Simplified Models for Long-Lived Particle Searches at the Large Hadron Collider

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Simplified Models for Long-Lived Particles

Long-lived particles (LLPs) arise in many well-motivated theories of physics beyond the Standard Model (SM), ranging from well-established scenarios such as the minimally supersymmetric Standard Model (MSSM) to newer theoretical frameworks such as neutral naturalness and hidden sector dark matter. Macroscopic decay lengths of new particles naturally arise from the presence and breaking of new symmetries, which can be motivated by flavor, cosmology (such as dark matter and baryogenesis), neutrino masses, as well as solutions to the hierarchy problem; indeed, LLPs are generically a prediction of new weak-scale hidden sectors [1–5]. A comprehensive search program for LLPs is therefore critical to fully leverage the LHC's immense capability to illuminate the physics of the weak scale and beyond.

LLPs present both major opportunities and major challenges for searches at the LHC. On the one hand, SM backgrounds are small for signals originating far from the collision point, making prospects for discovering displaced signals much better than for similar prompt signals in many scenarios. On the other hand, searches for LLPs demand specialized techniques at all stages of the analysis, from the trigger level to reconstruction to background estimation. Furthermore, as LLP searches involve aspects of detector response that cannot be reliably simulated with public Monte Carlo tools, it is notoriously difficult for individuals outside of the experimental collaborations to accurately apply search results to new theoretical models, potentially jeopardizing their future utility.

This document builds on the exceptional success of the existing LHC program for LLPs. We propose a systematic framework for future LLP searches that aims to ensure that experimental results are (i) *powerful*, covering as much territory as possible; (ii) *flexible*, so that they are broadly applicable to different types of models, (iii) *efficient*, reducing unnecessary redundancy among searches, and (iv) *durable*, providing a common framework for comparing and reinterpreting searches for years to come. We elaborate on these goals in Section 1.1. We expect that this common framework will help illuminate gaps in coverage and highlight areas where new searches are needed [6].

The simplified models framework has proven to be a highly successful approach for accomplishing the above goals for signatures featuring prompt decays of new particles [7] or dark matter produced at colliders [8]. Simplified models are so successful because the majority of search sensitivity is driven by only a few broad aspects of a given beyond-SM (BSM) signature such as the production process, overall production rate, and decay topology. Meanwhile, the sensitivity of searches is typically insensitive to other properties such as the spin of the particles involved.

Our aim here is to construct an initial basis of simplified models representative of theories containing one or two LLPs. The simplified model approach is even more powerful for LLP signatures: the typically lower backgrounds for displaced signatures allow searches to be more inclusive than similar prompt signatures, thus enabling a single analysis to have sensitivity to a wide variety of possible models for LLP production and decay. Our efforts build on earlier work proposing simplified model programs for LLPs motivated by particular considerations such as supersymmetry (SUSY) or dark matter (DM) [9–11].

We organize our simplified models in terms of **LLP channels** characterized by a particular LLP production mode and a particular decay mode. Because the production and decay positions of LLPs are physically distinct (if indeed the LLP decays at all), it is possible to factorize and consider separately their production and decay[1]. For each LLP channel, the lifetime of the LLP is taken to be a free parameter. We emphasize that the LLP channel defined here is *not* the same as an experimental signature that manifests in the detector: a single channel can give rise to many different signatures depending on where (or whether) the LLP decays occur inside the detector, while a single experimental search for a particular signature could potentially cover many simplified model channels. In this document, we focus on the construction and simulation of a concrete basis of LLP simplified model channels; the mapping of existing searches into our basis of simplified models will appear in the LHC-LLP Community White Paper [6], along with the highest-priority gaps in current coverage and proposals for new searches.

[1] In addition to production and decay, a third consideration is the propagation of particles through the detector. While particles that do not possess color charge undergo straightforward 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 through the detector. The subtleties with colored LLPs will be discussed more in subsection 1.4.3.

The basis of simplified models presented here is a starting point, rather than a final statement: the present goal is to provide a set of simplified models that covers many of the best-motivated and simplest models containing singly- and doubly-produced LLPs. Simplified models by design do not include all of the specific details and subtle features that may be found in a given complete model. Therefore, the provided list is meant to be expandable to cover new or more refined models as the LLP search program develops. For instance, extending the simplified model framework to separately treat final states with heavy flavor particles is of high interest (in analogy with the prompt case [12–14]); see Section 1.6 for a discussion of this and other future opportunities. High-multiplicity signatures such as dark showers or emerging jets present different experimental and theoretical issues. Also, a broader set of simplified models may be needed to present the results of experimental searches and to allow ready application of experimental results to UV models of interest. Investigations of these topics are undertaken in the upcoming Community White Paper, and we refer the reader to that work [6].

1.1 Goals of the Present 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 theories of LLPs and the corresponding mapping between models and experimental signatures. We therefore want our simplified model space to:

1. Use a minimal set of models to cover a wide range of the best-motivated theories of LLPs;
2. Furnish a simple map between models and signatures to enable a clear assessment of existing search coverage and possible gaps;
3. Expand flexibly when needed to incorporate theories and signatures not yet proposed;
4. Provide a concrete Monte Carlo signal event generation framework;
5. Facilitate the re-interpretation of searches by supplying a sufficiently varied set of standard benchmark models[2] for which experimental efficiencies can be provided for validation purposes.

[2] Note that in general more benchmark models will be needed for enabling reliable re-interpretation than are strictly necessary for discovering a new particle, *i.e.*, it is important to consider both whether two simplified models share a common signature in a search, and also whether they look similar enough to have similar reconstruction efficiencies

Note that points #1 and #5 are somewhat in tension with one another: we wish to have a compact set of models that can be the subject of systematic study in terms of experimental signatures, but expressing experimental results in terms of only this set of simplified models may make it challenging to re-interpret experimental searches for UV models that are not precisely described by one of the simplified models. In this section, we prioritize having a minimal set of simplified models for the purpose of studying experimental coverages and generating new search ideas, while we defer a discussion of simplified models in the presentation and reinterpretation of search results to the report of the Reinterpretations and Presentation of Search Results Working Group in the full white paper [6].

In the following sections, we construct a proposal for a minimal basis of simplified models for events with one or two LLPs. We begin with a discussion of the theories that dominate the predictions for LLPs at the LHC, and identify a set of 'umbrella' models that yield LLPs in Section 1.2. We next identify the relevant (simplified) production and decay modes for LLPs in Section 1.3, emphasizing that each production mode has a characteristic set of predictions for the number and nature of *prompt* objects accompanying the LLP.

In Section 1.4 we combine these production and decay modes into our simplified model basis and highlight how different umbrella models naturally populate the various LLP channels. Section 1.5 and Appendix A presents a framework and instructions for how the best motivated simplified model channels can be simulated in Monte Carlo using a new model library that is currently under development.

1.2 *Existing Well-Motivated Theories for LLPs*

Here we provide a brief distillation of many of the best-motivated theories with LLPs into five over-arching categories, focusing in particular on those that give rise to single and double production of LLPs at colliders. We emphasize that each of these categories is a broad umbrella containing many different individual models containing LLPs; in many cases, the motivations and model particulars among theories within a particular category may be very different, but tend to predict similar types of LLPs.

- **Supersymmetry-like theories (SUSY).** This category contains models with multiple new particles carrying SM gauge charges and a variety of allowed cascade decays. LLPs can arise as a result of approximate symmetries (such as R-parity [15] or indeed SUSY itself in the case of gauge mediation [16]) or through a hierarchy of mass scales (such as highly off-shell intermediaries in split SUSY [17], or nearly-degenerate multiplets [1, 2], as in anomaly-mediated SUSY breaking [3]). Our terminology classifies any non-SUSY models with new SM gauge-charged particles, such as composite Higgs or extra-dimensional models, under the SUSY-like umbrella because of the prediction of new particles above the weak scale with SM charges. In this category, LLP production is typically dominated by SM gauge interactions, whether of the LLP itself or of a heavy parent particle that decays to LLPs.

