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Level-1 Trigger Algorithm for Long-lived Particle Jets in Run 3

CMS Collaboration

Abstract

The CMS Hadron Calorimeter (HCAL) long lived particle (LLP) trigger is designed to expand the experimental coverage of the LLP parameter space by identifying delayed and displaced jets. The focus of this DP note is the HCAL barrel subdetector, which was upgraded prior to Run 3. The trigger algorithm identifies delayed jets, resulting from the decay of massive LLPs, and displaced jets, resulting from LLPs that decay inside the HCAL. We review the trigger implementation and simulated performance.

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Glossary

- **HCAL**: Hadron calorimeter, a subdetector in CMS designed to measure energy of charged and neutral hadrons
- **HB**: HCAL barrel, a subdetector of the HCAL, made of alternating brass absorber and plastic scintillator
- **i$\boldsymbol{\eta}$**: A detector coordinate, describing the angle relative to the beam axis (polar angle). HB extends from $-16 \leq i\eta \leq 16$, and each trigger tower width is one $i\eta$
- **i$\boldsymbol{\phi}$**: A detector coordinate, describing the azimuthal angle. There are 72 $i\phi$ segments covering $0 \rightarrow 2\pi$, and each trigger tower width is one $i\phi$
- **LLP**: Long lived particle
- **SOI**: Sample of interest, a selected 25 ns bunch crossing
- **L1T**: Level-1 Trigger (hardware)
- **HLT**: High Level Trigger (software)
- **p_T**: transverse momentum of a jet or particle
- **H_T**: scalar sum of the transverse momenta of the 6 highest energy jets in each half detector (plus and minus side)
- **Decay R**: the radial position of the LLP decay, calculated as $\mathrm{R} = \sqrt{\Delta x^2 + \Delta y^2}$ from the origin
- **d_{xy}**: impact parameter to measure how closely a track approaches the primary vertex, in the *xy* plane

Introduction

The CMS Hadron Calorimeter (HCAL) long lived particle (LLP) trigger is designed to expand the experimental coverage of the LLP parameter space by identifying delayed and displaced jets. The LLP trigger utilizes the recent Phase 1 upgrade [1, 2], which introduced a precision timing ASIC, programmable front-end electronics, and depth segmentation to the HCAL barrel (HB) and endcap. The focus of this DP note is the HB, which was upgraded prior to Run 3. The trigger algorithm identifies delayed jets, resulting from the decay of massive LLPs, and displaced jets, resulting from LLPs that decay inside the HCAL. We review the trigger implementation and simulated performance.

The HCAL LLP trigger identifies trigger towers with significant energy in higher depths and little energy in lower depths (depth flagged) or with pulses arriving at late times (timing flagged). 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. This is a "prompt veto" to reduce backgrounds. The HCAL trigger tower flags are then used in the Level-1 Trigger (L1T) jet algorithm to flag L1 jets, with two or more flagged towers per jet. After passing jet- and event-level kinematic selections, LLP-flagged L1 jets seed several dedicated High Level Triggers (HLTs) in Run 3.

[1] Candan Isik for the CMS Collaboration. "Phase 1 Upgrade of the CMS Hadron Calorimeter", 25 March 2022, CMS CR-2022/049. https://cds.cern.ch/record/2810162/files/CR2022_049.pdf?version=1

[2] "CMS Technical Design Report for the Phase 1 Upgrade of the Hadron Calorimeter", 26 September 2012, CMS-LHCC-2012-015. https://cds.cern.ch/record/1481837/files/CMS-TDR-010.pdf

