Long-lived particle searches at the ATLAS, CMS and LHCb experiments at the Large Hadron Collider at CERN

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Contents

1 Introduction

Long-lived particle (LLP) searches represent a fantastic opportunity for discovering beyond-the-Standard Model physics at CERN's Large Hadron Collider (LHC). The LHCb, CMS and ATLAS experiments have already conducted several searches for LLPs in proton-proton collision data in LHC Run 1, at center-of-mass energies of 7 and 8 TeV, and at the beginning of LHC Run 2, at 13 TeV. Such searches often require significantly customized analysis strategies involving non-standard detector objects, reconstruction methods and triggers. As a result, they have received modest coordinated attention compared to the overwhelming majority of LHC searches for particles that decay promptly and yield well-defined and well-calibrated detector objects.

With the successful establishment of a wide range of null results from the mainstream searches for prompt objects with the first data taken at 13 TeV — typically searching for particles and phenomena that benefit most from the sizable increase in center-of-mass energy — the challenge and goal for the remainder of the LHC research program is to design optimal searches for as wide a range of detector signatures as possible, to ensure that new physics is uncovered wherever it may be hiding. Given the myriad possible signal scenarios that can feature LLPs (including models involving dark photons, hidden valleys, R-parity violating supersymmetry, dark QCD sectors, heavy neutral leptons, etc.) and the attendant detector signatures, as well as the desirability of presenting results in a largely model-independent fashion, the LHC LLP Community (experimentalists and theorists) here summarizes the current state of such searches to better define LHC sensitivity to LLPs, to identify optimal experimental information to be presented in LLP results to ensure future recasting and reinterpretation, and to discuss prospects for future searches in Runs 2 and 3 and at the High-Luminosity LHC. Several workshops and conferences have been held in 2015 and 2016 [1] that have underscored the need to continue and evolve the study of LLP signatures at the LHC experiments to achieve these goals and this document is a compendium of notes and material from these events, as well as new, complementary studies.

This document is organized as follows: Section 2 presents the

[1] The "Long-Lived Particle Signatures Workshop", at the University of Massachusetts, Amherst, in November of 2015; "Searching for Exotic Hidden Signatures with ATLAS in LHC Run 2", in Cosenza, Italy, in March of 2016; "Experimental Challenges for the LHC Run II", at the Kavli Institute for Theoretical Physics, in May of 2016; and the "LHC Long-Lived Particles Mini-Workshop", at CERN in May of 2016

general theoretical motivations for BSM LLP searches at the LHC and discusses the experimental challenges related to such signatures. Section 3 enumerates the detector signatures the ATLAS, CMS, and LHCb experiments are capable of identifying and discusses in more detail the theoretical motivations for each, as well as a discussion of the existing searches, known gaps in coverage and proposals to improve coverage. Section 4 contains a set of recommendations for the presentation of LLP search results to ensure that such searches are optimally reinterpretable. Section 5 presents a discussion of the prospects for LLP searches in Runs 2 and 3 of the LHC and for the High-Luminosity LHC run planned for the future. Finally, Section 6 concludes.

2
Theoretical Motivations & Simplified Models

[Here the theory community will present a discussion of how particles obtain LHC-detector-visible (and beyond) lifetimes in BSM models and describe curated classes of models (including exhaustive citations) that highlight the ways in which the lifetime frontier is an ideal place where new physics could be hiding.]

2.1 General Motivations From Theory

General principles for why we expect long-lived particles to appear in beyond-the-SM physics. Examples include:

- Approximate symmetries (like RPV in SUSY)
- Split spectra where decays are mediated by off-shell heavy particles (like in split SUSY)
- Small mixings with SM particles or small couplings (like in hidden sectors/hidden valleys, neutrinos, dark matter, baryogenesis etc.)
- Degeneracies enforced by approximate symmetries (nearly degenerate higgsinos/winos in SUSY or new electroweak multiplets)

From the theory perspective, the lifetime $c\tau$ in most theory models is a quasi-free parameter, as is the mass of the new particle. It therefore makes sense to organize models according to production and decay modes, and there are a specific subset that are well-motivated and appear in most classes of LLP models. We discuss these in the next section. However, we recognize that changing the mass and lifetime can have dramatic effects on the experimental signatures, and this discussion is undertaken in Chapter 3.

