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Search for vector-like leptons with long-lived particle decays in the CMS muon system in proton-proton collisions at $\sqrt{s} = 13$ TeV

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Abstract: A first search is presented for vector-like leptons (VLLs) exclusively decaying into a light long-lived pseudoscalar boson and a standard model τ lepton. The pseudoscalar boson is assumed to have a mass below the $\tau^+\tau^-$ threshold, so that it decays exclusively into two photons. It is identified using the CMS muon system. The analysis is carried out using a data set of proton-proton collisions at a center-of-mass energy of 13 TeV collected by the CMS experiment in 2016–2018, corresponding to an integrated luminosity of 138 fb^{-1}. Selected events contain at least one pseudoscalar boson decaying electromagnetically in the muon system and at least one hadronically decaying τ lepton. No significant excess of data events is observed compared to the background expectation. Upper limits are set at 95% confidence level on the vector-like lepton production cross section as a function of the VLL mass and the pseudoscalar boson mean proper decay length. The observed and expected exclusion ranges of the VLL mass extend up to 700 and 670 GeV, respectively, depending on the pseudoscalar boson lifetime.

Keywords: Beyond Standard Model, Hadron-Hadron Scattering, Lepton Production, Tau Physics

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1 Introduction

The standard model (SM) of particle physics successfully explains the interactions of elementary particles. However, some fundamental questions remain unexplained, such as the hierarchy problem and the nature of dark matter. One important feature of the SM is that fermions are chiral i.e., left- and right-handed fermions experience different weak interactions. Beyond-the-SM (BSM) models hypothesize the existence of additional chiral fermions, but direct searches for such fermions and measurements of the production cross section and properties of the Higgs boson (H) at the CERN LHC have largely excluded their existence [1–4]. Therefore, if new elementary fermions exist, they should be of vector-like (nonchiral) nature. Vector-like fermions are among the simplest and well-motivated extensions of the SM [5–7]. They are predicted in various BSM scenarios, including, but not limited to, physics with extra dimensions [8, 9], string theories [10–12], supersymmetric models [13–16], and grand unification theories [17–19].

At the LHC, vector-like quarks (VLQs) would be produced in pairs via quantum chromodynamics (QCD) processes or singly via electroweak interactions [20, 21]. Searches for VLQs have probed a large phase space, excluding mass hypotheses up to around 1.5 TeV [22–24]. In contrast, vector-like leptons (VLLs) would be produced via s-channel electroweak processes with much smaller production cross sections than the ones of VLQs. The VLL production cross section depends on the VLL mass, weak isospin, and weak hypercharge.

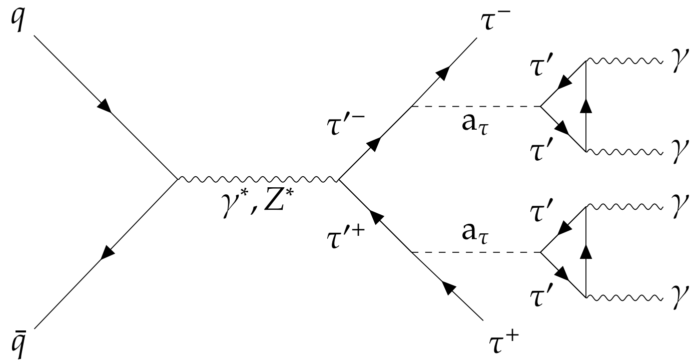

Figure 1. Feynman diagram of pair production of singlet vector-like leptons (τ'), which in turn both decay into an SM τ lepton and a new long-lived pseudoscalar boson (a_τ).

The VLLs typically decay via mixing with the SM τ lepton into νW, τZ, or τH [6, 7]. Alternative models predict more exotic decays into two SM third-generation quarks and one τ lepton via an off-shell leptoquark [25]. Searches for VLLs have been recently performed by the ATLAS and CMS collaborations using the data set of proton-proton (pp) collisions at $\sqrt{s} = 13\,\mathrm{TeV}$, corresponding to an integrated luminosity of about $140\,\mathrm{fb}^{-1}$ [24, 26–29]. In particular, singlet VLLs with prompt decays in the mass range between 125 and 150 GeV are excluded by the CMS search [28].

In many BSM theories, vector-like fermions are accompanied by light pseudoscalar bosons, also referred to as axion-like particles (ALPs). Examples include composite Higgs models [30], Little Higgs models [31, 32], and theories of quark and lepton compositeness [33, 34]. The presence of pseudoscalar bosons changes the collider phenomenology of the VLQs and VLLs and typically leads to final states that include low-mass diphoton resonances [35].

