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New trigger strategies for CMS during Run 3

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The CMS experiment at the Large Hadron Collider (LHC) features a sophisticated two-level triggering system composed of the Level 1 (L1) trigger, instrumented by custom-design hardware boards, and the High Level Trigger (HLT), a software based trigger exploiting a complete event information and full detector resolution. The CMS L1 trigger relies on separate calorimeter and muon trigger systems that provide jet, e/γ, τ, and muon candidates along with calculations of energy sums to the global trigger (GT), where selections are based on the candidate kinematics. During Run 2, the L1 trigger hardware was entirely upgraded to handle proton-proton collisions at a center-of-mass energy of 13 TeV with a peak instantaneous luminosity of 2.2×10^{34} cm^{-2}s^{-1}, more than double the design luminosity of the machine. In view of Run 3 of the LHC, an optimized selection at both the L1 trigger and HLT is crucial to achieving the ambitious CMS physics program. A wide range of measurements and searches will benefit from the new features and strategies implemented in the trigger system. Dedicated variables and non-standard trigger techniques to target long-lived particles searches and identify unconventional physics signatures have been developed. Moreover, the implementation of new kinematic computations in the L1 GT will improve b physics measurements and resonance searches. This talk will present these new features and their expected performance measured on benchmark physics signals.

41st International Conference on High Energy physics - ICHEP2022
6-13 July, 2022
Bologna, Italy

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1. Introduction: triggering at CMS

The successful physics program of the CMS experiment [1] during the second run of operation of the CERN LHC (2015-2018) targeted many different areas of interest to the high energy physics community, ranging from precision measurements of the standard model (SM) to searches for physics beyond the standard model (BSM). The Run 2 dataset collected by the LHC experiments opened the era of the Higgs boson precision measurements. Nowadays, at the start of LHC Run 3, the investigation of the Higgs sector through precision measurements looking for deviations from the SM expectations still represents a crucial topic in particle physics. On the other hand, searches for new phenomena are a powerful tool for discoveries.

The collection of good data to serve up the large variety of CMS analyses highly relies on an efficient trigger system [2], able to separate the interesting processes in the huge amount of background events provided by the proton-proton (p-p) collisions at the LHC. In fact, the LHC machine collides bunches of particles in the CMS and ATLAS experiments at a rate of about 40 MHz, but only a small portion of data is recorded for the offline analysis. The CMS trigger was designed to run at the highest luminosity of the LHC and optimize the SM Higgs boson search. The first step of the trigger decision happens in the L1 custom-design hardware boards able to take a fast decision with a latency of 4 μs and reduce the rate from 40 MHz to 100 kHz [3]. The second step at the HLT further reduces the rate at a level of about 1 kHz in a few hundred milliseconds, keeping a complete event information and full detector resolution.

The LHC Run 3 is expected to double the integrated luminosity of Run 2 aiming to reach the highest luminosity during the three years of operation and planning to maintain the maximum instantaneous luminosity for several hours at the beginning of each fill. The center-of-mass energy of the p-p collisions is increased to 13.6 TeV and the number of simultaneous collisions in a single bunch crossing (pileup) is expected to be larger than the Run 2 average (47 or 52 during 2022 versus 38 during 2018). In order to fully exploit the new incoming data, new trigger strategies are needed.

The first part of this work will focus on the optimized trigger system of the CMS detector on both the L1 and HLT sides and on the new developments for Run 3. In the second part, the highlights of the physics program that drove the preparation of the new list of algorithms and selection criteria, collectively called trigger menu, will be presented.

2. An optimised trigger system for the CMS detector during Run 3

New trigger strategies are needed to help the direct and indirect searches for new physics. The main focus of the Run 3 developments was the flavour physics program and the B parking strategy, new algorithms to target long-lived particles (LLP) signatures, and the enhancement of the sensitivity of Higgs analyses in particular in the context of the searches for double Higgs production. The possibility to design and optimize dedicated algorithms implied various developments both at the hardware and software level that will be presented in the next sections.

