PROCEEDINGS OF SCIENCE

Searches for Vector Like Leptons in CMS

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We present results from two distinct searches for Vector-Like Leptons (VLLs) conducted by the CMS experiment using data collected during LHC Run 2. The first analysis uses a model-independent approach probing multilepton final states, while the second one focuses on hadronic final states with multiple tau leptons, leveraging model-dependent techniques. Both searches target SU(2) doublet VLL scenarios with couplings to third-generation Standard Model (SM) leptons while the multilepton analysis also targets singlet VLL scenarios. The first analysis yields results that exclude VLL masses up to 1040 GeV in the doublet scenario and between 125-170 GeV in the singlet scenario. In the second analysis, the maximum likelihood fit prefers the presence of signal at the level of 2.8 standard deviations, for a representative VLL mass point of 600 GeV. Finally, projections for the High-Luminosity LHC (HL-LHC) suggest sensitivity improvements, extending the excluded mass range further into the multi-TeV region.

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1. Introduction

Vector-Like Leptons (VLLs) are predicted by various Beyond Standard Model (BSM) theories as potential solutions to unresolved Standard Model (SM) issues, such as the hierarchy problem, the existence of dark matter and discrepancies in muon g-2 experiments measurements of the muons anomalous magnetic moment [3]. These non-chiral particles can be SU(2) doublets or singlets and arise in models such as supersymmetry [12–14], grand unified theories (GUTs) [15, 16], and extra-dimension models [17, 18]. VLLs are further motivated by observed anomalies in B-physics, particularly in lepton flavor universality tests, such as measurements of the relative decay rates of B mesons into final states involving tau leptons versus lighter leptons ($R(D^*)$ and $R(D)$). Measurements of $R(D^*)$ and $R(D)$ from various experiments are shown in Figure 1, the combined results of which deviate from SM predictions by approximately 3 σ [4]. Using LHC Run 2 data, the CMS experiment [1, 2] has conducted two key searches for VLLs. One search [7] adopts a model-independent strategy considering a minimal SM extension, while the other [5] focuses on hadronic signatures, primarily involving tau leptons, within the context of the 4321 model [8–10]. Finally, projections for the sensitivity of VLL searches in the High-Luminosity LHC (HL-LHC) [6] are presented.

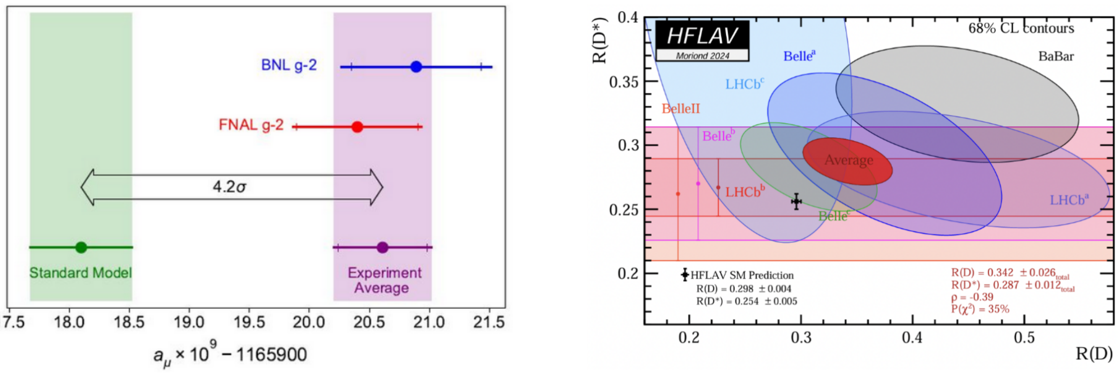

Figure 1: Left: Values of the muon's anomalous magnetic moment a_μ from different experiments compared to the SM expectation [3]. Right: Measurements of the relative decay rates of B mesons into final states involving tau leptons versus lighter leptons from various experiments compared against the SM expectation, where $R(D^*) = BF(B \to D^*\tau\nu_\tau)/BF(B \to D^* l\nu_l)$ and $R(D) = BF(B \to D\tau\nu_\tau)/BF(B \to Dl\nu_l)$ [4] .

