Search for vectorlike leptons in multilepton final states in proton-proton collisions at $\sqrt{s} = 13$ TeV

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A search for vectorlike leptons in multilepton final states is presented. The data sample corresponds to an integrated luminosity of 77.4 fb^{-1} of proton-proton collisions at a center-of-mass energy of 13 TeV collected by the CMS experiment at the LHC in 2016 and 2017. Events are categorized by the multiplicity of electrons, muons, and hadronically decaying τ leptons. The missing transverse momentum and the scalar sum of the lepton transverse momenta are used to distinguish the signal from background. The observed results are consistent with the expectations from the standard model hypothesis. The existence of a vectorlike lepton doublet, coupling to the third-generation standard model leptons in the mass range of 120–790 GeV, is excluded at 95% confidence level. These are the most stringent limits yet on the production of a vectorlike lepton doublet, coupling to the third-generation standard model leptons.

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I. INTRODUCTION

The standard model (SM) of particle physics is a quantum field theory that describes the known fundamental particles and their interactions. The predictions of the SM have been experimentally tested with great precision [1]. However, the SM does not explain several observations, such as the existence of dark matter and the baryon asymmetry in the Universe. In addition, there exist theoretical issues such as the hierarchy problem, that suggest that an extension of the SM, predicting new particles, is needed to provide a more complete description of nature.

In one class of new particles there are nonchiral color singlet fermions that couple to the SM leptons. The term nonchiral implies that the left- and right-handed components of these particles transform identically under gauge symmetries. These particles are thus referred to as vectorlike leptons (VLLs). They arise in a wide variety of models invoking, for example, supersymmetry or extra dimensions [2–5]. The VLLs are often classified by the SM lepton generation with which they are associated. VLLs and their associated SM leptons have identical lepton numbers.

This paper presents a search for an SU(2) doublet VLL extension [6] of the SM with couplings to the third-generation SM leptons. The search is carried out in final states with multiple charged leptons (e, μ, τ), using proton-proton (pp) collision data collected by the CMS detector at the LHC in 2016 and 2017. The model that we consider introduces a vectorlike τ lepton (τ'^{-}), its antiparticle ($\tau\tau'^{+}$), and the corresponding neutrinos (ν'_{τ} and $\bar{\nu}'_{\tau}$). At the LHC, they can be produced in $\tau'^{\pm}\nu'_{\tau}$, $\tau'^{+}\tau'^{-}$, and $\nu'_{\tau}\bar{\nu}'_{\tau}$ channels, with subsequent decays of τ' to $Z\tau$ or $H\tau$ and of ν'_{τ} to $W\tau$, where W, Z, and H are the SM W, Z, and Higgs bosons, respectively. At tree level, the τ' and ν'_{τ} are mass degenerate, whereas higher-order radiative corrections predict $< 0.3\%$ relative mass splitting between these two states, for VLL masses greater than 100 GeV. In this paper, τ' and ν'_{τ} are assumed to be mass degenerate. The mass of the VLL is the only free parameter both in the production cross section and in the branching fraction calculations. The tree-level Feynman diagrams for associated and pair production of the doublet model VLLs are shown in Fig. 1 along with possible subsequent decay chains that would result in a multilepton final state.

The ATLAS Collaboration performed a search for heavy lepton resonances decaying into a Z boson and a lepton in a multilepton final state at a center-of-mass energy of 8 TeV [7], constraining a singlet VLL model and excluding VLLs in the mass range of 114–176 GeV. However, to date, there are no such constraints on the doublet VLL model from any of the LHC experiments. The L3 Collaboration at LEP placed a lower bound of ≈100 GeV on additional heavy leptons [8]. Given these existing constraints, this analysis focuses on VLL masses greater than 100 GeV.

II. THE CMS DETECTOR

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a

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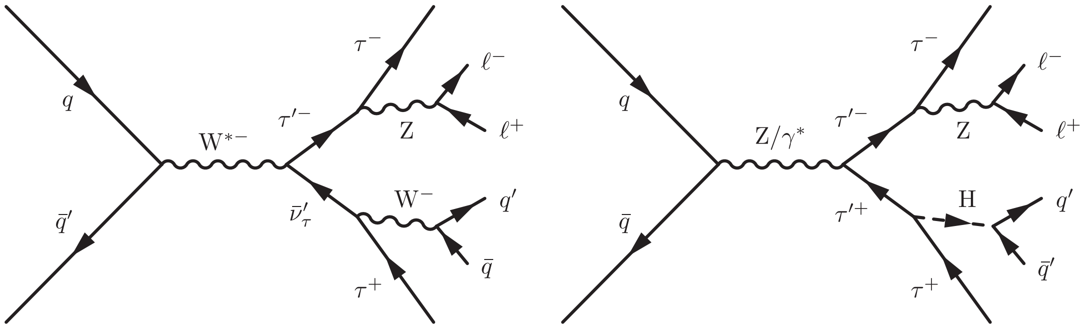

FIG. 1. Two illustrative leading-order Feynman diagrams for associated production of τ' with a ν'_τ (left) and for pair production of τ' (right) and possible subsequent decay chains that result in a multilepton final state.

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, each composed of a barrel and two end cap sections. Muons are measured in gas-ionization detectors embedded in the steel flux-return yoke outside the solenoid. The inner tracker measures charged particles with $|\eta| < 2.5$ and provides an impact parameter resolution of ≈ 15 μm and a transverse momentum (p_T) resolution of about 1.5% for 100 GeV charged particles. Extensive forward calorimetry complements the barrel and end cap detectors by covering the pseudorapidity range $3.0 < |\eta| < 5.2$. Collision events of interest are selected using a two-tiered trigger system [9]. The first level, composed of custom hardware processors, selects events at a rate of around 100 kHz. The second level, based on an array of microprocessors running a version of the full event reconstruction software optimized for fast processing, reduces the event rate to around 1 kHz before data storage. A detailed description of the CMS detector, along with a definition of the coordinate system and relevant kinematic variables, can be found in Ref. [10].

