PROCEEDINGS OF SCIENCE

Searches for vector-like quarks and leptons at CMS

Di Wang on behalf of the CMS Collaboration[a,*]

[a] *Deutsches Elektronen-Synchrotron (DESY), Notkestrasse 85, Hamburg, Germany*

E-mail: di.wang@cern.ch

New fermions, referred to as vector-like quarks and vector-like leptons, are hypothesized to address multiple questions ranging beyond the standard model, such as the hierarchy problem. These models are extensively searched by the CMS experiment. To date, no statistically significant excess has been observed. Upper limits are set on the production cross-sections. This talk presents the latest analyses searching for vector-like quarks and vector-like leptons, utilizing data collected by the CMS experiment at the CERN LHC, in proton-proton collisions at $\sqrt{s} = 13$ TeV.

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*Speaker

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1. Introduction

The standard model (SM) of particle physics has been proven to be a successful theory by many experiments. Nevertheless, there are many open questions that cannot be answered within the SM framework, such as the hierarchy problem and the origin of neutrino masses. To address these questions, fermions beyond those of the SM are hypothesized, including vector-like quarks (VLQs) and vector-like leptons (VLLs).

The VLQs are hypothetical quarks for which the left- and right-handed chiral components transform in the same way under the SM electroweak group. Their production cross section depends on the coupling between the VLQ and the SM particle. They can be produced singly or in pairs at the LHC and have been extensively searched for by the CMS experiment [1]. The pair production of VLQs proceeds typically through the strong interaction, as shown in the upper plots in Figure 1. The single production of VLQ can occur through a t-channel exchange of a W or Z boson via electroweak interaction, as shown in the lower left plot in Figure 1. In presence of vector bosons beyond the SM, the single VLQ production might also proceed through a W' boson via new interactions, as shown in the lower right plot in Figure 1.There are usually four types of VLQs considered, named T, B, X, and Y. The allowed decay modes for each of them are:

$$\begin{aligned} \mathrm{T} \rightarrow \mathrm{bW}^{+},\ \mathrm{T} \rightarrow \mathrm{tZ},\ \mathrm{T} \rightarrow \mathrm{tH} \\ \mathrm{B} \rightarrow \mathrm{tW}^{-},\ \mathrm{B} \rightarrow \mathrm{bZ},\ \mathrm{B} \rightarrow \mathrm{bH} \\ \mathrm{X}_{5/3} \rightarrow \mathrm{tW}^{+},\ \mathrm{Y}_{4/3} \rightarrow \mathrm{bW}^{-} \end{aligned} \tag{1}$$

The VLLs are color-singlet counterparts of the VLQs. They can be either structures as SU(2) doublets, (E,N), or as singlets, E, where E is the electrically charged and N is the neutral state. In the singlet models, the VLLs can be produced in pairs via the electroweak interaction, $\mathrm{pp} \rightarrow \mathrm{E}\bar{\mathrm{E}}$. In the doublet models, they can be produced in pairs through the process $\mathrm{pp} \rightarrow \mathrm{E}\bar{\mathrm{E}}/\mathrm{N}\bar{\mathrm{N}}$, or produced in association, $\mathrm{pp} \rightarrow \mathrm{E}\bar{\mathrm{N}}/\mathrm{N}\bar{\mathrm{E}}$. An E or N particle decays into a SM neutral boson and a lepton, following the decay modes below:

$$\begin{aligned} \mathrm{E} \rightarrow \mathrm{Z}\ell,\ \mathrm{E} \rightarrow \mathrm{H}\ell \\ \mathrm{N} \rightarrow \mathrm{W}\ell \end{aligned} \tag{2}$$

We present the latest analyses searching for VLQ and VLL in proton-proton collisions at a center-of-mass energy of 13 TeV at the CMS experiment in Run 2 (from 2016 to 2018). Section 2 introduces a VLL search with long-lived particle decays, Section 3 presents three analyses searching for singly produced VLQs, and Section 4 shows the combination results.

