IL NUOVO CIMENTO **48 C** (2025) 84
DOI 10.1393/ncc/i2025-25084-3

Colloquia: IFAE 2024

Unconventional search and long-lived particles at LHC: Signature and experimental challenges(*)

G. Gustavino
INFN, Sezione di Roma - Roma, Italy

received 2 December 2024

Summary. — The search for long-lived and unconventional particles at collider experiments presents a unique set of experimental challenges and opportunities. This contribution delves into their distinctive signatures and the innovative strategies employed to detect them at the LHC. A brief overview of the theoretical motivations together with the main experimental challenges to face are addressed highlighting the vast variety of searches aimed at exploiting the full potential of the existing detectors together with the commissioning and prospects of future dedicated experiments.

1. – Introduction

The proper lifetime is a property that characterises all the Standard Model (SM) particles and its value can span among many orders of magnitudes. From an experimental perspective, long-lived particles (LLPs) are particles that exhibit macroscopic lifetimes, either being effectively stable or travelling observable distances before they decay. This can be attributed to various factors: a feeble coupling as in the case of the b quark decays; a severe phase-space suppression as for the neutron due to the small mass-splitting with the proton; a heavy, off-shell particle, which acts as a mediator in the decay process implying that the LLP's width is suppressed similar to what is observed for muons.

From a theoretical perspective, LLPs are well-motivated also in many beyond the Standard Model (BSM) theories [1]. The upper bounds on the particle's lifetime are constrained by considerations on the primordial abundances from the Big Bang Nucleosynthesis (BBN) [2] and range between $0.1 \div 10^4$ s. However, such constraints are not stringent enough to impact LHC experiments significantly. The lower bounds on the lifetimes of LLPs depend on specific models, and these particles can also be compatible with the dark matter relic abundance.

(*) IFAE 2024 - "Energy Frontier" session

Creative Commons Attribution 4.0 License (https://creativecommons.org/licenses/by/4.0)

2. – Experimental considerations and challenges

Unconventional and LLP searches are particularly exciting from an experimental standpoint. They offer a vast range of spectacular signatures, ranging from displaced vertices and anomalous energy deposits to unexpected decay patterns within detectors. These scenarios remain largely unprobed, presenting a fertile ground for novel ideas and innovative detection methods.

Simplified dark sector benchmarks are often used to allow for reinterpretations in more complete, complex and novel theories. Such benchmarks usually introduce a mediator particle that can interact with a certain coupling both to SM and dark sector particles. The dark sector can include one or more particles including dark matter candidates as well as unknown interaction forces. Several mediator spin hypotheses and properties are considered yielding to scalar, vector, neutrino and axion-like portals.

A fundamental aspect to consider is the exponential decay nature of the particle decay. Indeed, particles with a short proper lifetime can decay with a large laboratory frame distance because of their momenta. Hence, the ensemble of sub-detectors of the LHC experiments must be used at their full potential to probe the vast range of allowed proper lifetimes. The reinterpretation of the results obtained from prompt or invisible decay searches allows to constraint regimes with short or very long proper lifetimes where a sizeable fraction of LLPs decay outside the detector acceptance. Then, different experimental technologies permit the investigation of different phase spaces in terms of particle decay lengths and masses. An example showing the complementarity of the several searches is shown in fig. 1 where the signal benchmark of two long-lived scalar particles coupled to the Higgs ($h \to ss$) decay into hadronic final states [3].

