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Search for single production of a vector-like T quark decaying into a Higgs boson and top quark with fully hadronic final states using the ATLAS detector

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A search is made for a vector-like T quark decaying into a Higgs boson and a top quark in 13 TeV proton-proton collisions using the ATLAS detector at the Large Hadron Collider with a data sample corresponding to an integrated luminosity of 139^{-1} fb. The all-hadronic decay modes $H \to b\bar{b}$ and $t \to bW \to bq\bar{q}'$ are reconstructed as large-radius jets and identified using tagging algorithms. Improvements in background estimation, signal discrimination, and a larger data sample, contribute to an improvement in sensitivity over previous all-hadronic searches. No significant excess is observed above the background, so limits are set on the production cross-section of a singlet T quark at 95% confidence level, depending on the mass, m_T, and coupling, κ_T, of the vector-like T quark to Standard Model particles. This search targets a mass range between 1.0 to 2.3 TeV, and a coupling value between 0.1 to 1.6, expanding the phase space of previous searches. In the considered mass range, the upper limit on the allowed coupling values increases with m_T from a minimum value of 0.35 for $1.07 < m_T < 1.4$ TeV up to 1.6 for $m_T = 2.3$ TeV.

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1. Introduction

Vector-like quarks appear in many Beyond Standard Model (BSM) theories as a way to explain problems such as the hierarchy problem. The simplest model considers only vector-like particles that couple to 3rd generation Standard Model (SM) quarks. Due to their vector-like nature, the mass of the vector-like quark is not constrained by current Higgs boson coupling measurements. Previous searches have ruled out vector-like particles below 1 TeV[1]. Above this threshold, single production of vector-like quarks overtakes pair production[2].

This analysis searches for the vector-like top quark partner, T, which has a charge of +2/3 like the SM top quark. The three decay modes of the vector-like T quark are $T \to Ht/Wb/Zt$. This analysis searches specifically for the $T \to Ht$ decay mode, with the top quark and Higgs boson both decaying hadronically. A resonance search is performed in the tH dijet invariant mass distribution.

2. Analysis

Due to the mass of the target particle being above 1 TeV, the resulting top quark and Higgs boson will be produced with high p_T. As illustrated in Figure 1, this analysis selects for two large-R jets, defining the *leading large-R jet* as having $p_T > 500$ GeV and the *second leading large-R jet* as having $p_T > 350$ GeV. Additionally, the mass of the large-R jets is restricted to $100 < m < 225$ GeV. Large-R jets with masses below 140 GeV can be additionally tagged as a Higgs boson candidate with a requirement on the jet substructure variable τ_{21} at 70% W.P., while jets with masses above 140 GeV can be tagged as a top quark candidate using a DNN Top Tagging Algorithm[3] at 80% W.P for fully contained top quark candidates. Variable radius (VR) track jets that are contained inside the large-R jets can be b-tagged using the DL1 Algorithm[4] at 70% W.P.

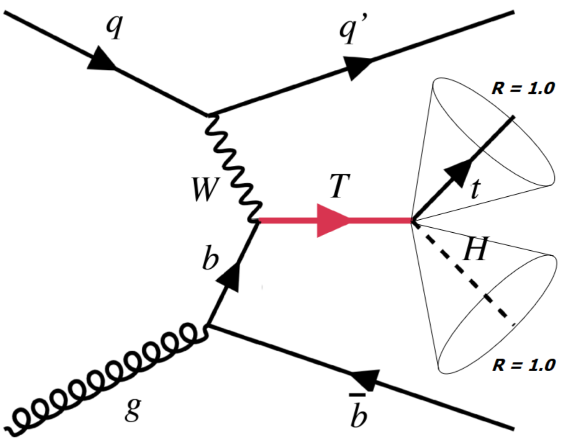


Figure 1: A feynman diagram showing the W-mediated single production of a vector-like T-quark decaying into a top quark and a Higgs boson. Additional graphics show the motivation behind the event selection, displaying two large-R jets containing the decay products of the T-quark.

The signal region is defined by the tagging states of the leading and second leading large-R jets. One large-R jet must be identified as a top quark candidate with at least one b-tagged subjet while the other must be identified as a Higgs boson candidate with at least two b-tagged subjets.

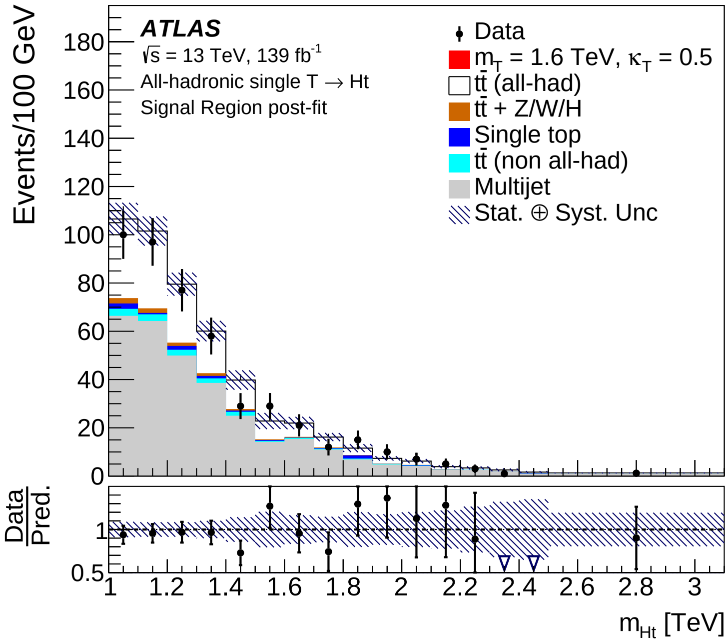


Figure 2: The dijet invariant mass distribution of the signal region. A T-quark hypothesis with parameters $m_T = 1.6$ TeV and $\kappa_T = 0.5$ is included. The blue hashed lines correspond to the sum in quadrature of the statistical and systematic uncertainties of the prediction in a given bin. The lower panel shows the ratio of the data to the prediction, along with the uncertainty in the ratio. A ratio outside the bounds of the axis is represented by a blue arrow. The last bin includes the event overflows. Contributions to the predicted distribution are stacked in the same order as they appear in the legend.