In this paper, a novel BSM physics model is studied in which a complex scalar field transforms as a singlet under the SU(2) gauge group and has Yukawa interactions with the weak-singlet VLL [36]. The mass mixing between the VLL and the SM third-generation charged lepton leads to the emergence of a heavy physical VLL (τ') and the well-established τ lepton. This complex scalar field has a vacuum expectation value and its charge-parity (CP)-odd component is lighter than τ'. The LHC phenomenology of this model is dominated by the VLL pair production $\mathrm{pp} \to \tau'^{+}\tau'^{-}$ with subsequent τ' decays to $\tau\mathrm{a}_\tau$, νW, τZ, and τH, where a_τ is a new physical pseudoscalar boson. If the mass of the τ' VLL (m_{VLL}) arises from a Lagrangian term independent of the vacuum expectation value, then $\tau' \to \tau\mathrm{a}_\tau$ is the dominant τ' decay channel. For pseudoscalar boson masses (m_{a}) smaller than twice the τ mass (m_τ), a_τ predominantly decays to two photons (γ) via a τ' loop. An example Feynman diagram of this process is presented in figure 1. Moreover, for typical values of parameters in this model (coupling between a_τ and τ' of order 0.1, m_{a} at the GeV scale and m_{VLL} of order several hundreds of GeV), a_τ will have a mean proper decay length ($c\tau_{\mathrm{a}}$) of a few tens of mm [36]. Given that a_τ is produced via the decay of a heavy particle, it typically has a very large momentum, thus a_τ may decay several meters away from the pp interaction point.

This article presents the first search for singlet VLLs decaying into a light long-lived a_τ and a τ lepton. The subsequent decay of a_τ is assumed to be exclusively into two photons.

The analysis is performed using a data set of pp collisions at $\sqrt{s} = 13\,\text{TeV}$ collected by the CMS experiment from 2016 to 2018, collectively known as Run 2, and corresponding to an integrated luminosity of $138\,\text{fb}^{-1}$. Events of interest contain at least one electromagnetically decaying a_τ in the muon system and at least one hadronically decaying τ lepton (τ_h). The collimated photons from the a_τ decay can produce a particle shower by interacting with the steel shielding material of the CMS muon system, similar to a sampling calorimeter. The shower is reconstructed as a localized high-multiplicity cluster of muon detector hits, denominated as a muon detector shower (MDS). The MDS object has been used in previous long-lived particle (LLP) searches by the CMS experiment [37–39]. Because of the calorimetric nature of the MDS signature, the MDS object is sensitive to the LLP energy rather than its mass. Therefore, this search would be equally sensitive to signal hypotheses for any $m_\text{a} < 2m_\tau$. A value of $m_\text{a} = 2\,\text{GeV}$ is used as a benchmark in this search. For $m_\text{a} > 2m_\tau$, a_τ would predominantly decay to τ leptons at tree level resulting in substantially shorter lifetimes [36]. Thus alternative search strategies focusing on τ lepton final states could provide greater sensitivity for such scenarios. The VLL signal presented here (figure 1) depends only on m_VLL and $c\tau_\text{a}$. The results are interpreted within the VLL singlet model, although the search is also sensitive to VLL doublet models. Tabulated results and signal efficiencies are provided in the HEPData record for this analysis [40].

This paper is outlined as follows: the CMS detector is briefly described in section 2, followed by a description of the simulation samples in section 3. Event reconstruction and selection are detailed in sections 4 and 5, respectively. The background estimation strategy is described in section 6. Sources of systematic uncertainties affecting the modeling of the signal and background are detailed in section 7. The results are presented in section 8, followed by a summary of this search in section 9.

2 The CMS detector

The central feature of the CMS detector 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 (η) coverage provided by the barrel and endcap detectors. Gas-ionization muon detectors embedded in the steel flux-return yoke outside the solenoid cover the region of $|\eta| < 2.4$. In Run 2, this system comprises three technologies: drift tubes (DTs), cathode strip chambers (CSCs), and resistive plate chambers (RPCs). More detailed descriptions of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found in refs. [41, 42].

The DT system covers the barrel region of $|\eta| < 1.2$. The DT chambers are arranged in five wheels along the beamline axis (z), and interleaved with layers of the steel flux-return yoke. Within each wheel, four concentric layers (stations) around the z axis are located approximately 4, 5, 6, and 7 m radially away from the interaction point, and named MB1–MB4 starting from the innermost one, where MB stands for “muon barrel”. Each chamber consists of rectangular drift cells arranged in parallel and grouped in four layers to form superlayers (SLs). When charged particles transverse a cell, they ionize the gas and produce charges that drift towards an anode wire. The signal pulse measured is recorded as a hit. While all chambers are equipped with two SLs to measure the hit coordinate in the $r - \phi$ plane (where ϕ is azimuthal angle in radians), only MB1–MB3 station chambers contain a central SL to determine the hit z position.

The CSC system extends the coverage in the endcap region of $0.9 < |\eta| < 2.4$. The CSC chambers are interleaved with the steel layers in four disks (stations) per endcap, located approximately 7.0, 8.0, 9.5, and 10.5 m away from the interaction point along the z axis. Each station consists of rings of chambers designated by MES/R, where "ME" means "muon endcap", S indicates the station number, and R is the ring number. The CSC chambers comprise six layers of cathode strips in the r direction and anode wires perpendicular to the strip. Charged particles crossing a chamber ionize the gas and produce signal pulses in both anode wires and cathode strips. The information from anode and cathode signals are combined to provide the space and time coordinates of the hit in each layer.

