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

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Introduction

Put introduction to the long-lived particle search program at the LHC. Brief overview of theory motivation (on a general level, with citation dumps) as well as the general challenges and opportunities of experimental searches for LLPs (again, broad brush with lots of citations).

1.1 *Goals of the White Paper*

In recent years, there has been a proliferation of work on LLP both on the theory and experiment side. This is due to the success of experimental techniques to reconstruct LLPs in earlier runs of the LHC and the theoretical development of well-motivated models that give rise to a range of LLP signatures. It is also in part due to the lack of positive signals of new particles in other, more conventional LHC searches, giving heightened urgency and importance in the coverage of LLP signatures.

To this end, the document serves to assess the current status of LLP searches at the LHC, determining where searches currently have good coverage of LLP searches and where there can be improvements. It also evaluates the impact of possible new triggers or upgrades on the performance of LLP searches in advance of the final decisions for Phase 2 upgrades. Finally, it provides recommendations for the presentation of search results to broaden the impact of existing and planned searches, and to chart a course for the near-future development of the program.

More concretely,

1. We develop a minimal (but expandable) simplified models framework for the LLP program that incorporates the best-motivated LLP theories and models

2. We use the simplified models framework to assess the sensitivity of current searches and identify the highest priority gaps in coverage

3. These in turn inform the development of triggers and decisions about upgrade technologies, and we summarize the impact of possible new upgrades (including existing and planned dedicated detectors such as Moedal, MilliQan, MATHUSLA, ...)

4. Provide a summary of recommendations for the presentation of new LLP searches

5. Identify the new frontiers of LLP searches in which more research and development is needed, particularly in the area of high-multiplicity LLP searches (dark showers)

2

Simplified Model Framework

New particles with long-lifetimes arise in many proposed extensions of the standard model. In some cases, experimental searches have targeted these new particles; in others, proposals have been made for new techniques to reconstruct LLPs in particular models. It is well-known that LHC searches for new physics, such as models of supersymmetry or dark matter, are sufficiently general that a new dedicated search is typically not necessary in order to cover every new proposed model. The exceptional success of the existing LHC program informs us that it is desirable to develop search strategies that ensure experimental results are broadly applicable to different types of models, reduce redundancy among experimental searches, and illuminate gaps in coverage and areas where new searches are needed.

The most commonly adopted framework for accomplishing these goals is the simplified model framework. The simplified model framework uses the fact that many searches are only sensitive to a few broad aspects of a particle's signature (such as the production mode, production rate, and decay topology) and not precise details such as the spin of the particle, its angular distribution, etc. With LLP signatures, the simplified models approach is even *more* appropriate: this is because searches tend to have low backgrounds and relatively inclusive searches can be done, each of which has sensitivity to LLPs with many different types of production and decay modes.

Because LLP particles are often produced and decay (if at all) in physically distinct locations, the production and decay processes can be factorized.[1] We can exploit this to construct a simple basis of LLP production modes and LLP decay modes; we define an **LLP channel** as a combination of a particular production and decay mode, with the lifetime of the LLP taken as a free parameter. We emphasize that the LLP channel as defined here is *not* the same as an experimental signature that manifests in the detector: a single simplified model channel could give rise to many, many different signatures depending on where the decays in occur in the detector (or outside), while a single experimental search for a particular signature could cover many simplified model channels for particular choices of parameters. We focus here on the theory definition,

[1] In addition to production and decay, a third consideration is the propagation of particles through the detector. While neutral or only electrically charged particles have straight-forward propagation, colored states, *e.g.*, SUSY *R*-hadrons, or particles with exotic charges, such as magnetic monopoles or quirks typically engage in a more complicated and often very uncertain traverse. The subtleties with colored LLPs will be discussed more in subsection 2.4.3, and exotic, conserved charges will not be discussed here.

which provides some control over the range of models that we expect to see at the LHC, while in Section 3 we map our basis of Simplified Models onto existing searches to determine the gaps in coverage and proposals for new searches.