- **Higgs-portal theories (Higgs).** In this category, LLPs couple predominantly to the SM-like Higgs boson. This possibility is well-motivated because the SM Higgs field provides one of the leading renormalizable portals for new gauge-singlet particles to couple the SM, and the experimental characterization of the Higgs boson leaves much scope for couplings of the Higgs to BSM physics [18, 19]. The most striking signatures here are exotic Higgs decays to low-mass particles [20] (as in many Hidden Valley scenarios [4, 5]), which can arise in models of neutral naturalness [21–23] and dark matter [24]. The Higgs is also special in that it comes with a rich set of associated production modes in addition to the dominant gluon fusion process, with vector-boson fusion (VBF) and Higgs-strahlung (VH) production modes allowing novel opportunities for triggering on and suppressing backgrounds to Higgs-portal LLP signatures.

- **Gauge-portal theories (ZP).** This category contains scenarios where new vector mediators can produce LLPs. These are similar to Higgs models, but where the vector mediator is predominantly produced from $q\bar{q}$-initiated final states without other associated objects. Examples include models where both SM fermions and LLPs carry a charge associated with a new Z' (for a review, see Ref. [25]), as well as either Abelian or non-Abelian "dark" photon or dark Z models [26] in which the couplings of new vector bosons to the SM are mediated by kinetic mixing. Scenarios with LLPs coupled to new gauge bosons are well motivated by theories of dark matter, particularly models with significant self-interactions [27–29] and/or sub-weak mass scales [30–34].
- **Dark-matter theories (DM):** Non-SUSY and hidden-sector DM scenarios are collected in this category, which encompasses models where the cosmological dark matter is produced as a final state in the collider process. The main feature distinguishing this category from the Higgs and gauge scenarios above is that dark matter, i.e., missing transverse momentum ($\not{E}_{\mathrm{T}}$), is a necessary and irreducible component of such signatures [4, 5, 10, 11, 35–40].
- **Heavy neutrino theories (RHν):** Models where new weak-scale states are responsible for SM neutrino mass generation [41–44] typically predict long-lived TeV-scale right-handed neutrinos that can be probed at the LHC [45, 46]. Characteristic features of models in this category are singly-produced LLPs via SM neutral and charged current interactions, and lepton-rich signatures.

In developing our simplified model framework below, we will construct maps between these UV model categories and the simplified model channels to illuminate some of the best-motivated combinations of production and decay modes for LLPs. This allows us in upcoming work to focus on the most interesting channels and assess their coverage in the work of the Experimental Coverage Working Group [6].

1.3 *The Simplified Model Building Blocks*

As discussed above, production and decay can largely be factorized in LLP searches. 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 umbrella categories of motivated theories.

1.3.1 *Production Modes*

Motivated by our over-arching UV frameworks, we can identify a minimal set of interesting production modes for LLPs. These production modes determine LLP signal yield both by giving an estimate for the overall LLP production cross section, and by determining the kinematic distribution of the LLP. Additionally, a given production mechanism will also make clear predictions for the number and type of *prompt* objects accompanying the LLP(s). These prompt accompanying objects (AOs) can be important for both triggering on events with LLPs and for background rejection, particularly when the LLP has a low mass.

- **Direct Pair Production (DPP):** Here the LLP is dominantly pair-produced non-resonantly from SM initial states. This is most straightforwardly obtained when the LLP is charged under a SM gauge interaction. In this case, an irreducible production cross section is then specified by the LLP gauge charge and mass. DPP can also occur in the presence of a (heavy) t-channel mediator (e.g., an initial quark-antiquark pair may exchange a virtual squark to pair produce bino-like neutralinos); in this case the production cross section is a free parameter.

- **Heavy parent (HP):** In this case the LLP can be produced in the decay of a heavy parent particle that is itself pair produced from the pp initial state. The production cross section is essentially a free parameter, and is indirectly specified by the gauge charges and masses of the heavy parent particles. Heavy parent production gives very different kinematics for the LLP than direct pair production production, and will often produce additional prompt accompanying objects in the rapid cascade decays of the parents.

- **Higgs (HIG):** The LLP is produced through its couplings to the SM-like Higgs boson. This case has an interesting interplay of possible production modes. The dominant production is via gluon fusion, which features no associated objects beyond initial state radiation (ISR); owing to its role in electroweak symmetry breaking, however, the Higgs has associated production modes (VBF, VH), each with its own characteristic features. The best prospects are for LLP masses below $m_h/2$, in which case the LLPs can be produced on-shell in SM-like Higgs boson decays. LLPs with heavier masses can still be produced via an off-shell SM-like Higgs, albeit at lower rates. The LLP can be pair produced or singly produced through the Higgs portal depending on the model, and may also be produced in conjunction with missing energy. The cross section (or, alternatively, the Higgs branching fraction into the LLP) is a free parameter of the model.

- **Heavy resonance (ZP):** Here 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 alternatively 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 (potentially in association

[3] The properties of the observed SM-like Higgs boson 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 production mode as opposed to the Higgs mode.

with missing transverse momentum). Here, ISR is the dominant source of accompanying prompt objects.

- **Charged current (CC):** In models with weak-scale right-handed neutrinos, the LLP can be produced in the leptonic decays of W/W'. Single production is favored. Prompt charged leptons from the charged-current interaction are typical prompt objects accompanying the LLP.

The generic presence of associated prompt objects (such as VBF or central jets, lepton, missing momentum, etc.) in many LLP production modes indicates that they may offer valuable handles to extend sensitivity for LLPs to otherwise hard-to-reach parts of parameter space.

1.3.2 Decay Modes

We now characterize a list of LLP decay modes. As we attempt to construct a minimal, manageable set of decay-mode building blocks, it is important to keep in mind that a given experimental search for LLPs can frequently be sensitive to a variety of possible LLP decay modes. As a result, it is not always necessary to divide LLP signatures into as many exclusive processes as might otherwise be needed for prompt signatures.

The fact that LLP searches can be sensitive to many decay modes is, in part, because LLPs that decay far from the collision point offer fewer avenues for particle identification, (*e.g.,* for an LLP decaying inside of the calorimeter, most decay products are reconstructed as missing energy, or an energy deposition in the calorimeter); consequently, particle identification criteria are typically relaxed in comparison to requirements on searches involving only a single primary vertex. Indeed, these "loose" collider objects can differ significantly from the corresponding "tight", prompt objects. Also, since backgrounds for LLP searches are often small, tight identification and/or reconstruction criteria typically found in exclusive prompt analyses are no longer needed to suppress backgrounds. For example, ATLAS has a displaced vertex search sensitive to dilepton and multitrack vertices that are relatively inclusive with respect to other objects originating from near the displaced vertex [47]. Similarly, CMS has an analysis sensitive to events with one each of a high-impact-parameter muon and electron without reconstructing a vertex or any other objects [48]. For all of these examples, the specific decay mode of the LLP may not be too important so long as certain objects (such as muons) are present or the decay occurs in a specific location, and so many LLP decay modes could be represented by only a few simplified models.

In some cases, however, the topology of a decay does matter. One potentially important factor that influences the sensitivity of a search to a particular model is whether the LLP decays into two SM objects vs. three, because the kinematics of multi-body decay are distinct from two-body decay and this may affect the acceptance of particular search strategies. An additional simplified model featuring a 3-body decay of the LLP may consequently be needed to span the space of signatures.

Below, we describe an irreducible set of decay modes that can be used to characterize LLP signatures. For each, we also provide an explicit example for how the decay would appear in a particular UV model. **We emphasize that the following decay modes are defined loosely with the understanding that their signatures will also be representative similar and/or related decay modes, for example $2j + \textit{invisible}$ can also be a proxy for $3j$ because searches for multi-body hadronic LLP decays can be sensitive to both.** It should also be noted that we are not recommending searches to be optimized to the exact, exclusive decay mode because that could suppress sensitivity to related but slightly more complicated decay chains.

- **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 $\gamma\gamma + X$ decays where the third object is not explicitly reconstructed. *Example: a singlino decaying to a singlet (which decays to $\gamma\gamma$) and a gravitino in Stealth SUSY [49].*

- **Single photon decays:** The LLP decays to γ + invisible (like in SUSY models). While the SUSY signal mandates a near-massless invisible particle, a more general signature allows for a heavy invisible particle, as can arise in theories of dark matter (ref). *Example: a bino decaying to photon plus gravitino in gauge-mediated models of SUSY breaking.*

- **Hadronic decays:** The LLP can decay into two jets (jj) (like in Higgs and gauge portal models, or RPV SUSY), jj + invisible (SUSY, dark matter, or neutrino models), or j + invisible (SUSY). Here, jet (j) means either a light-quark jet, gluon, or b-quark jet. *Example: a scalar LLP decaying to $b\bar{b}$ due to mixing with the SM Higgs boson, as in models of neutral naturalness*.