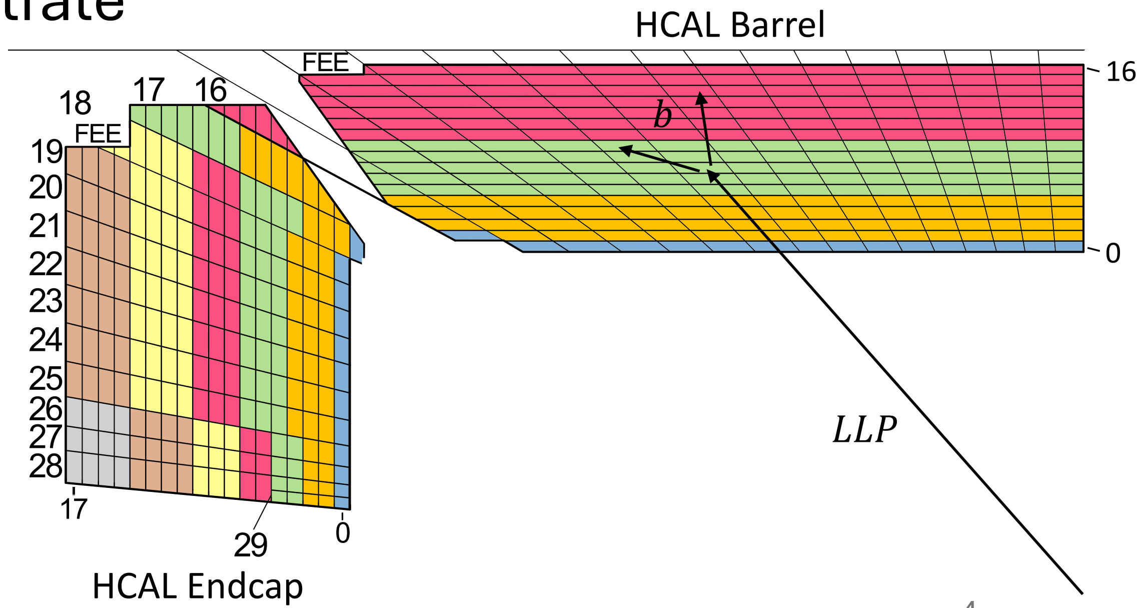
Simulation of LLP Trigger Performance

The HCAL-based LLP triggers identify both delayed and displaced LLP jets. The sensitivity to delayed jets is well illustrated with the data from HCAL phase scans taken in 2022 and 2023, in which the performance is evaluated during collisions, accounting for the real energy and time resolution of the detector. These results are documented in a DP note [3] and HCAL paper [4].

Here, the performance of the depth-based component is highlighted, using Run-3 LLP Monte Carlo. MC events demonstrate the performance well, as events are evaluated based on the decay radius of the LLP.

[3] CMS Collaboration. "Performance of long lived particle triggers in Run 3", CMS DP-2023/043. July 2023. https://cds.cern.ch/record/2865844?ln=en

[4] Gillian Baron Kopp, et. al. "A Novel Timing Trigger with the CMS Hadron Calorimeter", CMS DN-2023/022. October 2023. http://cds.cern.ch/record/2891496?ln=en



Signatures: energy deposited in **deep calorimeter layers**

Comparison to standard object triggers

At L1T in Run 3, the lowest unprescaled single jet trigger is 180 GeV, and reaches 80% efficiency at offline jet p_T of 200 GeV. The lowest unprescaled L1 H_T trigger is 280 GeV (as of 2023), and reaches 80% efficiency at H_T 320 GeV. Prior to this, the lowest unprescaled L1 H_T trigger was 360 GeV, and reached 80% efficiency at H_T 400 GeV. Performance plots for both are available in CMS DP-2023/054 [6]. A L1 H_T seed of 360 GeV has been the lowest seed used for the L1 H_T seeded displaced dijet HLTs in Run-2 and Run-3, and thus is referenced for comparison.

At HLT in Run 3, the lowest unprescaled single jet trigger is 500 GeV (reaching 80% efficiency at an offline jet p_T of 525 GeV) and the lowest H_T trigger is 1050 GeV (reaching 80% efficiency at 1150 GeV). Performance plots for both are available in CMS DP-2023/016 [7].

[6] CMS Collaboration, "Performance of L1 Jets and MET Trigger in early Run 3", 19 August 2023. CMS DP-2023/054. https://cds.cern.ch/record/2868796/files/DP2023_054.pdf

[7] CMS Collaboration, "Performance of jets and missing transverse momentum reconstruction at the High Level Trigger using Run 3 data from the CMS Experiment at CERN", 5 April 2023. CMS DP-2023/016. https://cds.cern.ch/record/2856238/files/DP2023_016.pdf?version=1

Trigger Efficiency Methodology

Trigger efficiency is shown as a function of offline (AK4) jet p_T, event H_T, and LLP decay radius. In all plots, an LLP (particle at GEN level) is required to match to an offline jet, with the following cuts:

