Overview of the HL-LHC Upgrade for the CMS Level-1 Trigger

Claire Savard on behalf of CMS Collaboration
University of Colorado, Boulder
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High Luminosity Large Hadron Collider

- Increase statistics to search for new and rare physics

- High statistics (4000 fb⁻¹)

- High luminosity (7.5 x 10³⁴ cm⁻²s⁻¹)

- Pile-up increase 200 PU

Dark matter signals (Emerging Jets)

SUSY particles

>15 million per year
CMS at the HL-LHC*

L1T and HLT/DAQ
- Tracker Tracks in L1T at 40 MHz
- L1T acceptance: 100 → 750 kHz
- HLT output at 7.5 kHz
- 40 MHz Scouting: Real time analysis
- L1T latency: 4 → 12.5 μs

Calorimeter Endcap
- High Granularity Calorimeter (HGCAL)
- 3D showers and precise timing
- Si, Scint+SiPM in Pb/W-SS

Tracker
- Si-Strip and Pixels increased granularity
- Design for tracking in L1-Trigger
- Extended coverage to $\eta \approx 3.8$

Barrel Calorimeters
- ECAL crystal granularity readout at 40 MHz with precise timing for $e/\gamma$ at 30 GeV
- ECAL and HCAL new Back-end boards

Muon Systems
- DT & CSC new FE/BE readout
- RPC back-end electronics
- New GEM/RPC $1.6 < \eta < 2.4$

Beam Radiation Instr. and Luminosity
- Bunch-by-bunch luminosity measurement:
  - 1% offline, 2% online

MIP Timing Detector
- Precision timing with:
  - Barrel layer: Crystals + SiPMs
  - Endcap layer: Low Gain Avalanche Diodes

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CMS Level-1 Trigger (L1T)

- Initial event selection in real time
- Reconstruction of physics objects
- FPGA-based hardware
- Goals:
  - Maintain current physics reach with 200PU
  - Extend to new signatures with advanced techniques
    - Ex: machine learning
L1T Architecture

- ATCA form factor PCBs
- Xilinx VU13P FPGAs
- 25 Gb/s optical fibers
Chapter 1. Introduction and overview

Figure 1.3: Functional diagram of the CMS L1 Phase-2 upgraded trigger design. The Phase-2 L1 trigger receives inputs from the calorimeters, the muon spectrometers and the track finder. The calorimeter trigger inputs include inputs from the barrel calorimeter (BC), the high-granularity calorimeter (HGCAL) and the hadron forward calorimeter (HF). It is composed of a barrel calorimeter trigger (BCT) and a global calorimeter trigger (GCT). The muon trigger receives input from various detectors, including drift tubes (DT), resistive plate chambers (RPC), cathode strip chambers (CSC), and gas electron multipliers (GEM). It is composed of a barrel layer-1 processor and muon track finders processing data from three separate pseudorapidity regions and referred to as BMTF, OMTF and EMTF for barrel, overlap and endcap, respectively. The muon track finders transmit their muon candidates to the global muon trigger (GMT), where combination with tracking information is possible. The track finder (TF) provides tracks to various parts of the design including the global track trigger (GTT). The correlator trigger (CT) in the center (yellow area) is composed of two layers dedicated to particle-flow reconstruction. All objects are sent to the global trigger (GT) issuing the final L1 trigger decision. External triggers feeding into the GT are also shown (more in Section 2.6) including potential upscope (mentioned as “others”) such as inputs from the MTD. The dashed lines represent links that could be potentially exploited (more details are provided in the text). The components under development within the Phase-2 L1 trigger project are grouped in the same area (blue area). The various levels of processing are indicated on the right: trigger primitives (TP), local and global trigger reconstruction, particle-flow trigger reconstruction (PF) and global decision. The reconstructed track parameters and track reconstruction quality flags are provided to the trigger system to achieve precise vertex reconstruction and matching with calorimeter and muon objects. This key feature maximizes the trigger efficiency while keeping the trigger rate within the allowed budget. A global track trigger (GTT) will be included, to reconstruct the primary vertices of the event along with tracker-only based objects, such as jets and missing transverse momentum. The GTT can also be used...
L1T Upgrades: Calorimeter and Muon Triggers

• Calorimeter trigger:
  • Higher granularity for high-resolution clusters and identification variables
  • Build $e/\gamma$, $\tau_h$, jets, energy sums

• Muon trigger:
  • Extended coverage $|\eta| < 2.4 \rightarrow 2.8$
  • Muon track finders separated in barrel, endcap, and overlap regions
L1T Upgrades: Correlator and Track Triggers

- **Global track trigger:**
  - Gets full tracker tracks from Track Finder
  - Build track objects: jets, vertices, $H_T$

- **Correlator trigger (Particle Flow):**
  - Particle Flow identifies and reconstructs all particles with sub-detectors info
  - Pileup Per Particle Identification (PUPPI) used to mitigate PU effects
  - Reconstructs hadronic jets, $E_T^{miss}$, $\tau_h$, $H_T$, ...

