The CMS Level-1 muon trigger for the LHC Run II

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Introduction - LHC Conditions

During its second run of operation, LHC delivered proton-proton collisions at a centre-of-mass energy of 13 TeV with **a peak instantaneous luminosity larger than $2{\cdot}10^{34}$ cm^{-2}s^{-1}**, more than twice the peak luminosity reached during the Run I and far larger than the design value. The upgraded CMS Level-1 trigger improved the performance at high luminosity and large **number of simultaneous inelastic collisions per bunch crossing (pile-up, PU), which averaged 55 at the beginning of each fill.**

The Upgraded CMS L1 Muon Trigger

Hardware-based Level-1 Trigger (L1) is the **first part of the CMS Trigger system**, which **reduces the collision event rate of 40 MHz delivered by LHC down to 100 kHz** that is sent to the High Level Trigger (HLT). The average output rate of HLT is 1 kHz. Level-1 Trigger receives **input from muon systems (DT, RPC, CSC), and from the calorimeters (ECAL, HCAL, HF).** L1 consists of two parts; muon track finders (MTFs) and calorimeter triggers (Calo Layer-1 plus Layer-2) which both send data to the global trigger (GT).

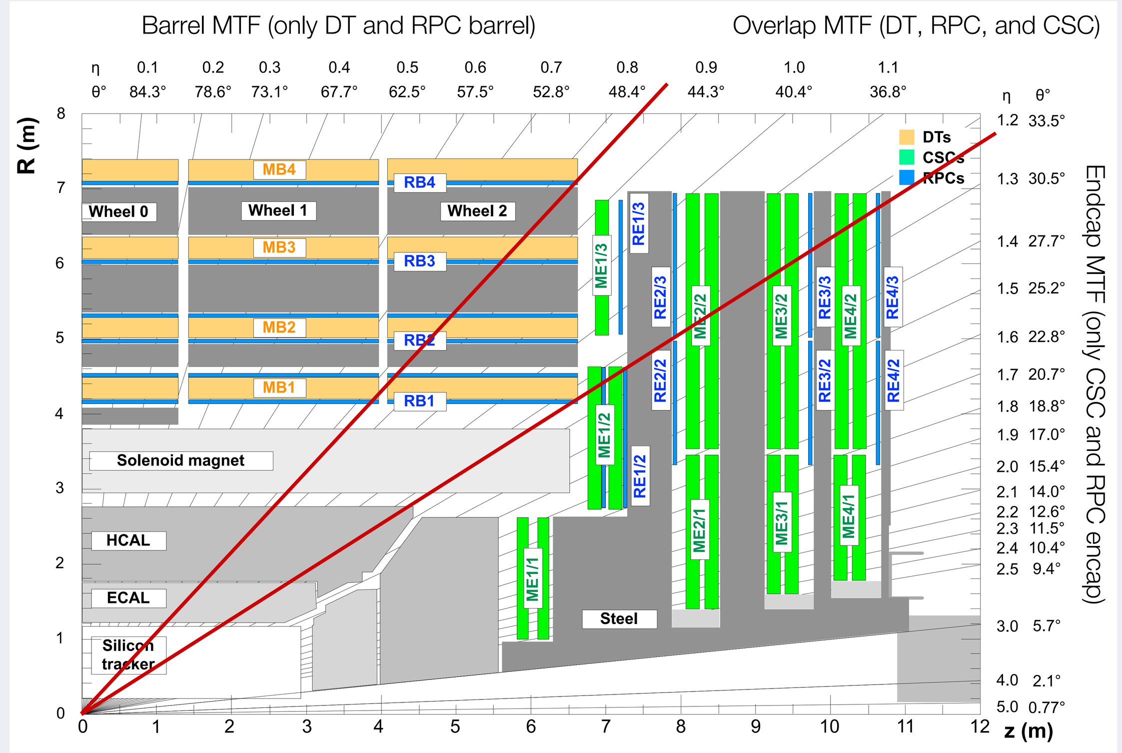

Figure 2: Muon track finder coverage for a quarter of the CMS (longitudinal view), displayed with the DT, RPC and CSC detectors. The approximate boundaries between the three track finders are marked with the red lines.