- **Semileptonic decays:** The LLP can decay into a lepton + 1 or 2 jets (like in SUSY or neutrino models). *Example: a right-handed neutrino decaying to a left-handed lepton and an on- or off-shell hadronically decaying W boson.*

- **Leptonic decays:** The LLP can decay into $\ell^+\ell^-$(+invisible), or $\ell^\pm$ + invisible (as in Higgs-portal, gauge-portal, SUSY, or neutrino models). ℓ may be any flavor of charged lepton, but the decays are lepton flavor-universal and (for $\ell^+\ell^-$ decays) flavor-conserving. *Example: a wino decaying to a neutralino and an on- or off-shell leptonic Z boson in SUSY.*

- **Flavored leptonic decays:** The LLP can decay into ℓ_α + invisible, $\ell_\alpha^+\ell_\beta^-$ or $\ell_\alpha^+\ell_\beta^-$ + invisible where flavors $\alpha \neq \beta$ (as in SUSY or neutrino models). *Example: a neutralino decaying to two leptons and a neutrino in R-parity-violating SUSY.*

In all cases, both the LLP mass and proper lifetime are free parameters. Therefore, stable particle searches are automatically included by taking any of the above decay modes and setting $c\tau \to \infty$. We emphasize that, depending on the location of the LLP within the detector, these decay modes may or may not be individually distinguishable: a displaced dijet decay will look very different from a displaced diphoton decay in the tracker, but nearly identical if the decay occurs in the calorimeter. We are identifying here promising channels, as distinct from detector signatures.

As an example of how the above listed decay modes cover the most important experimental signatures, we consider a scenario of an LLP decaying to top quarks. This scenario is very well-motivated (for instance, with long-lived stops on SUSY) and might appear to merit its own decay category of an LLP decaying to one or more top quark. However, the top quark immediately decays to final states that *are* covered in the above list, giving a semileptonic decay ($t \to b\ell^+\nu$) and a hadronic decay ($t \to bjj$), and so the above model-independent LLP decay modes cover this important scenario.

While it would be ideal to have separate experimental searches for each of the above decay modes (when distinguishable), it is rare for specific models to allow the LLP to decay in only one manner; instead, as in the LLP decay to top quark example above, a number of decay modes are typically allowed with corresponding predictions for the branching fractions. As another example, if a LLP couples to the SM via mixing with the SM Higgs boson, then the LLP decays via mass-proportional couplings giving rise to b- and τ-rich signatures. If, instead, the LLP decays through a kinetic mixing as in the case of dark photons or Z bosons, then the LLP can decay to any particle charged under the weak interactions, giving rise to a relatively large leptonic branching fraction in addition to hadronic decay modes. This allows some level of prioritization of decay modes based on motivated UV-complete models; for example, the Higgs-portal model prioritizes searches for heavy flavor quarks and leptons in LLP decay. Ultimately, however, it is desirable to retain independent sensitivity to each individual decay mode as much as possible. Indeed, for each decay mode listed above, models exist for which the given decay mode would be the discovery channel.

Invisible Final-State Particles: Where invisible particles appear as a product of LLP decay, additional model dependence arises from the unknown nature and mass of the invisible particle. The invisible particle could be a SM neutrino, DM, a lightest superparticle in SUSY, or another beyond-SM particle. The phenomenology depends strongly on the mass splitting, $\Delta \equiv M_{\mathrm{LLP}} - M_{\mathrm{invisible}}$. If $\Delta \ll M_{\mathrm{LLP}}$ (*i.e.*, $M_{\mathrm{LLP}} \sim M_{\mathrm{invisible}}$), the spectrum is squeezed and the decay products of the LLP are soft. This could, for instance, lead to signatures such as disappearing tracks or necessitate the use of ISR jets to reconstruct the LLP signature. If the mass splitting is large, $M_{\text{invisible}} \ll M_{\text{LLP}}$, then the signatures lose their dependence on the invisible particle mass.

We suggest three possible benchmarks: a squeezed spectrum with $\Delta \ll M_{\text{LLP}}$; a massless invisible state, $\Delta = M_{\text{LLP}}$ (which also includes the case where the invisible particle is a SM neutrino); and an intermediate splitting corresponding to a democratic mass hierarchy, $\Delta \approx M_{\text{LLP}}/2$.

1.4 *A Simplified Model Proposal*

In this section, we present a compact set of simplified model channels that, broadly speaking, covers the space of theoretical models in order to motivate new experimental searches. Such a minimal, compact set may not be optimal for reinterpretation of results (where variations on our listed production and decay modes may influence signal efficiencies and cross section sensitivities), but rather provides a convenient characterization of possible signals to ensure that no major discovery mode is missed. These models may therefore serve as a starting point for systematically understanding experimental coverage of LLP signatures and devising new searches, but may need to be extended in future for the purposes of facilitating reinterpretation. We undertake an in-depth discussion of these topics in the full White Paper [6].

We classify LLPs according to their SM gauge charges, as these dictate the dominant or allowed LLP production modes and can give rise to different signatures (for example, disappearing tracks and hadronized LLPs). We separately consider LLPs that are: (a) neutral, (b) electrically charged but color neutral, and (c) color charged.

We emphasize that in spite of the many simplified model channels proposed below, a small number of experimental LLP searches can have excellent coverage over a wide range of channels. Ultimately, the goal in future work will be to identify whether there are other searches that could have a similarly high impact on the space of simplified models, and identify where the gaps in coverage are.

1.4.1 *Neutral LLPs*

The simplified model channels for neutral LLPs are shown in Table 1.1. X indicates the LLP.

In our proposal, which we expect to be the first iteration of the simplified model framework, it is sufficient to consider as "jets" each of the following: $j = u, d, s, c, b, g$. It is worth commenting that b-quarks pose unique challenges and opportunities. Since b-quarks are themselves LLPs, they appear with an additional displacement relative to the LLP decay location. They also often give rise to soft muons in their decays, which could in principle lead to additional trigger or selection possibilities. However, these subtleties can be addressed in further refinements of the simplified models; we discuss this further in Section 1.6. Similarly, we consider e, μ, and τ to be included in the header of "leptons", with the proviso that searches should be designed where possible with sensitivity to each.

When multiple production modes are specified in one row of the table, this means that multiple especially well-motivated production channels give rise to similar signatures. Typically only one of these production modes will actually need to be included when developing a search, but we sometimes include multiple different production modes as individuals may variously prefer one over the other.

In each entry of the table, we indicate which umbrella category of well-motivated models (Section 1.2) can predict a particular (production) $\times$ (decay) mode. An asterisk (*) on the umbrella model indicates that $\not{E}_{\mathrm{T}}$ is required in the decay.

Production \ Decay	$\gamma\gamma(+\text{inv.})$	$\gamma + \text{inv.}$	$jj(+\text{inv.})$	$jj\ell$	$\ell^+\ell^-(+\text{inv.})$	$\ell^+_\alpha \ell^-_{\beta\neq\alpha}(+\text{inv.})$
DPP: sneutrino pair		SUSY	SUSY	SUSY	SUSY	SUSY
HP: squark pair, $\tilde{q} \to jX$ or gluino pair $\tilde{g} \to jjX$		SUSY	SUSY	SUSY	SUSY	SUSY
HP: slepton pair, $\tilde{\ell} \to \ell X$ or chargino pair, $\tilde{\chi} \to WX$		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*

Table 1.1: **Simplified model channels for neutral LLPs.** The LLP is indicated by X. Each row shows a separate production mode and each column shows a separate possible decay mode, and therefore every cell in the table corresponds to a different simplified model channel of (production)$\times$(decay). We have cross-referenced the UV models from Section 1.2 with cells in the table to show how the most common signatures of complete models populate the simplified model space. When two production modes are provided (with an "or"), either simplified model can be used to cover the same experimental signatures. Parentheses in the decay mode indicate the presence of additional $\not{E}_{\mathrm{T}}$ in some models. The asterisk (*) shows that the model definitively predicts missing momentum in the LLP decay.

