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Search for single production of vector-like quarks decaying into a b quark and a W boson in proton–proton collisions at $\sqrt{s} = 13$ TeV

The CMS Collaboration *

CERN, Switzerland

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ABSTRACT

A search is presented for a heavy vector-like quark, decaying into a b quark and a W boson, which is produced singly in association with a light flavor quark and a b quark. The analysis is performed using a data sample of proton–proton collisions at a center-of-mass energy of $\sqrt{s} = 13$ TeV collected at the LHC in 2015. The data set used in the analysis corresponds to an integrated luminosity of 2.3 fb^{-1}. The search is carried out using events containing one electron or muon, at least one b-tagged jet with large transverse momentum, at least one jet in the forward region of the detector, and missing transverse momentum. No excess over the standard model prediction is observed. Upper limits are placed on the production cross section of heavy exotic quarks: a T quark with a charge of 2/3, and a Y quark with a charge of −4/3. For Y quarks with coupling of 0.5 and $\mathcal{B}(Y \to bW) = 100\%$, the observed (expected) lower mass limits are 1.40 (1.0) TeV. This is the most stringent limit to date on the single production of the Y vector-like quark.

1. Introduction

The standard model (SM) of particle physics has been exceptionally successful in describing phenomena at the subatomic scale. The observation of a Higgs boson with a mass of 125 GeV and with properties consistent with the SM expectations [1–3] completed the SM. However, in the absence of enormous order-dependent cancellations, also known as fine-tuning, large SM quantum corrections would shift the bare Higgs boson mass to values far beyond the electroweak scale. New physics is required to stabilize the Higgs boson mass naturally at the electroweak scale, i.e. without invoking fine-tuning.

Many natural extensions of the SM have been proposed in recent decades. Some of these models postulate the existence of vector-like quarks (VLQs) [4–6], which are colored fermions with left- and right-handed chiral states both transforming in the same way under the gauge group $SU(3)_C \times SU(2)_L \times U(1)_Y$. The VLQs do not acquire masses through the Yukawa coupling to the Higgs field, and could cancel loop corrections from the SM top quark to the Higgs boson mass.

Searches for VLQs have already been performed in various decay modes using proton–proton collisions at $\sqrt{s} = 8$ TeV. These searches were primarily focused on the pair production mechanism and they ruled out VLQs with masses up to approximately 0.90 TeV [7–10]. The VLQ single production mechanism is coupling-dependent, and it could become the dominant contribution to the cross section at high VLQ masses. The strength of the VLQ-b-W coupling can be approximately characterized by a single dimensionless parameter that varies from 0 to $\sqrt{2}$ [11], where the latter would correspond to a coupling of full electroweak strength.

In this paper, we present a search for the single production of a heavy vector-like quark that decays into a b quark and a W boson using the 2015 LHC data set. This signature can arise from either a Y or a T quark with a charge of −4/3 or 2/3, respectively, produced in association with a light flavor quark and a b quark. The leading order Feynman diagram for Y and T quark production is shown in Fig. 1. The outgoing light flavor quark q' in the upper part of the diagram produces a jet in the forward region of the detector, which is a distinct signature of single production.

The Y quark is expected to decay with a branching fraction ($\mathcal{B}$) of 100% into a b quark and a W boson [12], while the T quark can also decay into tH and tZ via a flavor changing neutral current. Searches with the 2015 LHC data set for single production of a vector-like T quark decaying to tH and tZ have been performed by the CMS Collaboration [13–15]. If the T quark is a singlet, then it is expected to decay into bW 50% of the time.

The ATLAS Collaboration published a search for single production of Y and T quarks decaying into bW using 8 TeV proton–proton collisions [16]. The analysis presented here is the first such search using 13 TeV proton–proton data, and sets the most stringent limits to date on the production cross section for a single Y or T quark.

* *E-mail address:* cms-publication-committee-chair@cern.ch.

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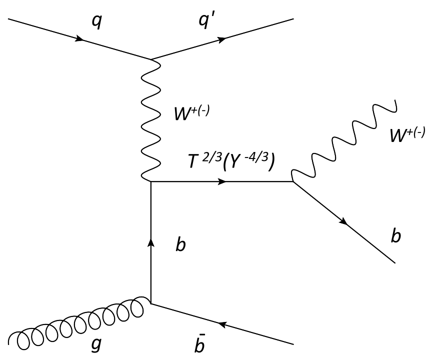

Fig. 1. Leading order Feynman diagram for singly produced Y or T quarks.

The search is carried out based on events containing one electron or muon, at least one b-tagged jet with large transverse momentum (p_{T}), at least one jet in the forward region of the detector, and missing transverse momentum.

2. CMS detector and event samples

The essential feature of the CMS detector is the superconducting solenoid, 6 m in diameter and 13 m in length, which provides an axial magnetic field of 3.8 T. Within the solenoid volume a multi-layered silicon pixel and strip tracker is used to measure the trajectories of charged particles with pseudorapidity $|\eta| < 2.5$. Outside of the tracker system, an electromagnetic calorimeter (ECAL) made of lead tungstate crystals and a hadron calorimeter (HCAL) made of brass and scintillators cover the region $|\eta| < 3.0$. The region $3.0 < |\eta| < 5.0$ is covered by the forward hadronic calorimeter, which is made primarily of steel and quartz fibers. Muons are measured in gas-ionization detectors embedded in the steel flux-return yoke of the solenoid, and covering the region $|\eta| < 2.4$. A more detailed description of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found in Ref. [17].

