Contribution Prospectives 2020

Searching for long-lived particles (LLP)

Contact author:

Name: Andreas Goudelis
Institution: LPC
Email: andreas.goudelis@clermont.in2p3.fr

Co-authors:

Jérémy Andrea, IPHC
Geneviève Bélanger, LAPTH
Aoife Bharucha, CPT
Felix Brümmer, LUPM
Éric Chabert, IPHC
Éric Conte, IPHC
Caroline Collard, IPHC
Pierre-Antoine Delsart, LPSC
Benjamin Fuks, LPTHE
Marie-Hélène Genest, LPSC
Vladimir Gligorov, LPNHE
Mark Goodsell, LPTHE
Sabine Kraml, LPSC

Summary

There is an increasing interest in long-lived particles: well motivated and appearing in numerous theories of physics beyond the Standard Model, they predict experimental signatures which have been less extensively covered at the LHC so far, making them an interesting target for the years to come. Many members of the French HEP community are already active in the field and propose to intensify this effort, covering model building, phenomenology, tools, reinterpretation, and experimental searches with existing and upgraded/new detectors (ATLAS, CMS, LHCb, and the proposed CODEX-b).

Long-lived Particles: Motivation

Long-lived particles (LLPs), i.e. particles whose decay length is large enough to be resolved at colliders, are not new to particle physics, and physics beyond the Standard Model (BSM). Axions, extremely light – and potentially long-lived – particles, were already proposed in the late 1970s in order to address the strong CP problem [1], whereas in the context of gauge-mediated supersymmetry breaking (GMSB) it has been known since the 1980s that the next-to-lightest supersymmetric particle (NLSP) can decay on macroscopic timescales to the lightest state in the spectrum, the gravitino (for a standard review see [2]).

It is only fair to say, however, that during the last decade there has been a particular upsurge of interest in LLPs. The reasons are twofold: first, the absence of BSM signals in prompt searches at the LHC inevitably raises the question of whether there might exist additional signatures which have not yet been considered. Even when relevant searches do exist, many only provide partial parameter space coverage and/or are subject to some degree of theoretical bias. Secondly, it has been realised that a large number of theoretical constructions, motivated by different questions in high-energy physics and *not* designed specifically to accommodate LLPs, *do* actually predict particles with macroscopic lifetimes. In practice, LLPs appear in situations in which the decay width of some particle is either phase-space suppressed or depends on some coupling which is extremely small, typically because the mass-splitting or coupling is protected by some (approximate or accidental) symmetry or because it is suppressed by some large mass scale. Examples of models which may incorporate one or more of these ingredients include several variants of supersymmetry (SUSY) (R-parity violation [3], generalised GMSB models [4], split SUSY [5], Bino-Wino coannihilation [6], stealth SUSY [7], etc.), heavy neutral leptons (which are related to baryogenesis in the nu-SM) [8], models with new confining gauge groups [9], neutral naturalness [10], and several mechanisms aiming to explain the observed dark matter (DM) abundance in the Universe [11]. A recent list can be found in the LHC LLP Community report, to which several members of the French HEP community have also contributed [12].

What renders these theoretically appealing scenarios phenomenologically exciting - and relevant for collider searches - is that many of them predict the existence of particles with non-negligible interactions with the Standard Model. This implies that the LLPs can be produced copiously at colliders and, depending on their exact nature, can give rise to a plethora of different experimental signatures [13] such as displaced leptons/jets (potentially accompanied by missing transverse energy), disappearing and/or kinked tracks, “emergent” jets, non-pointing photons or heavy stable charged particles (HSCPs). While they are well motivated, LLPs have not yet been covered as extensively in the LHC BSM search program as the models providing prompt signatures, as they often need dedicated trigger, reconstruction and analysis techniques which take more time to put in place. This makes LLPs a very interesting discovery target for the coming years. Furthermore, many LLP searches display peculiar signatures which are absent from the SM: the small expected background means that the sensitivity might grow linearly with the integrated luminosity for some of these searches [12]. Finally, foreseen upgrades and proposed extensions to the LHC detectors will help further improving the search coverage on the HL-LHC timescale.