2.2 Simplified Models for Long-Lived Particle Production

Simplified models are characterized by the LLP, X, and potentially a parent particle, P, such that X is produced in cascade decays of P.

2.2.1 LLP Pair Production

In many models, X is pair produced. The reason is that LLPs are typically stabilized by an approximate symmetry, and so single production is often (although not always) suppressed by the small coupling that gives it a long lifetime. In contrast, pair production of X is often allowed by the symmetry and the rates can be large.

The most important pair-production modes are outlined below. [Organize in a list instead? Don't know if there are too many sub-headings]

2.2.1.1 SM Gauge Interactions

If X has electroweak or strong charges, it can be produced through the SM gauge interactions. Note that charge conservation also then has implications for the decay modes (for example, if X carries color charge, then its decays necessarily include jets).

2.2.1.2 Resonant Production of Parent Particle

The parent particle can cascade decay to X, for example $P \to XX$. P could be a SM particle (Z, H, or a charged particle) or a BSM particle (Z', H', or a charged particle, etc.). If sufficiently light, the parent particle can also be produced in rare meson decays. The resonant production also gives a **characteristic mass scale** for the process, namely that X carries away a fraction of M_P in momentum.

Depending on the nature of P, there may be associated prompt objects. For example, if we take a Higgs portal production, there can be associated forward VBF jets or vector boson production.

2.2.1.3 Non-Resonant Production of Parent Particle

The parent can also be produced off-shell, leading to pair-production of X without resonance. This is most common in models where X is heavier than P, for example in a Higgs portal model where $M_X > M_h/2$. Such rates are typically tiny and so LLP searches are the best shot at discovering off-shell portals. In this case, the typical momentum scale of the event is set by M_X rather than M_P.

Depending on the nature of P, there may be associated prompt objects. For example, if we take a Higgs portal production, there can be associated forward VBF jets or vector boson production.

2.2.1.4 Parent Particle Pair Production

P can itself be pair-produced, decaying to a single X each. This is common in SUSY scenarios, with pair production of superpartners that cascade to a long-lived (N)LSP. In this case, the typical momentum scale of X is again set by the parent mass, but there may also be associated prompt objects associated with the prompt decay (for example, $\tilde{g} \to jj\tilde{\chi}_1$ (prompt), $\tilde{\chi}_1 \to jjj$ (displaced).

2.2.2 *LLP Single Production*

Single production of a LLP can happen in scenarios where there are two new BSM particles that can be pair-produced in association with one another, but one escapes the detector invisibly while the other undergoes a displaced decay. There are also a few situations where the LLP has a sufficiently large production portal that it is possible to singly create it through the same small coupling that mediates decay.

2.2.2.1 *Electroweak Associated Production*

This is common in SUSY and other models with new electroweak multiplets. In this case, we can have associated chargino-neutralino production, or $\tilde{\chi}_1 - \tilde{\chi}_2$ production. In each case, the heavier particle can decay with a long lifetime (either the chargino or the $\tilde{\chi}_2$), while the lighter particle escapes as missing momentum.

2.2.2.2 *Associated Production of Hidden-Sector States*

This is common in models of hidden sectors that contain a dark matter particle plus one or more additional particles. Examples include inelastic dark matter, where DM is produced in association with a heavier particle that decays with a long lifetime into DM + SM states, or DM plus a dark photon (where $M_{A'} < 2M_{\mathrm{DM}}$), such that A' can be radiated off of DM when produced but decays at a displaced vertex.