The data used for this analysis were recorded during the 2015 data taking period in proton–proton collisions at a center-of-mass energy of 13 TeV, corresponding to an integrated luminosity of $2.3\,\mathrm{fb}^{-1}$. The electron data sample was collected using a trigger that required at least one isolated electron with $|\eta| < 2.5$ and $p_{\mathrm{T}} > 27\,\mathrm{GeV}$. The muon data sample was collected using a trigger that required at least one isolated muon with $|\eta| < 2.1$ and $p_{\mathrm{T}} > 20\,\mathrm{GeV}$.

The VLQ signal efficiencies and background contributions are estimated using Monte Carlo (MC) samples. They are validated using background enriched data samples. The $\mathrm{t\bar{t}}$+jets, t- and tW-channel single top-quark production and the WW processes are simulated using POWHEG v2 [18–20]. Single top quark production via s-channel and the WZ process are simulated with MadGraph5_aMC@NLO v2 [21]. Inclusive boson production (W+jets and Z+jets) is simulated with MadGraph v5 [22]. PYTHIA 8.212 [23,24] is used for parton shower development and hadronization and to simulate QCD multijet events.

The VLQ processes considered in this paper are generated using the tree-level MC event generator MadGraph v5 for VLQ masses in the range from 0.70 to 1.80 TeV, in steps of 100 GeV. The VLQ width is set to 10 GeV for all masses. The NNPDF3.0 [25] parton distribution functions (PDFs) are used for both signal and SM MC processes to model the momentum distribution of the colliding partons inside the protons.

The cross sections used to normalize the SM processes are calculated to next-to-leading order (NLO) or to next-to-next-to-leading order (NNLO), where the latter is available [26–28]. For the signal, the NLO cross sections are taken from Refs. [29,30]. For the $\mathrm{t\bar{t}}$+jets, tW-channel single top-quark, and WW SM processes, NNLO cross sections are used, while NLO cross sections are applied to the remaining processes.

All generated events are processed through the CMS detector simulation based on Geant4 [31]. Additional minimum bias events, generated with PYTHIA 8.212, are superimposed on the hard-scattering events to simulate multiple proton–proton interactions (pileup) within the neighboring bunch crossings. The simulated events are weighted to reproduce the distribution of the number of pileup interactions, 20 on average, observed in data.

3. Event reconstruction

All physics objects in the event are reconstructed using a particle-flow (PF) algorithm [32,33], which uses information from all subsystems to reconstruct photons, electrons, muons, and charged and neutral hadrons. Charged particle tracks are used to reconstruct the interaction vertices. The vertex with the highest sum of squared p_{T} of all associated tracks is taken as the primary vertex of the hard collision. Filters are applied to reject events where electronic noise or proton-beam backgrounds mimic energy deposits in the detector.

Electron candidates are reconstructed by combining the tracking information with energy deposits in the ECAL in the range $|\eta| < 2.5$ (excluding the range $1.4442 < |\eta| < 1.566$, which is a transition region between endcap and barrel calorimeters). Tight identification criteria are applied to select well-reconstructed electron candidates. Candidates are identified [34] using information on the shower-shape, the track quality and the spatial match between the track and the electromagnetic cluster, the fraction of total cluster energy in the HCAL, and the resulting level of activity in the surrounding tracker and calorimeter regions. The energy resolution for electrons with $p_{\mathrm{T}} > 40\,\mathrm{GeV}$, measured using $\mathrm{Z} \to \mathrm{ee}$ decays, is on average 1.7% in the ECAL central region of the detector [34].

Muon candidates are identified using track segments reconstructed separately from hits in the silicon tracking system and in the muon system. To identify muon candidates, the track segments must be consistent with muons originating from the primary vertex and satisfying tight identification requirements. The matching of the muon and silicon track segments results in a relative p_{T} resolution of 1.3–2.0% in the central region of the detector for muons with $20 < p_{\mathrm{T}} < 100\,\mathrm{GeV}$, and for muons with p_{T} up to 1 TeV the resolution is 10% or better [35].

Lepton (electron or muon) reconstruction and trigger efficiencies are evaluated as a function of p_{T} and $|\eta|$ in both data and simulation, using a "tag-and-probe" method [36] with recorded and simulated samples of dileptonic Z events.

An isolation variable is employed to suppress leptons originating from QCD processes. We define a relative isolation as the sum of the p_{T} of particle tracks found in the tracker and energy deposits found in the calorimeters within a cone $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.3$ (0.4) around the trajectory of the electron (muon), divided by the lepton p_{T}. Relative isolation is corrected for the effects of pileup, and is required to be less than 0.15 for muons, and less than 0.4 (0.6) for electrons in the barrel (endcap) region.

Particles reconstructed by the PF algorithm are clustered into jets by using the direction of each particle at the interaction vertex. Charged hadrons found by the PF algorithm that are associated with pileup vertices are not considered. Particles that are identified as isolated leptons are removed from the jet clustering procedure. Jets are reconstructed with the anti-k_{T} algorithm [37,38] with a