- LLP must have $|\eta| \leq 1.26$
- LLP must be matched with $\Delta R \leq 0.4$ to an offline AK4 jet in HB, satisfying jet $|\eta| \leq 1.26$
  - If the LLP decays within the HCAL, require that $\Delta R \leq 0.4$ between LLP and jet center
  - If the LLP decays before the HCAL, require that $\Delta R \leq 0.4$ between LLP decay product and jet center

To demonstrate the trigger performance on the efficiency plateau as a function of each variable, cuts are made on the LLP decay position, jet p_T, and event H_T:

- **LLP decay R** plot: additionally require event H_T > 250 GeV and matched jet p_T > 100 GeV
- **Event H_T** plot: additionally require that at least one of the leading 6 jets has jet p_T > 40 GeV and is matched to an LLP with a decay radius of $214.2 \leq R < 295$ cm (decay occurring in HCAL depth 3 or 4, motivated by sensitivity of the depth-based trigger)
- **Jet p_T** plot: additionally require that the jet is matched to an LLP with a decay radius of $214.2 \leq R < 295$ cm

Thus, the denominator already includes the LLP – offline jet matching. The numerator requires the same LLP – offline jet matching, while also requiring:

- Any of the HCAL-based L1 LLP triggers are passed

Trigger Efficiency Methodology

LLP decay R plot:

$$\frac{\text{any of 5 HCAL−based L1T LLP jet triggers passed + denominator}}{\text{LLP with}|\eta|\leq 1.26\text{ is matched to an offline jet with }|\eta|\leq 1.26\text{ and jet }p_T>100\text{ GeV, and event HT}>250\text{ GeV}}$$

Event H_T plot:

$$\frac{\text{any of 5 HCAL−based L1T LLP jet triggers passed + denominator}}{\text{any of 6 leading jets with}|\eta|\leq 1.26\text{ and }p_T>40\text{ GeV are matched to an LLP with }|\eta|\leq 1.26\text{, and LLP decay }214.2<R<295\text{ cm}}$$

Jet p_T plot:

$$\frac{\text{any of 5 HCAL−based L1T LLP jet triggers passed + denominator}}{\text{jet with}|\eta|\leq 1.26\text{ is matched to an LLP with }|\eta|\leq 1.26\text{, and LLP decay }214.2<R<295\text{ cm}}$$

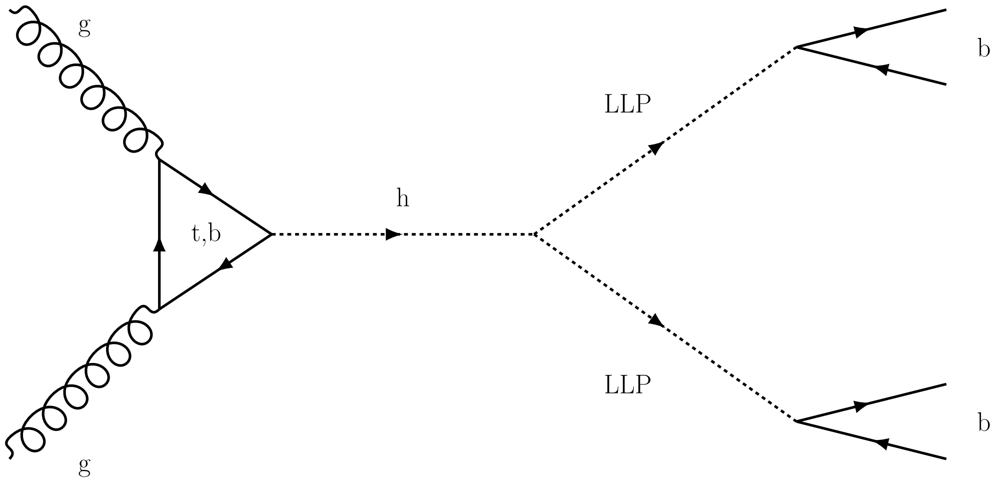
Long-Lived Particle Model and Parameters