2. Search for VLLs

The analysis searches for pair-produced vector-like τ leptons named τ' [3], which decay into SM tau leptons (τ) and long-lived pseudoscalars (a_τ). The a_τs are beyond standard model particles. The τ' are produced via s-channel electroweak process with a Z boson or a photon. In the signal process, a τ' decays into τa_τ, then the a_τ decays into two photons via a τ' loop diagram after a few meters of traveling from the interaction point (Figure 2). The final state consists of hadronically

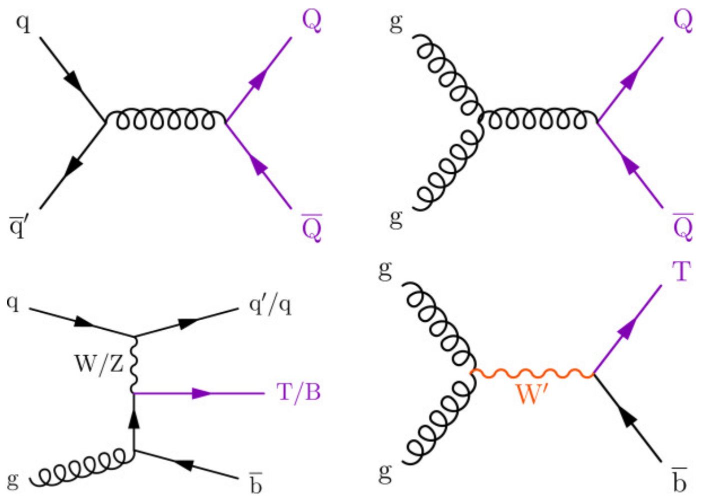

Figure 1: Feynman diagrams showing the productions of VLQ. Plot is from Ref [8]

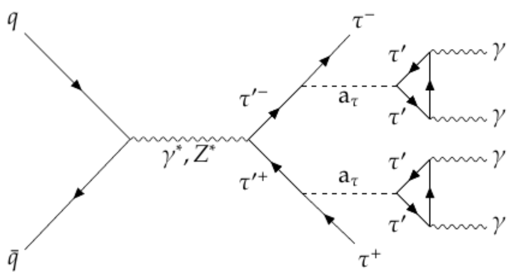

Figure 2: Feynman diagrams showing the productions of VLL, decaying into a_τ and τ

decaying tau leptons τ_h and displaced photons, which create particle showers in the CMS muon detector system. The discriminating variable is N_{hits}, which refers to the number of reconstructed muon detector hits in a cluster representing the shower. The signal clusters produce a large number of reconstructed hits compared to the background clusters, as can be seen in the left plot of Figure 3. The analysis is categorized into drift tube (DT) and cathode strip chambers (CSC), according to the two parts of the CMS muon detector in which the clusters are searched for.

No excess of data above SM predictions is observed. Upper limits at the 95% confidence level (CL) are set on the VLL production cross section, as a function of the VLL mass (m_{VLL}) and the a_τ lifetime ($c\tau_a$). The mass of a_τ is assumed to be 2 GeV. As shown in the right plot of Figure 3, the observed VLL mass exclusion is set at around 690 GeV, depending on the a_τ lifetime assumption.

3. Search for VLQs

The first VLQ analysis searches for single production of T or Y, decaying into a W boson and a bottom (b) quark, where the W boson decays into a lepton and a neutrino [4]. Six event categories are defined based on the combination of b-tagged jets and the lepton information in the final states. The discriminating variable is the VLQ invariant mass reconstructed using the recursive jigsaw algorithm [5]. A neural network multiclass classifier is developed to suppress backgrounds dominated by W+jets, $t\bar{t}$, and single top production. Each background shape is modeled by fitting

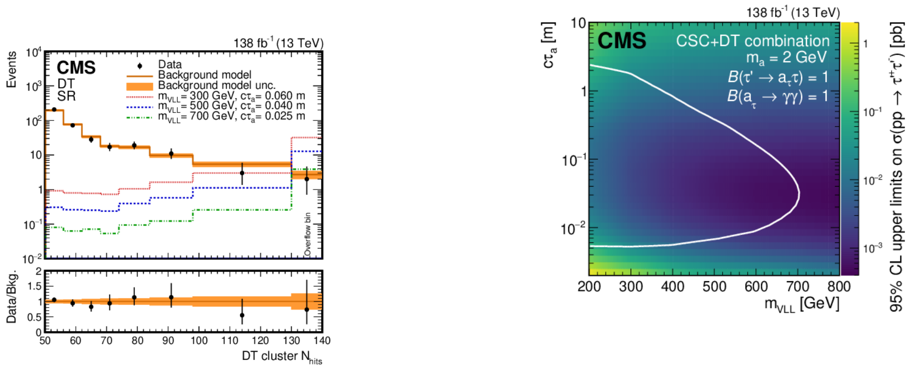

Figure 3: Left: Number of reconstructed hits in signal region of DT category in signal region; Right: The 95% CL observed upper limits on the VLL production cross section.

