PROCEEDINGS OF SCIENCE

Searches for vector-like quarks in CMS

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Searches for T and B vector-like quarks in the single and pair production modes, respectively, using the full Run 2 proton-proton collision data at $\sqrt{s} = 13$ TeV collected by the CMS experiment are presented. Limits on the production of these new particles are set in wide regions of the parameter space. Furthermore, the combinations of several individual analyses for electroweak production of T and pair production of B are shown, highlighting the impact on the sensitivity of the searches for different model assumptions.

12th Large Hadron Collider Physics Conference (LHCP2024)
3-7 June 2024
Boston, USA

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PoS(LHCP2024)011

1. Introduction

Several extensions to the standard model (SM) of particle physics address the hierarchy and naturalness problems of the theory by introducing new heavy fermions called vector-like quarks (VLQs). These are colored, spin 1/2 particles whose left- and right-handed components transform in the same way under the electroweak (EW) gauge symmetry group. Given that the mass of VLQs does not arise from Yukawa couplings, there are strong theoretical motivations for their existence as they are not constrained by current measurements of the Higgs boson cross section.

The phenomenology of VLQs is determined by parameters such as the couplings to SM particles, the assumed VLQ mass and width, and whether next-to-leading order effects in QCD are considered. Depending on the multiplet representation, four VLQ flavors are introduced: T (+2/3), B (−1/3), X (+5/3) and Y (−4/3).

At the LHC, VLQs can be produced in pairs via the strong interaction, or singly via EW mediated processes or new interactions. At low VLQ masses pair production dominates, but the cross section rapidly decreases as a function of mass due to phase-space suppression. Single production, in contrast, has a significant dependence on the chosen values for the VLQ width and for the different couplings to SM quarks and EW bosons. In most models, VLQs decay into a third-generation SM quark and either a W, Z or Higgs boson.

At the CMS experiment [1] of the LHC, an extensive search program for VLQs has been underway since the early years of Run 1. Figure 1 shows the mass limits for VLQs from searches that cover both pair and single production for all VLQ flavors, as well as production through heavy resonance decays. The dependence on the chosen values for the couplings to SM particles has also been studied in some of these searches. Further details can be found in [2].

In the following, two recent searches for VLQs using the full 138 fb^{-1} of the Run 2 dataset are presented, as well as combinations of different analyses for the single production of T and the pair production of B.

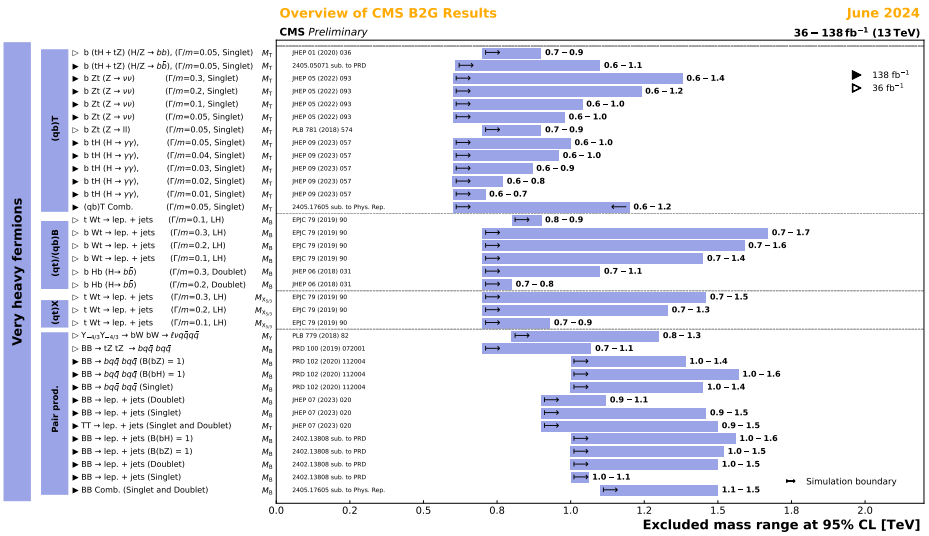

Figure 1: Summary of VLQ searches at CMS using Run 2 data at $\sqrt{s}$ = 13 TeV [3]. 95% CL lower mass limits are shown for each explored scenario.