2.2.2.3 *New Neutrino States*

If there exist a right-handed neutrino within kinematic reach of the LHC, it is singly produced via its mixing with the left-handed neutrino. For neutrino masses below the weak scale, the decay is mediated by off-shell weak gauge bosons and the lifetime can be naturally long (particularly if the mixing is small).

2.2.2.4 *Production in Rare Meson Decays*

[This kind of overlaps with neutrinos]

Because of the large numbers of mesons, it is possible that even particles with small couplings can be produced in rare meson decays. The LLP decay is typically suppressed by ratios of small masses to the weak scale, making it even more displaced.

2.2.3 *Multiple Production of Long-Lived Particles*

[THIS SECTION NEEDS WORK]

Models with new confining sectors (or large gauge couplings) can result in large amounts of hidden-sector radiation, some of which can decay back into SM particles with displaced vertices. The classic hidden valley signature is a large multiplicity of (typically soft) long-lived particles, potentially associated with prompt objects.

2.2.3.1 *Dark Shower*

If the hidden sector contains a new confining group, the hidden sector states shower and hadronize. Some hidden-sector hadrons may be stable, but others can mix with SM states such as the Higgs and pions, leading to long lifetimes. The challenge in these models is finding an adequate parameterization that is sufficiently general to capture most of the interesting dynamics without having too many free parameters. [Topic of discussion for workshop?]

[Do we want to include "soft clouds" or "soft soup" or whatever we were calling them in this section?]

2.2.3.2 *Quirks*

In this case, the quarks of the new confining group are much heavier than the confinement scale. The result is that the resulting "quirks" travel apart in the detector and are pulled back together, resulting in large amounts of radiation and non-trivial tracking patterns. If the quirks annihilate in the detector, this can also give rise to other striking signatures that are potentially out-of-time.

2.2.4 *Rare Meson Decays*

[I've actually folded this into the earlier discussions because I don't think this is really a separate category]

3
Experimental Reconstruction of Long-Lived Particles

[Here the theory community will present a discussion of how particles obtain LHC-detector-visible (and beyond) lifetimes in BSM models and describe curated classes of models (including exhaustive citations) that highlight the ways in which the lifetime frontier is an ideal place where new physics could be hiding.

It is suggested that the theory motivation be organized according to **LLP production modes**: Higgs or other SM particle decays, direct production through SM gauge interactions (SUSY-like), Hidden Valley, . . .

Then each of the experiments will contribute a discussion of why LLP searches are challenging and require non-standard methods.]

Figure 3.1 comes from an ATLAS search [1].

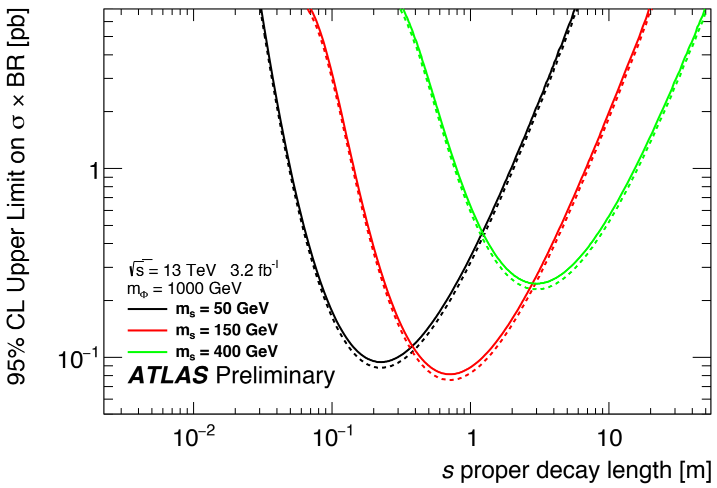

Figure 3.1: ATLAS search for a high-mass scalar Φ decaying to long-lived scalars, s, at $\sqrt{s} = 13$ TeV. From Ref. [1].

4 Signatures and Searches for Long-Lived Particles

Breaking down the possible LLP discovery methods at the LHC by detector signature. See partially worked example below.