An exotic decay of the 125 GeV Higgs boson (or decay of a high mass, exotic Higgs boson) produces two scalar long-lived particles (*S*), which each decays into two *b* quarks. The mass of the scalar is constrained to be $m_S \leq \frac{m_H}{2}$. The values for m_H, m_S, and $c\tau$ in the following plots are:

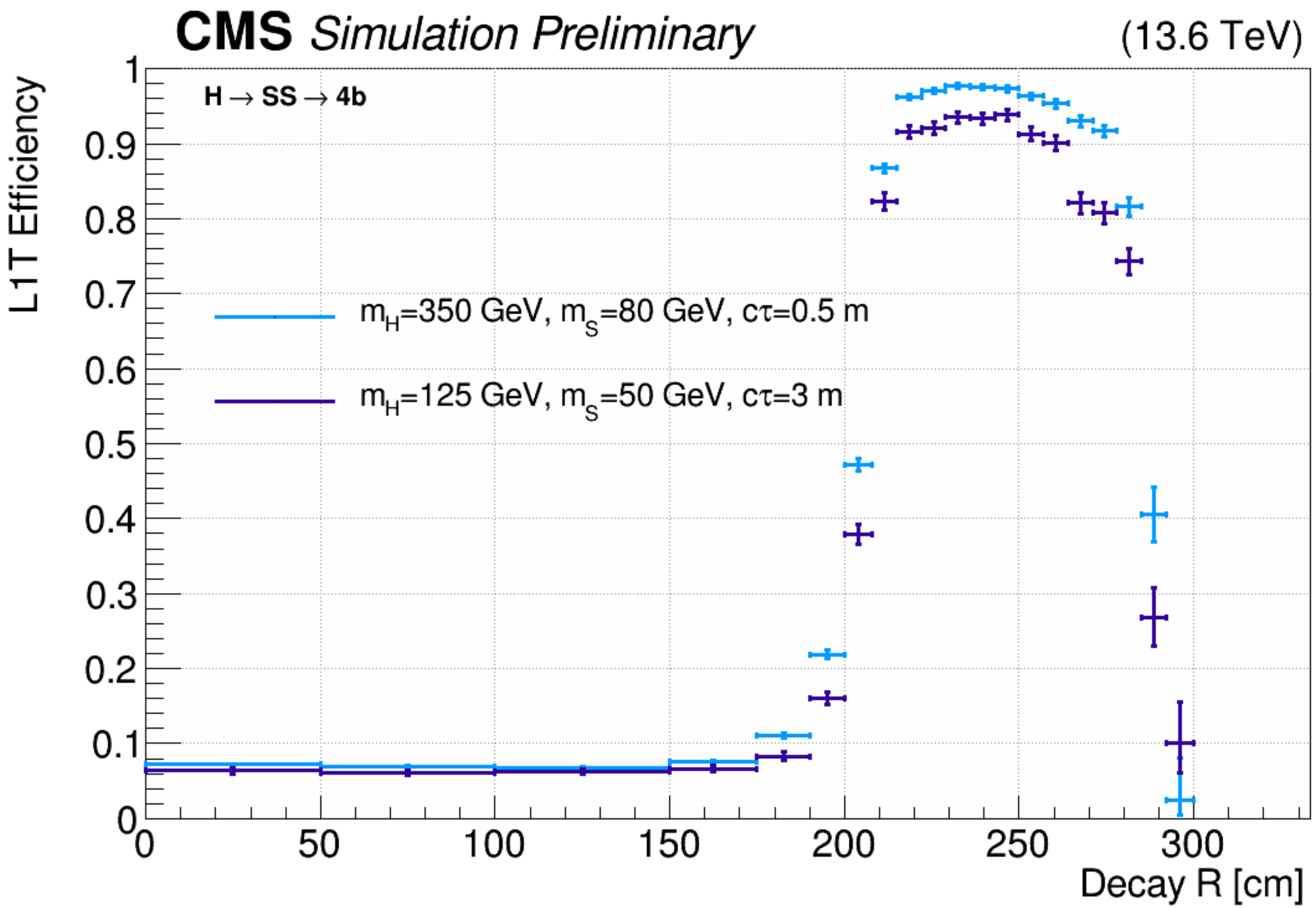
$$m_H = 125\ \text{GeV}, m_S = 50\ \text{GeV}, c\tau = 3\ \text{m}$$

