PROCEEDINGS OF SCIENCE

Searches for displaced jets at the LHC

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Particles beyond the Standard Model (SM) can have generically longer lifetimes than SM particles at the weak scale. These long-lived particles (LLPs) can decay far from the interaction vertex of the primary proton-proton collision when produced at experiments such as CERN's Large Hadron Collider (LHC). Here we report on searches for LLPs that are assumed to decay to a pair of standard model quarks that are identified as displaced jets with the ATLAS, CMS, and LHCb experiments. No significant discrepancies with respect to the Standard Model predictions have been found in data, so that limits for several benchmark signals have been set. In particular, the results are interpreted in the context of exotic decays of the Higgs boson to a pair of scalar LLPs ($H \rightarrow SS$) with a mass of 125 GeV and for masses between 200 GeV and 1 TeV.

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1. Introduction

Particles in the Standard Model (SM) have a huge variety of lifetimes, ranging from the Z boson ($\tau \sim 2 \times 10^{-25}$s) to the proton ($\tau \geq 1034$ years) and electron (stable), as shown in Figure 1. Similarly, models beyond the Standard Model (BSM) often forecast additional particles with a range of lifetimes. Particularly, new weak-scale particles can simply have long lifetimes due to a variety of factors, such as approximating symmetries that stabilise the long-lived particle (LLP), weak couplings between the LLP and lighter states, and suppressed phase space available for decays. This can result in macroscopic, observable displacements between the generation and decay points of an unstable particle for $c\tau \geq 10\mu$m (where c is the speed of light and τ is the mean proper lifetime) for particles travelling near the speed of light.

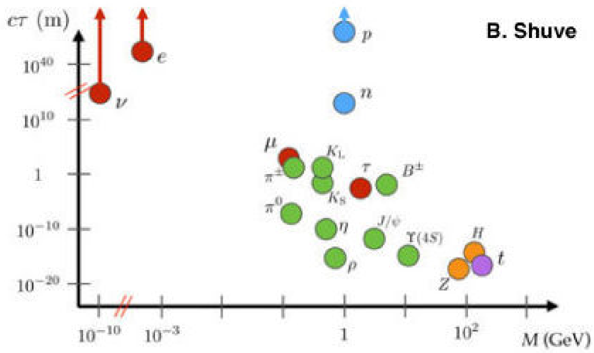

Figure 1: Particle lifetime cτ given in metres as a function of particle mass expressed in GeV for a variety of Standard Model particles. [1]

The experimental LLP indications at the Large Hadron Collider (LHC) are diverse and frequently extremely distinct from signals from SM processes by nature. LLP signatures can include, for instance, tracks with unique ionisation and propagation characteristics, small, localised energy deposits inside of the calorimeters without associated tracks, stopped particles (SPs) that decay out of time with collisions, displaced vertices (DV) in the inner detector (ID) or muon spectrometer (MS), as well as disappearing, reappearing, and kinked tracks. Figure 2 shows a schematic of a representative sample of the range of LLP signatures that are distinct from both SM signatures and the vast majority of BSM searches at the LHC.

LLPs linked to SM-like Higgs are well-motivated and so interesting, where SM Higgs BR still allows for O(20%) BSM couplings, where H(125) could mix with "dark sector Higgs" , decay to long-lived scalars (hidden sector) Figure 3, etc. The LLPs then decay back to SM particles (especially quarks), leading to displaced jet signatures most of the time. So, given the large variety of BSM scenarios that lead to displaced-jet signatures, we present in this paper an inclusive search for LLPs decaying into jets at the Large Hardon Collider (LHC).

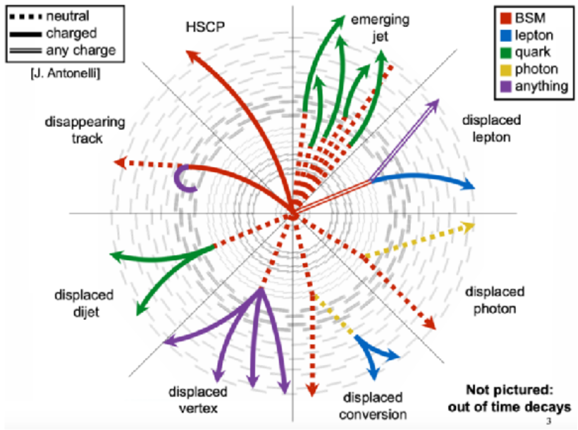

Figure 2: Schematic representation of several LLP signatures that may be looked for by central detectors. [1]