Theory motivations should be relatively succinct, deferring to the big-picture motivations in Section 2. The focus here should be on citing models giving rise to the *specific* listed signature to help experimentalists find theoretical motivation for a particular final state.

It has been proposed to sub-divide signatures only according to long-lived objects, and then include associated prompt production in with these signatures. For example, instead of having a separate section on "prompt jet + displaced jet", it would be included in the displaced jet section. This is to avoid signature proliferation. We'll try this approach for now and see if it looks good with more signatures fleshed out.

4.1 One Displaced Object

4.1.1 First example signature

4.1.1.1 Theoretical motivations

4.1.1.2 Existing searches and limits

4.1.1.3 Known gaps in coverage

4.1.1.4 Proposals to improve coverage and sensitivity of existing searches

4.2 Two Displaced Objects

4.2.1 Displaced Jets

4.2.1.1 Theoretical motivations

Many models give rise to predominantly (or exclusively) hadronic decays of long-lived particles. This can include:

1. Particles that decay via mixing with the SM Higgs boson. In this case, the LLP decays predominantly into $b\bar{b}$ pairs for $m_{\text{LLP}} >$

$2m_b$. Given that LLP signatures could have very small signal cross sections, it is important to recover the most common decay modes to maximize discovery potential. In many of these models, the LLP is itself produced in Higgs decays, motivating searches for relatively low-mass/soft objects.

2. Models of supersymmetry and many other solutions to the hierarchy problem feature top partner particles. LLPs can either be the top partners themselves or decay through processes mediated by the top partner. In either case, one expects to find final states rich in jets that may originate from the LLP. Exclusively hadronic final states are also expected in scenarios with baryon-number violation (such as baryonic R-parity violation), in which case the LLP decays into multiple jets.

3. ...

The above theories also often predict associated production of prompt objects in addition to the LLPs. If LLPs are produced through Higgs decays, then prompt forward jets or vector bosons accompany the LLPs via VBF/VH production modes. Similarly, SUSY can predict prompt jets or vector bosons if the LLP is at the bottom of a cascade decay chain.

In addition to the "major" motivations, dump citations here.

4.2.1.2 Existing searches and limits

1. **CMS Displaced Jets:** A search for a single LLP decaying to two jets in the inner detector. Tracks from the vertex are associated with the jets and jets with several prompt tracks are vetoed to reduce backgrounds. Search is sensitive to LLP decays to $2j + X$, since the dijet system is not required to point in the same direction as the secondary vertex. Search relies on an H_{T} trigger and has relatively high thresholds for the jets ($p_{\mathrm{T}} > 60$ GeV) and so the search requires high-mass LLPs [2].

2. **ATLAS Displaced Jets:** Several searches for a pair of LLPs decaying to two jets each. The search is sensitive to combinations of LLP decays in the muon spectrometer and/or inner detector. Decays in the MS are triggered using a dedicated Muon ROI Cluster trigger, which allows relatively low-momentum events to be recorded, whereas events that fail this trigger can be recorded with a jet + $\not{E}_{\mathrm{T}}$ trigger that necessarily requires more energetic objects. Signals covered by the jet + $\not{E}_{\mathrm{T}}$ trigger can be probed from lifetimes of cm-m scale, while signals relying on the Muon ROI trigger can only be probed if their lifetimes are sufficiently long to reach the MS [3].

3. **ATLAS HCAL Search:** A search for pairs of LLP decaying inside of the HCAL. Signal events are identified by narrow depositions of energy in the HCAL without associated ECAL depositions. A dedicated CalRatio trigger is used for the analysis, which allows

for events to be recorded below usual jet thresholds. The analysis is most sensitive to signals with lifetimes that match the HCAL geometry [4].

4. ...

