Dedicated triggers for displaced jets using timing information from electromagnetic calorimeter at HL-LHC

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ABSTRACT: In this paper, we study the prospect of ECAL barrel timing to develop triggers dedicated to long-lived particles decaying to jets at the level-1 of HL-LHC. We construct over 20 timing-based variables, and identify two of them which have better performances and are robust against increasing PU. We estimate the QCD prompt jet background rates accurately using the “stitching” procedure for varying thresholds defining our triggers and compute the signal efficiencies for different LLP scenarios for a permissible background rate. The trigger efficiencies can go up to $\mathcal{O}(80\%)$ for the most optimal trigger for pair-produced heavy LLPs having high decay lengths, which degrades with decreasing mass and decay length of the LLP. We also discuss the prospect of including the information of displaced L1 tracks to our triggers, which further improves the results, especially for LLPs characterised by lower decay lengths.

KEYWORDS: Higgs Properties, Specific BSM Phenomenology, Supersymmetry

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1 Introduction

In 2024, LHC will witness the last run of Phase-I before closing down for the Phase-II upgrade. Till the completion of Run-II in 2018, most of the results were consistent with the Standard Model of particle physics (SM), and we have not come across any clear indication of new physics with consequential statistical significance. Novel methods to search for physics beyond the Standard Model (BSM) are being studied and employed to
leave no stones unturned. Still, several avenues in BSM searches have not yet been explored to their full potential. In recent years, the need to extend our searches to include such exotic particles have gained quite some traction due to both exclusions of large regions of new physics parameter space with particles having conventional signatures at current experiments as well as the development of High Luminosity LHC (HL-LHC) with several hardware and software level improvements. Till now, most of the experimental searches focused on BSM particles decaying promptly. However, the focus has recently shifted to look for particles with longer lifetimes or long-lived particles (LLPs).

The presence of LLPs is well motivated in many BSM theories. Minimal super-symmetric extension of SM (MSSM) [1, 2] is one such laboriously studied BSM theory in the context of LLPs. A number of new particles with a longer lifetime can arise in MSSM. R-parity violating SUSY model [3] is one of the riveting SUSY models which predict the presence of long-lived particles. LLPs also arise in many other SUSY scenarios like gauge-mediated SUSY (GMSB) [4, 5], anomaly mediated SUSY (AMSB) [6], split SUSY [7, 8], and stealth SUSY [9]. Particles with longer lifetimes can also arise in many non-SUSY theories, like, heavy neutrino theories, dark matter theories, gauge and Higgs portal theories. For a detailed review of many such LLP models, see ref. [10] and the references therein.

Several phenomenological studies explore the possibilities of LLP searches covering a wide range of models and signatures, such as those in refs. [11–30]. Collaborations of two major general purpose detectors at LHC, CMS and ATLAS, have also been actively performing several BSM studies involving various LLP signatures. Displaced object searches, mainly focused on looking for displaced jets, displaced vertices and displaced leptons, have been extensively performed by both CMS [31–39] and ATLAS [40–49] collaborations. Along with these, CMS and ATLAS have also performed several non-vertex based LLP searches, involving disappearing tracks, trackless jets, jets with low electromagnetic energy fraction, non-pointing photons and emerging jets [50–59]. While ATLAS has been performing several LLP searches using the muon spectrometer [60–63], LLP signatures are now being probed at the CMS for the first time in the muon spectrometer [64]. At LHCb, several LLP searches have been performed involving dark photons, displaced leptons and displaced jets [65–70]. There are already strong constraints present on the production cross section of LLPs and their decay to displaced jets. For example, the CMS experiment has put stringent limits to date on LLPs decaying to jets using 132 fb$^{-1}$ of data collected at CMS till the completion of Run-II in Phase-I of LHC [31]. Most restrictive limits for LLPs of a particular mass arise in regions with mean proper decay length, $c\tau$, between 3 mm and 300 mm. For smaller and higher decay lengths, limits are less restrictive. Most confining limits are put on LLPs with masses greater than 500 GeV, while they are much less stringent for LLPs with smaller masses. For LLP of mass 50 GeV, pair production cross-sections above $\approx 10$ fb and 100 fb are excluded for mean proper decay lengths of 1 cm and 30 cm respectively.

Since large cross-sections of LLP processes are ruled out from experiments, it becomes very crucial to select LLP events with even lower cross sections. One of the critical aspects of any analysis is to select events efficiently at the online trigger levels, namely level-1 (L1) and High Level Trigger (HLT). Therefore, we need to ensure that we efficiently select events with LLPs at the first level trigger itself, otherwise, these events are lost forever. With L1
triggers having a smaller latency period, selecting LLP events becomes more challenging because of LLPs’ innate property to decay away from the beamline with significant time delay. Till Run-II of Phase-I of LHC, several standard L1 triggers like single and multi-jet triggers, lepton triggers, missing-$E_T$ (MET), and $H_T$ triggers were employed to select LLP events at the first level, which was possible due to the relatively low amount of pile-up (PU). At HL-LHC, the high amount of PU will pose a huge challenge, and L1 triggers will be primarily affected by the increased number of PU interactions per bunch crossing. Lighter LLPs, for example, those coming from the decay of the 125 GeV Higgs boson, will deposit a small amount of energy in the calorimeters and will be very hard to trigger on amid the huge PU background.

To deal with PU at HL-LHC, hardware, as well as software upgrades are proposed for detectors. The outer tracker will be upgraded to accommodate track reconstruction at L1 [71]. Due to the availability of tracks at L1, tracklessness property of LLP can be efficiently used to construct dedicated L1 triggers for LLPs as shown in ref. [19]. A whole new timing detector, MIP Timing Detector (MTD), will be placed between the outer tracker and the electromagnetic calorimeter (ECAL) to get precise timing information of minimum-ionising particles (MIPs), which will help to mitigate in-time as well as out of time PU [72]. Endcaps of both the electromagnetic and hadronic calorimeters (HCAL) will also undergo a massive upgrade, and the current detector elements will be replaced by the high granularity calorimeter (HGCAL) [73]. As a result of the upgrade to faster and more efficient electronic systems on-board detectors, particle flow (PF) candidates can be reconstructed at L1. Availability of tracks and PF candidates at L1 allows the implementation of Pileup Per Particle Identification (PUPPI) [74] algorithm at L1, which would help control the background rate for the triggers, which will be most affected by the huge amount of PU at HL-LHC.

Possibility of using timing information in LLP searches has been extensively studied in many experimental and phenomenological studies [19, 33, 52, 57, 75–80]. The possibility of using MTD based timing information at L1 to trigger on LLPs is studied in detail in ref. [19]. The CMS Phase-II L1 TDR [71] mentions a potential scope of using inputs from the MTD in an “External Trigger”, which can be fed into the Global Trigger at L1. Upgraded calorimeters will also have improved timing capabilities. While timing information of calorimeter energy deposits from ECAL and HCAL will be available at L1, HGCAL will not be able to provide timing information at L1 due to bandwidth constraints [71]. Availability of timing information at L1 from ECAL barrel calorimeter is expected to play an essential role in triggering long-lived particles, especially the ones where mean proper decay length$^1$ of the LLP is large.

To trigger on LLP events, CMS has specifically designed two dedicated L1 triggers harnessing the tracking capabilities, which include extended tracking till a transverse impact parameter ($d_0$) of 8 cm, and ECAL barrel timing [71]. Apart from the CMS Phase-II TDR [71], and ref. [19], there are not many detailed realistic studies for developing dedicated

$^1$For simplicity, mean proper decay length of the LLP will be referred to as decay length hereafter, unless stated otherwise.
LLP triggers for HL-LHC that properly includes the effect of increased PU and the detector resolution, which are essential parts of HL-LHC. The CMS TDR contains results for limited LLP benchmark points for a fixed amount of PU, which cannot be directly used for other LLP models. Extrapolating these results to other benchmark points within the same model with different PU is also difficult due to the absence of exact simulation details — like the ECAL barrel timing resolution used in their results and the dependence of this resolution with pseudorapidity ($\eta$). This motivates us to study in detail the prospect of triggering LLPs in scenarios where the LLPs decay to displaced jets. We focus on the following major questions in the present work:

- Are PUPPI based jet triggers that are optimised for prompt jets efficient to trigger on displaced jets coming from LLP decays?

- What are the most optimal timing variables constructed using ECAL barrel information to be used in L1 triggers? What factors affect them? Are these variables robust against the increasing PU and degrading timing resolution?

- Are these timing variables equally efficient for various LLP scenarios decaying to displaced jets?

- How can we make use of timing-based triggers to their full potential to trigger on various LLP scenarios? How can the trigger efficiencies be improved further?

- Can the displaced track collection at L1 be combined with timing information efficiently to improve further trigger efficiency of timing-based jet triggers for various LLP scenarios, and how do they complement each other?

Accurate estimation of background rates of a trigger without double counting when combining different regions of the phase-space of QCD multijet events is very crucial in understanding the feasibility of implementing the trigger. One of the primary goals of the present work is to compute the background rates precisely and to study how the rates of the triggers developed by us in this work vary in different contexts.

The rest of the paper is outlined as follows: in section 2, we define the signal models and backgrounds for our study along with the simulation details. In section 3, we discuss about HL-LHC upgrades at CMS and their updated L1 trigger menu for jets. We also talk about the possibility of using PUPPI based triggers for triggering events with displaced jets. In section 4, we discuss the adverse effects of high PU along with the effect of ECAL timing resolution on jet timing as the PU increases and timing resolution degrades with time. We also examine why some prompt QCD jets might have high timing values. In section 5, we define several timing variables constructed using different statistical measures and calculate the signal efficiency and background rate for various benchmark points of different LLP scenarios using triggers based on jet timing. In section 6, we present some discussions regarding the effect of the resolution, addition of displaced L1 tracks, narrower jets and high PU. Finally, we conclude in section 7.
2 LLP signal models, current bounds and computational setup

In this section, we briefly discuss various production processes of LLPs and their decay to jets as considered in this work, along with examples of concrete models that can give rise to such LLP scenarios. We present the current experimental bounds from the CMS and ATLAS studies of long-lived particles decaying to jets relevant for these scenarios. Broadly, LLPs can have two possible production modes in the colliders — direct production or from the decay of some on-shell SM or BSM particle. We study three different scenarios in the present work, where we cover both these kinds of LLP production. After introducing the LLP scenarios, we briefly discuss the background process considered in this work and our computational setup.

2.1 (A) LLPs coming from the decay of the SM Higgs boson

\[ pp \rightarrow h(125 \text{ GeV}) \rightarrow XX, X \rightarrow jj. \]

In the first scenario, we have considered the production of LLPs through the decay of an on-shell 125 GeV Higgs boson and the subsequent decay of each LLP to a pair of jets. The Higgs portal is one of the leading renormalizable portals connecting new gauge-singlet particles to the SM. It is also experimentally motivated due to the scope to include couplings of Higgs boson to new physics particles and different production modes of the Higgs boson.

An example of a model where the Higgs boson decays to long-lived exotic particles is the Dark Matter model with light fermionic WIMPs and light scalar mediator [81]. Such a model can generate large velocity-dependent scattering cross-sections between the WIMPs, solving the small scale crisis of structure formation in the Universe. The scalar mediator mixes with the SM Higgs boson and therefore, its couplings to SM fermions are all suppressed by this mixing. For very small values of mixing, the mediator can have long lifetimes, given that WIMPs are heavier than the mediator. Since the mediators couple to SM fermions through their Yukawa couplings, mediators having masses greater than 10 GeV predominantly decay to $b$-quarks, giving rise to displaced jets.

A search of displaced vertices in the ATLAS inner detector have excluded branching ratios of Higgs to long-lived mediators above 10% at 95% confidence level for decay lengths between 4 mm and 100 mm [49] for a LLP of mass $\sim 40$ GeV with 139 fb$^{-1}$ of data using the $Zh$ production mode. In comparison, the CMS displaced jets search uses the gluon-gluon fusion (ggF) production mode and excludes branching fractions larger than 1% at 95% CL for decay lengths as low as 1 mm and as large as 340 mm with an integrated luminosity of 132 fb$^{-1}$ [31]. For a recent phenomenological study computing the sensitivity of long-lived scalar mediators coming from Higgs boson decay combining all the dominant production modes of Higgs boson using the CMS muon spectrometer, see ref. [28]. In the present work, we focus on the dominant production mode of SM Higgs boson, i.e., the ggF, which has a cross-section of 50.32 pb at center of mass energy, $\sqrt{s} = 14$ TeV.