2.1   Goals of the Simplified Model Framework

The purpose of the simplified model framework is to provide a simple, common language that experimentalists and theorists can use to describe LLP theories and the corresponding mapping between models and experimental signatures. We therefore want our simplified model space to:

1. Cover the most interesting theories of LLPs with a minimal set of models;

2. Map easily between models and signatures so that the current coverage and gaps may be easily identified;

3. Apply to theories and signatures not yet proposed;

4. Expand flexibly to incorporate theories and signatures not yet proposed;

5. Provide a concrete Monte Carlo signal event generation framework;

6. Facilitate the re-interpretation of searches by supplying benchmark models[2] for which experimental efficiencies can be provided for validation purposes.

2.2   Existing Well-Motivated Theories for LLPs

Here, we categorize a few broad classes of models that have conventionally provided the best motivation for LLPs. We should emphasize that there are many theories beyond these that motivate LLPs; however, many such theories broadly fall under the umbrella of one of the following UV theories and so we can cite them but not give a detailed description.

- **SUSY-like theories (SUSY):** these are models with multiple new particles carrying SM gauge charges and a variety of allowed cascade decays. Lifetimes can be long due to approximate symmetries (such as *R*-parity or gauge mediation) and decays mediated by highly off-shell intermediaries (as in split SUSY). Here we classify any non-SUSY models with heavy SM charged particles, such as composite Higgs or extra-dimensional models, under the SUSY-like umbrella.

- **Higgs-portal theories (Higgs):** these include scenarios with exotic Higgs decays to low-mass particles (as in many Hidden Valley scenarios), and is well motivated by the fact that the Higgs can still have a 30% branching fraction to exotic final states.

[2] Note that more benchmark models may be needed for re-interpretation than are strictly necessary for discovering a new particle, *i.e.,* we should be mindful both of whether two simplified models share a common signature in a search, and also whether they look similar enough to have similar reconstruction efficiencies

The Higgs is also special in that it comes with its own set of associated production modes, such as VBF or Higgs-strahlung.

- **Gauge-portal theories (ZP):** these include scenarios with new vector mediators decaying to exotic LLPs. These are similar to Higgs models, but where the mediator is predominantly produced from $q\bar{q}$-initiated final states without other associated objects.

- **Dark-matter theories (DM):** this class focuses on non-SUSY dark matter and hidden-sector scenarios, and encompasses models where dark matter is produced as a final state in the collider process. The main distinguishing feature from the Higgs and gauge scenarios above is that dark matter (missing momentum) is a necessary and irreducible component of each signature.

- **Heavy neutrinos and friends (RHν):** if there exist new weak-scale states responsible for giving SM neutrinos mass, the new particles can typically be long lived. The signatures tend to be lepton-rich due to the connection with SM neutrino masses.

In developing our simplified model framework, we will construct maps between the UV models and the simplified model channels to illustrate some of the best motivated combinations of production and decay modes for LLPs. This will then allow us to focus on the most interesting scenarios and determine their coverage in particular parts of the model parameter space.

2.3   The Simplified Model Building Blocks

Recall that in LLP searches production and decay can be factorized. This allows us to specify the relevant production and decay modes for LLP models separately; we then put them together and map the space of models into the existing motivated theories.

2.3.1   Production Modes

According to the earlier models, we can identify a minimal set of interesting production modes for LLPs:

- **Direct Pair Production (DPP):** If the LLP is charged under a SM gauge interaction, it can be directly produced via the corresponding gauge boson. The production cross section is specified by the LLP gauge charge and mass. This also results from a t-channel mediator, and in this case the production cross section is a free parameter.

- **Heavy parent (HP):** If the LLP can be produced in the decay of a heavy parent particle that is itself charged under the SM gauge interactions. The production cross section is essentially a free parameter and is indirectly specified by the charge and mass of the heavy parent. The heavy parent production gives a very different kinematics for the LLP than gauge production.