We remind the reader that the production modes listed in Table 1.1 encompass also the associated production of characteristic prompt objects. For example, the Higgs production modes not only proceed through gluon fusion, but also through vector boson fusion and VH production, both of which result in associated prompt objects such as forward tagging jets, leptons, or missing momentum. All of the production modes listed in Table 1.1 could be accompanied by ISR jets that aid in triggering or identifying signal events. It is therefore important that searches are designed to exploit such associated prompt objects whenever they can improve signal sensitivity.

To demonstrate how to map full models onto the list of simplified models (and vice-versa), we consider a few concrete cases. For instance, if we consider a model of neutral naturalness where X is a long-lived scalar that decays via Higgs mixing (for instance, X could be the lightest quasi-stable glueball), then the process where the SM Higgs h decays to $h \to XX$, $X \to b\bar{b}$ would be covered with the Higgs production mechanism and a dijet decay. Entirely unrelated models, such as the case where X is a bino-like neutralino in $h \to XX$, $X \to jjj$ could be covered with the same simplified model because most hadronic LLP searches do not have exclusive requirements on jet multiplicity. Similarly, a hidden sector model with a dark photon, A', produced in $h \to A'A'$, $A' \to f\bar{f}$ would also give rise to the dijet signature when f is a quark, whereas it would populate the $\ell^+\ell^-$ column if f is a lepton. Finally, a scenario with multiple hidden sector states X_1 and X_2, in which X_2 is an LLP and X_1 is a stable, invisible particle, could give rise to signatures like $h \to X_2X_2$, $X_2 \to X_1 jj$ that would be covered by the same Higgs production, hadronic decay simplified model; however, we see how $\not{E}_T$ can easily appear in the final state, and that the LLP decay products may not all be hadronic. Therefore, the simplified models in Table 1.1 can cover an incredibly broad range of signatures, but only if searches are not overly optimized to particular features such as $\not{E}_T$ and resonant LLP reconstruction[4].

[4] This should not, of course, be interpreted as saying that searches shouldn't be done that exploit these features. Instead, our position is that experiments should bear in mind the range of topologies and models covered by each cell in Table 1.1 when designing searches, and that some more inclusive signal regions should be established where possible.

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

For an electrically charged LLP, we need to consider far fewer production modes because of the irreducible gauge production associated with the electric charge. We still consider a heavy parent scenario where the heavy parent has a QCD charge, as this could potentially dominate the production cross section. We summarize our proposals in Table 1.2.

Note that we lump all resonant production into the Z' simplified model. The reason is that the SM Higgs cannot decay into two on-shell charged particles due to the model-independent limits from LEP on charged particles masses, $M \gtrsim 75 - 90$ GeV (see, for example, Ref. [50]). 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 often result in cosmologically stable charged relics or necessitate different decay modes than those listed here. We note that there exist already dedicated searches for heavy quasi-stable charged particles with non-standard charges [51, 52]; 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.

Production \ Decay	$\ell + \text{inv.}$	$jj(+\text{inv.})$	$jj\ell$	$\ell\gamma$
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*		

Table 1.2: **Simplified model channels for electrically charged LLPs,** $|Q| = 1$**.** The LLP is indicated by X. Each row shows a separate production mode and each column shows a separate possible decay mode, and therefore every cell in the table corresponds to a different simplified model channel of (production)×(decay). We have cross-referenced the "well-motivated" UV models from Section 1.2 with cells in the table to show how the most common signatures complete models can be linked to the simplified model space. When two production modes are provided (with an "or"), both production simplified models can be used to cover the same experimental signatures. Parentheses in the decay mode indicate the presence of additional $\not{E}_T$ in some models. The asterisk (*) shows that the model definitively predicts missing momentum in the LLP decay.

1.4.3 *LLPs with Color Charge*

LLPs with charges under the strong interactions are more constrained than even electrically charged LLPs. Because of the non-Abelian nature of the strong interactions, the gauge pair production cross section of the LLP is specified by the LLP mass and its representation under the color group, $SU(3)_C$.

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

Table 1.3: **Simplified model channels for LLPs with color charge.** The LLP is indicated by X. Each row shows a separate production mode and each column shows a separate possible decay mode, and therefore every cell in the table corresponds to a different simplified model channel of (production)×(decay). We have cross-referenced the "well-motivated" UV models from Section 1.2 with cells in the table to show how the most common signatures complete models can be linked to the simplified models. When two production modes are provided (with an "or"), both production simplified models can be used to cover the same experimental signatures. Parentheses in the decay mode indicate the presence of additional $\not{E}_T$ in some models.

A complication of the QCD-charged LLP is that the LLP hadronizes prior to its decay. We comment on a few aspects of hadronization for LLPs that are charged under the standard model $SU(3)_C$ gauge group. First, the modeling of hadronization is directly related to many properties of the long-lived parton, such as electric charge, flavor, spin, etc. Many LLP searches at the LHC are particularly sensitive to the electric charge of the long-lived BSM hadrons (referred to henceforth as R-hadrons in keeping with the standard SUSY nomenclature). For instance, only the charged R-hadrons can be found in heavy stable charged particle search, and for some vertex reconstruction based searches the LLP is either required to be neutral or has a higher efficiency in the absence of a prompt track stub associated with the LLP. Event generators such as Pythia8 [53] has routines to simulate R-hadronization and is believed to provide a reasonable estimate of these distributions. For example, Pythia8 estimates that the neutral R-hadron fraction from a gluino (color-octet fermion, $\tilde{g}$) is approximately 54%, while the neutral R-hadron fraction for a stop (scalar top partner) is estimated to be 44% [9].

R-hadrons that interact with detector materials can result in higher energy losses, dE/dx, than conventional hadrons and even in a change of electric charge. For instance, some estimates [54, 55] suggest that heavy, meta-stable gluinos would initially mostly form mesons, e.g., $(u\tilde{g}\bar{d})$, but drop to the lower-energy, neutral, singlet baryon $\tilde{\Lambda} = (\tilde{g}uds)$ state when interacting with the protons and neutrons within the calorimeters. To take into account the possibility of the charge being stripped off when passing through the detectors, the experimental searches for heavy stable charged particles includes a tracker-only signal region, where activity in the muon system is not used [56, 57]. Within GEANT4 [58] there is a modeling of how an R-hadron propagates through the detector material [59].

If the R-hadron decays, especially via a multi-body decay, it can be more accurate to decay the LLP using the full matrix element with event generators such as Madgraph5 [60, 61]. In this case, the Pythia8 R-hadronization routine cannot be used, as the BSM colored particle is already decayed and its daughters are color connected to other parts of the event. As the corrections from these color connections provide $\mathcal{O}(\Lambda_{QCD})$ changes to the momentum of the final state particles, it is typically reasonable to ignore effects of color connection unless the kinetic energy transferred to the daughters in the LLP rest frame is not large relative to Λ_{QCD}. For example, in the case of compressed decays, a careful treatment of the hadronization of the displaced decay products, which thus far has not been performed in the literature, would be needed.

1.5 *Proposal for a Simplified Model Library*

The simplified models outlined in the above sections provide a common language for theorists and experimentalists to study the sensitivity of existing searches, propose new search ideas, and interpret results in terms of UV models. Each of these activities demands a simple framework for the simulation of signal events that can be used to evaluate signal efficiencies of different search strategies and map these back onto model parameters. Requiring individual users to create their own MC models for each simplified model is impractical, redundant, and invites the introduction of errors into the analysis process.

In this section, we propose and provide a draft version of a *simplified model library* consisting of model files and Monte Carlo (MC) generator cards that can be used to generate events for various simplified models in a straightforward fashion. Because each experiment uses slightly different MC generators and settings, this allows each collaboration (as well as theorists) to generate events for each simplified model based on the provided files. Depending on how the LLP program expands and develops over the next few years, it may become expedient to go a step further and add to the simplified model library sets of events in a standard format (such as the Les Houches format) that can be directly fed into parton-shower and detector-simulation programs; given the factorization of production and decay of LLPs that is valid for all but QCD-charged LLPs, this could involve two mini-libraries: a set of production events for LLPs, a set of decays for LLPs, along with a protocol for "stitching" the events together.

The current version of the library can be found here: **[provide link]**. In Appendix A we also provide tables that list how to simulate each LLP simplified model channels with one of the specified base models.

