PROCEEDINGS OF SCIENCE

Searches for vector-like quarks at CMS

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The CMS Collaboration has a robust program of searches for vector-like quarks. The first search available using 137 fb^{-1} of proton-proton collision data with $\sqrt{s}$ = 13 TeV collected by the CMS experiment in Run 2 of the LHC is presented here. This search targets vector-like B quarks that decay to bH or bZ combinations in a hadronic final state. Lower limits on the mass of the B quark are determined for several branching fraction hypothesis, extending CMS sensitivity to these particles by 300 – 500 GeV, depending on the decay mode.

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PoS(ICHEP2020)250

1. Introduction

Vector-like quarks (VLQs) are new fermions that are predicted in a variety of new physics models, such as Little Higgs or Composite Higgs models [1, 2]. They are non-chiral quarks, which gives rise to the adjective "vector-like" — VLQs have different interactions with the Standard Model (SM) forces than do chiral quarks. This allows VLQs to act as a "top partner" and reduce the effect of divergent quantum corrections to the Higgs boson mass. They can be produced in pairs via the strong force or alone via an electroweak interaction. The most common models suggest strong coupling between VLQs and third generation SM quarks, though other couplings are possible. The decays of the VLQ depend on the electroweak multiplet of new particles proposed: singlets, doublets, and triplets all have different decays for the vector-like T, B, X, or Y quarks [2].

The CMS and ATLAS collaborations have strong search programs with benchmarks of vector-like T and B quarks. CMS searches with 36 fb^{-1} of proton-proton collision data with $\sqrt{s}$ = 13 TeV from 2016 reached sensitivity to T quark masses above 1.2 TeV for many decay modes, but sensitivity remained considerably lower for vector-like B quarks [3–6]. The search presented here is the first published using 137 fb^{-1} of data from Run 2 of the LHC, and targets B quark production [7].

2. Search for $\mathrm{B\overline{B}}$ in hadronic decays

This search is for $\mathrm{B\overline{B}}$ production with decays of the B quarks to either bH or bZ in hadronic final states. If both B quarks decay to bH (Fig. 1, left), the final state may contain six b quarks, which is strikingly unique from most SM processes. It is possible that all six b quark jets are resolved, or perhaps one or both of the H/Z bosons is sufficiently Lorentz-boosted for its decay products to be reconstructed as a single jet in the CMS detector [8]. This search features three independent channels containing 6-jet, 5-jet, and 4-jet events, allowing for a range of boosts. The VLQ mass is reconstructed by assigning jets to particles in the decay according to a minimization technique. Figure 1 (center) shows that this reconstruction gives a narrow peak near the generated VLQ mass, using the 5-jet channel and the bHbH final state as an example.

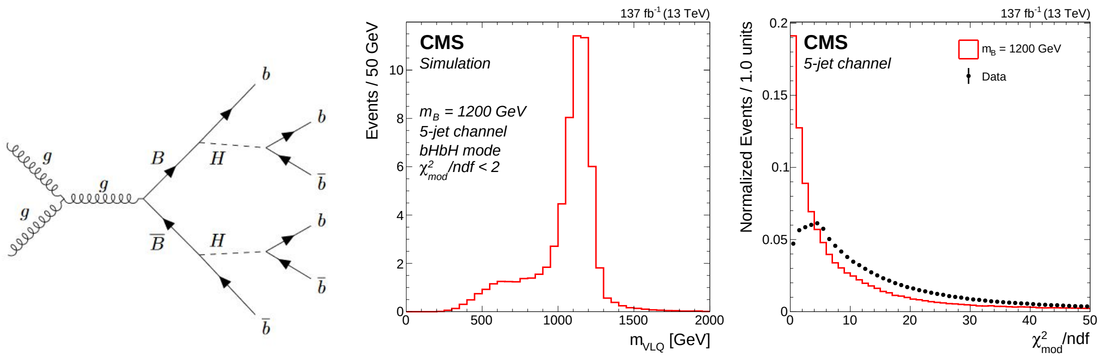

Figure 1: Left: an example Feynman diagram showing two bH decays. Center, right: Distributions of the reconstructed VLQ mass in simulated signal (center), and χ^2_{mod} in signal and data (which represents the background) [7]. All figures show 5-jet events with the bHbH decay mode hypothesis.