2. Model-Independent Multilepton Analysis

This model-independent search [7] considers a minimal extension of the SM. VLLs can decay into SM boson-lepton pairs as seen in Figure 2, with their decay rates governed by their mass. This analysis investigates multilepton final states, focusing on events involving light leptons and hadronically decaying tau leptons (τ_h). Events are divided into seven orthogonal channels, as illustrated in Figure 3.

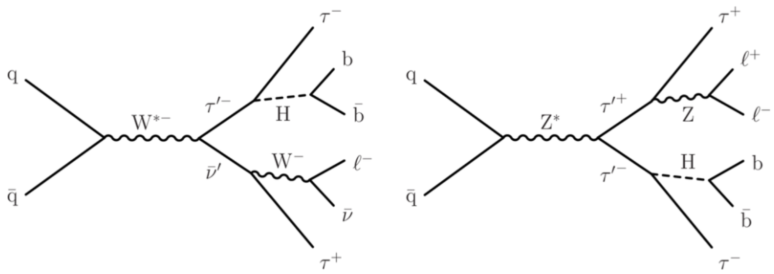

Figure 2: Example processes illustrating production and decay of doublet (left) and singlet (right) VLL pairs at the LHC in the minima SM extension scenarios [7].

Trilepton channels	Quadlepton channels*
• **3L**: 3 light leptons, 0 had. taus	• **4L**: 4 light leptons, 0 had. tau
• **2L1T**: 2 light leptons, 1 had. tau	• **3L1T**: 3 light leptons, 1 had. tau
• **1L2T**: 1 light lepton, 2 had. taus	• **2L2T**: 2 light lepton, 2 had. taus
	• **1L3T**: 2 light lepton, 2 had. taus
	** No veto on additional leptons → only lead. four objects are considered*

Figure 3: Event categorization into orthogonal channels based on the number of light leptons and τ_h leptons.

2.1 Background Estimation

The dominant backgrounds in this search arise from SM processes that generate three or more leptons, such as WZ, ZZ, $t\bar{t}Z$, and $t\bar{t}W$. These irreducible backgrounds are estimated using simulations and validated in dedicated control regions (CRs). Contributions from misidentified leptons, including photon conversions, are estimated using data-driven methods.

2.2 Signal Regions

The signal regions (SRs) are defined in two ways: a model-independent scheme and a BDT-based model-dependent method. The model-independent SRs rely on kinematic properties of the final states (e.g.L_T, p_T^{miss}) to cover a broad phase space for VLL signals, an example of which is shown in Figure 4. In contrast, the BDTs are trained on object and event level variables to enhance sensitivity for specific VLL mass ranges as shown in Figure 5.

2.3 Results

The search excludes VLL masses up to 1040 GeV in the doublet scenario, while in the singlet scenario, masses between 125-170 GeV are excluded. Results are shown in Figure 6. No significant deviations from the SM background were observed.

3. Hadronic Signature Analysis in the 4321 Model

The second analysis searches for VLLs in the context of the 4321 model [5], where VLLs couple primarily to third-generation fermions through interactions with leptoquarks. This shown

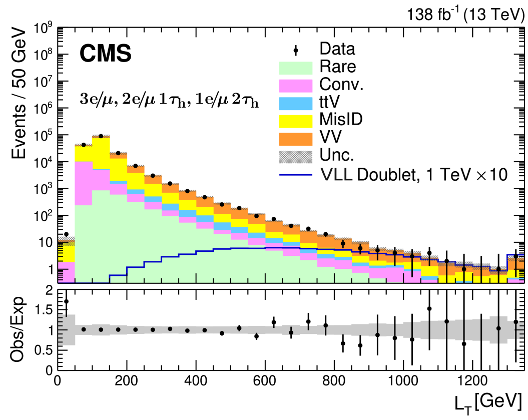

Figure 4: The L_T distribution is shown for events in the trilepton channels. The lower panel shows the ratio of observed events to the total expected background prediction. The gray band on the ratio represents the quadratic sum of statistical and systematic uncertainties in the SM background prediction shown after fitting the data under the background-only hypothesis. An example signal hypothesis for the production of the vector-like tau lepton in the doublet scenario with a mass of 1 TeV, before the fit, is overlaid. Taken from [6].

