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Search for pair production of vector-like quarks in the $bW\bar{b}W$ channel from proton–proton collisions at $\sqrt{s} = 13$ TeV

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ABSTRACT

A search is presented for the production of vector-like quark pairs, $T\bar{T}$ or $Y\bar{Y}$, with electric charge of 2/3 (T) or −4/3 (Y), in proton–proton collisions at $\sqrt{s} = 13$ TeV. The data were collected by the CMS experiment at the LHC in 2016 and correspond to an integrated luminosity of 35.8 fb^{-1}. The T and Y quarks are assumed to decay exclusively to a W boson and a b quark. The search is based on events with a single isolated electron or muon, large missing transverse momentum, and at least four jets with large transverse momenta. In the search, a kinematic reconstruction of the final state observables is performed, which would permit a signal to be detected as a narrow mass peak (≈7% resolution). The observed number of events is consistent with the standard model prediction. Assuming strong pair production of the vector-like quarks and a 100% branching fraction to bW, a lower limit of 1295 GeV at 95% confidence level is set on the T and Y quark masses.

1. Introduction

Vector-like quarks (VLQs) are hypothetical spin-1/2 fermions, whose left- and right-handed components transform in the same way under the standard model (SM) symmetries, and hence have vector couplings. Nonchiral VLQs appear in a number of beyond-the-SM scenarios, such as "Randall–Sundrum" and other extra-dimensional models [1,2]; the beautiful mirrors [3], little Higgs [4–8], and composite Higgs [9] models; grand unified theories [10]; and also other models that provide insights into the SM flavor structure [11]. These models provide possible solutions to a number of problems, such as electroweak symmetry breaking, a poor general fit to the precision electroweak data, the origin of flavor patterns, and the hierarchy problem. In particular, the hierarchy problem, namely the instability within the SM of the Higgs boson mass parameter to quantum corrections, can be solved through the introduction of VLQ contributions that cancel the contributions from the top quark.

In general, VLQs T, with charge +2/3, are expected to mix significantly only with the top quark, leading to the dominant T quark decay $T \to bW$ [12]. We consider the case in which this decay has a branching fraction $\mathcal{B}(T \to bW) = 100\%$. Also in some models [13], a VLQ Y with an electric charge of −4/3 is predicted, either with or without the presence of a T VLQ. The Y quark is expected to decay with a 100% branching fraction via the same bW channel. Since jets originating from the hadronization of b quarks and $\bar{b}$ antiquarks are not distinguished in this analysis, the results presented apply equally to the strong pair production of both T and Y VLQs. We consider the case where either only T quarks or only Y quarks are produced. This assumption produces a more conservative estimation of the lower mass limit on VLQs. Throughout the rest of this paper, we will use T to represent both the T and Y VLQs.

In this paper, results are presented of a search for the strong pair production of heavy VLQs and their subsequent decays through the signal channel

$$T\bar{T} \to bW\bar{b}W \to b\ell\nu\bar{b}q\bar{q}'$$

in proton–proton (pp) collisions at $\sqrt{s} = 13$ TeV using the CMS detector at the CERN LHC, where ℓ is an electron or muon from the leptonic decay of one of the W bosons, and q and $\bar{q}'$ are the quark and antiquark from the hadronic decay of the other W boson. The analyzed data set corresponds to an integrated luminosity of 35.8 fb^{-1}. This analysis is an extension to higher mass values of an earlier CMS search for the T quark at $\sqrt{s} = 8$ TeV. Both the previous analysis and the present one are based on a kinematic reconstruction with a constrained fit to the $bW\bar{b}W$ final state in the signal decay channel shown above. Kinematic reconstruction

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enables detection of the signal as a narrow mass peak. The previous results were combined with other CMS T quark searches in Ref. [14]. The present observed lower mass limits for a T quark decaying 100% via the bW channel are 920 GeV for CMS [14] at $\sqrt{s} = 8$ TeV, and 770 GeV at 8 TeV [15] and 1350 GeV at 13 TeV for ATLAS [16].

The search strategy requires that one of the W bosons decays leptonically, producing an electron or a muon accompanied by a neutrino, and the other decays hadronically to a quark–antiquark pair. We select events with a single isolated muon or electron, missing transverse momentum, and at least four jets with high transverse momenta, arising from the hadronization of the quarks in the final state. We classify such events as μ+jets or e+jets.

We perform a constrained kinematic fit on each selected event for the signal decay process shown above. The full kinematic quantities of the final state are reconstructed, and the invariant mass of the T quark, m_{reco}, is obtained. We consider also cases when W bosons decaying hadronically at high Lorentz boosts are reconstructed as single jets. Such merged jets are then resolved into two subjets by employing jet substructure techniques based on the "soft drop" grooming algorithm [17]. These resolved subjets are counted individually when selecting four-jet final states and contribute separately in the kinematic fit (see Section 5). Events with leptonically decaying W bosons include those decaying into a τ lepton (in the decay sequence $\mathrm{W} \to \tau + \nu$, $\tau \to \ell + 2\nu$). They are treated in the same way as events with direct decays to muons or electrons.