We provide model files in the popular Universal Feynrules Output (UFO) format [62], which is designed to interface easily with parton-level simulation programs such as `MadGraph5_aMC@NLO` [61]. The goal is to cover as many of the simplified models of Section 1.3 with as few UFO models as possible; this limits the amount of upkeep needed to maintain the library and develops familiarity with the few UFO models needed to simulate the LLP simplified models. We then give specific instructions for how to simulate each simplified LLP channel using the UFO models. **NOTE: as this document is still in draft form, the library is not yet complete. If you need a simplified model that has not yet been filled in, or would like to contribute to completion of the library, please contact the organizers listed in the simplified model repository.**

1.5.1 *Base Models for Library*

In order to reproduce the simplified model channels of Section 1.3, we need a collection of models that:

- Includes additional gauge bosons and scalars to allow vector- and scalar-portal production of LLPs;
- Includes new gauge-charged fermions and scalars to cover direct and simple cascade production modes of LLPs;
- Includes a right-handed-neutrino-like state with couplings to SM neutrinos and leptons;
- Allows for the decays of the LLP particle through all of the decay modes listed in Section 1.3, either through renormalizable or higher-dimensional couplings.

Fortunately, an extensive set of UFO models is already available for simulating the production of beyond-SM particles. We note that extensions or generalizations of only four already-available UFO models are needed at the present time:

1. **The Minimally Supersymmetric SM (MSSM):** the use of this model is motivated by and allows for the simulation of SUSY-like theories. The model contains a whole host of new particles with various gauge charges and spins. Therefore, an MSSM-based model allows for the simulation of many of the simplified model channels. In particular, we note that existing UFO variants of the MSSM that include gauge-mediated supersymmetry breaking (GMSB) couplings (including decays to light gravitinos) and R-parity violation (to allow for the decay of otherwise stable lightest SUSY particles) already cover most of the SUSY-motivated LLP scenarios.

2. **The Hidden Abelian Higgs Model (HAHM):** this UFO model contains new scalars and gauge bosons and so can be used to simulate both Higgs-portal and gauge-portal (ZP) theories. The model consists of the SM supplemented by a "hidden sector" consisting of a new $\mathrm{U}(1)$ gauge boson and corresponding Higgs field. The physical gauge and Higgs bosons couple to the SM via kinetic and mass mixing, respectively, and can be easily supplemented with new matter fields. The HAHM allows for straightforward simulation of Higgs-portal production of LLPs, as well as Z' models and many hidden sector scenarios. The UFO implementation is from Ref. [63].

3. **The Left-Right Symmetric Model (LR):** this UFO model is best for simulating UV theories with right-handed neutrinos (RHν). The UFO model supplements the SM by an additional $\mathrm{SU}(2)_\mathrm{R}$ symmetry, which gives additional charged and neutral gauge bosons. The model also contains a right-handed neutrino which is the typical LLP candidate, which can be produced via SM W, Z, or the new gauge bosons.

4. **Dark Matter Simplified Models (DM-SM)**: these UFO models are best for simulating UV theories in the dark-matter class (DM). These UFO models have been created by the LHC-DM working group [8]. They typically consist of a new, beyond-SM mediator (such as a scalar of a Z') coupled to invisible DM particles. With minimal modification, the would-be-DM particles can be made unstable and decay at a LLP. These models are particularly good for simulating LLP production via a heavy resonance (ZP), and can also simulate continuum production of LLPs in the limit where the mediator is taken to be light and off-shell. **Work on modifying the DM-simplified models is ongoing; volunteers to assist with this task are welcome!**

A detailed list of processes that can be used to simulate each simplified model channel is provided in Appendix A. Because the library is only meant to be used to simulate events for determining acceptances, the signal cross section is not important and so, for example, SM gauge interactions can be used as proxies for much weaker exotic interactions. Similarly, the spins of the particles are generally of subdominant importance: replacing the direct production of a fermion with the direct production of a scalar will not fundamentally alter the signature. As long as results are expressed in terms of sensitivity to cross sections and not couplings, the results can be qualitatively (and in some cases, quantitatively) applied to any similar production mode regardless of spin. However, we caution the reader that changing the spin of the LLP (or its parent) can change the angular distribution, and since in some cases LLP searches are typically more sensitive to aspects of event geometry than prompt searches, the second-order effects of spin could have more of an effect than for prompt simplified models.

1.6 Future Opportunities and Challenges

We conclude our discussion of simplified models by returning to topics that we glossed over in an attempt to provide a compact set of models that cover what is currently the most motivated and interesting theory space. However, this is only the first step of a simplified models program that is comprehensive in terms of generating LHC signatures and also allowing straightforward reinterpretation of experimental results for UV models. The framework we have developed with separate, modular components for LLP production and decay is amenable to expansion, and we encourage members of the theory and experimental communities to continue to do so over the coming years to ensure maximal utility of the simplified models framework.

One significant simplification we have undertaken in our framework is to define a "jet" as any of $j = u, c, d, s, b, g$. In reality, different partons give rise to different signatures, especially when one of the "jets" is a heavy-flavor quark. $b-$ and $c-$jets have some useful distinguishing features, such as the fact that the underlying heavy-flavor meson decays at a displaced vertex and that there are often associated soft leptons resulting from meson decays. In particular, it is possible that the soft muons associated with B-meson decays could be used to enhance trigger and reconstruction prospects for LLPs decaying to b-jets. However, heavy quarks also constitute one of the major backgrounds for LLP searches, and so LLPs decaying to b- and c-jets may necessitate dedicated treatment in future. Similarly, LLP decays to τ leptons may merit further specialized study.

Another property of the current framework is that it is restricted to LLP signatures of low multiplicities. By "low multiplicity", we mean collider signatures with one or two LLPs. These models are also suitable for scenarios with three or four LLPs per event, since the LLP signatures are typically extremely rare and so only one or two typically need to be selected to greatly suppress backgrounds. As the multiplicity grows, however, the simplified model space we have presented requires modification. This is both because the individual LLPs grow softer, making them harder to reconstruct on an individual level, and they become less separated in the detector, which makes isolation and identification of signal a challenge. In extreme cases, signals can even mimic pile-up [64]. High multiplicity signatures therefore require dedicated modeling, and we defer the study of these signatures to the full White Paper [6].

Finally, we conclude by noting that simplified models are built to provide a general framework to cover a broad swath of models. Any simplified model set-up, however, cannot cover every single UV model without becoming as complex as the UV model space itself. There will always be very well-motivated models that predict specific signatures that are challenging to incorporate into the simplified model framework outlined here: experimental searches for these signatures should still be done where possible, but we encourage theorists and experimentalists alike to think carefully about how to design such searches so as to retain maximal sensitivity to simplified models that may give rise to similar signatures.

A

Appendix: Details of Simplified Model Library

A.1 Instructions for the Simplified Model Library

We refer here extensively to the simplified models in Tables 1.1-1.3. Because it is already quite an extensive task to come up with simplified models for so many (production)×(decay) modes, we for now restrict ourselves to the "filled" entries in Tables 1.1-1.3. If you are interested in performing an experimental search or developing a simplified model library entry for one of the "unfilled" entries, please contact the conveners of the simplified model library found at the library link: **[provide link]**.

Note that in all of the simplified model proposals below, any particles *not* present in the production or decay chain should have their masses set to a very large value ($M \gtrsim 5$ TeV) to ensure they are sufficiently decoupled from direct production at the LHC.

A.1.1 Neutral LLPs

The instructions for simulating the simplified model channels for neutral LLPs are given as follows: Double Pair Production (DPP) in Table A.1, Heavy Parent (HP, QCD-charged parent) in Table A.2.

We then proceed to the Higgs (HIG) production modes in Tables A.4-A.6.

For the Z' (ZP) production modes, we use a set of simplified models described in Tables A.7-A.9. A relatively simple model file is provided for each table. In addition, a more adjustable 'advanced' model file is provided which includes all ZP production and decay modes, and allows for features such as individual couplings to each generation of quarks. This comes at the cost of a greatly increased set of parameters, and the possibility of including unwanted diagrams if the process is not carefully specified. A simple python script is provided to generate the processes and set unwanted parameters to zero for those users wishing to use the advanced model files.