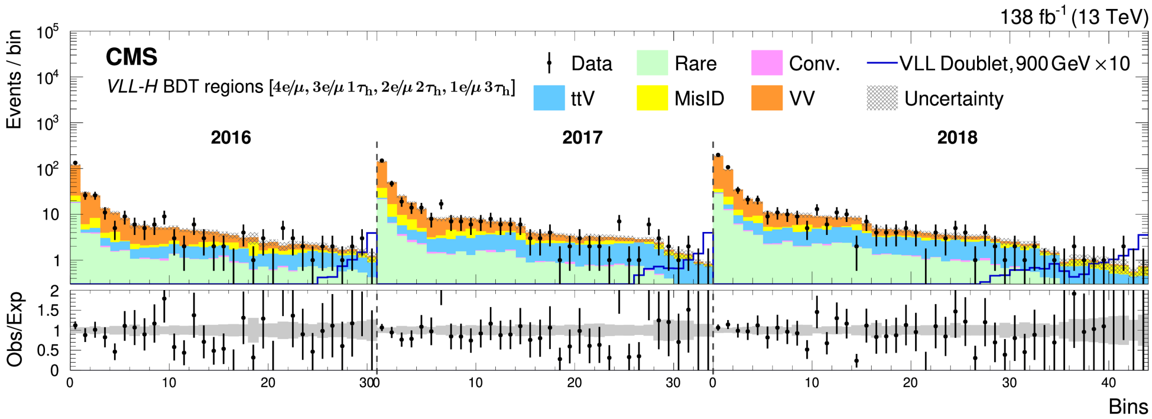

Figure 5: BDT region defined for the four-lepton channels for the full Run-2 data set. The lower panel shows the ratio of observed events to the total expected background prediction. The gray band on the ratio represents the quadratic sum of statistical and systematic uncertainties in the SM background prediction after fitting the data under the background-only hypothesis. An example signal hypothesis for the production of the vector-like tau lepton in the doublet scenario for a VLL mass of 900 GeV, before the fit, is overlaid. Taken from [6].

in the diagram of Figure 7. This analysis focuses on hadronic final states containing at least three b-tagged jets and multiple tau leptons. Events are categorized based on the multiplicity of τ_h leptons (0, 1, or 2) as shown in Figure 8 and uses a combination of graph neural networks (GNNs) and data-driven methods to distinguish signal from background.

3.1 Machine learning classifiers

A machine learning based strategy is employed to construct the observables for signal and background discrimination. A graph neural network approach is selected, in particular the use of ABCNet [11]. Up to 10 objects per event are utilized including jets and hadronic τ leptons to