In this scenario, masses of LLPs will be relatively smaller ($m_X \lesssim m_h/2 \approx 62.5$ GeV). We study various mass points ranging between 10 GeV to 50 GeV with mean decay lengths ranging between 1 cm to 500 cm. Decay lengths of LLP in the lab frame depend on the boost of the LLP as well as on the mean decay length of the LLP in its rest frame. Since
the LLP comes from the decay of the on-shell Higgs boson with mass 125 GeV, the former’s boost depends on its mass difference with the Higgs boson. As a result, 50 GeV LLPs will be pair produced with very small boost as compared to 10 GeV LLPs. Overall, LLPs in this scenario have smaller hadronic activities in the detectors due to small boosts and therefore, will be harder to trigger on.

2.2 (B) LLPs directly pair-produced and each decaying to a pair of jets

\[ pp \rightarrow XX, X \rightarrow jj. \]

In the second scenario, we have considered direct pair-production of LLPs in the colliders from a quark-initiated process mediated by $\gamma/Z$. The long-lived particles are assumed to further decay into a pair of quarks each, giving rise to two displaced jets. This kind of scenario can arise in $R$-parity violating (RPV) supersymmetric models. For instance, a pair of sneutrinos ($\tilde{\nu}$) are produced in the colliders which eventually decay to two quarks each, using the RPV LQD coupling [3]. Constraints from experiments restrict these kinds of couplings to very small values, which can make the sneutrinos have longer lifetimes. For this scenario, we have considered the decay of sneutrinos to a pair of light quarks ($u/d/s$).

The CMS displaced jets search has excluded pair-production cross-sections greater than 0.07 fb [31] for LLPs heavier than 500 GeV which decay to a quark-antiquark pair with 100% branching fraction and $c\tau$ between 2 mm and 250 mm with 132 fb$^{-1}$ of data. Limits are less restrictive for lower masses, like cross-sections till 1 fb are allowed even for the most sensitive decay length of 10 mm for a 100 GeV LLP. The CMS collaboration have also translated the results of their displaced jets search to models with specific RPV-LQD coupling in stop decays ($\tilde{t} \rightarrow b\ell$) and RPV-UDD coupling in gluino decays ($\tilde{g} \rightarrow tbs$) in ref. [31].

2.3 (C) LLPs directly pair-produced and each decaying to three jets

\[ pp \rightarrow XX, X \rightarrow jjj. \]

In the third scenario, we have considered a similar production process as in the previous scenario (B); however, each of the LLPs, $X$, decays to three quarks in this scenario, leading to six displaced jets in the final state if both the LLPs decay before the calorimeters. A scenario like this can also arise in RPV SUSY models, where a pair of lightest neutralinos ($\chi^0_1$) are pair-produced directly from a quark-initiated process and further decay to three quarks due to a UDD type RPV coupling [3]. As discussed earlier, RPV couplings are usually constrained to small values which can make the lightest supersymmetric particle (LSP), here $\chi^0_1$, long-lived. In this scenario, we have considered the decay of neutralinos to three light quarks ($u/d/s$). This scenario has an increased jet multiplicity compared to the previous two scenarios and, we will study whether this enhances its sensitivity or reduces it due to more softer jets.

For both scenarios (B) and (C), we study LLPs with masses ranging between 100 GeV to 500 GeV having $c\tau$ between 1 cm to 500 cm. Since the LLPs are directly produced in these two scenarios, we can consider much heavier LLPs than the first scenario. Jets coming from the decay of such LLPs will, therefore, have higher transverse momenta and hence, more hadronic activity. Thus, they will be relatively easier to trigger on as compared to scenario (A). For rest of the paper, we have denoted benchmark points in each scenario with the notation (M, $c\tau$) where M denotes the mass of the LLP in GeV and $c\tau$ denotes its
Figure 1. Fraction of events decaying before the ECAL, i.e., within a radial distance of 1.29 m, and half-length of 3 m, as a function of the mean proper decay length ($c\tau$) of the LLP having a mass of 10 GeV and 30 GeV in scenario (A), and 150 GeV and 500 GeV in scenario (B).

mean proper decay length in cm. In the present work, we focus mostly on the ECAL barrel timing, and therefore, it is important to have an idea of how much fraction of the LLPs having various masses and decay lengths from the scenarios considered here decay before the ECAL, i.e., within a radial distance of 1.29 m, and half-length of 3 m. Figure 1 shows the variation of the fraction of LLPs decaying before the ECAL with the decay length of the LLP for LLPs coming from Higgs boson decay (scenario (A)) with masses 10 GeV and 30 GeV, and pair-produced LLPs (scenario (B)) with masses 150 GeV and 500 GeV. We observe that with decreasing mass and increasing decay length of the LLP, this fraction decreases, and it falls off to very low values ($\sim 8\%$) close to $c\tau = 500$ cm for our lightest benchmark of 10 GeV. For the 30 GeV LLP coming from Higgs boson decay, around 100% of the LLPs decay within the ECAL for $c\tau = 10$ cm which decreases to about 70% for $c\tau = 100$ cm, whereas for the 500 GeV benchmark, which has direct production, even at a $c\tau = 100$ cm, the fraction of decays within the ECAL is 90%. Thus, we have significant decays of LLPs within the ECAL spanning a range of masses and lifetimes in all our scenarios. We now need to study how many of these pass L1 triggers when their decay products are required to leave energy deposits in the ECAL barrel with significant time delays.

2.4 Background

Most of the SM processes are prompt and, therefore, can be easily separated from the displaced and time delayed signatures of long-lived particles. Still LLP searches have backgrounds from sources like beam halo, or interactions with the detector materials, or spurious detector noise, simulations of which are outside the scope of the present phenomenological study. However, we simulate the backgrounds that will dominantly affect the analysis using jet timing from the ECAL. These backgrounds are briefly described below, and their simulation details are outlined in section 2.5.
• **Jets from QCD dijet background.** For LLP scenarios considered in our study, QCD dijet events will constitute a major background in our analysis using jet timing. Although these jets consist of mostly relativistic prompt particles, some of the lower $p_T$ jets can have higher values of jet timing. The cross-section of QCD dijet process is around 0.21 mb with jets having a transverse momentum, $p_T > 30$ GeV. This is overwhelmingly large compared to the cross-section of our LLP signal processes, which are already constrained to be below a few fb. Therefore, even a small number of QCD dijet events having jets with large timing can contribute as a major background in our analysis.

• **Jets from pile-up.** Due to the increased luminosity, the HL-LHC runs suffer from high PU, as we will further discuss in section 3. There will be around 140 (200) vertices per bunch crossing of protons in the beginning (end) of the HL-LHC runs. Jets from these vertices can lie in the tail of the jet timing distribution due to low $p_T$ and the spatial and temporal spread of the PU vertices. In addition, many particles from different PU vertices can fall within the jets coming from the hard process, which can bias the timing of the jet to lower or higher values. It is, therefore, important to properly simulate the high PU environment of HL-LHC for this study.

2.5 Simulation details and computational setup

We simulate all our LLP processes as well as the QCD background using PYTHIA8 [82] at a center of mass energy of $\sqrt{s} = 14$ TeV. For LLP signals, we generate the processes described in sections 2.1, 2.2 and 2.3 with varying masses and decay lengths as specified earlier in each of these scenarios. For the current study, we have simulated QCD dijet events divided in several parton level $p_T$ bins for a proper simulation of the tail of the $p_T$ distribution. We have generated events in eight $p_T^{\text{gen}}$ bins — \{30,50\} GeV, \{50,75\} GeV, \{75,100\} GeV, \{100,125\} GeV, \{125,150\} GeV, \{150,175\} GeV, \{175,200\} GeV, and $> 200$ GeV. For the PU events, we simulate 1,000,000 minbias events with the inelastic soft QCD using the SoftQCD:inelastic option in PYTHIA8. For all the processes we use LHAPDF6 [83] with the cteq6l1 PDF set and the corresponding CMS UE tune.

We have used Delphes-3.5.0 [84] along with the Phase-II detector card available with the Delphes package for the fast detector simulation. We have reconstructed jets using anti-$k_T$ jet clustering algorithm with some fixed cone-size which we motivate later. We merge the minbias events with the hard collision events of various LLP signals and QCD dijet background using the PileUpMerger module of Delphes as previously done in ref. [19]. Delphes is primarily developed to simulate processes involving prompt particles, and therefore, Delphes is modified to accommodate displaced particles. All particles are propagated to the beginning of the ECAL since we will use its timing information, and their pseudorapidity ($\eta$) and azimuthal angle ($\phi$) are taken to be the one at the ECAL for jet formation. Particles produced within the ECAL and till the end of HCAL are also used for jet formation since, in the experiment, these particles will have energy deposits in the calorimeters and hence, contribute to the jets, however, they might not contribute to the

\(^{2}\)PileUpMerger module of the Delphes is adapted to correctly place pileup vertices on the beamline.
jet timing. In the next section, we briefly discuss the Phase-II upgrades of the HL-LHC runs along with the PUPPI algorithm and how the latter affects displaced jets from LLPs.

3 High luminosity LHC: Phase-II upgrades and PUPPI algorithm

The Phase-II upgrade of the LHC or High Luminosity LHC (HL-LHC) will witness increased $pp$ collisions during each bunch crossing with instantaneous luminosity increasing to $\approx 5.0 \times 10^{34} \text{cm}^{-2}\text{s}^{-1}$ and peaking at $\approx 7.5 \times 10^{34} \text{cm}^{-2}\text{s}^{-1}$ for the ultimate scenario. Amount of PU will increase to 140 interactions per bunch crossing and will peak at 200 compared to a peak instantaneous luminosity of $1.0 \times 10^{34} \text{cm}^{-2}\text{s}^{-1}$ for Run-1 and 2 of Phase-I LHC design with around 30–50 PU vertices. Several hardware upgrades related to electronic systems and various sub-detectors are proposed to improve physics performance and mitigate the high PU’s adverse effects on physics analyses. Also, the PUPPI algorithm can be used at L1 of HL-LHC. In this section, we discuss these in some detail.

3.1 Phase-II upgrades

Major hardware upgrades for HL-LHC are motivated by the requirement to maintain the Phase-I physics performance at higher luminosity and increased PU interactions. We start this section with a brief discussion of the Phase-II upgrades available at L1, most of which we have already introduced in section 1:

- One of the major hardware upgrades at HL-LHC will be the upgrade of electronics of barrel calorimeters for both front-end and back-end systems to accommodate extended level-1 (L1) latency period of $12.5 \mu\text{s}$, increased L1 trigger rate up to $750\text{kHz}$ and high data transfer rate [85].

- Upgrade of electronic systems on-board the ECAL detector will also provide precise timing information and help reduce the noise coming due to increased luminosity. After the hardware upgrade, ECAL is expected to deliver $30\text{ps}$ timing resolution for $20\text{GeV}$ energy deposition at the beginning of HL-LHC when integrated luminosity will be around $300\text{fb}^{-1}$ [85]. However, this timing resolution is expected to degrade with increasing luminosity.

- Outer tracker of CMS at HL-LHC will be upgraded, which will pave the way for the availability of the tracking information at L1 trigger system [71]. The Phase-II outer tracker will be upgraded to stacked silicon strip modules which will enable the reconstruction of tracks at L1. Tracks will be reconstructed at L1 using hits correlations between two closely stacked silicon strip sensors. Tracks with $p_T > 2\text{GeV}$, with a $d_0 = 0$ constraint, will be selected based on the stubs formed in the tracker layers.

- Extended tracking for displaced tracks is being studied at L1 for HL-LHC [71]. Decay products of LLPs come from a displaced vertex and if charged, will lead to displaced tracks in the tracker. Availability of tracking information for these displaced particles will enable us to have more handle on triggering events for e.g., with LLPs decaying to jets. Extended tracking is being studied for displaced tracks with $d_0$ up to $8\text{cm}$. 
Another substantial upgrade at the CMS for HL-LHC will be the implementation of the particle flow (PF) algorithm at L1. The PF algorithm, which has already been implemented at HLT and offline analyses at CMS for Phase-I of LHC, helps reconstruct and identify each particle individually after combining information from various sub-detectors of CMS. Availability of both track and calorimeter information at L1 has made possible the integration of PF algorithm at L1 in the “Correlator Trigger” where information from various standalone detector segments is optimally combined to precisely identify and reconstruct all particles [71].

Finally, the availability of tracking and PF information at L1 opens the door for implementing PU mitigation techniques at L1. One of the most important PU mitigation algorithms already being used during Phase-I of LHC in HLT and offline analyses, known as PUPPI, is being studied to be implemented at L1.