2.1 New features for new trigger strategies at L1

A large effort was invested during the second long shutdown (LS2) to develop new features at L1 and new trigger algorithms oriented to the LLP signatures and rare signals at L1. The upgraded

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HCAL detector provides new information for the L1 calorimeter objects, such as the timing and deposit depth, that can be exploited in the subsequent data processing The HCAL electronics was upgraded to read out in four depths in the barrel region and up to seven in the endcap. Moreover, good timing capabilities are provided by the new Time-to-Digital converter (TDC) with a resolution of 0.5 ns. These improvements are exploited to design a LLP jet identification algorithm to target delayed and displaced jets, that are characterized by energy deposits in deep calorimeter layers and little energy in the early depths, and delayed time of arrival of hits. In addition, the ECAL detector developed a double amplitude weights mechanism [4] in order to provide at the same time the correct amplitude for in-time signals and a larger amplitude to target out-of-time signals. This new feature is useful not only to tag delayed objects, but also to improve the removal of ECAL spike pulses. Figure 1 (left) shows the fraction of spike energy removed by the double weights algorithm as a function of the energy for two different double weights working points. A subtraction of more than 95% of the trigger tower energy for out-of-time spikes with a transverse energy of 5 GeV is achievable. Finally, a new way of targeting displaced particles looking for hadronic muon showers has been developed. The algorithms rely on counting hits in the cathode strip chambers (CSCs) looking for multiple track segments in a single chamber or neighbouring chambers.

Dedicated improvements for the LLP muon topologies have been also studied. The main limitation of the Run 2 algorithms is represented by the beamspot constrained measurement of the muon coordinates. The extrapolation of the track parameters back to the primary vertex led to the misreconstruction of the transverse momentum of muons from a long-lived particle. Moreover, muons with large displacements were sometimes not reconstructed at all at L1. The usage of new quantities like the unconstrained p_T and the invariant mass computation based on this quantity and of the new Kalman Barrel Muon Track Finder (kBMTF) allows a large gain in efficiency for muons with a large displacement, up to 80%, as measured in 2018 cosmics data and shown in Figure 1 (right) [5].

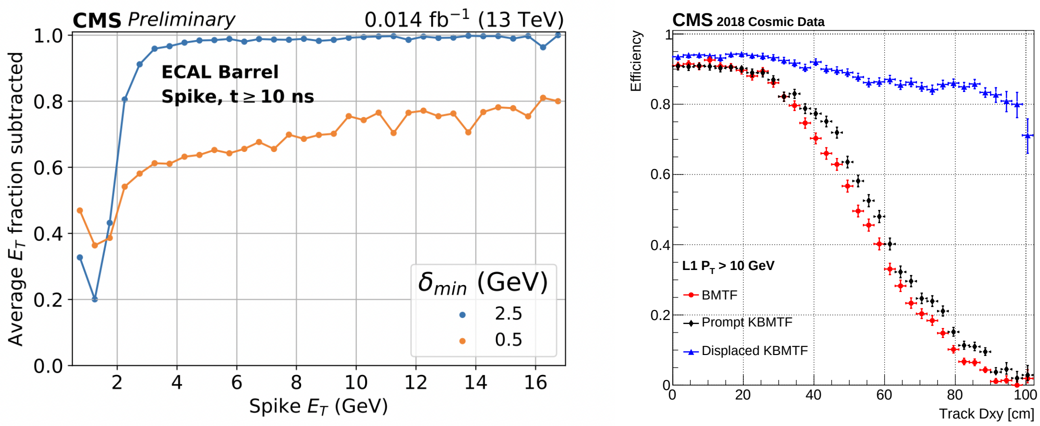

Figure 1: New L1 trigger features for Run 3: the ECAL double amplitude weights mechanism (left) [4] and the improved kBMTF algorithm for displaced muons (right) [5].

Finally, new kinematic computations in the GT have been implemented to improve the sensitivity and the rate reduction of specific triggers: the three-body invariant mass for muon final states, exploited to develop new triggers for the $\tau \rightarrow 3\mu$ search; the check of the coincidence between

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calorimeter objects (jets and τ) based on the angular separation with a corresponding removal logic to avoid to count two times the same object as different types and, consequently, improve the sensitivity of the jets+τ triggers.

