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Supplemental Material
Enhancing Long-lived particles searches at the LHC with precision timing information

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In this supplemental material, we provide more information for: (a) the signal benchmark considerations, (b) the time delay at CMS MTD, (c) (more) background considerations and (d) trigger discussions.

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(a) the signal benchmark considerations

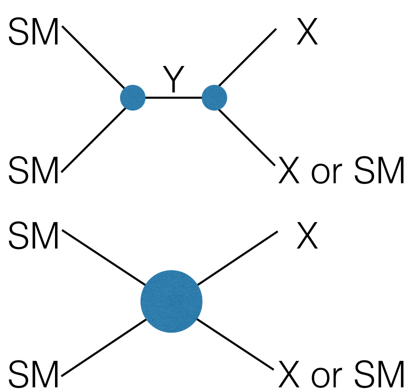

FIG. S1. Two classes of signal kinematics for LLPs.

In general, there are two classes of qualitatively different production channels for the LLPs, as shown in Fig. S1. 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 well-known 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, and BSM particles such as W', Z', and so on. They all share some common characteristics. The rate of this process is controlled by the production rate of the resonance and the branching ratio into the LLP(s). The decay length of the LLP, $d = \gamma\beta c\tau$, plays an important role in determining signal rate within the detector volume. Moreover, the boost γ is also important in determining the time delay. In this class of models, the boost of the LLP is set by the mass ratio $\gamma \propto m_Y/m_X$.

In the second class of models, shown in the lower panel of Fig. S1, the LLP(s) can be produced directly without going through a resonance. This would be the case, for example, for heavier X with SM interactions. A typical benchmark would be the production of SUSY electroweakinos. The signal of this class of models have distinct features as well. In particular, they will be produced close to the threshold, with velocity being a fraction of the speed of light. In this case, a large time delay is always expected.

This choices of SigA and SigB in the main text are chosen to capture above two representative classes of the LLP kinematics.

(b) the time delay at ATLAS MS

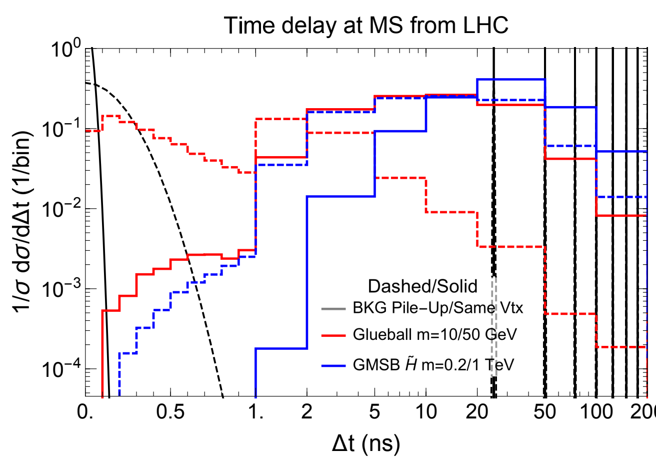

FIG. S2. The differential Δt distribution for typical signals and backgrounds at 13 TeV LHC for ATLAS MS. The legends are the same as in Fig. 2.

Timing information has 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 [1–3], the time delay parameter adopted in the non-pointing photon searches at the CDF and recently at the LHC [4–10], and (very loosely) in the stopped particle searches [11]. Precision timing thus opens a new window to search for Beyond Standard Model (BSM) signals.

In Fig. S2, we show typical time delay Δt for the ATLAS MS for benchmark signals and the backgrounds. In comparison with the time delay distribution for CMS MTD, shown in Fig. 2, the signal delays are enlarged by roughly an order of magnitude. After the cut $\Delta t > 1$ ns, the heavy particles in the signal are almost not affected, and only 10 GeV X lose some fraction of events. This fact is in good agreement with Fig. 3.

We have considered two concepts of timing layer at the LHC. The CMS MTD 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 the longer travel distance, see Fig. 3. Therefore, a less precise timing resolution can still achieve similar physics goals for MS system. 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 next step, given the promising results shown in this study. In summary, the precision timing enhanced search for LLPs is very generic and can suppress SM background significantly. The timing information should act as a new dimension in the future searches.

(c) QCD background explanations

In the ATLAS MS search, we have chosen the detector transverse length between 4.2 m and 10.6 m. However, the ATLAS MS displaced vertex search [12], 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-through jet can still be vetoed effectively.

