Long-lived particles at the LHC: Catching Them In Time

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We explore the physics potential of using precision timing information at the LHC in the search for long-lived particles (LLP). In comparison with the light Standard Model particle produced from the hard interactions, the decay products of massive LLPs arrives at detectors with sizable time delay. We propose new strategies to take advantage of this property, using the initial state radiation jet for timestamping the event and only requiring a single LLP to decay inside the detector. This search strategy can be effective for a broad range of models. In addition to outlining the general approach of using timing information, we demonstrate its effectiveness with the projected reach for two benchmark scenarios: Higgs decaying into a pair of LLPs, and pair production of long-lived neutralinos in the gauge mediated supersymmetry breaking scenario. Our strategy increases the sensitivity to the lifetime of the LLP by orders of magnitude and exhibits better behavior particularly in the large lifetime region compared to traditional LLP searches at colliders. The timing information significantly reduces the Standard Model background and therefore provides a powerful new dimension for LLP searches.

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The presence of Long-Lived particles (LLP) can be the most striking feature of many new physics models [1–11]. At the same time, vast swaths of the possible parameter space of the LLP remain unexplored by LHC searches. LHC general purpose detectors, ATLAS and CMS, provide full angular coverage and sizable volume, making them ideal for LLP searches. However, close to the interaction point, such searches can suffer from the large SM background. The LLPs produced at the LHC generically travel slower than the SM background and may decay at macroscopic distances away from the interaction point. Hence, they are separated from the SM background with sizable time delay. In this study, we focus on the strategy of using precision timing as a new tool to suppress the background and enhance the reach for the LLP at the LHC. Recently, precision timing upgrades with a timing resolution around 25-30 picoseconds, by the CMS collaboration for the barrel and endcap region in front of the Electromagnetic Calorimeter (EC) [12] and by the ATLAS collaboration in endcap and forward region [13], have been proposed to reduce pile-up for the upcoming runs with higher luminosities.1 In order to formulate a strategy applicable to a broad range of models, we propose the use of a generic ISR jet for timestamping the hard collision and require only single LLP decay inside the detector. Such a strategy can greatly suppress the SM background and reach a sensitivity orders of magnitude better than traditional searches. Precision timing opens a new window to search for Beyond Standard Model (BSM) signals.

FIG. 1. Two classes of signal kinematics for LLPs.

In general, there are two classes qualitatively different channels for the LLPs, as shown in Fig. 1. In the first class (upper panel), the LLP(s), denoted as X, are produced through the decay of a heavier resonance (Y), which can contain one or more LLPs. Perhaps the most popular model in this class is when the resonance is the Higgs boson (Y = h). This is highly motivated by possible connection of new physics and electroweak symmetry breaking. At the same time, the resonance can certainly be other SM particles, such as W, Z and the top quark. It could also be other new physics particles. They all share

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1 Timing information has also been applied to BSM searches in identifying new physics in some very limited cases. Such examples include the time of flight parameter adopted in the heavy stable charged particle searches [14–16], the time delay parameter adopted in the non-pointing photon searches at the CDF and recently ATLAS [17–19], and (very loosely) in the stopped particle searches [20].
### Basics of timing

While the particle identification and kinematic reconstruction are highly developed, the timing information is less used as prompt decays are often assumed for BSM signals. However, the signature of an LLP, in general, could have a significant time delay since the mass of the new particle can be comparable to its momentum. Here we outline a general BSM signal search strategy of using the timing information, and more importantly, the corresponding consideration for the background. A typical signal event of LLP is shown in Fig. 2. An LLP, denoted as $X$, travels a distance $\ell_X$ into a detector volume and decays into two light SM particles $a$ and $b$, which then reach timing layer at a transverse distance $L_{T1}$ away from the beam axis. In a typical hard collision, the SM particles generally travel close to the speed of light. The trajectories of charged SM particles can be curved, which increase the path length in comparison with neutral SM particles. For simplicity, we only consider neutral LLP signals where background from such charged particles can be vetoed using particle identification and isolation.\(^2\) Hence, the decay products of $X$, taking particle $a$ for example, arrives at the timing layer with a time delay of

$$
\Delta t = \frac{\ell_X}{\beta_X} + \frac{\ell_a}{\beta_a} - \frac{\ell_{SM}}{\beta_{SM}},
$$

with $\beta_a \simeq \beta_{SM} \simeq 1$. It is necessary to have prompt decay products or Initial State Radiation (ISR) which arriving at timing layer with the speed of light to derive the time of the hard collision at the primary vertex (to “timestamp” the hard collision). ISR jets could easily be present for all processes, and we use this generic feature to “timestamp” the hard collision for the proposed new searches in this letter.\(^3\)

