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New CMS Trigger Strategies for the Run 3 of the LHC

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The Compact Muon Solenoid (CMS) experiment at the Large Hadron Collider (LHC) features a sophisticated two-level triggering system composed of the Level-1 Trigger (L1T), instrumented by custom-design hardware boards, and the High Level Trigger (HLT), a software based trigger based on the complete event information and full detector resolution. The CMS L1T relies on separate calorimeter and muon trigger systems that provide jet, e/γ, τ, and muon candidates along with computations of energy sums to the Global Trigger, where selections are made based on the candidate kinematics. During its second run of operation, the L1T hardware was entirely upgraded to handle proton-proton collisions at a center-of-mass energy of 13 TeV with a peak instantaneous luminosity of $2.2 \cdot 10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$, more than double the design luminosity of the machine. For the Run 3 of the LHC, an optimized and expanded L1T and HLT physics menu has been developed to meet the requirements of the ambitious CMS physics programme. A wide range of measurements and searches will profit from the new features and strategies implemented in the trigger system. Dedicated variables and non-standard trigger techniques targeting Long Lived Particles searches and other unconventional physics signatures have been developed. Moreover, the implementation of new kinematic computations at the trigger level will improve B physics measurements and resonance searches. This talk will present these new features along with their expected performance measured on benchmark physics signals.

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1. CMS Trigger System in Run 3 of the LHC

After a very successful physics programme during the second run of operation of the LHC (2015-2018), the CMS experiment [1] has improved many features of its trigger system to increase the physics reach of the experiment. The CMS trigger system [2] is designed to select interesting physics processes out of 40 MHz of LHC collisions using a two-level trigger: The hardware-based Level-1 Trigger (L1T) [3] is implemented on custom design electronics, and the software-based High Level Trigger (HLT) runs on commercial computer farms. The L1T selects interesting collision events with a latency of about 4 μs using a reduced readout from the detectors. Events are then further processed at HLT using the full detector readout with simplified reconstruction. The events selected by the HLT are fully reconstructed to be used in physics analyses.

For the Run 3 of the LHC, the maximum output rate of the L1T was increased to 105 kHz in 2022 and then to 110 kHz in 2023 from the design value of 100 kHz, which allowed CMS to add new L1T algorithms that target rare and unconventional signatures. The HLT farm was upgraded to add GPUs that run as coprocessors to the existing CPUs, and the output rate of the HLT was increased to around 5 kHz in Run 3 from around 1.5 kHz in Run 2 for full offline reconstruction. In addition to fully reconstructed data, another data stream called HLT data scouting is used to record events at a higher rate but only using HLT reconstruction. HLT data scouting was extended to all physics objects with an output rate of around 22 kHz for Run 3, which allows CMS to record a significant portion of the L1T output rate for physics analyses. Furthermore, a 40 MHz L1T scouting system was added to the CMS trigger and data acquisition (DAQ) systems to potentially broaden the physics reach of CMS by recording the simplified detector readout from all collisions events without using a trigger decision [4].

The following sections will describe the new features added to the CMS L1T and HLT systems for Run 3, and the changes to the trigger algorithms that enable the ambitious physics programme of the CMS experiment in Run 3 of the LHC.

2. New Features in Level-1 Trigger

The CMS L1T was expanded to include many new features in Run 3 of which a few examples are described in this section. These new features and triggering techniques extend the CMS reach to interesting topologies, benefiting from the flexibility of the L1T system.

One main focus in Run 3 is to extend the CMS capabilities to trigger on particles originating from the decays of long-lived particles (LLPs). Upgrades of the CMS hadronic calorimeter (HCAL) allow for the identification of calorimeter deposits that are delayed in time or occur in higher depths of the HCAL. This timing and depth information can be used to trigger on delayed and displaced jets that can originate from decays of LLPs. The L1 calorimeter trigger receives the LLP jet flag from the HCAL, and new L1T algorithms were created in Run 3 that use this information to trigger on LLP jets to increase acceptance to such signals.

