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Prospects for LLP searches at the LHC in Run 3 and HL-LHC

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An overview of approaches to challenging LLP scenarios searches at the LHC in Run 3 and HL-LHC is presented. Several examples of unexplored signatures are provided, with potential sensitivities which can be achieved at the existing or future experiments.

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1. Limitations of future projections

There exist few projections of future sensitivities to long-lived particles (LLP) made available by the LHC collaborations. Typically, the actual analyses carried out with datasets smaller than the ones expected in the future, exhibit a comparable if not a better sensitivity to the same physics model. The reason behind, that a projection, by construction, is based on the state-of-the-art approach and does not take into account ideas appearing later, one example being a HL-LHC sensitivity to the Higgs-boson-mediated dark photon search presented in Ref. [1], and the actual achieved constraints produced three years later [2], which surpass those in the projection. If a new idea is not limited by hardware operation or available dataset, then it inevitably leads to a new search rather than a projection. Thus, with planned hardware improvements to the LHC detectors and already existing data handling advances, a sensitivity to LLPs in the next LHC run or in the HL-LHC era will always be better than a projection produced during the last years. And once a novel idea is implemented, integrated luminosity increase by an order of magnitude would not change the picture dramatically. A discovery opportunity lies almost exclusively in the uncharted and yet unthought of territory.

Search strategy optimization includes several ingredients. It is necessary to address various production mechanisms, such as Higgs-boson portal, neutrino portal, direct or associated new particle production. With going to larger decay volume, one can trade off precision with sensitivity to lower couplings. Diverse decay channels are largely explored, including leptons, photons, jets, missing transverse momentum final states. One possibility not studied so far is looking into missing mass in the exclusive decays. Finally, going for unconventional signatures is the hardest to predict or classify: short tracks, fractionally charged particles, emerging jets, semivisible jets, soft unclustered energy patterns. One common challenge to the LLP searches is recording the dataset of interest, i.e. triggering on these signatures. In the preparation to the new LHC run, previous offline-analysis inventions are employed as trigger algorithms, and some of the HL-LHC developments are moved forward and implemented already now if hardware permits.

2. Transformative ideas for LLP searches

As a guideline to the next LHC run, a comprehensive review of opportunities is available in Ref. [3], showing the potential of upgraded detectors and data-taking strategies which are expected to make a difference in the LLP searches. The new hardware-level trigger features in ATLAS and CMS detectors will allow to use calorimeter timing, have higher trigger efficiency for displaced muons, and to select events leading to showers in the muon system. The LHCb detector will switch to a fully software readout, leading to a high flexibility for exotic signatures. The ATLAS and CMS detector upgrades towards HL-LHC will allow to utilize tracking in the hardware-level trigger [4, 5].

The timing in the electromagnetic calorimeter (ECAL), aiming at slowly moving TeV-range particles which decay either in the tracker volume or in the ECAL, has been utilized to explore models with gluinos having proper decay length between 0.3 and 100 m [6]. The dataset recorded with the trigger relying on the high transverse missing momentum has been used, with an offline selection on the ECAL timing of 3 ns. In the next run, it will be possible to record events with rather soft jets, having transverse momentum larger than 20 GeV, and with a delay in a calorimeter of about 1.5 ns, which will allow to explore many other scenarios of neutral LLPs decaying to jets.

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An unconventional idea to build a large decay volume with little standard model background is explored by the ATLAS collaboration, when looking for the neutral LLP decays in the hadronic calorimeter (HCAL), asking for a little or no energy deposit in the ECAL, that particle should pass before the decay [7]. Such segmentation of the calorimeters will be explored with the new dedicated triggers by the CMS collaboration as well. Moving further outside the detector, the developments for hardware-level displaced muon trigger done in view of the HL-LHC by the CMS collaboration [5], are already implemented for the next LHC run and are successfully tested with cosmic ray data [8].