2. Search for single production of T decaying to tH/tZ in the all-hadronic final state

A search for the single production of a T VLQ in the all-hadronic final state, designed for the tZ and tH decay modes, is performed [4]. This analysis searches for a resonant peak in the reconstructed 5-jet invariant mass distribution. Since this search aims to reconstruct the T candidate from resolved jets, only VLQ masses between 0.6 and 1.2 TeV are considered. The baseline selection requirements demand the presence of at least 6 small-radius jets, of which at least 3 must be b-tagged. To reconstruct the T quark candidates, a multistep χ^2 minimization procedure is used, in which first the Higgs or Z candidates are reconstructed from the b-tagged jet collection, and the remaining jets are then used to reconstruct the W and top quark candidates.

Events are categorized depending on the reconstructed invariant mass. A high-mass selection is implemented which takes into account the moderate Lorentz boost of the final state. This selection has a drawback, which is that it distorts the shape of the invariant mass distribution, sculpting it at low masses. Hence, a low-mass selection is applied for masses below 800 GeV to ensure a falling spectrum.

The total background contribution is estimated directly from data. Three independent regions are defined based on the working point of the b-tagging algorithm. The background yields are determined from the regions with relaxed b-tagging requirements and extrapolated to the signal region by means of transfer functions and normalization factors, which are based on the ratios of selection efficiencies in each of the regions. The total contribution is then constructed bin-by-bin using a simultaneous binned maximum likelihood fit. This data-driven approach was validated in 45 control regions, enriched in multijet or $t\bar{t}$ events. In all these regions, the method proved to give an accurate description of the data.

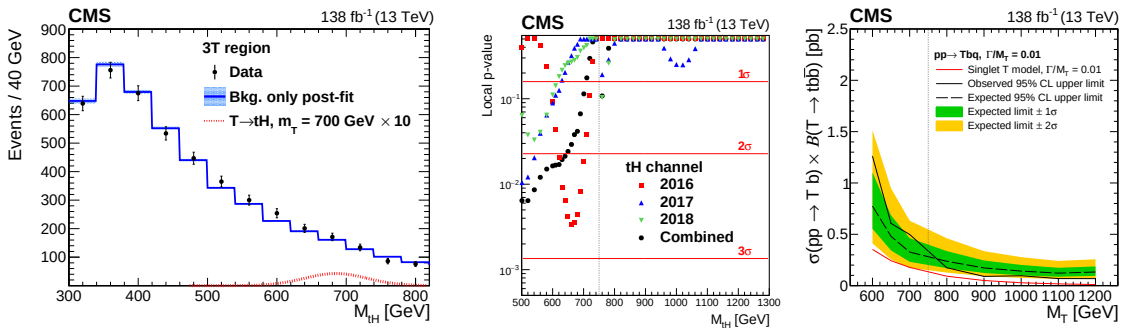

Figure 2: Left: Example of the 5-jet invariant mass distribution after a background-only fit to the complete dataset in the tH channel for the low-mass selection. Center: Observed p-values for the tH channel for each year and their combination. Right: Observed and expected 95% CL limits on the cross section for associated production with a b quark for the combined tH and tZ final states. Plots taken from [4].

The histogram on the left of Fig. 2 shows the 5-jet invariant mass distribution in one signal region for the low-mass selection. When combining all categories, from all years, no evidence for single T production is observed. A fluctuation observed with only 2016 data, around 680 GeV, vanishes when using the full statistics (Fig. 2, center). Since no significant deviation from SM predictions is observed, 95% confidence level (CL) upper limits are set on the cross section times branching fraction to $tb\bar{b}$ (Fig. 2, right). For a narrow-width singlet, these limits range from 1260

to 68 fb for masses between 600 GeV and 1.2 TeV. These limits are stronger than the ones obtained in a previous search by CMS [5] on this same channel by a factor of three.

3. Search for pair production of B in the dileptonic and all-hadronic final states

A search for pair production of a B quark is performed, optimized for relatively high VLQ masses [6]. The three possible decay modes of the B are allowed and two categories for the final state are explored: fully hadronic and dileptonic. Events are further classified based on the jet multiplicity, which takes into account possible merging of jets due to Lorentz boosts, and also the presence of jets from ISR or FSR in the dileptonic channel.