The CMS muon trigger estimates the muon p_T based on the curvature of the muon track from hits in CMS muon detectors. The p_T estimation methods normally have an implicit constraint that the muon track originates from the collision point ("beamspot") for optimal resolution. This "vertex constrained p_T" estimate can lead to an underestimation of the p_T of muons that originate from a displaced secondary vertex. In Run 3, new algorithms that can estimate the "vertex unconstrained p_T" were added to the CMS muon track finders. In the barrel region of CMS ($|\eta| < 0.83$), the Kalman Barrel Muon Track Finder (kBMTF) [5] algorithm that was integrated in 2018 is now the baseline algorithm for Run 3. This algorithm uses a Kalman Filter method to estimate both the vertex constrained and vertex unconstrained p_T of the muon as well as its transverse distance from the beamline d_0. Although, the vertex constrained p_T assignment is highly efficient (> 90%) for muons with a transverse displacement smaller than 40 cm, the efficiency falls rapidly for $d_0 >$ 40 cm. However, the vertex unconstrained p_T assignment retains a high efficiency of above 80% up to a muon track displacement of 100 cm, as shown in Figure 1 (left). Vertex unconstrained p_T assignment algorithms in the overlap ($0.83 < |\eta| < 1.24$) and endcap ($1.24 < |\eta| < 2.4$) regions are still under development and will be enabled at a later point in Run 3.

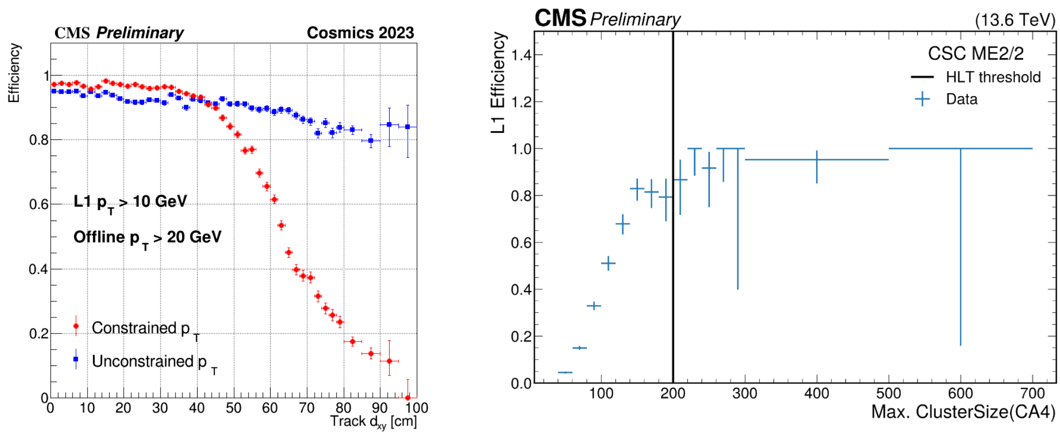

Figure 1: The trigger efficiency of kBMTF algorithms with vertex constrained p_T (blue) and vertex unconstrained p_T (red) as a function of muon track d_{xy} measured using a sample of cosmic ray muons in 2023 (left) [6]. L1 HMT efficiency as a function of the largest CSC hit cluster size reconstructed at HLT (right) [7].

In addition to algorithms targeting displaced muons, a new way of targeting LLPs in muon systems was developed for Run 3. This algorithm is based on a high multiplicity of hits in the cathode strip chambers (CSCs) of the endcaps that are caused by LLP decays beyond the CMS calorimeter systems. The CSC chambers flag any event with a hit multiplicity above a set threshold, and this information is then used in the endcap muon trigger to select events with a high multiplicity of CSC hits. This high multiplicity trigger (HMT) has been implemented since the start of Run 3 in the L1T and HLT, and it shows near 100% efficiency of triggering on events with very high hit multiplicity in CSC chambers as shown in Figure 1 (right).

Finally, new kinematic computations are implemented in the final stage of the L1T, called the global trigger (GT), to compute three-body invariant mass and also the ratio of invariant mass of two objects (m_{inv}) and their separation $\Delta R = \sqrt{\eta^2 + \phi^2}$. The three-body invariant mass computation is used in triggers targeting the decays of τ leptons to three muons, allowing for lower muon p_T thresholds, while the $m_{\mathrm{inv}}/\Delta R$ ratio is used to improve dimuon resonant searches for dark photon signals.

