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Search for long-lived particles produced in association with a Z boson in proton-proton collisions at $\sqrt{s} = 13\,\text{TeV}$

The CMS Collaboration*

Abstract

A search for long-lived particles (LLPs) produced in association with a Z boson is presented. The study is performed using data from proton-proton collisions with a center-of-mass energy of 13 TeV recorded by the CMS experiment during 2016–2018, corresponding to an integrated luminosity of 117 fb^{-1}. The LLPs are assumed to decay to a pair of standard model quarks that are identified as displaced jets within the CMS tracker system. Triggers and selections based on Z boson decays to electron or muon pairs improve the sensitivity to light LLPs (down to 15 GeV). This search provides sensitivity to beyond the standard model scenarios which predict LLPs produced in association with a Z boson. In particular, the results are interpreted in the context of exotic decays of the Higgs boson to a pair of scalar LLPs ($\text{H} \to \text{SS}$). The Higgs boson decay branching fraction is constrained to values less than 6% for proper decay lengths of 10–100 mm and for LLP masses between 40 and 55 GeV. In the case of low-mass (15 GeV) scalar particles that subsequently decay to a pair of b quarks, the search is sensitive to branching fractions $\mathcal{B}(\text{H} \to \text{SS}) < 20\%$ for proper decay lengths of 10–50 mm. The use of associated production with a Z boson increases the sensitivity to low-mass LLPs of this analysis with respect to gluon fusion searches. In the case of 15 GeV scalar LLPs, the improvement corresponds to a factor of 2 at a proper decay length of 30 mm.

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[*] See Appendix A for the list of collaboration members

1 Introduction

Long-lived particles (LLPs) with macroscopic decay lengths arise in many extensions of the standard model (SM) of elementary particles. The long list of classes of models where LLPs are found includes supersymmetry [1–8], little Higgs [9], twin Higgs [10], hidden valley models [11, 12], and dark sector models [13–16]. Long-lived particles may also play a role in explaining baryogenesis [17] or in accommodating neutrino masses [18]. The LLPs produced in proton-proton (pp) collisions at the CERN LHC could decay into SM particles away from the interaction point of the colliding beams.

Models which propose a form of neutral naturalness [19] are of particular interest. In these models, the hierarchy problem is resolved through the existence of a partner of the top quark that is not color-charged under the SM $SU(3)_c$ group but is instead charged under a mirror color group of a hidden sector, and that thereby evades the stringent experimental bounds on strongly produced particles. The Higgs boson (H) may then decay into long-lived bound states of the mirror color group, which subsequently decay into SM particles through the kinetic mixing with the Higgs boson itself. The LLP decays through an off-shell Higgs boson predominantly to a pair of quarks [20]. Such decays will therefore manifest themselves as displaced jets that originate from the hadronization of the final-state quarks.

Previous searches at the LHC for displaced jets have typically relied on jets with large transverse momentum (p_T), whose presence is required in order to pass the trigger requirements. Those searches thereby have had limited sensitivity to decays to displaced jets with low p_T. Here we present an alternative approach that exploits a new LLP search channel, namely the associated production of LLPs with a Z boson, where prompt leptons (electrons and muons) provide an effective trigger for events with low-p_T jets. Figure 1 shows a simplified model where the Higgs boson is produced in association with a Z boson, and subsequently decays to a pair of long-lived scalar particles (S). To tag a jet from an S decay as being displaced, we rely on information from the CMS tracking system, which provides the greatest sensitivity for mean proper decay lengths of 10 cm. Searches for LLPs produced in Higgs boson decays have been recently performed at $\sqrt{s} = 13$ TeV by the CMS [21, 22] and ATLAS experiments [23–26], where they have focused on the production of the Higgs boson through gluon fusion.