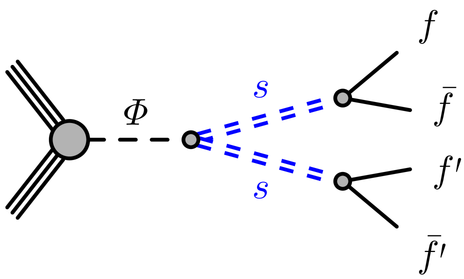

Figure 3: A diagram of the scalar portal model studied in this paper. The LLPs are represented by double lines and labelled s, and the final-state SM fermions are labelled as f. [2]

2. Displaced Jets in association with a Z Boson

This analysis provides an advantage of a unique LLP search channel, namely the production of LLPs in association with a Z boson, where prompt leptons (electrons and muons) provide an efficient trigger for low-p_T jet events, Figure 4. The long-lived scalars decay to a pair of quark b(d)-jets. The displaced jet here is defined by passing pre-defined selections based on the three "tagging variables" calculated from the properties of tracks associated with jets as previously described by the CMS Collaboration [4]. Figure 5 shows $\hat{IP}^{2D}_{Sig}$ of the tagging variable distributions in simulation and data.

This search's basic approach is to use the displaced jet multiplicity (Ndis) in the event to distinguish between the signal and the background processes. Signal events normally contain N$_{dis}$ > 2, whereas SM background processes show a sharply dropping distribution in N$_{dis}$. To estimate the number of misidentified displaced jets from SM background processes, an approach based on control samples in data of low-p_T opposite-sign dilepton pairs (representing the dominant SM Z boson production) and different-flavor (eμ) displaced jets was used. As a result, no significant excess has been observed over a smoothly falling background. As shown in Figure 6, this search [3] presents the most stringent CMS upper limits on the B (H $\rightarrow$ BSM particles) for low mass (~15 GeV) particles decaying to b quarks.

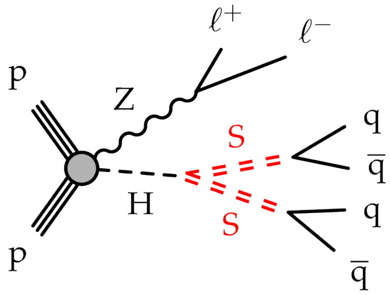

Figure 4: Feynman diagram of a simplified model for the Higgs boson decays to a pair of long-lived scalar particles (S). The Higgs boson is produced in association with a Z boson, where the Z boson decays to a pair of leptons. The long-lived scalars decay into a pair of quark jets (q) [3].

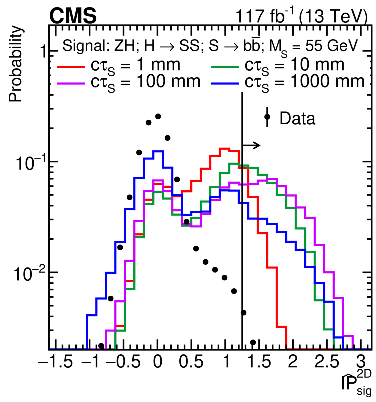

Figure 5: Distribution of $\hat{IP}^{2D}_{Sig}$ for tagging variable for four signal samples, where the decay lengths of the signals range from 1 to 1000 mm. Overlaid on the figures is a line with an arrow pointing to the region where values of the variable are used to aid in distinguishing possible displaced jets from background jets [3].

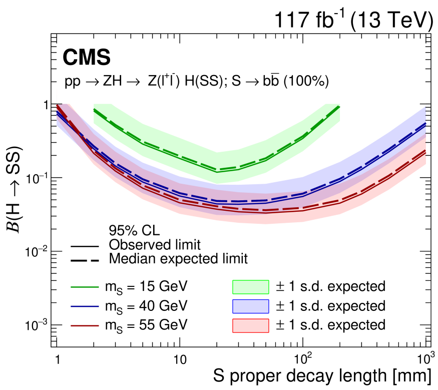

Figure 6: Exclusion limits at 95% CL on the Higgs boson branching fraction to long-lived scalars B(H $\rightarrow$ SS). Limits are presented for scalar decays to b quarks as a function of the mean proper decay length of the scalar. The limits for the different scalar masses are shown in different colors for each scalar decay mode [3].