As outlined in ref. [71], the L1 trigger menu is proposed to use jets after applying the PUPPI algorithm to perform selections robust under the high PU environment of HL-LHC. Therefore, to understand the efficiency of standard jet triggers at L1 of HL-LHC, it is vital to check the performance of the PUPPI algorithm on displaced jets, which is otherwise optimised for prompt jets. In the subsequent sections, we first explain the PUPPI algorithm and how it mitigates PU, and then study the effect of applying it to LLP scenarios where we have displaced jets in the final state.

3.2 PUPPI algorithm at HL-LHC: prompt vs displaced jets

At HL-LHC, the presence of track collection and particle flow information at L1 has opened the possibility of reconstructing jets, combining both tracks and calorimeter deposits along with the application of the PUPPI algorithm, for jet based triggers. PUPPI algorithm [74] uses the PF information collected and combined from various sub-detectors to mitigate the neutral PU contribution on a particle-by-particle basis. Availability of track information at L1 also aids in separately identifying the charged PU contribution with the knowledge of the Primary Vertex (PV) position. For limited usage at L1, we only need the position of the hard scattering vertex. PF tracks are assigned different bins along the $z$-axis after sorting them according to their $z$-position. Bin corresponding to the maximum scalar sum $p_T$ is taken as the position of the PV. This method of vertexing is known as the “FastHisto” method and can be implemented at L1 well within the latency limit.

Tracks that are not originating from the PV are regarded as coming from PU vertices and are discarded. The PUPPI algorithm defines a local shape variable for each neutral particle to distinguish between a hard collision versus a soft component coming from PU. ECAL and HCAL energy deposits with no reconstructed track in the tracker fall in the category of neutral particles. PUPPI algorithm uses the PV position to calculate the local shape variable for each neutral particle in an event by taking into account the charged particles in the neighbourhood of the neutral particle within a cone of a certain radius. Finally, every neutral particle is re-weighted by the weight calculated using the local shape variable, $p_T$ of the particle, and the amount of PU in each event. A modified version of the PUPPI algorithm is implemented at L1 [71], keeping in mind the small latency period...
available at L1. Collection of PF candidates is used as the input to the L1 PUPPI algorithm, which will be available at L1 due to the presence of tracking at L1. For each neutral particle, the local shape variable, $\alpha$, is calculated using eq. \eqref{eq:alpha}:

\[
\alpha = \log \sum_{i \in \text{PV}, \Delta R < 0.3} \frac{\min(p_T^i, p_T^{\text{max}})^2}{\max(\Delta R, \Delta R^{\text{min}})^2}
\] (3.1)

The sum in eq. \eqref{eq:alpha} runs over all the charged particles with $p_T > 2$ GeV coming from the PV which lie within a cone of radius $0.07(\Delta R^{\text{min}}) < \Delta R < 0.3$ from the neutral particle in the barrel region. To avoid disproportionate contribution from a single charged particle, an upper limit is set on the $p_T$ of the charged particle ($p_T^{\text{max}}$), taken to be 50 GeV here.

Particle flow algorithm is already emulated in Delphes-3.5.0 with good consistency \cite{84}. There are three collections required as inputs to the PUPPI algorithm at L1: PF photons, neutral hadrons and tracks, where the tracks collection also includes displaced tracks from “Extended Tracking”. The displaced tracks at L1 follow an efficiency curve as a function of their transverse impact parameter from the beamline as given in the L1 TDR \cite{71}. An important thing to note here is that the displaced tracks which are not reconstructed at L1 will appear in the collection of neutral particles since they have energy deposits in the calorimeter with no corresponding tracks.

As outlined in section 2.5, PU is generated using PYTHIA8 soft QCD process and then merged with the hard process using PileUpMerger module of Delphes. To study the sole effect of PU, we merge the PU interactions with the $pp \rightarrow \nu \bar{\nu}$ process since the neutrinos will go undetected throughout the detector and will not deposit any energy in the calorimeters. Jet clustering is done at L1 using “sliding window method” \cite{71} with PUPPI candidates as inputs which gives similar efficiency as the clustering done using anti-$k_T$ algorithm with a cone size of $R = 0.4$. So, we have clustered jets using anti-$k_T$ algorithm within a cone of $R = 0.4$.

Now that the PUPPI algorithm is discussed in some detail, we study this algorithm in light of displaced scenarios arising from LLPs. We will study the feasibility of triggering LLP events by triggers constructed using PUPPI jets. While PUPPI jets can be effectively used to trigger the events where particles are promptly produced. For LLPs, we face a two-fold problem:

- The PUPPI algorithm depends on the identification of the PV. For LLPs, due to lack of enough prompt tracks at L1, the probability of reconstructing the PV incorrectly increases, as also pointed out in ref. \cite{19}. Therefore, in a fair amount of cases some PU vertex can satisfy the maximum scalar sum $p_T$ condition and be identified as the PV, whereas the vertex actually corresponding to the LLP production might get misidentified as a PU vertex.

- Decay products of the LLPs can have higher displacements such that they evade even the “Extended Tracking”, and as mentioned earlier, these will mostly contribute to the collection of neutral particles at L1. As a result, the number of L1 tracks that can be fed into the PUPPI algorithm to calculate the local shape variable will decrease, which will further reduce the efficacy of using PUPPI jets to trigger on displaced jets.
Performance of the PUPPI algorithm degrades in going from heavier to lighter LLPs since the heavier LLPs will comparatively have more associated charged tracks at their production vertex, which will help in correctly identifying the PV. Moreover, lighter LLPs have more boost and longer decay lengths in the lab frame, leading to fewer L1 tracks associated with them, even with the extension to displaced tracking at L1. Similarly, for LLPs having longer decay lengths, fewer and fewer tracks can be reconstructed at L1, thus, decreasing the efficacy of the PUPPI algorithm further with increasing decay length. As a demonstration of how these problems affect the distribution of the local shape variable, we have calculated $\alpha$ for neutral particles in LLP scenarios (A) and (B), as described in sections 2.1 and 2.2 and compare the distributions of $\alpha$ in some benchmark points from these scenarios, merged with an average of 140 PU vertices per collision, with that obtained from merging $pp \rightarrow \nu\bar{\nu}$ process with PU, where the latter captures the sole effect of PU.

The left panel of figure 2 shows the distributions of the local shape variable for LLPs having a mass of 30 GeV with decay lengths 10 cm and 100 cm decaying to jets from scenario (A) in the 140 PU environment of HL-LHC compared to the distribution obtained only from PU. As we can clearly see, the PUPPI algorithm fails to distinguish neutral particles coming from PU and the LLP signal since there is almost no distinction between the two distributions. The right panel of figure 2 shows similar distributions for LLPs from scenario (B) with a mass of 150 GeV and decay lengths of 10 cm and 100 cm. In this case, there is some distinction between neutral particles from just PU and LLP merged with PU, the latter having a longer tail at higher $\alpha$ values, as compared to scenario (A), where the LLP is lighter. Also, we observe that with increasing decay length, more and more particles start looking like particles from the PU vertex, for reasons described earlier.
To sum up our observations, PU mitigation using the PUPPI algorithm is not optimal for LLP scenarios, especially for lighter LLPs and those with higher decay lengths. For heavier LLPs, triggers constructed using PUPPI objects can perform better than lighter LLPs; however, even for heavier LLPs, the performance of the PUPPI algorithm in displaced searches is going to be sub-optimal.

In addition to PUPPI based jet triggers, two separate triggers are designed specifically to explore physics involving displaced jets. As discussed earlier, “Extended Tracking” available at L1 enables reconstruction of displaced tracks at L1 with the tracking efficiency varying with $d_0$. Trigger based on jets constructed using L1 tracks, using both extended and prompt track-finding approaches, is included in the trigger menu dedicated for the displaced physics searches. Another displaced jet trigger is constructed based on the ECAL timing information, which will also be available at L1. Timing is an important way to select out LLP events since heavier LLPs with large decay lengths travel slower in the colliders due to lesser boost before decaying, and as a result, their decay products will have a time delay compared to prompt relativistic particles from SM processes. For this timing-based calo-jet trigger, ECAL timing for jets is calculated by averaging the energy-weighted ECAL time-stamp of ECAL towers ($T_{\text{raw}}$) [86].

Information regarding displaced triggers as given in L1 TDR [71] is not sufficient enough to understand the peculiarities of timing-based jet triggers. We now advance our discussion and study closely the timing of a jet — its different measures, how efficiently these can distinguish between displaced and prompt jets, and how these are affected by the various experimental conditions, like detector resolutions and PU.

4 ECAL barrel timing of a jet: ramifications of the HL-LHC conditions

Previous section discussed how the standard PUPPI jet trigger might not be the best choice for selecting LLP events, especially in the scenarios where LLPs are lighter with larger decay lengths. Dedicated triggers developed by the CMS for displaced searches give an extra handle on selecting LLP events. We now focus on the timing of a jet obtained from ECAL at L1, and discuss the possibility of exploring it for further development of dedicated triggers for LLPs in the light of physics scenarios mentioned in section 2. However, before advancing, there are several effects which are needed to be studied in detail which will have a major influence on how dedicated timing triggers perform in various conditions. The initial HL-LHC runs will have 140 PU interactions which are expected to increase to 200 interactions per event by the end of HL-LHC. The timing resolution of the detectors will also degrade over time as luminosity increases. In the following sections, we will discuss the effect of increased PU interactions on jet distributions, especially on the timing of a jet and how we can deal with PU efficiently. We will also discuss how the timing of the jet will get modified with degrading resolution as we move from an integrated luminosity of 300 fb$^{-1}$ to 4500 fb$^{-1}$.

4.1 Effect of PU on the timing of a jet

Mitigation of PU for displaced jets is going to be a big challenge at L1. As seen in section 3.2, jet triggers constructed using PUPPI objects will be suitable for triggering events with
prompt jets at L1 without the high PU being much of an issue. However, standard PUPPI jet triggers will not be efficient in selecting events which contain jets originating from the decay of a LLP. We would require different strategies to handle PU for searches involving LLPs decaying to jets. Let us begin by studying the effect of PU on jet distributions, like jet multiplicity, for LLP signals and QCD background. For this, we have chosen the benchmark with a mass of the LLP being 30 GeV and decay length 100 cm from LLP scenario (A). As discussed earlier, LLPs coming from the decay of 125 GeV Higgs boson are comparatively lighter, and the heavier LLPs have lesser boost, and therefore, further decay to jets with relatively smaller energy deposition in the calorimeters (ECAL and HCAL), making them harder to trigger on. For comparison, we have considered QCD dijet events in the bin with $p_T^{\text{gen}} \in \{30, 50\}$ GeV as the background process. We have considered four PU scenarios with 0, 60, 140, and 200 PU interactions per bunch crossing, where the first one corresponds to the ideal situation, and the other three correspond to PU conditions at Run-II, and beginning and end of HL-LHC, respectively. The spread of vertices in the time and z-direction is taken as given in the Delphes card for Phase-II CMS. We have clustered the ECAL and HCAL towers into jets with the anti-$k_T$ algorithm with fixed cone size, which is required to have at least one tower with hadronic energy ($E_{\text{had}}$) greater than 2 GeV in the jet. We have also applied a scale factor of 1.2 in the Delphes card for the jets. Clustered jets with $R = 0.4$, having $p_T > 20$ GeV and $|\eta| < 1.44$ are selected in an event for signal and background in the four different PU scenarios and we count number of such jets in an event. We find that mean jet multiplicity is around 2 for both signal and background at 0 PU, which increases to $\approx 6$ for 60 PU, $\approx 20$ for 140 PU, and $\approx 30$ for 200 PU. There is a dramatic increase in the jet multiplicity as we increase the PU to 200, indicating that jet distributions will be dominated by the jets coming from PU interactions at high PU. Since PU will have the same effect on both QCD and LLP distributions, it will be impossible to distinguish between signal and background at high PU. Also, since PU will be uniformly distributed throughout the detector, signal jets will get highly contaminated with energy deposits coming from PU as we move towards high PU conditions. This contamination will have an adverse effect on physics variables constructed for jets.