III. EVENT RECONSTRUCTION AND PARTICLE IDENTIFICATION

Events collected for this search are recorded using a combination of triggers requiring a single electron or a single muon. For events collected in 2016 (2017), the electron trigger requires an electron with $p_T > 27\,(35)$ GeV, while the muon trigger requires a muon with $p_T > 24\,(27)$ GeV. Information from all subdetectors is combined using the CMS particle-flow (PF) algorithm [11] to reconstruct and identify individual particles (charged hadrons, neutral hadrons, photons, electrons, and muons). Collectively these are referred to as PF objects.

For each event, PF objects originating from the same interaction vertex are clustered into jets using the infrared- and collinear-safe anti-k_T algorithm [12,13], with a radius parameter of 0.4. The momenta of all PF objects in each jet are summed vectorially to determine the jet momentum. The reconstructed vertex with the largest value of summed physics-object p_T^2 is taken to be the primary pp interaction vertex. The physics objects are the jets, clustered using the jet finding algorithm [12,13] with the tracks assigned to the vertex as inputs, and the associated missing transverse momentum, taken as the negative vector sum of the p_T of those jets. Additional interactions within the same or nearby bunch crossings (pileup) can contribute spurious extra tracks and calorimetric energy depositions to the jet momentum. Hence, charged particles identified as originating from pileup vertices are discarded and an offset correction [14] is applied to account for the remaining neutral pileup particle contributions. Additional jet energy corrections are applied to account for the nonlinear response of the detectors [15].

The missing transverse momentum vector ($\vec{p}_T^{\,\text{miss}}$) is calculated as the negative vectorial p_T sum of all the PF objects belonging to the primary vertex. The p_T^{miss} is defined as the magnitude of this vector. For calculating p_T^{miss} in 2016, we use PF objects located in the full fiducial volume of the detector, whereas for 2017, PF objects within $2.5 < |\eta| < 3.0$ and with $p_T < 50$ GeV are excluded to mitigate noise effects related to the aging of the CMS ECAL.

Electron candidates are reconstructed by combining ECAL superclusters and Gaussian sum filter [16] tracks from the silicon tracker [17]. Muon candidates are reconstructed by combining the information from both the silicon tracker and the muon spectrometer [18]. Hadronically decaying τ lepton candidates (τ_h) are selected using the hadron-plus-strips algorithm [19]. This algorithm has been designed to optimize the performance of τ_h reconstruction by considering specific τ_h decay modes. It starts with hadronic jets and reconstructs τ_h candidates from the tracks (“prongs”) and energy deposits in strips of the ECAL, in the one-prong, one-prong $+\pi^0$, and three-prong decay modes. We require the reconstructed leptons to lie within the region of pseudorapidity $|\eta| < 2.5$, 2.4, and 2.3 for the electron, muon, and τ_h candidates, respectively.

Lepton candidates arising from pp collisions can be broadly categorized into prompt, nonprompt, and conversion leptons. A prompt lepton can be produced in the decay of a W, Z or Higgs boson. Events from background processes such as WZ and ZZ contain multiple prompt leptons and thus these backgrounds are classified as prompt backgrounds. A nonprompt lepton can arise in heavy flavor hadron decays within a jet, or from hadrons that punch through to the muon system, or from hadronic showers with large electromagnetic fractions. A small fraction of reconstructed leptons from nonprompt sources mimic leptons from prompt sources and are referred to as misidentified leptons. The background arising from such sources is referred to as the misidentified background (MisID). A conversion lepton is one which is produced when a radiated photon converts to a pair of leptons. The background arising from such processes is referred to as the conversion background.

Unlike prompt leptons, misidentified leptons are expected to have significant nearby hadronic activity. An isolation requirement that compares the p_{T} of a lepton to the p_{T} sum of particles in its immediate neighborhood strongly reduces the backgrounds from misidentified leptons. We use relative isolation criteria for both electrons and muons. Relative isolation is defined as the scalar p_{T} sum of photons, and charged and neutral hadrons, as reconstructed by the PF algorithm within a specified ΔR cone around the lepton candidate, normalized to the lepton candidate p_{T}. The ΔR between a particle and the lepton is defined as $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$, where $\Delta\eta$ is the difference in pseudorapidity and $\Delta\phi$ is the difference in the azimuthal angle (in radians). This relative isolation is required to be less than 7% or 8% within a cone of size $\Delta R = 0.3$ for electrons whose energy deposits are reconstructed in the ECAL barrel ($|\eta| < 1.48$) or in the end cap ($1.48 < |\eta| < 3.00$), respectively, and less than 15% within a cone of size $\Delta R = 0.4$ for muons. The τ_{h} candidates are required to pass an isolation requirement based on a multivariate analysis [20]. The isolation quantities are corrected for pileup by considering only those charged PF candidates that are consistent with having originated from the primary vertex and by subtracting a per-event average pileup contribution to the neutral PF components. We further reduce the MisID backgrounds by imposing requirements on the longitudinal (d_z) and transverse (d_{xy}) impact parameters of the leptons with respect to the primary vertex in the event. Electrons in the barrel (end cap) must satisfy $|d_z| < 0.1\,(0.2)$ cm and $|d_{xy}| < 0.05\,(0.1)$ cm. Muons must satisfy $|d_z| < 0.1$ cm and $|d_{xy}| < 0.05$ cm. For τ_{h} leptons, we require $|d_z| < 0.2$ cm.

