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# Long-Lived Particle Triggering with the CMS Hadron Calorimeter

**Gillian Baron Kopp**[a,*] **on behalf of the CMS Collaboration**

[a] *Department of Physics, Princeton University*
*Princeton, NJ, 08540*

*E-mail:* gillian.baron.kopp@cern.ch, gkopp@princeton.edu

Long-lived particles are a compelling direction in which to search for physics beyond the Standard Model, and implementing dedicated long-lived particle (LLP) triggers provides an excellent avenue to expand experimental coverage into this challenging parameter space. We present a novel Compact Muon Solenoid (CMS) Level-1 LLP trigger that exploits the Run 3 upgrade of the Hadron Calorimeter (HCAL), which introduced a precision timing ASIC, programmable front-end electronics, and depth segmentation to the CMS HCAL barrel. The hardware- and firmware-based trigger algorithm identifies delayed jets, resulting from the decay of massive LLPs, and displaced jets, resulting from LLPs that decay inside the HCAL. This approach significantly increases sensitivity to LLP signatures with soft hadronic final states, including exotic decays of the Higgs boson. Simulated LLP events demonstrate the sensitivity to displaced jets, with high trigger efficiency for LLPs decaying in the calorimeter volume. Recent HCAL timing scans provide a valuable look at artificially delayed jets in collision data and are crucial to understanding the trigger performance. The data collected with the new triggers implemented for Run 3 provides a first look at the capabilities to capture softer events and expand the phase space accessible in ongoing LLP searches.

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## 1. Introduction

The Compact Muon Solenoid (CMS) experiment at the Large Hadron Collider (LHC) is a general-purpose experiment designed to test the Standard Model and search for new physics by collecting and analyzing data from proton-proton collisions at a center of mass energy of 13.6 TeV. The CMS detector consists of multiple subdetectors, all built cylindrically around the collision point [1]. The hadron calorimeter (HCAL) is made of alternating layers of scintillator and brass absorber, and the barrel spans radially from 1.77 to 2.95 m. The recent Phase 1 upgrade (2018-2021) of the CMS HCAL introduced a precision timing ASIC, programmable front-end electronics, and depth segmentation to the HCAL barrel (HB) and endcap (HE) [2]. When collecting data from proton-proton collisions, the CMS data acquisition system makes rapid decisions about which events to keep for further offline analysis. This is done with a two level trigger system, where the Level-1 trigger (L1T, hardware) cuts the event rate from 40 MHz to 100 kHz, and the High Level Trigger (HLT, software) reduces the rate from 100 kHz to approximately 5 kHz. For Run 3 of the LHC (2022-2025), a novel L1T has been implemented in CMS utilizing the upgraded HB.

This trigger is sensitive to long-lived particles (LLPs), which are present in many well-motivated models of physics beyond the Standard Model and are often limited at the trigger level. The CMS HCAL long-lived particle (LLP) trigger expands the experimental coverage of LLP parameter space at the trigger level by identifying delayed and displaced jets with L1 triggers seeding HLT paths, listed in Tables 7 and 8 of [5]. The time and depth segmentation of HCAL are utilized to identify delayed jets, resulting from the decay of massive LLPs, and displaced jets, resulting from LLPs decaying inside the HCAL. The HCAL upgrade increases the segmentation to four depth layers in the barrel, and each depth layer records a time and energy measurement. This enables the trigger to target displaced jets from an LLP decaying within the calorimeter system (Figure 1 (left)) and delayed jets from an LLP arriving at the calorimeter at a relatively late time (Figure 1 (right)). The trigger's performance, evaluated through simulation and collision data, demonstrates its sensitivity to both delayed and displaced jets.

