Status of searches in the long-lived particle and dark sectors, including full run-2 and HL-LHC prospects

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Abstract

Particles beyond the standard model can generically have lifetimes that are long compared to SM particles at the weak scale. When produced at the LHC at CERN, these long-lived particles (LLPs) can decay far from the primary proton-proton interaction, or even completely pass through the detector before decaying. Such LLP signatures are distinct from those of promptly-decaying particles that are targeted by the majority of searches for new physics at the LHC. These LLP analyses often require customized techniques to collect, reconstruct, and analyze the data. These proceedings present an overview of Run 2 searches for LLPs at ATLAS, CMS, and LHCb, as well as some idea of what can be expected from LLP searches at the High-Luminosity LHC.

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Searches in the Long-Lived Particle and Dark Sectors

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Particles beyond the standard model can generically have lifetimes that are long compared to SM particles at the weak scale. When produced at the LHC at CERN, these long-lived particles (LLPs) can decay far from the primary proton-proton interaction, or even completely pass through the detector before decaying. Such LLP signatures are distinct from those of promptly-decaying particles that are targeted by the majority of searches for new physics at the LHC. These LLP analyses often require customized techniques to collect, reconstruct, and analyze the data. These proceedings present an overview of Run 2 searches for LLPs at ATLAS, CMS, and LHCb, as well as some idea of what can be expected from LLP searches at the High-Luminosity LHC.

1 Introduction

The lifetimes of particles in the standard model (SM) span a large range, from the Z boson with a lifetime of $2 \times 10^{-25}$ s to the electron, which is stable. Likewise, beyond the SM (BSM) scenarios predict particles with a variety of lifetimes. In particular, long-lived particles (LLPs) appear in BSM scenarios such as compressed Supersymmetry (SUSY), Anomaly-Mediated SUSY Breaking (AMSB), split-SUSY, heavy neutral leptons, dark photons, or R-parity violating (RPV) SUSY. Furthermore, we should search for LLPs because they can provide a dark matter candidate, as dark matter must be a neutral, stable, BSM particle. In addition, there has been no sign of new physics, and we should leave no stone unturned by also considering particles with large lifetimes, particularly at the CERN LHC.

As can be seen in Figure 1, LLPs come in many different varieties. They can be charged or neutral and have a variety of different final states, decay locations, and lifetimes $^1$. Along with the variety of LLP searches comes a variety of challenges. These can include dedicated triggers, unique object reconstruction, atypical sources of background, and unusual variables to distinguish the signal from background.

These proceedings will showcase a few recent example LLP searches to illustrate the variety of signatures and challenges in these searches. This document will show how the challenges are in truth, opportunities for innovation and creativity. These proceedings are organized as follows: Section 2 will describe three searches for LLPs performed in Run 2 at ATLAS, CMS, and LHCb. Section 3 will describe the High-Luminosity LHC (HL-LHC) and the ATLAS and CMS Phase 2 upgrades, as well as two examples for prospects for LLP searches in Phase 2. Section 4 will ask and answer the question of what else we are missing in these searches, and Section 5 will summarize.

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Figure 1 – A diagram of several different LLP signatures. Heavy Stable Charged Particles (HSCPs) and disappearing tracks are examples of LLP signatures that can be searched for directly with the main detectors at the LHC, while the other examples in this figure show how the LLP decay product(s) can be observed.

2 Searches for LLPs in Run 2

2.1 Displaced vertex and a displaced muon with the ATLAS experiment

A search for LLPs that decay to at least one displaced muon with a displaced vertex was performed with a data sample corresponding to an integrated luminosity of 136 fb$^{-1}$ of proton-proton collisions at a center of mass energy of 13 TeV, collected by the ATLAS experiment. The results were interpreted with an RPV SUSY signal benchmark scenario in which pair-produced top squarks each decay to a quark and a muon. An event display of the signal benchmark is shown in Figure 2 upper left, and the Feynman diagram of the signal is shown in Figure 2 upper right. If the $\lambda'_{23}$ coupling is small, the top squark could be long-lived.