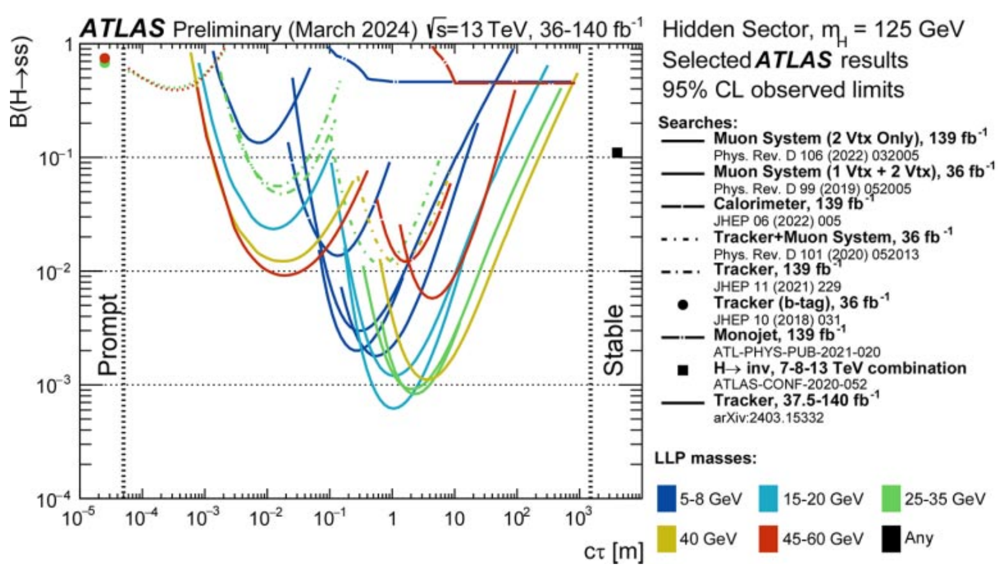

Fig. 1. – The 95% confidence level exclusion limits on the Higgs boson branching to a pair of long-lived neutral spin-0 bosons (s) as a function of the proper decay length ($c\tau$) of s. The coloured lines represent the regions excluded by the analyses listed in the legend, and the colours of the lines refer to the LLP mass (or mass range) under consideration. The plot shows a selection of the most sensitive individual ATLAS 13 TeV results [3].

There are two main classes of searches for LLP at collider experiments: direct and indirect detections. The former exploits the direct interaction of the LLP with the detector through its energy loss, the time-of-flight or measuring special track properties. This category of searches is suitable for the search for charged LLP. In the case of neutral LLP, the indirect approach is adopted looking for their SM or invisible decay products.

Searching for LLPs at the LHC involves several significant experimental challenges. One primary issue lies in the trigger systems, particularly the low-level triggers, which generally lack the detailed information necessary to tag LLPs or their decays effectively. Consequently, experiments often rely on "prompt" physics object triggers, such as initial-state radiation jets, missing transverse energy, or charged leptons. This approach reduces the sensitivity of the search and increases the model dependence of the results.

Reconstruction of LLP signatures also poses a unique challenge, as standard reconstruction algorithms are not designed to handle the atypical trajectories and decay patterns of such particles. Dedicated techniques are necessary to accurately identify and reconstruct the signals from LLPs, which adds complexity to the analysis process.

Background estimation is another challenging aspect due to the unusual sources of background that can mimic these unconventional signatures. Traditional simulation-based methods are often insufficient, requiring the adoption of data-driven approaches. These methods are more reliable but can be limited by the available data and the complexity of background processes.

Estimating the signal efficiency for LLP searches is particularly difficult, as there are no Standard Model (SM) processes that provide sufficiently similar decay signatures to serve as benchmarks. This lack of a "standard candle" for LLPs complicates the calibration and validation of detection techniques, making it harder to quantify the performance of the adopted tools and algorithms accurately.

3. – Experimental signatures

The several layers of the detector provide different approaches to hunting LLPs.

3˙1. *Inner tracker-based searches*. – Inner detectors are used for tracking reconstructions and a key point to search for LLPs is the ability to reconstruct tracks non-pointing to the primary vertex, or large-radius tracks (LRT), and displaced vertices (DVs). ATLAS [4], CMS [5] and LHCb [6] collaborations made huge progress in this context for Run 3. An overhaul version of the displaced track reconstruction algorithm was developed in ATLAS [7] allowing to reduce the fake tracks, deriving by randomly combined hits and pile-up tracks, by a factor of 20. This yielded a drastic reduction in CPU consumption and allowed its integration in both offline and online reconstruction chains. In CMS the new High-Level Trigger (HLT) tracking reconstruction algorithm has been implemented using heterogeneous computing, making use of a GPU farm. This has significantly improved the overall tracking purity performance, increasing by a factor of 1.5 the efficiency of $t\bar{t}$ events while reducing the fake tracks contamination by a factor of 2 [8]. LHCb developed a new software-based trigger at the first level, HLT1, implemented on GPUs. A second HLT2 combines the track information from the VELO and the external tracker providing new sets of tracks with maximum displacement from the interaction point of up to about 2 m [9], opening up new horizons in its LLP research program.