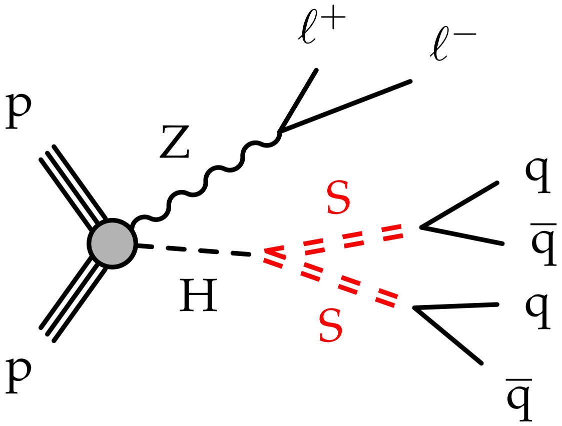

Figure 1: Feynman diagram of a simplified model for the Higgs boson decaying to a pair of long-lived scalar particles (S). The Higgs boson is produced in association with a Z boson, where the Z boson decays to a pair of leptons. The long-lived scalars decay to a pair of quark jets (q).

The paper is organized as follows. A brief description of the CMS detector is given in Section 2.

Section 3 describes the data and the simulated events used. Section 4 explains the displaced-jet identification strategy and the event selection. The estimation of the background is described in Section 5, and the treatment of systematic uncertainties is given in Section 6. Results of the search are described in Section 7, which is followed by a summary of the paper in Section 8.

Tabulated results are provided in the HEPData record for this analysis [27].

2 The CMS detector

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the solenoid volume are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter (ECAL), and a brass and scintillator hadron calorimeter (HCAL), each composed of a barrel and two endcap sections. Forward calorimeters extend the pseudorapidity ( ) coverage provided by the barrel and endcap detectors. Muons are measured in gas-ionization detectors embedded in the steel flux-return yoke outside the solenoid.

The silicon tracker measured charged particles within the pseudorapidity range < 2.5 (< 3.0) during the LHC running period in 2016 (2017–2018). For the data used in this paper, the silicon tracker consisted of 1440 (1856) silicon pixel detector modules during the 2016 (2017–2018) running period and 15,148 silicon strip modules throughout the 2016–2018 data-taking period. For jet constituents with $1 < p_{\mathrm{T}} < 10\,$GeV and < 1.4 (< 3.0), the track resolutions are typically 1.5% in p_{T} and 25–90 m (20–75 m) in the transverse impact parameter during 2016 (2017–2018) [28].

In the region < 1.74, the HCAL cells have widths of 0.087 in and 0.087 in azimuth ( ). In the - plane, and for < 1.48, the HCAL cells map onto 5 5 arrays of ECAL crystals to form calorimeter towers projecting radially outwards from a point close to the nominal interaction point. For > 1.74, the coverage of the towers increases progressively to a maximum of 0.174 in and . Within each tower, the energy deposits in ECAL and HCAL cells are summed to define the calorimeter tower energies, which are subsequently used to provide the energies and directions of hadronic jets.

Events of interest are selected using a two-tiered trigger system [29]. The first level, composed of custom hardware processors, uses information from the calorimeters and muon detectors to select events at a rate of around 100 kHz within a time interval of less than 4 s [30]. The second level, known as the high-level trigger, consists of a farm of processors running a version of the full event reconstruction software optimized for fast processing, and reduces the event rate to around 1 kHz before data storage. A more detailed description of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found in Ref. [31].

3 Data and simulated samples

This search uses a sample of pp collisions collected in 2016–2018 at $\overline{s} = 13\,$TeV, corresponding to an integrated luminosity of 137.6 fb ^{1}. During part of the 2016 data-taking period there was a decreased tracking efficiency within the tracker system that resulted in spurious displaced jets; therefore collision events occurring during the first 20 fb ^{1}, when the effect took place, are excluded from this search. After removing the affected events, the effective total integrated luminosity used by the search is 117 fb ^{1}.

Events in this search were recorded using lepton-based triggers. One set of triggers requires an isolated pair of either electrons or of muons [32]. Another set of triggers requires electron-muon pairs, where both the electron and muon are required to be isolated. The electron-muon pair triggers, which are included as part of the study of the background, are discussed later in this paper.

The performance of the analysis of ZH events containing LLPs is evaluated using simulated events. Quark- and gluon-initiated associated Higgs boson production processes are generated with POWHEG 2.0 [33–38] at leading order (LO) and next-to-LO (NLO) precision, respectively. Higgs boson decays to long-lived scalars are generated with PYTHIA 8.226 [39]. The LLP is simulated as a generic scalar particle with a 100% branching fraction to either heavy quarks (studied here using b quarks) or light quarks (studied here using d quarks). The mass of the scalar particle corresponds to 15, 40, or 55 GeV, and the proper mean lifetime is varied within the range 1–1000 mm. These ranges are consistent with the recommendations of the LHC Higgs Cross Section Working Group [40].