3. Hadronic Decay in Muon Endcaps

This search outlined the first LHC search that makes use of a muon detector as a sampling calorimeter to identify showers caused by LLP decay. The cathode strip chambers (CSCs) located at the CMS endcaps detect particle (Figure 7) showers as clusters of a large number of hits. With the excellent shielding provided by the inner CMS detector, the background is suppressed to a low level and a search for a single LLP decay is possible. Trigger on p_T^{miss} since LLPs are decaying outside of the tracker and calorimeters. The number of hits in the cluster (N$_{h}its$) and the azimuthal angle between the cluster location and p_T^{miss} the ($\Delta\phi$) are used to make the final discrimination between signal and background. The distribution of N$_{hits}$ remains high at large N$_{h}its$ values for signal events, but for background events the distribution of N$_{hits}$ decreases sharply with increasing N$_{hits}$ values.

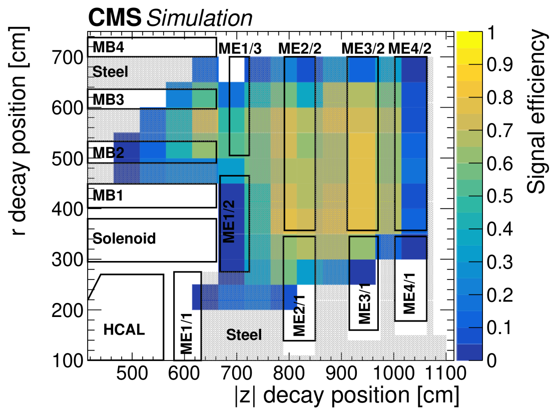

Figure 7: The signal efficiency of the combined cluster reconstruction as a function of the simulated r and z decay positions of S decaying to $b\bar{b}$ is calculated for a mass of 15 GeV and a uniformly distributed mixture of events with cτ between 1–10 m. The barrel and end cap muon stations are drawn as black boxes and labelled with their station names, showing the geometry of the muon detectors [5]

After comparing what is predicted with real data found in the signal region, no significant deviation from the SM background is observed, and the most stringent limits on the branching fraction of Higgs boson to LLP decaying to $d\bar{d}$, $b\bar{b}$, and $\tau\bar{\tau}$ are set for proper decay lengths $c\tau >$ 6, 20, and 40 m, and LLP masses of 7, 15, and 40 GeV, respectively. For $c\tau > 100$ m, this search [5] outperforms the previous best limits [[6],[7]] by a factor of 6 (2) for an LLP mass of 7–15 GeV, as shown in the upper limits of Figure 8.

4. Inclusive displaced-jets search

As mentioned in the introduction, a large number of models predict LLPs decaying into displaced jets. Therefore, it is important to make the displaced-jet search as model-independent as possible. In this search [8], an inclusive search for LLPs decaying into jets is presented, with at least one LLP having a decay vertex within the CMS tracker acceptance but which is displaced from the primary vertex by up to 550 mm in the plane transverse to the beam direction.

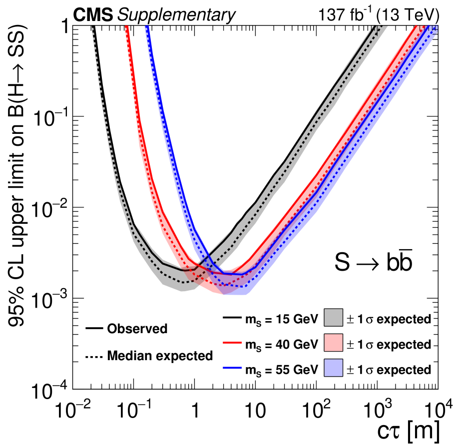

Figure 8: The 95% CL expected (dotted curves) and observed (solid curves) upper limits on the branching fraction B(H → SS) as functions of $c\tau$ for the d quarks decay modes. The exclusion limits are shown for four different mass hypotheses: 7, 15, 40, and 55 GeV [5].

These established current stringent limits for a large number of models predicting long-lived particles with various final state topologies. For example, in the model where the standard model-like Higgs boson decays to two long-lived scalar particles that each decay to a quark-antiquark pair, branching fractions larger than 1% are excluded at 95% C.L. for mean proper decay lengths between 1 mm and 340 mm , see Figure 9. A group of supersymmetric models with pair-produced long-lived gluinos or top squarks decaying into various final-state topologies containing displaced jets is also tested. Gluino masses up to 2500 GeV and top squark masses up to 1600 GeV are excluded at 95% C.L. for mean proper decay lengths between 3 and 300 mm.