In general, complementarity of different detector subsystems should be used to achieve the best discovery potential for new physics. Figure 1 (left) illustrates a probability for a particle to decay while passing a detector for several lifetime hypotheses at a given boost. In case of a short or an intermediate lifetime, it is necessary to search for the displaced vertices in tracker or delayed showers in calorimeter for neutral LLPs, and short tracks for charged ones. However, when moving to very large lifetimes, it becomes necessary to integrate as large decay volume as possible if the standard model background allows, to maximize search sensitivity. For neutral LLPs, using standalone muons reconstructed only in muon system effectively uses all detector length before the muon system as a decay volume; searching for showers in the muon system takes all muon system length as a decay volume; and missing momentum signature integrates all the length outside of the detector. For charged LLPs, one universal handle is to use anomalous energy deposits dE/dx in the detector. When moving from inside to the outer parts of the detector in the search, the information on the mass of the decaying particle deteriorates, but at the same time the discovery potential for a beyond the standard model process might increase significantly.

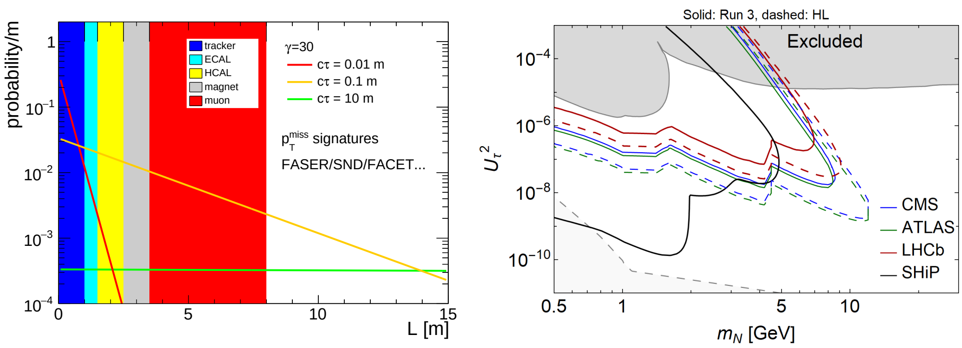

Figure 1: (left) LLP probability to decay as a function of displacement. (right) Sensitivity to HNLs with muon detector showers signature.

Novel searches are carried out by the ATLAS and CMS collaborations by looking for the showers in the muon system [9, 10]. This allows to go all-inclusive with respect to possible decays of LLPs, apart from the invisible decays and decays to muons only, and has a benefit of integrating over a large decay volume. The search done with existing dataset in CMS relies on missing transverse momentum trigger [10], and hence probes a specific signature of LLPs produced together with an initial-state radiation, which leads to a suppression of a production cross section, and limitation of the possible models to test. With the hardware-level trigger on muon system showers which is deployed in the coming LHC run if will be possible to carry out a more general search and probe full production cross section of new particles. One example would be to look for heavy neutral

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leptons (HNL) produced in decays of b quarks, W or Z bosons, and decaying to visible final states in muon system. Assuming signal efficiency similar to the one reported in Refs. [9, 10], and no standard model background, the HNLs matrix element of mixing with τ neutrinos U_τ^2 could be probed down to the level of 10^{-8} and 10^{-9} at the LHC and HL-LHS as shown in Fig. 1 (right). The LHCb detector is competitive with ATLAS and CMS sensitivities despite the lower integrated luminosity thanks to its rather long muon system and forward acceptance. These projections show more optimistic results compared to the estimates done with more conventional signatures [11–14].

For the LHCb experiment, most LLP searches rely on the excellent performance of the vertex locator (VELO) which is about 50 cm long. It is possible to trade mass resolution for larger decay volume by using tracks not requiring VELO hits, and thus enlarging decay volume to about 2.5 m. Recently it has been demonstrated that momentum measurement is possible with tracks reconstructed only with the tracking stations downstream the magnet [15] which gives an access to 7 m decay length. New triggerless readout will allow to fully exploit this approach in the future.