The ATLAS detector at the LHC is a multi-purpose particle detector with a forward-backward symmetric cylindrical geometry and a near 4$\pi$ coverage in solid angle. It consists of an Inner Detector (ID) surrounded by a thin superconducting solenoid, electromagnetic and hadronic calorimeters, and a Muon Spectrometer (MS) incorporating three large superconducting toroidal magnets.

This analysis makes use of some special event reconstruction. First, it uses large radius tracking to improve the efficiency for reconstructing displaced tracks. Secondly, it uses a dedicated secondary vertex algorithm to reconstruct displaced vertices. Then, at least one displaced muon is selected per event, along with at least one displaced vertex. The displaced vertex must have at least three tracks associated to it, and an invariant mass greater than 20 GeV. Figure 2 lower left shows the distribution of the number of tracks associated with the displaced vertex, for the sources of background, the signal benchmark, and the data.

There are several sources of background in this search, namely, cosmic rays, reconstruction algorithm fakes, and muons from decays of heavy-flavor quarks. Most of these backgrounds are removed by dedicated vetoes. Any background events that remain after the full selection is applied are predicted by a data-driven approach. A counting experiment is performed in two different signal regions, where in total, less than 3 events are predicted and 1 event is observed.

Limits at 95% CL are placed on the top squark mass and lifetime, which can be seen in Figure 2 lower right. Top squark masses up to 1.7 TeV are excluded for a lifetime of 0.1 ns, and top squark masses below 1.3 TeV are excluded for lifetimes between 0.01 and 30 ns.

2.2 Delayed jets with the CMS experiment

A search for heavy neutral LLPs that decay to at least one displaced, nonprompt jet and missing transverse momentum was performed with a data sample corresponding to an integrated lumi-
nosity of 137 fb\(^{-1}\) of proton-proton collisions collected by the CMS experiment in 2016–2018\(^{7a}\). The results were interpreted with a Gauge-Mediated SUSY Breaking benchmark scenario\(^{9}\). A sketch of how particles in this model would appear in the CMS detector is shown in Figure 3 upper left, and the Feynman diagram is shown in Figure 3 upper right. In this model, a gluino decays to a gluon and a gravitino, and the gluino could be long-lived if the coupling is small.

The central feature of the CMS apparatus\(^{10}\) is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the solenoid volume are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter (ECAL), and a brass and scintillator hadron calorimeter (HCAL), each composed of a barrel and two endcap sections. Forward calorimeters extend the pseudorapidity coverage provided by the barrel and endcap detectors. Muons are detected in gas-ionization chambers embedded in the steel flux-return yoke outside the solenoid.

This analysis is unique because it is the first use of timing from the ECAL to identify delayed jets. Timing from the ECAL has previously been used to identify delayed photons\(^{11,12}\), but this search is the first use of ECAL timing for delayed jets. Timing information is used to distinguish the background from the signal. There are several sources of background in this search. One such source is core timing resolution effects, that is, scintillation time differences due to radiation. Another source of background is that due to satellite bunches, which are collisions of very low luminosity bunches at 2.5 ns steps from main collisions. A third source of background is beam halo muons, which are muons arising from beam interacting with the collimators. A final source of background is cosmic ray muon deposits in the ECAL. Cleaning selections are imposed to reject much of the contributions from the dominant sources of background. The remaining backgrounds are predicted with data-driven methods, as they are not well modelled in simulation.

The main discriminating variable, the jet time \(t_{\text{jet}}\), is shown in Figure 3 lower left. The

\(\text{The preliminary result presented at the conference has since been superseded by Ref.}^{8}\)
jet time is the median time of all matched ECAL cells satisfying some quality criteria. As can be seen in this figure, most of the background is from core effects (shown in orange) and has a small \( t_{\text{jet}} \), namely, it is prompt. The signal benchmark, shown as the dotted red, pink, and purple lines, has a long \( t_{\text{jet}} \) tail. The signal region is defined as a single bin with \( t_{\text{jet}} > 3 \) ns. The binning in the figure > 3 ns is for illustration only. In this signal region, \( 1^{+2.5}_{-1} \) events are predicted, and 0 events are observed.