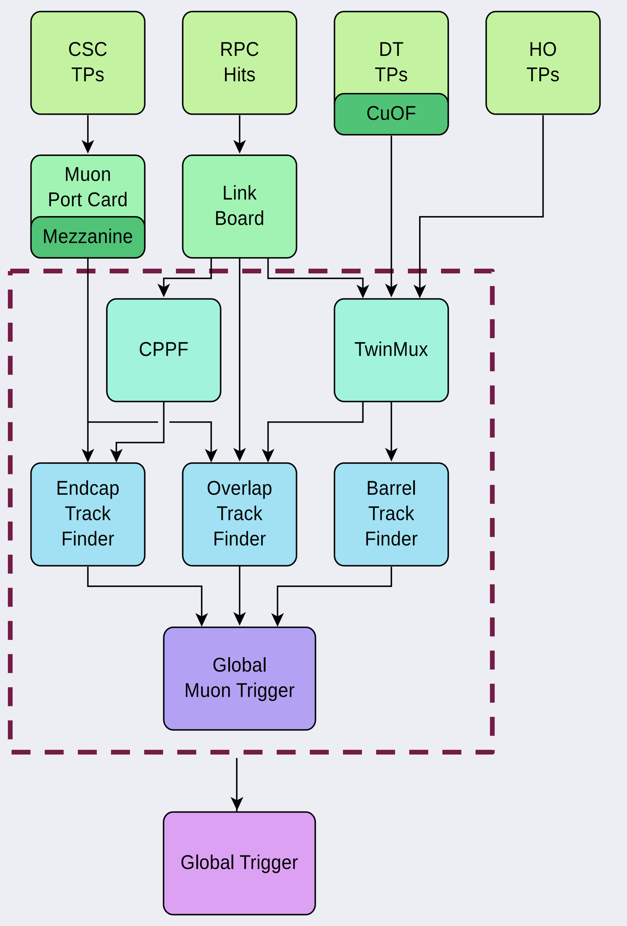

Figure 1: Full system of the L1 Muon Trigger in 2017. The HCAL outer barrel part (HO) trigger primitives (TPs) were sent to TwinMux but not used for triggering in 2017.

The upgraded muon trigger achieves more accurate transverse momentum (p_T) calculation, increased efficiency, and much lower rates by combining hits from DT, RPC, and CSC in the muon track finders. Pattern-based (overlap MTF) and BDT algorithms (endcap MTF) are implemented directly on the trigger boards, allowing high-momentum signal muons to be distinguished from the overwhelming low-momentum background.

The global muon trigger (GMT) sorts and cancels duplicate muons.
As L1 does not use tracker information, **the muon track extrapolation to the vertex was added in the GMT in 2017 to measure the muon coordinates more precisely.** Estimating the muon coordinates at the vertex is based on the muon pT, η, and charge. **Improvements are observed in variables that are sensitive to the measurement of the muon coordinates, for example the dimuon invariant mass resolution.**

Compared to Run I, the global trigger offers an increased selectivity, and richer menu. It can receive more candidate objects, and allows at least twice as many algorithms as before. The upgrades also include the possibility to add dedicated cross-triggers adapted to each physics analysis group, and to implement sophisticated algorithms using the invariant mass.

Muon Track Finder Algorithms

All algorithms are implemented in custom electronic boards following the Micro Telecommunications Computing Architecture (MicroTCA) standard. The GT and GMT use the Master Processor 7 (MP7) that is based on **Virtex-7. The barrel MTF uses MP7** cards, whereas **the overlap and encap MTFs are based on Modular Track Finder 7 (MTF7)** cards. Each MTF forwards three best track candidates to the GMT.