Typically, $\ell_{SM}/\beta_{SM}$ range between several nanoseconds (ns), for entering EC, to tens of ns, for exiting the MS. As a result, with tens of picosecond (ps) timing resolution, we have a sensitivity to percent level time delay caused by slow LLP motion, e.g., $1 - \beta_X > 0.01$ with boost factor $\gamma < 7$. In Fig. 3, we show typical time delay $\Delta t$ for a hypothetical timing layer at the outer part of the ATLAS MS system for benchmark signals and the background, and the distributions for EC are put in appendix. The two benchmark signals considered here are the glueballs from Higgs boson decays, and the electroweakino pair production in the Gauge Mediated SUSY Breaking (GMSB) scenario. Both the glueballs and lightest neutralino proper lifetimes are set to be $c\tau = 10$ m. The 10 GeV glueballs (red dashed line) have larger average boost comparing to the 50 GeV glueballs.

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\(^2\) Charged stable (at the scale of tracker or detector volume) particles are highly constrained by the heavy stable charged particle searches by both ATLAS and CMS [14–16].

\(^3\) Although Jets contain soft (and hence slow) particles, the majority of the constituent particles in a jet still travel with nearly the speed of light [12, 21–23].
FIG. 3. The differential $\Delta t$ distribution for typical signals and backgrounds at 13 TeV LHC. The plot is normalized to the fraction of events per bin with a varying bin size, where for $\Delta t$ less than 1 ns are shown in linear scale and then in logarithmic scale otherwise. Two representative signal models are shown, the delay time for the glueballs from the Higgs decay (red curves) and the GMSB neutralinos from Drell-Yan pair production (blue curves), with a light and a heavy benchmark mass shown in dashed and solid curves, respectively. For all signal events, the proper lifetime is set 10 m, and the distribution only counts for events decayed within $[L_{T_1}, L_{T_2}]$ of $[4.2, 10.6]$ m in the transverse direction, which follows the geometry of ATLAS MS in the barrel region. For the background distribution shown in gray curves, we assume bunch spacing of 25 ns. The solid and dashed gray curves represent backgrounds from a same hard collision vertex and hence with a precision timing uncertainty of $\delta^{\text{PT}}_t = 30$ ps and from the pile-up with a spread of $\delta_t = 190$ ps, respectively, in units of fraction per 0.1 ns. The corresponding distribution for EC can be obtained approximately by scaling the horizontal axis according to the ratio of size of the detector volume (solid red line), and hence have a sizable fraction of the signals with delay time less than one nanosecond. For the electroweakinos pair production, the signals are not boosted and hence significantly delayed compared to the backgrounds, with 99% of the signal with $\Delta t > 1$ ns.

Search strategy.— We consider the signal with an ISR jet timestamping the primary vertex and another SM object from the LLP decay (e.g., jet for this study) which has large time delay $\Delta t$. To study the sensitivity to BSM signals with timing, we propose two searches using such information, one with CMS geometry for a precision timing layer located at the beginning of EC, and one with ATLAS geometry for a precision timing layer located at the end of MS. They are tabulated as follows:

|       | $L_{T_2}$ | $L_{T_1}$ | Trigger | $\epsilon_{\text{trig}}$ | $\epsilon_{\text{sig}}$ | $\epsilon_{\text{fake}}^j$ | Ref. |
|-------|----------|----------|---------|--------------------------|--------------------------|-----------------------------|-----|
| EC    | 1.17 m   | 0.2 m    | DelayJet| 0.5                      | 0.5                      | $10^{-3}$                    | [12]|
| MS    | 10.6 m   | 4.2 m    | MS RoI  | 0.25                     | 0.25                     | $5 \times 10^{-9}$          | [24]|