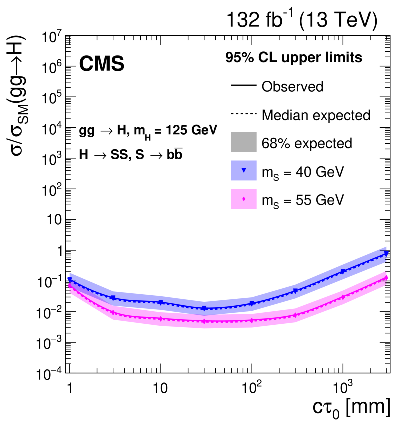

Figure 9: The expected and observed 95% upper limits on the branching fraction of the SM-like Higgs boson decaying to two long-lived scalar particles, assuming gluon-gluon fusion. The Higgs boson production cross section of 49 pb at 13 TeV with mH = 125 GeV is shown at different masses and $c\tau$ for the scalar particle S: the upper limits when each scalar particle decays to a bottom quark-antiquark pair. The solid (dashed) curves represent the observed (median expected) limits [8].

5. Hadronic Decay in Calorimeter

This search is presented for hadronic LLP decays within the ATLAS hadronic calorimeter, with a wide range of mass scenarios [9]. For a SM Higgs boson with a mass of 125 GeV, branching ratios above 10% are excluded at a 95% confidence level for values of c times LLP mean proper lifetime in the range between 20 mm and 10 m depending on the model. A dedicated CalRatio trigger is used to identify narrow, trackless jets with high $\frac{E_H}{E_{EM}}$. An adversarial neural network is used to distinguish the signal jets among BIB (Beam Induced Background) and SM mutlijets , where the adversary reduces the impact of any potential mis-modelling of the Neural Network (NN) input variables, as shown in Figure 10. After that, a Boosted Decision Tree (BDT) model for signal-background separation is used, including the NN outputs as one of the input variables. Finally, ΔR_{min} (jets,tracks) and BDT score identify the signal region, allowing for background estimation through the data-driven ABCD method. The observed numbers of events are consistent with the expected background, and limits for several benchmark signals are determined. Limits are set on hidden sector benchmark models with mediator masses ranging from 60 GeV to 1 TeV and long-lived scalar masses ranging from 5 GeV to 475 GeV, as illustrated in Figure 11.

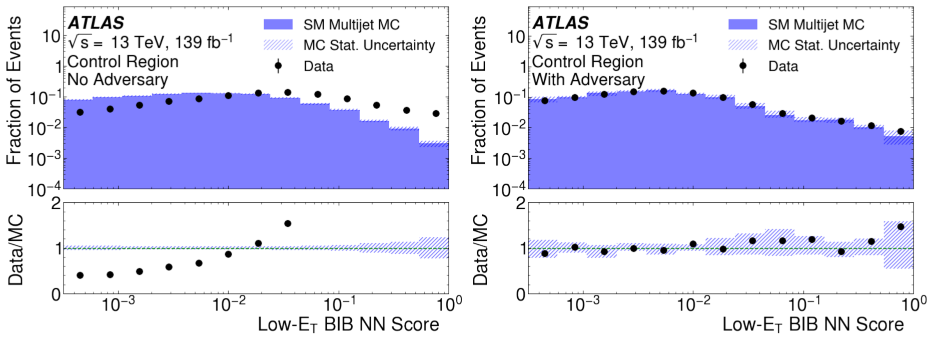

Figure 10: Scores of the NN output in the dijet control region for (a) low-E_T training without an adversary network and (b) training with an adversarial network[9].

