PROCEEDINGS OF SCIENCE

# VLQ searches and hadronic final states at CMS experiment

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Physics beyond the Standard Model continues to be a captivating and pivotal field for understanding the fundamental interactions of nature. In this work, we explore the most recent results from Compact Muon Solenoid experiment at Large Hadron Collider.
Recent results based on a sample of proton-proton collision events at $\sqrt{s} = 13TeV$, corresponding to an integrated luminosity of $138 fb^{-1}$, are shown for three different searches: single production of Vector Like Quark T in tH decay channel, pair production of Vector Like Quarks T and B, and an heavy resonances search in diboson pair final state.

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## 1. Introduction

The Standard Model (SM) of particle physics, while successful, leaves several fundamental questions unanswered, including the integration of gravity, the nature of Dark Matter, and the baryon-antibaryon asymmetry. It also struggles to explain the stability of the Higgs boson mass at high energies. To address these issues and restore naturalness to the SM, many Beyond the Standard Model (BSM) theories, such as Little Higgs and Composite Higgs, have been proposed. Such theories can be tested at the Compact Muon Solenoid [1, 2] (CMS) experiment at Large Hadron Colliders by searching for new predicted particles, as new heavy fermions like Vector-Like Quarks (VLQs), or new heavy resonances, like Radions, Gravitons, W', or Z'.

## 2. Vector-Like Quarks

VLQs can be produced either in pairs through strong interactions or singly via electroweak interactions. Below, we discuss searches for VLQ T by both single and pair production, as well as VLQ B via pair production.

### Single production of Vector-Like Quark T in tH ($\gamma\gamma$) channel

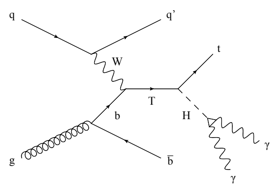


**Figure 1:** Leading-order Feynman diagram for single T' production in Wb fusion and its subsequent decay into tH ($H \to \gamma\gamma$)[3].

A search for single production of VLQ T in the tH channel with Higgs decay to $\gamma\gamma$, as illustrated in Fig.1, is presented [3]. The search classifies events into two categories: leptonic and hadronic decays of the top quark. The leptonic category requires events to have a pair of photons and at least one electron or muon, with an additional requirement of at least one b-tagged jet to target the $t \to bW$ decay. The hadronic category demands three jets, with at least one being b-tagged.

In the leptonic category, QCD, $\gamma$ + jets, and $\gamma\gamma$ + jets processes contribute to 25% of the total background, while in the hadronic category, they account for 95% of the total background. A Boosted Decision Tree (BDT), BDT-SMH, is implemented in each category for signal SM Higgs (SMH) background discrimination. Additionally, a BDT, BDT-NRB, is trained to suppress non-resonant backgrounds in the hadronic category. Upper limits are setted on $\sigma_{T'bq} B_{T' \to tH}$, considering theoretical cross sections for singlet T' production with representative $\kappa_T$-values fixed. Similarly, upper limits on the coupling parameter of T' with SM particles ($\kappa_T$) are presented, assuming a narrow width approximation, Fig.2.

### Pair production of Vector-Like Quarks T$\bar{\text{T}}$/B$\bar{\text{B}}$

In this section, we present the search for pair production of VLQs T and B [4], Fig.3. Three final states are considered: the single-lepton channel, the same-sign charge dilepton channel, and the

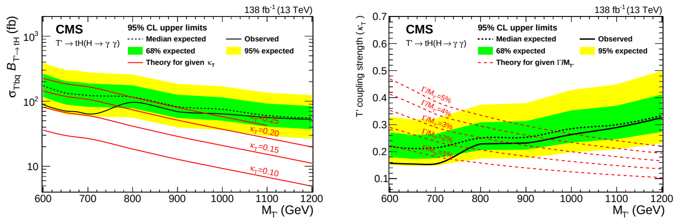


**Figure 2:** The combined, leptonic plus hadronic, expected (dotted black) and observed (solid black) upper limits at 95% CL on the T' coupling to third-generation quarks, $\kappa_T$, under the narrow width approximation displayed as a function of $M_{T'}$. The green (yellow) band represents the 68% (95%) of the limit values expected under the background-only hypothesis [3].

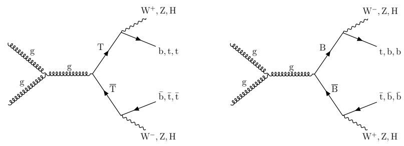

**Figure 3:** Representative Feynman diagrams of the pair production of $T\bar{T}$ (left) and $B\bar{B}$ (right), with decays to third generation quarks and SM bosons [4].