For both searches, we assume a similar performance of timing resolution of 30 ps. For the MS search, because of the larger time delay and much less background due to “shielding” by inner detectors, a less precise timing (e.g., 150 ps) could also achieve similar physics reach. The $\epsilon_{\text{trig}}$, $\epsilon_{\text{sig}}$ and $\epsilon_{\text{fake}}^j$ are the efficiencies for trigger, signal selection and a QCD jet faking the delayed jet signal with $p_T > 30$ GeV in EC or MS, respectively.

For the EC search, we assume a new trigger strategy of a delayed jet using the CMS upgrade timing layer. This can be realized by comparing the prompt jet with $p_T > 30$ GeV that reconstructs the four-dimensional primary vertex (PV4d) with the arrival time of another jet at the timing layer. The delayed and displaced jet signal, after requiring minimal decay transverse distance of 0.2 m ($L_{T_1}$), will not have good tracks associated with it. Hence, the major SM background is from trackless jets. The jet fake rate of $\epsilon_{\text{fake}}^{\text{EC}} = 10^{-3}$ is calculated using Pythia [25] by simulating the trackless jets, where all charged constituent hadrons are too soft to be observed or missed due to tracking inefficiency. The trackless jet fraction is measured in the validation data for the low-electromagnetism jet search at the ALTAS [26], and it is found to be $10^{-2}$. They also found a huge additional suppression through the energy deposition ratio between EC and hadronic calorimeter. Moreover, due to the decay of the LLP within the tracking volume, the signal contains low quality tracks in contrast to the truly neutral jets, and the energy deposition in the EC for the signal will be more than that of the neutral jets, we hence consider our jet fake rate assignment of $10^{-3}$ to be reasonably conservative.

For the MS search, we consider a new timing layer at the outer layer of the MS of ATLAS. We take the MS Region of Interest (MS RoI) trigger for very similar search from ATLAS [27] as reference, with an efficiency of $\epsilon_{\text{trig}} = 0.25$ and 0.5 for the two benchmark BSM signals, and a signal selection efficiency of $\epsilon_{\text{sig}} = 0.25$. The backgrounds are mainly from the punch-through jets, and its fake efficiency can be inferred to be $\epsilon_{\text{fake}}^{\text{MS}} = 5.2 \times 10^{-9}$, normalized to 1300 fake MS barrel events at 8 TeV [27]. Our Reference ATLAS MS displaced vertex search [24], due to the vertex reconstruction requirement, can only effectively select signal events decaying in the 4-7 m range, reducing the derived search sensitivity with the full MS volume approximately by a factor of two. We expect that with the help of the timing layer and a relaxed vertex reconstruction requirement, the effective decay range could be extended to the full MS while maintaining the same signal efficiency. In comparison with LLP decay in the 7-10 m range of the MS, there is no detector activities in the layers prior to that. Hence, the dominant background from punch can still be vetoed effectively.

Background consideration.— The main sources of the SM background faking such delayed and displaced signal are from jets or similar hadronic activities. The origin of
background can be classified into same-vertex (SV) hard collision and pile-up (PU). For this study, we assume the time-spread distributions follow Gaussian distribution.\(^4\)

\[
\frac{d\mathcal{P}(\Delta t)}{d\Delta t} = \frac{1}{\sqrt{2\pi} \delta_t} e^{-\frac{\Delta t^2}{2\delta_t^2}},
\]

(2)

where the time spreads \(\delta_t\) differ for different sources of backgrounds.