Limits at 95% confidence level (CL) are set on the gluino mass and lifetime, as can be seen in Figure 3 lower right. Gluino masses up to 2.5 TeV are excluded for proper lifetimes of 1 m.

Figure 3 – Figures related to the delayed jets search\(^7\). Upper left: A sketch of how the GMSB signal benchmark would look in the CMS detector. Upper right: The Feynman diagram for the GMSB signal benchmark. Lower left: The jet time distribution, for the GMSB signal benchmark, the main sources of background, and the data. Lower right: The 95% CL limits for gluino mass and lifetime.

### 2.3 Prompt and long-lived dark photons with the LHCb experiment

A search for dark photons (\( A' \)) that decay to opposite-sign muons was performed with proton-proton collision data collected by the LHCb experiment in 2016 corresponding to an integrated luminosity of \( 1.6 \text{ fb}^{-1} \). The analysis was divided into two categories: when the dark photons are prompt and when they are long-lived. The prompt search focused on the regime where the mass of the dark photon was between twice the mass of the muon and 70 GeV. The long-lived search focused on dark photon masses between 214 and 350 MeV, in order to maximize its sensitivity. Figure 4 upper left shows the Feynman diagrams considered. In these scenarios, if the mass times the coupling is small, the dark photon can be long-lived.

The LHCb detector\(^{14}\) is a single-arm forward spectrometer covering the pseudorapidity range \( 2 < \eta < 5 \), designed for the study of particles containing \( b \) or \( c \) quarks. The detector includes a high-precision tracking system consisting of a silicon-strip vertex detector surrounding the proton-proton interaction region, a large-area silicon-strip detector located upstream of a dipole magnet with a bending power of about 4 T m, and three stations of silicon-strip detectors.
and straw drift tubes placed downstream of the magnet. Different types of charged hadrons are distinguished using information from two ring-imaging Cherenkov detectors. Photons, electrons and hadrons are identified by a calorimeter system consisting of scintillating-pad and preshower detectors, an electromagnetic and a hadronic calorimeter. Muons are identified by a system composed of alternating layers of iron and multiwire proportional chambers.

There are two main sources of background in the long-lived dark photon search. The first background contribution is from photon conversions to $\mu^+\mu^-$ in the silicon-strip vertex detector. This background contribution is reduced by creating a map of the material in the detector, such as the one shown in Figure 4 upper right, in order to veto events that occur in the material. The other major source of background in this search is from two semileptonic b-hadron decays. This contribution is reduced by identifying other tracks coming from b-hadron decays with boosted decision trees.

The analysis is performed by scanning the dimuon mass and binning the events in the dark photon lifetime and decay fit $\chi^2$. Limits are set at 90% CL on the dark photon mass and coupling strength $\epsilon^2$. These limits can be seen, for both the prompt and long-lived search, in Figure 4 lower left. A zoomed-in version of this figure, displaying the limits on the long-lived dark photon scenario, is shown in Figure 4 lower right.

This was the first search to achieve sensitivity to long-lived dark photons using a displaced-vertex signature. Future improvements are already underway, including an improved trigger for the 2017 run. In addition, a large improvement in sensitivity is expected in Run 3, due to the increased integrated luminosity and the removal of LHCb’s hardware trigger.

Figure 4 – Figures related to the dark photon search. Upper left: The Feynman diagram for the dark photon signal benchmark. Upper right: A material map of the LHCb detector. Lower left: The 90% CL limits for dark photon mass and coupling strength. Lower right: The 90% CL limits for the long-lived dark photon mass and coupling strength.

