Performing precision measurements and new physics searches at the HL-LHC with the upgraded CMS Level-1 Trigger

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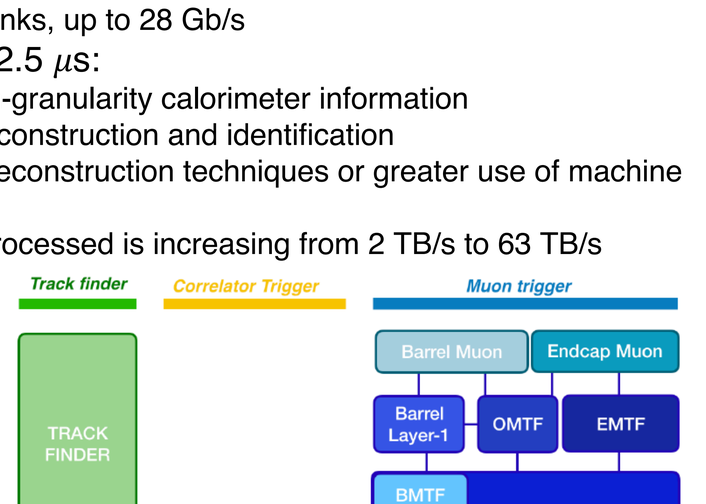
Introduction

The CMS Phase-2 physics program will fully exploit the High Luminosity configuration (HL-LHC), with an integrated luminosity of 4000 fb^{-1} and an increased average number of proton-proton collisions per bunch crossing (pileup) of around 200. This increased pileup poses the main challenge for the Level-1 (L1) Trigger. The upgrade of the trigger system will enhance the physics selectivity and maintain the performance necessary throughout the 10 year-long HL-LHC program.



The LHC baseline plan, showing the energy of the collisions (upper red line) and luminosity (lower red lines). Starting in 2027, the machine will be in the HL-LHC.

CMS Phase-2 Trigger

Two-level trigger architecture:

- Level-1 trigger: operates at hardware level and uses the information of the calorimeters, the muon chambers, and now the tracker, with an input rate of 40 MHz and an output of 750 kHz
- High-level trigger (HLT): has access to the full granularity of the detector, and reduces the output rate to 7.5 kHz

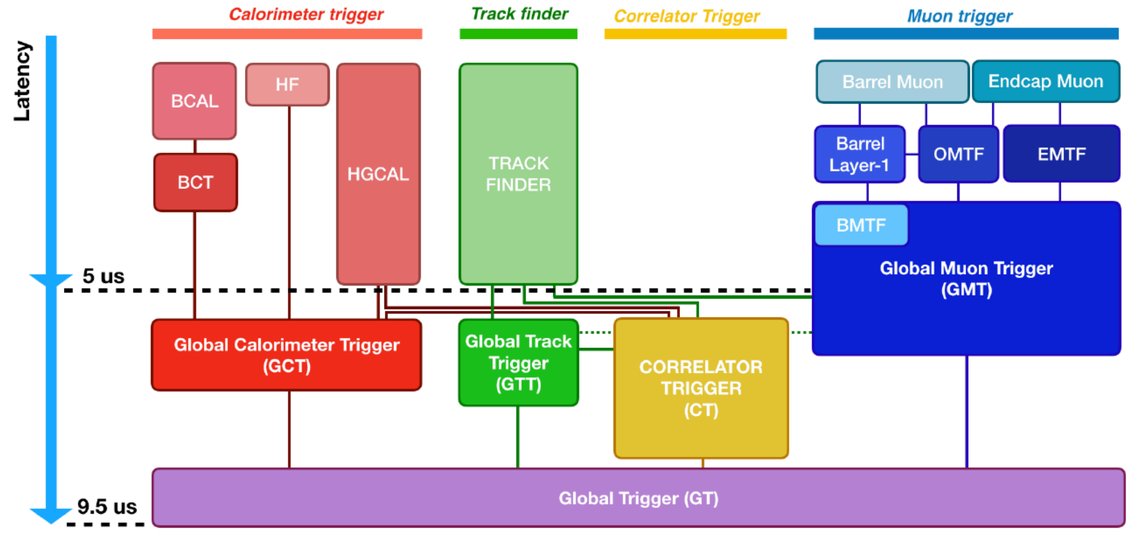
Upgrades to the L1 trigger

Upgraded trigger decision components:

- New FPGAs and processors, Xilinx UltraScale+ class
- Improved high-speed optical links, up to 28 Gb/s