The SV background for the signals mainly comes from SM multi-jet process. At least one prompt jet is required to reconstruct PV4d and provide the timestamp, while another trackless jet from the same hard collision faking long-lived signals. The fake jet has an intrinsic time delay \(\Delta t = 0\). However, due to limited timing resolution in reconstructing the PV4d, it could have a time spread. The time resolution with the planned precision timing upgrade from CMS is \(\delta^{\text{PT}}_t = 30\) ps. At 13 TeV with integrated luminosity \(L = 3\) ab\(^{-1}\), the total number of such background events can be estimated,

\[
\begin{align*}
\text{EC} : & \quad N^\text{SV}_{\text{bkg}} = \sigma_j \mathcal{L}_\text{int} \epsilon_{\text{trig}} \epsilon_{\text{fake}} \approx 1 \times 10^{11} \quad (\text{3}) \\
\text{MS} : & \quad N^\text{SV}_{\text{bkg}} = \sigma_j \mathcal{L}_\text{int} \epsilon_{\text{trig}} \epsilon_{\text{fake}} \approx 4 \times 10^5,
\end{align*}
\]

(3)

where \(\sigma_j \approx 1 \times 10^8\) pb is the multi-jets cross-section with \(p_T^j > 30\) GeV, \(\epsilon_{\text{trig}}\) and \(\epsilon_{\text{fake}}\) are the efficiencies for the background to fake the signal in triggering and signature without timing information. The background differential distribution with respect to apparent delay time \(\Delta t\) can be estimated as,

\[
\frac{\partial N_{\text{bkg}}(t)}{\partial \Delta t} = N^\text{SV}_{\text{bkg}} P(\Delta t; \delta^{\text{PT}}_t).
\]

(4)

The time delay cut on \(\Delta t\) reduces such background through the tiny factor of \(P(\Delta t; \delta^{\text{PT}}_t)\) if \(\Delta t/\delta^{\text{PT}}_t\) is greater than a few. The LLP signal pays a much smaller penalty factor than the background due to its intrinsic delay, as shown in Fig. 3.

The background from the pile-up contains two hard collisions within the same bunch crossing but does not occur at the same time. The majority of such background can be eliminated by the standard isolation requirement, jet grooming procedure, etc. The background from the pile-up requires the coincidence of a triggered hard event and fake signal events from pile-up (hard) collision whose PV4d fails to be reconstructed. Since pile-up events also have spatial spread, the interaction point information \(z\) would also enter the estimation of such background. Therefore, given that the typical spread is few cm, it can induce a time shift at most \(\approx O(100)\) ps [12], typically with an addition suppression of a geometrical factor. Adding in quadrature, this will at most give an insignificant increase the spread in time \(\delta^{\text{PU}}_t \approx 60\) ps. It has even less impact for MS, the pile-up background is already small before timing cut. Thus, it can be safely neglected here.

At the HL-LHC, the total number of background events can be estimated,

\[
\begin{align*}
\text{EC} : & \quad N^\text{PU}_{\text{bkg}} = \sigma_j \mathcal{L}_\text{int} \epsilon_{\text{trig}} \frac{\epsilon_{\text{fake}}}{\epsilon_{\text{inc}}} \approx 2 \times 10^7, \\
\text{MS} : & \quad N^\text{PU}_{\text{bkg}} = \sigma_j \mathcal{L}_\text{int} \epsilon_{\text{trig}} \frac{\epsilon_{\text{fake}}}{\epsilon_{\text{inc}}} \approx 50,
\end{align*}
\]

(5)

where \(\epsilon_{\text{inc}} = 80\) mb is the inelastic proton-proton cross-section at 13 TeV [28]. \(n_{\text{PU}} \approx 100\) is the average number of inelastic interactions per bunch crossing using instantaneous luminosity \(\mathcal{L} = 2 \times 10^{34}\) cm\(^{-2}\)s\(^{-1}\) [29]. In Eq. (5), one hard collision needs to timestamp the event, while the other hard collision contains at least two jets, all of which have to be neutral to miss the primary vertex reconstruction. Otherwise, this second hard collision will leave tracks and reconstructed as another vertex in the tracker, thus get vetoed. Therefore, the background \(N^\text{PU}_{\text{bkg}}\) is suppressed by at least one additional factor of neutral jet fraction \(f^{\text{jet}}_n \approx 10^{-3}\). This additional factor \(f^{\text{jet}}_n\), more strictly speaking, should be the probability for a multi-jet process whose PV4d is failed to be reconstructed and mis-assigned to the triggered PV4d, which need to be estimated through full detector simulation and calibrated with data.

