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Search for single production of a heavy vector-like T quark decaying to a Higgs boson and a top quark with a lepton and jets in the final state

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ABSTRACT

A search for single production of vector-like top quark partners (T) decaying into a Higgs boson and a top quark is performed using data from pp collisions at a centre-of-mass energy of 13 TeV collected by the CMS experiment at the CERN LHC, corresponding to an integrated luminosity of 2.3 fb^{-1}. The top quark decay includes an electron or a muon while the Higgs boson decays into a pair of b quarks. No significant excess over standard model backgrounds is observed. Exclusion limits on the product of the production cross section and the branching fraction are derived in the T quark mass range 700 to 1800 GeV. For a mass of 1000 GeV, values of the product of the production cross section and the branching fraction greater than 0.8 and 0.7 pb are excluded at 95% confidence level, assuming left- and right-handed coupling of the T quark to standard model particles, respectively. This is the first analysis setting exclusion limits on the cross section of singly produced vector-like T quarks at a centre-of-mass energy of 13 TeV.

1. Introduction

Over the past decades several theoretical models have been formulated trying to give new insights into electroweak symmetry breaking and the mechanisms that stabilise the mass of the Higgs boson. Many of these models predict the existence of heavy vector-like quarks. Examples are little Higgs models [1–3], models with extra dimensions [4,5], and composite Higgs boson models [6–10].

The distinctive property of vector-like quarks is that their left- and right-handed components transform in the same way under the electroweak symmetry group $\text{SU}(2)_\text{L} \times \text{U}(1)_\text{Y}$ of the standard model (SM). As a consequence, vector-like quarks can obtain mass through direct mass terms in the Lagrangian of the form $m\overline{\psi}\psi$, unlike the SM chiral quarks, which obtain mass through Yukawa coupling.

The discovery of a Higgs boson by the ATLAS [11] and CMS [12, 13] Collaborations and the electroweak fits within the framework of the SM [14] strongly disfavour the existence of a fourth generation of chiral fermions. Given the limited impact that vector-like quarks have on the properties of the SM Higgs boson, they are not similarly constrained [15].

This letter presents the results of the first search for singly produced vector-like top quark partners with charge +2/3 (T) at a centre-of-mass energy of $\sqrt{s} = 13$ TeV. Single production is of particular interest, since its rate dominates over the rate of pair production at large quark masses. Many of the models mentioned above predict that the T quark will predominantly decay to third-generation SM quarks via three channels: tH, tZ, and bW [15]. Searches for T quarks have been performed by the ATLAS and CMS Collaborations setting lower limits on the T quark mass ranging from 715 to 950 GeV for various T quark branching fractions [16–22].

While most of the past searches considered pair production of the T quarks via the strong interaction, the single production mode where the T quark is produced via the weak interaction has recently been investigated by the ATLAS Collaboration [16,19,20] at 8 TeV, and is targeted in this letter. The strength of the T quark coupling to electroweak bosons has an effect both on the cross section and the width of the T quark [23]. There are no a priori constraints on the electroweak T quark coupling. Therefore, not only the general coupling to the electroweak sector but the couplings of the T quark to bW, tZ, and tH can also take arbitrary values. The present analysis targets decays of the T quark into a Higgs boson and a top quark. It will be sensitive to the existence of a T quark only if sufficiently large couplings to bW or tZ are present as well, since the T quark production through a Higgs

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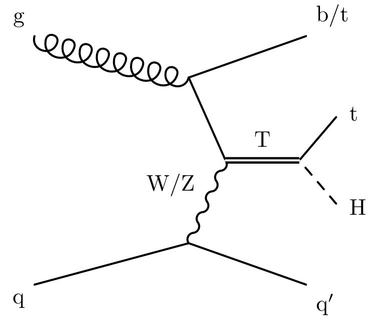

Fig. 1. Feynman diagram of the production and decay mechanisms of a vector-like T quark, as targeted in this analysis.

boson is strongly suppressed. An example of a Feynman diagram for this process is shown in Fig. 1.

The analysis is performed on the proton–proton collision data collected during 2015 by the CMS experiment at the CERN LHC at $\sqrt{s} = 13$ TeV. The search is optimised for decays of the T quark into a Higgs boson and a top quark, where the top quark decay includes a lepton (electron or muon) and the Higgs boson is required to decay into b quarks. For a T quark mass in the TeV range, the Higgs boson and the top quark obtain large Lorentz boosts leading to merged jets and nonisolated leptons in the final state. Jet substructure analysis in combination with algorithms for the identification of b quark jets (b tagging) can efficiently identify boosted decays of the Higgs boson into b quark pairs [22]. An additional distinctive feature of the signal is the presence of a jet in the regions close to the beam pipe, a so-called forward jet. This jet results from the light-flavour quark that is produced in association with the T quark. Background processes due to top quark pair production are dominant, followed by W+jets and quantum chromodynamics (QCD) multijet processes.