In the $h \to ss$ scenarios with hadronic final states, background sources for these searches include DVs from random crossings, heavy flavour jets, and interactions with detector material. The ATLAS experiment has pioneered new production channels such as vector boson fusion (VBF) and vector boson-associated production (VH) [10]. The new track reconstruction algorithm improves by a factor of 40 the signal over the square root of fake tracks ratio ($N_s/\sqrt{N_b}$). The analysis strategy requires at least one displaced jet, instead of two of the previous version of the analysis, enhancing the sensitivity to various signatures and achieving a tenfold improvement on $\mathcal{B}(h \to ss)$ by reprocessing the Run 2 dataset. The CMS experiment introduced new dedicated Run 3 triggers to target the gluon-gluon fusion (ggF) production process. They require two jets with one or fewer prompt tracks, yielding 4 to 17 times higher efficiency than in Run 2. New reconstruction methods for displaced secondary and tertiary vertices were developed together to deploy displaced jet taggers based on Graph Neural Networks (GNN) [11]. With these innovations, CMS achieved a factor of 10 sensitivity improvement with only a quarter of the Run 2 statistics and expects an additional 40-100% signal efficiency gain using the 2023 data parking triggers [12].

Emerging jets are a distinctive signature arising from a QCD-like dark sector that produces dark showers. In this distinctive and experimentally challenging to investigate scenario, dark pions can have a non-zero lifetime, leading to high DV multiplicity and displaced tracks. For CMS, new results from Run 2 are obtained using a GNN tagger to effectively discriminate between emerging jets and standard QCD jets [13]. ATLAS has yet to release public results and has implemented a new dedicated trigger for Run 3. This selects jets with a small fraction of prompt tracks, allowing for a 40% reduction in the p_{T} threshold to explore lower mediator masses [14] (fig. 2(a)).

Fractional (FCP), multi-charged (MCP) and slow long-lived particles represent another intriguing class of BSM scenarios that are investigated with a direct detection approach. These particles are characterised by muon-like tracks with anomalous energy loss per unit length (dE/dx). The relative searches exploit the relationship $dE/dx \propto \frac{z^2}{\beta^2}$ to distinguish these new physics particles from SM physics objects. Background sources include instrumental effects, δ-rays, and random large ionisations from the Landau tail.

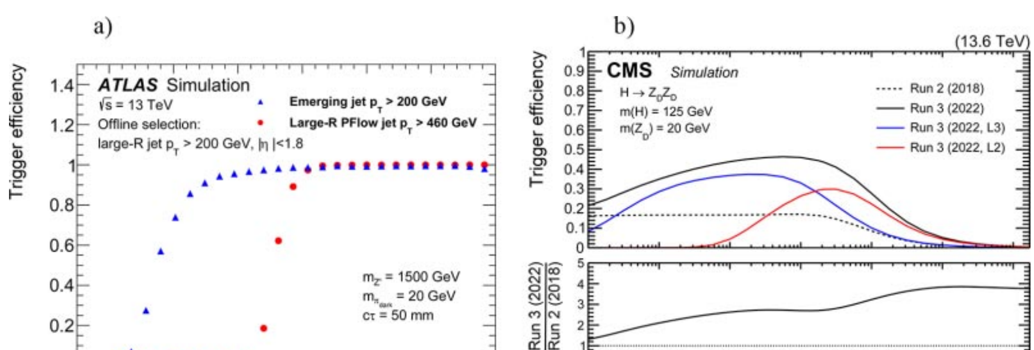

Fig. 2. – (a) Efficiency of the emerging jet trigger compared to a single large-radius jet trigger for a Z' decaying into two dark pions with $c\tau = 50$ mm. The efficiency is calculated as a function of the leading large-R jet p_{T} [14]. (b) Efficiencies of the Run 2 (red) and Run 3 (blue and red) displaced dimuon triggers as a function of $c\tau$ for the dark photon (HAHM model) signal events with $m_{Z_D} = 20$ GeV. The lower panel shows the ratio of the overall Run 3 (2022) efficiency to the Run 2 (2018) efficiency [26].

For MCPs, the ATLAS analysis focuses on the dE/dx significance, defined with respect to a minimum ionising particle as $S(dE/dx) = \frac{dE/dx - \langle dE/dx_\mu \rangle}{\sigma(dE/dx)_\mu}$, and the fraction of high threshold hits in the Transition Radiation Tracker [15]. Slow LLPs are investigated by extracting their $\beta\gamma$ from $\langle dE/dx \rangle$ in the pixel tracker using the Bethe-Bloch formula [16]. For FCPs, the CMS analysis discriminates the BSM scenarios from the background counting the tracks as a function of the number of hits with low dE/dx values [17].