Let us now discuss the effect of PU on ECAL timing of a jet and how can we mitigate the adverse effects of PU on the timing of the LLP jets. ECAL timing for jets is calculated by averaging the energy-weighted ECAL time-stamp of ECAL towers ($T_{\text{raw}}$) [86]. The timing for each tower is calibrated using the definition $\Delta t = T_{\text{raw}} - T_{\text{prompt}}$ where $T_{\text{prompt}}$ is the time taken by a relativistic prompt particle produced at the interaction point to reach at the same ($\eta, \phi$) position as the tower. In order to remove out-of-time PU, we reject ECAL crystals with the time difference, $|\Delta t| > 20$ ns. We have studied four PU scenarios like before — 0, 60, 140, and 200 average number of vertices per bunch crossing. As the number of PU interactions per bunch crossing increases, so does the amount of PU contamination inside the jet. We find that the tail of the timing distribution of LLP jets reduces with increasing PU, the effect being more pronounced for 140 and 200 PU. A large number of particles from PU inside the signal jet smear the jet timing, and jets that had more significant timing, to begin with, now have smaller timing values due to enormous PU contribution. Since, PU is uniformly distributed inside the detector, PU contribution
Figure 3. The timing of the jets ($\Delta T_{\text{Ewt \ mean}}$) with jet cone radius $R = 0.2$, $0.3$, and $0.4$ for LLP scenario (A) with benchmark point ($M_X = 30\text{ GeV}, \ c\tau = 100\text{ cm}$) as well as QCD dijet events ($p_T^{\text{gen}} \in \{30, 50\} \text{ GeV}$) for 0 PU (top left) and LLP scenario (A) with benchmark point ($M_X = 30\text{ GeV}, \ c\tau = 100\text{ cm}$) for 60 PU (top right), 140 PU (bottom left), and 200 PU (bottom right).

inside the jet will depend on the jet area. The smaller the jet area, the smaller will be the PU contribution. Reducing the jet cone size can effectively mitigate the PU contribution given that jets from the signal process are not affected, and a smaller cone radius captures most of the hadronic activity of the signal. This condition works in our favour, as it was shown in refs. [13, 15, 19], that displaced jets coming from LLP decays deposit energy in a smaller area of the $\eta$$-\phi$ plane. To further study the feasibility of using smaller cone sizes for our analysis, we show the effect of different cone sizes on jet timing distribution for LLP and QCD in figure 3. We have plotted the jet timing distributions for LLP scenario (A) with four PU conditions along with QCD dijet events ($p_T^{\text{gen}} \in \{30, 50\} \text{ GeV}$) for 0PU since timing of QCD jets is not affected much with increase in PU. We have considered the LLP benchmark point with decay length 100 cm and the mass of the LLP is taken to be 30 GeV. Timing for each jet is calculated using ECAL crystals with energy deposits greater than 0.5 GeV as a first-level removal of some of the detector noise and energy deposits from PU, which can also have a high time delay, without affecting the jet distributions.

We can clearly see from the top left panel of figure 3, that for 0 PU, when jets are clustered purely from the energy deposits coming from the decay of the LLP signal with no PU contribution, the timing of the jet does not change with a decrease in the jet cone radius from $R = 0.4$ to $R = 0.2$, which again inspires the use of smaller cone radius when dealing with displaced jets from LLP processes. As the amount of average number of PU
per event is increased to 200, $R = 0.4$ jets being most contaminated by the PU have a shorter tail in the timing distribution, while for $R = 0.2$ and 0.3 jets, we can see more jets with more significant jet timing with longer tail in the $\Delta T_{\text{mean}}^{\text{Ewt}}$ distribution which clearly indicates that jets clustered with $R = 0.2$ and 0.3 have much less PU contamination even in the ultimate PU scenario. The distributions in the 0 PU condition show that the timing of the signal jets is not affected by the reduction of jet cone size from $R = 0.4$ to $R = 0.3$; however, the long tails in the timing distributions are revived at higher PU scenarios for $R = 0.3$. This aids in discriminating displaced jets from prompt ones in a better way at HL-LHC. For the rest of the paper, we have used jets clustered using the anti-$k_T$ algorithm with jet cone radius fixed at $R = 0.3$, unless stated otherwise, since using narrower jets effectively decreases the PU contamination inside the jet.

4.2 Effect of the ECAL timing resolution on jet timing

In time-sensitive analyses, ECAL timing resolution will be a key factor. From the preliminary studies done at CMS, it is expected that the ECAL detector will be able to achieve a timing resolution of 30 ps for 20–25 GeV ECAL towers at the beginning of HL-LHC. The timing resolution of the ECAL detector will degrade over time. As given in TDR [85], the major contribution to timing resolution will be from noise coming from readout electronics which will increase as luminosity increases over time. ECAL TDR has shown the time resolution discretely for $\eta = 0, 0.0$ and $\eta = 1.45$ as a function of energy. We have assumed that timing resolution will vary linearly between $\eta = 0, 0.0$ and $\eta = 1.45$, and thus, we have linearly extrapolated the resolution function for all $\eta$ values between 0 and 1.45. At $\eta = 0, 0.0 (1.45)$, ECAL timing resolution is 27 (34) ps, 40 (57) ps, 75 (141) ps and 111 (223) ps corresponding to integrated luminosity of 300 fb$^{-1}$, 1000 fb$^{-1}$, 3000 fb$^{-1}$, and 4500 fb$^{-1}$ respectively for 20 GeV energy deposit at ECAL. Timing of each ECAL crystal is smeared following the Gaussian distribution for each scenario where we have applied a $p_T$ and $\eta$ dependent timing resolution corresponding to integrated luminosity of 300 fb$^{-1}$, 1000 fb$^{-1}$, 3000 fb$^{-1}$, and 4500 fb$^{-1}$.

Figure 4 shows timing distribution for two LLP benchmarks ($M_X = 30$ GeV, $c\tau = 10$ cm and 100 cm) from scenario (A) and QCD dijet events ($p_T^{\text{gen}} \in \{30, 50\}$ GeV). LLP with shorter decay length is affected more with degrading timing resolution. We can see a slightly longer tail in the timing distribution for LLP with $c\tau = 10$ cm compared to the QCD dijet events at the beginning of HL-LHC when timing resolution is much better, and this distinction degrades in going towards the end of HL-LHC. The tail of distribution for LLP characterised with a higher decay length of 100 cm is affected comparatively less with degrading timing resolution because the timing of the jets coming from highly displaced LLPs is relatively quite large compared to the noise. With degrading timing resolution, tail in the timing distribution of QCD jets also broadens as we move from 300 fb$^{-1}$ to 4500 fb$^{-1}$. Thereby, we can conclude that timing resolution will significantly affect how timing distributions will look like for jets coming from QCD dijet and LLP processes, and there will be more spread in the timing distribution of the jets as we go towards the end of the HL-LHC due to degradation in the timing resolution. Hence it will become more and more challenging to distinguish LLP events from QCD ones towards the end of HL-LHC.
Figure 4. The timing distribution ($\Delta T_{\text{mean}}^{\text{Ewt}}$) of the jets for LLP (A) benchmark ($M_X = 30 \text{GeV}$, $c\tau = 10 \text{cm}$) and QCD dijet background ($p_T^{\text{gen}} = \{30,50\} \text{ GeV}$) with $R = 0.3$ cone radius without any timing resolution (top left), and with timing resolution after 300 fb$^{-1}$ (top right), 1000 fb$^{-1}$ (center left), 3000 fb$^{-1}$ (center right) and 4500 fb$^{-1}$ (bottom) of integrated luminosity collected in the 140 PU scenario.

4.3 Why do prompt QCD jets having high time delays?

In the previous sections, we have observed that even some prompt jets from QCD dijet process have high timing values. In this section, we try to understand the origin of such jets from QCD. We have seen that resolution of the ECAL timing is one of the reasons for smearing the jet timing and hence giving larger values even when the actual jet is not delayed. There are two other factors that might add to the tail of the prompt jet timing distribution to higher values. First being the intrinsic spread of the beamspot in both the
temporal and longitudinal direction, which can make even prompt jets appear delayed with high $\Delta T^{\text{Ewt}}_{\text{mean}}$. Second is the presence of some long-lived SM particles like $K_S$, $\Lambda$, $\Omega$ etc. whose decay products can be delayed and hence shift the jet timing to higher values. This effect becomes less and less relevant as we collect more and more data and move towards higher luminosity, since then the degraded timing resolution dominates the jet timing. We now discuss briefly the effect of beamspot spread on the timing of QCD jets.

For HL-LHC, the position of vertices on the beamline will follow a Gaussian distribution with a standard deviation of approximately 220 ps in time and 55 mm in longitudinal ($z$) direction around the center as shown in the left panel of figure 5. We already know that spread in the timing distribution of QCD jets is determined by the ECAL timing resolution (see figure 4). It can also be due to this intrinsic spread of the beamspot in both the temporal and longitudinal direction. We have already studied the effect of ECAL timing resolution on the shape of timing distribution in the previous section. In figure 5 (right), we show energy-weighted mean timing of QCD jets without applying any ECAL timing resolution, with and without the spread in both the temporal and longitudinal directions, and also with only one of them kept on. The time delay caused by the longitudinal spread of the beamspot at the central region near $\eta = 0$ is the smallest and it keeps on increasing as we move towards $|\eta| = 1.4$. However, this effect gets washed out once we have the temporal spread of vertices as well, which has a much higher spread ($\sigma_T = 220$ ps) than the magnitude of the effect of the longitudinal spread of beamspot on the time delay of a jet with increasing $|\eta|$. As we can also see from figure 5, while the longitudinal spread of vertices contributes to the time delay, the spread of vertices in time plays the dominant role in increasing the timing of QCD jets.

The beamspot spread can be corrected at the MTD which is expected to have a 30 ps timing resolution, and since it gives timing of charged particles, we know where these tracks
originate as well, which helps in calibrating the timing better. For ECAL, we face a two-fold difficulty — the production vertices of photons depositing their energy in the ECAL is uncertain since there are no corresponding tracks in the Tracker, and the timing resolution of the ECAL degrades as the $p_T$ of the photons decrease or their pseudorapidity increase. Even in the case where we have some idea of the photon vertex from the pointing nature of its energy deposit, it might be still difficult to correct for the beamspot spread if the timing resolution of the ECAL is greater than the beamspot time spread ($\sim 220$ ps). For example, for a photon having $p_T$ 1–2 GeV, the timing resolution varies between 800 ps–400 ps at $|\eta| = 0$, which further degrades to 1000 ps–600 ps at $|\eta| = 1.45$, both at the end of collection of 1000 fb$^{-1}$ of data. Since we are dealing with 30–40 GeV jets, we mostly expect such low energy photons. In this regard, we have closely followed L1 TDR [71] and refs. [87, 88] to construct the timing of jets from the ECAL where contribution of the beamspot spread to the jet timing is taken into account. The effect of longitudinal spread is less since the spread of vertices is a Gaussian with the standard deviation to be only 55 mm in z-direction, which is very small as compared to the radial distance of the ECAL from the beamline, which is around 1290 mm.

All these effects — the increased amount of PU at HL-LHC, the timing resolution of the ECAL detector, which degrades with data taking, the spread of vertices in the temporal and longitudinal directions as well as the presence of SM long-lived particles, are important factors affecting the timing of a jet. We now discuss how the ECAL timing can be used for dedicated triggers of long-lived particles decaying to jets.

5 Developing triggers for displaced jets based on ECAL timing

The previous section discusses various factors affecting the timing of a jet, and how we can control PU for LLP signal by constructing narrow jets. In this section, we study how the ECAL timing information of a jet can be exploited in various ways to identify displaced jets from the large background of prompt jets from SM processes, dominated mainly by QCD dijet events. Furthermore, we discuss how this can be used to construct L1 triggers for the HL-LHC.

5.1 Timing variables

Jets are objects consisting of many particles, and as a result, the timing of a jet has to be some statistical measure using the individual timing of the jet components. Since we are focusing on the CMS ECAL timing here, we need to define the jet timing in terms of the timing of each ECAL crystal associated with a jet. In previous sections, we have always talked about the energy-weighted mean timing of the jet, $\Delta T^{\text{Ewt, mean}}$, which has also been used by the CMS collaboration in designing their trigger based on ECAL timing [71]. We can construct many such variables defining the timing of a jet. In the present work, we have constructed several timing variables using the ECAL timing information available at L1 to understand which of them might be useful in differentiating prompt jets from displaced jets.
The following list describes the various measures used by us to define jet timing:

- $\Delta T_{\text{mean}}$: mean of the timing of all the ECAL crystals contained within the jet.
  \[
  \Delta T_{\text{mean}} = \frac{\sum \Delta T_i}{N} \tag{5.1}
  \]
  where $i$ runs over all the ECAL crystals inside the jet and $N$ is the total number of crystals associated with the jet.

- $\Delta T_{\text{median}}$: median of the timing of all the ECAL crystals in a jet.

- $\Delta T_{\text{RMS}}$: RMS (root mean square) of the timing of all the ECAL crystals in a jet.
  \[
  \Delta T_{\text{RMS}} = \sqrt{\frac{\sum \Delta T_i^2}{N}} \tag{5.2}
  \]
  where $i$ runs over all the ECAL crystals inside the jet and $N$ is the total number of crystals associated with the jet.

- $\sum \Delta T$: sum of the timing of all the ECAL crystals in a jet.