- **Higgs (HIG):** The LLP can be produced in decays of the SM Higgs boson, and therefore has all of the same associated production modes (VBH, VH). Note that if the LLP mass is heavier than $m_h/2$, it can also be produced via the off-shell Higgs portal. The LLP can be pair produced or singly produced (in association with MET). The cross section (or Higgs branching fraction) is a free parameter of the model.

- **Heavy resonance (ZP):** Similar to the Higgs portal, but the LLP is produced in the decay of an on-shell resonance, such as a heavy Z' gauge boson initiated by $q\bar{q}$ initial state or a heavy scalar[3], Φ. Note that production via an off-shell resonance is kinematically similar to the direct production (DPP) above. As with HIG, the LLP can be pair-produced or singly-produced (in association with MET).

- **Charged current (CC):** In the case of a right-handed neutrino, the LLP can be produced in the leptonic decays of W/W'. Single production is favored.

[3] The properties of the observed light Higgs suggest that any new scalar would minimally impact EWSB and thus would have at most only a very small rate from VBF and VH processes, for this reason, we place heavy scalars in the heavy resonance model as opposed to the Higgs model above.

2.3.2   *Decay Modes*

It is important to note that LLP searches are typically fairly inclusive. This is in part due to the fact that particle ID is less possible for decays far in the detector (*e.g.,* for decays inside of the calorimeter, everything looks like a calorimeter deposition). It is also because backgrounds are often low enough that tight cuts typically found in exclusive analyses are not needed to suppress backgrounds. For example, ATLAS has a displaced vertex search sensitive to dilepton and multitrack vertices that are relatively agnostic to other objects originating from near the displaced vertex. Similarly, CMS has an analysis sensitive to high-impact-parameter leptons without reconstructing a vertex. However, in some cases the topology does matter: for example, one potentially important factor is whether the LLP decays into two SM objects or three, because this determines whether its mass is resonantly reconstructed by looking for two objects in a decay.

We therefore emphasize that the following decay modes are intended to cover similar/related decay modes, for example $2j +$ *invisible* **is also a proxy for** $3j$ **because searches for non-resonant hadronic LLP decays can be sensitive to both. It should also be emphasized that searches should not be optimized to the exact, exclusive decay mode because that could suppress sensitivity to related but slightly more complicated models.**

- **Diphoton decays:** The LLP can decay resonantly to $\gamma\gamma$ (like in Higgs-portal models) or to $\gamma\gamma +$ invisible (in dark matter models). This latter mode stands as a proxy for other 3-body decays where you don't explicitly reconstruct the third object.

- **Single photon decays:** The LLP decays to $\gamma +$ invisible (like in SUSY gauge mediation). While the gauge mediation signal man-

dates a near massless invisible final state, a more general dark matter framework can come with a heavy final state particle.

- **Hadronic decays:** The LLP can decay into two jets (jj) (like in Higgs-portal, gauge-portal models, or RPV SUSY), jj + invisible (like in SUSY, dark matter, or neutrino models), or j + invisible (like in SUSY). Here, jet (j) means either a light-quark jet, gluon, or b-quark jet.

- **Semileptonic decays:** The LLP can decay into a lepton + 1 or 2 jets (like in SUSY or neutrino models).

- **Leptonic decays:** The LLP can decay into $\ell^+\ell^-$, $\ell^+\ell^-$ + invisible, or $\ell^\pm$ + invisible (as in Higgs-portal, gauge-portal, SUSY, or neutrino models). ℓ is any flavor of charged lepton, but the decays are lepton-flavor conserving.

- **Flavored leptonic decays:** The LLP can decay into $\ell_\alpha^+\ell_\beta^-$ or $\ell_\alpha^+\ell_\beta^-$ + invisible where flavors $\alpha \neq \beta$ (as in SUSY or neutrino models).

In all examples, $c\tau$ is a free parameter. Therefore, stable particle searches are also covered by taking the $c\tau \to \infty$ limit of any decay mode. The mass of the LLP is also a free parameter, and in the case of an invisible particle in the LLP decay, there are three well-motivated choices of the quantity $\Delta \equiv M_{\text{LLP}} - M_{\text{inv}}$: $\Delta = M_{\text{LLP}}$ (*i.e.*, massless invisible state like light DM or a neutrino); $\Delta = M_{\text{LLP}}/2$, corresponding to a democratic mass hierarchy; $\Delta = \epsilon \ll M_{\text{LLP}}$, representing a squeezed spectrum.