IV. SIGNAL AND BACKGROUND SIMULATION

Simulated samples are used to estimate the contribution of all prompt and conversion background processes. The WZ and ZZ processes are generated at next-to-leading order (NLO) using POWHEG v2 [21–25]. The Z/γ^*, $Z/\gamma^* + \gamma$, $t\bar{t}$, $t\bar{t} + \gamma$, and triboson processes are generated at NLO using MADGRAPH 5_aMC@NLO v5.2.2 [26] and processes with the Higgs boson are generated using POWHEG v2 [27,28] and the JHUGEN v6.2.8 generator [29–32]. Signal events are generated using MADGRAPH 5_aMC@NLO at leading order (LO) precision. For all simulation data, the parton showering, fragmentation, and hadronization steps are done using PYTHIA 8.230 [33] with tune CUETP8M1 [34] for 2016 samples and CP5 [35] for 2017 samples.

All 2016 samples are generated with the same order of the NNPDF3.0 parton distribution function (PDF) [36] as the order of the MC generator. All 2017 samples are generated with the NNPDF3.1 next-to-next-to-leading (NNLO) order PDF [37], irrespective of the order of the MC generator. The response of the CMS detector is simulated using dedicated software based on the GEANT4 toolkit [38]. Additional weights are applied to all simulated events to account for differences in the trigger and lepton identification efficiencies between data and simulation. For the simulated events, additional minimum bias interactions are superimposed on the primary collision, reweighted in such a way that the frequency distribution of the extra interactions matches that observed in data.

V. EVENT SELECTION CRITERIA

We collectively refer to electrons and muons as light leptons to distinguish them from τ_{h} leptons. Events are then categorized as those with four or more light leptons (4L), exactly three light leptons (3L), and exactly two light leptons along with at least one τ_{h} lepton (2L1T). In the 2L1T channel, we have a further division based on whether the two light leptons are of opposite sign (OS) or same sign (SS). In all categories, the leptons are ordered by decreasing transverse momenta and those with the largest p_{T} are labeled as the leading leptons. The leading light lepton is required to satisfy $p_{\mathrm{T}} > 38\,(28)$ GeV if it is an electron (muon). These thresholds are imposed so that the corresponding single lepton triggers are fully efficient for events that would subsequently satisfy the offline selection. All of the other leptons are required to satisfy $p_{\mathrm{T}} > 20$ GeV.

We use the scalar p_{T} sum of the leptons (denoted as L_{T}) to discriminate signal from SM backgrounds in all channels. The L_{T} distribution is divided into 150 GeV bins, each of which is treated as a separate experiment. In the 2L1T and 4L categories that contain more than one τ_{h} and more than four light-lepton candidates, respectively, only the leading τ_{h} and the leading four light leptons are used in the calculation of L_{T}.

In order to improve sensitivity for the signal, in each of the 4L, 3L, and 2L1T (OS, SS) categories, the events are divided into low- and high-$p_{\mathrm{T}}^{\mathrm{miss}}$ regions. While the 4L category is divided into $p_{\mathrm{T}}^{\mathrm{miss}} < 50$ GeV and > 50 GeV regions, the 3L and 2L1T (OS, SS) categories are divided into $p_{\mathrm{T}}^{\mathrm{miss}} < 150$ GeV and > 150 GeV regions. These categories form the bases of signal regions (SRs) that would be sensitive to the presence of a VLL signal. They

TABLE I. The signal regions defined in this analysis. The on-Z mass window is defined as $76 < m_{\ell\ell} < 106$ GeV, while the below-Z condition is defined as $m_{\ell\ell} < 76$ GeV.

$\mathrm{N}_{\mathrm{leptons}}$	$p_{\mathrm{T}}^{\mathrm{miss}}$ (GeV)	CR veto
$\geq 4e/\mu$	<50	Two OSSF on-Z pairs and $p_{\mathrm{T}}^{\mathrm{miss}} < 50$ GeV
	>50	
$3e/\mu$	<150	OSSF on-Z pair and $p_{\mathrm{T}}^{\mathrm{miss}} < 100$ GeV, or OSSF below-Z pair and $p_{\mathrm{T}}^{\mathrm{miss}} < 50$ GeV, or OSSF below-Z pair and on-Z $m_{3\ell}$
	>150	
$2e/\mu$ OS (or SS) $+ \geq 1\tau_{\mathrm{h}}$	<150	$p_{\mathrm{T}}^{\mathrm{miss}} < 50$ GeV
	>150	

are complemented by orthogonal control regions (CRs) that are expected to be dominantly populated by backgrounds. Additionally, all events with a light-lepton pair invariant mass below 12 GeV are vetoed regardless of the flavor and sign of the pair, in order to suppress low mass quarkonia resonances. The SRs are described in Table I, where OSSF refers to an opposite-sign, same-flavor lepton pair. A detailed description of the CRs is given in Sec. VI.

VI. BACKGROUND ESTIMATION

The WZ and ZZ background yields are normalized to data using dedicated CRs. For the WZ CR, we select events with exactly three light leptons, one OSSF pair invariant mass satisfying the 91 ± 15 GeV window ("on-Z"), and $50 < p_{\mathrm{T}}^{\mathrm{miss}} < 100$ GeV. The ratio of the expected WZ yield to data (after correcting for non-WZ events) is found to be 1.14 ± 0.06 (1.07 ± 0.05) for the 2016 (2017) data analysis, where the uncertainty includes both statistical and systematic contributions. Similarly, for the ZZ background, we select events with exactly four leptons, two distinct OSSF pairs both satisfying the on-Z requirement, and $p_{\mathrm{T}}^{\mathrm{miss}} < 50$ GeV. The ratio of the expected ZZ yield to data is found to be 1.01 ± 0.05 (0.98 ± 0.05) for the 2016 (2017) search.