- $\Delta T_{\text{Ewt}}_{\text{mean}}$: energy-weighted mean of the timing of all the ECAL crystals in a jet.
  \[
  \Delta T_{\text{Ewt}}_{\text{mean}} = \frac{\sum \Delta T_i \times E_i}{\sum E_i}, \quad i \equiv \text{crystals inside the jet} \tag{5.3}
  \]

- $\Delta T_{\text{ETwt}}_{\text{mean}}$: transverse energy-weighted mean of the timing of all the ECAL crystals in a jet.
  \[
  \Delta T_{\text{ETwt}}_{\text{mean}} = \frac{\sum \Delta T_i \times E_{T,i}}{\sum E_{T,i}}, \quad i \equiv \text{crystals inside the jet} \tag{5.4}
  \]

The timing of each crystal is calibrated with respect to the origin as discussed earlier, and for the energy and transverse energy-weighted measures, calibration is applied before re-weighting with energy. We have also constructed all of the above timing variables using two more timing calibration techniques where the timing of each crystal in the jet is calibrated with respect to the PV and the jet vertex (JV) from which that particular jet is originating. Note that PV is reconstructed using prompt track collection available at L1 by selecting the vertex with largest $\sum p_T^2$. The JV is found out in a similar way by using all the prompt tracks associated with the jet, i.e., lying within $\Delta R < 0.3$ of the jet axis at the ECAL, and selecting the vertex with the maximum $\sum p_T^2$ value.

In addition, we compute the mean timing of the jet using only five or ten crystals with the maximum time delay at ECAL ($\Delta T_{\text{Max5}}_{\text{mean}}, \Delta T_{\text{Max10}}_{\text{mean}}$) or maximum value of time delay multiplied by the energy of the crystal ($\Delta T \times E_{\text{Max5}}_{\text{mean}}, \Delta T \times E_{\text{Max10}}_{\text{mean}}$), given the jet has at least five or ten towers associated with it. Again, the timing of each crystal is calibrated with respect to the origin. If the jet has less than five or ten towers within it, $\Delta T_{\text{Max5}}_{\text{mean}}$ and $\Delta T_{\text{Max10}}_{\text{mean}}$ are assigned same values as $\Delta T_{\text{mean}}$, and $\Delta T \times E_{\text{Max5}}_{\text{mean}}$ and $\Delta T \times E_{\text{Max10}}_{\text{mean}}$ are assigned same values as $\Delta T_{\text{Ewt}}_{\text{mean}}$, respectively. The motivation behind constructing such
variables is to reduce the contribution from the timing of ECAL energy depositions coming
from PU vertices which reduce the jet timing, as we have seen earlier. Moreover, variables
using the towers with highest $\Delta T \times E$ ensure that low-energy PU energy deposits with high
timing do not contaminate these variables — for displaced jets from LLPs, usually towers
with high time delay contribute and for prompt jets from QCD dijet events, towers with
high energy which usually have lower time delays contribute.

We now study the distributions of the variables in both the 0 PU and 140 PU scenarios
to understand the effect of PU on these variables and to select the timing variables
which are more PU resistant in addition to having the good capability to differentiate
between the LLP signal and the background. The correlation matrices of these variables
for two LLP benchmarks each from scenario (A) and (B) along with QCD dijet events
($p_T^{\text{gen}} \in \{30, 50\} \text{ GeV}$) has been shown in figure 13 of appendix B. We list down our
observations below:

- Even in the absence of PU, we find that the distributions of LLP benchmarks with
  shorter decay length of 10 cm are not much distinguishable from the QCD background,
in contrast to the 100 cm decay length benchmarks with longer tails in the timing
distributions, which reduces on adding 140 PU since these are average measures.

- We have observed that timing variables with energy-weighted timing are more PU
  resistant than the rest of the variables which is expected since weighting the timing
  with the energy of the tower reduces contamination from low energy PU. In addition,
  the RMS timing of the jet is also robust against PU which might be due to its
  robustness against the presence of both negative and positive values in the data, which
  comes from the spread of the PU vertices in the time and $z$ direction.

- We have found that the effect of calibration on the timing of ECAL towers from PV
  and JV has a negligible impact on jet timing compared to the situation where the
  timing of each ECAL tower is calibrated with respect to the origin.

After observing distributions for various timing variables, we have short-listed two timing
variables out of the above-mentioned ones, which are the most PU resistant and provide a
good distinction between the background and the signal — $\Delta T_{\text{Ewt mean}}$ and $(\Delta T \times E)_{\text{Max5 mean}}$. In
figure 6, we have shown distributions and ROC of these two shortlisted timing variables for
two LLP scenarios (A) and (B) with two benchmark points each — having decay lengths
10 cm and 100 cm and a mass of 30 GeV in scenario (A) and 150 GeV in scenario (B), along
with one QCD bin having $p_T^{\text{gen}} \in \{30, 50\} \text{ GeV}$. All these distributions have been shown for the
ECAL timing resolution corresponding to 1000 fb$^{-1}$ luminosity. We infer from the ROC
plots in the 140 PU case that the $(\Delta T \times E)_{\text{Max5 mean}}$ variable performs slightly better than the
$\Delta T_{\text{Ewt mean}}$ variable for the benchmark from scenario (A). For the benchmark from scenario (B),
$(\Delta T \times E)_{\text{Max5 mean}}$ performs much better than $\Delta T_{\text{Ewt mean}}$, and the former is also more robust against
PU. We can get around 75% and 99% background rejection for a signal efficiency of 50% for
the 30 GeV LLP from scenario (A) and 150 GeV LLP from scenario (B) respectively, where
each of them have a decay length of 100 cm, which decreases with decreasing decay length.
After carefully studying the various timing variables — how their distributions look for displaced jets and prompt jets, in the absence and presence of PU, we now proceed further to use these to construct triggers that will be useful for selecting events with LLPs decaying to jets efficiently, maintaining reasonable background rejection at L1 of HL-LHC CMS.

5.2 Triggering using timing variables

As we can see from the timing distributions of QCD jets after the addition of 140 PU, they have a comparatively longer tail in the timing distributions compared to the 0 PU scenario. We have discussed this earlier in section 4.3 that large jet timing in the QCD distribution can be due to various factors, like $\eta$-$\phi$ position as well as $p_T$ of the jet constituents, timing resolution of the ECAL crystals, the temporal and longitudinal spread of vertices and SM long-lived particles. Besides these, the timing of the jet, which is solely calculated using ECAL towers, can be affected if the number of ECAL towers is relatively less and most of the energy of the jet is deposited in HCAL. In such cases, only a few ECAL towers are available to calculate the timing of the jet, which can be statistically insufficient to accurately determine the timing of the jet.

We can see from figure 7, putting a minimum cut on the number of ECAL towers, say $N_{\text{tow}} \geq 3$ significantly reduces the number of QCD prompt jets having higher timing. Therefore, we can use this cut to reduce QCD jets with high timing values without affecting the signal much.
Figure 7. Energy-weighted mean timing of a jet ($\Delta T_{\text{Ewt\,mean}}$) without and with cuts on the number of ECAL towers, $N_{\text{low}} \leq 3$ and $N_{\text{low}} \geq 3$, for jets from the QCD dijet events ($p_T^{\text{gen}} \in \{30, 50\}$ GeV).

In table 1, we show how signal efficiency for three LLP scenarios changes along with rate after putting different threshold on the timing values for two considered timing variables. We select jets with $p_T > 40$ GeV uniformly for all three LLP scenarios with two benchmark points each. As we can see from the tables, signal efficiency is comparatively higher for all the scenarios for lower timing thresholds but it comes at the cost of increased background rate which we need to keep under control, below 30 kHz. Change in signal efficiency and rate with varying the timing threshold is much more pronounced for $\Delta T_{\text{Ewt\,mean}}$ where the background rate for a cut of $\Delta T_{\text{Ewt\,mean}} > 0.5$ ns increases up to 950 kHz from 32 kHz for a cut of $\Delta T_{\text{Ewt\,mean}} > 1$ ns, while the signal efficiency increases up to 28.7 % from 19.7 % on decreasing the threshold from 1 ns to 0.5 ns for LLP scenario (A) benchmark with LLP of mass 30 GeV and 100 cm decay length.

A crucial part of constructing triggers is to ensure that the trigger rate is within the acceptable bandwidth, i.e., the number of events passing the trigger selection cuts per second is not impractically large. Therefore, it is essential to keep a check on the QCD dijet background rates from our triggers. We have generated our QCD background in different $p_T^{\text{gen}}$ bins, which we need to combine with the minimum bias sample, without any overlap in phase-space, which can lead to overestimation of rates. For this purpose, we have used the “stitching” procedure as described in ref. [89], which we discuss and validate in appendix C. In this procedure, each event is assigned a rate depending on the weight calculated for that event using eq. (C.1), explained in appendix C. The total rate of our trigger is computed by summing over the individually assigned rates of each background event, passing our trigger criteria.

To remind the readers, we are reconstructing jets using anti-$k_T$ clustering algorithm with jet cone radius $R = 0.3$. We have applied an energy and $\eta$ dependent timing resolution corresponding to 1000 fb$^{-1}$ on the ECAL towers before calculating the jet timing. We have chosen the resolution corresponding to 1000 fb$^{-1}$ since that is the integrated luminosity.
| LLP Scenario | Mass [GeV], cτ [cm] | $\Delta T^{\text{Ewt}}_{\text{mean}}$ | $(\Delta T \times E)^{\text{max5}}_{\text{mean}}$ |
|--------------|---------------------|---------------------------------|---------------------------------|
|              | Time [ns] Efficiency [%] (Rate [kHz]) | Time [ns] Efficiency [%] (Rate [kHz]) | Time [ns] Efficiency [%] (Rate [kHz]) |
| LLP(A) 30, 10 | >0.5 6.59 (950) >5.0 1.86 (38) |
|             | >0.75 1.59 (93) >5.5 1.65 (27) |
|             | >1.0 0.74 (32) >6.0 1.40 (24) |
|             | >1.5 0.43 (6) >6.5 1.23 (19) |
| LLP(A) 30, 100 | >0.5 28.73 (950) >5.0 18.40 (38) |
|             | >0.75 22.58 (93) >5.5 17.35 (27) |
|             | >1.0 19.67 (32) >6.0 16.53 (24) |
|             | >1.5 16.55 (6) >6.5 15.90 (19) |
| LLP(B) 150, 10 | >0.5 18.35 (950) >5.0 16.09 (38) |
|             | >0.75 6.33 (93) >5.5 14.22 (27) |
|             | >1.0 3.25 (32) >6.0 12.58 (24) |
|             | >1.5 1.49 (6) >6.5 11.10 (19) |
| LLP(B) 150, 100 | >0.5 47.25 (950) >5.0 41.19 (38) |
|             | >0.75 37.82 (93) >5.5 39.23 (27) |
|             | >1.0 31.90 (32) >6.0 37.41 (24) |
|             | >1.5 24.29 (6) >6.5 35.78 (19) |
| LLP(C) 150, 10 | >0.5 18.18 (950) >5.0 24.19 (38) |
|             | >0.75 8.01 (93) >5.5 22.41 (27) |
|             | >1.0 5.49 (32) >6.0 20.91 (24) |
|             | >1.5 3.60 (6) >6.5 19.54 (19) |
| LLP(C) 150, 100 | >0.5 41.03 (950) >5.0 39.07 (38) |
|             | >0.75 33.18 (93) >5.5 37.40 (27) |
|             | >1.0 28.69 (32) >6.0 35.72 (24) |
|             | >1.5 23.18 (6) >6.5 34.43 (19) |

Table 1. Signal efficiencies and background rates for LLP scenarios (A), (B) and (C) benchmarks with LLP of mass 30 GeV and 150 GeV respectively with decay lengths 10 and 100 cm for various timing thresholds on $\Delta T^{\text{Ewt}}_{\text{mean}}$ and $(\Delta T \times E)^{\text{max5}}_{\text{mean}}$.

that is expected to be collected in the 140 PU scenario, which we have mostly focused on till now. The resolution corresponding to 1000 fb$^{-1}$ lies somewhere between the best and the worst resolutions of the ECAL timing information at the beginning and end of HL-LHC runs. Figure 8 shows the rate as a function of jet $p_T$ with varying cuts on the two different jet timing measures identified from the previous section — $\Delta T^{\text{Ewt}}_{\text{mean}}$ (left) and $(\Delta T \times E)^{\text{max5}}_{\text{mean}}$.
Figure 8. Rate of background events as a function of jet $p_T$ with varying cuts on the $\Delta T_{\text{Ewt}}^{\text{mean}}$ (left) and $\Delta T_{\text{Max5}}^{\text{mean}}$ (right) timing of the jet for ECAL timing resolution corresponding to 1000 fb$^{-1}$ in the 140 PU scenario.