Model Building and Phenomenology

As already mentioned, part of the increasing interest in LLPs is due to the realisation that they can appear in a fairly straightforward manner in numerous BSM constructions. In the context of SUSY, for example, the components of the Wino multiplet are characterised by extremely small mass splittings arising from radiative corrections. Then, if the lightest supersymmetric particle (LSP) is a Wino-like neutralino, the charged members of the multiplet decay into the neutral state with a decay length of the order of a few centimeters (see e.g. [14]). In the context of GMSB, it is rather the messenger-scale suppression of the gravitino couplings to the rest of the particle spectrum that renders the NLSP long-lived, with potential signatures depending on the exact nature of the latter. Other SUSY scenarios include approximate R-symmetry, where the LSP and NLSP are neutral and almost degenerate. Several researchers that are currently members of French institutes have constructed and studied such SUSY models e.g. [15].

More generally one can construct classes of models consisting of a SM multiplet, where a charged LLP is separated by a small mass splitting from a lighter neutral component. The splitting may arise from radiative corrections or, for more flexibility, from mixing with an additional SM singlet. The collider and DM prospects have been studied by a French group in Ref. [16] for the case of SU(2) n-plets where n=3,4,5, and several modifications of existing searches and new searches were proposed.

Recently, signatures of axion-like particles have received significant interest, partly because they decay purely to SM fields, typically a pair of gluons or photons, and their couplings are suppressed by a naturally (very) high scale. If they are to be LLPs in collider experiments, they cannot be the QCD axion, but ALPs are generic in string theory.

Dark matter has provided some of the strongest motivation for a variety of LHC searches. Conventional models based on the thermal freeze-out picture typically predict signals in prompt searches involving a substantial amount of missing energy produced along with visible objects. However, during the last few years alternative DM genesis mechanisms have been garnering increasing attention. In particular, in the freeze-in picture [17,18], DM only interacts extremely weakly (“feebly”) with the SM particles and is often accompanied by heavier particles, which are charged under the SM gauge group and can be produced at the LHC, decaying with macroscopic lifetimes to the DM, giving rise to signatures involving displaced leptons/jets accompanied by missing energy, disappearing/kinked tracks and HSCPs. Researchers of French institutes not only possess important expertise in constructing [19,20] and studying the phenomenology [20] of such models, but have also developed the only publicly available numerical code, micrOMEGAs 5, which can be used to compute the freeze-in DM abundance in general extensions of the SM [21] and, hence, confront experimental results from collider searches for LLPs with cosmological predictions. Recently, another DM production mechanism that naturally involves LLPs was proposed, the so-called “conversion-driven freeze-out” or “coscattering” scenario [22,23]. The incorporation of this mechanism in micrOMEGAs is underway by members of LAPTh and LPC, along with numerous other phenomenological studies on LLPs involving members of French institutes.

Re-interpretation and Tools

As discussed above, models and scenarios with LLPs have seen an enormous rise in interest in recent years regarding both, collider physics and cosmology/dark matter. A plethora of concrete realisations has been put forward on the model building and phenomenology sides, typically involving very small mass splittings, highly split spectra, secluded sectors, or tiny couplings. While all of these models already promote a large variety of possible LLP signatures, new theoretical ideas are constantly emerging, often motivated by new approaches to the hierarchy problem or dark matter. It is therefore of great interest to our community to be able to reinterpret the LHC's LLP experimental results for all these models, including new ones which may be developed in the future.

Such reinterpretation of experimental results can generically be done in two ways: by applying appropriate simplified-model results to more complete models, or by reproducing the experimental analysis in a Monte Carlo event simulation. Either approach necessitates the development of sophisticated software tools as well as a close theory-experiment interaction to make sure that all relevant information on the analyses and results be provided by the experimental collaborations in sufficient detail and clarity [24], chapter 5 of [25]. French theorists (within the IN2P3 notably researchers from the LPSC theory group, in the last 3 years via the LHCiTools master project) are heavily involved and indeed playing leading roles in this endeavour through their engagement in dedicated workshops and working groups (Les Houches, LLP community, Re-Interpretation Forum) and the development of *public tools*, concretely `MadAnalysis5` with its Public Analysis Database [26,27] for recasting by means of event simulation, and `SModelS` [28,29] for re-interpreting simplified-model results.

