Searches for vector-like quarks at CMS

Justin Pilot, on behalf of the CMS Collaboration[*]

University of California, Davis

E-mail: jrpilot@ucdavis.edu

This contribution details results of recently completed searches for massive vector-like top and bottom quark partners using proton-proton collision data collected with the CMS detector at the CERN LHC at a center-of-mass energy of 13 TeV. Single and pair production of vector-like quarks are studied, with decays into a variety of final states, containing top and bottom quarks, electroweak gauge and Higgs bosons. Analyses utilize several categories of reconstructed objects, from multi-leptonic to fully hadronic final states. Improved exclusion limits on both the vector-like quark mass and cross sections are obtained, for combinations of the possible vector-like quark branching ratios.

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[*]Speaker.

1. Introduction

Vector-like quarks (VLQs) are a feasible solution to the hierarchy problem, and arise in many extensions to the SM. These particles are named vector-like because their left- and right-handed components transform the same way under the $SU(2)$ symmetry group. The VLQs presented here are denoted T and B. The T (B) quark has three dominant decay modes: tH, tZ, and bW (bH, bZ, and tW). A VLQ singlet scenario is studied, with branching ratios to tW/bW bosons being 50%, and branching ratios to bZ/tZ and bH/tH being 25% each. A doublet scenario is also considered, with no decay to tW/bW, and the other branching ratios equivalent.

There are two production mechanisms for VLQs at the Large Hadron Collider (LHC). The pair production mode is through the strong interaction, and is essentially model independent, while the single production mode requires associated forward jets, and depends strongly on the couplings to SM quarks. Vector-like quarks are expected to be produced at the LHC with high rates, with the expected production cross sections ranging from 0.1 to 1000 fb for VLQs with masses from 1600 to 600 GeV [2]. Above 600 GeV, single VLQ production begins to dominate relative to the pair production mode, as they have received a greater enhancement from the change in LHC center-of-mass energy from 8 to 13 TeV.

This presentation will summarize the recent VLQ search results from the CMS experiment [1].

2. Search for VLQs using leptons

A recent search for VLQ pair production TT or BB has been completed utilizing leptons in the final state [3]. The combination of different lepton counts in the final state with jet substructure techniques to identify hadronic decays of W or Higgs bosons enhances the sensitivity to the VLQ signal.

The search encompasses several unique categories. In the single lepton category, events are divided based on the number of identified W, H, and b tagged objects. Depending on the signal region, the quantity $\min[M(\ell, b)]$ is computed to separate the top quark pair background from the VLQ signal by finding the lepton and b quark combination that gives the lowest reconstructed mass. This quantity will be higher for VLQ events compared to SM backgrounds, as seen in Fig 1. In other categories, the sum of lepton and jet energies, S_T, is used to discriminate the signal.

Figure 1: Distribution of $\min[M(\ell, b)]$, used to discriminate signal from background in the search for VLQ pairs using leptons. [3]

In the same-sign dilepton and trilepton categories of this analysis, backgrounds from charge misidentification and non-prompt leptons are taken into account, with events containing non-
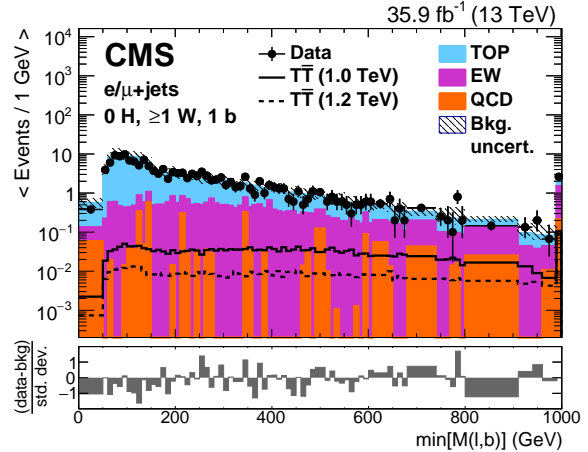
prompt leptons being the leading contribution in the trilepton signal regions. For the same-sign dilepton signal regions, a simple counting experiment is performed, while for the trilepton signal regions, the S_T distribution is used to discriminate signal.

A scan over branching ratios is performed, with VLQ mass exclusion limits ranging from 900 to 1300 GeV. For the singlet scenario, T quarks with masses below 1.2 TeV are excluded (1.16 TeV expected), while B quarks with masses below 1.17 TeV are excluded (1.13 TeV expected). These results represent significant improvements upon Run 1 results.