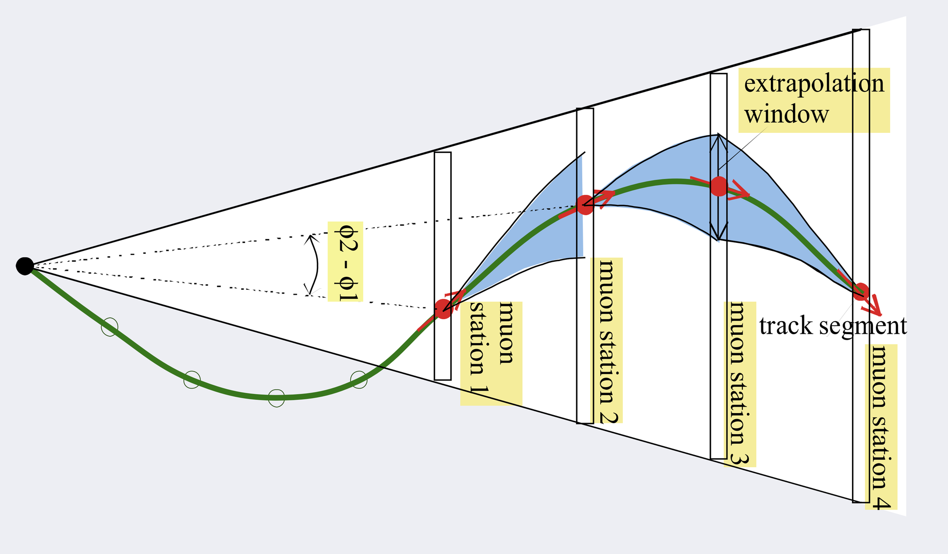

Figure 3: In the barrel, DT track segments and RPC hits are combined into so-called *super-primitives.* The barrel MTF constructs muon tracks using the super-primitives by searching for compatible segments in extrapolation window. Candidate kinematics are read from LUTs implemented in FPGA.

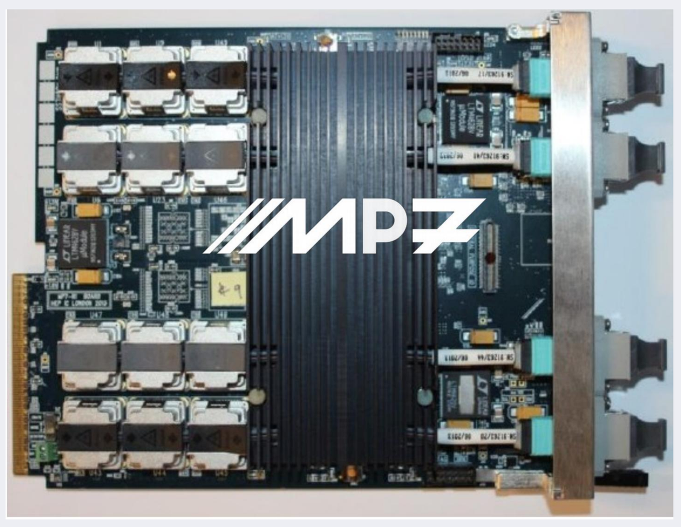

Figure 4: High performance stream processing board MP7, developed by Imperial College, is used in the GT and GMT. The barrel MTF also uses MP7 cards.

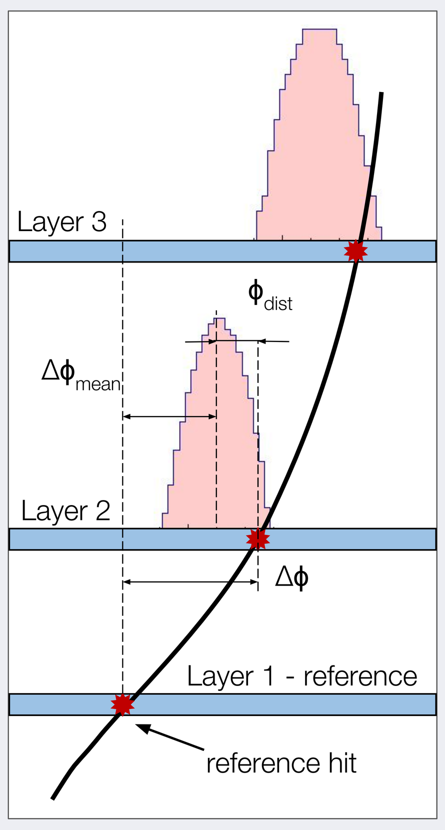

Figure 5: The overlap MTF combines simultaneously DT, RPC, and CSC primitives into single tracks using a Golden Pattern (GP) algorithm. The hit pattern is compared to a limited number of pre-computed hit patterns. These GPs hold information about the bending distribution in each layer for a given muon p_T. Several reference hits can be used, each yielding in an alternative muon p_T hypothesis. The track parameters of the GP closest to the actual hit pattern are chosen. The final result is cleaned from fakes and duplicates.