For every event, a T quark candidate four-momentum is reconstructed, with mass M_T. Events are selected by imposing requirements on the T quark candidate and other attributes of the event. The M_T variable is used as the final discriminant in a combined signal plus background fit to the data. The shape of the total background is estimated from a signal-depleted region in the recorded data.

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 solenoid volume are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter (ECAL), and a brass and scintillator hadron calorimeter (HCAL), each composed of a barrel and two endcap sections. Forward calorimeters extend the coverage provided by the barrel and endcap detectors to regions close to the beam pipe. Muons are measured in gas-ionisation detectors 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. [24].

A particle-flow (PF) algorithm [25,26] is used to combine information from all CMS subdetectors in order to reconstruct and identify individual particles in the event: photons, electrons, muons, and charged and neutral hadrons. The energy of photons is directly obtained from the ECAL measurement. The energy of electrons is determined from a combination of the electron momentum at the primary interaction vertex determined by the tracker, the energy of the corresponding ECAL cluster, and the energy sum of all bremsstrahlung photons spatially compatible with originating from the electron track. The momentum resolution for electrons with transverse momentum $p_T \approx 45$ GeV and above from $Z \to ee$ decays ranges from 1.7% for non-showering electrons in the barrel region to 4.5% for showering electrons in the endcaps [27]. Muons are measured in the pseudorapidity range $|\eta| < 2.4$ with detection planes made using three technologies: drift tubes, cathode strip chambers, and resistive-plate chambers. Matching muons to tracks measured in the silicon tracker results in a relative p_T resolution of 1.2–2.0% for muons with $20 < p_T < 100$ GeV in the barrel and better than 6% in the endcaps. The p_T resolution in the barrel is better than 10% for muons with p_T up to 1 TeV [28]. The energy of charged hadrons is determined from a combination of their momentum measured in the tracker and the matching of ECAL and HCAL energy deposits, corrected for the response function of the calorimeters to hadronic showers. Finally, the energy of neutral hadrons is obtained from the corresponding corrected ECAL and HCAL energy.

Jets are reconstructed from the individual particles identified by the PF event algorithm, clustered by the anti-k_t algorithm [29,30]. Two different jet sizes are used independently: jets with a size parameter of 0.4 ("AK4 jets") and 0.8 ("AK8 jets"). Jet momentum is determined as the vector sum of the charged particle momenta in the jet that are identified as originating from the primary interaction vertex, and the neutral particle momenta. An area-based correction is applied to jet energies to take into account the contribution from additional proton–proton interactions within the same or adjacent bunch crossings ("pileup") [31]. The energy of a jet is found from simulation to be within 5–10% of the true jet momentum at particle level over the entire p_T spectrum and detector acceptance. Jet energy corrections are derived from simulation, and are confirmed with in situ measurements of the energy balance in dijet and photon+jet events [32]. A smearing of the jet energy is applied to simulated events to mimic detector resolution effects observed in data. For the identification of b jets, the combined secondary vertex b tagging algorithm is used [33]. The algorithm uses information from secondary b hadron decay vertices to distinguish b jets from other jet flavours. The jet energy resolution is typically 15% at 10 GeV, 8% at 100 GeV, and 4% at 1 TeV. Jets are reconstructed up to $|\eta| = 5$ while b tagging is restricted by the tracker acceptance to $|\eta| < 2.4$.

The missing transverse momentum vector $\vec{p}_T^{\,\text{miss}}$ is defined as the negative vector sum of the p_T of all PF particle candidates in an event. Its magnitude is referred to as E_T^{miss}.

3. Data and simulated samples

Events in the electron channel are selected using an electron trigger, which requires an electron with $p_T > 45$ GeV and the additional presence of at least two jets, with $p_T > 200$ GeV and 50 GeV, respectively for the jets with the highest and second highest p_T. Events in the muon channel are collected with a single-muon trigger, requiring the presence of a muon candidate with $p_T > 45$ GeV and $|\eta| < 2.1$. The muon trigger does not require a jet. Neither of the triggers places any requirement on the isolation of the leptons. If an event is selected by both the electron and the muon trigger, which happens almost exclusively in top quark pair events containing an electron and a muon, it is assigned to the muon channel. The data collected with the muon trigger correspond to a luminosity of $\mathcal{L} = 2.3$ fb^{-1}, while the electron trigger provides a luminosity $\mathcal{L} = 2.2$ fb^{-1}.

Signal samples are generated using MADGRAPH5_aMC@NLO 2.2.2 [34] at leading order (LO) QCD accuracy. The cross section to produce a heavy T quark decaying to top quark and Higgs boson in association with a bottom or top quark is set to 1 pb unless indicated differently. Signal masses are simulated between 700 and