A complementary analysis [5] also uses leptons to search for singly-produced T quarks, using the tZ decay mode, excluding a VLQ T quark with mass below 1.2 TeV in the singlet scenario.

3. Targeting $B \rightarrow bH$ with Higgs tagging

Another recent analysis utilizes the single VLQ production mode to search for single B quarks produced in association with a forward jet [4]. Requiring this forward jet enhances the signal purity, as SM events tend to have fewer forward jets compared to the single VLQ signature, as seen in Figure 2. In addition, the analysis targets the specific bH decay mode of the B quark. Using subjet b tagging as well as jet mass observables, the Higgs signature can be efficiently identified while rejecting SM backgrounds.

The analysis divides events based on the number of forward jets, and uses a data-driven method to estimate the dominant QCD multijet background. That background is estimated using control regions formed by inverting requirements on the Higgs candidate jet mass and the number of subjet b tags found. Finally, the invariant mass of the b and Higgs candidates is computed to discriminate the VLQ signature, where a peak is expected relative to the SM background.

This search for bH yields cross section limits in the range of 1.28 to 0.07 pb, for B masses between 0.7 and 1.8 TeV. Currently, no mass exclusion is obtained in the search range, however, this is the first analysis to assume a non-negligible VLQ width and include its effects in the signal model.

4. Search in tW channel with jet substructure

The final analysis to be discussed is again a search for B quarks in the single production mode, but targeting the tW decay mode [6]. At least one electron or muon is required in this analysis. Jet substructure techniques are used to identify boosted hadronic top quark or W boson candidates. Events are then divided based on the number of these objects identified in the final
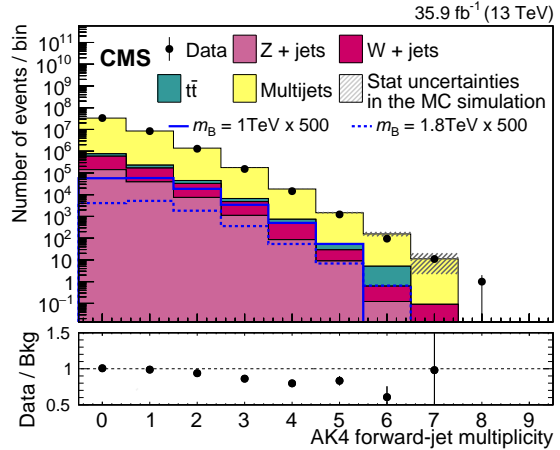

Figure 2: The distribution of the number of forward jets in selected events, with the VLQ signal peaking at larger values than the background. [4]

state. The mass of the *B* quark is recon-
structed by combining the top quark and leptonic *W* candidates. A χ^2 method is used to assign objects to the top quark and/or *W* boson candidate in other signal regions. Minimizing this χ^2 quantity, including terms for the top quark and *W* boson masses, as well as the angular separation of the two, provides the best resolution and signal discrimination.

The backgrounds in all signal regions are estimated from data by inverting the requirement of at least one forward jet in the event. Shapes from this control region are then extrapolated to the signal region. One of the signal regions, requiring a boosted top jet candidate, is shown in Figure 3. Limits are set on VLQ *B* production, excluding cross sections above 0.3 pb for a *B* quark mass of 700 GeV, and cross sections above 0.03 pb for a *B* quark mass of 1.8 TeV.

5. Summary

This document details some of the recent results in the search for vector-like quarks by the CMS collaboration. Searches targeting the single production mode are becoming more powerful in Run 2 due to the greater increase in cross section relative to the pair production mode. The full set of results of CMS searches for VLQs can be found at Ref. [7].
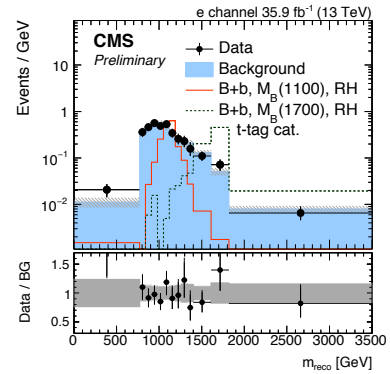

Figure 3: Data-driven background for the signal region containing a boosted top jet candidate. [6]

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