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

February 21, 2017

Emmy Noether *Bryn Mawr College, Pennsylvania, USA*

Contact editors: lhc-llp-admin@cern.ch

Contents

1 Introduction 7

2 Theoretical Motivations & Simplified Models 9

2.1 General Motivations From Theory 9

2.2 Simplified Models for Long-Lived Particle Production 9

2.2.1 LLP Pair Production 10

2.2.1.1 SM Gauge Interactions 10

2.2.1.2 Resonant Production of Parent Particle 10

2.2.1.3 Non-Resonant Production of Parent Particle 10

2.2.1.4 Parent Particle Pair Production 10

2.2.2 LLP Single Production 11

2.2.2.1 Electroweak Associated Production 11

2.2.2.2 Associated Production of Hidden-Sector States 11

2.2.2.3 New Neutrino States 11

2.2.2.4 Production in Rare Meson Decays 11

2.2.3 Multiple Production of Long-Lived Particles 11

2.2.3.1 Dark Shower 12

2.2.3.2 Quirks 12

2.2.4 Rare Meson Decays 12

2.3 Long-Lived Particle Decay Modes 12

3 Experimental Reconstruction of Long-Lived Particles 13

3.1 Using the LHC Detectors to Look for LLPs 13

3.1.1 Inner Detector Tracking 13

3.1.2 Calorimetry 14

3.1.3 Muon Spectrometer 14

3.1.4 RICH Detectors (LHCb) 14

3.1.5 *Combinations of Main Detector Systems* 14
3.1.5.1 *Lepton ID Algorithms* 14
3.1.5.2 *Jets* 14
3.1.5.3 *Displaced lepton jets* 14
3.1.5.4 *Combination of LHCb subsystems* 15
3.1.5.5 *Other Combinations* 15
3.1.6 *Non-Presence of pp Collisions* 15
3.2 *Summary of Existing LLP Searches* 15

4 *Signatures and Searches for Long-Lived Particles* 17
4.1 *Decay of a Single LLP In Detector* 17
4.1.1 *Displaced Lepton Pair (tracker)* 17
4.1.2 *Displaced lepton jet (tracker + muon system)* 17
4.1.3 *Displaced tau(s) (tracker)* 17
4.1.4 *Displaced jet pair (tracker)* 17
4.1.5 *Displaced lepton + multi-tracks (tracker)* 18
4.1.6 *Displaced multi-tracks (tracker)* 18
4.1.7 *Displaced tracks (muon system)* 18
4.1.8 *Slow, non-pointing photon (tracker)* 18
4.1.9 *Displaced, late calo hits* (e.g., *decay in calo, no tracks, CalRatio)* 18
4.1.10 *Out-of-time calo hit* (e.g., *stopped gluino)* 18

5 *Summary of Gaps in Current Searches and New Signatures* 19

6 *Recommendations for the presentation of search results* 21

7 *Prospects for LLP searches in Runs 2 and 3 of the LHC and the HL-LHC* 23
7.0.1 *LLP Searches With Auxiliary Detectors* 23

8 *Conclusions* 25

9 *Acknowledgements* 27

A *Appendix: Plannsed Detector Upgrades* 29

B *Appendix: Explicit example of recommendations for search results* 31

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 subheadings]

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]

2.3 *Long-Lived Particle Decay Modes*

Determined in part by charge of LLP (for example, a strongly interacting LLP will necessarily decay to at least one jet). However, most of the decay modes can apply to any LLP. The most important part is the *visible* part of each decay mode, although the invisible final-states can give rise to missing momentum and mean that the vertex is not fully reconstructible.

- Jets
- Electrons and muons
- Taus
- SM gauge bosons (on- or off-shell)
- Higgs bosons
- Photons
- Missing momentum

3 Experimental Reconstruction of Long-Lived Particles

LLP searches present an interesting experimental challenge, because detectors were designed to look for SM particles (that typically decay promptly or travel most of the way through the detector). However, it is also an exciting possibility for looking for long-lived BSM physics, because a spectacular new-physics signature may have significantly less background than the corresponding prompt search.

3.1 Using the LHC Detectors to Look for LLPs

In this section, we review the different ways in which the LHC detectors can be used to reconstruct long-lived objects. In some sense, this is a list of signatures that are currently possible to reconstruct that look different from prompt SM physics. This list will necessarily change as the detectors are upgraded or new clever uses are found. In each section, we include a short summary and references to documents that provide more details on reconstruction (where available).