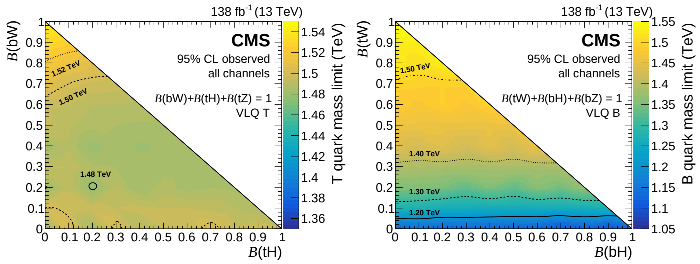


**Figure 4:** The 95% CL observed lower mass limits on pair-produced T (left) and B (right) quark masses, from the combined fit to all channels, as functions of their branching ratios to H and W bosons [4].

multilepton channel with at least three leptons. The single-lepton channel yields a final state with a charged lepton, a neutrino, and large-radius jets, making it sensitive to all TT decays and B decays to tW. The same-sign dilepton channel primarily identifies VLQ pair production with $T \longrightarrow tH$ and $B \longrightarrow tW$ decays, leading to two leptons with the same charge. The multilepton channel is mainly sensitive to $T \longrightarrow tZ$ and $B \longrightarrow tW$ decays, resulting in three or more leptons, a rare final state in the SM. Different techniques are used in each channel for signal-to-background discrimination. The analysis sets upper limits at a 95% confidence level (CL) on the production cross sections of $T\bar{T}$ and $B\bar{B}$ pairs using a binned maximum likelihood fit across multiple categories. Fig.4 displays a scan over various branching fraction combinations, excluding T quarks with masses below 1.48–1.54 TeV and B quarks with masses below 1.12–1.56 TeV, depending on the branching fraction.

## 3. Diboson pairs in all jet final state

In this study, a search for new heavy resonances decaying into WW, WZ, ZZ, WH, or ZH boson pairs in the all-jets final state has been conducted [5]. These resonances can be produced by gluon

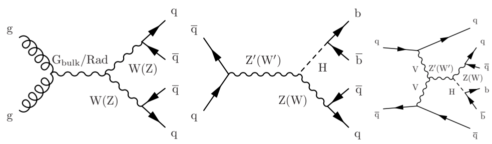

**Figure 5:** Feynman diagrams of the signal processes ggF (left), DY (central) produced and VBF (right) produced. In order graviton or radion decaying to WW(ZZ); Z' and W' decaying to Z(W)H, (right) Z' and W' decaying to HZ(W) [5].

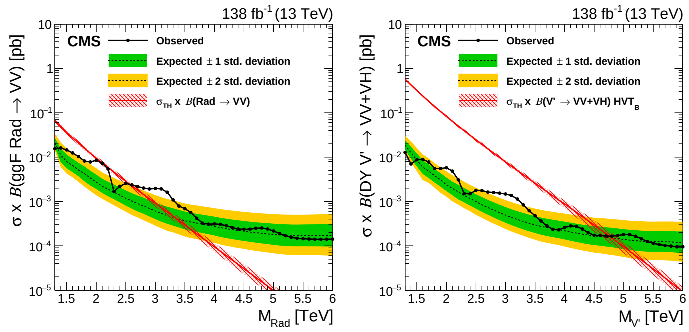


**Figure 6:** Observed and expected 95% CL upper limits on the product of the production cross section ($\sigma$) and the branching fraction, obtained after combining all categories with $138 fb^{-1}$ of data at $\sqrt{s} = 13TeV$, for $Rad \to VV$ (left), HVT model B $V' \to VV + VH$ (right) [5].

fusion (ggF), Drell-Yan (DY) processes, or vector boson fusion (VBF), resulting in two large-radius jets in the final state, some example shown in Fig.5. The selection of the two jets is based on the 'groomed' jet mass and the DeepAK8 neural network jet tagging algorithm scores, which defines signal regions. Control regions for background estimation are also defined using the same tagger. Two main categories are defined: VBF and ggF/DY, with two possible final states, VH and VV. The main backgrounds involve non-resonant and partially resonant processes, prompting a 3D maximum likelihood fit of signal and background templates to data in the $(m_{jj}, m_{jet1}, m_{jet2})$ space. Upper limits on the production cross-section at a 95% confidence level (CL) have been established, as shown in Fig.6. Assuming the $W' \to WZ$ hypothesis, we observe a global significance of $2.3\sigma$ for mass ranges between 2.1 and 2.9 TeV. Unfortunately, searches in semileptonic final states did not uncover any excesses within the same mass range [6, 7].

## 4. Conclusions

We provided an overview of recent BSM search outcomes at the CMS experiment, emphasizing the sensitivity of the current VLQs T search in $tH(\gamma\gamma)$, covering masses up to 1.1 TeV.Notably, TT production results set unprecedented limits across all decay modes, while BB production exhibits the strongest constraint in tW decay. Diboson pair production results in the all-hadronic final state revealed an observed excess in the data, unfortunately, there is no confirmation from the semileptonic searches.

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