The Drell–Yan process (DY), which is the main background in this search, is simulated at NLO in quantum chromodynamics (QCD) using the MADGRAPH5_aMC@NLO 2.4.2 [41] generator with up to two additional partons in the final state at the matrix element (ME) level. The corresponding cross section is calculated with FEWZ v3.1b2 [42] at next-to-NLO (NNLO) in QCD and NLO precision in electroweak theory. The top quark-antiquark ($\mathrm{t\bar{t}}$) background is simulated with NLO precision in QCD using the MADGRAPH5_aMC@NLO generator, and its cross section is obtained from the TOP++ v2.0 [43] prediction that includes NNLO corrections in QCD and resummation of the next-to-next-to-leading-logarithm soft-gluon terms. The single top quark processes are simulated at NLO in QCD via either POWHEG 2.0 or MADGRAPH5_aMC@NLO and their cross sections are computed, at the same order of precision, using HATHOR v2.1 [44]. For the simulated samples corresponding to the 2016 (2017–2018) data-taking periods, the NNPDF v3.0 (v3.1) NLO (NNLO) parton distribution functions, PDFs, are used [45, 46]. The CUETP8M1 tune [47] is used for the simulated samples corresponding to the 2016 data-taking period, while the CP5 tune [48] is used for the 2017 and 2018 simulated data. For processes generated at NLO (LO) in QCD with the MADGRAPH5_aMC@NLO generator, events from the ME characterized by different parton multiplicities are merged via the FxFx [49] (MLM [50]) prescription. The simulated events at the ME level for both the signal and background processes are interfaced with PYTHIA 8.226 or a later version to simulate the shower and hadronization of partons in the initial and final states, along with the underlying event description.

For all simulated processes, the detector response is simulated using a detailed description of the CMS detector based on GEANT4 [51]. Object and event reconstruction are performed with the same algorithms as are used for the data. Minimum bias events are superimposed on each simulated hard scattering event to reproduce the effect of extra pp interactions within the same or neighboring bunch crossing as the recorded event (pileup). The frequency distribution of the additional events is adjusted to match that observed during each data-taking period.

4 Search strategy and selections

The basic strategy of this search is to use the displaced jet multiplicity ($N_{\mathrm{j}}^{\mathrm{dis}}$) in the event to distinguish the signal from the background processes, where a displaced jet is defined as a jet that passes specified selections made on the three tagging variables described later in this section. Signal events typically contain $N_{\mathrm{j}}^{\mathrm{dis}}$ 2, while SM background processes exhibit a sharply falling distribution in $N_{\mathrm{j}}^{\mathrm{dis}}$.

Backgrounds include events with displaced jets arising from decays of long-lived SM particles, nuclear interactions with the tracker material, photon conversions, and mismeasurement of jet constituents. Since the simulation may not capture these effects perfectly, we use a strategy based on control samples in data to estimate the number of misidentified displaced jets from SM background processes, by considering control samples of low-p_{T} opposite-sign dilepton pairs (modeling the dominant SM Z boson production) and of different-flavor (e) pairs (modeling the subdominant contribution from $\mathrm{t\bar{t}}$ and single top quark production). Rare background processes, including SM multiboson production, are estimated adequately from simulation, as their contribution to the signal sample is small.

The energy of each electron is determined from a combination of the electron momentum at the primary interaction vertex, to be defined below, as determined by the tracker, the energy of the corresponding ECAL cluster, and the energy sum of all bremsstrahlung photons spatially compatible with originating from the electron track [52]. The momentum of each muon is obtained from the curvature of the corresponding track [53]. Electron pairs are required to have a minimum p_{T} of 25 (15) GeV for the leading (subleading) candidate, while for muon pairs the thresholds are 25 (12) GeV. Electrons and muons are required to have < 2.5 and < 2.4, respectively. The resulting efficiencies for electrons and muons, measured in SM Z boson simulation and data, are above 90%.

