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Design of a Level-1 Long-Lived Particle Trigger in the CMS Hadron Calorimeter

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Abstract

The Hadron Calorimeter (HCAL) in the Compact Muon Solenoid (CMS) experiment at the Large Hadron Collider (LHC) was recently upgraded for Run 3 to introduce depth segmentation and online timing measurements, expanding the physics capabilities. In particular, the augmentation of the calorimeter information at the hardware trigger level enables quick identification and recording of long-lived particle decays using lower thresholds on energy-based event quantities. The depth segmentation and online timing capabilities are utilized in novel HCAL-based hardware-level triggers to identify displaced and delayed long-lived particles (LLPs), either decaying inside the calorimeter volume or arriving at a delayed time. This increases the sensitivity to LLP decays occurring up to almost 6 m from the collision point. This two-pronged calorimeter trigger approach leverages the new capabilities of the CMS HCAL to expand the phase space accessible in ongoing LLP searches. These triggers were deployed for Run 3 of the LHC, beginning data-taking in 2022, and we review the trigger implementation and calibration.

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Design of a Level-1 Long-Lived Particle Trigger in the CMS Hadron Calorimeter

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The Hadron Calorimeter (HCAL) in the Compact Muon Solenoid (CMS) experiment at the Large Hadron Collider (LHC) was recently upgraded for Run 3 to introduce depth segmentation and online timing measurements, expanding the physics capabilities. In particular, the augmentation of the calorimeter information at the hardware trigger level enables quick identification and recording of long-lived particle decays using lower thresholds on energy-based event quantities. The depth segmentation and online timing capabilities are utilized in novel HCAL-based hardware-level triggers to identify displaced and delayed long-lived particles (LLPs), either decaying inside the calorimeter volume or arriving at a delayed time. This increases the sensitivity to LLP decays occurring up to almost 6 m from the collision point. This two-pronged calorimeter trigger approach leverages the new capabilities of the CMS HCAL to expand the phase space accessible in ongoing LLP searches. These triggers were deployed for Run 3 of the LHC, beginning data-taking in 2022, and we review the trigger implementation and calibration.

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[*] Speaker

1. Introduction

Long-lived particles are a well-motivated and promising direction to search for new physics, and appear often in models describing the particle nature of dark matter. Searches for long-lived particles (LLPs) are often limited by trigger selections assuming that particles originate from the interaction point. However, LLPs can travel millimeters to meters before decaying into observable particles. LLPs may also have a delayed arrival time due to either their slow-moving velocity or an increased path length traversed (as compared to a direct path from the collision to detector). Thus, dedicated triggers sensitive to these displaced and delayed decays are needed. The first hardware level LLP trigger was implemented in the Compact Muon Solenoid (CMS) experiment for Run 3 (2022-2026) of the Large Hadron Collider (LHC), using upgrades of the hadron calorimeter (HCAL).

The CMS experiment is designed for precision Standard Model measurements and new physics searches, using the information recorded by each subdetector about the proton-proton collision [1]. The initial event selection occurs in the two-tiered trigger system, reducing the event rate from 40 MHz to 100 kHz at Level 1 (L1, hardware) and to ≈5 kHz at the high level trigger (HLT, software). Recent upgrades of the HCAL made it possible to implement an LLP trigger at L1. The HCAL is made of alternating scintillator and brass absorber layers and was upgraded for Run 3 to include a precision timing ASIC, programmable front-end electronics, and depth segmentation in the barrel (HB) and endcap (HE) [2]. The dedicated ASIC, a QIE11 chip, reports pulse arrival time, and combined with the depth segmentation, this enables the identification of LLP decays.

2. Trigger Algorithm and Design

The upgraded HCAL reports time and energy from four depth layers in the barrel. This segmentation provides sensitivity to the shower profile, particularly for displaced jets resulting from LLPs decaying in the calorimeter volume (Figure 1). The pulse arrival time identifies jets delayed by multiple ns. The trigger sensitivity to displaced and delayed jets is detailed in [6].