Finally, to close all options, in addition to traditional missing transverse momentum signatures, there is a possibility to use a missing mass in exclusive decays as described in Ref. [16]. This approach requires usage of cascade decays allowing to constrain the kinematics of the system and to infer the invariant mass of a nonreconstructed particle. This method has already been used for studying B meson decays involving τ leptons [17], and it can be generalized for LLP searches.

3. Projections beyond HL-LHC

One common feature to many LLP searches and projections is thinking out of the box with the experiments we already have, which really has come long way since the start of the LHC operation. The conclusion to be brought forward to the next facilities is the necessity to plan for a rich LLP programme in advance and to incorporate dedicated detector solutions as e.g. in Ref. [18]. Another such example is presented in the proposal of the additional subdetectors to be added to FCC-hh facilities to probe neural LLPs, with an example sensitivity to HNLs shown in Fig. 2 [19]. It allows to cover parameter space not accessible at the FCC-ee or SHiP experiments.

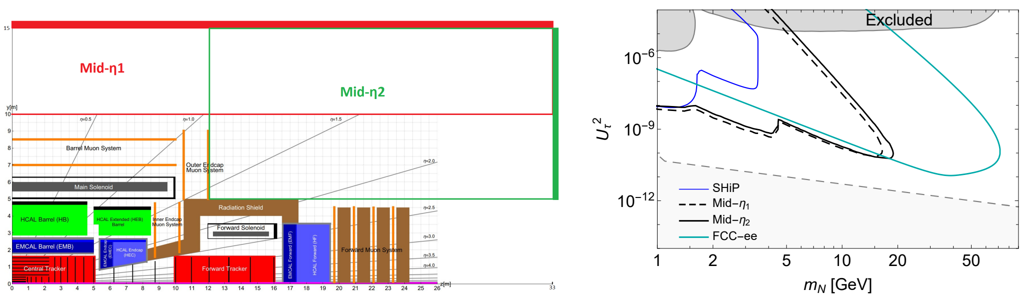

Figure 2: (left) Proposed Mid-η1 and Mid-η2 additional detectors at FCC-hh. (right) Sensitivity to HNLs with these detectors [19].

To conclude, the new LHC run is an imminent testing ground for many new ideas conceived recently. The LLP programme is continuous burst of creativity in data-handling [20, 21] and has potential for motivating new technological solutions [22]. During the HL-LHC era many new ideas will be born and realized while collecting a record dataset of proton-proton collisions.

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References

[1] ATLAS collaboration, *Search prospects for dark-photons decaying to displaced collimated jets of muons at HL-LHC*, ATLAS Note ATL-PHYS-PUB-2019-002, https://cds.cern.ch/record/2654518 (2019).

[2] ATLAS collaboration, *Search for light long-lived neutral particles that decay to collimated pairs of leptons or light hadrons in pp collisions at $\sqrt{s}$ = 13~TeV with the ATLAS detector*, 2206.12181.

[3] D. Acosta et al., *Review of opportunities for new long-lived particle triggers in Run 3 of the Large Hadron Collider*, 2110.14675.

[4] ATLAS collaboration, *Technical Design Report for the Phase-II Upgrade of the ATLAS TDAQ System*, Scientific Committee Paper CERN-LHCC-2017-020, ATLAS-TDR-029, https://cds.cern.ch/record/2285584 (2017), DOI.

[5] CMS collaboration, *The Phase-2 Upgrade of the CMS Level-1 Trigger*, Scientific Committee Paper CERN-LHCC-2020-004, CMS-TDR-021, https://cds.cern.ch/record/2714892 (2020).

[6] CMS collaboration, *Search for long-lived particles using nonprompt jets and missing transverse momentum with proton-proton collisions at $\sqrt{s}$ = 13 TeV*, Phys. Lett. B **797** (2019) 134876 [1906.06441].