Jets are reconstructed offline from the energy deposits in the calorimeter towers, clustered using the anti-k_{T} algorithm [54, 55] with a distance parameter of 0.4. In this process, the contribution from each calorimeter tower is assigned a momentum, the absolute value and the direction of which are given by the energy measured in the tower and the coordinates of the tower relative to those of the vertex. The raw jet energy is obtained from the sum of the tower energies, and the raw jet momentum by the vectorial sum of the tower momenta, which results in a nonzero jet mass. The raw jet energies are then corrected to establish a uniform relative response of the calorimeter in , and a calibrated absolute response in p_{T}. Jets are required to have a minimum p_{T} of 35 GeV and to fall within the silicon strip tracker acceptance < 2.4. Cuts are applied to suppress contributions from electronic noise, electrons, and muons. 'High purity' tracks with p_{T} 1 GeV [28] are subsequently matched to the jets using a distance parameter of 0.4. The direction of each track included in the matching is extrapolated to the front face calorimeter and used to evaluate whether the jet is displaced.

With the objects used in the analysis, the search sample is defined as follows. Events are required to have a primary interaction vertex (PV), where among the candidate vertices associated with a given pp bunch crossing, the PV is taken to be the one with the largest value of summed physics-object p_{T}^{2}. The objects of interest are the jets, clustered using a jet finding algorithm [54, 55] with the tracks assigned to candidate vertices as inputs, and the associated missing transverse momentum, taken as the negative vector sum of the p_{T} of those jets. Additionally, there must be at least one opposite-sign, same-flavor lepton pair in the event. The lepton pair is required to have an invariant mass between 70 and 110 GeV and a p_{T} of at least 100 GeV. The selection requirement on the p_{T} of the lepton pair serves to suppress DY events with a typically low dilepton p_{T}, and to enhance the relative contribution of associated Higgs boson production. We require that there be no additional leptons with p_{T} larger than 15 GeV, and at least one jet.

In addition to the search sample, we define two control samples that are used for the background estimation presented in Section 5. The Z boson control sample has the same requirements as the signal sample, except the dilepton p_{T} must range between 10 and 100 GeV. A second control sample is used to estimate the background from $t\bar{t}$ and single top quark production, and is hereafter referred to as the top quark control sample. The top quark control sample is selected by requiring different-flavor lepton pairs with a p_T of at least 10 GeV.

In order to identify displaced jets, the properties of the tracks associated with jets are used to calculate three displacement variables known as "tagging variables," as previously reported by the CMS Collaboration [56]. Distributions of the tagging variables in data and simulation are shown in Fig. 2. The first tagging variable is the jet impact point significance ($\hat{\text{IP}}^{\text{2D}}_{\text{sig}}$), defined as the median of the logarithm (base 10) of the impact point significance ($d_{xy}/ \ _{d_{xy}}$) of all the tracks matched to the jet, with d_{xy} being the track transverse impact parameter and $_{d_{xy}}$ its uncertainty. The SM background processes, largely composed of prompt jets whose tracks have d_{xy} values of the order of $_{d_{xy}}$, exhibit an $\hat{\text{IP}}^{\text{2D}}_{\text{sig}}$ value peaked near zero. On the other hand, displaced decays of LLPs tend to have jets with larger $\hat{\text{IP}}^{\text{2D}}_{\text{sig}}$ values. For $\hat{\text{IP}}^{\text{2D}}_{\text{sig}} > 1.25$, the chosen threshold, it means that the transverse impact parameter is about 18 $_{d_{xy}}$ and thus highly significant. The second tagging variable is the jet transverse angle ($\hat{\ }^{\text{2D}}$), which is calculated as the median logarithm (base 10) of the angle between the track direction and the vector connecting its innermost hit in the silicon tracker to the PV. Prompt jets have $\hat{\ }^{\text{2D}}$ near zero as the vector connecting the PV to the track's innermost hit tends to be aligned with the jet-axis. In the case of LLPs, the directions of these vectors are not necessarily aligned, thus corresponding to larger angles. The last tagging variable is $_{\text{max}}$, which is calculated as follows: for each reconstructed vertex (v_i), we define as

$$(v_i) = \frac{_{\text{tracks } \ v_i} p_{\text{T}}^{\text{track}}}{_{\text{all tracks}} p_{\text{T}}^{\text{track}}}, \tag{1}$$

the ratio of the summed-p_T for the tracks within the jet that are associated with that particular vertex to the total summed-p_T for all tracks within the jet. The $_{\text{max}}$ variable corresponds to the maximum value across all reconstructed vertices. The LLPs form displaced jets that typically exhibit $_{\text{max}}$ values near zero, as the tracks belonging to these jets do not originate from any collision vertex.