Finally, we provide instructions for the charged-current (CC) production modes in Table A.10. This production mode is most easily simulated using a left-right symmetric model or other right-handed-neutrino model.

Decay Mode	Simplified Model Library Process
$X \to \gamma$+inv.	MSSM+GMSB. LLP is a bino ($\tilde{\chi}^0$) produced due to $pp \to \tilde{\chi}^0\tilde{\chi}^0$ via t-channel squark exchange ($M_{\tilde{q}} > 5$ TeV). Bino decays to photon + gravitino, $\tilde{\chi}^0 \to \gamma + \tilde{G}$.
$X \to jj$	MSSM+RPV. LLP is sneutrino LSP ($\tilde{\nu}$) that is pair-produced via weak gauge interactions. $\tilde{\nu} \to q\bar{q}$ via the QLd^c operator.
$X \to jj$+inv.	MSSM. LLP is second neutralino (wino) LSP $\tilde{\chi}_2^0$ that is pair-produced via weak gauge interactions. $\tilde{\chi}_2^0 \to q\bar{q}\tilde{\chi}_1^0$ via an off-shell sfermion, and the $\tilde{\chi}_1^0$ is invisible with arbitrary mass.
$X \to jjj$	MSSM+RPV. While this is partially covered by $jj+$ inv. in the case where the additional quark is not reconstructed, we include it here for completeness. LLP is wino LSP ($\tilde{\chi}^0$) that is pair-produced via weak interactions. $\tilde{\chi}^0 \to q_\alpha q_\alpha q_\beta$ via an off-shell sfermion and the $u^c_\alpha d^c_\alpha d^c_\beta$ operator.
$X \to jj\ell_\alpha$	MSSM+RPV. LLP is wino LSP ($\tilde{\chi}^0$) that is pair-produced via weak interactions. $\tilde{\chi}^0 \to \ell_\alpha q\bar{q}$ via an off-shell sfermion and $L_\alpha Q d^c$ operator.
$X \to \ell^+_\alpha \ell^-_\alpha$	MSSM+RPV. LLP is sneutrino $\tilde{\nu}_\beta$ of flavor β that is pair-produced via weak interactions. $\nu_\beta \to \ell^+_\alpha \ell^-_\alpha$ via the $L_\alpha L_\beta E^c_\alpha$ operator.
$X \to \ell^+_\alpha \ell^-_\alpha$(+inv.)	MSSM. LLP is second neutralino $\tilde{\chi}_2^0$ that is pair-produced via weak interactions. $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 \ell^+_\alpha \ell^-_\alpha$ via an off-shell slepton.
$X \to \ell^+_\alpha \ell^-_\beta$(+inv.)	MSSM+RPV. LLP is sneutrino $\tilde{\nu}_\alpha$ of flavor α that is pair-produced via weak interactions. $\nu_\alpha \to \ell^+_\alpha \ell^-_\beta$ via the $L_\alpha L_\beta E^c_\alpha$ operator. An additional massless invisible final state can be obtained with a wino LLP decaying into $\ell^+_\alpha \ell^-_\beta \nu_\alpha$ through the same operator and an off-shell slepton. The massive invisible case is less motivated for $\alpha \neq \beta$.

Table A.1: Simplified model library process proposals for Double Pair Production (DPP) production mode. Where a "wino" LSP is specified, an admixture of Higgsino is required to lead to direct pair production of the neutral wino component. As an alternative, one could have $pp \to \tilde{\chi}^\pm\tilde{\chi}^0$, $\tilde{\chi}^\pm \to W^{\pm *}\tilde{\chi}^0$ promptly, and take the $\tilde{\chi}^\pm$ to be degenerate with $\tilde{\chi}^0$ such that the additional charged decay products are essentially unobservable.

Decay Mode	Simplified Model Library Process
$X \to \gamma$+inv.	MSSM+GMSB. LLP is a bino $(\tilde{\chi})$ produced via $pp \to \tilde{q}\tilde{q}^*$, $\tilde{q} \to \tilde{\chi} + q$. Bino decays to photon+ gravitino, $\tilde{\chi} \to \gamma + \tilde{G}$.
$X \to jj$	MSSM+RPV. LLP is squark LSP $\tilde{q}$ that is produced via $pp \to \tilde{g}\tilde{g}$, $\tilde{g} \to q\tilde{q}$. Then, $\tilde{q} \to qq$ via an RPV coupling.
$X \to jj$+inv.	MSSM. LLP is wino LSP $\tilde{\chi}_2^0$ that is produced via $pp \to \tilde{q}\tilde{q}^*$, $\tilde{q} \to q\tilde{\chi}_2^0$. Then, $\tilde{\chi}_2^0 \to q\bar{q}\tilde{\chi}_1^0$ via an off-shell quark.
$X \to jjj$	MSSM+RPV. LLP is bino LSP $\tilde{\chi}$ that is produced via $pp \to \tilde{q}\tilde{q}^*$, $\tilde{q} \to q\tilde{\chi}$. Then, $\tilde{\chi} \to q_\alpha q_\alpha q_\beta$ via the $u^c_\alpha d^c_\alpha d^c_\beta$ operator.
$X \to jj\ell_\alpha$	MSSM+RPV. LLP is bino LSP $(\tilde{\chi})$ that is produced via $pp \to \tilde{q}\tilde{q}^*$, $\tilde{q} \to q\tilde{\chi}$. $\tilde{\chi} \to \ell_\alpha q\bar{q}$ via an off-shell sfermion and $L_\alpha Q d^c$ operator.
$X \to \ell_\alpha^+\ell_\alpha^-$ or $\ell_\alpha^+\ell_\beta^-$	MSSM+RPV. LLP is sneutrino $(\tilde{\nu})$ that is produced via $pp \to \tilde{g}\tilde{g}$, $\tilde{g} \to jj\tilde{\chi}$, $\tilde{\chi} \to \tilde{\nu}\bar{\nu}$. Then, $\nu_\alpha \to \ell_\alpha^+\ell_\beta^-$ or $\nu_\beta \to \ell_\alpha^+\ell_\alpha^-$ via the $L_\alpha L_\beta E^c_\alpha$ operator.
$X \to \ell_\alpha^+\ell_\alpha^-$+inv.	MSSM. LLP is second neutralino $(\tilde{\chi}_2^0)$ that is produced via $pp \to \tilde{q}\tilde{q}^*$, $\tilde{q} \to q\tilde{\chi}_2^0$. Then, $\tilde{\chi}_2^0 \to \ell_\alpha^+\ell_\alpha^-\tilde{\chi}_1^0$.
$X \to \ell_\alpha^+\ell_\beta^-$+inv.	MSSM+RPV. LLP is bino $(\tilde{\chi}^0)$ that is produced via $pp \to \tilde{q}\tilde{q}^*$, $\tilde{q} \to q\tilde{\chi}^0$. Then, $\tilde{\chi}^0 \to \ell_\alpha^+\ell_\beta^-\nu_\alpha$ via $L_\alpha L_\beta E^c_\alpha$ operator and off-shell slepton (massless invisible only).

Table A.2: Simplified model library process proposals for Heavy Parent (HP) production mode where the parent particle carries a QCD charge. In most of the above cases, a squark parent can be replaced by a gluino parent with an additional jet in its decay.