A big effort is required in the near future to extend these tools for the purpose of LLPs, to make full use of the Run 2 legacy results and prepare for new results from Run 3. The challenges are manifold and include, for instance, fast detector simulation for LLP signatures, the simultaneous treatment of prompt and long-lived analyses, the development of a new automatised formalism for the description of simplified model topologies, super-fast interpolation algorithms for multidimensional efficiency maps, and so on. Likewise, both `MadAnalysis5` and `SModelS` should be extended beyond ATLAS and CMS results, to include also results from dedicated LLP experiments, like FASER, CODEX-B or MATHUSLA [30]. In this context, theorists from the LPSC also propose to develop, within a new IN2P3 theory project, a framework for unified global fits, allowing to combine all sorts of theoretical and experimental constraints.

In summary, researchers from French institutes (CPT, IPHC, LAPTh, LPC, LPTHE, LPSC) have already made cutting-edge contributions to the - increasingly flourishing - field of LLP studies, through the construction of scenarios predicting the existence of LLPs, the phenomenological study of LLP models and the development of computational tools that facilitate on one hand the optimal exploitation of experimental results from the LHC and, on the other hand, the combination of these results with constraints stemming, e.g., from cosmology. This activity needs to be intensified and supported by the IN2P3, but also enriched by encouraging and supporting the further development of corresponding more activities at the experimental level.

Searching for LLPs with ATLAS

The search for DM candidates at the LHC is a vast program covering e.g. R-parity conserving SUSY, invisible Higgs decay, and the direct production of DM particles in simplified models. In Run-3 and at HL-LHC, it will be possible to strengthen the limits of these searches [31], but it is also crucial to cover less explored scenarios, such as those involving LLPs, which can now benefit from a very good understanding of the objects in the detector thanks to many years of data taking. One class of such scenarios is the existence of a dark sector which includes a DM candidate.

After having been involved in SUSY and direct, simplified-model-based DM searches, the ATLAS group from LPSC has recently started being involved in dark QCD searches, in which dark quarks hadronize into dark hadrons which eventually decay back to SM particles. These dark showers can be evinced by the presence of jets with unusual characteristics of their associated inner detector tracks and/or of their calorimeter energy deposition pattern, as these jets come from the decay of dark-sector particles which can have different couplings and sizable lifetimes (see [14] and references therein).

Beside the ongoing analysis, work on jet performance is foreseen, benefiting from an important pre-existing expertise in this area, as well as studies of the interplay between the various prompt and long-lived searches in the dark QCD sector, both of which will help prepare Run-3 analyses. The group is also involved in the HL-LHC upgrade of the inner tracker: with respect to the current inner detector, its larger volume and increased number of silicon layers will increase the efficiency of reconstructing displaced vertices up to larger radii [32], which will contribute to increasing the sensitivity of such searches.

Searching for LLPs with CMS

After having driven searches in the context of supersymmetry with the direct production of stop pairs and more inclusive search of mono-top covering especially the case of single stop production, the CMS group of IPHC has started to work on LLP searches to extend the coverage of BSM searches

Long-lived stops could form bound states, R-hadrons, which could entirely cross the whole tracker system, and even the entire detector if their lifetime is long enough. The experimental signature would thus be a high p_T track which would be characterized by a low relativistic beta factor inducing a large energy deposit in the tracker device and a large time-of-flight in the external layers, mainly in the muon chambers. This signature of heavy (almost) stable charged particles is more generic and covers many other cases in SUSY (chargino, gluino, stau, ..) and beyond (generic new charged states). The IPHC group is currently working on this analysis with the whole run II data. This analysis will be extended to the run III period where the sensitivity will be increased thanks to the additional luminosity while we will still benefit from the cluster charge measurement in both the pixel and strip detectors.