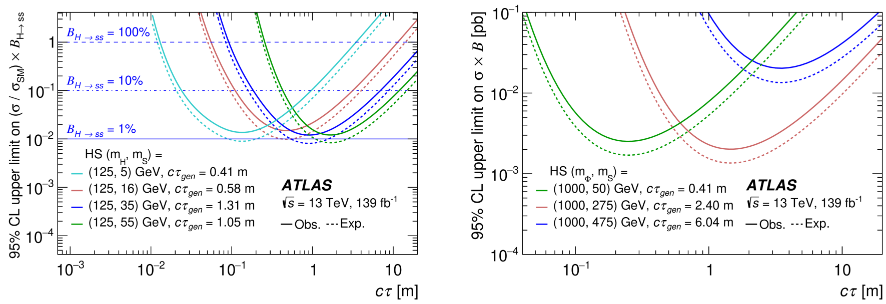

Figure 11: Summary of 95% CL expected and observed limits: (a) the BR of a SM Higgs boson mediator to pairs of neutral LLPs considered in this analysis. The cross-section for SM Higgs boson gluon–gluon fusion production is assumed to be 48.6 pb; (b) the hidden sector (HS) models considered in this analysis, where the mediator is not the SM Higgs boson shows the highest m_ϕ hypothesis with m_ϕ = 1 TeV [9].

6. Displaced Jets + DVs in Muon Spectrometer

Presented here is a search for two displaced vertices from pair-produced long-lived particles decaying into jets. The search employs techniques for reconstructing vertices of LLPs decaying to jets in the ATLAS muon spectrometer displaced between 3 m and 14 m with respect to the primary interaction vertex. Studying the hadronic activity between the HCal's outer region and the MS's middle station, the signal region is defined by two isolated MS Displaced Vertices (DVs) (no jets or tracks in the ΔR cone around the DV axis), as shown in Figure 12. The observed numbers of events are consistent with the expected background and limits for several benchmark signals are determined. The limits are stronger for intermediate LLP masses, while they become weaker for very low and very high masses. The paper presents the first exclusion limits for branching fractions for the Higgs boson with a mass of 125 GeV that are below 0.1%, as illustrated in Figure 13. , as well as the first results for the decay of LLPs into $t\bar{t}$ in the ATLAS muon spectrometer.

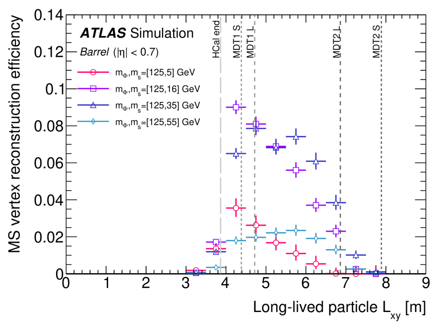

Figure 12: Barrel MS DV reconstruction efficiency for scalar portal samples with m_ϕ = 125 GeV for vertices that pass the baseline event selection and satisfy the vertex isolation criteria as a function of the transverse decay position of the LLP. The vertical lines show the relevant detector boundaries. [10].

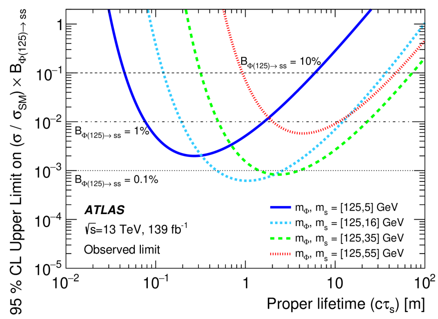

Figure 13: Comparison between observed and expected 95% CL limits on $(\sigma/\sigma_{SM}) \times B$ for m_ϕ = 125GeV [10].

7. Hidden Sector summary

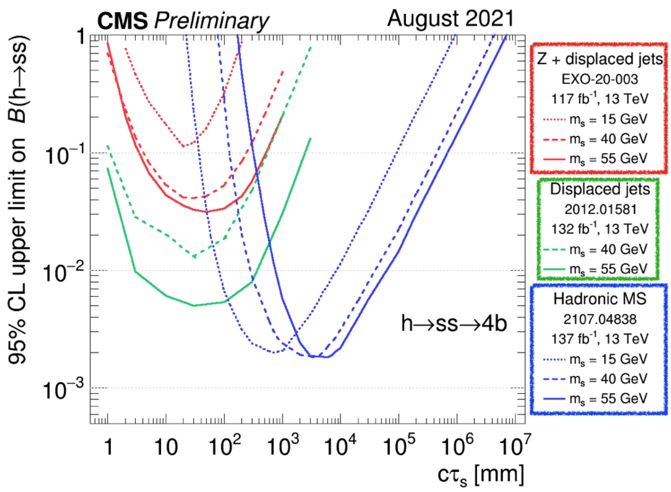

Figure 14: Summarises the observed 95% CL exclusion limit from several CMS hadronic long-lived particle studies on the branching fraction of the standard model higgs boson, h, to two neutral long-lived scalars, s, as a function of the scalar's proper lifetime. The long-lived scalar is assumed to decay to bottom quark pairs with a 100% branching fraction.