Decay Mode	Simplified Model Library Process
$X \to \gamma$+inv.	MSSM+GMSB. LLP is a bino $(\tilde{\chi}^0)$ produced via $pp \to \tilde{\chi}^+\tilde{\chi}^-$, $\tilde{\chi}^+ \to W^+\tilde{\chi}^0$ ($\tilde{\chi}^+$ is a wino). Bino decays to photon+ gravitino, $\tilde{\chi} \to \gamma + \tilde{G}$.
$X \to jj$	MSSM+RPV. LLP is sneutrino LSP $(\tilde{\nu})$ produced via $pp \to \tilde{\chi}^+\tilde{\chi}^-$, $\tilde{\chi}^+ \to \tilde{\nu}\ell^+$. The sneutrino decays via $\tilde{\nu} \to q\bar{q}$ via the $u^c_\alpha d^c_\alpha d^c_\beta$ operator.
$X \to jj$+inv.	MSSM. LLP is wino $\tilde{\chi}_2^0$ that is produced via $pp \to \tilde{\chi}^+\tilde{\chi}^-$, $\tilde{\chi}_2^+ \to W^+\tilde{\chi}_2^0$. Then, $\tilde{\chi}_2^0 \to q\bar{q}\tilde{\chi}_1^0$ via an off-shell squark.
$X \to jjj$	MSSM+RPV. LLP is bino LSP $(\tilde{\chi}^0)$ that is produced via $pp \to \tilde{\chi}^+\tilde{\chi}^-$, $\tilde{\chi}^+ \to W^+\tilde{\chi}^0$. Then, $\tilde{\chi}^0 \to qqq$ via an off-shell sfermion and the $u^c d^c d^c$ operator.
$X \to jj\ell_\alpha$	MSSM+RPV. LLP is bino LSP $(\tilde{\chi}^0)$ that is produced via $pp \to \tilde{\chi}^+\tilde{\chi}^-$, $\tilde{\chi}^+ \to W^+\tilde{\chi}^0$. Then, $\tilde{\chi}^0 \to qq'\ell_\alpha$ via an off-shell sfermion and the $Qd^c L_\alpha$ operator.
$X \to \ell_\alpha^+\ell_\alpha^-$ or $\ell_\alpha^+\ell_\beta^-$	MSSM+RPV. LLP is sneutrino $(\tilde{\nu})$ that is produced via $pp \to \tilde{\chi}^+\tilde{\chi}^-$, $\tilde{\chi}^+ \to \ell^+\tilde{\nu}$. Then, $\nu_\alpha \to \ell_\alpha^+\ell_\beta^-$ or $\nu_\beta \to \ell_\alpha^+\ell_\alpha^-$ via the $L_\alpha L_\beta E^c_\alpha$ operator.
$X \to \ell_\alpha^+\ell_\alpha^-$+inv.	MSSM. LLP is second neutralino $(\tilde{\chi}_2^0)$ that is produced via $pp \to \tilde{\chi}^+\tilde{\chi}^-$, $\tilde{\chi}^+ \to W^+\tilde{\chi}_2^0$. Then, $\tilde{\chi}_2^0 \to \ell_\alpha^+\ell_\alpha^-\tilde{\chi}_1^0$ via an off-shell slepton and the $L_\alpha L_\beta E^c_\alpha$ operator.
$X \to \ell_\alpha^+\ell_\beta^-$+inv.	MSSM+RPV. LLP is bino $(\tilde{\chi}^0)$ that is produced via $pp \to \tilde{\chi}^+\tilde{\chi}^-$, $\tilde{\chi}^+ \to W^+\tilde{\chi}^0$. Then, $\tilde{\chi}^0 \to \ell_\alpha^+\ell_\alpha^-\nu_\beta$ or $\tilde{\chi}^0 \to \ell_\alpha^+\ell_\beta^-\nu_\alpha$ via an off-shell slepton and the $L_\alpha L_\beta E^c_\alpha$ operator.

Table A.3: Simplified model library process proposals for Heavy Parent (HP) production mode where the parent particle carries electroweak charge.

Decay Mode	Simplified Model Library Process
$X \to \gamma\gamma$	HAHM. LLP is the singlet scalar Higgs (h_D) produced via $pp \to h$, $h \to h_\mathrm{D} h_\mathrm{D}$. Then, $h_\mathrm{D} \to \gamma\gamma$ via mixing with the SM Higgs.
$X \to \gamma\gamma$+inv.	MSSM. LLP is the second neutralino ($\tilde{\chi}_2^0$) produced via $pp \to h$, $h \to \tilde{\chi}_2^0 \tilde{\chi}_2^0$. Then, $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 \gamma\gamma$ via an off-shell SM Higgs.
$X \to jj$	HAHM. LLP is singlet scalar Higgs (h_D) produced via $pp \to h$, $h \to h_\mathrm{D} h_\mathrm{D}$. Then, $h_\mathrm{D} \to jj$ via mixing with the SM Higgs.
$X \to jj$+inv.	MSSM. LLP is wino $\tilde{\chi}_2^0$ that is produced via $pp \to h$, $h \to \tilde{\chi}_2^0 \tilde{\chi}_2^0$. Then, $\tilde{\chi}_2^0 \to jj\tilde{\chi}_1^0$ via an off-shell squark.
$X \to \ell_\alpha^+ \ell_\alpha^-$	HAHM. LLP is hidden gauge boson (Z_D) that is produced via $pp \to h$, $h \to Z_\mathrm{D} Z_\mathrm{D}$. Then, $Z_\mathrm{D} \to \ell_\alpha^+ \ell_\alpha^-$ via mixing with the SM gauge bosons.
$X \to \ell_\alpha^+ \ell_\alpha^-$+inv.	MSSM. LLP is the second neutralino ($\tilde{\chi}_2^0$) produced via $pp \to h$, $h \to \tilde{\chi}_2^0 \tilde{\chi}_2^0$. Then, $\tilde{\chi}_2^0 \to \ell_\alpha^+ \ell_\alpha^- \tilde{\chi}_1^0$ via an off-shell slepton.

Table A.4: Simplified model library process proposals for Higgs (HIG) production mode where the Higgs decays to two LLPs. These modes are particularly important because they can come in association with forward jets (VBF) or leptons and $\not{E}_\mathrm{T}$ (VH). Note that, in cases of $M_X > M_h/2$, the same production modes could still occur if the Higgs is taken to be off-shell.

Decay Mode	Simplified Model Library Process
$X \to \gamma\gamma$	(N)MSSM. LLP is a pseudoscalar or singlino (a) produced via $pp \to h$, $h \to \tilde{\chi}_2^0 \tilde{\chi}_2^0$, $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 a$. Finally, $a \to \gamma\gamma$.
$X \to \gamma\gamma$+inv.	MSSM. LLP is the second neutralino ($\tilde{\chi}_2^0$) produced via $pp \to h$, $h \to \tilde{\nu}\tilde{\nu}^*$, $\tilde{\nu} \to \tilde{\chi}_2^0 \nu$. Then, $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 \gamma\gamma$ via an off-shell SM Higgs.
$X \to jj$	MSSM+RPV. LLP is a sneutrino ($\tilde{\nu}$) produced via $pp \to h$, $h \to \tilde{\chi}_1^0 \tilde{\chi}_1^0$, $\tilde{\chi}_1^0 \to \tilde{\nu}\bar{\nu}$. Then, $\tilde{\nu} \to jj$ via the RPV operator LQd^c.
$X \to jj$+inv.	MSSM. LLP is the second neutralino ($\tilde{\chi}_2^0$) that is produced via $pp \to h$, $h \to \tilde{\nu}\tilde{\nu}^*$, $\tilde{\nu} \to \nu\tilde{\chi}_2^0$. Then, $\tilde{\chi}_2^0 \to jj\tilde{\chi}_1^0$ via an off-shell squark.
$X \to \ell_\alpha^+ \ell_\alpha^-$	MSSM+RPV. LLP is a sneutrino ($\tilde{\nu}_\beta$) produced via $pp \to h$, $h \to \tilde{\chi}_1^0 \tilde{\chi}_1^0$, $\tilde{\chi}_1^0 \to \tilde{\nu}_\beta \bar{\nu}_\beta$. Then, $\tilde{\nu}_\beta \to \ell_\alpha^+ \ell_\alpha^-$ via the RPV operator $L_\alpha L_\beta E_\alpha^c$.
$X \to \ell_\alpha^+ \ell_\alpha^-$+inv.	MSSM. LLP is the second neutralino ($\tilde{\chi}_2^0$) that is produced via $pp \to h$, $h \to \tilde{\nu}\tilde{\nu}^*$, $\tilde{\nu} \to \nu\tilde{\chi}_2^0$. Then, $\tilde{\chi}_2^0 \to \ell_\alpha^+ \ell_\alpha^- \tilde{\chi}_1^0$ via an off-shell slepton.

Table A.5: Simplified model library process proposals for Higgs (HIG) production mode where the Higgs decays to two LLPs plus invisible. These modes are particularly important because they can come in association with forward jets (VBF) or leptons and $\not{E}_\mathrm{T}$ (VH). Note that, in cases of $M_X > M_h/2$, the same production modes could still occur if the Higgs is taken to be off-shell.