Table 2. Selection cuts for the two dedicated timing triggers with thresholds for the two jet timing variables, number of ECAL towers associated with a jet and the jet $p_T$ which keeps the background rate $\approx 30$ kHz.

| Timing variable | Time (ns) | Number of ECAL towers | $p_T$ (GeV) |
|-----------------|-----------|-----------------------|-------------|
| $\Delta T_{\text{Ewt}}^{\text{mean}}$ | $> 1.1$ | $\geq 3$ | $> 35$ |
| $(\Delta T \times E)_{\text{Max5}}^{\text{mean}}$ | $> 5.5$ | $-$ | $-$ |

(right). We demand the presence of at least 3 ECAL towers to calculate $\Delta T_{\text{Ewt}}^{\text{mean}}$ in order to get rid of high jet timings coming from jets with lower ECAL energy depositions compared to HCAL. As we can see from figure 8, for 40 GeV jets, we can restrict background rate to less than $\approx 30$ kHz by putting $\Delta T_{\text{Ewt}}^{\text{mean}} > 1$ ns, or $(\Delta T \times E)_{\text{Max5}}^{\text{mean}} > 5.5$ ns.

These rate plots motivate the choice of appropriate $p_T$ and timing variable cuts which maintain reasonable background rates. The L1 trigger bandwidth is expected to be around 750 kHz at HL-LHC. We believe that a rate of 30 kHz might be reasonable enough to fix our trigger cuts. We then perform a cut based analysis by applying these cuts on the signal to calculate the signal efficiencies of these triggers for the fixed background rate of 30 kHz. Our triggers are single jet triggers above some $p_T$ threshold with some minimum number of ECAL towers, and satisfy the jet timing cut. For each of the two variables, $\Delta T_{\text{Ewt}}^{\text{mean}}$ and $(\Delta T \times E)_{\text{Max5}}^{\text{mean}}$, we have separate cuts such that the rate is not more than 30 kHz. We have enumerated the cut thresholds for each variable in table 2. As can be seen from table 2, we have reduced the $p_T$ threshold from 40 GeV to 35 GeV, and made the timing thresholds stricter in order to maintain the rate below 30 kHz. We calculate the efficiency of our timing triggers for all three LLP scenarios — for LLP scenario (A), we calculate efficiency for LLPs in the mass range of $\{10,50\}$ GeV and for LLP scenarios (B) and (C), we compute
the efficiency for LLPs with masses in the range \{100,500\} GeV. For all scenarios, we vary the decay length in the range \{1,500\} cm.

We present the signal efficiencies in the form of grids in the plane of mass and decay length of the LLP for the three LLP scenarios, which can be directly used in other theoretical studies of LLPs. Figure 9 show the efficiency grids of the three LLP scenarios considered in this work with varying masses and decay lengths of the LLPs, each with the two sets of triggers, whose cuts are tabulated in table 2. We observe that efficiency increases with an increase in the mass of the LLPs, which is due to the fact that massive LLPs have lesser boost, and hence cause more time delay of their decay products. With increasing decay length, the efficiency first increases due to increasing time delays and then decreases for much larger $c\tau$ values because a significant number of LLPs decay after the ECAL without depositing a sufficient amount of energy in ECAL. We can see this for the LLP benchmark point with 500 cm decay length, where the efficiency decreases in all the three LLP scenarios.

We discuss our results below:

- **Scenario (A).** We observe that for LLP scenario (A), where the LLPs are produced from Higgs boson decay, energy-weighted mean timing ($\Delta T_{\text{Ewt}}^{\text{mean}}$) performs the best among the chosen two timing variables. An efficiency of around 16% can be achieved for 10 GeV LLP with 50 cm decay length, 19% can be achieved for 30 GeV LLP with 100 cm decay length, and for 50 GeV LLP, an efficiency of around 23% can be achieved for 200 cm decay length, at a rate of around 30 kHz. Comparing these efficiencies to the initial fraction of decays within the ECAL, as shown in figure 1, we find that for 30 GeV LLPs even though around 100% of the decays happen within the ECAL for $c\tau = 10$ cm, only 0.74% survives the timing cuts, since most of these have very low displacements, and hence lower jet timing. For 30 GeV LLP with $c\tau = 500$ cm, 24% of events have at least one LLP decaying within the ECAL, and 19.41% pass the timing cuts. At HL-LHC, with an integrated luminosity of 1000 fb$^{-1}$, if we translate these numbers to the sensitivity on the branching fraction of Higgs boson to decay to such LLPs, we get the following upper limits on $\text{Br}(h \to XX)$ assuming 100% decay of the LLP to jets and that 50 signal events passing the L1 trigger using the $\Delta T_{\text{Ewt}}^{\text{mean}}$ might be enough:

\begin{itemize}
  \item $\text{Br}(h \to X X) \lesssim 6.2 \times 10^{-6}$ for $M_X = 10$ GeV, $c\tau = 50$ cm
  \item $\text{Br}(h \to X X) \lesssim 5.1 \times 10^{-6}$ for $M_X = 30$ GeV, $c\tau = 100$ cm
  \item $\text{Br}(h \to X X) \lesssim 5.4 \times 10^{-6}$ for $M_X = 40$ GeV, $c\tau = 100$ cm
\end{itemize}

Scaling the current limit from the CMS collaboration using 132 fb$^{-1}$ of the data collected till Run-2 of Phase-I of LHC [31] (excluding branching above 0.03) to Run-3 with 300 fb$^{-1}$ and HL-LHC with 1000 fb$^{-1}$ integrated luminosity gives 0.01 and 0.004 respectively.

\begin{itemize}
  \item $\text{Br}(h \to X X) \lesssim 4.3 \times 10^{-6}$ for $M_X = 50$ GeV, $c\tau = 200$ cm
\end{itemize}

Timing variables are sensitive to higher decay lengths and therefore, we are able to improve the limits on branching from $4 \times 10^{-3}$ to $5.4 \times 10^{-6}$ for the 40 GeV LLP having 100 cm decay length by including our timing based triggers. Our numbers
Figure 9. Efficiency of selecting events for LLP scenarios (A) (top), (B) (middle) and (C) (bottom) in percent for various values of LLP mass and decay length using $\Delta T^{\text{ewt}}_{\text{mean}}$ (left) and $(\Delta T \times E)^{\text{max}5}_{\text{mean}}$ (right). Efficiency is calculated by applying cuts on the jet $p_T$, respective timing variables, and number of ECAL towers according to table 2 to keep the background rate $\approx 30$ kHz.
are not the final exclusion limits for the benchmarks studied in this work which will depend on the HLT as well as offline analyses, rather they are indicative of the Level-1 signal selection efficiency/sensitivity for these benchmarks.

- **Scenario (B).** For pair produced LLPs in scenario (B), \((\Delta T \times E)_{\text{mean}}^{\text{Max5}}\) performs better than the other variable for LLP masses greater than 100 GeV, especially for smaller decay lengths. With this variable, efficiencies of around 39%, 58%, and 82% can be achieved for LLPs of mass 150 GeV, 250 GeV, and 500 GeV, respectively, decaying to two jets for 100 cm decay length in this scenario. From figure 1, we find that 100% of events with 150 GeV LLPs and \(c\tau = 10\) cm have at least a single LLP decaying before the ECAL, out of which 14.25% pass the trigger based on \((\Delta T \times E)_{\text{mean}}^{\text{Max5}}\) variable, and for \(c\tau = 100\) cm, these numbers are 80% and 39% respectively. With increasing mass and \(c\tau\), we can retain more events after L1 from the parton level decay efficiencies within the ECAL.

At HL-LHC, with an integrated luminosity of 1000 fb\(^{-1}\), we get the following upper limits on the production cross sections of such LLPs, assuming 100% decay of the LLP to two jets using the \((\Delta T \times E)_{\text{mean}}^{\text{Max5}}\) trigger:

\[- \sigma \lesssim 0.18\, \text{fb} \quad \text{for} \quad M_X = 100\, \text{GeV}, \ c\tau = 100\, \text{cm}\]

CMS has excluded direct pair production cross-section of LLP decaying to two jets above 20 fb using 132 fb\(^{-1}\) of data for Run-2 for 100 GeV LLP with 100 cm decay length [31], which when scaled for Run-3 and HL-LHC, excludes production cross-sections above 8.8 fb and 2.6 fb respectively.

\[- \sigma \lesssim 0.13\, \text{fb} \quad \text{for} \quad M_X = 150\, \text{GeV}, \ c\tau = 100\, \text{cm}\]

\[- \sigma \lesssim 0.09\, \text{fb} \quad \text{for} \quad M_X = 250\, \text{GeV}, \ c\tau = 100\, \text{cm}\]

\[- \sigma \lesssim 0.076\, \text{fb} \quad \text{for} \quad M_X = 300\, \text{GeV}, \ c\tau = 100\, \text{cm}\]

For this benchmark, the CMS analysis excludes production cross-section greater than 0.67 fb, which we can expect to improve to 0.3 fb and 0.088 fb after the end of Run-3 and initial runs of HL-LHC, respectively.

\[- \sigma \lesssim 0.06\, \text{fb} \quad \text{for} \quad M_X = 500\, \text{GeV}, \ c\tau = 100\, \text{cm}\]

We find that our timing based trigger is expected to greatly improve the limit for the 100 GeV benchmark from 2.6 fb to 0.18 fb for \(c\tau = 100\) cm, whereas a slight improvement is expected for the heavier benchmark of 300 GeV. Please note that this particular CMS analysis is based on displaced vertex finding and therefore, is sensitive to lower lifetimes where our timing based analysis loses its sensitivity. We also remind the readers that the HL-LHC projection with our timing based triggers assumes observation of 50 signal events at L1.

- **Scenario (C).** Similar to scenario (B), \((\Delta T \times E)_{\text{mean}}^{\text{Max5}}\) performs better than the other variable in this case as well, and we get efficiencies of around 38%, 54%, and 76% for LLPs of mass 150 GeV, 250 GeV, and 500 GeV, respectively, decaying to three jets for 50 cm decay length.
At HL-LHC, with an integrated luminosity of 1000 fb$^{-1}$, we get the following upper limits on the production cross sections of such LLPs, assuming 100% decay of the LLP to three jets using the $(\Delta T \times E)_{\text{Max}}^{5}$ mean trigger:

\begin{itemize}
  \item $\sigma \lesssim 0.13 \text{ fb}$ for $M_X = 150 \text{ GeV}, \ c\tau = 50 \text{ cm}$
  \item $\sigma \lesssim 0.09 \text{ fb}$ for $M_X = 250 \text{ GeV}, \ c\tau = 50 \text{ cm}$
  \item $\sigma \lesssim 0.07 \text{ fb}$ for $M_X = 500 \text{ GeV}, \ c\tau = 50 \text{ cm}$
\end{itemize}

In each of the three scenarios, we have presented the level-1 sensitivity corresponding to 50 events passing our triggers. The actual discovery or exclusion limits will depend on several factors, like the identification of displaced vertex at the HLT and offline analyses, and suppression of SM backgrounds, which is beyond the scope of the present study.

\section{Possible improvements and discussions}

Hitherto, we have discussed various timing variables of a jet and then identified two of them, depending on their ability to distinguish between the displaced and prompt jets and robustness against PU, and construct two different triggers for displaced jets using these variables. In this section, we discuss various methods which can further help in improving the trigger performance that we discussed in the previous section. Moreover, we have done our analysis using a particular set of scenario — ECAL timing resolution, cone-size of jets, and amount of PU, and we explore in this section whether our timing variables are robust and how much our results vary with these varying scenarios.

\begin{itemize}
  \item \textit{Impact of better resolution in the initial runs of HL-LHC}. As we discussed in section 4.2, timing resolution will play a very critical role in the timing-based trigger performance. As mentioned in the ECAL TDR \cite{85}, the timing resolution of ECAL detector will worsen over time with an increase in the collected integrated luminosity. Initial runs of CMS at HL-LHC will have better timing resolution for ECAL towers of the same energy as compared to the final runs at the end of HL-LHC. Till now, we have considered the resolution corresponding to 1000 fb$^{-1}$ of collected luminosity, which is moderate, compared to the best resolution at 300 fb$^{-1}$ integrated luminosity at the beginning of HL-LHC and a much worse resolution when around 3000 fb$^{-1}$ of data is collected by the end of HL-LHC. To understand the effect of the resolution, we now calculate the background rate as a function of the $p_T$ of the jet with varying cuts on the two jet timing variables, $\Delta T_{\text{Ewt}}^{\text{mean}}$ and $(\Delta T \times E)_{\text{Max}}^{5}$ mean, after applying timing resolution corresponding to an integrated luminosity of 300 fb$^{-1}$ and 3000 fb$^{-1}$, and is shown in figure 10.