The collision time for two bunches of protons has a typical temporal spread of \(\delta^{\text{PU}}_t = 190\) ps [12]. The differential background from pile-up can be estimated as,

\[
\frac{\partial N^\text{PU}_{\text{bkg}}(\Delta t)}{\partial \Delta t} \approx N^\text{PU}_{\text{bkg}} P(\Delta t; \delta^{\text{PU}}_t).
\]

(6)

The key difference between the background from the pile-up and the same hard collision is that the typical time spread is determined by the beam property for the former, and by the timing resolution for the latter. They typically differ by a factor of a few, e.g., \(190\) ps versus \(30\) ps for CMS with the current upgrade plan. For the EC (MS) search, if we apply cut \(\Delta t > 1\) (0.4) ns, the total estimated events from SM background is \(1.3\) (0.86), where the SV background become completely negligible.

Backgrounds which do not from the hard collision are hard to simulate, such as cosmic ray, beam halo, mis-connected tracks, interaction with detector material, etc. Thanks to the rich studies searching for LLP in all subdetectors at the LHC, their properties are well measured and can be vetoed effectively. Furthermore, with the hard signature (large energy deposition of more than 30 GeV) and high track multiplicities with sizable time-delay, the

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\(^4\) The validity of these description should be scrutinized by experimental measurement, e.g. from Zero-Bias events. From Refs. [12, 15, 19], our description is appropriate up to probability of \(10^{-3}\) to \(10^{-6}\) level—the limit where the distribution are shown.
signal can be well separated from these backgrounds. In the future, the object reconstruction with separation not only in spatial but also in time should help discriminate the various backgrounds.

In addition, in specific searches, signal typically has additional feature. For example, in our case, we actually have two visible objects with different time delays. Taking advantage of such characteristics, we expect the background can be further suppressed.

As a side note, triggering on delayed signals concerning the primary interaction vertex could become a very interesting and important application for the general class of long-lived particle signals [30–32]. Triggers with additional timing information (such as sizable delay) would complement current trigger system that focuses on very hard events, using $H_T$, $p_T$ of jets, leptons, photons, and missing $E_T$ [33, 34]. A much softer threshold could be achieved with sizable time delays as an additional criterion, which would be extremely beneficial for LLP, especially for compressed signal searches.

**Augmented sensitivity on LLP through precision Timing.**—Our first example is Higgs decaying to LLP with subsequent decays into bb pairs. This occurs in model [10] where the Higgs is the portal to a dark QCD sector whose lightest states are the glueballs. The decays of the $0^+$ glueballs are long-lived. This benchmark has not been studied without exploiting the timing information [35, 36]. Typical energy of the glueball is set by the Higgs mass, and the time delay depends on glueball mass. The signal of LLPs produced through the decay of an intermediate resonance in other new physics scenarios would have similar characteristics.

The second example is the decay of the lightest SUSY electroweakino in the GMSB scenario. Its decay into SM bosons ($Z$, h, or $\gamma$) and gravitino is suppressed by the SUSY breaking scale $\sqrt{F}$, and it can be naturally long-lived. Amongst all the possible electroweakinos, the bino is well-studied in a non-pointing photon search [19]. We study the case in which Higgsino is the lightest electroweakino with decay $\tilde{\chi}^0_1 \rightarrow hG$. Our selection would be general so that all visible Higgs decays into SM particles will be captured. In our simulation, we generate event samples with the Higgs bosons decaying into dijets. This two-body decay topology corresponds to approximately 70% of Higgs decays. This benchmark represents the timing behavior of pair produced particles at the LHC without an intermediate resonance.

For both of our examples, timestamping the hard collision is achieved by using a ISR jet:

$$\text{SigA: } pp \rightarrow h + j, \ h \rightarrow X + X, \ X \rightarrow \text{SM}, \quad (7)$$

$$\text{SigB: } pp \rightarrow \tilde{\chi} \tilde{\chi} + j, \ \tilde{\chi}^0_1 \rightarrow h + \tilde{G} \rightarrow \text{SM} + \tilde{G}. \quad (8)$$

For SigB, other electroweakinos $\tilde{\chi}$, such as charginos $\tilde{\chi}^\pm$ or heavier neutralino $\tilde{\chi}^0_2$, promptly decay into the lightest neutralino state $\tilde{\chi}^0_1$ plus soft particles.