Total latency increased to 12.5 μs:

- Allows use of tracker and high-granularity calorimeter information
- Enables higher-level object reconstruction and identification
- Potential to use particle-flow reconstruction techniques or greater use of machine learning based approaches
- Total amount of information processed is increasing from 2 TB/s to 63 TB/s



Four independent data processing paths:

- Calorimeter trigger: builds e/γ candidates, hadronically decaying taus, jets and energy sums
- Muon trigger: generates track-matched muons; extends coverage to $|\eta| = 2.8$
- Track trigger: reconstructs tracks; the Global Track Trigger reconstructs primary vertices and tracker-only based objects, such as jets and energy sums
- Correlator trigger: global event reconstruction; produces particle-flow candidates and hosts a version of the Pileup Per Particle Identification (PUPPI) algorithm, which removes pileup

Global Trigger: receives all output objects from the independent processing paths; issues the final L1 trigger decision

Simplified Level-1 Trigger Menu

The Level-1 menu evolves with shifting physics priorities and adapts to changes in beam conditions and detector performance. The menu is able to maintain the physics performance from the current running (Run 2), even at 200 pileup.

L1 Trigger seed	Offline Threshold [GeV]	Rate [Hz]
Single TkMuon	22	12
Double TkMuon	15, 7	1
Triple TkMuon	5, 3, 3	16
Single TkElectron	36	24
Single TkIsoElectron	28	28
Double TkElectron	25, 12	4
Single TkIsoPhoton	51	43
Double TkIsoPhoton	22, 12	50

L1 Trigger seed	Offline Threshold [GeV]	Rate [Hz]
Single CaloTau	150	21
Double CaloTau	90, 90	25
Double PuppiTau	52, 52	7
Single PuppiJet	180	70
Double PuppiJet	112, 112	71
Puppi H_T	450	11
Puppi E_T^{miss}	200	18
Total Level-1 Menu Rate (+30%)		**472**

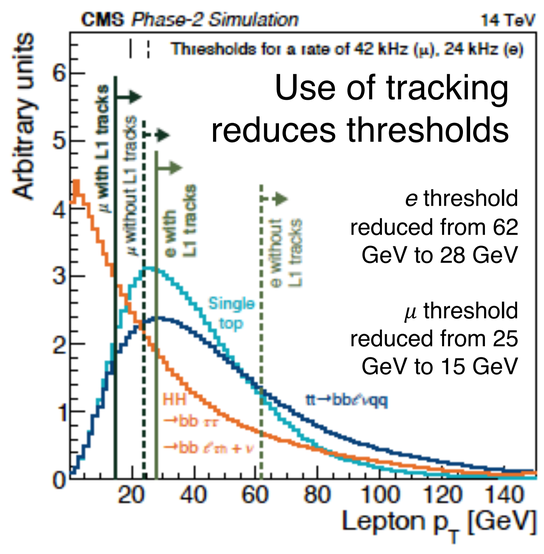
**Full Level-1 menu includes cross triggers that are not listed in the table above

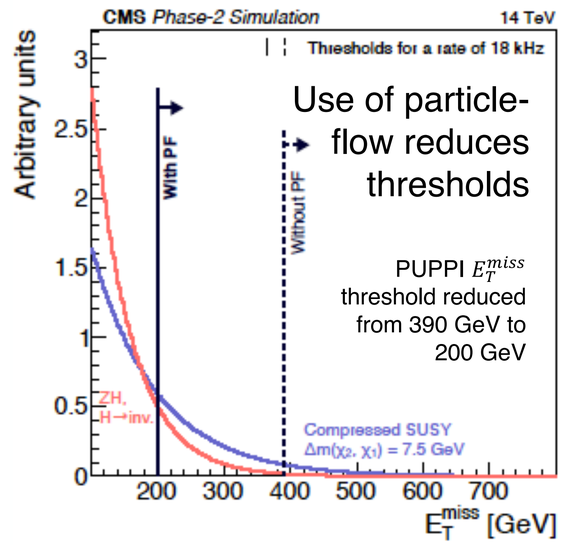
Physics Reach

A broad spectrum of physics analyses will become possible with the new capabilities offered by the detector upgrade, the inclusion of tracking at Level-1, and the use of particle-flow algorithms.