2.2 Run 3 developments at HLT

During the LS2, many developments have been studied and integrated to improve the HLT capabilities and performances. First of all, a new tracking based on the optimized pixel track reconstruction, known as Patatrack [6], has been implemented. The better performance of the Patatrack algorithm for pixel tracking [8] has allowed to reduce the HLT tracking to a single-iteration approach. In addition, the tracking can also be offloaded to GPUs. The good performance of the Run 3 HLT single-iteration tracking are compared to the Run 2 HLT tracking in Figure 2. In the Run 3 HLT tracking, no track is reconstructed with $p_T \leq 0.3$ GeV. As a consequence, the total amount of fake tracks reconstructed in the Run 2 HLT tracking is sensibly larger with respect to Run 3. Many new LLP paths can take advantage from the new tracking that has been propagated to the muon reconstruction, the b tagging and τ tagging, and the B physics tracking.

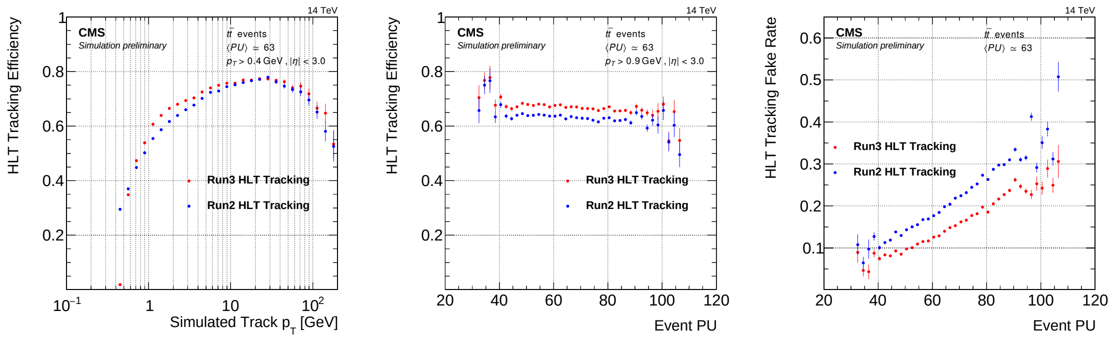

Figure 2: Performance of the Run 2 (blue) and Run 3 (red) HLT tracking: tracking efficiency as a function of the simulated track p_T (left), of the event pileup (middle), and tracking fake rate versus pileup (right) [8].

On the calorimeter objects side, more performant tagging capabilities of low level calorimeter objects and an improved τ reconstruction using pixel tracks can be exploited. The larger usage in trigger paths of new tagger algorithms like DeepJet [11], DeepTau [12], and ParticleNet [13], on top of the default algorithm represented by DeepCSV [14], and the training of these models based on the online reconstruction has improved the tagging performances. In Figure 3 (left), the b jet identification efficiency versus the jet misidentification rate is shown [8]. The offline and online performance of DeepJet (black and red solid curves) is compared with the corresponding dashed lines for DeepCSV. New τ triggers for $H \rightarrow \tau\tau$, $HH \rightarrow bb\tau\tau$, $H \rightarrow bb$, and MSSM $H \rightarrow bb$ will particularly benefit of these improvements.

On the muon side, a new muon reconstruction and inside-out and outside-in seeding based on machine learning have been implemented.

Finally, the performance of jets reconstructed with Patatrack pixel tracks as inputs to the particle flow (PF) is significantly improved [9], as shown in Figure 3 for the jet response (middle) and the charge multiplicity (right). The better quality of pixel tracks allows them to be used as input to the PF algorithm at higher rates, extending the reach of physics analyses to lower energies and weaker couplings.

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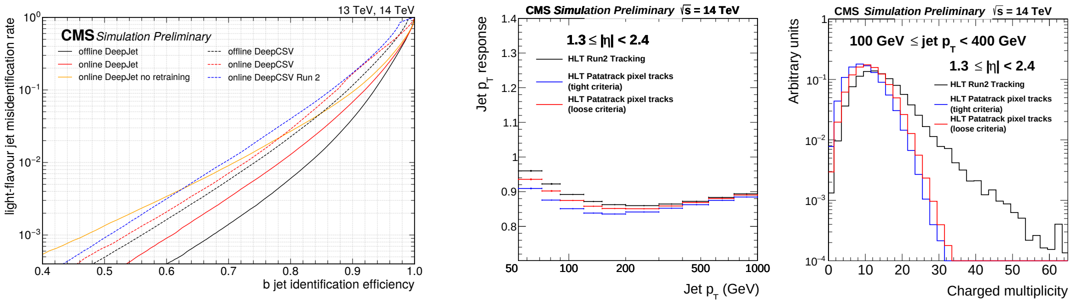

Figure 3: Performance of the new tagger algorithms used at HLT (left) [8]; improved jet response (middle) and charge multiplicity (right) for the new jet reconstruction based on the Patatrack pixel tracks [9].