The conversion background consists of events with photons from final-state radiation, where the photon converts asymmetrically to two additional leptons, only one of which is reconstructed in the detector. A selection of events with three light leptons with an OSSF pair below the Z boson mass (<76 GeV), $\mathrm{M}_{3\ell}$ satisfying the on-Z window, and with $p_{\mathrm{T}}^{\mathrm{miss}} < 50$ GeV is used to calculate the ratio of the conversion background prediction in simulation to data. The quantity $m_{3\ell}$ is defined as the invariant mass of the three light leptons. The ratio is measured to be 0.95 ± 0.11 (0.87 ± 0.10) for the 2016 (2017) data analysis. For the 2017 analysis, the $Z/\gamma^{*} + \gamma$ and $t\bar{t} + \gamma$ simulation samples are used, while for the 2016 analysis, the Z/γ^{*} and $t\bar{t}$ simulation samples are used because of the unavailability of enhanced samples.

The measured ratios are then applied to the WZ, ZZ, and conversion background estimates to correct for any residual differences in the efficiency and acceptance between data and simulation. The CRs are also used to verify the performance of the simulation in modeling the kinematic distributions of interest. Figure 2 shows the transverse mass m_{T} and the L_{T} distributions in the WZ CR and the $m_{4\ell}$ and L_{T} distributions in the ZZ CR for data and simulation, in the combined 2016 and 2017 datasets. The quantity $m_{4\ell}$ is defined as the invariant mass of the leading four light leptons. The quantity m_{T} is defined as $m_{\mathrm{T}} = \sqrt{2 p_{\mathrm{T}}^{\mathrm{miss}} p_{\mathrm{T}}^{\ell} [1 - \cos(\Delta\phi_{m_{\mathrm{T}}})]}$, where p_{T}^{ℓ} refers to the p_{T} of the lepton that is not part of the OSSF pair closest to the Z boson mass and $\Delta\phi_{m_{\mathrm{T}}}$ is the difference in azimuth between $W\vec{p}_{\mathrm{T}}^{\mathrm{miss}}$ and $\vec{p}_{\mathrm{T}}^{\ell}$. The prompt backgrounds from triboson and associated Higgs boson production are estimated from simulation using the calculated cross sections at NLO and are henceforth referred to as the VVV and the $H + X$ backgrounds, respectively. Similarly, the background from $t\bar{t}V$ and $t\bar{t}Z$ is estimated from simulation and is referred to as the $t\bar{t}V$ background.

The MisID background arises from processes such as $Z +$ jets and $t\bar{t} +$ jets. This background is estimated using a three-dimensional implementation of a matrix method [39]. In this method, rates are measured in data CRs for leptons to pass the analysis lepton selections, given that these leptons pass looser offline selections. It is assumed that these rates for prompt and misidentified leptons behave similarly across the different CRs and SRs. We measure these rates in dedicated CRs: one with a dilepton selection for prompt rates and another with a trilepton signal-depleted selection with one OSSF on-Z pair and $p_{\mathrm{T}}^{\mathrm{miss}} <$ 50 GeV for misidentification rates. The rates are parameterized as functions of lepton p_{T} and η. An additional correction factor is applied as a function of the number of charged particles, to account for rate variations due to the hadronic activity in the event. For τ_{h} misidentification rates, an additional parameterization is needed, based on the p_{T} of the jet matched to the τ_{h}. This is required to account correctly for rate variations due to the boost of the lepton system. The rate measurements are dominated by $Z +$ jets events and are corrected using simulation to an average of the $Z +$ jets and $t\bar{t} +$ jets events. Figure 3 demonstrates the agreement between the expected background and the observed data yields, as a function of the dilepton mass and L_{T}, in a signal-depleted 2L1T (OS) selection.