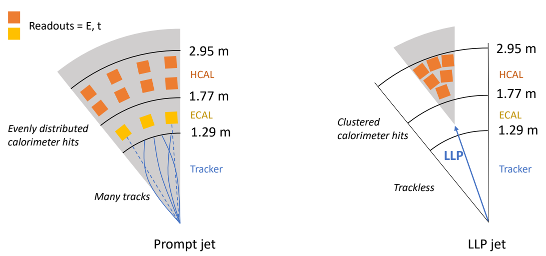

Figure 1: Diagram of a prompt jet (left) producing evenly distributed hits in energy and time in the calorimeters, as compared to a displaced LLP jet (right) producing very clustered hits in the hadron calorimeter.

From each HCAL cell (a single depth, $i\eta$, and $i\phi$), an energy and time (TDC) measurement is reported. The $i\eta$ and $i\phi$, both with a width of $\Delta\eta = \Delta\phi = 0.087$, refer to HCAL towers, with each barrel (endcap) tower having four (seven) depths. The TDC reported from each cell is 6 bits (in 0.5 ns steps), but in HB this is reduced to 2 bits in a LUT, reporting "prompt", "slightly delayed", "delayed", and no TDC. The boundary between prompt and slightly delayed is set at 6 ns (in 2024, this is changed to 9 ns for depth 1 only).

The HCAL LLP trigger identifies HB trigger towers with significant energy in higher depths and little energy in lower depths ("depth flagged", for displaced jets) or with pulses arriving at late times ("timing flagged", for delayed jets). The depth-flagged towers require $>$ 5 GeV in either HCAL depth 3 or 4, and $<$ 1 GeV in both HCAL depth 1 and 2. For the timing-flagged towers, at least one delayed

(> 6 ns) and energetic hit (> 4 GeV) is required, and the tower must not have any prompt (≤ 6 ns) and energetic (> 4 GeV) cells ("prompt veto" to reduce backgrounds). Four HCAL uHTR bits save the depth and timing results. The logical `OR` of the depth and timing flagged towers is reported as a 1-bit LLP flag per HB tower, and the L1 jet algorithm requires two or more flagged towers per jet (Figure 2). After passing jet- and event-level kinematic selections, LLP-flagged L1 jets seed several dedicated HLTs [4]. The L1 triggers are of the form `L1_HTT*_SingleLLPJet*` (with HTT thresholds as low as 120 GeV, and jet E_T thresholds as low as 40 GeV) and `L1_DoubleLLPJet40`, and the implemented Run 3 HCAL-based LLP L1 and HLTs are listed in Tables 7 and 8 of Ref. [5].

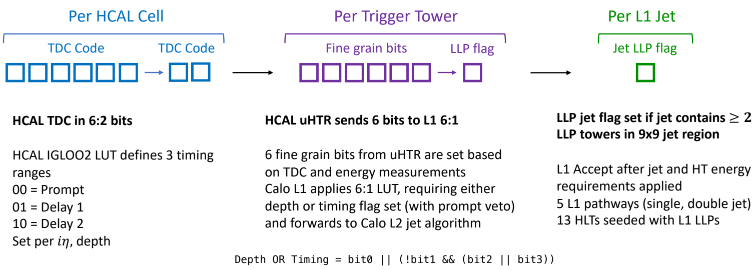

Figure 2: Diagram of the information flow from the HCAL energy and time measurements (blue) through the HCAL uHTR, reporting six fine grain bits per trigger tower. The L1 6:1 LUT (purple) reduces this to a one-bit LLP flag per trigger tower. The L1 jet algorithm (green) sets one bit per jet if at least two flagged towers are included within the 9x9 region of trigger towers contained within the jet.