Jets are assigned to particles in the decay using several constraints: some jet pairs or merged jets must be consistent with H or Z bosons, and the two VLQ candidates formed should have consistent mass. A modified χ^2 metric is constructed from several terms : the mass of the 2-jet pair should match its simulated value, any large-jet groomed mass should match its simulated value, and the final term compares VLQ masses and attempts to minimize it. Equation 1 shows this metric for 5-jet events, with m_{dijet} referring to the mass of a 2-jet pair, m_{merged} referring to the mass of a boosted H or Z boson jet, m_{VLQ} referring to the reconstructed VLQ mass, and the various σ values referring to the widths of these mass distributions in simulation. Similar definitions of χ^2_{mod} are used for the other combinations of jets considered in the 4-jet and 6-jet channels. As shown in Fig. 1 (right), the signal peaks sharply at zero in this metric while the background has a significantly larger mean value.

$$\chi^2_{\text{mod}}(\text{5-jet channel}) = \frac{(m_{\text{dijet}} - \overline{m}_{\text{dijet}})^2}{\sigma^2_{m_{\text{dijet}}}} + \frac{(m_{\text{merged}} - \overline{m}_{\text{merged}})^2}{\sigma^2_{m_{\text{merged}}}} + \frac{(\Delta m_{\text{VLQ}} - \overline{\Delta m}_{\text{VLQ}})^2}{\sigma^2_{\Delta m_{\text{VLQ}}}}. \quad (1)$$

3. Background estimation

In hadronic final states the dominant multijet background must be estimated from data. Before applying b tagging criteria, the data contains an overwhelming amount of background and very little signal. Figure 2 shows data events in the 5-jet bHbH category with $\chi^2_{\text{mod}} < 4$, in which we fit an exponential function to the falling slope in order to predict the shape of the background distribution as a function of VLQ mass. To normalize this shape distribution to an accurate background rate, we need to understand what fraction of background events are retained when b tagging criteria are applied. We require 4 b-tagged jets in the 6-jet channel; 3 in the 5-jet channel; and 2 in the 4-jet channel. For the bHbH and bHbZ signal hypotheses, the 4-jet channel should also include one boosted "double b" tag, indicating that a massive particle decayed to two b quarks within a single jet. These are very stringent b tagging requirements and they all rely on taggers that are developed using deep machine learning [9, 10].

The rate at which background events pass the b tagging requirements is measured in a low mass sideband, where the reconstructed VLQ mass is less than 1000 GeV. This value must be propagated to the high mass region, where the fraction may vary. A region of data with large χ^2_{mod} values (12 – 48) is used to map out the variation of the b tagging rate as a function of VLQ mass (Fig. 2, center). The total background estimate for a certain VLQ mass is given by the exponential fit to the data, multiplied by the low-mass b tagging fraction and by the normalized mass variation function.

The b tagging requriements are very strict. Figure 3 shows the fraction of events accepted in background (left) and in signal (center). Signal-like events are near the bottom of the y-axis while background-like events are at the top. The color scale shows the b tagging rate, which is quite consistent along the vertical axis, showing that the corrections derived at high χ^2_{mod} are valid for events with low χ^2_{mod}. The signal, in contrast, shows strong b tagging efficiency across the χ^2_{mod} and mass ranges.

4. Results

Figure 3 (right) shows the distributions of reconstruction VLQ mass in the signal region. The b tagging criteria are applied and χ^2_{mod} is constricted to less than 2 – 5.5, depending on the number

PoS(ICHEP2020)250

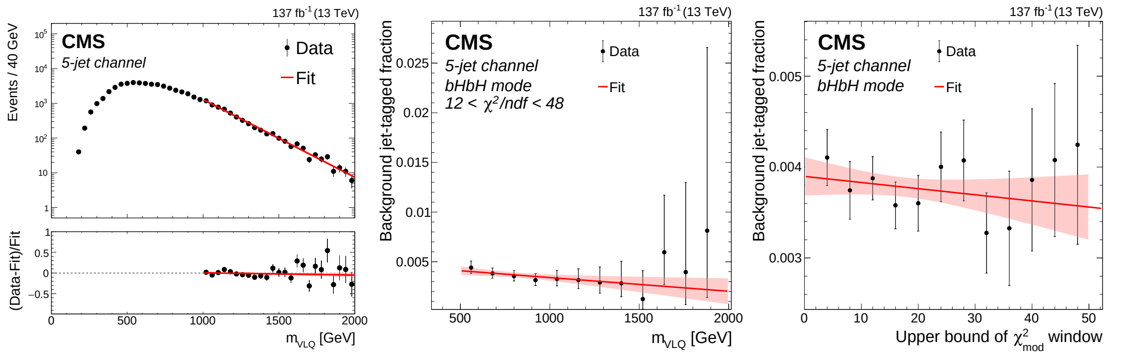

Figure 2: Distributions of the reconstructed VLQ mass in 5-jet events with $\chi^2_{\text{mod}} < 4$ for the bHbH decay mode (left), the fraction of high-χ^2_{mod} events passing b tagging requirements as a function of VLQ mass (center), and the fraction of low-mass events passing b tagging requirements as a function of the chi^2_{mod} window [7]. Data are shown as black points and fitted functions are shown as red curves with shaded error bands.

of jets and the decay mode. Figure 3 (right) shows the bHbH hypothesis with smoothly falling background distributions and peaking signal mass distributions. The background uncertainty is dominated by the statistical uncertainty in the various fits, while the signal uncertainty is dominated by pileup effects and uncertainties in the b tagging algorithms. No significant excess of data over the background prediction is observed in any channel.