The RPC detectors are double-gap chambers operated in avalanche mode. Signals are collected by readout strips, which are located in between the two gas gaps. The RPCs are characterized by their time resolution of around 1 ns, providing hits with a precise bunch-crossing assignment. They are mounted in both CSC and DT stations, covering the region of $|\eta| < 1.9$.

Events of interest are selected using a two-tiered trigger system. 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 fixed latency of about 4 μs [43]. 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 [44, 45].

3 Simulated samples

This search targets signal events with $\mathrm{pp} \to \tau'^{+}\tau'^{-}$ production. The branching fractions $\mathcal{B}(\tau' \to \tau \mathrm{a}_\tau)$ and $\mathcal{B}(\mathrm{a}_\tau \to \gamma\gamma)$ are assumed to be 100%. The hard scattering process is generated at leading order (LO) using the MadGraph5_aMC@NLO2.6.5 matrix element generator [46] and the VLL model presented in ref. [36]. Signal samples are generated with τ' masses in the range of 200–800 GeV, where the trigger selection efficiencies are expected to be high, in steps of 100 GeV. A value of 2 GeV is taken for m_a. The parameter $c\tau_\mathrm{a}$ is set to various values in MadGraph5_aMC@NLO, ranging from 2 mm to 10 m. Since only a discrete set of $c\tau_\mathrm{a}$ values were generated, signal hypotheses with intermediate $c\tau_\mathrm{a}$ values are derived by reweighting the proper decay length distribution. Signal events are normalized to the next-to-LO (NLO) cross sections [36] and the total integrated luminosity. Simulation is not used to estimate background events. The background estimate is derived using a purely data-driven method described in section 6.

Generated events are interfaced with pythia8.230 [47] to simulate parton showering and hadronization processes. Additional pp interactions in the same or neighboring bunch crossings (pileup) are modeled by superimposing simulated minimum bias interactions onto the hard scattering process. Simulated events are reweighted to match the distribution of the number of pileup interactions observed during each data-taking period. The underlying event tune CP5 [48] and NNPDF3.1 [49] parton distribution functions are used in all simulated samples. All generated events are passed through a simulation of the CMS detector response based on the GEANT4 toolkit [50].

4 Event reconstruction

Reconstruction and identification of each particle in the event are performed by the particle-flow (PF) algorithm [51], with an optimized combination of information from the various elements of the CMS detector. The energy of prompt photons that do not originate from the a_τ decay is obtained from the ECAL measurement. The energy of displaced di-photons from the a_τ decay is not measured by the MDS object. The energy of electrons is determined by a combination of the electron momentum at the primary interaction vertex as determined by the tracker, the energy of the corresponding ECAL cluster, and the energy sum of all bremsstrahlung photons spatially compatible with those originating from the electron track. The energy of muons is obtained from the curvature of the corresponding track. The energy of charged hadrons is determined from a combination of their momentum measured in the tracker and the matching ECAL and HCAL energy deposits, corrected for the response function of the calorimeters to hadronic showers. Finally, the energy of neutral hadrons is obtained from the corresponding corrected ECAL and HCAL energies.

The primary interaction vertex (PV) is defined as the vertex corresponding to the hardest scattering in the event, evaluated using only tracking information, as described in section 9.4.1 of ref. [52].

Muons are measured in the region $|\eta| < 2.4$, with detection planes comprising DTs, CSCs, and RPCs. The efficiency to reconstruct and identify muons is greater than 96%. Matching muons to tracks measured in the silicon tracker results in a relative transverse momentum (p_T) resolutions of 1% in the barrel and 3% in the endcaps, for muons with $p_\mathrm{T} < 100\,\mathrm{GeV}$; and better than 7% in the barrel for muons with $p_\mathrm{T} < 1\,\mathrm{TeV}$ [53].

Hadronic jets are reconstructed by clustering PF candidates using the anti-k_T algorithm [54, 55] with a distance parameter of 0.4. Pileup interactions can contribute with additional tracks and calorimetric energy depositions to the jet momentum. To mitigate this effect, charged particles identified to be originating from pileup vertices are discarded and an offset correction is applied to correct for remaining contributions [56]. Jet energy corrections are derived from simulation to bring the measured response of jets to that of particle-level jets on average. In situ measurements of the momentum balance in dijet, photon+jet, Z+jet, and multijet events are used to account for any residual differences in the jet energy scale between data and simulation [57]. The jet energy resolution typically is between 15 and 20% at 30 GeV, 10% at 100 GeV, and 5% at 1 TeV [57]. Additional selection criteria are applied to each jet to remove jets potentially dominated by anomalous contributions from various subdetector components or reconstruction failures [58].

For each event, the missing transverse momentum vector $\vec{p}_\mathrm{T}^\mathrm{miss}$ is computed as the negative vector p_T sum of all the PF candidates, and its magnitude is labeled as $p_\mathrm{T}^\mathrm{miss}$ [59]. The $\vec{p}_\mathrm{T}^\mathrm{miss}$ is modified to account for corrections to the energy scale of the reconstructed jets in the event.