2.4   *Our Simplified Models Proposals*

We separately consider LLPs that are: (a) neutral, (b) electrically charged but color neutral, and (c) carry color charge. These are considered separately because the relevant production modes are different (the latter two have irreducible production through SM gauge interactions) and their signatures can be different (such as disappearing tracks and hadronized LLPs).

Once again, we emphasize that in spite of the many simplified model channels, there are a small number experimental LLP searches that have excellent coverage to a wide range of channels. The goal is ultimately to identify whether there are other searches that could have a similarly high impact, and where the gaps are.

2.4.1   *Neutral LLPs*

Reminder: $j = u, d, s, c, b, g$, $\ell = e, \mu, \tau$. When multiple production modes are specified in one row (typically one or more in parentheses), this means that multiple especially well motivated production channels give rise to similar signatures. Typically only one of these

production modes will need to be included in a search, but we include the different production modes to indicate where people's favorite models may lie. *X* indicates the LLP.

In each entry of the table, we indicate where a particular (production) × (decay) mode is predicted in the most well-motivated version of the UV theory class. If the UV model is indicated in parentheses, MET is required in the decay.

Channel	$\gamma\gamma(+\text{inv.})$	$\gamma + \text{inv.}$	$jj(+\text{inv.})$	$jj\ell$	$\ell^+\ell^-(+\text{inv.})$	$\ell_\alpha^+\ell_{\beta\neq\alpha}^-(+\text{inv.})$
DPP: sneutrino pair		SUSY	SUSY	SUSY	SUSY	SUSY
HP: $\tilde{q} \to jX$ (or $\tilde{g} \to jjX$)		SUSY	SUSY	SUSY	SUSY	SUSY
HP: $\tilde{\ell} \to \ell X$ (or $\tilde{\chi} \to \{W/Z\}X$)		SUSY	SUSY	SUSY	SUSY	SUSY
HIG: $h \to XX$ (or $\to XX + \text{inv.}$)	Higgs (DM)		Higgs (DM)		Higgs (DM)	
HIG: $h \to X + \text{inv.}$	DM		DM		DM	
ZP: $Z(Z') \to XX$ (or $\to XX + \text{inv.}$)	Z' (DM)		Z' (DM)		Z' (DM)	
ZP: $Z(Z') \to X + \text{inv.}$	DM		DM		DM	
CC: $W(W') \to \ell X$			(RHν)	RHν	(RHν)	(RHν)

2.4.2   *Electrically Charged LLPs: $|Q| = 1$*

Here, we need to consider *far fewer* production modes because of the irreducible gauge production associated with the electric charge. We still consider one heavy parent scenario where the heavy parent has a QCD charge, as this could potentially dominate the production cross section. Note we lump all resonant production into the Z' simplified model. The reason is that the SM Higgs cannot decay into two charged particles due to the model-independent limits from LEP on charged particles masses $M \gtrsim 75$ GeV. Similarly, there are fewer decay modes because of the requirement of charge conservation.

For concreteness, we recommend using $Q = 1$ as a benchmark for charged LLPs for the purpose of determining allowed decay modes. Although other values of Q are possible, these typically result in cosmologically stable charged relics or necessitate different decay paths than those listed here. We note that there are dedicated searches for heavy quasi-stable charged particles with either $Q \gg 1$ or $Q \ll 1$; because those searches are by construction not intended to be sensitive to the decays of the LLP, the existing models are sufficient for characterizing these signatures and they do not need to be additionally included in our framework.