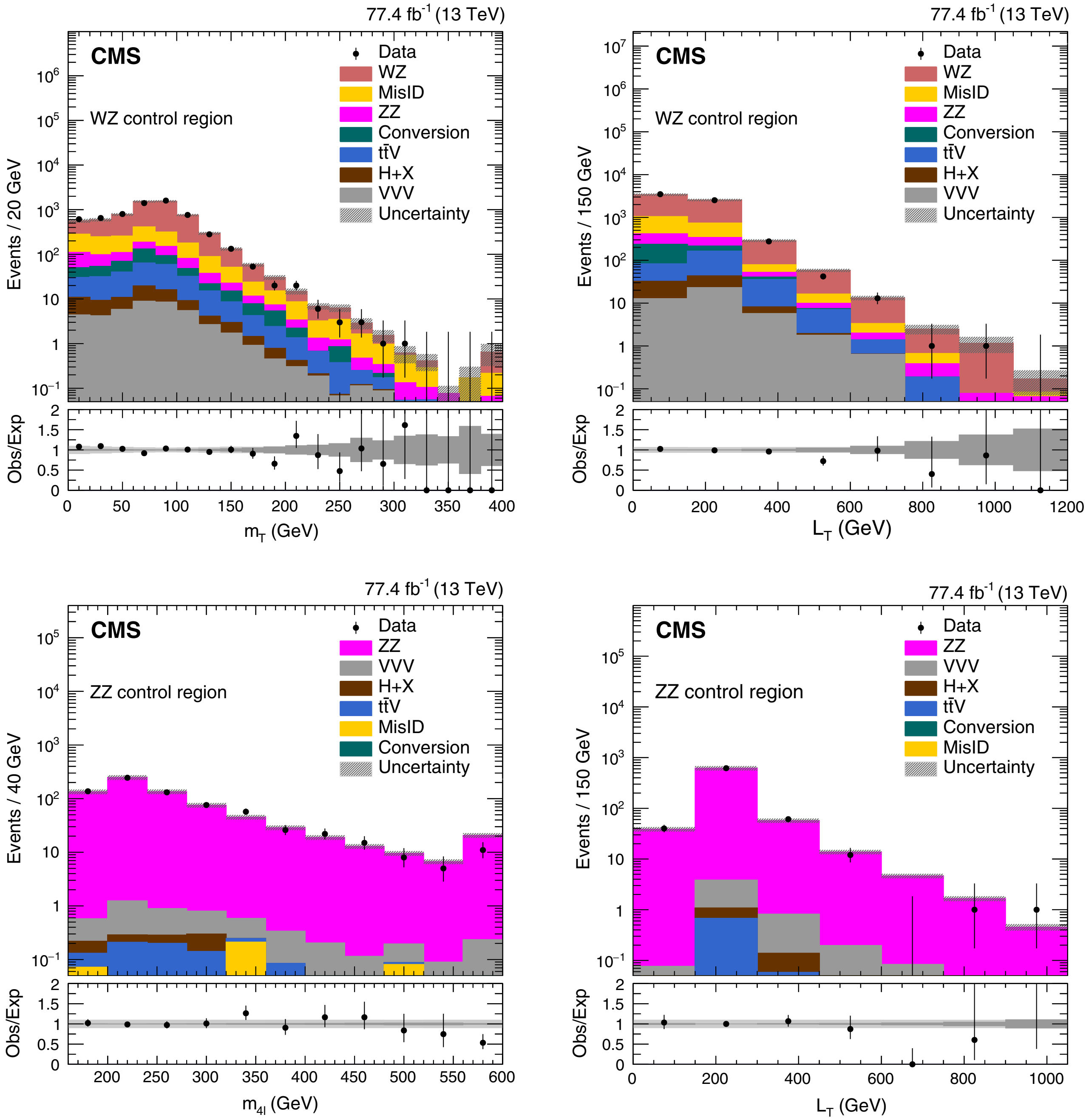

FIG. 2. The upper row shows the m_{T} (left) and the L_{T} (right) distributions in the WZ control region in data and simulation. The WZ control region contains events with three leptons and an OSSF pair with mass on-Z, and $50 < p_{\mathrm{T}}^{\mathrm{miss}} < 100$ GeV. The lower row shows the $m_{4\ell}$ (left) and the L_{T} (right) distributions in the ZZ control region. The ZZ control region contains events with two OSSF lepton pairs, both of which are on-Z, and $p_{\mathrm{T}}^{\mathrm{miss}} < 50$ GeV. The total SM background is shown as a stack of all contributing processes. The hatched gray bands in the upper panels represent the total uncertainty in the expected background. The lower panels show the ratios of observed data to the total expected background. In the lower panels, the light gray band represents the combined statistical and systematic uncertainty in the expected background, while the dark gray band represents the statistical uncertainty only. The rightmost bins include the overflow events.

VII. SYSTEMATIC UNCERTAINTIES

The primary sources of systematic uncertainty in the SM background arise from those in the MisID background and from those in the WZ and ZZ backgrounds. The systematic uncertainty in the MisID background contribution arises primarily via the uncertainties in the measurement of prompt and misidentified rates in the matrix method. In addition, the uncertainties in the $Z+\text{jets}$ and $t\bar{t}+\text{jets}$ rates contribute to the systematic uncertainty in this background.