The τ_h candidates are reconstructed from jets, using the hadrons-plus-strips algorithm [60], which combines one or three tracks with energy deposits in the calorimeters, to identify the τ_h decay modes. Neutral pions are reconstructed as strips with dynamic size in η-ϕ from reconstructed electrons and photons, where the strip size varies as a function of the p_T of the electron or photon candidate. Decay modes with one or three charged hadrons, with or without neutral pions, are considered in this analysis. The DeepTau algorithm is used [61] to distinguish genuine τ_h decays from jets originating from the hadronization of quarks or gluons, and from electrons or muons. It combines the information from all individual reconstructed particles near the τ_h axis with properties of the τ_h candidate and the event. The jet misidentification rate of this algorithm depends on the p_T and quark flavor of the jet. In simulated events from W boson production in association with jets, it has been estimated to be 0.43% for a genuine τ_h identification efficiency of 70% at the chosen working point.

When LLPs decay within or just in front of the muon system, the material of the steel return yoke will induce a particle shower. Such showers will generate a localized and isolated cluster of muon detector hits. The CSC hits are reconstructed by combining the signal pulses in wire groups and cathode strips. The DT hits are reconstructed from signal pulses by the anode wires at the center of DT cells. Since DT chambers provide either the ϕ or z coordinate, the DT hit position is assumed to be at the center of the DT chamber in the orthogonal direction.

The MDS objects are formed by clustering either CSC or DT hits based on their η and ϕ coordinates using the density-based spatial clustering of applications with noise (DBSCAN algorithm [62]) with a distance parameter $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.2$. Given that minimum ionizing muons can produce up to 24 hits in the CSC and 44 hits in the DT system, a minimum of 50 hits per cluster are required in the DBSCAN algorithm. The efficiency to reconstruct an MDS object depends on the LLP decay mode (hadronic or electromagnetic). This analysis studies LLPs with electromagnetic decays. Consequently, particle showers are produced and contained at most within one station and stopped by the steel material between stations. When a_τ decays near or within the CSC or DT system, the inclusive cluster efficiency is approximately 35 and 45%, respectively. The simulated cluster reconstruction efficiency, including both DT and CSC clusters, as a function of the r and $|z|$ decay positions of a_τ is shown in figure 2. The modeling of the MDS object in simulation has been studied using a sample enriched with $Z \to \mu^+\mu^-$, where one of the muons emits a photon through bremsstrahlung. The photon produces an electromagnetic shower in the muon system, and thus it is reconstructed as an MDS cluster. Differences in data and simulation efficiencies are accounted for as systematic uncertainties described in section 7.

5 Event selection

This analysis focuses on signal events with candidates for at least one τ_h and at least one a_τ decay in the muon system. Given that the a_τ decays beyond the calorimeters, its momentum is not properly accounted for by the PF algorithm and a large value of p_T^{miss} is reconstructed in the event. We exploit this feature and analyze the data collected by triggers with online $p_T^{miss} > 120\,\text{GeV}$. After trigger selection, we impose a minimum offline p_T^{miss} of 200 GeV to be above the threshold where the p_T^{miss} trigger becomes fully efficient. The p_T^{miss} signal selection efficiency, calculated assumming at least one a_τ decays within the geometric acceptance, ranges from 6 to 62%, depending on the m_{VLL} mass hypothesis.

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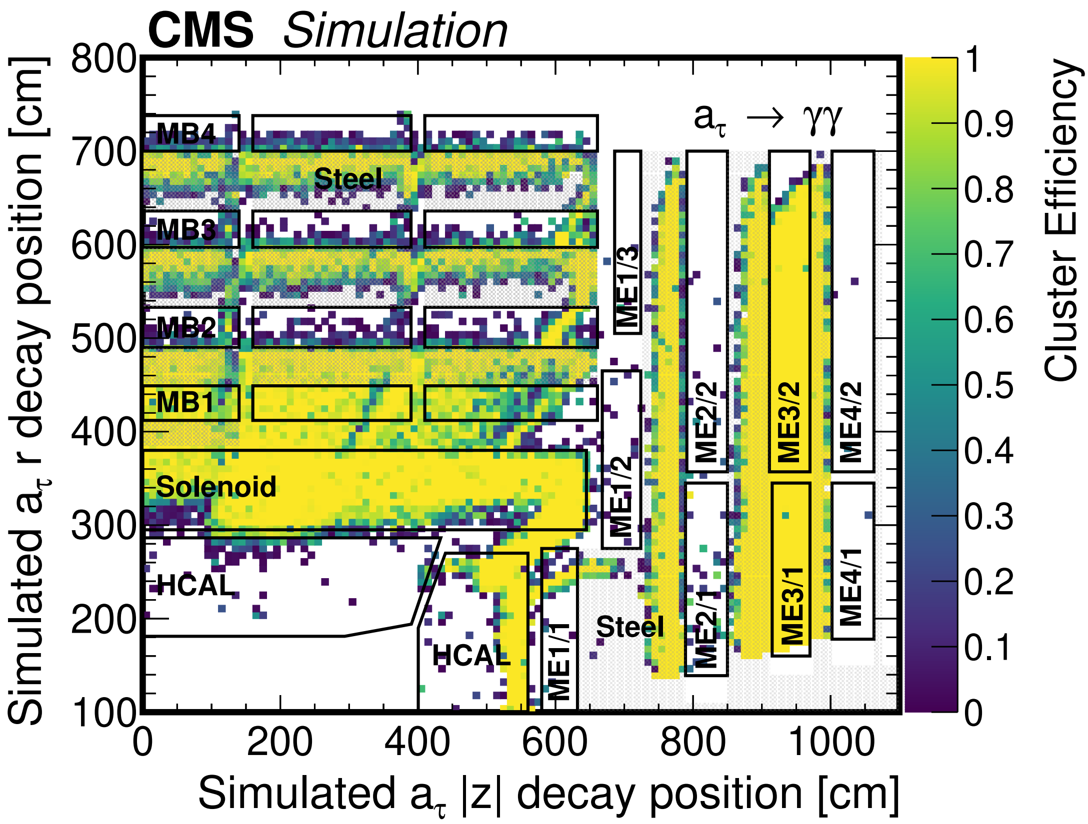