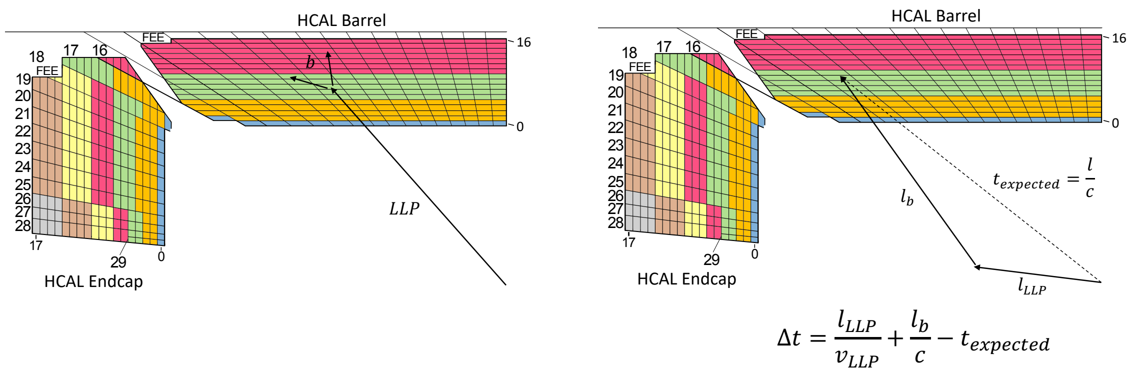


**Figure 1:** The upgraded HCAL with four depths in the barrel (seven in the endcap) is sensitive to both displaced (left) and delayed (right) calorimeter jets produced by LLPs. An LLP decay in the HCAL barrel (left) deposits most energy in depths 3 and 4, shown in green and fuchsia. LLP decay products arriving late due to a slow-moving massive LLP or a geometric path length difference (right) produce a delayed jet. The CMS HCAL-based Level-1 triggers developed for Run-3 of the LHC are sensitive to both signatures.

## 2. Long-Lived Particle Model

Long-lived particles are a compelling direction to search for physics beyond the Standard Model, and these searches are often limited at the trigger level, as standard triggers are not always sensitive to LLP events due to the assumption that particles originate at the collision point. The newly implemented HCAL-based LLP triggers address this limitation, and their performance is evaluated on a model with an exotic decay of the Higgs boson producing two long-lived particles. Searches for this model often lead to high energy-based requirements to reduce backgrounds. Implementing dedicated triggers increases the acceptance of otherwise difficult-to-capture events.

The Higgs boson can couple to any massive particle and thus is a possible avenue to physics beyond the Standard Model. A well-motivated model proposes an exotic decay of the 125 GeV Higgs boson (or decay of a high mass, exotic Higgs boson), producing two scalar long-lived particles ($S$), each decaying into two $b$ quarks (illustrated in Figure 2). The mass of the scalar is constrained to be $m_S \leq m_H/2$. The values for $m_S$, $m_H$, and $c\tau$ considered are:

$$m_H = 125\text{ GeV},\ m_S = 50\text{ GeV},\ c\tau = 3\text{ m} \quad (1)$$

$$m_H = 350\text{ GeV},\ m_S = 80\text{ GeV},\ c\tau = 0.5\text{ m} \quad (2)$$

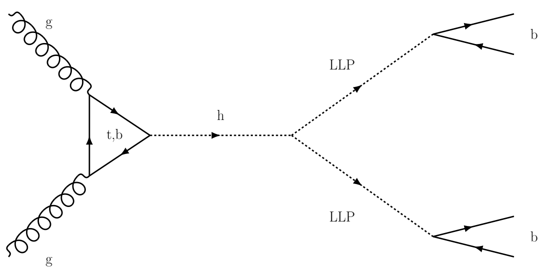


**Figure 2:** Diagram of an exotic Higgs decay to two long-lived particles, each decaying into $b$ quarks.

## 3. Trigger Performance

The HCAL-based LLP triggers identify both delayed and displaced LLP jets. The performance of the depth-based component is demonstrated using Run-3 LLP Monte Carlo simulations, evaluating events based on the radial decay position of the LLP. Results are shown in Section 3.1. Data from HCAL phase scans taken in 2022 and 2023 demonstrate the sensitivity to delayed jets in Section 3.2. These scans artificially delay jets across the entire detector, enabling the trigger performance to be evaluated during collisions, accounting for the detector's real energy and time resolution [5].

### 3.1 Displaced Jet Trigger Efficiencies in Simulation

Trigger efficiency is shown as a function of offline jet $p_T$ (transverse momentum), event $H_T$ (scalar sum of the transverse momenta of the six highest energy jets in each half detector region), and LLP decay radius $R$. In all plots, an LLP particle is required to be matched to an offline jet based on $\Delta R(\text{jet, LLP}) \leq 0.4$ with $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$, where both the LLP and jet satisfy $|\eta| \leq 1.26$. All plots overlay trigger efficiencies for $H \to SS \to b\bar{b}b\bar{b}$, with $m_H = 350$ GeV, $m_S = 80$ GeV, $c\tau = 0.5$ m in blue, and $m_H = 125$ GeV, $m_S = 50$ GeV, $c\tau = 3$ m in purple.