Channel	ℓ + inv.	$jj(+\text{inv.})$	$jj\ell$
DPP: chargino pair (or slepton pair)	SUSY	SUSY	SUSY
HP: $\tilde{q} \to jX$	SUSY	SUSY	SUSY
ZP: $Z' \to XX$	Z' (DM)	Z' (DM)	Z'
CC: $W' \to X + \text{inv.}$	(DM)	(DM)	

2.4.3   LLPs with Color Charge

Because QCD is a non-Abelian group, the gauge pair production cross section of the LLP is specified by the LLP mass and its representation under SU(3).

A complication of the QCD-charged LLP is that the LLP hadronizes prior to the decay. While the hadronization will not affect any hard kinematic features of its decay, it can result in interesting phenomena such as stopping in the detector, charge flipping, etc. These have been greatly explored in the context of *R*-hadrons in SUSY and we refer those interested in performing such searches to the relevant literature. **[BS: What more do we want to say about this?]**

Channel	j + inv.	$jj(+\text{inv.})$	$j\ell$
DPP: squark pair (or gluino pair)	SUSY	SUSY	SUSY

2.5   Conventions for the Simplified Models Library

Can have library of FeynRules UFO models for production & decay modes, separately stitch these together. **[BS: Would folks rather have LHE files or the relevant cards for running MG? Need to figure out.]**

2.6   Limitations, Exceptions and Caveats to the Simplified Models

- Focused on the simplest and best-motivated models for now. Already many channels to consider! But this can be expanded as more work is done to fill in gaps

- Focused on low-multiplicity signatures (so does not include dark showers, part of ongoing working group)

- Cannot cover every single model! Some searches may need to be sensitive to exact features of a specific model, particularly as we push to be more background-dominated search regions.

3
Experimental Coverage & Recommendations for New Searches

[BS: I think we should start with a short list of the most pressing "gaps", and then show the more comprehensive mapping of existing searches into the simplified models parameter space

3.1 Summary of High-Priority Searches Needed

3.2 Sensitivity of Current Searches to Simplified Models

[BS: My proposal is to organize according to channel (all-hadronic, semi-leptonic, leptonic, photons, etc). It may be that some searches have sensitivity to many (for example, ATLAS/CMS displaced jets is also sensitive to electrons, photons, etc) but I can't think of a better way of doing it]

3.2.1 Detector-Stable

3.2.2 All-Hadronic Decays

3.2.3 Semi-Leptonic Decays

3.2.4 Leptonic Decays

3.2.5 Photonic Decays

3.3 Overview of Gaps

Here is where we synthesize the information of the last section, identifying the gaps, and then pick 5-10 that go into the first section.

4
Trigger and Detector Upgrades

4.1 Summary of Current Trigger Sensitivity & Proposals

Summary from Trigger WG specifying where the current triggers
have coverage, and list proposals for hadronic seed for displaced
jet trigger. Also highlight high-multiplicity, low-threshold lepton
triggers that are useful for low-mass LLPs.

4.2 Prospects for Trigger Upgrades

FTK, L1 track trigger ("stubs"), LHCb online reconstruction, timing
layer

4.3 Prospects for Offline Reconstruction with Detector Upgrades

Timing layer, HGcal, other upgrades?

4.4 Current and Proposed Dedicated LLP Detectors

Limit to 1-1.5 pages each, focus on projected sensitivity and com-
plementarity

4.4.1 MOEDAL

4.4.2 milliQan

4.4.3 MATHUSLA

5
Recommendations for the Presentation of Search Results

6

The Next Frontiers: Dark Showers and Quirky Signatures

A short section (3-5 pages?) outlining how dark showers don't easily fall into existing simplified models or experimental search programs. Give a few examples of specific models (emerging jets model, 1-2 others) as well as some concrete experimental methods being used now. This should motivate and lead into the work of the Dark Showers WG, although if they have concrete results by the time the white paper goes out we can include those.

6.1   Dark Showers

6.2   Quirks

7
Conclusions

Conclude and finish.

A
Appendix: Summary of Backgrounds for LLP Searches

2-3 page summary of the findings of the Backgrounds WG

B
Appendix: Overview of Current Experimental Searches

Short description of each relevant experimental analysis (invite contributions?)