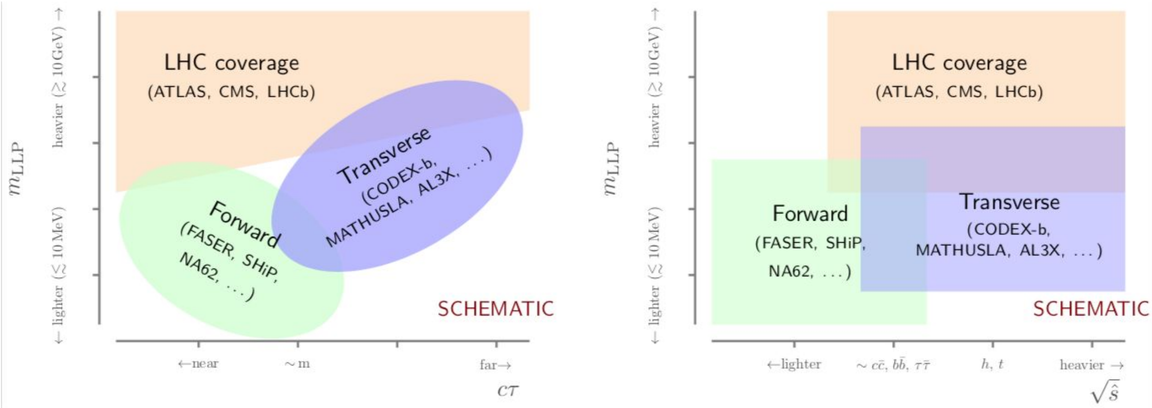
The prospectives for HL-LHC on that particular search have been reported in the tracker TDR [33]. While most layers will not have any more the capability to deliver a charge measurement (binary FE), one kind of sensor (macro pixels) will be equipped with an ASIC delivering a 2 bit measurement, the second bit being related to an adjustable threshold useful to detect high charge deposit. Moreover, the inner pixels will keep its ability to measure the charge through the time-over-threshold technique. One interesting feature of the CMS upgrade detector is the addition of a timing layer covering both the barrel and the end-cap with an excellent resolution (O(30 ps)). Triggering on such topology might be a challenge at HL-LHC which will be mitigated by the presence of the tracker already at L1 level.

Several searches for long-lived particles utilizing the tracker system rely on displaced vertices reconstruction and the related tracks (displaced leptons or jets). While being generic, they are less efficient for very large displacement (beyond the pixel volume). The CMS group of IPHC is willing to improve the performances of the track algorithm, which suffers from a low efficiency for highly displaced tracks. These improvements will be applied to the dedicated searches for LLPs, such as the production of new heavy particles decaying into heavy flavor objects. To further improve tracking and analysis performances, the use of

Machine Learning techniques will be investigated. These new approaches will be used for the analysis of LHC and HL-LHC data.

Searching for LLPs with LHCb and CODEX-b

The central challenge in detecting LLPs is that not only their masses but also their lifetimes may span many orders of magnitude. This makes it impossible from first principles to construct a single detector which would have the ultimate sensitivity to all possible LLP signatures; multiple complementary experiments are necessary, as shown in the Figure below. Despite its non-hermetic geometry and lower instantaneous luminosity, LHCb nevertheless has competitive reach for certain kinds of light LLPs, in particular dark photons or LLPs produced in b→s transitions, which can be difficult for ATLAS and CMS to trigger on [34-40]. Future proposed LHCb upgrades [41] are expected to maintain and further enhance this sensitivity. In particular, the move to an all-software trigger from Run 3 onward will give LHCb a unique flexibility in selecting highly displaced signatures from the very earliest stages of the data processing.



Together with theory colleagues members of the LPNHE LHCb group have proposed [42] to augment the intrinsic capacities of LHCb with a dedicated LLP detector called CODEX-b. This would live in the DELPHI cavern and could be integrated into the LHCb DAQ and readout. The central advantages of CODEX-b are:

- Very competitive sensitivity to a wide range of LLP models, either exceeding or complementary to the sensitivity of other existing or proposed detectors;
- An achievable zero background environment, as well as an accessible experimental location in the DELPHI/UXA cavern with all necessary services already in place;
- Straightforward integration into LHCb's triggerless readout and the ability to tag events of interest with the LHCb detector;
- A compact size and consequently modest cost, with the realistic possibility to extend detector capabilities for neutral particles.

Recently an Expression of Interest for CODEX-b has been published [43]. It is desirable to install a small demonstrator for CODEX-b during Run 3 in order to validate the basic principles behind the full detector design and integration in LHCb. A proposal for such a demonstrator has been submitted to the LHCb Technical Board where it is under review, and we hope for a green light from the LHCb side by the end of 2019. The LPNHE LHCb group is also seeking approval from the lab to take charge of the backend electronics, mechanical support structure, and a significant part of the detector maintenance and operations.