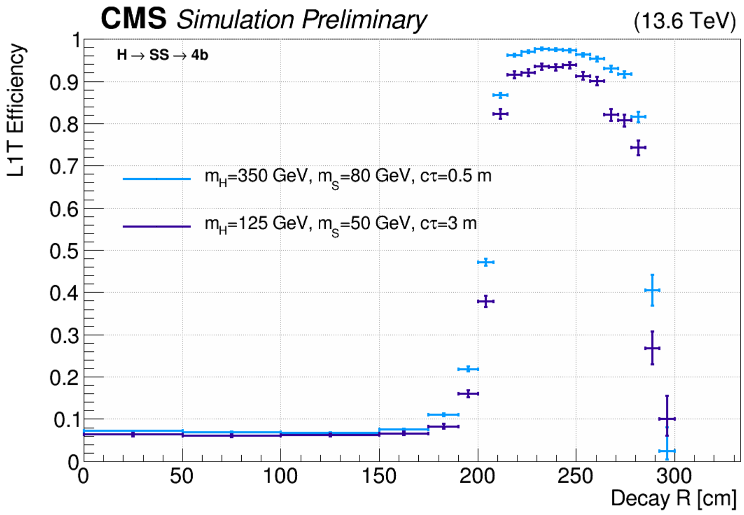


**Figure 3:** Level 1 trigger efficiency vs. LLP decay radius, with the high efficiency between 2 and 3 meters corresponding to LLPs decaying within the HCAL volume [4].

The HCAL barrel extends radially from 177 to 295 cm, and the depth-based LLP trigger identifies jets with significant energy deposited in depths 3 and 4 (ranging from 214.2 cm to 295 cm). LLPs decaying in this range are identified with high efficiency, as shown in Figure 3. The L1 trigger reaches more than 90% efficiency for LLP decays within HCAL depth 3 and 4, the region targeted by the depth trigger to identify displaced LLP jets.

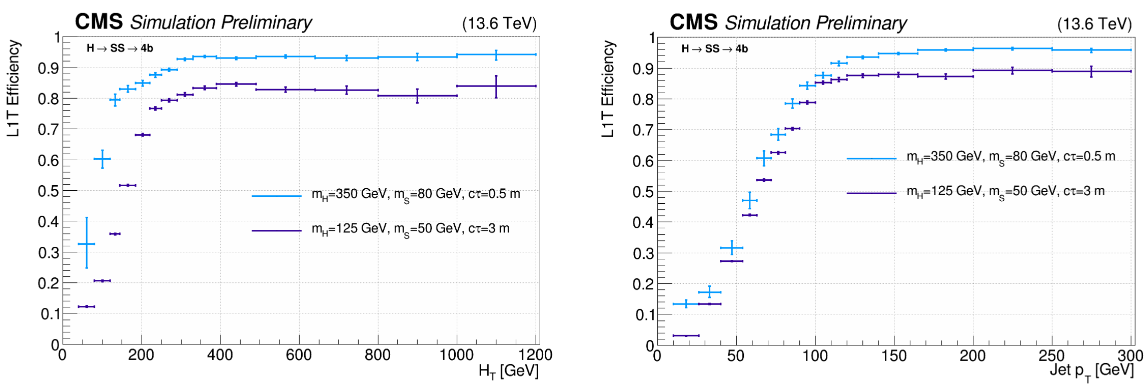


**Figure 4:** Level 1 trigger efficiency as a function of event $H_T$ (left) and jet $p_T$ (right) for offline jets matched to LLPs decaying in HCAL depths 3 and 4 ($214.2 \leq R < 295$ cm) [4].

Figure 4 demonstrates the high trigger sensitivity at relatively low object energies to LLPs decaying within the HCAL barrel. For displaced decays, both samples reach the efficiency plateau at 125 GeV in jet $p_T$ and 300 GeV in event $H_T$. Notably, this enables these dedicated LLP triggers to gain sensitivity to relatively low-energy events that are excluded by energy-based triggers. Without these dedicated hardware level triggers, standard object triggers used in LLP analyses reached 80% efficiency at a jet $p_T$ of 200 GeV or event $H_T$ of 400 GeV.