The trajectories of charged SM particles can be curved in the magnetic field, which increase the path length in comparison with neutral SM particles. We use the standard jet algorithm, and define the time of jet by the first arrival objects inside the cone. With sufficient information in the tracker, we can even avoid using curved (low-p_T) tracks to define the time. In this regard, the arrival time of a jet is defined by the leading components. 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 [13–16].

The trackless jet fraction is measured in the validation data for the low-electromagnetism jet search at the ALTAS [17], and it is found to be 10^{-2}. However, they also found a huge additional suppression through the energy deposition ratio between electromagnetic and hadronic calorimeters. We have calculated the trackless jet fraction using *Pythia* and obtained 10^{-3}. Considering the suppression, our estimation is reasonable.

The pile-up events have both time and spatial spread. Therefore, the interaction point information z would also enter the estimation of such background. However, given that the typical spread is few cm, it can induce a time shift at most $\approx \mathcal{O}(100)$ ps [13], typically with an addition suppression of a geometrical factor. Adding in quadrature, this will at most give an insignificant increase the spread in time by ≈ 60 ps. One can use larger time delay cut to alleviate this effect. It has even less impact for MS search, where the pile-up background is already small before timing cut.

The number of SV backgrounds with 30 ps resolution are 10^{-232} and 10^{-35} for MTD and MS respectively, with time cut at 1 ns and 0.4 ns. For 60 ps resolution, the Gaussian suppression power decreased by one-quarter (1/4) in the exponent. The number of SV backgrounds become 10^{-51} and 10^{-5} for MTD and MS respectively. The SV backgrounds become negligible after timing cut compared with PU one. We note this shows for SV background, although the background seems to be big to begin with, our timing cut choice is very conservative and leave huge room for non-Gaussianity from such background.

In the future, the object reconstruction with separation not only in spatial but also in time should help discriminate these various backgrounds. In specific searches, signal typically has additional feature to further suppress the background. For instance, 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.

(d) trigger discussions

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 [18–22]. 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 [23, 24]. 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 BSM signal searches.

[1] **CMS** Collaboration, S. Chatrchyan *et al.*, "Searches for long-lived charged particles in pp collisions at $\sqrt{s}$=7 and 8 TeV," *JHEP* **07** (2013) 122, arXiv:1305.0491 [hep-ex].

[2] **CMS** Collaboration, S. Chatrchyan *et al.*, "Search for heavy long-lived charged particles in pp collisions at $\sqrt{s} = 7$ TeV," *Phys. Lett.* **B713** (2012) 408–433, arXiv:1205.0272 [hep-ex].

[3] **ATLAS** Collaboration, M. Aaboud *et al.*, "Search for metastable heavy charged particles with large ionization energy loss in pp collisions at $\sqrt{s} = 13$ TeV using the ATLAS experiment," *Phys. Rev.* **D93** no. 11, (2016) 112015, arXiv:1604.04520 [hep-ex].

[4] D. A. Toback and P. Wagner, "Prospects of searches for neutral, long-lived particles which decay to photons using timing at CDF," *Phys. Rev.* **D70** (2004) 114032, arXiv:hep-ph/0407022 [hep-ph].

[5] M. Goncharov *et al.*, "The Timing system for the CDF electromagnetic calorimeters," *Nucl. Instrum. Meth.* **A565** (2006) 543–550, arXiv:physics/0512171 [physics].

[6] **CDF** Collaboration, A. Abulencia *et al.*, "Search for heavy, long-lived particles that decay to photons at CDF II," *Phys. Rev. Lett.* **99** (2007) 121801, arXiv:0704.0760 [hep-ex].

[7] **CDF** Collaboration, T. Aaltonen *et al.*, "Search for Heavy, Long-Lived Neutralinos that Decay to Photons at CDF II Using Photon Timing," *Phys. Rev.* **D78** (2008) 032015, arXiv:0804.1043 [hep-ex].

[8] **CDF** Collaboration, T. Aaltonen *et al.*, "Signature-Based Search for Delayed Photons in Exclusive Photon Plus Missing Transverse Energy Events from $p\bar{p}$ Collisions with $\sqrt{s}$=1.96 TeV," *Phys. Rev.* **D88** no. 3, (2013) 031103, arXiv:1307.0474 [hep-ex].