All these developments will benefit from the new HLT farm developed for Run 3, that is composed of two-hundred nodes with 25600 CPU cores and 400 GPUs in total. The increased usage of GPUs allows to redesign the HLT algorithms for parallel architectures. For the start of Run 3, the calorimeter and pixel local reconstruction plus the pixel tracking have been ported to GPU and CMS is currently offloading 30% of the HLT reconstruction to GPUs. The GPU reconstruction has been implemented and fully commissioned during 2022, both offline and online.

3. An optimized trigger menu for the Run 3 physics program

All improvements mentioned above allowed to design dedicated algorithms to select collision events for the Run 3 physics program in different sectors. A selection of the main developments that drove the preparation of the new trigger menu is described below.

B physics program and the B parking strategy The significance of the B anomalies and of the breaking of lepton universality in beauty-quark decays has been strengthened by the latest LHCb results [15]. Any significant deviation of R(D^*), R(K), and R(K^*) from the unity would imply BSM physics. For this reason, the investigation of the B physics sector supported by a dedicated data-taking approach called B parking is particularly important for CMS. The parking strategy was already explored during 2018 and targeted the collection of a huge amount of $b\bar{b}$ events (10 billions in 2018) at high rate without prompt reconstruction due to the CPU limitations [10]. The goal of CMS for Run 3 is to contribute to the investigation of the R(K) anomaly exploiting a revised parking strategy based on double muon, double electron, and single muon triggers. The novelty of the CMS proposal for Run 3 is the inclusion of soft dielectron triggers with an angular distance requirement to ensure the collection of more $K \to ee$ events for the measurement.

Two other B physics processes have been targeted by the trigger developments for Run 3 as they offer an excellent opportunity to test the SM: the $B_s \to \mu\mu$ measurement and the $\tau \to 3\mu$ search. On one side, the $B_s \to \mu\mu$ process in $b \to sll$ transitions allows to perform precision tests of the lepton flavour universality with the advantage that SM contributions are suppressed, and the theoretical predictions are very precise. A dedicated dimuon trigger strategy have been developed by CMS to achieve a comparable sensitivity with LHCb during Run 3 given the expected increase of the statistics by a factor two and three respectively for the two experiments. On the other side,

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the $\tau \to 3\mu$ process is oriented to the study of flavour violation with charged leptons that is possible through neutrino oscillation and has been never observed so far. New double- and triple-muon algorithms with lower p_T thresholds will help to recover events in the endcap and improve the sensitivity, exploiting the three-muon invariant mass cut to have a better control of the trigger rates.

Exotic searches: LLPs and new resonances A large focus has been on the development of new triggers for the exotic searches, both for LLPs, predicted by many extensions of the SM, and for new resonances. Displaced muons and displaced jets searches in different final states will be largely affected by the new available features at L1: efficiency at high displacement (more than 80%) is highly recovered for muons, while for jets new hadronic showers triggers show an efficiency on non-prompt signatures from ~35% to ~65%. As an example of new resonances, the low mass diphoton searches are sensitive to different BSM scenarios at the LHC. They will profit from a new trigger strategy at L1: the thresholds of both the photons are lowered and a loose isolation cut and a spatial restriction to the barrel region are required to handle the rates.

4. Summary

Numerous new strategies were developed in the CMS trigger system, both at L1 and HLT, to start the LHC Run 3 in July 2022. As a result of these developments, an optimized trigger menu has been prepared including new algorithms to target a specific physics program, accounting for an additional rate from new L1 trigger algorithms around 19 kHz at the highest luminosity and a total HLT rate around 2 kHz. Performance measurements of the new L1 and HLT algorithms on the new data are being an important focus of the first year of data-taking in order to ensure a complete commissioning of the new CMS trigger for Run 3.

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