Finally, we determine requirements for each of the three tagging variables that together maximize the discovery reach for this search. Jets are identified as displaced when $\hat{\text{IP}}^{\text{2D}}_{\text{sig}} > 1.25$, $\hat{\ }^{\text{2D}} > \ \ 1.5$, and $_{\text{max}} < 0.45$. These selections were determined via a multi-step optimization, where the selection cuts correspond to a relatively large signal significance, as calculated using the Punzi significance method [57]. The statistical uncertainty on the background was considered during the optimization. The distribution of the number of displaced jets, $N_{\text{j}}^{\text{dis}}$, is then used to distinguish the signal from background, where an excess of events where $N_{\text{j}}^{\text{dis}} \ \ 2$ would indicate the presence of a signal. The signal efficiency with respect to the baseline requirement to select a Z boson in association with a jet was measured. The resulting efficiency for signal events in the $N_{\text{j}}^{\text{dis}} \ \ 2$ bin, was found to be 5.4, 16.1, and 19.5% (5.9, 19.8, and 22.3%) in the 4b (4d) quarks final state for masses of 15, 40, and 55 GeV, respectively, and for a mean proper decay length of 10 mm. The corresponding background rejection, inferred from simulation, was found to be $7.6 \ \ 10^5$.

5 Background estimation

In the case of the two main sources of background: DY and top quark (including $t\bar{t}$ and single top) production, the background estimation is carried out using the control samples defined

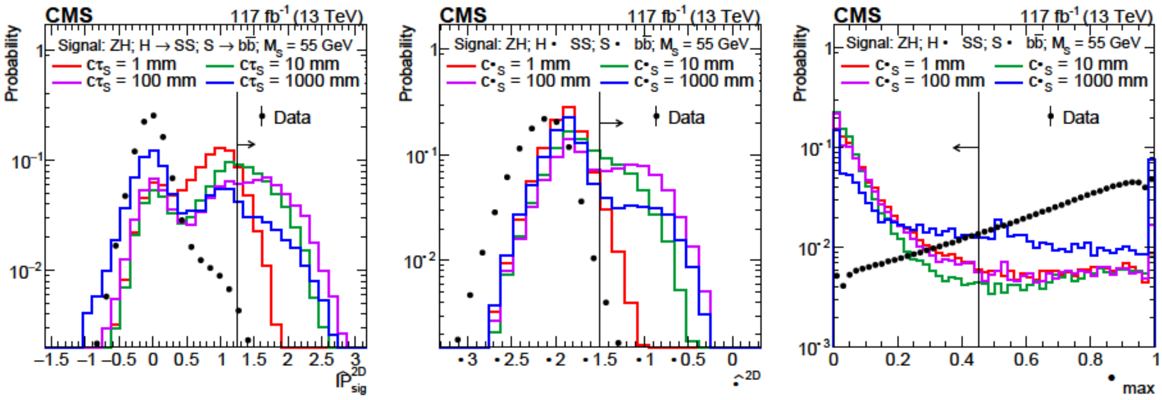

Figure 2: Distributions of the three tagging variables for data and for four signal samples, where the decay lengths of the signal range from 1 to 1000 mm. The left figure displays the distributions for the $\hat{\mathrm{IP}}^{2D}_{\mathrm{sig}}$ tagging variable, while the center and right figures display the distributions for the $\hat{\Theta}^{2D}$ and α_{max} tagging variables, respectively. Overlaid on the figures is a line with an arrow pointing to the region of where values of the variable are used to aid in distinguishing possible displaced jets from background jets.

