern based in overlap and endcap regions
  - \( p_T \) assignment based on \( \Delta \phi \) in barrel, patterns in overlap, BDT regression in endcap

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CERN-EP-2020-065
Level-1 Trigger Performance

- Phase-1 upgrade of the L1 system in 2016 exploited full calorimeter granularity to give better energy and position resolutions while remaining within rate constraints.

- Run-2 performance of L1 triggers also benefitted from pileup subtraction.

> CMS Preliminary 2016 Data 3.1 fb⁻¹ (13 TeV)  
> CMS Preliminary 2018 Data 11.0 fb⁻¹ 13 TeV

All reconstruction performances greatly independent of pileup.

2010 to 2015

2016 onwards

CMS DP-2019/020
CMS DP-2018/044
CMS DP-2018/040

Electron/photon

Muon

Jet

Tau
The impending Phase-2 upgrade for the high luminosity phase or HL-LHC will see upgraded detectors, adding to efficiency gains at L1.

- Inclusion of tracking, PF algorithm
- Increased granularity in calorimeter trigger, increased muon system pseudorapidity coverage
- Use of state-of-the-art processing boards running more complex algorithms at 12.5 $\mu$s latency, optical links to send data at 28 GB/s, 750 kHz output bandwidth

Serenity boards running PF-jet algorithm, 98% events have perfect agreement with software.

NN based algorithms for tau reconstruction

New displaced muon triggers using Kalman filter

CMS Phase-2 Simulation 14 TeV, 200 PU

CMS-TDR-021
High Level Trigger

- Software algorithms running asynchronously on commercial computing hardware
  - Same code and similar algorithms used for offline reconstruction but very optimized
  - 100 times faster than offline reconstruction
  - 30,000 CPU cores at the end of Run-2
- Make use of full detector data to select events for offline storage and analysis
- Modular approach to speed up online reconstruction
  - Alternate event builder and event filter steps
  - Starts with the fastest step, regional reconstruction around L1 seeds
  - Run time-consuming tracking and particle-flow only for interesting events after filtering
- Hundreds of HLT paths targeting broad event topologies
- Aim to select one out of every 100 events
- Output bandwidth ~2 GB/s
- In Run-2 HLT included improvements resulting from Phase-1 upgrades of Pixel and HCAL sub-systems

Decision takes typically ~300 ms
In addition to HLT objects, many physics analysis oriented trigger paths defined at HLT, performance depends on specific requirements.
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High Level Trigger HL-LHC Upgrade

- Manyfold increase in detector readouts during HL-LHC, CPUs unable to cope with demand in performance
- Adoption of heterogeneous architecture: using GPUs as a strategy for providing the necessary computing power at an affordable price
- Main features in algorithm improvement: 3D shower reconstruction, pixel tracks and vertex reconstruction, more pileup suppression...
- Output bandwidth increase to ~61 GB/s, with rate at 7.5 kHz
Towards Run-3 (I)

- Some Phase-2 improvements already ready to be implemented during Run-3
- Foresee higher pileup profile compared to Run-2, new features needed to compensate the physics program

  L1 Trigger:
  - Inclusion of GEM in the muon track finder
  - HCAL depth and timing information
  - Kalman filter for muon tracks

  HLT:
  - Exercise heterogeneous GPU architecture
Towards Run-3 (II)

- Computing resource constraints: present average HLT rate limit 1 kHz at peak luminosity
  - Limited bandwidth: data recording and transfer limited to ~5 GB/s on average
  - Prompt reconstruction: all recorded data must be fully reconstructed offline within ~48h
  - The total amount of storage space is limited (tape and disk)

- Workaround to go beyond 1 kHz:
  - **Reduce event size with Scouting**: reduce event size by saving only online/trigger objects that will be used directly in data analyses; already established method in CMS since Run-1
  - **Reduce computing resources with Parking**: “park” data on tape, skipping prompt reconstruction and reconstruct the data later (during technical stops); during Run-2 large fraction of scouting data were parked

- For Run-3, expanding the reach to high rates and more exotic phase spaces

![Di-muon mass spectrum using Run-2 scouting data](CMS DP-2018/055)
Summary

- Trigger system is a behemoth dealing with extreme computing demands to meet the physics goals of the LHC

- Performance gains over the past years made possible by integrating new technologies and advanced algorithms
  - Increased L1 granularity
  - Improved trigger algorithms targeting rare final states

- Good performance in Run-2
  - Sharper efficiency turn-ons, rates under control
  - Little pileup dependence

- Major improvements planned for HL-LHC to extend reach to new physics processes, some already to be tested during Run-3
  - Addition of tracking and correlator layer in L1 coupled with upgraded hardware, GPUs at HLT

That's NOT all folks!

Stay tuned for exciting new physics