4.2.1.3 *Known gaps in coverage*

1. **Low-Mass LLPs:** LLPs with relatively low masses (which can, for instance, be produced in exotic Higgs decay modes) give rise to relatively soft displaced signatures. Such signals would be missed in searches with high trigger and reconstruction thresholds, such as the CMS Displaced Jets search and the jet + $\not{E}_T$-based search in the ATLAS Displaced Jets analysis. By contrast, the ATLAS searches for decays to displaced jets in the HCAL and MS are sensitive to softer objects, but are only valid in a particular range of lifetimes. For example, for LLPs with very long lifetimes, it would be rare to have two decays inside of either the HCAL or MS per event, and such particles could be missed.

2. **Singly produced LLPs:** The ATLAS displaced jet searches typically require pairs of displaced vertices, and therefore would not have sensitivity to models with a single displaced object (whether because only one LLP is produced at a time, or the other LLPs escape the detector). The CMS search is sensitive to a single displaced vertex, but requires quite large momentum objects and would therefore not be sensitive to softer LLP decays. Additionally, if the hadrons from LLP decay are merged into a single jet, the search would not be sensitive because of the requirement of two jets.

3. **Boosted LLPs:** Some searches require strict isolation requirements, such as the vertex reconstruction in the MS (to reduce punch-through backgrounds) or the search for LLP decays in the HCAL. This could be a problem for models with high multiplicities of particles produced at the primary vertex, which result in failed isolation criteria.

4. **Very short lifetimes:** Searches in the inner detector can require impact parameters as large as 1 cm to suppress heavy-flavor backgrounds, while searches in the MS and HCAL are clearly insensitive to very short lifetimes. For heavy LLPs with lifetimes comparable to B mesons, the signal is swamped in heavy-flavor backgrounds and current searches are not sensitive.

5. ...

4.2.1.4 *Proposals to improve coverage and sensitivity of existing searches*

1. **Low-Mass LLPs:** A major challenge of reconstructing low-mass, hadronically decaying LLPs is the requirement of passing the

trigger. This motivates using associated objects to pass the trigger that is unrelated to the LLP: suggestions include Higgs associated production modes such as VBF and Higgs-strahlung, monojet + $\not\!\!E_{\mathrm{T}}$ triggers in dark sector models, single lepton, etc.

2. **Singly produced LLPs:** A major benefit of searches of pairs of LLPs is that backgrounds can be greatly reduced. For models with singly produced LLPs, the LLPs typically arise in association with other objects. Tagging these objects (such as jets + $\not\!\!E_{\mathrm{T}}$, forward jets, leptons, or resonances) could be used to reduce backgrounds in lieu of requiring a second displaced LLP to recover some sensitivity to scenarios with only one DV.

3. **Very short lifetimes:** Often, lifetime is inversely correlated with mass, and so very short lifetimes are associated with heavier LLPs. One possibility would be to use a large mass or other kinematic features to distinguish signal from B-meson DVs, recognizing the very significant challenge associated with such an analysis.

4. ...

4.3 Et cetera

5
Summary of Gaps in Current Searches and New Signatures

Provide a summary of gaps in current coverage and ideas for new signatures.

6
Recommendations for the presentation of search results

How should the experiments present results to ensure optimal recastability and reinterpretation? A minimal set of efficiencies, model-independent experimental quantities, etc.

7
Prospects for LLP searches in Runs 2 and 3 of the LHC and the HL-LHC

Calculate, estimate, extrapolate and speculate.

7.0.1 LLP Searches With Auxiliary Detectors

Brief mention of LLP searches with existing and proposed experiments such as MilliQan, Moedal, Mathusla, . . .

8 Conclusions

Conclude and finish.

Put **summary tables and figures** to identify signatures that are currently covered as well as gaps. We should also think about putting these between the introduction and Section 2 if we want to make them more prominent!

9
Acknowledgements

Recognition and thanks.

A
Appendix: Plannsed Detector Upgrades

A worked-out example.

B
Appendix: Explicit example of recommendations for search results

A worked-out example.

Bibliography

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[3] 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**.1 (2015) 012010, arXiv: 1504.03634 [hep-ex].

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