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

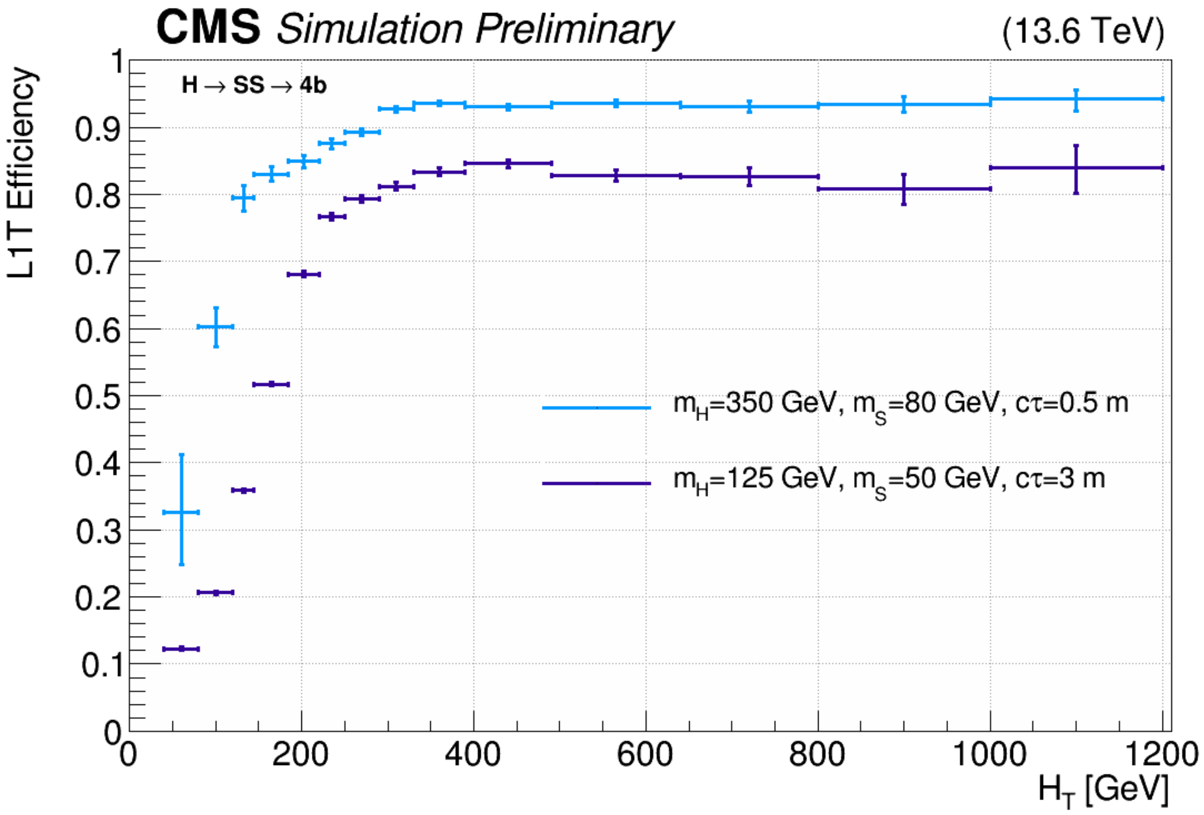
In general, the higher mass sample reaches a higher L1T efficiency as the heavier LLPs are more likely to produce jets that pass the stringent calorimeter energy deposits (multiple cells over 5 GeV in an individual depth) for the depth-based trigger. Lower mass samples are typically more difficult to trigger on, especially as their H_T spectra is lower and therefore energy-based cuts are more difficult to satisfy. The high mass sample also reaches higher L1T efficiencies in jet p_T and event H_T due to the decay kinematics. In this sample, the LLP is more boosted, 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.