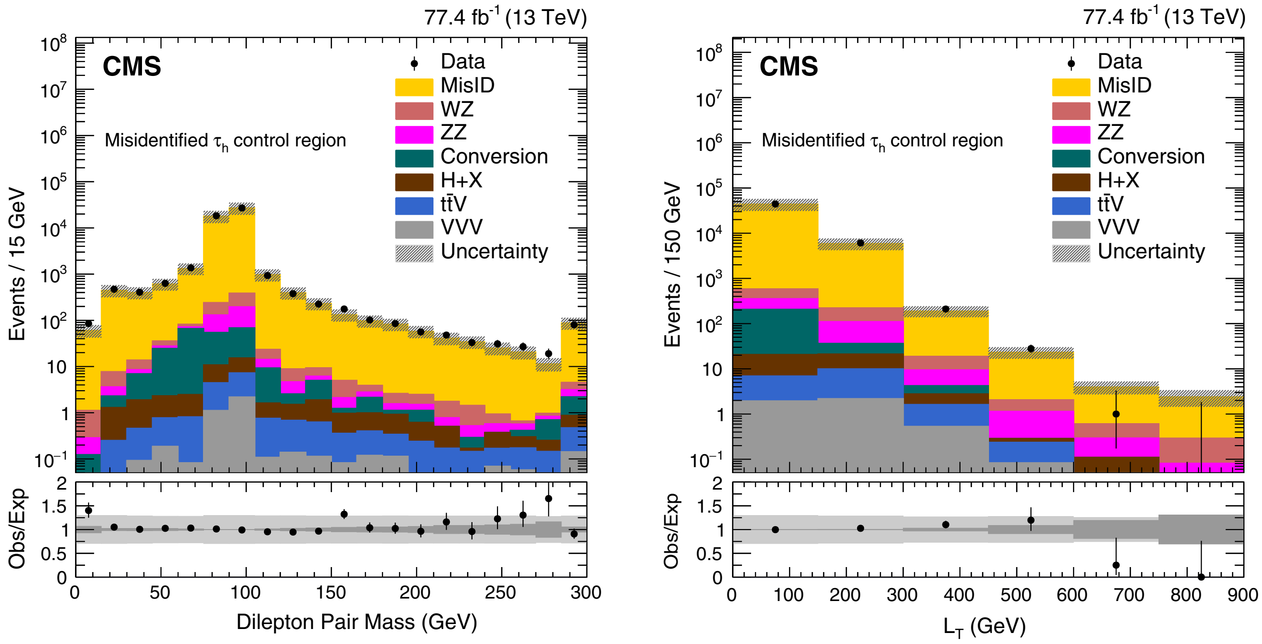

FIG. 3. The dilepton mass (left) and the L_T (right) distributions in data and simulation in a misidentified τ_h control region. This control region contains 2L1T (OS) events with $p_T^{miss} < 50$ GeV. The total SM background is shown as a stack of all contributing processes. The hatched gray bands in the upper panels represent the total uncertainty in the expected background. The lower panels show the ratios of observed data to the total expected background. In the lower panels, the light gray band represents the combined statistical and systematic uncertainty in the expected background, while the dark gray band represents the statistical uncertainty only. The rightmost bins include the overflow events.

We vary the rates within their respective uncertainties and observe the change in the background yield in all SRs. The final estimates vary by 20%–35% depending upon the year the data were collected and the SR. The WZ and ZZ background estimates have systematic uncertainties of 4%–5% arising from the normalization factor measurements in the dedicated CRs. The conversion background estimate has a systematic uncertainty of 11%.

To account for differences between the data and simulation, a number of different sources of systematic uncertainty are considered. Lepton energy (or momentum) scale uncertainties, as well as jet and lepton resolution uncertainties, are applied at the per-object level, where the corresponding object momenta are varied up and down by their corresponding uncertainties. This results in a 2%–10% impact on the background prediction, depending on L_T and the SR. The uncertainty in the trigger efficiency results in a 2%–3% uncertainty in the background prediction. Additionally, an integrated luminosity measurement uncertainty of 2.5% (2.3%) is applied to the simulated rare background estimates for the 2016 [40] (2017 [41]) analysis. For the subdominant, rare background processes such as $t\bar{t}V$, triboson, or associated Higgs boson production, a 50% systematic uncertainty is applied to the theoretical cross sections to cover the PDF and the renormalization and factorization scale uncertainties. The pileup modeling uncertainty is evaluated by varying

TABLE II. The sources of systematic uncertainty and the typical variations (percent) observed in the affected background and signal yields in the analysis. All sources of uncertainty are considered as correlated between the 2016 and 2017 data analyses except for the lepton identification and isolation, the single lepton trigger, and the integrated luminosity. The label ALL is defined as WZ, ZZ, rare ($t\bar{t}V$, VVV, Higgs boson), and signal processes.

Source of uncertainty	Typical variations (%)	Processes
MisID background	20–35	⋯
Rare background normalization	50	⋯
Conversion background normalization	11	⋯
WZ background normalization	5	⋯
ZZ background normalization	4–5	⋯
Lepton identification and isolation	6–8	ALL
Single lepton trigger	<3	ALL
Electron energy scale and resolution	2–5	ALL
Muon momentum scale and resolution	2–10	ALL
Hadronic τ lepton energy scale	<5	ALL
Jet energy scale	5–10	ALL
Unclustered energy scale	1–10	ALL
Integrated luminosity	2.3–2.5	Rare/signal
Pileup modeling	<4	ALL

the cross section used in the reweighting procedure up and down by 5%, which results in a 4% impact on background yields according to simulation. The typical variations for various sources of systematic uncertainty are provided in Table II.

VIII. RESULTS

The L_T distributions for the 4L and 3L SRs are shown in Fig. 4, while those for various 2L1T SRs are shown in Fig. 5. We do not observe any significant discrepancies between the background predictions and the observed data.