Bibliography

[1] Peccei, R. D. and Quinn, H. R., CP conservation in the presence of pseudoparticles, Phys.Rev.Lett. 38 (1977) 1440-1443

[2] Giudice, G. F. and Rattazzi, R, Theories with Gauge-Mediated Supersymmetry Breaking, Phys.Rept. 322 (1999) 419-499

[3] Barbler, R. et al, R-parity violating supersymmetry, Phys.Rept. 420 (2005) 1-202

[4] Meade, P., Seiberg, N. and Shih, D., General Gauge Mediation, Prog.Theor.Phys.Suppl. 177 (2009) 143-158

[5] Giudice, G. F. and Romanino, A., Split Supersymmetry, Nucl.Phys. B699 (2004) 65-89, Erratum: Nucl.Phys. B706 (2005) 487-487

[6] Nagata, N., Otono, H. and Shirai, S., Probing Bino-Wino Coannihilation at the LHC, JHEP 1510 (2015) 086.

[7] Fan, J., Reece, M. and Ruderman, J., Stealth Supersymmetry, JHEP 1111 (2011) 012

[8] Gorbunov, D. and Shaposhnikov, M., How to find neutral leptons of the nuMSM?, JHEP 0710 (2007) 015, erratum: JHEP 1311 (2013) 101

[9] Strassler, M. and Zurek, K.M., Echoes of a hidden valley at hadron colliders, Phys. Lett. B 651 (2007) 374

[10] Chacko, Z., Goh, H.-S. and Harnik, R., The Twin Higgs: Natural electroweak breaking from mirror symmetry, Phys.Rev.Lett. 96 (2006) 231802

[11] Garny, M., Heisig, J., Lülf, B. and Vogl, S., Coannihilation without chemical equilibrium, Phys.Rev. D96 (2017) no.10, 103521; Hall, L. J., Jedamzik, K., March-Russel, J. and West, S. M., Freeze-in production of FIMP dark matter, JHEP 1003 (2010) 080

[12] Alimena, J. et al, Searching for Long-Lived Particles beyond the Standard Model at the Large Hadron Collider, 2019, [arXiv:1903.04497](https://arxiv.org/abs/1903.04497) [hep-ex].

[13] Lee, L. et al, Collider Searches for Long-Lived Particles Beyond the Standard Model, Prog. Part. Nucl. Phys. 106, pp. 210-255, [arXiv:1810.12602](https://arxiv.org/abs/1810.12602).

[14] Han, T., Mukhopadhyay S. and Wang X., Electroweak Dark Matter at Future Hadron Colliders, Phys.Rev. D98 (2018) no.3, 035026, arXiv:1805.00015 [hep-ph].

[15] Bharucha, A., Goudelis, A. and McGarrie, M., En-gauging Naturalness, Eur.Phys.J. C74 (2014) 2858, arXiv:1310.4500 [hep-ph].

[16] Bharucha, A., Brümmer, F. and Ruffault, R., Next-to-minimal dark matter at the LHC, JHEP 1811 (2018) 195, arXiv:1804.02357 [hep-ph], and with Desai, N., Well-tempered n-plet dark matter, JHEP 1709 (2017) 160, arXiv:1703.00370 [hep-ph].

[17] McDonald, J., Thermally generated gauge singlet scalars as selfinteracting dark matter, Phys.Rev.Lett. 88 (2002) 091304, hep-ph/0106249.

[18] Hall, L. J., Jedamzik, K., March-Russell, J., West, S. M., Freeze-In Production of FIMP Dark Matter, JHEP 1003 (2010) 080, arXiv:0911.1120 [hep-ph].

[19] Goudelis, A., Mohan, K., A. and Sengupta, D., Clockworking FIMPs, JHEP 1810 (2018) 014, arXiv:1807.06642 [hep-ph].

[20] Bélanger et al., LHC-friendly minimal freeze-in models, JHEP 1902 (2019) 186, arXiv:1811.05478 [hep-ph].

[21] Bélanger et al., micrOMEGAs5.0 : Freeze-in, Comput.Phys.Commun. 231 (2018) 173-186, arXiv:1801.03509 [hep-ph].

[22] D'Agnolo, R. T., Pappadopulo, D. and Ruderman, J. T., Fourth Exception in the Calculation of Relic Abundances, Phys.Rev.Lett. 119 (2017) no.6, 061102, arXiv:1705.08450 [hep-ph].