Looking back at figure 4, we have seen that the timing distribution corresponding to 300 fb$^{-1}$ has a much narrower peak than the resolution at 3000 fb$^{-1}$. Therefore, in the latter case, we expect that we have to devise much stricter cuts on jet variables in order to keep the rate under control. We observe this for both the timing variables in figure 10. From figure 10, we find that we can restrict the background rate at
around 30 kHz by selecting jets with $p_T > 40$ GeV and $\Delta T^{E_{\text{jet}}}_{\text{mean}} > 0.75$ ns, whereas for these same cuts the rate increases to around 2000 kHz. In order to keep the rate under control during final runs with $3000 \text{ fb}^{-1}$, jet $p_T$ and timing need to be constrained more aggressively, which will deteriorate the efficiency of selecting LLP events. To achieve a rate below 30 kHz, we have to use selection cuts of $p_T > 50$ GeV and $\Delta T^{E_{\text{jet}}}_{\text{mean}} > 1.5$ ns.

However, in the initial HL-LHC runs, due to better resolution, we can apply more relaxed cuts maintaining low background rates, seen in figure 10. Let us now check whether these reduced cuts can improve the signal efficiency. We use the same $p_T$ and $N_{\text{low}}$ cuts as used by us in the 1000 fb$^{-1}$ case mentioned in table 2, with the timing cuts reduced for each variable to $\Delta T^{E_{\text{jet}}}_{\text{mean}} > 0.85$ ns and $(\Delta T \times E)_{\text{mean}}^{\text{max}} > 5.0$ ns. We have calculated the efficiency of the timing trigger at 300 fb$^{-1}$ using these cuts for three LLP scenarios for a few benchmark points, as listed in table 3. There is improvement in the signal efficiency for each benchmark point in all the three LLP scenarios for triggers constructed using $\Delta T^{E_{\text{jet}}}_{\text{mean}}$ and $(\Delta T \times E)_{\text{mean}}^{\text{max}}$. The improvement is not as large to compensate for the reduced collected luminosity compared to 1000 fb$^{-1}$ (around a factor of 3), however, we can conclude here that the initial runs of CMS at HL-LHC will be slightly more sensitive to trigger LLP events while keeping the rate under control.

• **Inclusion of displaced tracks at L1.** Availability of displaced tracks at L1 along with ECAL timing information will give an extra handle to trigger on LLP events. L1 triggers based on timing information of displaced objects start becoming sensitive in selecting LLPs with higher decay lengths and can miss LLPs with smaller decay lengths. Inclusion of displaced tracks information along with timing information to construct dedicated LLP triggers can significantly increase the signal efficiency,
Table 3. Trigger efficiency for three benchmark masses from the three LLP scenarios with $c\tau = 10 \text{ cm}$ and 100 cm calculated by putting suitable thresholds on the two timing variables to keep the background rate restricted at $\approx 30 \text{ kHz}$ when the ECAL timing resolution corresponding to 300 fb$^{-1}$ luminosity is applied.

| LLP Scenario | Mass (GeV) | $\Delta T_{\text{Ewt mean}}$ (\%) | $(\Delta T \times E)_{\text{mean}}$ max (\%) |
|--------------|------------|----------------------------------|-----------------------------------------------|
| LLP (A)      | 30, 10     | 0.88                             | 1.79                                          |
|              | 30, 100    | 21.46                            | 18.18                                         |
| LLP (B)      | 150, 10    | 4.44                             | 15.50                                         |
|              | 150, 100   | 35.16                            | 40.85                                         |
| LLP (C)      | 150, 10    | 6.43                             | 23.53                                         |
|              | 150, 100   | 31.41                            | 38.70                                         |

Figure 11. Rate of background events as a function of jet $p_T$ with the combination of varying cuts on the $\Delta T_{\text{Ewt mean}}$ (left) and $(\Delta T \times E)_{\text{mean}}$ max (right) timing of the jet for ECAL timing resolution corresponding to integrated luminosity of 300 fb$^{-1}$ and number of displaced L1 tracks inside a jet within $\Delta R = 0.3$ at ECAL, in the 140 PU scenario.

especially for LLP scenarios where LLP has a relatively shorter lifetime whose decay products will have very small time delay as measured in the ECAL. We have combined information about the multiplicity of displaced tracks inside a jet with the jet timing to construct a new hybrid trigger where a jet will be selected if it satisfies the timing threshold or if the jet has a certain number of displaced tracks inside $\Delta R = 0.3$ of the jet axis. Displaced tracks are selected at L1 with efficiency as cited in the CMS Phase-II L1 TDR [71], and we also put a cut of $d_0 > 1 \text{ cm}$ to reduce QCD background. In figure 11, we have shown the background rate as a function of jet $p_T$ for resolution corresponding to 300 fb$^{-1}$ with varying cuts on the two timing variables, $\Delta T_{\text{Ewt mean}}$ and $(\Delta T \times E)_{\text{mean}}$ max, along with the number of displaced L1 tracks inside the jet.
| LLP Scenario | Mass (GeV) | $\Delta T_{E_{\text{L1}}}|_{\text{mean}}$ (%) | $(\Delta T \times E_{\text{L1}})|_{\text{max}}$ (%) |
|--------------|------------|---------------------------------|---------------------------------|
| LLP (A)      | 30, 10     | 4.60                            | 5.41                            |
|              | 30, 100    | 22.14                           | 18.84                           |
| LLP (B)      | 150, 10    | 24.79                           | 32.32                           |
|              | 150, 100   | 39.45                           | 44.42                           |
| LLP (C)      | 150, 10    | 39.59                           | 47.29                           |
|              | 150, 100   | 39.64                           | 44.52                           |

**Table 4.** Trigger efficiency for three benchmark masses from the three LLP scenarios with $c\tau = 10\text{ cm}$ and 100 cm calculated by putting suitable thresholds on the two timing variables as well as the number of displaced L1 tracks associated with the jet to keep the background rate restricted at $\approx 30\text{ kHz}$ when the ECAL timing resolution corresponding to $300\text{ fb}^{-1}$ luminosity is applied.

The left panel of figure 11 shows that the rates increase to about 60 kHz when we select events having at least one $p_T > 40\text{ GeV}$ jets with either at least 2 associated displaced L1 tracks or with $\Delta T_{E_{\text{L1}}}|_{\text{mean}} > 0.85\text{ ns}$, same as in the previous section where we discuss the impact of resolution at $300\text{ fb}^{-1}$. We can further constrain the background rates to below 20 kHz by requiring at least 3 displaced L1 tracks inside the jet, keeping the cuts on the timing variables the same, and increasing the minimum number of displaced tracks to 4 does not reduce the rate much. We have calculated the signal efficiency for two benchmark points in all the three LLP scenarios by fixing the jet timing cut in both the timing variables to be the same as taken in the previous section and mentioned in figure 11 or impose the condition of displaced track multiplicity to be greater than or equal to 3 in a $p_T > 35\text{ GeV}$ jet. For these set of cuts, the background rate is restricted at $\approx 30\text{ kHz}$, and the signal efficiencies are shown in table 4. Comparing the values of signal efficiencies obtained in table 4 with table 3, we can see that there is a huge improvement in the signal efficiency for benchmark points with $c\tau = 10\text{ cm}$ across all three scenarios for trigger constructed using both the timing variables. For comparison, CMS collaboration has excluded branching fraction of Higgs boson to LLP above 0.003 till Run-2 and for Run-3 and HL-LHC, limit scales up to 0.0013 and $3.9 \times 10^{-4}$ respectively, for LLP of mass of 40 GeV with 10 cm decay length. Inclusion of displaced track information along with timing will be crucial to select LLPs with shorter decay lengths as we can exclude branching fraction above $6.12 \times 10^{-5}$ for LLP of mass 30 GeV with 10 cm decay length if we translate the improved signal efficiency shown in table 4 to branching fraction for the current scenario as discussed in this section assuming we select 50 such LLP events at L1.

- **Narrower jets with $R = 0.2$.** As we discussed in section 4.1, jets with narrow cone size have lesser PU contribution, and QCD jets are most affected as jet cone size is reduced while LLP jets being narrow can be comfortably contained in a smaller area. In previous sections, we have used $R = 0.3$ jets which reduced PU contamination inside
jets to a considerable amount, and contamination of jet timing by energy deposits coming from PU was also reduced compared to $R = 0.4$. We now study the effect of reducing the cone size further down to $R = 0.2$ and how this affects the signal efficiency and background rates. We recluster jets using anti-$k_T$ jet clustering algorithm with a reduced jet cone size of $R = 0.2$ and impose the same conditions as applied in the last section for $R = 0.3$ jets when the resolution corresponding to 300 fb$^{-1}$ is used. We find that in going from jets with a cone size of $R = 0.3$ to $R = 0.2$, the background rate decreases for the same $p_T$ cut. Since the rates decrease slightly, we can reduce the cuts of the timing variables keeping the rates around 30 kHz, which can help in increasing the signal efficiencies. We find that the efficiencies increase slightly for the shorter decay length of 10 cm, which is more prominent for scenarios (B) and (C) where the LLP has direct pair-production in the collider. For the 100 cm decay length, the efficiencies slightly decrease when we consider $R = 0.2$ jets instead of $R = 0.3$ jets.

- The ultimate HL-LHC scenario with 200 PU. For the ultimate scenario at HL-LHC, the number of PU interactions will reach up to 200 vertices per bunch crossing. To keep the background under permissible range, we have to revisit the thresholds for the timing variables used in the previously discussed triggers. We calculate the rate for QCD background for the two timing variables as discussed above after smearing the timing of the ECAL towers with the resolution corresponding to an optimistic scenario where timing resolution corresponds to the one when integrated luminosity reach around 1000 fb$^{-1}$, and the background now merged with an average of 200 PU vertices per hard collision instead of 140. We find that there is almost a two-fold increase in the rate when PU interactions increase from 140 to 200 for the $\Delta T_{\text{Ewt}}^{\text{mean}}$ variable, if the cuts are kept the same. To keep the rate under 30 kHz, we have to put tighter constraints on the values of the timing variables — $\Delta T_{\text{Ewt}}^{\text{mean}} > 1.2$ ns with $N_{\text{low}} \geq 4$, and $(\Delta T \times E)_{\text{mean}}^{\text{Max5}} > 8$ ns (compared to 1.1 ns with $N_{\text{low}} \geq 3$ and 5.5 ns at 140 PU), respectively.

With this tighter set of cuts, we now compute the signal efficiencies of the three LLP scenarios for two benchmark points in each scenario, shown in table 5. Due to the increased thresholds to maintain the background rate below 30 kHz, signal efficiency decreases with the increase in PU when compared to 140 PU as shown in the table 5. At 200 PU, $(\Delta T \times E)_{\text{mean}}^{\text{Max5}}$ performs at par with $\Delta T_{\text{Ewt}}^{\text{mean}}$ for LLP(A) benchmark with 100 cm decay length while for benchmark with 10 cm decay length, there is two-fold increase in the signal efficiency when compared with $\Delta T_{\text{Ewt}}^{\text{mean}}$. Performance of $(\Delta T \times E)_{\text{mean}}^{\text{Max5}}$ is considerably better than the other variable for LLP scenarios (B) and (C) for both benchmark points.

To improve the signal efficiency for LLP benchmarks with shorter decay lengths, we can perform a similar analysis as done for the 140 PU scenario and combine the displaced tracks information with the timing information of the jet. The background rate for 200 PU can be restricted to 30 kHz by requiring at least four displaced tracks inside the jet along with the respective timing, and $N_{\text{low}}$ cuts as explained in the previous discussion. Signal efficiency for three LLP scenarios for two benchmark points each is calculated with an updated set of requirements. Performance of $\Delta T_{\text{Ewt}}^{\text{mean}}$...
Table 5. Trigger efficiency for three benchmark masses from the three LLP scenarios with $c\tau = 10 \text{ cm}$ and 100 cm calculated by putting suitable thresholds on the two timing variables to keep the background rate restricted at $\approx 30\text{kHz}$ when the ECAL timing resolution corresponding to 1000 fb$^{-1}$ luminosity is applied in the 200 PU scenario. For comparison, we have quoted the corresponding signal efficiencies for the 140 PU scenario with the same timing resolution and same constraint on the background rate.

| LLP Scenario | Mass (GeV) | $\Delta T_{\text{mean}}^\text{Ewt}$ (%) | $(\Delta T \times E)_{\text{mean}}^{\text{max}}$ (%) |
|--------------|------------|----------------------------------------|---------------------------------------------|
|              | $c\tau$ (cm) | 200 PU | 140 PU | 200 PU | 140 PU |
| LLP (A)      | 30, 10     | 0.50  | 0.74  | 1.03  | 1.68  |
|              | 30, 100    | 18.04 | 19.41 | 16.58 | 17.53 |
| LLP (B)      | 150, 10    | 2.12  | 2.90  | 8.37  | 14.25 |
|              | 150, 100   | 27.26 | 30.48 | 34.76 | 39.43 |
| LLP (C)      | 150, 10    | 4.52  | 4.98  | 17.66 | 22.48 |
|              | 150, 100   | 25.51 | 27.58 | 34.16 | 37.60 |

improves by a factor of three for LLP scenario (A), while for LLP scenarios (B) and (C), signal efficiency improves by a factor of 6 for LLP benchmark with 10 cm decay length. For $(\Delta T \times E)_{\text{mean}}^{\text{max}}$, there is a two-fold improvement in the performance for LLP with 10 cm decay length across all scenarios.