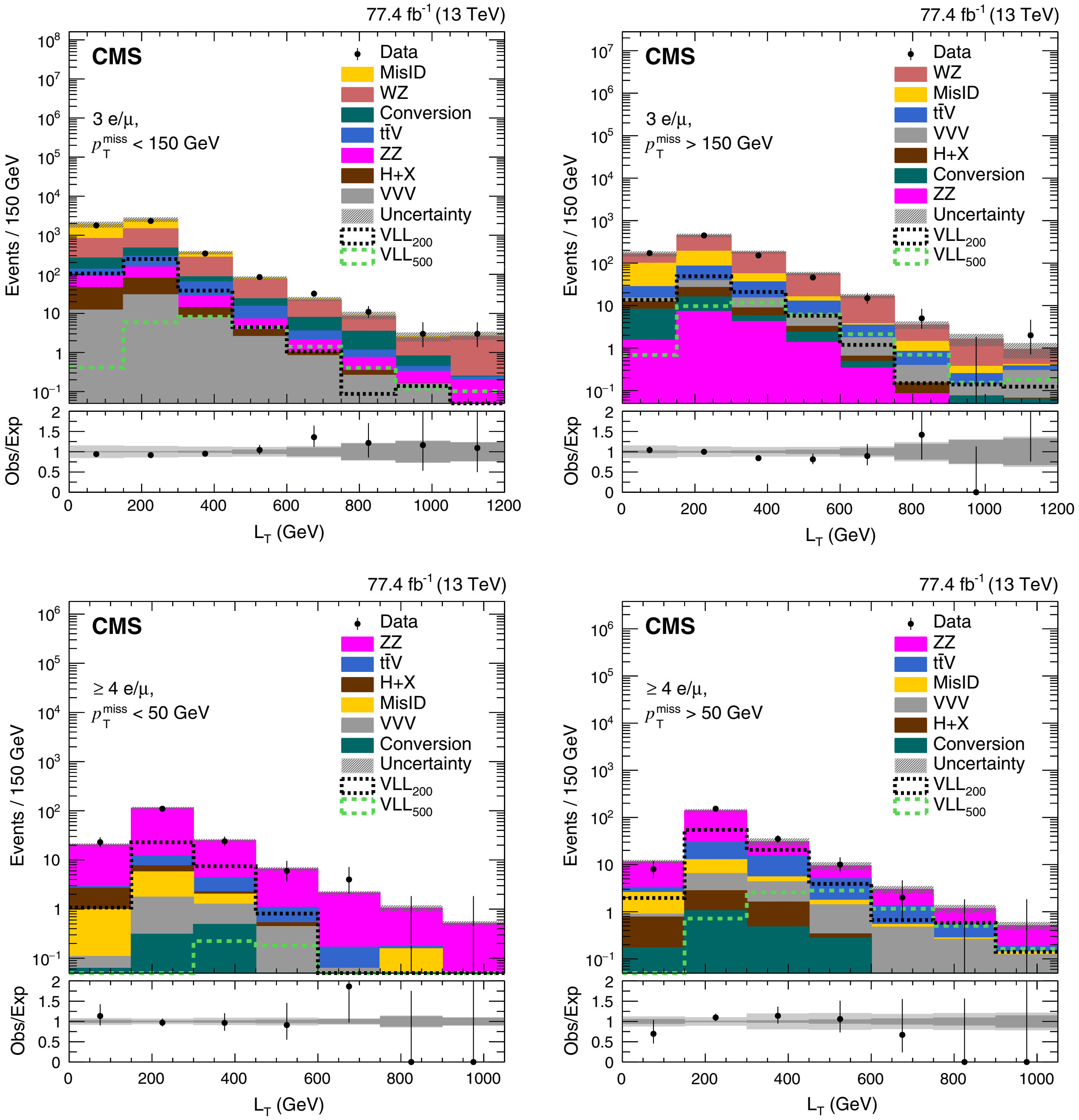

FIG. 4. The L_T distributions for the 3L signal regions with $p_T^{miss} < 150$ GeV (upper left) and $p_T^{miss} > 150$ GeV (upper right) and for the 4L signal regions with $p_T^{miss} < 50$ GeV (lower left) and $p_T^{miss} > 50$ GeV (lower right). The total SM background is shown as a stack of all contributing processes. The predictions for VLL signal models (the sum of all production and decay modes) with $m_{\tau'/\nu'} = 200$ and 500 GeV are shown as dashed lines. The hatched gray bands in the upper panels represent the total uncertainty in the expected background. The lower panels show the ratios of observed data to the total expected background. In the lower panels, the light gray band represents the combined statistical and systematic uncertainty in the expected background, while the dark gray band represents the statistical uncertainty only. The rightmost bins include the overflow events.