*See Sioni Summers talk on Particle Flow*
L1T Upgrades: 40 MHz Scouting

- Collects subset of trigger primitives and objects through spare optical links
- Uses:
  - Monitoring, diagnosis, lumi measurements
  - Find correlations among contiguous BX
  - Analyze signatures unreachable through standard triggers
L1T Objects

Calorimeter trigger
- DT
- RPC
- CSC
- GEM
- iRPC

Muon trigger
- OMTF
- EMTF

Track trigger
- TP

Detector Backend systems
- BC
- HF
- HGCAL
- BCT

Global

External Triggers
- PPS
- BPTX
- BRIL
- Others

Primary Vertex (PV)

STA e/γ

STA Calo τ/Jets/H_T

STA μ

TM μ

TM e

TM tracker-iso e

Tracker-iso γ

PF Candidates

PUPPI Candidates

PUPPI τ/Jets/E_T^{miss}/H_T

Menu: masses, Δη, ΔΦ, Δr, BDT/NN, ...

Phase-2 trigger project
Sub-Detector Example: GTT

- Track inputs: \( \{q, \phi, \tan(\lambda), z, n_{stub}, \text{quality} \ldots \} \)
- Global Track Trigger (GTT) builds track objects
  - \( H_T, E_T^{\text{miss}} \), primary vertex, jets

GTT floor plan:
- ~15% LUT, ~20% FF, ~25% BRAM, ~3% DSP
Algorithm Example: NN Vertexing

**In:** tracker track properties

**Out:** likelihood track belongs to primary vertex

Useful for pile-up mitigation, important for Particle Flow
L1T Physics Reach

CMS-TDR-021
Physics Reach Example: Exotic Higgs

• \( h \to \phi \phi \to 4j \), LLP
• L1 extended tracking builds displaced tracks and jets
  • Also calo timing, displaced STA muons, etc.
• Phase 2, \( H_T \) trigger rate

![Tracking efficiency vs. Particle d_0 (cm)]

Expected # of signal events

![Graph showing expected number of signal events vs. cτ (cm) with different scenarios]
Summary

• HL-LHC increases statistics, increases pile-up
• L1-Trigger upgraded for more complicated events/increase acceptance
• Upgrades allow reconstruction of more sophisticated, offline-like, objects to improve triggering
• Physics reach extended with better triggering algorithms
Backup
L1T Upgrades: Particle Flow

• Layer 1
  • Produces particle-flow (PF) candidates; constructed from the matching of calorimeter clusters and tracks
  • Pileup Per Particle Identification (PUPPI) algorithm mitigating the degradation of the energy resolution due to PU

• Layer 2
  • Building and sorting final trigger objects
  • Applying additional ID and Isolation

• PF+PUPPI: needed to sustain Run 2 Jets & MET thresholds
L1T Upgrades: Track Finder

- Reconstruction of tracker tracks at 40 MHz
  - $\frac{q}{R}, \phi, \tan(\lambda), z_0, n_{stub}, \text{quality}…$

Stubs (pair of hits)

Tracklets (2 stubs in a row)

Tracks (extend tracklet)

Duplicate removal (merge similar)

Kalman filter (calc track params)
L1T Upgrades: Global Track Trigger

• Takes in tracker tracks, builds high-level physics objects
  • $H_T$, $E_T^{miss}$, primary vertex

Primary vertex helps remove pile-up tracks
**L1T Upgrades: Track Quality GBDT**

**In:** tracker track properties

**Out:** likelihood track originated from true particle

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<th>Model</th>
<th>Python AUC</th>
<th>HLS AUC</th>
<th>Latency (clk)</th>
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<th>FF %</th>
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VU9P 240 MHz
L1T Physics Reach: Rare B-meson decays

• $B_s^0 \rightarrow \Phi(K^+K^-)\Phi(K^+K^-)$
  • A rare FCNC process forbidden at the tree level in the SM
  • Trigger on the fully hadronic final state with L1 Tracks
  • Reconstruct $\Phi$ candidates using pairs of oppositely charged tracks originating from the same vertex
  • Then reconstruct $B_s^0$ candidates from pairs of $\Phi$ candidates originating from the same vertex