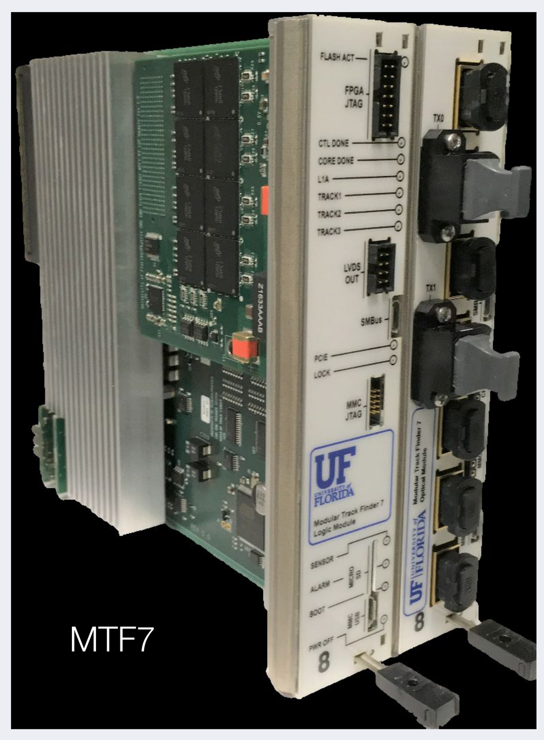

Figure 6: The endcap MTF uses information from both CSC and RPC. Pattern recognition process selects candidate track hits in a given bunch-crossing. All track segments are compared to predefined patterns, requiring a sufficient number of matches to declare a potential track. Offline BDT studies are performed to fill the p_T LUTs. To achieve this, the endcap MTF has a special MTF7 with a fast and large (GB) memory unlike the two other MTFs.

Rate reduction and overall efficiency

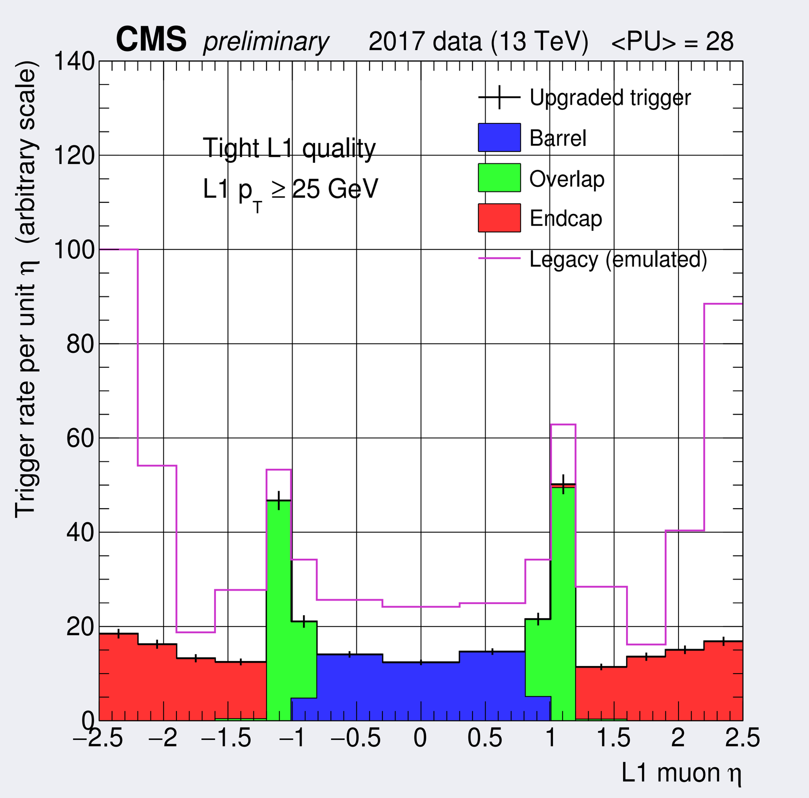

Figure 7: The distribution of muons per unit η passing a p_T threshold of 25 GeV, built by the three track finders (barrel, overlap, and endcap) in the upgraded L1 muon trigger (2017), and compared with the emulated legacy trigger (2015), in arbitrary units. The rate reduction is 50% for a p_T threshold of 25 GeV. The most common single muon trigger threshold used in CMS in 2017 was 25 GeV.