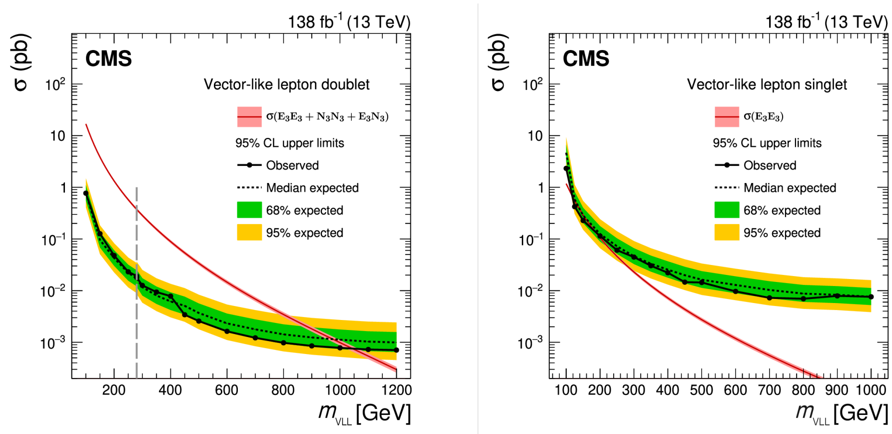

Figure 6: Observed and expected upper limits at 95% CL on the production cross section for the vector-like tau leptons in the doublet model (left) and singlet model (right). For the doublet vector-like lepton model, to the left of the vertical dashed gray line, the limits are shown from the model-independent scheme, while to the right the limits are shown from the model dependent BDT regions. For the singlet vector-like lepton model, the limit is shown from the model-independent scheme for all masses [6].

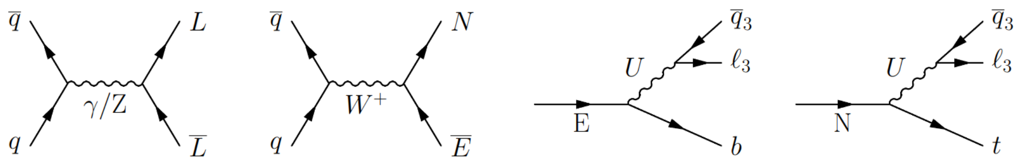

Figure 7: Feynman diagrams showing (left) electroweak production of VLL pairs through s-channel bosons where L represents the VLL, either neutral (N) or charged (E) and (right) vector-like lepton decays mediated by a vector leptoquark, U, decaying primarily to third-generation leptons and quarks. Taken from [5].

construct the graph. Two classifiers are trained targeting the QCD and $t\bar{t}$ backgrounds considering several kinematical features for the training shown in Figure 9.

3.2 Background Estimation

In the 0-τ_h category, the main background arises from QCD multijet events, and is estimated using an ABCD method based on the missing transverse energy and the output of the relevant GNN. The 1-τ_h and 2-τ_h regions are dominated by $t\bar{t}$ events which are modeled using simulation. Finally, misidentified τ_h leptons contribute significantly to the background in this region and are estimated using a data-driven method. Distributions of the post-fit observables in the different signal extraction regions are shown in Figure 10.

3.3 Results

This search observes a broad mild excess in both the 1τ_h and 2τ_h regions with a local significance of 2.8σ at a representative VLL mass point of 600 GeV. The exclusion limits for the VLL pair production cross section, shown in Figure 11, are set between 10-30 fb, depending on the assumed mass hypothesis.

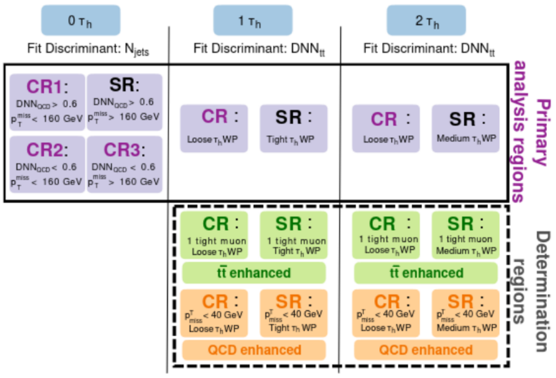

Figure 8: Diagram of the event categorization and the various signal and control regions used in the analysis. The regions within the solid box are used for the signal extraction while the regions in the dashed box are used for the data driven background determination. Taken from [5].

Variable	Description
η	Pseudorapidity
ϕ	Azimuthal angle
$\log(\frac{p_T}{\mathrm{GeV}})$	Logarithm of the p_T
$\log(\frac{m}{\mathrm{GeV}})$	Logarithm of the mass
Q	Charge
DEEPJET score	b tagging discriminant

Figure 9: List of input features used during training of the ABCNet model. Taken from [5].

4. Projections for the HL-LHC

Looking ahead, searches at the High-Luminosity LHC (HL-LHC) will provide greater sensitivity to VLL production. Projections indicate that the excluded mass range for VLLs will extend beyond 1 TeV, reaching into the multi-TeV region. The increased luminosity will enable further exploration of VLL scenarios, including those with couplings to first- and second-generation SM leptons. Results of the projection studies are shown in Figure 12.