Reduced trigger thresholds

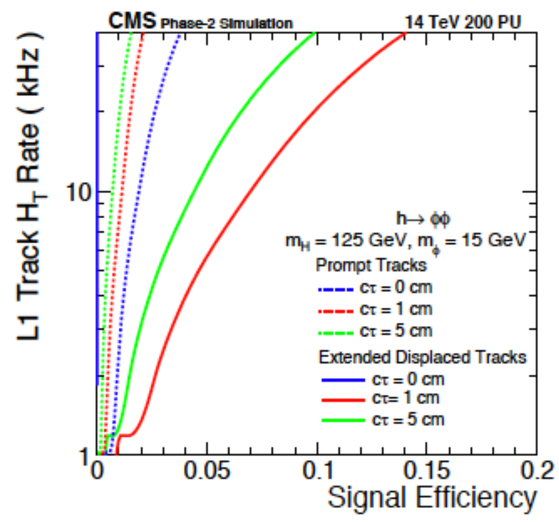
Due to the tracking, many of the upgraded trigger algorithms achieve lower rates, even at 200 pileup, releasing bandwidth. We can then reduce some thresholds in order to increase the acceptance for key physics signals, for example, channels that trigger using leptons (left) or PUPPI E_T^{miss} (right).

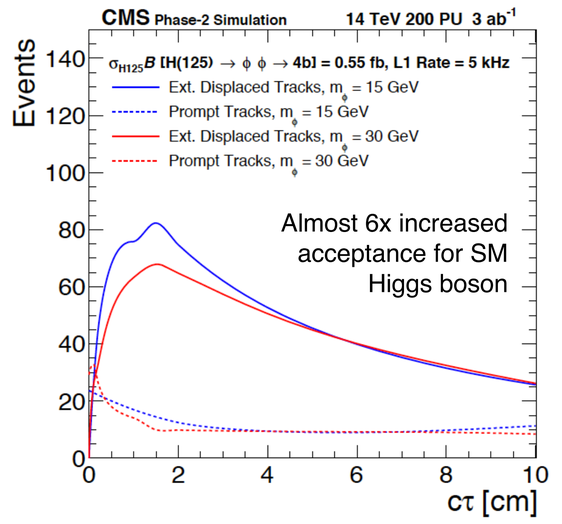




Displaced jets

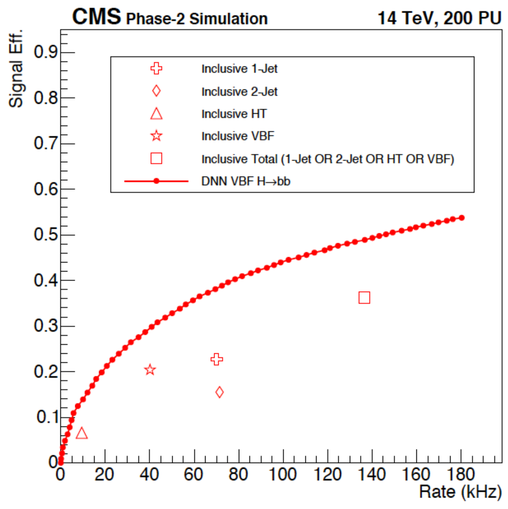
An extension of the L1 track-finding, clustering tracks without a beamspot constraint into jets provides a new handle to trigger on Beyond the Standard Model (BSM) physics. The improved L1 performance with the displaced jets can be seen in the evolution of the trigger rate versus the signal efficiency (right) and in the increased acceptance (left) for the SM Higgs boson.





Machine learning and particle-flow

The thresholds used by the Phase-1 L1 trigger for the dedicated VBF trigger algorithm can remain similar for HL-LHC by using particle-flow reconstructed jets. Moreover, the signal acceptance can be significantly improved: use of a deep neural net (DNN) outperforms all cut-based algorithms for an inclusive VBF $H \to b\bar{b}$ trigger, with an efficiency of 0.49 compared to 0.36 for the cut-based triggers (right).



Scouting system

Trigger scouting: harvests physics objects produced at various levels of the trigger system, only storing high-level information. This system has the advantage of systematically searching for correlations among sequential bunch crossings, and can be used to identify potential signatures unreachable through standard trigger processes. Will provide real-time trigger component diagnostics and could benefit a variety of physics channels:

- Rare Higgs decays
- Displaced muons for long-lived particle studies
- Single-τ final states
- Soft hadron final states
- QCD measurements with high statistics

[1] CMS Collaboration, The Phase-2 Upgrade of the CMS Level-1 Trigger, CERN-LHCC-2020-001, CMS-TDR-20-001 (2020)