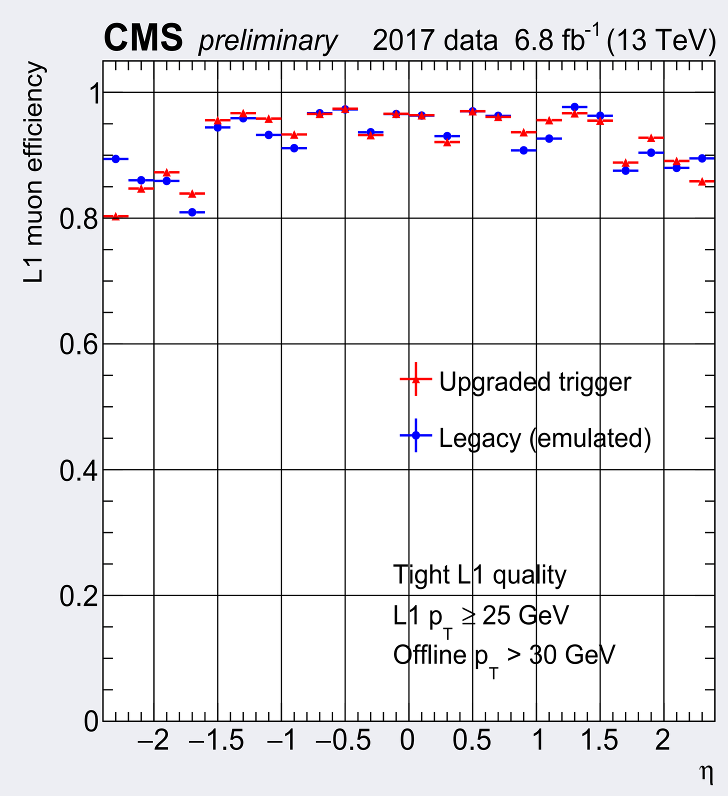

Figure 8: Trigger efficiency vs. offline muon η for a p_T threshold of 25 GeV, compared between the upgraded (2017) and legacy (2015) systems. Tight quality cuts are used, removing L1 muons from the endcaps with trigger primitives from fewer than three stations. In 2017 the efficiency was lower in the negative endcap region due to the water leak problem that disabled two muon chambers in the first station, each covering 10° in ϕ.