5. Conclusion

The CMS experiment has conducted two complementary searches for Vector-Like Leptons using LHC Run 2 data. In the first, a minimal SM extension scenario is considered, resulting to VLL masses up to 1040 GeV being excluded in the doublet and between 125-170 GeV in the singlet scenario. The second search is performed in the context of the 4321 model, and hadronic final states are explored. Results show a broad mild excess, with a maximum local significance of 2.8 sigma at a representative VLL mass of 600 GeV. Ongoing and future analyses at the HL-LHC will significantly improve sensitivity, providing critical insights into these BSM candidates.

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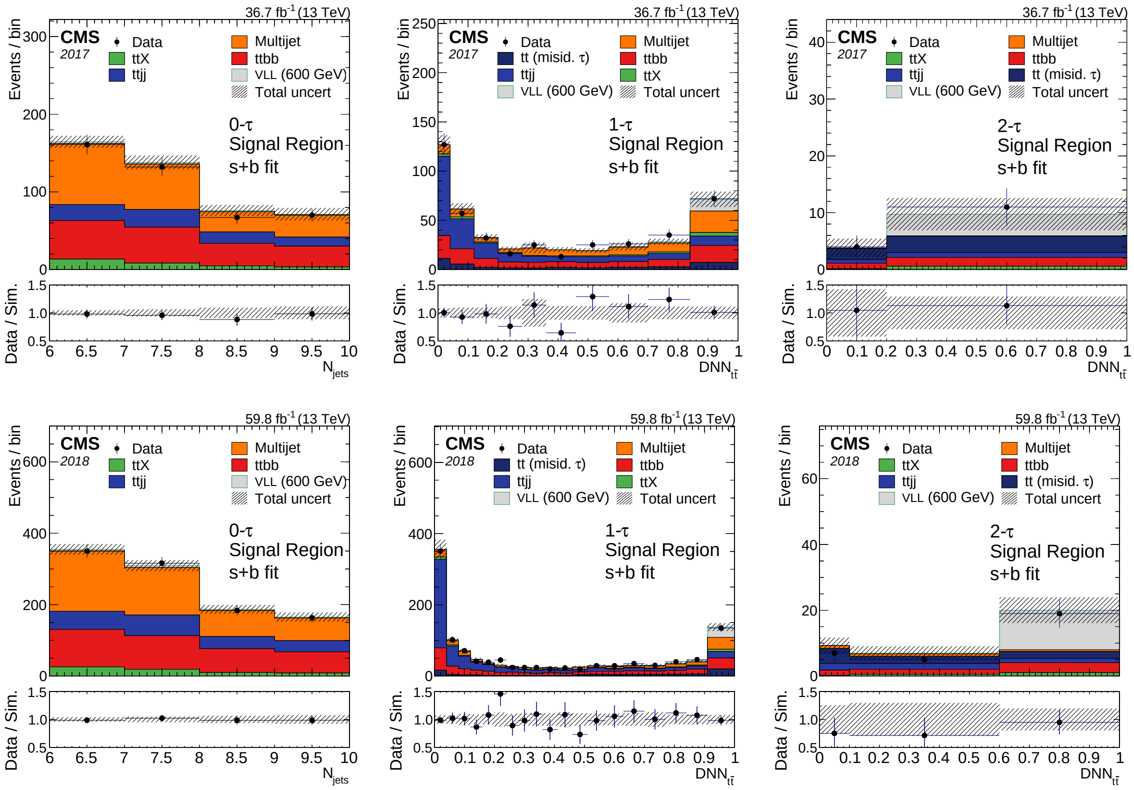

Figure 10: Post-fit plots for 2017 (top row) and 2018 (bottom row) showing the fitted distributions in the signal region for the different τ_h multiplicity channels (from left to right: 0-τ_h, 1-τ_h, 2-τ_h).Taken from [5].