Figure 2. The cluster reconstruction efficiency, including both DT and CSC clusters, as a function of the simulated r and $|z|$ decay positions of the pseudoscalar boson a_τ decaying to $\gamma\gamma$ in events with $p_T^{miss} > 200$ GeV, for a VLL mass of 700 GeV, a pseudoscalar boson mass of 2 GeV, and a range of pseudoscalar boson mean proper decay lengths $c\tau_a$ uniformly distributed between 0.01 and 0.1 m. The barrel and endcap muon stations are drawn as black boxes and labeled by their names. The regions between muon stations are mostly composed of steel from the return yoke. The cluster reconstruction efficiency presented here corresponds to electromagnetic decays, in contrast to that of hadronic decays shown in ref. [38].

We require events to have at least one reconstructed τ_h candidate with $p_T > 30$ GeV, $|\eta| < 2.3$, satisfying the identification criteria described in section 4. The τ_h selection efficiency is between 50 and 85% depending on the signal hypothesis, with around 98% background rejection.

Selected events are required to contain at least one MDS cluster. They are categorized into DT- and CSC-cluster categories, based on the cluster type. There is only one cluster selected per event. If a DT cluster and a CSC cluster are present in the event, the event will be assigned to the DT category. Both categories have similar SM background sources that could induce a particle shower in the muon system, and therefore produce an MDS cluster. Ordered by relative importance, the background sources are the following: (i) energetic particles from quark/gluon hadronization or secondary interactions not stopped by the shielding material, known as jet punch-through; (ii) muons that undergo bremsstrahlung in the muon system; (iii) isolated hadrons from pileup or underlying events (single particle punch-through); and

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(iv) cosmic ray muon showers. To reject these backgrounds, additional requirements are applied to MDS clusters, as detailed in the following subsections.

5.1 The DT-cluster category

The DT-cluster category targets signal events in which the a_τ is reconstructed as a DT cluster. To suppress punch-through jet and muon bremsstrahlung backgrounds, we veto clusters with a centroid within $\Delta R = 0.4$ of a jet with $p_T > 15\,\text{GeV}$ and $|\eta| < 3.0$ or a muon with $p_T > 15\,\text{GeV}$ and $|\eta| < 2.4$. In addition, we observe shower events induced by cosmic rays where a large number of hits are observed in multiple muon chambers in adjacent wheels. These are suppressed by vetoing clusters containing more than 8 MB1 hits within $\Delta\phi < \pi/4$ in any of the wheels adjacent to the wheel containing the cluster hits.

We also require the cluster to coincide with at least one RPC detector hit in the same wheel and within $\Delta\phi < 0.5$. The time measurements of those RPC hits are matched to discrete bunch crossing times. Then, the DT cluster time ($t^{\text{DT}}_{\text{cluster}}$) is defined as the most frequently occurring bunch crossing time among the matched RPC hits. Lastly, the DT cluster time is required to match the PV bunch crossing time ($t^{\text{DT}}_{\text{cluster}} = 0$), to reject clusters produced from pileup or interactions from nearby bunch crossings, denominated out-of-time (OOT) pileup.

5.2 The CSC-cluster category

The CSC-cluster category targets signal events in which the a_τ is reconstructed as a CSC cluster. The jet and muon vetoes described in section 5.1 are applied to the CSC cluster. Clusters matched to a DT segment or RPC hit in the MB1 station within $\Delta R < 0.4$ are also rejected in order to remove clusters produced from muons traversing the DT region $0.8 < |\eta| < 1.2$ and showering in the CSC chambers. Clusters with an ME1/1 hit are removed because of the large punch-through jet background due to the reduced shielding present in this region. Finally, clusters with $|\eta| > 2.2$ are rejected to suppress muon bremsstrahlung background not accounted for by the muon veto due to inefficient muon reconstruction.