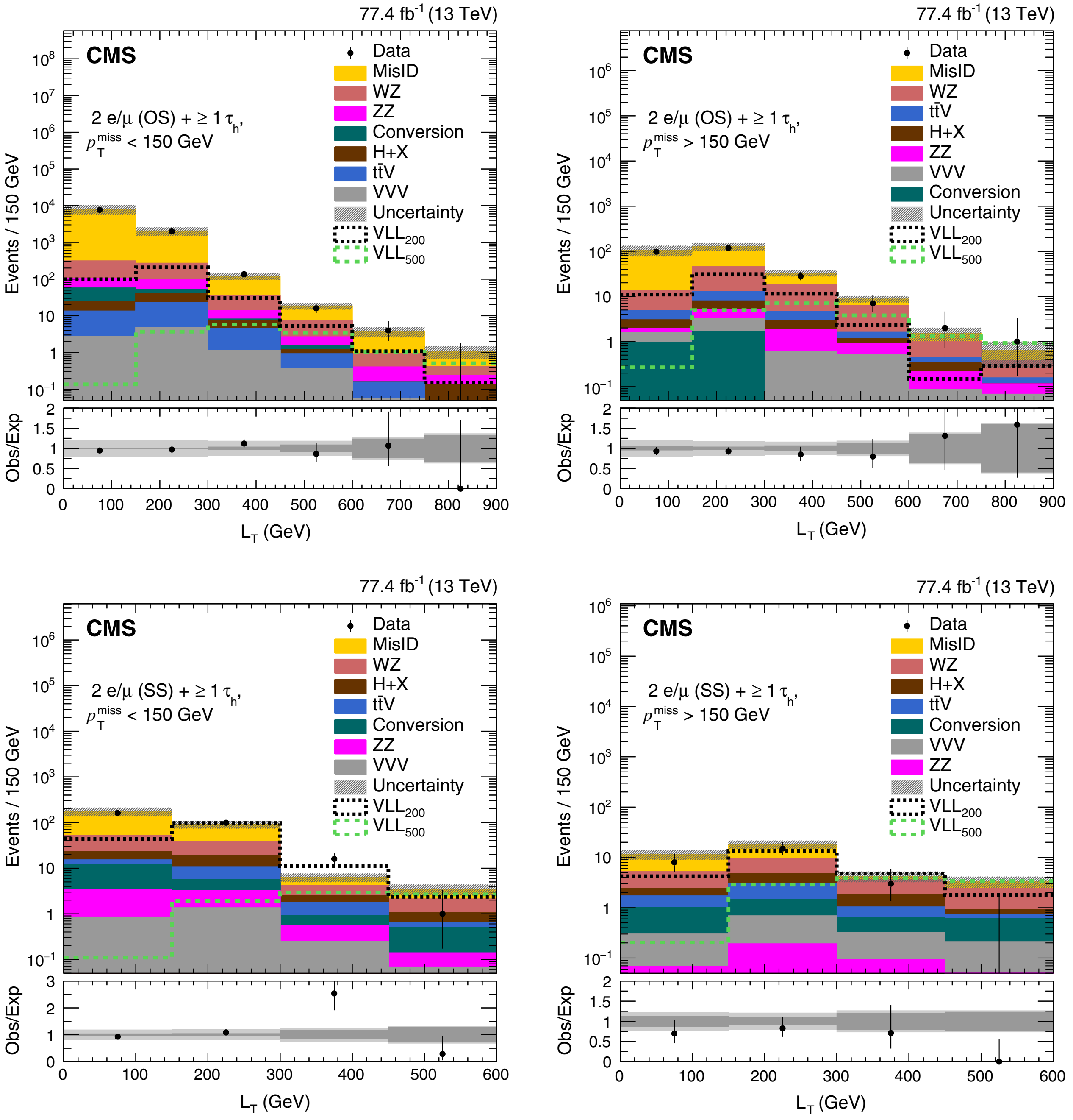

FIG. 5. The L_T distributions for the 2L1T OS signal regions with $p_T^{miss} < 150$ GeV (upper left) and $p_T^{miss} > 150$ GeV (upper right) and for the 2L1T SS signal regions with $p_T^{miss} < 150$ GeV (lower left) and $p_T^{miss} > 150$ GeV (lower right). The total SM background is shown as a stack of all contributing processes. The predictions for VLL signal models (sum of all production and decay modes) with $m_{\tau'/\nu'} = 200$ and 500 GeV are also shown as dashed lines. The hatched gray bands in the upper panels represent the total uncertainty in the expected background. The lower panels show the ratios of observed data to the total expected background. In the lower panels, the light gray band represents the combined statistical and systematic uncertainty in the expected background, while the dark gray band represents the statistical uncertainty only. The rightmost bins include the overflow events.

Limits are set on the combined cross section for associated ($\tau'\nu'_\tau$) and pair ($\tau'\tau'/\nu'_\tau\nu'_\tau$) production of VLLs. To obtain upper limits on the signal cross section at 95% confidence level (C.L.), we use a modified frequentist approach with a test statistic based on the profile likelihood in the asymptotic approximation and the CL$_s$ criterion [42–44]. The upper limits are shown in Fig. 6. We use a linear interpolation of the expected event yields between the simulated signal samples in the limit calculations. Systematic uncertainties are incorporated into the likelihood as nuisance parameters with log-normal probability distributions, while statistical uncertainties are modeled

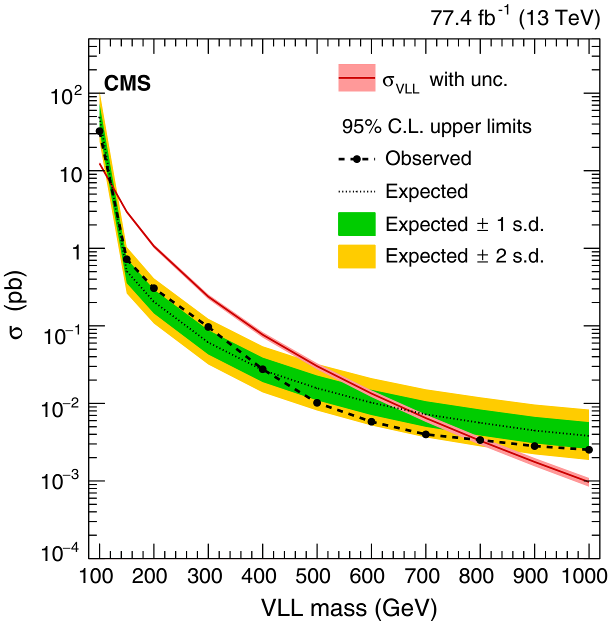

FIG. 6. The 95% confidence level upper limits on the total cross section for associated ($\tau'^{\pm}\nu'_{\tau}$) and pair ($\tau'^{+}\tau'^{-}/\nu'_{\tau}\bar{\nu}'_{\tau}$) production of VLLs. Also shown is the theoretical prediction for the production cross section of a vectorlike lepton doublet coupling to the third-generation SM leptons. The observed (expected) exclusion limit on the masses of VLLs is in the range of 120–790 (120–680) GeV.

with gamma functions. The observed limits are within 2 standard deviations of the expected limits from the background-only hypothesis. Because of the preferential coupling of VLLs to τ leptons, the major contribution to these results comes from the 2L1T SRs. The analysis sensitivity benefits from the large signal-to-background ratio in the 2L1T (SS) SRs, despite the small production rate for this channel. The measurements in the 2L1T channels alone exclude VLLs in the mass range 120–740 GeV. On combining all the 4L, 3L, and 2L1T SRs, with the hypothesis of an SU(2) mass degenerate VLL doublet with couplings to the third generation SM leptons, we exclude VLLs with mass in the range of 120–790 GeV at 95% C.L.

IX. SUMMARY

A search for vectorlike leptons coupled to the third-generation standard model leptons has been performed in several multilepton final states using 77.4 fb^{-1} of proton-proton collision data at a center-of-mass energy of 13 TeV, collected by the CMS experiment in 2016 and 2017. No significant deviations of the data from the standard model predictions are observed. These results exclude a vectorlike lepton doublet with a common mass in the range 120–790 GeV at 95% confidence level. These are the most stringent limits yet on the production of a vectorlike lepton doublet, coupling to the third-generation standard model leptons.

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