3 Future prospects for LLPs in Phase 2

3.1 The HL-LHC and the ATLAS and CMS Phase 2 upgrades

The HL-LHC will feature 14 TeV center-of-mass energy proton-proton collisions, 3 ab$^{-1}$ of integrated luminosity by the end of the program, and a maximum of about 200 pileup interactions. The ATLAS and CMS detectors will be upgraded for the HL-LHC. Generally,
these upgrades will involve greater geometrical coverage of all subdetectors, high resolution for all subdetectors, a new L1 track trigger in CMS, and new dedicated timing subdetectors.

3.2 Disappearing tracks with the ATLAS experiment at the HL-LHC

The prospects for searching for charged LLPs that decay to neutral particles with a disappearing track signature with the ATLAS experiment at the HL-LHC were studied. Figure 5 left shows a sketch of how this signature could appear in the ATLAS detector, and Figure 5 middle shows a Feynman diagram considered with the AMSB signal benchmark. If the chargino and the neutralino are almost mass degenerate, the chargino can be long-lived.

A truth-level analysis was performed with a parameterized detector response. Events were selected with short tracks, no leptons, and large missing transverse momentum. A large gain in disappearing track sensitivity with 3 ab$^{-1}$ of integrated luminosity at the HL-LHC over the current Run 2 limits can been seen in Figure 5 right. Furthermore, even more tracking and vertexing improvements are possible for disappearing tracks, such as reconstructing the soft pion track.

3.3 Delayed photons with the CMS experiment at the HL-LHC

The prospects for searching for LLPs that decay to delayed photons and missing transverse momentum with the CMS detector at the HL-LHC were studied. Delayed photons could arise in GMSB scenarios such as the one shown in Figure 6 left. If the coupling of the neutralino to the gravitino is small, the neutralino can be long-lived.

A generator-level study with a smeared photon time distribution was performed. In particular, information from the new precision timing detector proposed for the upgraded CMS detector was employed in this study. The results are shown in Figure 6 right, where one can observe that the new timing detector greatly improves the sensitivity to LLPs with short lifetimes and large masses.

4 What else?

Only a few example Run 2 searches for LLPs and prospects for LLPs at the HL-LHC were shown above. Many other searches for LLPs with the ATLAS, CMS, and LHCb detectors have been done, are in progress, or are planned for Run 3 and the future.

Besides searches at the three main LHC and HL-LHC experiments, there are also approved and proposed experiments dedicated to looking for LLPs. For example, FASER has recently been approved and can search for long-lived dark photons and similar particles in the extreme
Figure 6 – Figures related to the delayed photon prospects\textsuperscript{21}. Left: A Feynman diagram for the GMSB benchmark. Right: The 95\% CL limits for the neutralino lifetime and $\Lambda$ at the HL-LHC.

forward direction. MATHUSLA\textsuperscript{23} can search for very long-lived weakly interacting neutral particles with a large-volume, air-filled surface detector. Furthermore, MilliQan\textsuperscript{24} searches for millicharged particles with a detector pointed at the CMS interaction point.

Besides all of this, there are other things we can try, moving forward. For instance, we can focus more on soft displaced objects, displaced tau leptons, kinked tracks, or dedicated searches for quirks\textsuperscript{25}. In addition to these signatures, we can take advantage of data scouting and data parking in the future\textsuperscript{26}. There is a particular opportunity for LLP searches in the LHC Run 3, if triggers can be improved or new ones implemented. Again, this is just a taste of what is possible: there is space for many more ideas.

5 Summary

A variety of searches for exotic long-lived particles are being performed with the ATLAS, CMS, LHCb, and dedicated LLP experiments. Exotic LLP searches often require non-standard techniques to collect, reconstruct, and analyze the data. This makes these searches unusual and challenging, but also fun to perform. No signal has been observed yet at these experiments, but there is more to do. The community should be sure to not miss new physics, and therefore we must look everywhere for a hint of it. In addition, LLP searches will benefit from the Phase 2 upgrades and the increased physics potential at the High-Luminosity LHC and beyond. In summation, we have already eaten the low-hanging fruit – it’s time to expand our palate.

References