2. The CMS detector

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the superconducting solenoid volume are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter (ECAL) with preshower detector, and a brass and scintillator hadron calorimeter (HCAL), each composed of a barrel and two endcap sections. Forward calorimeters extend the pseudorapidity [18] coverage provided by the barrel and endcap detectors. The detector is nearly hermetic, allowing for momentum balance measurements in the plane transverse to the beam direction. Muons are detected in gas-ionization chambers embedded in the steel flux-return yoke outside the solenoid.

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. [18].

3. Event samples

The analysis is based on integrated luminosities of 35.8 fb^{-1} in the muon channel and 35.6 fb^{-1} in the electron channel. The trigger providing the muon data sample requires the presence of at least one muon with $p_{\mathrm{T}} > 50$ GeV and pseudorapidity $|\eta| < 2.5$. For the electron data sample, events are required to have a single isolated electron with $p_{\mathrm{T}} > 32$ GeV and $|\eta| < 2.1$.

Simulated event samples are used to estimate the signal efficiencies and background contributions. The following background production processes are modeled: $\mathrm{t\bar{t}}$+jets; W+jets and Z+jets (single boson production); single top quark via the tW, s- and t-channel processes; WW, WZ, and ZZ (diboson production); and quantum chromodynamic (QCD) multijet production. The dominant background is from $\mathrm{t\bar{t}}$+jets production. All other background processes are collectively referred to as non-$\mathrm{t\bar{t}}$. The non-$\mathrm{t\bar{t}}$ background excluding multijets is called the electroweak background.

The $\mathrm{t\bar{t}}$ + jets events are generated using the POWHEG v2.0 [19–22] event generator. The diboson samples are produced using the PYTHIA 8.205 [23] generator. The W+jets, Z+jets, and QCD multijet simulated events are produced with the generator MADGRAPH5_aMC@NLO v2.2.2 [24]. Single top quark events are generated with POWHEG and MADGRAPH5_aMC@NLO.

The simulated $\mathrm{T\overline{T}}$ signal events are generated with MADGRAPH5_aMC@NLO at leading order for T quark masses from 800 to 1600 GeV in 100 GeV steps. The total $\mathrm{T\overline{T}}$ inclusive cross section ($\mathrm{gg} \to \mathrm{T\overline{T}} + X$) is computed for each T quark mass value at next-to-next-to-leading order, using a soft-gluon resummation with next-to-next-to-leading-logarithmic accuracy [25]. Signal samples are produced in the narrow-width approximation in which the width of the generated T quark mass distribution of 1 GeV is much less than the mass resolution of the detector.

The generated events are processed through the CMS detector simulation based on GEANT4 [26]. Additional minimum-bias events, generated with PYTHIA, are superimposed on the hard-scattering events to simulate multiple inelastic pp collisions in the same or nearby beam crossings (pileup). The simulated events are weighted to reproduce the distribution of the number of pileup interactions observed in data, with an average of 23 collisions per beam crossing. All samples have been generated with the NNPDF 3.0 set [27] of parton distribution functions (PDFs), using the tune CUETP8M1. PYTHIA is used to shower and hadronize all generated partons.

4. Event reconstruction

Events are reconstructed using a particle-flow (PF) algorithm [28] that combines information from all the subdetectors: tracks in the silicon tracker and energy deposits in the ECAL and HCAL, as well as signals in the preshower detector and the muon system. This procedure categorizes all particles into five types: muons, electrons, photons, and charged and neutral hadrons. An energy calibration is performed separately for each particle type.

Muon candidates are identified by multiple reconstruction algorithms based on hits in the silicon tracker and signals in the muon system. The standalone-muon algorithm uses only information from the muon chambers. The silicon tracker muon algorithm starts from tracks found in the silicon tracker and then associates them with matching signals in the muon detectors. In the global-muon algorithm, for each standalone-muon track a matching tracker muon is found by comparing parameters of the two tracks propagated onto a common surface. A global-muon track is fitted by combining hits from the silicon tracker muon and the standalone-muon track, using the Kalman-filter technique [29]. The PF algorithm uses global muons.

Electron candidates are reconstructed from clusters of energy deposited in the ECAL matched with tracks in the silicon tracker. Electron tracks are reconstructed using a dedicated modeling of the electron energy loss and are fitted with a Gaussian sum filter algorithm. Finally, electrons are further distinguished from charged hadrons using a multivariate approach [30].

Charged leptons, originating from decays of heavy VLQs, are expected to be isolated from nearby jets. Therefore, a relative isolation parameter (I_{rel}) is used, which is defined as the sum of the p_{T} of charged hadrons, neutral hadrons, and photons in a cone with distance parameter $\Delta R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2}$ around the lepton direction, where $\Delta\phi$ and $\Delta\eta$ are the azimuthal and pseudorapidity differences, divided by the lepton p_{T}. The isolation cone radius is taken as $\Delta R = 0.4$ for muons. Pileup corrections to I_{rel} are computed using tracks from reconstructed vertices [29]. For electrons, $\Delta R = 0.3$ and pileup corrections are calculated using jet effective areas [31,32] separately for the barrel and endcap regions.

Particles found by the PF algorithm are clustered into jets using the PF jet identification procedure [28]. Using the charged-hadron subtraction (CHS) algorithm, charged hadrons associated