In the dileptonic channel, between 3 and 5 small-radius jets are required, combined with the presence of an opposite-sign lepton pair with a mass consistent with the Z boson. The fully hadronic channel requires more jets and no leptons satisfying the dileptonic criteria, to ensure orthogonality. To classify events into the different classes, a modified χ^2 metric is used. All possible jet combinations are tested and the decay mode with the lowest value is then selected as the reconstructed mode. This modified χ^2 parameter is constructed based on the fractional mass difference between the two reconstructed VLQ candidates, and on the masses of the hadronically decaying EW bosons. The cut on the χ^2 is optimized for each class.

The background contribution is derived from sideband and control regions in data. For the fully hadronic category, the total number of events in a given VLQ mass bin is weighted by a factor that accounts for the background reduction due to implementing the b-tagging requirements. This factor is estimated from a sideband region at low mass, but its variation as a function of mass is also considered. For the dileptonic category, the number of VLQ candidates, obtained from a fit in a control region without any b-jet requirements, is normalized by the ratio of events in the signal region to the number of events in the control region.

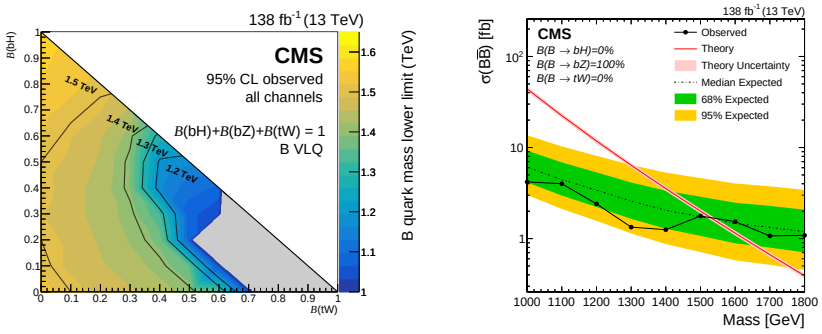

Figure 3: Left: Observed exclusion limits on the VLQ mass at 95% CL as a function of the $\mathcal{B}$ to bH and tW. The gray area represents regions in which the exclusion limit is less than 1 TeV. Right: Limit at 95% CL on the cross section for VLQ B pair production considering a $\mathcal{B}$ to tZ of 100%. Plots taken from [6].

The reconstructed invariant mass distributions across all classes in the different categories show no significant deviation from the background expectations. Limits are derived as a function of the assumed branching fractions to the different decay modes. These are shown in the triangular plot on the left-hand side of Fig. 3. The increased sensitivity is more evident when the branching fractions ($\mathcal{B}$) to bZ are larger, due to the fact that the dileptonic category is being included. For

example, when a $\mathcal{B}$ to bZ of 100% is assumed, masses for the B VLQ below 1.5 TeV are excluded, as shown in the right plot of Fig. 3. These are amongst the most stringent limits on B VLQ to date.

4. CMS combination results

4.1 Combination of single T searches

Three Run 2 searches for single T quark production have been combined [2]. The decay modes considered are: $\gamma\gamma$ and $b\bar{b}$ for the Higgs boson decay, and $b\bar{b}$ and invisible for the tZ channel. Since these are, by construction, mutually exclusive final states, the different analyses constitute statistically independent observations. Even though in some of the individual searches different widths have been explored, only NWA scenarios are included in the combination. The mass points common to the three searches range from 600 to 1200 GeV. The upper limits on the cross section as a function of the T quark mass in a singlet scenario show that the combination significantly improves the sensitivity (Fig. 4, left). Limits have also been set as a function of the assumed width (Fig. 4, right). Masses of up to 1.3 TeV have been excluded at 95% CL for some of the largest width scenarios. In these large width scenarios, the limits are driven by the Higgs to diphoton channel.