3.1.1 Inner Detector Tracking

- Non-pointing inner detector tracks (large impact parameters)
- Appearing inner detector tracks (missing hits in innermost layers)
- Disappearing inner detector tracks (missing hits in outermost layers)
- Highly dE/dx tracks (good for highly charged or slow particles)
- Low dE/dx tracks (good for fractionally charged particles)
- Kinked tracks (disappearing track linked to appearing track, not pointing in same direction)
- Displaced multitrack vertices (vertex location far from beamspot, and/or direction not pointing to beamspot)

3.1.2 Calorimetry

- Anomalous HCAL vs. ECAL depositions
- Timing information (consistent with slow, non-pointing, or out-of-time particles)
- Pointing information from depth segmentation and shower shape variables
- Anomalous shower shapes (good for monopoles)

3.1.3 Muon Spectrometer

- Short, not necessarily pointing tracks
- Anomalous dE/dx
- Timing information (to identify slow particles, distinguish outward vs. inward tracks)
- Dimuon vertices from MS-only muon tracks
- Multitrack vertices from short tracks

3.1.4 RICH Detectors (LHCb)

Can be used to reconstructed charged LLPs with mass well-separated from pions, kaons and protons. Can cover momentum range $\sim 1 - 150$ GeV and $\beta > 0.6$.

[More details needed here]

3.1.5 Combinations of Main Detector Systems

3.1.5.1 Lepton ID Algorithms

- Electron = inner track + EM cluster
- Muon = inner track + track in muon system
- Hadronic tau = inner track(s) + calo clusters

3.1.5.2 Jets

Typically a combination of tracks + calo clusters

- Multiple displaced vertices within a jet (*e.g.*, emerging jets)
- Displaced vertex followed by a jet

3.1.5.3 Displaced lepton jets

A lepton jet is a collimated collection of muons, electrons, and pions. Perhaps also include other collimated, displaced objects here?

- Combination of low-EMF jet + muon-system only muon tracks ($ee + \mu\mu$)

- low-EMF jet (*ee*)
- Collimated, muon-system only muon tracks

3.1.5.4 Combination of LHCb subsystems

Combination of vertex locator + tracking stations (LHCb) + PID detectors can be sensitive to charged LLP decaying to charged particles (used to reconstruction $K+ \to 3\pi$)

3.1.5.5 Other Combinations

- Calorimeter clusters or tracks in muon system that lack inner-detector tracks
- High dE/dx track + time-of-flight measurement in calorimeter or muon system
- Multitrack vertex in muon system with no associated inner-detector tracks

3.1.6 Non-Presence of pp Collisions

Use forward detectors or knowledge of LHC bunch-filling scheme

3.2 Summary of Existing LLP Searches

Here, we include a table of existing LLP searches, with references to the search and hyperlinked to more detailed discussion in Chapter 4 [maybe also include links to theory and experiment motivation chapters?]

4
Signatures and Searches for Long-Lived Particles

Proposed layout for each signature:

1. What is the experimental signature?
2. Reference to relevant theory section simplified models, and provide models that give rise to signature (are there associated objects?, provide citations)
3. What searches have currently been done?
4. What are the experimental challenges associated with the signature, including: trigger & reconstruction limitations, presence of $\not{E}_{\mathrm{T}}$ in decays in reconstructing LLP, primary expected backgrounds, prospects for improvement
5. Projection for recommended simplified model

4.1 Decay of a Single LLP In Detector

The location in parentheses denotes **location** of LLP decay. For single LLP, may especially need to consider associated production channels to improve sensitivity! Include in discussion of sections below.

4.1.1 Displaced Lepton Pair (tracker)

At least one search exists

Includes LHCb searches in B decays, such as $B \to K^* X$, $X \to \mu^+\mu^-$

4.1.2 Displaced lepton jet (tracker + muon system)

At least one search exists (??)

4.1.3 Displaced tau(s) (tracker)

4.1.4 Displaced jet pair (tracker)

At least one search exists

Need to separately consider b jets?

4.1.5 *Displaced lepton + multi-tracks (tracker)*

At least one search exists

4.1.6 *Displaced multi-tracks (tracker)*

At least one search exists

4.1.7 *Displaced tracks (muon system)*

4.1.8 *Slow, non-pointing photon (tracker)*

4.1.9 *Displaced, late calo hits* (e.g., *decay in calo, no tracks, CalRatio)*

4.1.10 *Out-of-time calo hit* (e.g., *stopped gluino)*

At least one search exists

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

[1] *Search for long-lived neutral particles decaying in the hadronic calorimeter of ATLAS at* $\sqrt{s} = 13$ TeV *in* 3.2 fb^{-1} *of data*, ATLAS-CONF-2016-103 (2016).

[2] V. Khachatryan et al., *Search for Long-Lived Neutral Particles Decaying to Quark-Antiquark Pairs in Proton-Proton Collisions at* $\sqrt{s} = 8$ *TeV*, Phys. Rev. **D91**.1 (2015) 012007, arXiv: 1411.6530 [hep-ex].

[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].

[4] G. Aad et al., *Search for pair-produced long-lived neutral particles decaying in the ATLAS hadronic calorimeter in* pp *collisions at* $\sqrt{s}$ = *8 TeV*, Phys. Lett. **B743** (2015) 15–34, arXiv: 1501.04020 [hep-ex].