3. New Developments at HLT

For Run 3, a number of new algorithm developments were implemented at HLT to improve HLT performances and to utilize new L1T features. A new tracking algorithm, which performs tracking in a single global iteration with hits recorded by the pixel and strip trackers, is now the default algorithm at the HLT. This algorithm is seeded by pixel tracks reconstructed by the Patatrack algorithm [8] that can run on the new GPU farms. The new single iteration tracking at HLT offers improved performance compared to the three iteration algorithm of Run 2, despite having fewer iterations and less computing time required.

Two new neural network (NN) algorithms, DeepJet [9] and ParticleNet [10], were deployed at HLT for Run 3, which offer improved performance in jet flavor identification which is essential for many CMS searches. These algorithms have much lower jet flavor misidentification rates compared to the DeepCSV algorithm [11] which was used in Run 2. DeepJet provides a misidentification rate reduction of around a factor of 3 compared to DeepCSV, and ParticleNet provides an additional factor of 2.5 compared to DeepCSV.

In addition to the improvements on reconstruction and identification algorithms, there are also new HLT algorithms targeting LLPs. Some of the displaced jet triggers that existed in Run 2 enhanced their tracking algorithms allowing significant improvements compared to Run 2 for LLP masses below 100 GeV. New delayed jet triggers were implemented, by taking advantage of the newly available electromagnetic calorimeter (ECAL) timing information at the HLT, to reduce the existing thresholds as seen in Figure 2 (left). The ECAL timing information based triggers are fully efficient for jets with delays of more than 4 ns as seen in Figure 2 (right), and improve the signal efficiency significantly compared to the triggers used in Run 2.

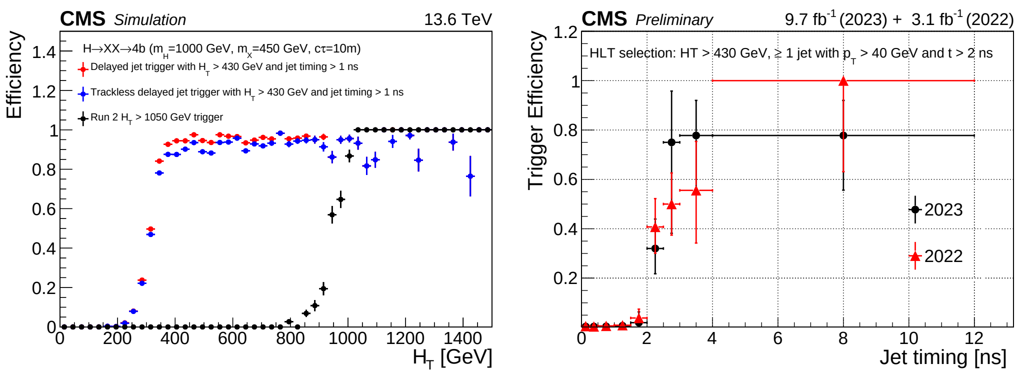

Figure 2: Trigger efficiency for a signal model H→ XX → 4b with m_H = 1000 GeV, m_X = 450 GeV, and $c\tau$ = 10 m comparing inclusive (trackless) delayed jet triggers added in Run 3 in red (blue) against triggers used in Run 2 (black) (left). Trigger efficiency as a function of jet timing for 2022 and 2023 data taking periods shows a clear turn-on feature, reaching 100% at 4 ns (right) [12].

New HLT paths that target LLPs were implemented by using the new L1T information for HMTs, displaced muons, and displaced and delayed jets. Several new algorithms are now included at HLT to reconstruct clusters in CSCs in the endcap and drift tubes (DTs) in the barrel for events that were triggered with HMT at L1T. These new HLT paths increase the signal efficiency for neutral LLPs that decay beyond the calorimeters up to a factor of 20 depending on the signal model under scrutiny. The displaced muon triggers in the HLT now use the L1 triggers that are based on the vertex unconstrained p_T assignment in the barrel to improve the signal efficiency for LLPs with long lifetimes. Additionally, these triggers now veto prompt backgrounds more efficiently thus allowing for lower p_T thresholds at the HLT. The resulting improvements lead to a factor of 2 to 4 improvement in signal efficiency for LLPs decaying to dimuons compared to the Run 2 triggers. These displaced muon triggers were used in the first CMS search in Run 3 data, which shows results comparable to the ones obtained with full Run 2 data despite using a third of the integrated luminosity [13].