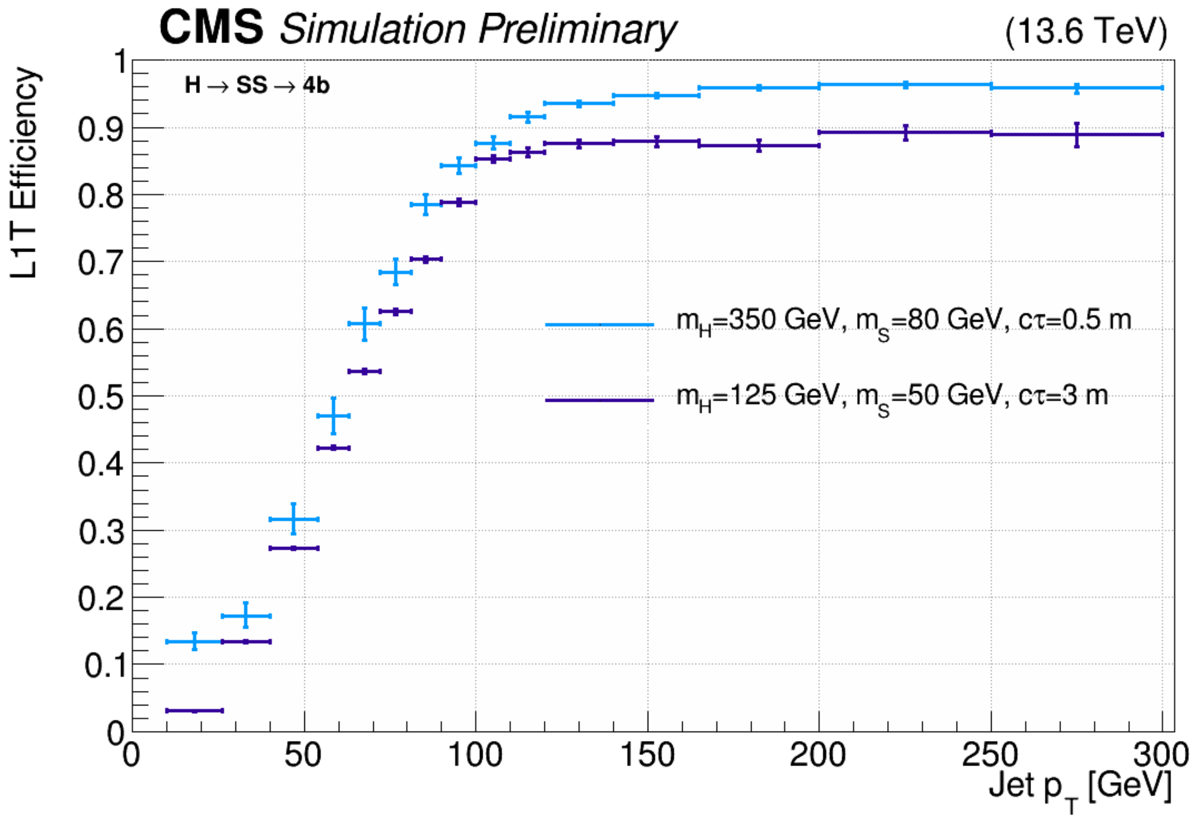


$$H \to SS \to \bar{b}b\bar{b}b$$



HCAL-based LLP L1 trigger efficiency vs. LLP decay radius. The LLP is required to be within $|\eta| \leq 1.26$ and be matched to an offline (AK4) jet with $p_T > 100$ GeV. The L1 trigger has an efficiency of more than 90% for LLP decays within HCAL depth 3 and 4 ($214.2 \leq R < 295$ cm), the region targeted by the depth trigger to identify displaced LLP jets. This plot overlays trigger efficiencies for $H \rightarrow SS \rightarrow 4b$, 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.





HCAL-based LLP L1 trigger efficiencies vs. offline event H_T (left) and jet p_T (right) for jets matched to LLPs decaying in the HCAL depths 3 and 4 ($214.2 \leq R < 295$ cm). The efficiency plateau is reached at 300 GeV in event H_T and 125 GeV in jet p_T for both samples. Notably, this enables these dedicated LLP triggers to gain sensitivity to relatively low energy events that are excluded by energy-based triggers. This plot overlays trigger efficiencies for $H \rightarrow SS \rightarrow 4b$, 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.

Conclusions

The dedicated long-lived particle triggers utilize 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 use of dedicated L1 LLP triggers to seed HLTs enables events with significantly lower event and jet energy thresholds to be saved for offline analysis, greatly expanding the phase space accessible by the LLP trigger program of CMS.