Decay Mode	Simplified Model Library Process
$X \to \gamma\gamma$+inv.	MSSM. LLP is the second neutralino ($\tilde{\chi}_2^0$) produced via $pp \to h$, $h \to \tilde{\chi}_2^0 \tilde{\chi}_1^0$. Then, $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 \gamma\gamma$ via an off-shell SM Higgs.
$X \to jj$+inv.	MSSM. LLP is the second neutralino ($\tilde{\chi}_2^0$) that is produced via $pp \to h$, $h \to \tilde{\chi}_2^0 \tilde{\chi}_1^0$. Then, $\tilde{\chi}_2^0 \to jj\tilde{\chi}_1^0$ via an off-shell squark.
$X \to \ell_\alpha^+ \ell_\alpha^-$+inv.	MSSM. LLP is the second neutralino ($\tilde{\chi}_2^0$) that is produced via $pp \to h$, $h \to \tilde{\chi}_2^0 \tilde{\chi}_1^0$. Then, $\tilde{\chi}_2^0 \to \ell_\alpha^+ \ell_\alpha^- \tilde{\chi}_1^0$ via an off-shell slepton.

Table A.6: Simplified model library process proposals for Higgs (HIG) production mode where the Higgs decays to single LLP plus invisible. These modes are particularly important because they can come in association with forward jets (VBF) or leptons and $\not{E}_\mathrm{T}$ (VH). Note that, in cases of $M_X > M_h/2$, the same production modes could still occur if the Higgs is taken to be off-shell.

Decay Mode	Simplified Model Library Process
$X \to \gamma\gamma$	LLP is scalar s_2, produced via $pp \to Z' \to s_2 s_2$, then $s_2 \to \gamma\gamma$.
$X \to \gamma\gamma$+inv.	LLP is fermion x_2, produced via $pp \to Z' \to x_2 x_2$, then $x_2 \to \gamma\gamma x_1$.
$X \to jj$	LLP is scalar s_2, produced via $pp \to Z' \to s_2 s_2$, then $s_2 \to q\bar{q}$. $s_2 \to \ell_\alpha^+ \ell_\alpha^-$ couplings are proportional to SM Yukawa couplings.
$X \to jj$+inv.	LLP is fermion x_2, produced via $pp \to Z' \to x_2 x_2$, then $x_2 \to q\bar{q} x_1$.
$X \to \ell_\alpha^+ \ell_\alpha^-$	LLP is scalar s_2, produced via $pp \to Z' \to s_2 s_2$, then $s_2 \to \ell_\alpha^+ \ell_\alpha^-$. $s_2 \to \ell_\alpha^+ \ell_\alpha^-$ couplings are proportional to SM Yukawa couplings.
$X \to \ell_\alpha^+ \ell_\alpha^-$+inv.	LLP is fermion x_2, produced via $pp \to Z' \to x_2 x_2$, then $x_2 \to \ell_\alpha^+ \ell_\alpha^- x_1$.

Table A.7: Simplified model library process proposals for Z' (ZP) production mode where the Z' decays to two LLPs. For this section, we use a DM simplified model, where fermion x_2 is the LLP for $X \to SM+$ inv modes and scalar s_2 is the LLP for $X \to SM$ modes. The same models can also be used for off-shell Z' where $M_X > M_{Z'}/2$. The model file includes all processes in the table; the undesired couplings can be set to zero and energy scales to be very large.

Decay Mode	Simplified Model Library Process
$X \to \gamma\gamma$	LLP is scalar s_2, produced via $pp \to Z' \to x_3 x_3, x_3 \to s_2 x_1$, then $s_2 \to \gamma\gamma$.
$X \to \gamma\gamma$+inv.	LLP is fermion x_2, produced via $pp \to Z' \to x_3 x_3, x_3 \to x_2 s_1$, then $x_2 \to \gamma\gamma x_1$.
$X \to jj$	LLP is scalar s_2, produced via $pp \to Z' \to x_3 x_3, x_3 \to s_2 x_1$, then $s_2 \to q\bar{q}$. $s_2 \to \ell_\alpha^+ \ell_\alpha^-$ couplings are proportional to SM Yukawa couplings.
$X \to jj$+inv.	LLP is fermion x_2, produced via $pp \to Z' \to x_3 x_3, x_3 \to x_2 s_1$, then $x_2 \to q\bar{q} x_1$.
$X \to \ell_\alpha^+ \ell_\alpha^-$	LLP is scalar s_2, produced via $pp \to Z' \to x_3 x_3, x_3 \to s_2 x_1$, then $s_2 \to \ell_\alpha^+ \ell_\alpha^-$. $s_2 \to \ell_\alpha^+ \ell_\alpha^-$ couplings are proportional to SM Yukawa couplings.
$X \to \ell_\alpha^+ \ell_\alpha^-$+inv.	LLP is fermion x_2, produced via $pp \to Z' \to x_3 x_3, x_3 \to x_2 s_1$, then $x_2 \to \ell_\alpha^+ \ell_\alpha^- x_1$.

Table A.8: Simplified model library process proposals for Z' (ZP) production mode where the Z' decays to two LLPs plus invisible. For this section, we use a DM simplified model, where the Z' decays into $x_3 x_3$, and x_3 then decays into the LLP (fermion x_2 for SM+inv decay mode or scalar s_2 for SM decay mode), plus invisible (scalar s_1 or fermion x_1 respectively). The same models can also be used for off-shell Z' where $M_X > M_{Z'}/2$. As before, one model file includes all processes in the table.

Decay Mode	Simplified Model Library Process
$X \to \gamma\gamma$+inv.	LLP is fermion x_2, produced via $pp \to Z' \to x_1 x_2$, then $x_2 \to \gamma\gamma x_1$; or a scalar s_2, produced via $pp \to Z' \to s_1 s_2$, then $s_2 \to \gamma\gamma$.
$X \to jj$+inv.	LLP is fermion x_2, produced via $pp \to Z' \to x_1 x_2$, then $x_2 \to jj x_1$; or a scalar s_2, produced via $pp \to Z' \to s_1 s_2$, then $s_2 \to jj$.
$X \to \ell_\alpha^+ \ell_\alpha^-$+inv.	LLP is fermion x_2, produced via $pp \to Z' \to x_1 x_2$, then $x_2 \to \ell^+ \ell^- x_1$; or a scalar s_2, produced via $pp \to Z' \to s_1 s_2$, then $s_2 \to \ell^+ \ell^-$.

Table A.9: Simplified model library process proposals for Z/Z' (ZP) production mode where the Z' decays to single LLP plus invisible. For this section, we use a DM simplified model, where the Z' couples to an $x_1\, x_2$ or $s_1\, s_2$ pair. x_1 and s_1 behave as DM, the LLP x_2 decays into $x_1 + SM$, and the LLP s_2 decays into SM. The model file again includes all processes in the table.

Decay Mode	Simplified Model Library Process
$X \to jj$+inv.	LR. LLP is the right-handed neutrino (ν_R) produced via $pp \to W^\pm$, $W^\pm \to \ell^\pm \nu_R$. Then, $\nu_R \to q\bar{q}\nu$ via an off-shell W. For massive invisible state, it may be possible to use a cascade $\nu_{R2} \to q\bar{q}\nu_{R1}$ treating the lightest right-handed neutrino as stable.
$X \to jj\ell^\pm$	LR. LLP is the right-handed neutrino (ν_R) produced via $pp \to W^\pm$, $W^\pm \to \ell^\pm \nu_R$. Then, $\nu_R \to q\bar{q}'\ell^\pm$ via an off-shell W.
$X \to \ell^+_\alpha \ell^-_\alpha$+inv. or $X \to \ell^+_\alpha \ell^-_\beta$+inv.	LR.LLP is the right-handed neutrino (ν_R) produced via $pp \to W^\pm$, $W^\pm \to \ell^\pm \nu_R$. Then, $\nu_R \to \ell^+_\alpha \ell^-_\alpha \nu_\beta$ or $\nu_R \to \ell^+_\alpha \ell^-_\beta \nu_\alpha$ via an off-shell W/Z.

Table A.10: Simplified model library process proposals for charged current (CC) production mode, $W^\pm_{\rm SM}/W'^\pm \to X + \ell^\pm$; these can be simulated using left-right symmetric models using either the W or W' (for simplicity, in the table above we only state explicitly W). Right-handed neutrino lifetimes are most naturally long for sub-weak-scale masses.

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