The higher mass sample generally reaches a higher L1T efficiency as the heavier LLPs are more likely to produce jets that pass the stringent calorimeter energy deposits (multiple cells over 5 GeV in an individual depth) for the depth-based trigger [6]. Lower mass samples are typically more difficult to trigger on, especially as their $H_T$ spectra are lower, and therefore, energy-based cuts are more difficult to satisfy. Due to the decay kinematics, the high mass sample also reaches higher L1T efficiencies in jet $p_T$ and event $H_T$. The LLP is more boosted in this sample, leading to more collimated decay products. This is beneficial as the trigger requires multiple nearby depth-flagged trigger towers. LLP $c\tau$ primarily impacts the signal acceptance rather than efficiency.

### 3.2 Delayed Jet Trigger Efficiencies in Collisions

Data from phase scans during collisions demonstrates the performance of the timing-based trigger's identification of delayed jets. During these scans, the HCAL clock is changed relative to the LHC clock, artificially delaying jets across the whole detector by pushing prompt jets into the delayed region. The HCAL clock is scanned relative to nominal settings, from -4 ns to +10 ns in 2 ns steps. This scan is ideal as it is one of the only ways to evaluate the delayed jet performance while accounting for the timing and energy resolution of the detector during collisions. Data from the scan are also used to align the calorimeter based on the high-precision online timing, which is vital for the performance of this timing-based trigger [7].

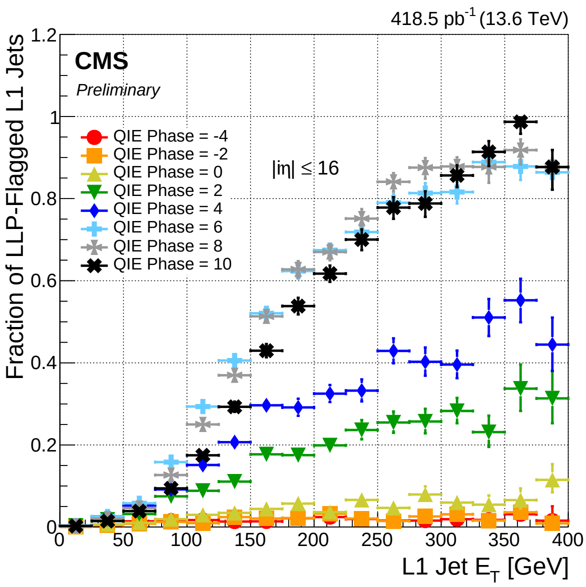


**Figure 5:** The HCAL LLP-flagged Level-1 trigger delayed jet fraction vs. jet $E_T$ during the 2023 HCAL phase scan demonstrates that the delayed jet fraction reaches 1 as the phase delay is increased [3].

Figure 5 shows that the fraction of LLP-flagged L1 jets increases as the delay increases (denoted as QIE phase), reaching high efficiencies for delays of 6 ns and above. This demonstrates that the new LLP triggers are sensitive to time delays, and identify jets arriving at a later time than prompt jets, an expected signature of LLP jets.

An L1 jet is LLP-flagged when at least two flagged HCAL LLP towers (depth or timing-based) are contained in the 9$x$9 towers around the jet [6]. A high efficiency of identifying jets delayed by 6 ns or greater is achieved, as expected based on the timing ranges set by the HCAL [5]. The fraction of LLP-flagged L1 jets is compared to all L1 jets from a dataset of events enriched with jets or missing transverse energy, and the distribution is sculpted by the requirement that a jet must have at least two cells with $E_T > 4$ GeV.

## 4. Conclusions

The dedicated long-lived particle triggers exploit the Run-3 upgrade of the HCAL, which provides depth segmentation and precision timing readouts. The depth segmentation allows for sensitivity to LLPs decaying within the calorimeter volume, and the signal points shown demonstrate trigger sensitivity to LLP signals across a wide kinematic range. The precision timing from the HCAL allows for sensitivity to LLPs arriving at the calorimeter at a delayed time, and scans during proton-proton collisions demonstrate that jets arriving late are identified with high efficiency. Dedicated L1 LLP triggers to seed HLTs enable events with significantly lower event and jet energy thresholds to be saved for offline analysis, greatly expanding the phase space accessible by CMS's LLP trigger program in Run 3.

## References


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