in the previous section. Since the displaced jet tagging variables can be affected by a variety of instrumental effects, we estimate the number of displaced jets in the search sample from the control samples by performing a simultaneous binned maximum likelihood fit. For each displaced jet multiplicity bin i, we define transfer factors from the control samples to the signal sample using simulation. The DY transfer factors (R_i^{Z}) are defined as the ratio of the yields in the ith bin in the search sample to the corresponding bin in the Z boson control sample, where both yields are obtained from the DY simulation. Similarly, the transfer factors for the top quark background processes (R_i^{t}) are the ratios of the yield in the ith bin in the search sample to the corresponding bin in the top quark control sample, where both yields are obtained from the simulation of $\mathrm{t\bar{t}}$ and single top quark processes. A third set of transfer factors ($R_i^{\mathrm{t}\to\mathrm{Z}}$) is used to account for the contamination from top quark background processes in the Z boson control sample. The $R_i^{\mathrm{t}\to\mathrm{Z}}$ variable is defined as the ratio of the yields in the ith bin in the Z boson control sample to the corresponding bin in the top quark control sample, where both yields are obtained from the simulation of $\mathrm{t\bar{t}}$ and single top quark processes.

The R_i values, their associated uncertainties, as well as the yields in the control and signal samples are used as the ingredients in a likelihood model, which fits the background contributions and the signal yield. The fit is performed simultaneously across the signal and control samples. The background yields in the search sample, for each displaced jet multiplicity bin i, are the sum of the yields from the individual background processes. The contributions from the main background processes (DY and top quark production) in the signal sample are estimated as the product of the R_i values and a set of freely floating parameters, which represent the yield in each of the i bins for a specific background process in the corresponding control sample. By performing a fit in the signal and control samples we are able to obtain simultaneously for each process the yields in the control samples and the values of the transfer factors, and from these the estimated total background yield in the signal sample.

The systematic uncertainties affecting the R_i transfer factors, which are described in Section 6, are included in the simultaneous fit. Each systematic uncertainty source is modeled as a log-normal constraint in the likelihood using a set of derived relative uncertainties (σ^i_{rel}) and a single normally distributed nuisance parameter x according to the expression $R_i(1+\sigma^i_{\mathrm{rel}})^x$, such that the mean of the transfer factor is the central value extracted from the simulation. The corresponding statistical uncertainty in R_i is propagated and treated as uncorrelated among the bins.

For rare background processes such as SM multiboson events or SM Higgs boson decays, the contributions to the search sample are taken directly from the simulation, and correspond to less than 2% of the total background yield.

6 Systematic uncertainties

The main sources of systematic uncertainty are related to the possibility that the transfer factors obtained from the simulation do not accurately reflect the data, and the values are detailed in Table 1.

In order to check the validity of the treatment of systematic uncertainties and rule out other possible systematic effects, we construct seven independent validation samples (VS, Table 2), by inverting the requirement on one or more of the displaced jet tagging variables, where the signal contamination in each validation sample is negligible. We perform the background estimation procedure for each validation region in the same manner as in the main search sample, as detailed in Section 5. If the background estimation is working as intended and the treatment of the systematic uncertainties is adequate, we should find that the binned-likelihood model will accurately reproduce the displaced jet multiplicity distribution in all the validation samples. No significant deviations are observed when performing the fit in the validation samples (see Fig. 3), thus validating the background estimation method and the treatment of the systematic uncertainties.

Table 1: The systematic uncertainties in the background and signal yield expectations. Dashes indicate that the systematic effect is not applicable or is negligible.

Uncertainty source	Signal (%)	Background (%)
Luminosity	1.8	—
Dilepton trigger scale factors	1	—
Lepton energy scale	0.5–1.0	—
Lepton ID and ISO scale factors	1–2	—
Jet energy scale	4–8	2–4
Tagging variable shape correction	1–20	1–5
Transfer factor (statistical)	—	1–90
Simulated signal sample size	1–10	—
Control region (statistical)	—	0.1–5.0