To emphasize the power of timing, we rely mostly on the timing information to suppress background and make only minimal cuts. In this case, we need only one low $p_T$ ISR jet, with $p_T^j > 30$ GeV and $|\eta_j| < 2.5$. In both signal benchmarks, we require at least one LLP decays inside the detector. We generate signal events using MadGraph5 [38] at parton level and adopt the UFO model file from [39] for the GMSB simulation. After detailed simulation of the delayed arrival time for the different lifetime of the LLPs and geometrical selections, we derive the projection sensitivity to SigA and SigB using the cross sections obtained in Ref. [40] and Refs. [41, 42], respectively.

For SigA, the 95% C.L. sensitivity is shown in Fig. 4. The decay branching ratio of $X \rightarrow jj$ is assumed to be 100%, where $j$ here is light flavor quark. For $X \rightarrow bb$, a similar plot is provided in the appendix. The EC and MS searches, with 30 ps timing resolution, are plotted in thick dashed and solid lines. For MS, the best reach of $\mathrm{BR}(h \rightarrow XX)$ is about a few $10^{-6}$ for $c\tau < 10$ m. It is relatively insensitive to the mass of $X$ because both 10 GeV and 50 GeV $X$ are moving slowly enough to pass the time cut. The best reach points for different mass of $X$ occurs at different $c\tau$ and approximately inversely proportional to $m_X$. This is because the maximal probability for the decay to be at a fixed $d = c\tau\gamma = (L_{T2} - L_{T1})/(\log(L_{T2}/L_{T1}))$. For large $c\tau$ at the EC search, the lighter $X$ has worse BR sensitivity reach than heavier ones, since the detector is shorter than MS and $c\tau$ cut efficiency is smaller for lighter $X$. Interestingly, for $c\tau \lesssim 10^{-2}$ m, the reach of light $X$ becomes better than heavy $X$. For the MS search, a less precise timing resolution (200 ps) has also been considered with cut $c\tau > 1$ ns to suppress back-
The projected 95% C.L. limit on the Higgsino mass–lifetime plane for signal process of Higgsino pair production in association with jets, with subsequent decay of the lightest Higgsino $\tilde{\chi}^0 \rightarrow hG$ and $h \rightarrow b\bar{b}$ in GMSB scenario. We decoupling other electroweakinos and hence have Higgsino-like chargino $\tilde{\chi}^\pm$ and neutralino $\tilde{\chi}_2^0$ nearly degenerate with $\tilde{\chi}_1^0$.

After the cut, the backgrounds from SV and PU for MS search are 0.11 and $7.0 \times 10^{-3}$ respectively, and SV background dominates. For PU background, the final time spread includes the timing resolution and PU intrinsic time spread in quadrature. The reach for heavy $X$ is almost not affected, while the sensitivity to the branching ratio can be reduced by at most a factor of a few for light $X$.

We compare EC and MS (thick lines) with 13 TeV HL-LHC (with $3\text{ ab}^{-1}$ integrated luminosity) projections, two displaced vertex (DV) search at EC using zero background assumption (thin dotted) and one DV at MS using a data-driven method with optimistic background estimation (thin dashed) from [36]. It is clear that timing cuts greatly reduces background and provides better sensitivity. For the long lifetime, the limit is proportional to $c\tau$ for searches requiring one LLP to be reconstructed as the signal, and $(c\tau)^2$ for searches requiring two LLPs to be reconstructed as the signal. Therefore one LLP decay is better. The projected limits from invisible Higgs decay at 13 TeV [37] is also plotted in Fig. 4.