[7] ATLAS collaboration, *Search for neutral long-lived particles in pp collisions at $\sqrt{s}$ = 13 TeV that decay into displaced hadronic jets in the ATLAS calorimeter*, JHEP **06** (2022) 005 [2203.01009].

[8] CMS collaboration, *Measurements of the HLT performance of displaced muons using Cosmics data*, CMS Detector Performance Summaries CMS-DP-2019-028; CERN-CMS-DP-2019-028, https://cds.cern.ch/record/2690807 (2019).

[9] ATLAS collaboration, *Search for events with a pair of displaced vertices from long-lived neutral particles decaying into hadronic jets in the ATLAS muon spectrometer in pp collisions at $\sqrt{s}$=13 TeV*, Phys. Rev. D **106** (2022) 032005 [2203.00587].

[10] CMS collaboration, *Search for Long-Lived Particles Decaying in the CMS End Cap Muon Detectors in Proton-Proton Collisions at $\sqrt{s}$ =13 TeV*, Phys. Rev. Lett. **127** (2021) 261804 [2107.04838].

[11] I. Boiarska, K. Bondarenko, A. Boyarsky, S. Eijima, M. Ovchynnikov, O. Ruchayskiy et al., *Probing baryon asymmetry of the Universe at LHC and SHiP*, 1902.04535.

[12] M. Drewes and J. Hajer, *Heavy Neutrinos in displaced vertex searches at the LHC and HL-LHC*, JHEP **02** (2020) 070 [1903.06100].

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[13] K. Bondarenko, A. Boyarsky, M. Ovchynnikov, O. Ruchayskiy and L. Shchutska, *Probing new physics with displaced vertices: muon tracker at CMS*, *Phys. Rev. D* **100** (2019) 075015 [1903.11918].

[14] M. Borsato et al., *Unleashing the full power of LHCb to probe stealth new physics*, *Rept. Prog. Phys.* **85** (2022) 024201 [2105.12668].

[15] F.J. Botella, L.M. Garcia Martin, D. Marangotto, F.M. Vidal, A. Merli, N. Neri et al., *On the search for the electric dipole moment of strange and charm baryons at LHC*, *Eur. Phys. J. C* **77** (2017) 181 [1612.06769].

[16] A.B. Rodríguez, V. Chobanova, X. Cid Vidal, S.L. Soliño, D.M. Santos, T. Mombächer et al., *Prospects on searches for baryonic Dark Matter produced in b hadron decays at LHCb*, *Eur. Phys. J. C* **81** (2021) 964 [2106.12870].

[17] LHCb collaboration, *Search for the lepton flavour violating decay $B^+ \to K^+\mu^-\tau^+$ using B^{*0}_{s2} decays*, *JHEP* **06** (2020) 129 [2003.04352].

[18] M. Chrząszcz, M. Drewes and J. Hajer, *HECATE: A long-lived particle detector concept for the FCC-ee or CEPC*, *Eur. Phys. J. C* **81** (2021) 546 [2011.01005].

[19] A. Boyarsky, O. Mikulenko, M. Ovchynnikov and L. Shchutska, *Exploring the potential of FCC-hh to search for particles from B mesons*, 2204.01622.

[20] J. Barron, D. Curtin, G. Kasieczka, T. Plehn and A. Spourdalakis, *Unsupervised hadronic SUEP at the LHC*, *JHEP* **12** (2021) 129 [2107.12379].

[21] F. Canelli, A. de Cosa, L.L. Pottier, J. Niedziela, K. Pedro and M. Pierini, *Autoencoders for semivisible jet detection*, *JHEP* **02** (2022) 074 [2112.02864].

[22] L.A. Anchordoqui et al., *The Forward Physics Facility: Sites, experiments, and physics potential*, *Phys. Rept.* **968** (2022) 1 [2109.10905].

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