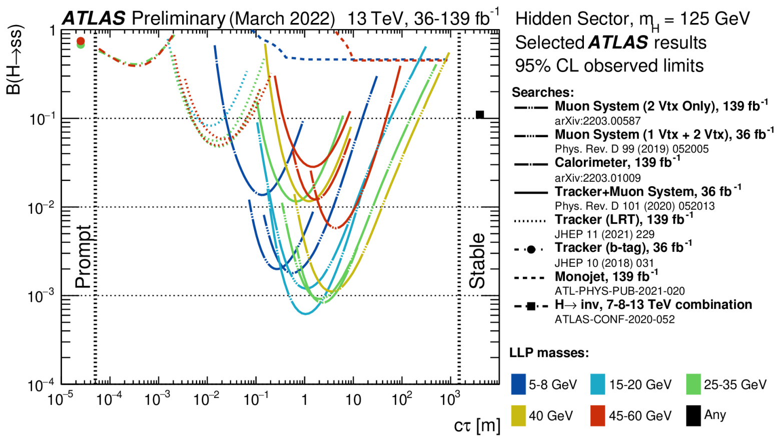

Figure 15: At a 95% confidence level, regions in the Higgs branching fraction versus $c\tau$ plane are excluded for a Hidden Sector model in which a 125 GeV mediator Higgs boson decays to a pair of long-lived neutral scalars (s). The coloured lines represent the regions excluded by the analyses listed in the legend, and the colours of the lines refer to the long-lived scalar mass (or mass range) under consideration. Also shown are exclusions for models where the neutral scalars are prompt or detector-stable. This shows a selection of the most sensitive individual ATLAS 13 TeV results. For clarity, parts of the exclusion curves outside the most sensitive region are omitted.

8. long-lived particles Decaying to Jet Pairs

A search is presented for long-lived particles with a mass in the range of 25–50 GeV/c^2 and a lifetime between 2 and 500 ps. The particles are assumed to be pair-produced in the decay of a 125 GeV/c^2 Standard-Model-like Higgs boson and to decay into two jets. Besides decays to $b\bar{b}$, which are the best motivated in the context of hidden-valley models , decays to $c\bar{c}$ and $s\bar{s}$ quark pairs are also considered. The search strategy is looking for a single displaced vertex with two associated jets as only one of the two decays into the LHCb acceptance. Dijet opening angle ΔR and invariant mass are used to discriminate between signal and background.

No evidence for so far unknown long-lived particles is observed, and limits are set as a function of mass and lifetime. A good sensitivity is obtained for a mass of about 50 GeV and a lifetime of about 10 ps w.r.t Run1 data, as shown in Figure 16. These measurements [11] complement other constraints on this production model at the LHC [12],[13] by placing stronger constraints on small masses and lifetimes.

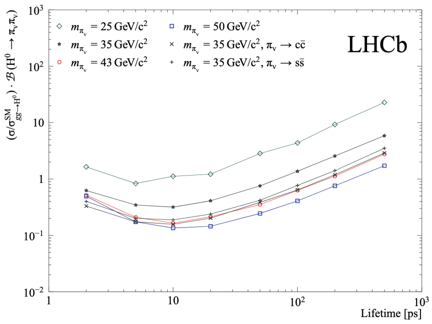

Figure 16: Observed upper limit versus lifetime for different π_v masses and decay modes. The decay $\pi_v \to b\bar{b}$ is assumed, unless specified otherwise [11].

9. Conclusion

In this paper, six analyses targeting long-lived particles decaying to jets at ATLAS, CMS, and LHCb are presented. In particular, the results are interpreted in the context of exotic decays of the Higgs boson to a pair of scalar LLPs (H → SS) with a mass of 125 GeV and for masses between 200 GeV and 1 TeV. No significant excess of events in the signal region is observed relative to the standard model background prediction. The CLs method is used to set 95% CL limits on the cross-section times branching ratio as a function of c times the long-lived particle mean proper lifetime. More researches are being conducted, and more updates with the entire Run 2 dataset and the first Run 3 dataset are expected.

References

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