For SigB, we show the projected 95% C.L. exclusion reach in the plane of Higgsino mass $m_{\tilde{\chi}}$ in GeV and proper lifetime $c\tau$ in m in Fig. 5. The projected coverage of the EC and MS searches in blue and red shaded regions, respectively. Due to the slow motion of $\tilde{\chi}_1$, we show the projections with a tight (solid lines) and a loose (dashed lines) $\Delta t$ requirement. We can see minor differences between different delayed time cut choices for this signal. Although in the previous section, EC and MS signal with $\Delta t > 1$ and 0.4 ns cuts have background event of order 1, we also show the sensitivity reach with a sizable background of 100 at the HL-LHC. We observe a similar generic behavior for the coverage of EC and MS searches in term of the lifetime for SigB.

Furthermore, we draw gray dashed-dotted lines for the corresponding model parameter $\sqrt{F}$ of the fundamental SUSY breaking scale for GMSB in the figure for reference. To compare with the reach of existing long-lived particle searches and their projection, we follow Ref. [6] and quote the most sensitive CMS displaced dijet search conducted at 8 TeV [43], and show the projected sensitivity at 13 TeV assuming statistical dominance for the background. We can see significant improvement for timing enhanced LLP searches, almost doubling the reach of $m_{\tilde{\chi}}$ with lifetime around one meter. Furthermore, timing searches extend the sensitivity to very long lifetime, up to $10^5$ m for a 200 GeV long-lived Higgsinos.

In Fig. 4 and 5, an upper bound on $\Delta t$, $\Delta t < 25$ ns, is required for EC to stay in the same proton bunch. If there is no such requirement, the pile-up background will increases linearly with the number of proton bunches in the time window. For the MS search, the recording time extends to hundreds of ns, and the pile-up background can be eliminated by screening the approximately ±0.5 ns window for each bunch crossing, which has negligible impact on the signal efficiency.

Discussion. We demonstrate that exploiting timing information can significantly enhance the LLP searches at CMS and ATLAS. To emphasize the utility of timing, we have only made minimal requirements on the signal, with one ISR jet and a time delayed signal. Further optimization can be developed for more dedicated searches. The timestamping ISR jet can be replaced by other objects, like leptons and photons. Depending on the process, one can also use objects from prompt decay. For example, in the Higgs signal, the final state $j h$ can be changed to $W h$, with the $W$ boson decay leptonically. The charged lepton from the $W$ boson can trigger the event and calibrate the time as well, in the meantime, the background is reduced from QCD to electroweak cross-sections. At the same time, the signal is only reduced by a smaller production cross-section, and all other features remain similar. For instance, in R-parity violating SUSY, the pair produced squarks and gluinos can promptly decay to neutralino plus jets. Those jets can provide the timestamp for the event as well. In addition, for specific searches, one should also optimize the selection of the signal based on the decay products of the LLPs.

We have considered two concepts of timing layer at the LHC. The CMS EC timing upgrade for HL-LHC already provides significant improvement. The MS system has the notable benefits of low background, a large volume for the LLP to decay and more substantial time delay for the LLP signal due to longer travel distance. As an estimate of the best achievable sensitivity, given that the MS is an ideal place to look for LLPs at the LHC, we have also considered a hypothetical timing layer outside of the ATLAS MS. We found robust enhanced sensitivity.
to LLPs at MS using the timing information. Moreover, due to the extended time delay of the LLPs in the volume of MS, less precise timing can still achieve similar physics goals. As a result, it can serve as an estimate of the best achievable sensitivity using timing information in LLP searches. A feasibility study on new timing layer options like this, balancing technology, design, cost, and physics goals would be a natural future step, given the promising results shown in this study. In summary, the timing enhanced search for LLP is quite generic and can suppress SM background significantly. The timing information should be a new dimension in the future searches.

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**APPENDIX**

![Time delay at EC from LHC](image)

**FIG. 6.** The differential $\Delta t$ distribution for typical signals and backgrounds at 13 TeV LHC for CMS EC timing layer. The legends are the same as in Fig. 3.

In Fig. 6, we show typical time delay $\Delta t$ for the CMS EC timing layer for benchmark signals and the background. In comparison with the time delay distribution at MS, shown in Fig. 3, the signal delays are lessen by roughly an order of magnitude but still very large with respect to the SM backgrounds. After cut $\Delta t > 1$ ns, the heavy particles in the signal are not affected much, and only 10 GeV $X$ lose significant fraction of events. This fact is in good agreement with Fig. 4.

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