7 Summary and conclusion

With several ongoing dedicated analyses with exciting future prospects, an ample amount of theory motivation supports the need for LLP searches to be performed with more vigour to look for physics beyond the standard model. LLPs can leave different types of exotic signatures in the detector based on their final state, as discussed in the text. In this paper, we have mainly focused on the scenarios where LLP decays to jets in the final state. We have studied two well-motivated scenarios where LLPs are produced through the decay of the 125 GeV Higgs boson and where they are directly pair-produced in the context of CMS detector at HL-LHC. With several future upgrades in the pipeline, the need to develop dedicated triggers for displaced searches becomes imminent. In the present work, we have studied how ECAL based timing triggers at level-1 can be effectively used for LLP searches at HL-LHC. In section 1, we have specified our goal in terms of several questions. We summarise our findings below:

- **Displaced jets and PUPPI.** We have performed a preliminary analysis to study how the PUPPI algorithm, usually optimised for prompt jets, performs for displaced jets. We find that it is difficult to differentiate jets from the decay of lighter LLPs and jets coming from minimum bias events, and therefore, they might be rejected at L1. For heavier LLPs, for example, in LLP scenarios (B) and (C), PUPPI triggers will perform comparatively better, and we can trigger some events containing displaced jets, since energy deposited by LLP in the calorimeters for such scenarios will be
sufficient enough. However, even for heavier LLPs, the signal efficiency will degrade with an increase in decay length.

- **Timing variables — factors affecting them and most optimal variables.** We have constructed and studied more than 20 timing variables and their performance for jets from QCD dijet events and some LLP benchmarks, both without and with the 140 PU environment of HL-LHC. We have found that smaller cone sizes can contain most of the energy deposition of displaced jets, and help in reducing the PU contribution, and therefore, we consider jets clustered using anti-$k_T$ with $R = 0.3$. Resolution of the ECAL barrel timing also plays a crucial role in determining the jet timing, and it degrades with increasing collected luminosity. Another major factor affecting jet timing is the spread of vertices in the temporal and longitudinal directions. The presence of SM long-lived hadrons, like $K_S$ and $\Lambda$, inside the jet and their decay products, can also increase the jet timing. From the timing distributions of the many timing variables, we have identified two variables that have good separation power between the LLP signal and QCD prompt jets background as well as are fairly robust against PU — $\Delta T_{E_{Wt}}^{\text{mean}}$ and $(\Delta T \times E)_{\text{mean}}^{\text{max5}}$.

- **Accurate background rate calculation using “stitching”**. We have combined rates of QCD dijet events from different $p_T^{\text{gen}}$ bins, and the minimum bias events using the “stitching” procedure to ensure we do not double count any region of phase space. From the background rates for varying cuts on the jet $p_T$ and one from the two timing variables, we fix the thresholds for our cuts for a feasible rate, like 30kHz, and then apply these cuts on our LLP signal benchmarks. To the best of our knowledge, such an estimation of background rates for various timing-based triggers in different PU scenarios considering proper resolutions corresponding to the degrading ECAL timing resolutions with increasing luminosity is not available elsewhere in the literature.

- **Performance of different triggers based on the optimal variables.** While $\Delta T_{E_{Wt}}^{\text{mean}}$ has better performance for LLPs in scenario (A) for lighter LLPs with large decay length, $(\Delta T \times E)_{\text{mean}}^{\text{max5}}$ performs better than the other variables for LLPs in all three scenarios for lighter as well heavier LLPs for both small and large decay lengths. Also, in scenario (A), for lower decay lengths $(\Delta T \times E)_{\text{mean}}^{\text{max5}}$ based timing trigger has better performance. Keeping the background rate restricted at approximately 30kHz with 140 PU at HL-LHC with ECAL timing resolution corresponding to an integrated luminosity of around 1000 fb$^{-1}$, we can achieve signal efficiency of around 19% for $M30, c\tau100$ from $\Delta T_{E_{Wt}}^{\text{mean}}$ based trigger and efficiency of around 1.7% for $M30, c\tau10$ from $(\Delta T \times E)_{\text{mean}}^{\text{max5}}$ based trigger for LLP scenario (A). For heavier pair produced LLPs, we can achieve signal efficiency of around 39% and 38% for benchmark $M150, c\tau100$ in scenario (B) and (C) respectively. For benchmarks with shorter decay lengths, signal efficiency of around 14% and 22% can be achieved for $M150, c\tau10$ in scenarios (B) and (C), respectively, with the $(\Delta T \times E)_{\text{mean}}^{\text{max5}}$ based trigger.

- **Possibilities for improvement, and the 200 PU scenario.** The initial HL-LHC runs will have better ECAL timing resolution at 300 fb$^{-1}$ of collected luminosity, which helps
us to reduce the thresholds without affecting the rate, and hence improve the signal efficiency. Using narrower jet cone size can also slightly improve the performance for LLP benchmarks with lower decay lengths, but signal efficiency for LLPs with larger decay lengths have a slight reduction. For the ultimate scenario at HL-LHC, an increase in PU interaction from 140 to 200 will increase the QCD background rate by around a factor of 2 for the $\Delta T_{\text{Ewt mean}}$ based trigger, which implies that the thresholds of the cuts have to be increased. For ECAL timing resolution corresponding to $1000 \text{fb}^{-1}$ and 200 PU, we can achieve signal efficiency of around 18% with the $\Delta T_{\text{Ewt mean}}$ based trigger for LLP benchmark $M30, c\tau100$ in LLP scenario (A). We get signal efficiency of around 35%, 34% for benchmarks $M150, c\tau100$ in LLP scenarios (B) and (C) respectively with the $(\Delta T \times E)_{\text{max5 mean}}$ based trigger.

- **Inclusion of displaced L1 tracking and its complementarity with timing.** The inclusion of displaced L1 tracks along with timing information to construct displaced jet triggers will significantly increase the signal efficiency for LLPs, especially the ones with shorter decay lengths. Signal efficiency of approximately 5%, 25% and 40% can be achieved for benchmarks $M30, c\tau10, M150, c\tau10$, and $M150, c\tau10$ in LLP scenarios (A), (B), and (C) respectively when the $\Delta T_{\text{Ewt mean}}$ trigger is combined inclusively with demanding at least 3 displaced tracks inside a jet. Signal efficiency of approximately 32% and 47% can be obtained for benchmark point $M150, c\tau10$ in scenario (B) and (C) respectively after inclusion of displaced tracks with $(\Delta T \times E)_{\text{max5 mean}}$ based timing trigger. Displaced tracks based triggers are more sensitive to lower decay lengths as compared to delayed jet triggers, and hence, improve the sensitivity in a complementary region. Signal efficiency for shorter decay lengths at 200 PU can also be improved by including displaced tracks information along with timing information as demonstrated for 140 PU scenario.

In conclusion, the feasibility of ECAL timing to construct various dedicated triggers at L1 of HL-LHC has been studied in detail in this work, considering various aspects, like the high PU environment of HL-LHC, degrading resolution, etc., and it is sensitive to LLPs having a range of masses and lifetimes in various scenarios. The background rate plots and signal efficiencies presented in the form of grids in the mass and decay length plane for the three LLP scenarios can be directly used in other theoretical studies of LLPs.

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Figure 12. Distribution of weight of each neutral particle calculated using the procedure followed in ref. [71] for QCD dijet process with $p_T^{\text{gen}} \in \{30, 50\} \text{ GeV}$ and $\{100, 150\} \text{ GeV}$ (top left), and LLP of mass $30 \text{ GeV}$ from scenario (A) (top right) and $150 \text{ GeV}$ from scenario (B) (bottom) with $c_T = 10 \text{ cm}$ and $100 \text{ cm}$ each, all merged with an average of $140 \text{ PU}$ vertices. Distribution for minimum bias events is also shown for comparison in each case.

A PUPPI weights

Weight is calculated for each neutral particle using following formulae:

$$w_i = \frac{1}{1 + e^{-x_{\text{tot}}}}$$  \hspace{1cm} (A.1)

$$x_{\text{tot}} = x_\alpha + x_{pT} - x_{\text{PU}}$$ \hspace{1cm} (A.2)

$$x_\alpha = \min(\max(c_\alpha(\alpha - \alpha_0), -x_{\alpha_{\max}}), +x_{\alpha_{\max}})$$ \hspace{1cm} (A.3)

$$x_{pT} = c_{pT}(p_T - p_{T}^0)$$ \hspace{1cm} (A.4)

$$x_{\text{PU}} = \log(N_{\text{PU}}/200) + c_0$$ \hspace{1cm} (A.5)

Here, $x_{\alpha_{\max}}$, $c_{pT}$, $c_0$ and $c_\alpha$ are tunable parameters (which can be read from a lookout table as given in ref. [71]) while value of $\alpha_0$ and $p_{T}^0$ represents mean values from PU. $N_{\text{PU}}$ is the number of tracks not associated with the identified PV. Finally, $p_T$ of the neutral particle is multiplied by the weight as calculated above. Charged PF tracks coming from the PV are combined with re-weighted neutral particles to participate in the jet clustering. Figure 12 shows the PUPPI weights for neutral particles calculated using the above formula for QCD dijet and LLP decaying to jets processes.

B Correlation matrices of timing variables

C Calculation of QCD background rate using “stitching”

In order to calculate background event rate, we generate QCD samples in 7 $p_T^{\text{gen}}$ bins covering phase space $\{30, 50\} \text{ GeV}$, $\{50, 75\} \text{ GeV}$, $\{75, 100\} \text{ GeV}$, $\{100, 125\} \text{ GeV}$, $\{125, 150\} \text{ GeV}$, $\{150, 175\} \text{ GeV}$, $\{175, 200\} \text{ GeV}$ and $>200 \text{ GeV}$. QCD samples in different $p_T^{\text{gen}}$ bins are stitched together along with minbias events in order to calculate the event rate accurately.
Figure 13. Correlation between the various timing variables defined in section 5.1 for four benchmark points of LLP — two from scenario (A) with $M_X = 30$ GeV, $c\tau = 10$ cm (top left and $c\tau = 100$ cm center left), and two from scenario (B) with $M_X = 150$ GeV, $c\tau = 10$ cm (top right and $c\tau = 100$ cm center right), and QCD dijet process ($p_T \in \{30, 50\}$ GeV) (bottom) using the resolution corresponding to 1000 fb$^{-1}$ luminosity.
Event weight in terms of rate is calculated using the following formula as given in ref. [89]:

$$w^I = \frac{F}{N_{incl} + \sum_j N_j \times \frac{n_j}{(N_{PU}+1) \times p_j}}$$  \hspace{1cm} (C.1)$$

where, $F$ corresponds to the $pp$ collision frequency of approximately 28 MHz. $N_{incl}$ corresponds to total number of events containing $N_{PU}+1$ inelastic collisions where $N_{PU}$ is the mean number of pile-up events in a collision. $N_j$ is the number of events in a particular QCD sample for the $j^{th} p_T^{\text{gen}}$ bin. $n_j$ refers to number of inelastic $pp$ interaction from PU or hard interaction falling in the $p_T^{\text{gen}}$ interval $j$. $p_j$ corresponds to the probability of single $pp$ inelastic collision to fall in the $j^{th} p_T^{\text{gen}}$ bin. The probabilities $p_j$ for a particular $p_T^{\text{gen}}$ bin is calculated by taking the ratio of cross-section of the collision for that particular bin and cross-section when no condition is imposed on the $p_T^{\text{gen}}$. We have shown the weight calculated using monte-carlo stitching method in figure 14 (left). We have also compared the HL-LHC single jet rate as calculated in ref. [89] to our calculations in figure 14 (right) and rate matches fairly well.
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