Top-related SM backgrounds are estimated using MC simulations. A data driven technique, the generalized ABCD method, is used to estimate the multijet background, using extra control regions to calculate correlation factors between the tagging algorithms in order to better improve the multijet estimate.

The parameter of interest is the dijet invariant mass distribution, with candidate signal events aiming to reconstruct the vector-like T quark mass. This distribution, as seen in Figure 2, is fit using the Profile-likelihood method, and the CL_S [5] method is used to set 95% confidence level upper limits on the signal cross-section.

3. Results

The phase space probed by this analysis defined by two variables, the mass of the vector-like T quark, m_T, and the coupling strength, κ_T. MC samples are prepared with m_T ranging from 1.0 TeV up to 2.3 TeV in 0.1 TeV steps, and κ_T from 0.1 up to 1.6 in 0.1 steps. The decay-width-to-mass ratio, Γ/M_T, can be obtained from m_T and κ_T.

The exclusion limits across the 2D m_T and κ_T phase space can be seen in Figure 3. The lowest excluded κ_T values are found between $1.1 < m_T < 1.4$ TeV for $\kappa_T > 0.3$, rising with mass up to $\kappa_T = 1.6$ for $m_T = 2.3$ TeV.

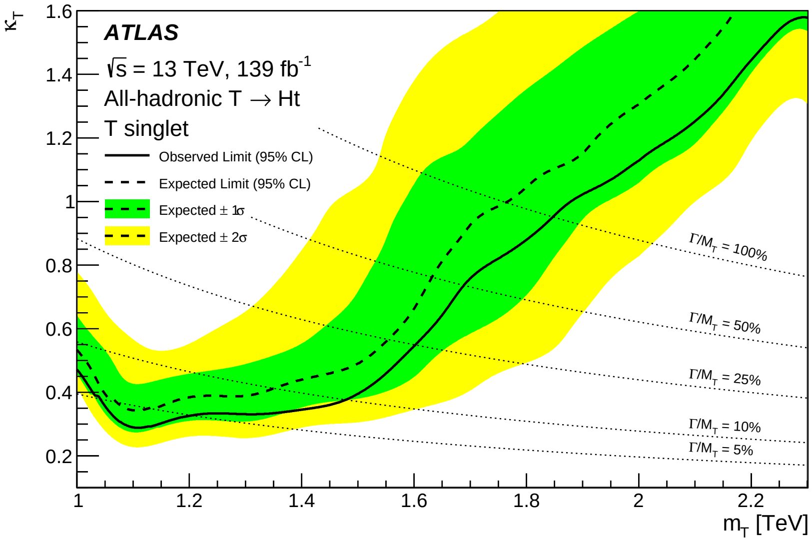
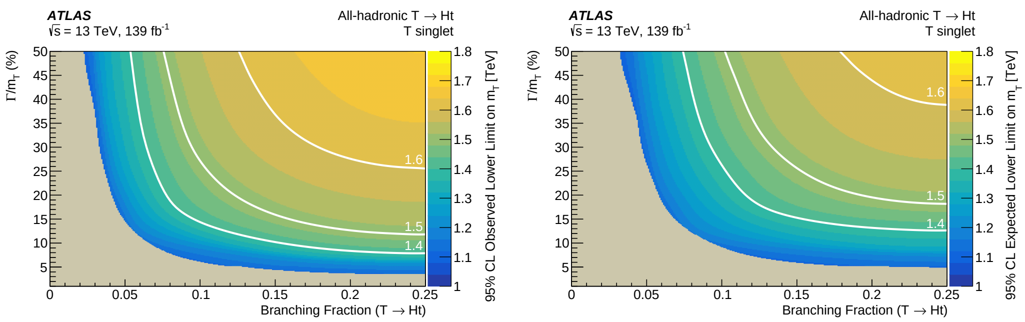


Figure 3: Observed and Expected 95% CL upper limits on the single T-quark coupling κ_T as a function of m_T are shown as solid and dashed lines, respectively. The green (yellow) band is the 68% (95%) confidence interval around the median expected limit, as determined using pseudo-experiments. All values of κ_T above the solid line are excluded. The dashed curves represent contours of fixed Γ/M_T.



(a) **(b)**

Figure 4: Observed (a) and Expected (b) 95% CLlower limits on the T-quark mass as a function of the T-quark width-to-mass ratio and the branching fraction of the $T \to Ht$ decay. The colour scale on the right side of each plot defines the 95% CL limit on the T-quark mass. Masses below the observed limit are excluded. The dashed white contour lines denote isolines of equal exclusion on the mass in units of TeV.

For interpretations on the branching ratios of the T decay, $\mathcal{B}(T \to Ht)$ and $\mathcal{B}(T \to Zt)$ are assumed to be equal with $\mathcal{B}(T \to Wb) = 1 - \mathcal{B}(T \to Zt) - \mathcal{B}(T \to Ht)$. The observed and expected 95% CL limits on the T-quark mass as a function of the width-to-mass ratio and the branching fraction for $T \to Ht$ are shown in Figure 4.

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