The signal yield observed is directly affected by the uncertainty in the integrated luminosity, estimated to be 1.8% [58–60]. Lepton energy scale uncertainties affect the efficiency of the Z boson mass constraint in the search sample; these are varied according to values extracted from a study of leptonic Z boson decays and result in 0.5–1.0% uncertainties in the signal yields. Lepton efficiency uncertainties are extracted from a tag-and-probe analysis [61] and are 1–2%. Uncertainties in the jet energy scale affect the jet p_{T} selection efficiency at the level of 4–8% (2–4%) for signal (background). Varying the shape of the displaced jet tagging variable distributions to account for the measured simulation mismodeling results in an uncertainty of 1–20% (1–5%) for signal (background), depending on the multiplicity bin. The statistical uncertainty in the transfer factors increases with the displaced jet multiplicity and reaches a maximum of 90% in the $N_{\mathrm{j}}^{\mathrm{dis}}$ 2 bin, thus representing the largest source of uncertainty in the search. The statistical uncertainty contribution in the signal sample from the control samples is due to the finite size of the control samples in data and is found to be 0.1–5%. The statistical uncertainty in the yields of the background processes taken from simulation is found to be negligible. The signal simulation statistical uncertainty is found to be 1–10% in the signal sample, depending on the signal model and the $N_\mathrm{j}^\mathrm{dis}$ bin.

Table 2: Summary of the track-based displaced-jet tagging requirements to define the validation samples.

	$\hat{\mathrm{IP}}^\mathrm{2D}_\mathrm{sig\ cut}$	$\hat{\ }^\mathrm{2D}_\mathrm{cut}$	$_\mathrm{max\ cut}$
VS_1	1.25	1.5	0.45
VS_2	1.25	1.5	0.45
VS_3	1.25	1.5	0.45
VS_4	1.25	1.5	0.45
VS_5	1.25	1.5	0.45
VS_6	1.25	1.5	0.45
VS_7	1.25	1.5	0.45
Sig S	1.25	1.5	0.45

7 Results

The result of the background estimation procedure is compared with the observed data in Fig. 3, where we show the content of the $N_\mathrm{j}^\mathrm{dis}$ 2 bin in each of the seven validation samples, along with the content in the signal sample. Additional minor background processes, hereafter referred to as "Other" backgrounds, are included in Fig. 3. "Other" backgrounds include processes such as the production of SM dibosons, SM Higgs bosons, W+jets, and QCD. No excess in the data with respect to the SM background is observed. In the most sensitive bin in the signal sample, $N_\mathrm{j}^\mathrm{dis}$ 2, we observe 3 events with an expected background of 3.5 1.8.

We set upper limits on the Higgs boson branching fraction to a pair of long-lived scalars for different masses and as a function of the mean proper decay length of the scalar. We follow the LHC $\mathrm{CL_s}$ criterion [62, 63] by using the profile likelihood ratio test statistic and the asymptotic formula [64] to evaluate the 95% confidence level (CL) observed and expected limits on the Higgs boson branching fraction to a pair of long-lived scalars. Systematic uncertainties are propagated by incorporating nuisance parameters that represent the different sources of the uncertainty, which are profiled in the maximum likelihood fit [65]. Two scenarios are considered: S decays to a pair of b quarks and S decays to a pair of d quarks. The 95% CL upper limits are shown in Fig. 4. We constrain the Higgs boson branching fraction to long-lived scalars decaying to d (b) quarks at the 3–4 (4–5)% level for masses of 40 and 55 GeV and mean proper decay lengths in the range 10–100 mm. The upper bound on the Higgs boson branching fraction to 15 GeV long-lived scalars decaying to d (b) quarks is about 14 (13)% in the 20–35 mm range of mean proper decay lengths. In addition to intepreting the results in the context of exotic Higgs boson decays to long-lived scalar partilces, we note that this search will be sensitive to beyond the SM scenarios in which LLPs are produced in association with a Z boson.

8 Summary

A search for long-lived particles (LLPs) produced in association with a Z boson decaying to a pair of electrons or muons has been performed. The decays of LLPs in the tracker volume result in a displaced-jet signature, which is used to distinguish signal from SM background.