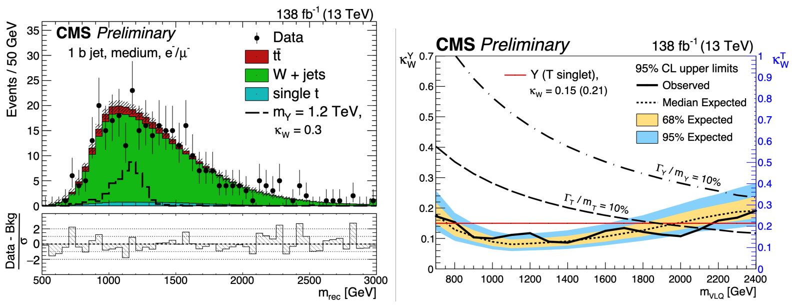

Figure 4: Left: m_{rec} distribution in signal region after the maximum likelihood fit; Right: The 95% CL observed upper limits on the VLQ coupling parameter.

the MC simulated background distributions. The left plot in Figure 4 shows the VLQ invariant mass distribution in one of the six categories.

No signal is observed. Upper limits at the 95% CL on the coupling parameter κ_W are set, as shown in the right plot of Figure 4. The results provide the most stringent limits on single production of Y/T $\rightarrow$ bW, and exclude the preferred coupling in the (B, Y) doublet hypothesis favored by the electroweak fit.

The second VLQ analysis targets single production of T decaying to a top quark and a neutral scalar boson [6], where the top quark decays leptonically and the neutral scalar boson decays into a b quark-antiquark pair. The neutral scalar boson can be an SM Higgs boson or a new BSM particle labeled as ϕ. The main variable for signal extraction is the reconstructed T mass, where the ϕ boson is reconstructed as a large-radius jet. 16 regions, including 8 signal regions, are defined based on the top quark tagging, the b-jet tagging, and the number of forward jets. The left plot in Figure 5 shows the distributions of the reconstructed mass of the T candidate in one of the signal region categories, where the data shows good agreement with the background-only hypothesis. A multiclass boosted decision tree (BDT) is trained for top tagging to discriminate the signal from the main background, including $\mathrm{t\bar{t}}$, W+jets, single top, and QCD multi-jets.

No excess is observed in the signal region, and the data agree with the background-only hypothesis. Upper limits are set at the 95% CL on the T production cross-section times the

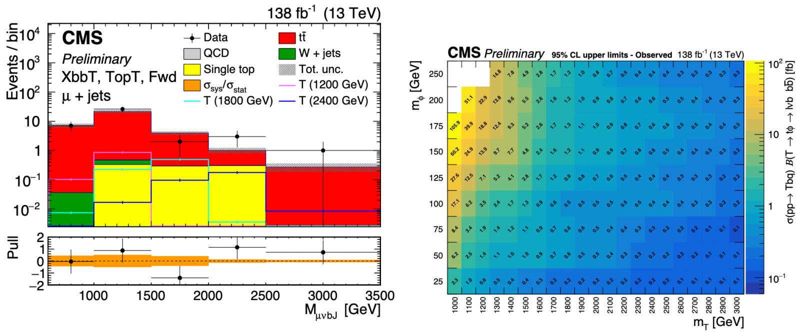

Figure 5: Left: Reconstructed mass of the T candidate in the signal region from one of the categories; Right: The 95% CL observed upper limits on the T production cross section as a function of the T and ϕ masses.