4. Improvements to Data Parking and Scouting

The computing resources required for full offline reconstruction of data is one of the limiting factors of the HLT output rate. In CMS, an alternative approach, called data parking, is used to increase the amount of data stored by delaying the reconstruction of data until computing resources are available. Data parking was already used in CMS in Run 1 and Run 2 to record data to be used mainly in B physics analyses [14]. In Run 3, the output rate for data parking strategy is increased to around 3 kHz from few hundred Hz in Run 2 to record data targeting VBF Higgs production, HH → 4b searches, and LLP hadronic decays in addition to B physics searches. The new HLT parking paths use events selected by L1 triggers with lower thresholds compared to the regular HLT paths and have looser selection criteria at HLT. This increases signal efficiency for the physics searches, especially in low mass and low p_T regions of the phase space. Figure 3 (left) shows the improvement in trigger efficiency for the HH → 4b search due to the new data parking paths for signal events with two b-tagged jets.

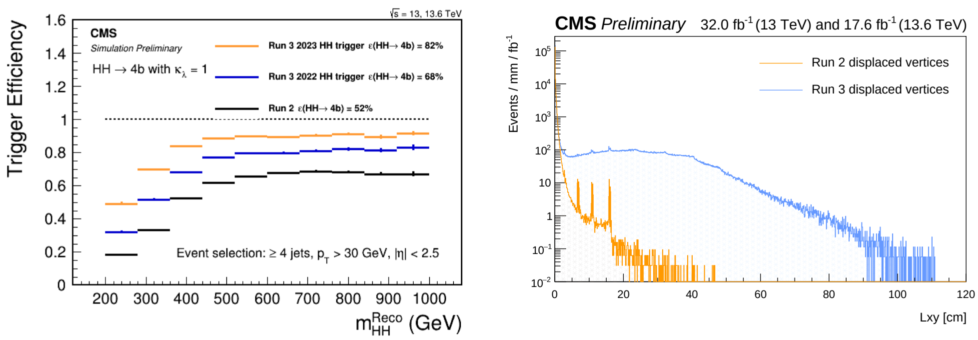

Figure 3: Trigger efficiency as a function of the invariant mass m_{HH} for the simulated Standard Model HH→4b process with $\kappa\lambda = 1$ shown for Run 2 (black), Run 3 2022 (blue) and Run 3 2023 trigger (orange) (left) [15]. Comparison between the transverse decay length (L_{xy}) distribution for Run 2 (orange) and Run 3 (blue) for events with opposite sign dimuon pairs with a shared displaced vertex (right) [16]. Far more events are collected in the high displacement phase space.

Another limiting factor for CMS trigger and DAQ systems is the bandwidth. The HLT output rate can be increased to higher values if the size of data per event is reduced. The HLT data scouting is a method of recording collision data at a very high rate with reduced event size due to using only HLT level reconstructed data instead of the full raw event data. Data scouting, which was first implemented in Run 1, is greatly improved for Run 3 to include all physics objects available at HLT at a significantly increased rate (22 kHz). Data collected by scouting triggers can access very low p_T objects that are otherwise not recorded in regular data, which makes data scouting a great tool for analyses targeting low p_T and low mass particles. Additionally, the improvements to displaced muon triggers available in data scouting now allow for larger muon displacements as shown in Figure 3 (right), which significantly increases the reach of low mass LLP searches in scouting data in Run 3.

5. Summary

The CMS trigger is greatly enhanced for Run 3 of the LHC, with many new and improved algorithms both at L1T and HLT. These improvements mostly target rare and unconventional signatures such as B physics, low p_T particles, Higgs physics, and LLPs. Furthermore, the expansion of data parking and scouting programs have allowed CMS to collect even more data for physics analyses than what would be available through regular data acquisiton methods. While Run 3 of the LHC will provide a similar amount of integrated luminosity as Run 2, the improved trigger algorithms and data recording strategies will increase the sensitivities of CMS searches far above the level that would be obtained by simply doubling the integrated luminosity delivered to CMS.

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