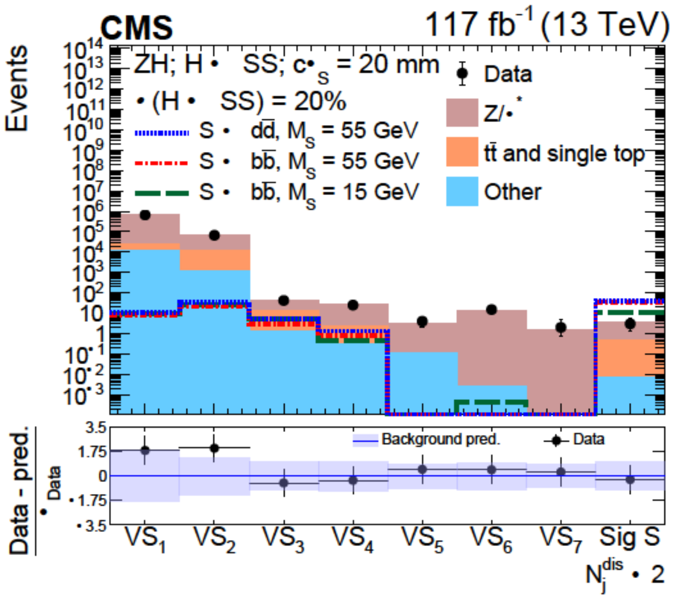

Figure 3: The background estimate and the observed data in the $N_j^{\mathrm{dis}} \geq 2$ bin, for each of the seven validation samples (VS_1 through VS_7), along with the signal sample (Sig S). Signal model distributions for scalar masses of 15 and 55 GeV with a proper mean decay length of 20 mm are also shown. The Higgs boson branching fraction to long-lived scalars ($\mathcal{B}(\mathrm{H} \to \mathrm{SS})$) is set to 20%.

No excess over the expected SM event rate is observed. The results of this search provide sensitivity to beyond the SM scenarios that predict LLPs produced in association with a Z boson. In particular, stringent exclusion limits on exotic Higgs boson decays to long-lived scalars are obtained. The Higgs boson decay branching fraction $\mathcal{B}(\mathrm{H} \to \mathrm{SS})$ is constrained to values less than 6% for proper decay lengths of 10–100 mm and for long-lived particle masses between 40 and 55 GeV. In the case of low-mass ($\approx$15 GeV) scalar particles that subsequently decay to a pair of b quarks, the search is sensitive to branching fractions $\mathcal{B}(\mathrm{H} \to \mathrm{SS}) < 20\%$ for mean proper decay lengths of 10–50 mm. This correspomnds to an improvement in sensitivity with respect to gluon fusion searches by a factor of 2 at a proper decay length of 30 mm.

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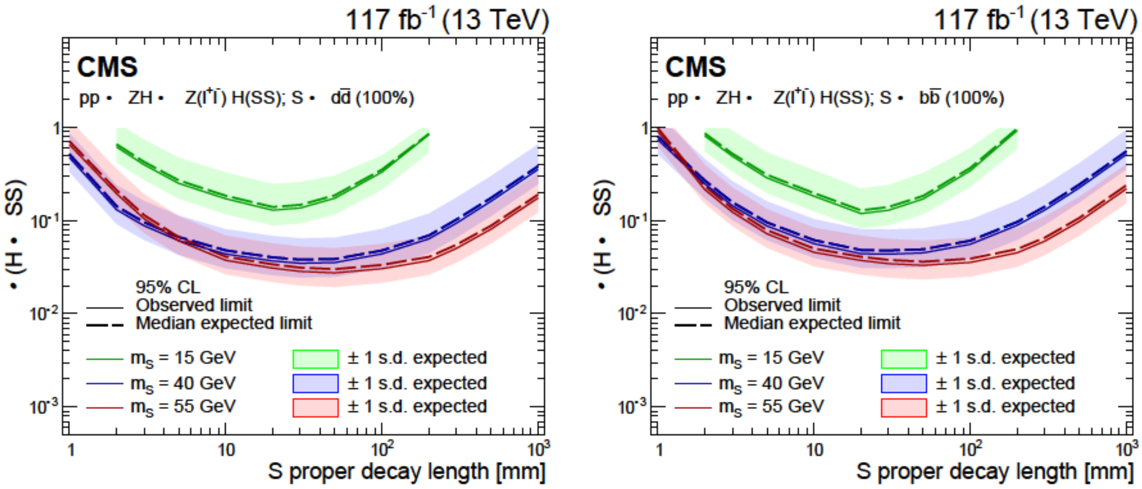

Figure 4: Exclusion limits at 95% CL on the Higgs boson branching fraction to long-lived scalars $\mathcal{B}(\mathrm{H} \to \mathrm{SS})$. Limits are presented for scalar decays to d quarks (left) and b quarks (right) as a function of the mean proper decay length of the scalar. The limits for the different scalar masses are shown in different colors for each scalar decay mode.

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