The CSC cluster time ($t^{\text{CSC}}_{\text{cluster}}$) and time spread ($t^{\text{CSC}}_{\text{spread}}$) are defined as the average and root-mean-square spread of the timestamps of the hits comprising the cluster, respectively. To reject clusters from the OOT pileup background, $-5.0 < t^{\text{CSC}}_{\text{cluster}} < 12.5\,\text{ns}$ and $t^{\text{CSC}}_{\text{spread}} < 20\,\text{ns}$ are required.

6 Background modeling

Signal LLPs are expected to produce large numbers of hits in the muon system compared to background processes. Therefore, we use the distribution of number of hits in the cluster (N_{hits}) as the signal discriminant in both DT- and CSC-cluster categories. The signal region (SR) is defined as events passing the selections detailed in section 5. The SR background estimate is derived from data events in a signal-depleted region.

Since the cluster properties are expected to be independent of the τ_h selection, a control region (CR) is defined by requiring at least one reconstructed τ_h candidate but inverting the τ_h DeepTau identification requirements with respect to the ones applied to the SR events. The expected background N_{hits} distribution shape is taken from the CR and normalized to the data measured in the SR with a constant scaling factor. Fisher F-tests [63] and saturated

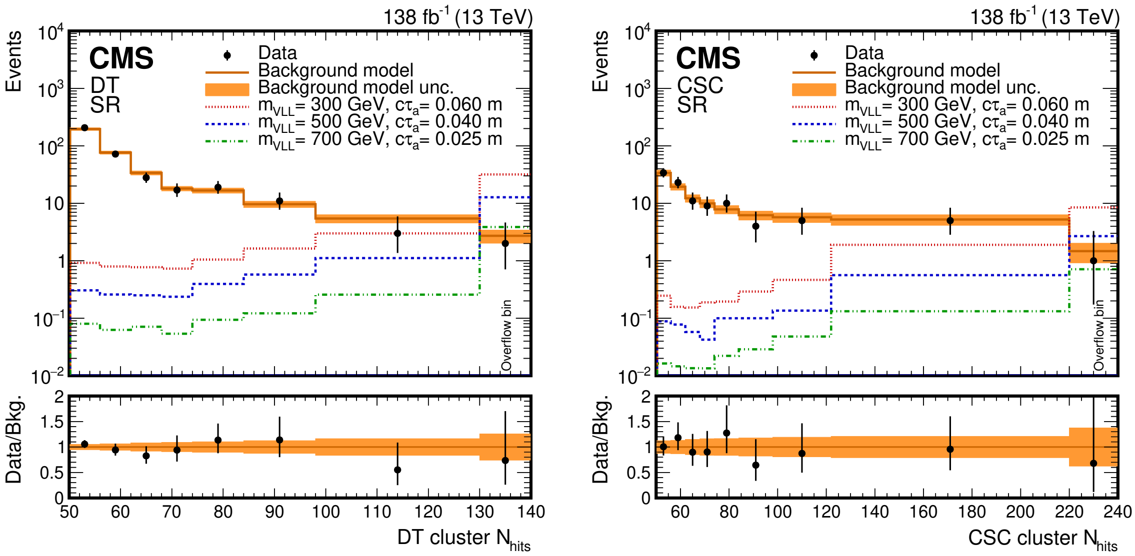

Figure 3. Distributions of the number of hits in the cluster (N_{hits}) for the DT (left) and CSC (right) cluster categories in the signal region (SR). The black markers represent the data. The solid orange line and associated orange band show the background prediction and corresponding uncertainty. The red dotted, blue dashed and green dashed-dotted lines denote different signal hypotheses for a pseudoscalar boson with a mass of 2 GeV. The last histogram bin contains all overflow events. The lower panel in each plot shows the ratio of the data to the estimated background.

model goodness-of-fit tests [64, 65] have been performed establishing that a higher-order polynomial dependence, beyond a constant scaling factor between the SR and CR distributions as a function of N_{hits}, is not needed. The SR N_{hits} distributions are presented in figure 3.

This background model is validated in OOT validation regions that are orthogonal to the SR. The DT and CSC OOT regions contain events passing all selection criteria, except that a negative cluster time is required: $t^{\text{DT}}_{\text{cluster}} < 0$ and $t^{\text{CSC}}_{\text{cluster}} < -12.5\,\text{ns}$, respectively. In analogy to the SR, the shape of the expected background N_{hits} distribution is taken from the CR and normalized to data measured in the OOT with a constant scaling factor. Statistical tests are performed and show that a constant scaling factor is sufficient to model the background distribution in both DT and CSC OOT validation regions. The validation OOT distributions of N_{hits} are shown in figure 4.

7 Systematic uncertainties

The background uncertainty arises from the statistical fluctuation in the CR data. Since good agreement is observed between the background estimation and data in the OOT validation regions, no additional uncertainty is considered. Background uncertainties are uncorrelated across categories.