3. Delayed Jet Sensitivity

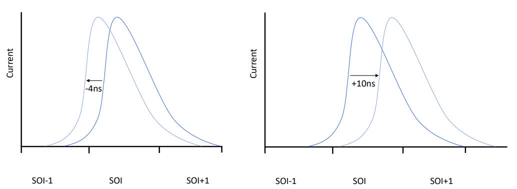

Figure 3: Diagram of the phase scan, where pulses are artificially moved early (left) or late (right) by scanning the HCAL clock.

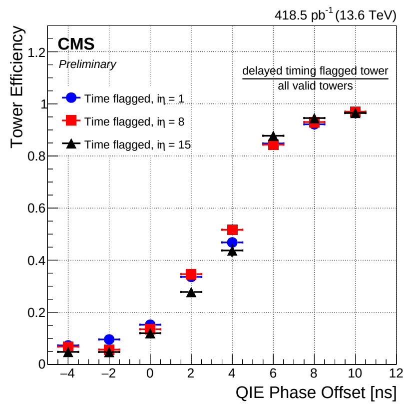

Figure 4: Fraction of towers flagged as delayed vs timing offset (ns) [3].

The delayed jet sensitivity of the trigger is demonstrated through an HCAL timing scan, where the time of the HCAL clock is changed relative to the LHC clock (Figure 3) [7]. The fraction of delayed towers as a function of time offset reaches 1 when the delay is over 6 ns (Figure 4). As expected, there is a sharp turn-on between timing delays of 0-6 ns, with the prompt range set at 6 ns. At low phase offset values, a small fraction of towers are flagged as delayed due to the pulse arrival time spread. With prompt collision pulses, the tails extend into delayed region, causing a few towers to be flagged as delayed.

During the timing scan, rates of the HCAL-based LLP triggers change by over an order of magnitude, demonstrating the strong dependence on HCAL timing. Trigger rates are maximized at an HCAL timing delay of +6 ns, as jets are pushed into the delayed region (Figure 5). The LLP jet triggers implemented in CMS for Run 3 use the HCAL and L1 trigger systems reprogrammable firmware to enable sensitivity to both displaced and delayed jets, as validated through a timing scan.

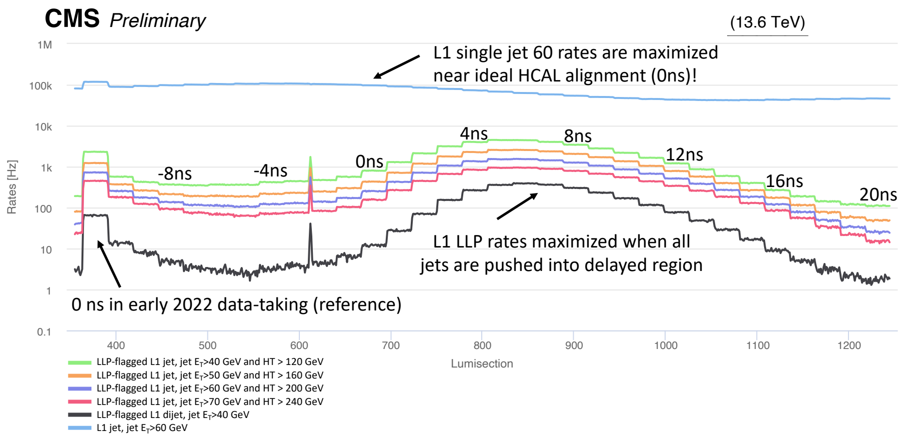

Figure 5: LLP and reference trigger rates during the timing scan, with relative timing offsets indicated. Highest rates are when jets are delayed (+6 ns) and deposit most energy in the bunch crossing of interest [3].

The first Level 1 LLP hardware trigger in CMS has been implemented and has been collecting proton-proton collision data since the start of Run 3 in 2022. It uses the depth segmentation of the upgraded HCAL to identify displaced jets, and the timing to identify delayed jets. This information is reduced to report a single bit LLP flag per L1 jet, used in both L1 and HLT paths.

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