[23] Garny, M., Heisig, J., Lülf, B. and Vogl, S., Coannihilation without chemical equilibrium, Phys.Rev. D96 (2017) no.10, 103521, arXiv:1705.09292 [hep-ph].

[24] Kraml, S. et al., Searches for New Physics: Les Houches Recommendations for the Presentation of LHC Results,' Eur. Phys. J. C 72 (2012) 1976, arXiv:1203.2489.

[25] Alimena, J. et al., Searching for Long-Lived Particles beyond the Standard Model at the Large Hadron Collider, arXiv:1903.04497.

[26] Dumont, B. et al., Toward a public analysis database for LHC new physics searches using MADANALYSIS 5, Eur.Phys.J. C75 (2015) no.2, 56, arXiv:1407.3278.

[27] Conte, C., Fuks, B., Confronting new physics theories to LHC data with MADANALYSIS 5, Int.J.Mod.Phys. A33 (2018) no.28, 1830027, arXiv:1808.00480.

[28] Kraml, S., Kulkarni, S., Laa, U., Lessa, A., Magerl, W., Proschofsky-Spindler, D. and Waltenberger, W., SModelS: a tool for interpreting simplified-model results from the LHC and its application to supersymmetry, Eur.Phys.J. C74 (2014) 2868, arXiv:1312.4175.

[29] Ambrogi et al., F., SModelS v1.2: long-lived particles, combination of signal regions, and other novelties, arXiv:1811.10624.

[30] Curtin, D et al, Long-Lived Particles at the Energy Frontier: The MATHUSLA Physics Case, arXiv:1806.07396 [hep-ph]

[31] Cid Vidal, X. et al, Beyond the Standard Model Physics at the HL-LHC and HE-LHC, https://arxiv.org/abs/1812.07831

[32] ATLAS Collaboration, Technical Design Report for the ATLAS Inner Tracker Pixel Detector, CERN-LHCC-2017-021, ATLAS-TDR-030, 2017, http://cds.cern.ch/record/2285585

[33] CMS Collaboration, Technical Design Report for the The Phase-2 Upgrade of the CMS Tracker, CERN-LHCC-2017-009. CMS-TDR-014, https://cds.cern.ch/record/2272264

[34] R. Aaij et al (LHCb collaboration), Search for long-lived scalar particles in B+->K+Chi(mu+mu-) decays PHYS. REV. D95 (2017) 071101, arxiv:1612.07818 [hep-ex]

[35] R. Aaij et al (LHCb collaboration), Search for hidden sector bosons in B->K*0mu+mu- decays, PHYS. REV. LETT. 115 (2015) 161802, arxiv:1508.04094 [hep-ex]

[36] R. Aaij et al (LHCb collaboration), Search for dark photons produced in 13 TeV pp collisions, PHYS. REV. LETT. 120 (2018) 061801, arxiv:1710.02867 [hep-ex]

[37] R. Aaij et al (LHCb collaboration), Search for A'->mu+mu- decays, submitted to PRL, arxiv:1910.06926 [hep-ex]

[38] R. Aaij et al (LHCb collaboration), Updated search for long-lived particles decaying to jet pairs, EUR. PHYS. J. C77 (2017) 812, arxiv:1705.07332 [hep-ex]

[39] R. Aaij et al (LHCb collaboration), Search for massive long-lived particles decaying semileptonically in the LHCb detector, EUR. PHYS. J. C77 (2017) 224, arxiv:1612.00945 [hep-ex]

[40] R. Aaij et al (LHCb collaboration), Search for Higgs-like bosons decaying into long-lived exotic particles, *Eur. Phys. J. C* 76 (2016) 664, arxiv:1609.03124 [hep-ex]

[41] R. Aaij et al (LHCb collaboration), Physics case for an LHCb Upgrade II - Opportunities in flavour physics, and beyond, in the HL-LHC era, LHCB-PUB-2018-009; CERN-LHCC-2018-027, http://cds.cern.ch/record/2636441

[42] V.V. Gligorov et al, Searching for Long-lived Particles: A Compact Detector for Exotics at LHCb, Phys.Rev. D97 (2018) no.1, 015023, arXiv:1708.09395

[43] G. Aielli et al, Expression of Interest for the CODEX-b Detector, arXiv:1911.00481