The simulation of the muon detector response in an environment with a large multiplicity of secondary particles is validated by studying data and simulation in a region with $Z \to \mu^+\mu^-$ events, where a muon undergoes bremsstrahlung and the associated photon produces an MDS cluster. Uncertainties in the CSC and DT cluster reconstruction efficiency are estimated to be

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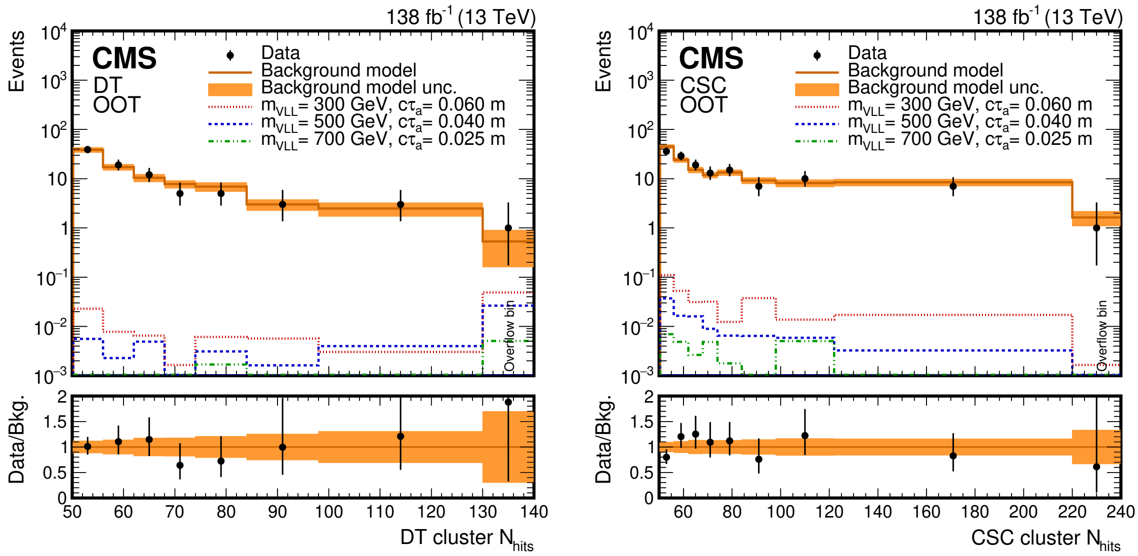

Figure 4. Distributions of the number of hits in the cluster (N_{hits}) for the DT (left) and CSC (right) cluster categories in the out-of-time (OOT) region. The black markers represent the data. The solid orange line and associated orange band show the background prediction and corresponding uncertainty. The red dotted, blue dashed and green dashed-dotted lines denote different signal hypotheses for a pseudoscalar boson with a mass of 2 GeV. The last histogram bin contains all overflow events. The lower panel in each plot shows the ratio of the data to the estimated background.

around 13 and 16%, respectively. Simulation correction factors are also derived to account for the mismodeling of cluster selection efficiencies, and their uncertainties are propagated to the final result. For CSC clusters, a 6.8% correction factor is applied to the muon veto efficiency, with a systematic uncertainty of 4.5%. The uncertainties in the CSC cluster time spread and cluster time selections are 2.8 and 0.9%, respectively. In addition, a 1% uncertainty is assigned to account for differences in the CSC readout conditions in simulation and data, which could lead to an overestimation of the N_{hits} in the cluster.

The τ_{h} identification efficiencies in simulation are corrected to match those in data. The uncertainties of these correction factors are propagated to the final result as uncertainties in the expected signal yield (5–11%). Lastly, we also account for experimental uncertainties in the signal yield prediction: pileup (1%), τ_{h} energy scale (1%), jet energy scale (1–4%), trigger efficiency (1–4%), and total integrated luminosity (1.6%) [66–68]. Theoretical uncertainties in the signal modeling are found to have a negligible impact on the analysis. The signal systematic uncertainties, except for the ones in the cluster modeling, are assumed to be correlated across categories.

8 Results

No statistically significant deviation from a background-only hypothesis is observed. We evaluate the upper limits on the VLL production cross section using the modified frequentist CL_s [69, 70] criterion with the profile likelihood ratio as the test statistic [71]. The CL_s value is calculated using an asymptotic approximation of the test statistic [72]. The sources of

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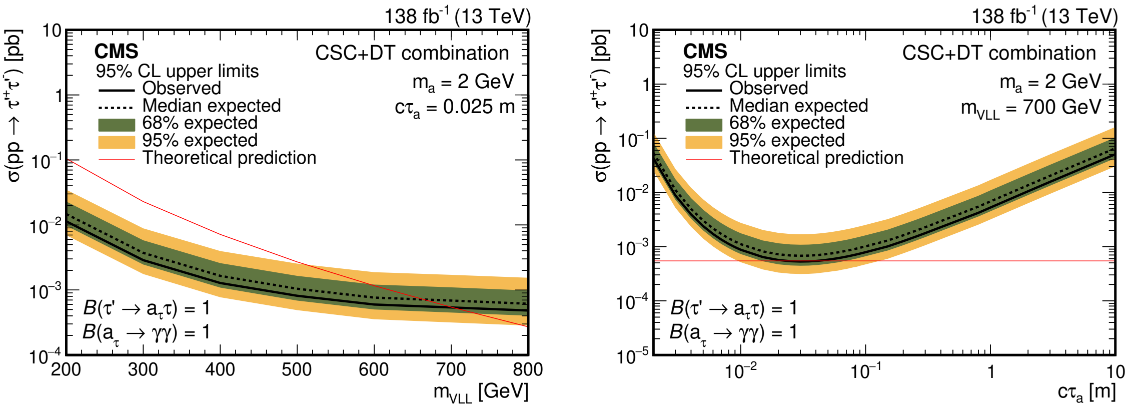