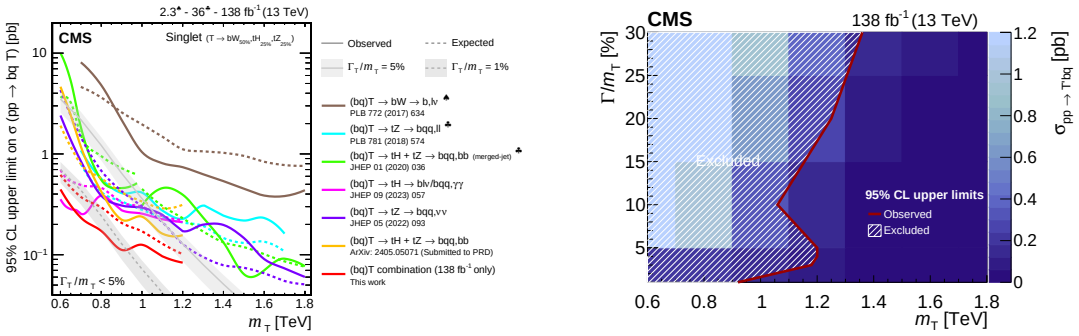

Figure 4: Left: Observed and expected limits on the production cross section of a single T quark in association with a b quark in a singlet scenario as a function of the T quark mass. Limits obtained from the combination of the individual analyses are shown in red. Right: Observed upper limits on the product of the single production cross section and the tZ/tH $\mathcal{B}$ for a singlet T quark as a function of the VLQ mass and width. The red line indicates the boundary of the excluded region. Plots taken from [2].

4.2 Combination of BB searches

BB final states with mutually exclusive lepton selection criteria have been combined [2], and a simultaneous fit to all template distributions has been performed to determine a common signal strength. As shown in the left plot in Fig. 5, pair production of a B VLQ is excluded for masses below 1.49 TeV. This is a significant increase with respect to any of the individual searches. The gain in sensitivity coming from this combination depends on the assumed branching fraction. For example, in the middle plot of Fig. 5, in which a 100% branching fraction to bH is assumed, there is not a significant gain in sensitivity and, in fact, an individual search not included in the combination gives stronger limits. However, in the singlet scenario (Fig. 5, right), with the standard assumed branching fractions, a significant gain in sensitivity can be observed by combining the two individual searches.

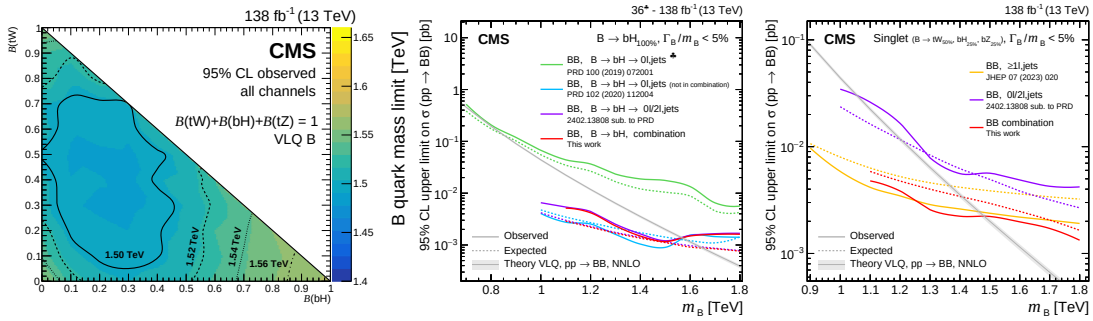

Figure 5: Left: Observed lower limits on the B quark mass from the combination of two pair production searches. Center: Observed and expected upper limits on the pair production cross section of B VLQs decaying to bH as a function of mass. Right: Observed and expected upper limits on the pair production cross section of B VLQs assuming $\mathcal{B}$ of the singlet representation. Plots taken from [2].

5. Summary

VLQs constitute an interesting avenue for searching for beyond the standard model physics at the CMS experiment. The results of two recent individual searches for VLQs were presented, which showcase the sophisticated analysis techniques that are being implemented to deal with the complex final states and that result in stringent limits on the production of these particles. Also, the combination of several individual analyses for single and pair production of T and B VLQs, respectively, was presented, that increased the sensitivity of the searches in some regions of the parameter space.

References

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