3˙2. *Calorimeter-based searches.* – These analyses probes up to lifetimes of $c\tau \sim \mathcal{O}(\mathrm{m})$. LLP searches in the electromagnetic calorimeter (ECAL) focus on signatures of delayed photons, which can originate from the same or different decays [18, 19]. The primary backgrounds include prompt photons and fake photons from electrons or jets. The median time of ECAL cells in the jet is a critical discriminant variable. The strategy exploits the segmentation and time resolution of the EM calorimeter, utilising pointing and timing measurements for identification.

LLP searches in the hadronic calorimeter (HCAL) look for trackless jets with a high hadronic calorimeter fraction. Backgrounds here include QCD jets, beam-induced backgrounds (BIB), and cosmic rays. Key distinguishing features are the lack of associated tracks and precision timing. Dedicated triggers are developed to enhance the efficiency of these searches: ATLAS leverages the ratio of hadronic to electromagnetic energy (E_H/E_{EM}) [20], while CMS focuses on jet timing to identify potential LLP events [21].

3˙3. *Muon spectrometer-based searches.* – Muon spectrometer-based searches for LLPs take advantage of the unique designs of the ATLAS and CMS detectors. ATLAS, with its large fiducial volume and air gaps, is well-suited for reconstructing displaced tracks and vertices. CMS, with its compact spectrometer and extensive steel components, can act as a sampling calorimeter, to detect shower decays. These searches allow probing up to lifetimes of $c\tau \sim \mathcal{O}(10\mathrm{m})$, often achieving near-zero background conditions.

The primary signature in these analyses is high multiplicity hadron showers in the muon spectrometer. Backgrounds include punch-through jets and BIB. ATLAS defined dedicated triggers focusing on multiple Regions of Interest (ROIs) and a dedicated DV algorithm that identifies multiple tracklets in the Monitored Drift Tubes (MDTs) [22]. CMS instead focuses on reconstructing high multiplicity clusters with at least 50 hits to discriminate background from signals [23].

In dark photons scenarios, characterised by light mediators, ATLAS look for collimated jet structures of leptons or light hadrons. With the usage of a neural network tagger trained on low-level inputs, the analysis can probe LLP masses down to sub-GeV [24,25]. CMS also developed displaced di-muon trigger algorithms in Run 3 allowing to reduce by more than a factor of 2 the Run 2 existing p_{T} thresholds [26] (fig. 2(b)). This yields up to four times sensitivity gain in terms of trigger efficiency. These improvements result in a substantial sensitivity enhancement in dark photon scenarios in Run 3, even just utilising a dataset of about 2.5 times lower than the one collected during Run 2.

4. – Dedicated experiments

In addition to the primary LHC detectors (ATLAS, CMS, and LHCb), several other dedicated experiments have been developed to search for LLPs and MCPs at larger angles. These expand the coverage in different regions of parameter space, focusing on various LLP masses and lifetimes.

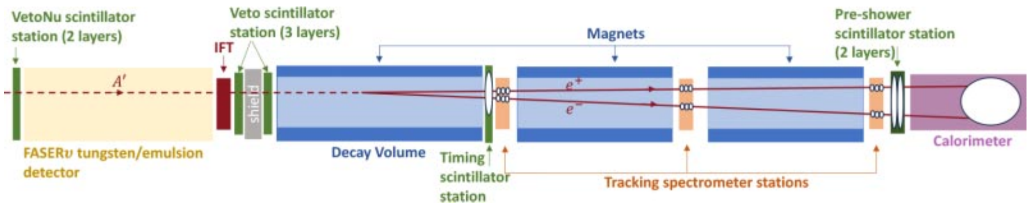

Fig. 3. – A sketch presenting a side view of the FASER detector, showing the different detector systems. The signature of a dark photon (A') decaying to an electron-positron pair inside the decay volume depicting the taken measurements with white blobs and the reconstructed tracks with solid red lines. [32].

Transverse detectors and project proposals such as CODEX-b [27] and MATHUSLA [28] are designed to probe LLPs at larger distances from the interaction point. These operate in a region complementary to the main LHC detectors, allowing for the exploration of longer proper decay lenghts.

Forward and fixed target experiments, including FASER [29], SHIP [30] and NA62 [31] are positioned along the beamline to detect LLPs produced in the forward direction. These experiments are optimised for low-mass scenarios and can effectively search for light, weakly interacting particles that escape detection in the central detectors.