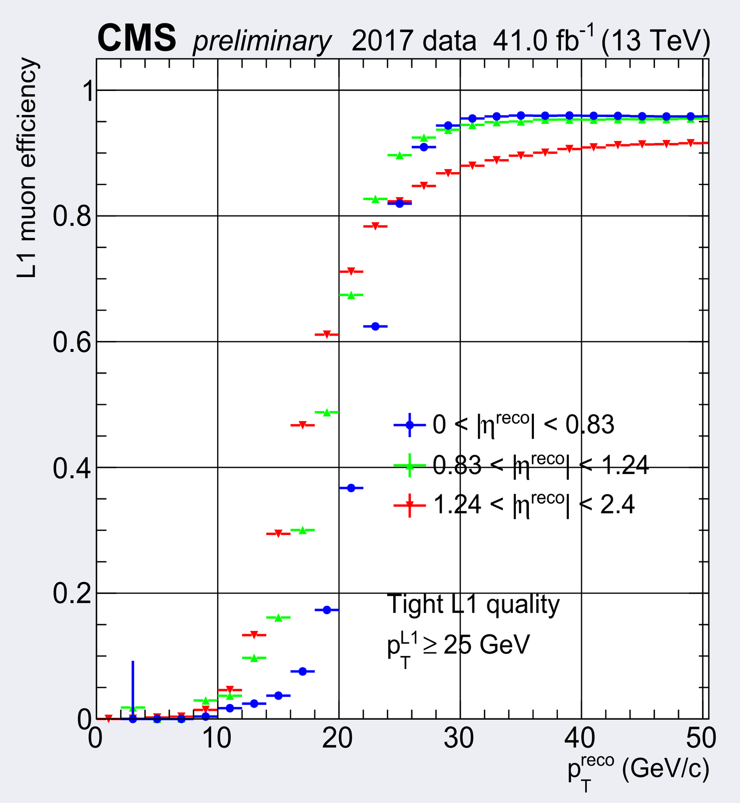

Figure 9: Trigger efficiency vs. p_T for the barrel (blue), overlap (green), and endcap (red) track finder regions. The turn-on curve is the sharpest in the barrel where the magnetic field is the strongest. The track finders are independent hardware trigger systems that build tracks and assign transverse momentum using only muon chamber information.

Dimuon performance

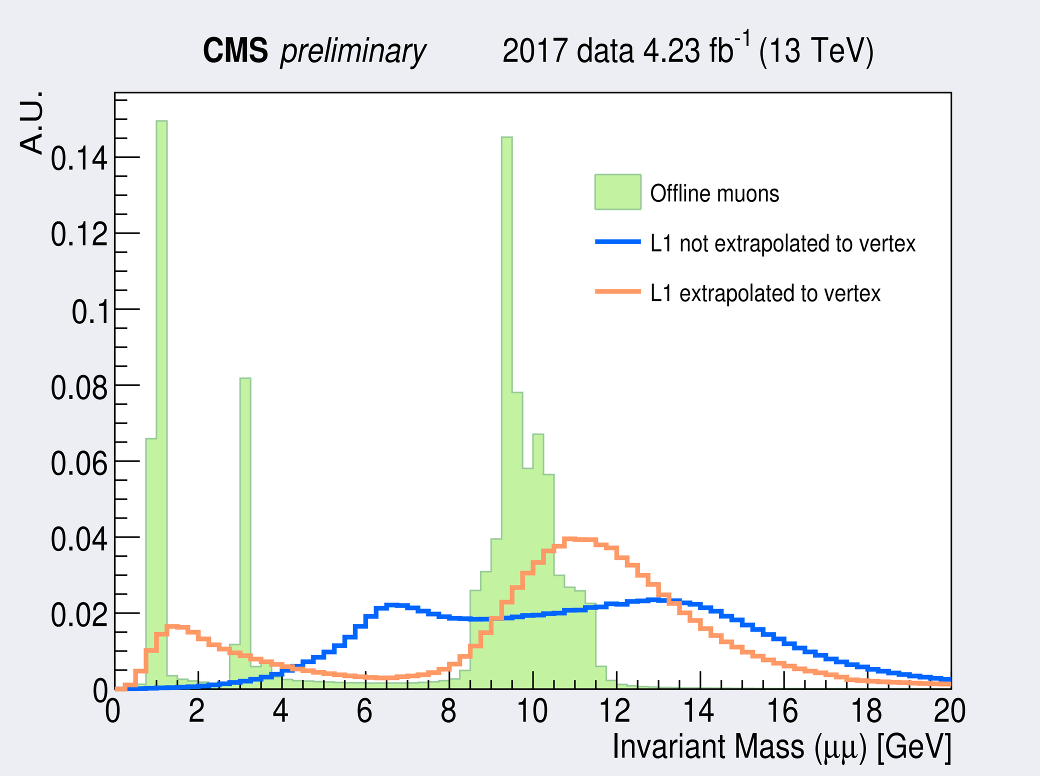

Figure 10: The invariant mass spectrum of two offline muons (green), compared to the same spectra of two online muons with (orange) and without (blue) L1 track extrapolation to the vertex. The muon track extrapolation to the vertex (added in 2017) improves the L1 dimuon invariant mass resolution. The online spectrum appears shifted compared to the offline spectrum due to p_T offsets designed to make the L1 muon trigger 90% efficient at any given p_T threshold.

References:

1. CMS Collaboration, "CMS Technical Design Report for the Level-1 Trigger Upgrade", CERN-LHCC-2013-011, CMS-TDR-12, https://cds.cern.ch/record/1556311.
2. Level-1 Trigger Public Performance Results, and references therein, https://twiki.cern.ch/twiki/bin/view/CMSPublic/L1TriggerDPGResults.

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