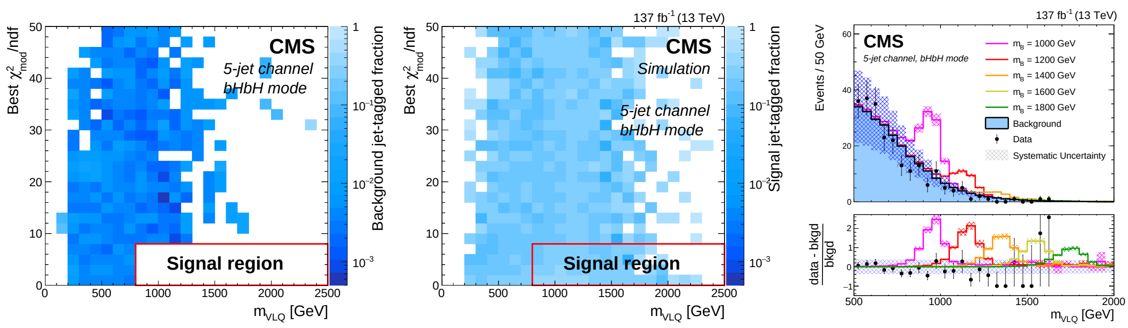

Figure 3: Distributions of the fraction of background (left) and signal (center) events passing the b tagging requirements, as functions of VLQ mass and χ^2_{mod} [7]. The right figure shows the final distribution of background (blue histogram), signal (solid lines), and data (black points) for the 5-jet bHbH channel.

The limits on the production cross section are the most sensitive to date for BB production by the CMS collaboration. Figure 4 (left) shows the lower mass limit for B quarks based on decay mode, ranging from 1300 GeV in the 100% bZ decay mode to 1570 GeV in the 100% bH decay mode. This is an improvement in sensitivity of 300 – 500 GeV in the various bH and bZ dominated decay modes. The strongest improvement (Fig. 4, right) is found in the 50% bH/50% bZ decay mode. The full suite of upcoming CMS searches for VLQs with full Run 2 data will be combined for a legacy result on the production of these unique new physics particles.

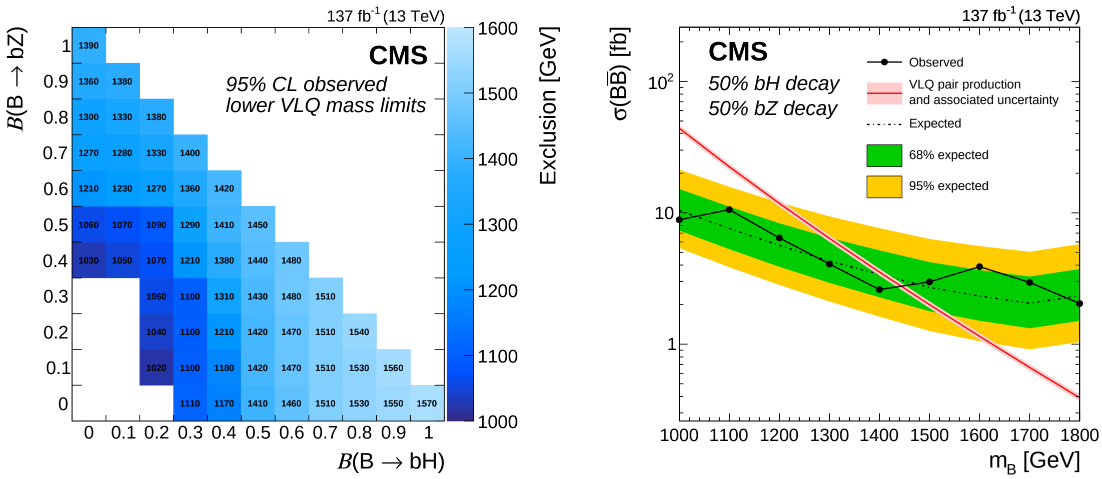

Figure 4: Observed lower limits on the B quark mass for a variety of branching fraction scenarios (left), and upper limits on the $B\overline{B}$ production cross section for a B quark with $\mathcal{B}$(bH) = $\mathcal{B}$(bZ) = 50% (right) [7].

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