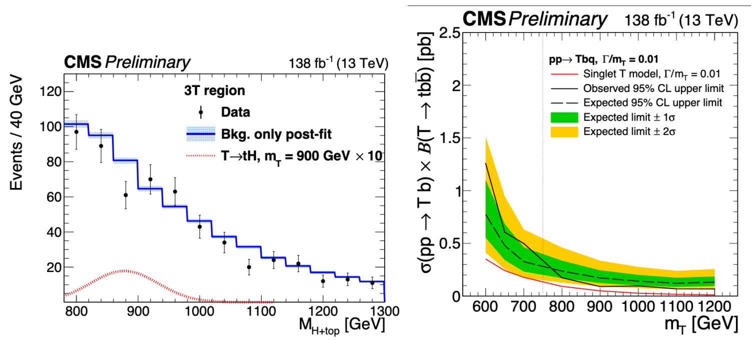

Figure 6: Left: Reconstructed mass of the T candidate in the signal region; Right: The 95% CL observed upper limits on the T production cross section combining all channels in Run 2.

branching ratio of T$\rightarrow$ tϕ $\rightarrow$ b$\ell\nu$bb, as a function of T mass and ϕ mass, as shown in the right plot of Figure 5. In case the neutral scalar boson is an SM Higgs boson, the T mass hypothesis below 1200 GeV is excluded assuming a singlet T quark of resonance width Γ of 5% of the mass.

The third VLQ analysis searches for T $\rightarrow$ tH/Z in all-hadronic final states. The main observable is the T candidate mass reconstructed from five jets, which are selected by matching their reconstructed mass to the known top quark and Higgs boson mass values. The cut-based event selection criteria are optimized for the low-mass and high-mass regions, respectively, suppressing background mainly rarising from QCD multijet and t$\bar{\text{t}}$ production. The background model is derived from data in the relaxed b-tagging region. The left plot in Figure 6 shows the reconstructed mass distributions of the T candidate with results from fits under the background-only hypothesis. No statistically significant signal is found. Upper limits are set at 95% CL on the T production cross-section combining the all-hadronic channels from the T $\rightarrow$ tH and T $\rightarrow$ tZ modes in Run 2, as shown in the right plot of Figure 6.

4. Combination of VLQ and VLL searches

The review paper [8] summarizes the current CMS searches for new fermions, including VLQs, VLLs, and heavy neutral leptons, in Run 2. The left plot in Figure 7 shows the combination of several searches targeting pair produced vector-like b quarks, setting 95% CL upper limits on the

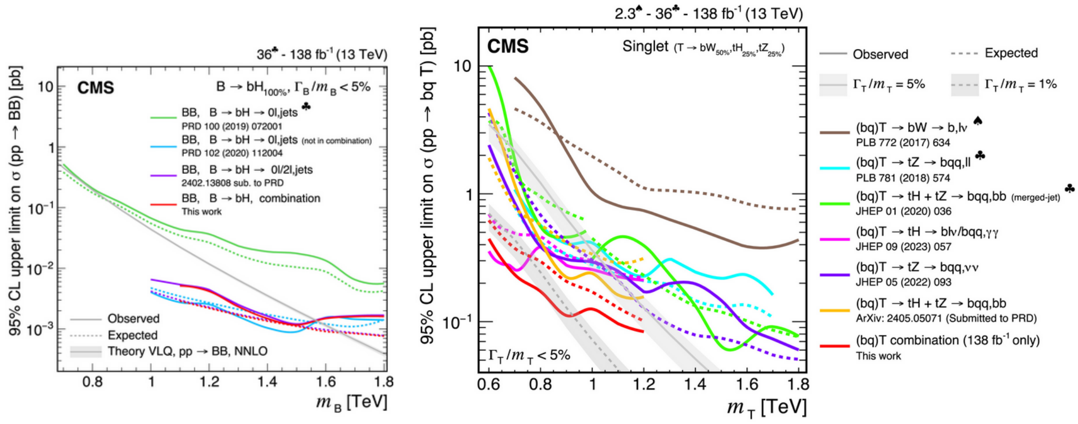

Figure 7: Left: Reconstructed T mass in signal region; Right: The 95% CL observed upper limits on the T production cross section combining all channels in Run 2. The red curves show the combined results.

production cross section of $B\bar{B}$, assuming a $B \to tH$ branching fraction of 100%. The right plot in Figure 7 shows the combination of several single vector-like top quarks searches in three T decay modes, setting upper limits on the T production cross-section. Additionally, the discovery potential for new fermions at the High-Luminosity LHC is discussed in the paper.

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