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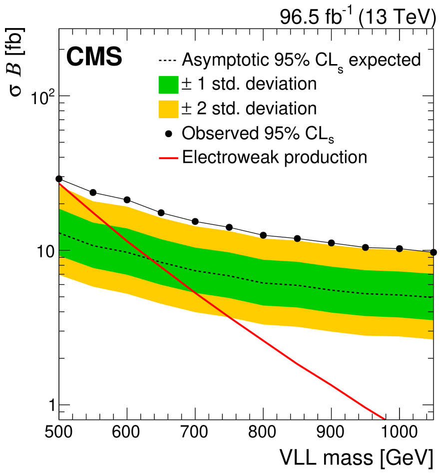

Figure 11: Expected and observed 95%CL upper limits on the product of the VLL pair production cross section and the branching fraction to third-generation quarks and leptons, combining the 2017 and 2018 data and all τ_h multiplicity channels.The theoretical prediction in the 4321 model for EW production of VLLs is also shown [5].

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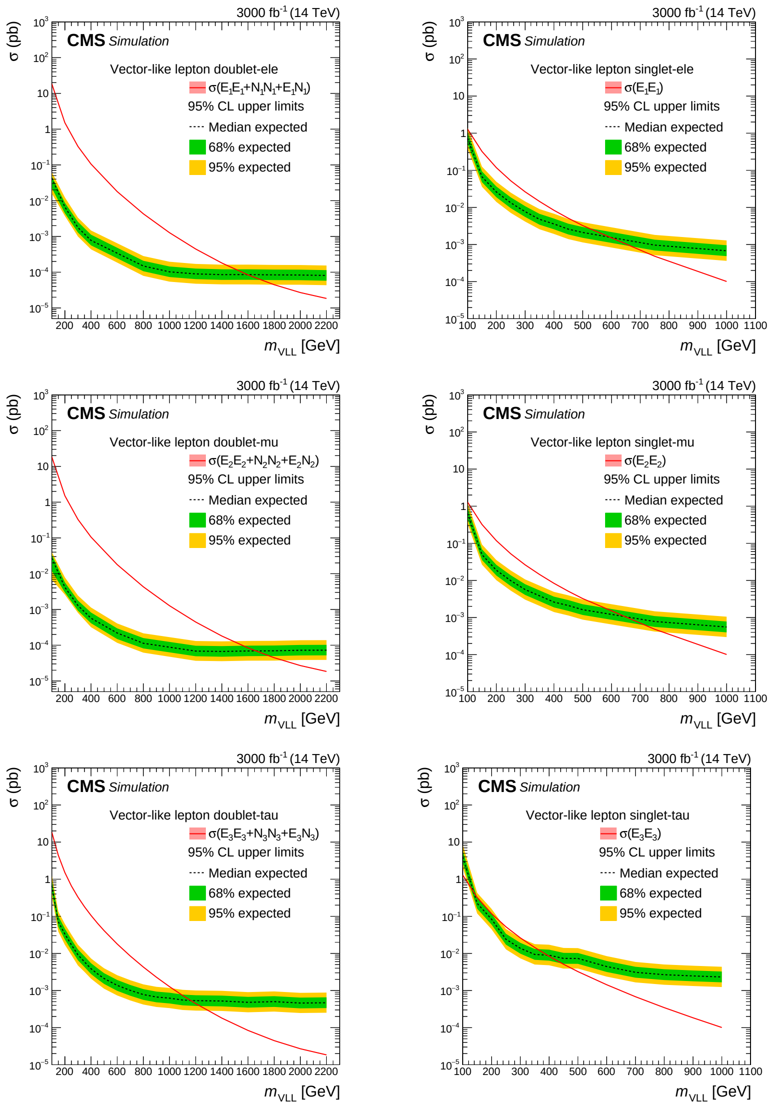

Figure 12: Expected HL-LHC exclusion limits for vector-like electrons (upper row), muons (middle row), and tau leptons (lower row) in the doublet model (left) and the singlet model (right). In both cases, limits are calculated using L_T+p_T^{miss} from the model independent SRs described in Sec. 2.2 for all masses [6].

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