Figure 5. The 95% CL observed and expected upper limits on the VLL production cross section as a function of the VLL mass for the pseudoscalar boson mean proper decay length $c\tau_a = 0.025\,\mathrm{m}$ (left), and as a function of $c\tau_a$ for VLL mass of 700 GeV (right). The pseudoscalar boson mass is 2 GeV. The NLO theoretical prediction [36] is shown as a red line.

systematic uncertainties detailed in section 7 are modeled by log-normal distributions in the likelihood function. The final results are obtained by a simultaneous fit of the N_{hits} distributions in both DT- and CSC-cluster categories using the CMS statistical analysis tool COMBINE [73], which is based on the ROOFIT [74] and ROOSTATS [75] frameworks. The DT-cluster category contributes the most to the overall sensitivity due to its higher signal-to-background ratio. The exclusion limits obtained using the asymptotic approximation are consistent within 10% with those based on pseudo-experiments.

The observed and expected upper limits at 95% confidence level (CL) on the VLL cross section are presented as a function of VLL mass and $c\tau_a$ in figure 5. In this search, VLL masses below 700 GeV are observed to be excluded with 670 GeV expected, depending on $c\tau_a$. Figure 6 shows the observed limit as a function of both the VLL mass and $c\tau_a$.

9 Summary

The first search for singlet vector-like leptons (VLLs) that decay into a light long-lived pseudoscalar boson and a τ lepton has been presented. It is performed using the CMS data set of proton-proton collisions at 13 TeV collected in 2016–2018, corresponding to an integrated luminosity of 138 fb^{-1}. This analysis targets a reconstructed signature with at least one hadronically decaying tau lepton and with at least one muon detector shower resulting from the pseudoscalar boson decay in the CMS muon system. Selected events are categorized based on the presence of a cluster of muon detector hits in the barrel or the endcap region. No significant deviation from the background-only hypothesis is observed. The results of each category are combined to derive upper limits on the VLL production cross section as a function of the VLL mass and the pseudoscalar boson proper decay length. For pseudoscalar boson mean proper decay lengths in the range of 0.005–2.4 m, VLL masses up to 700 GeV are excluded at 95% confidence level. These are the most stringent constraints on the production of singlet VLLs with long-lived decays.

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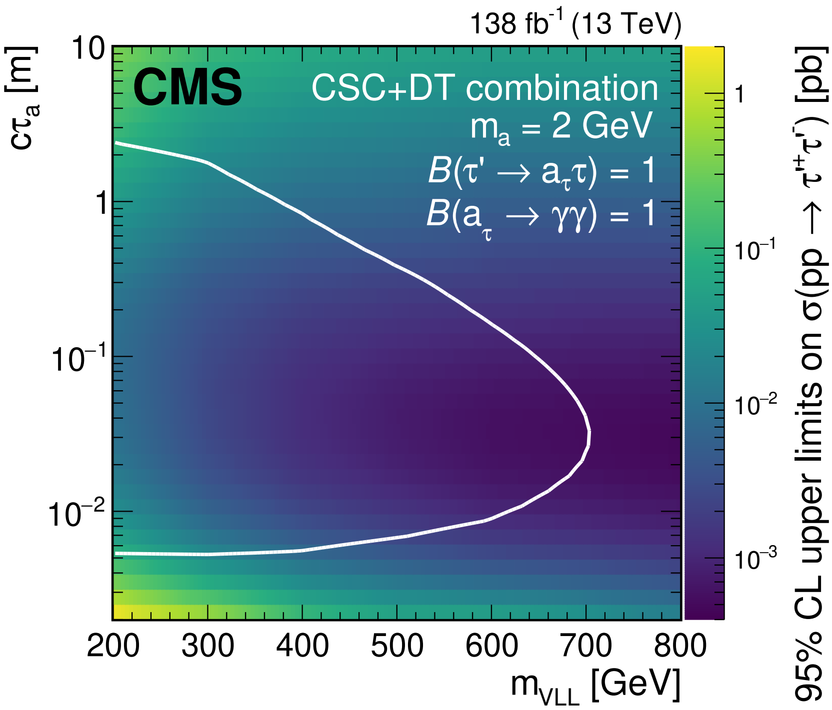

Figure 6. The 95% CL observed upper limits on the VLL production cross section as a function of the VLL mass and the pseudoscalar boson mean proper decay length $c\tau_a$. The pseudoscalar boson mass is 2 GeV. The area enclosed by the white line corresponds to the excluded region.

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