Among these FASER, situated 480m downstream of the ATLAS interaction point, started to collect data in Run 3. The detector geometry characterised by a multi-layer scintillator and tracking systems spaced by decay volumes with a magnet field allows to tagging of particles decaying within the experimental apparatus. A sketch of the detector with a dark photon signature is shown in fig. 3. The detector design allows to reach near-background zero conditions dominated by neutrino material interactions. The results obtained in the searches for dark photon [32] and axion-like [33] particles already set constraints in a region of the phase-space inaccessible by other experiments.

Finally, dedicated experiments such as MOEDAL [34] and milliQAN [35] are designed to detect magnetic monopoles and other highly ionizing particles and particles with a small electric charge. These broaden further the search program of unconventional particles at LHC exploring phenomena not accessible from other existing detectors.

5. – Conclusions

The search for unconventional and LLPs at the LHC is a vibrant and comprehensive research program that leverages the strengths of various detector technologies to explore different lifetime regimes. Such searches often face statistical limitations and the foreseen data collection plan is crucial, particularly for those with background-zero conditions where the sensitivity scales with the integrated luminosity.

To address the several challenges and improve the effectiveness of probing anomalous signatures, several innovative strategies are being implemented. New dedicated trigger strategies enable to widen and complement the current reaches. The integration of advanced machine-learning techniques allowed for the detection of unusual patterns in the data hugely enhancing the sensitivity of the current searches.

Looking ahead to Run 4 and beyond, the development and deployment of new detector technologies and dedicated experiments will allow to deepen the investigation and broaden the coverage of the current searches further enriching the LLP physics program.

REFERENCES

[1] Alimena J. *et al.*, *J. Phys. G*, **47** (2020) 090501.
[2] Fradette A. and Pospelov M., *Phys. Rev. D*, **96** (2017) 075033.
[3] ATLAS Collaboration, ATL-PHYS-PUB-2024-003.
[4] ATLAS Collaboration, *JINST*, **3** (2008) S08003.
[5] CMS Collaboration, *JINST*, **3** (2008) S08004.
[6] LHCb Collaboration, *JINST*, **3** (2008) S08005.
[7] ATLAS Collaboration, *Eur. Phys. J. C*, **83** (2023) 1081.
[8] CMS Collaboration, CMS-DP-2022-014.
[9] Calefice L. *et al.*, *Front. Big Data*, **5** (2022) 1008737.
[10] ATLAS Collaboration, arXiv:2403.15332.
[11] CMS Collaboration, CMS-PAS-EXO-23-013.
[12] CMS Collaboration, CMS-DP-2023-043.
[13] CMS Collaboration, CMS-PAS-EXO-22-015.
[14] ATLAS Collaboration, *JINST*, **19** (2024) P06029.
[15] ATLAS Collaboration, *Phys. Lett. B*, **847** (2023) 138316.
[16] ATLAS Collaboration, *JHEP*, **06** (2023) 158.
[17] CMS Collaboration, arXiv:2402.09932.
[18] CMS Collaboration (Sirunyan A. M. *et al.*), *Phys. Rev. D*, **100** (2019) 112003.
[19] ATLAS Collaboration, *Phys. Rev. D*, **108** (2023) 012012.
[20] ATLAS Collaboration, *JHEP*, **06** (2022) 005.
[21] CMS Collaboration, *Phys. Lett. B*, **797** (2019) 134876.
[22] ATLAS Collaboration, *Phys. Rev. D*, **106** (2022) 032005.
[23] CMS Collaboration, arXiv:2402.01898.
[24] ATLAS Collaboration, *JHEP*, **06** (2023) 153.
[25] ATLAS Collaboration, arXiv:2311.18298.
[26] CMS Collaboration, *JHEP*, **05** (2024) 047.
[27] CODEX-b Collaboration, *Eur. Phys. J. C*, **80** (2020) 1177.
[28] MATHUSLA Collaboration, arXiv:1811.00927.
[29] FASER Collaboration, *JINST*, **19** (2024) P05066.
[30] SHiP Collaboration, arXiv:1504.04956.
[31] NA62 Collaboration, *JINST*, **12** (2017) P05025.
[32] FASER Collaboration, *Phys. Lett. B*, **848** (2024) 138378.
[33] FASER Collaboration, CERN-FASER-CONF-2024-001.
[34] MoEDAL Collaboration, *Int. J. Mod. Phys. A*, **29** (2014) 1430050.
[35] milliQan Collaboration, *Phys. Rev. D*, **104** (2021) 032002.