[9] **CMS Collaboration** Collaboration, "Search for long-lived neutral particles in the final state of delayed photons and missing energy in proton-proton collisions at $\sqrt{s} = 8$ TeV," Tech. Rep. CMS-PAS-EXO-12-035, CERN, Geneva, 2015. http://cds.cern.ch/record/2063495.

[10] **ATLAS** Collaboration, G. Aad *et al.*, "Search for nonpointing and delayed photons in the diphoton and missing transverse momentum final state in 8 TeV pp collisions at the LHC using the ATLAS detector," *Phys. Rev.* **D90** no. 11, (2014) 112005, arXiv:1409.5542 [hep-ex].

[11] **CMS** Collaboration, A. M. Sirunyan *et al.*, "Search for decays of stopped exotic long-lived particles produced in proton-proton collisions at $\sqrt{s} = 13$ TeV," *Submitted to: JHEP* (2017) , arXiv:1801.00359 [hep-ex].

[12] **ATLAS** Collaboration, G. Aad *et al.*, "Search for long-lived, weakly interacting particles that decay to displaced hadronic jets in proton-proton collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector," *Phys. Rev.* **D92** no. 1, (2015) 012010, arXiv:1504.03634 [hep-ex].

[13] C. Collaboration, "TECHNICAL PROPOSAL FOR A MIP TIMING DETECTOR IN THE CMS EXPERIMENT PHASE 2 UPGRADE," Tech. Rep. CERN-LHCC-2017-027. LHCC-P-009, CERN, Geneva, Dec, 2017. https://cds.cern.ch/record/2296612. This document describes a MIP timing detector for the Phase-2 upgrade of the CMS experiment, in view of HL-LHC running.

[14] B. Andersson, G. Gustafson, G. Ingelman, and T. Sjostrand, "Parton Fragmentation and String Dynamics," *Phys. Rept.* **97** (1983) 31–145.

[15] **ATLAS** Collaboration, G. Aad *et al.*, "Jet energy measurement with the ATLAS detector in proton-proton collisions at $\sqrt{s} = 7$ TeV," *Eur. Phys. J.* **C73** no. 3, (2013) 2304, arXiv:1112.6426 [hep-ex].

[16] M. Klimek, "Tagging Boosted Objects with Timing Detectors," 2018. https://indico.fnal.gov/event/16151/session/9/contribution/75/material/slides/0.pdf.

[17] "Search for pair produced long-lived neutral particles decaying in the ATLAS hadronic calorimeter in pp collisions at $\sqrt{s} = 8$ TeV," Tech. Rep. ATLAS-CONF-2014-041, CERN, Geneva, Jul, 2014. https://cds.cern.ch/record/1740972.

[18] R. E. Shrock, "A Test for the Existence of Effectively Stable Neutral Heavy Leptons," *Phys. Rev. Lett.* **40** (1978) 1688.

[19] **FMMF** Collaboration, E. Gallas *et al.*, "Search for neutral weakly interacting massive particles in the Fermilab Tevatron wide band neutrino beam," *Phys. Rev.* **D52** (1995) 6–14.

[20] J. R. Ellis, A. R. Raklev, and O. K. Oye, "Gravitino dark matter scenarios with massive metastable charged sparticles at the LHC," *JHEP* **10** (2006) 061, arXiv:hep-ph/0607261 [hep-ph].

[21] J. R. Ellis, A. R. Raklev, and O. K. Oye, "Measuring massive metastable charged particles with ATLAS RPC timing information.,".

[22] S. Banerjee, G. Bélanger, B. Bhattacherjee, F. Boudjema, R. M. Godbole, and S. Mukherjee, "Novel signatures for long-lived particles at the LHC," arXiv:1706.07407 [hep-ph].

[23] **ATLAS** Collaboration, G. Aad *et al.*, "Triggers for displaced decays of long-lived neutral particles in the ATLAS detector," *JINST* **8** (2013) P07015, arXiv:1305.2284 [hep-ex].

[24] Y. Gershtein, "CMS Hardware Track Trigger: New Opportunities for Long-Lived Particle Searches at the HL-LHC," *Phys. Rev.* **D96** no. 3, (2017) 035027, arXiv:1705.04321 [hep-ph].