

Search for exotic heavy quark partners

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A summary of the CMS Collaboration results on searches for new heavy quarks, predicted by many models beyond the Standard Model (BSM), is presented. Results were produced with data collected at the Large Hadron Collider at a center-of-mass energy of 7 TeV and 8 TeV, with integrated luminosities ranging between 5.0 and 19.6 fb^{-1} . No evidence for new massive quarks was observed and exclusion limits were set for some BSM scenarios.

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1. Introduction

At present, there is experimental evidence for just three generations of fermions in the Standard Model (SM), though their number is not fixed by the theory. The only theoretical constraint comes from the QCD asymptotic freedom, which requires the number of generations to be less than 9 [1]. On the other hand, the existence of a fourth generation of fermions is subject to some experimental constraints from precision electroweak data [2] and direct searches performed at the Tevatron and at the Large Hadron Collider (LHC).

Searches for new heavy quarks are of particular interest, as these quarks are predicted in many new physics models aimed at solving some of the limitations of the SM. The most natural extension of the SM consists of adding a fourth chiral generation of fermions, which, providing additional sources of CP violation, could explain the observed matter-antimatter asymmetry in the universe [1]. Another possibility is the addition of new heavy vector-like quarks, defined as quarks for which both chiralities have the same transformation properties under the SM gauge group. Vector-like quarks are predicted by many extensions of the SM, like little Higgs models or extra dimension [3].

Recent results of Higgs searches at LHC have additionally constrained the existence of new heavy quarks. In particular, a fourth chiral generation of quarks is disfavored by the observation of the SM-like Higgs boson with mass of 126 GeV, although it could still be incorporated in beyond SM scenarios with an extended Higgs sector [4].

This paper presents the results of the CMS direct searches for new heavy quarks, based on data collected in 2011 and 2012 at a center-of-mass energy of 7 TeV and 8 TeV, with integrated luminosities ranging between 5.0 and 19.6 fb^{-1} . A detailed description of the CMS detector is provided in Ref. [5], while the full descriptions of the analyses presented here can be found in Ref. [6, 7, 8, 9].

2. Search for new heavy quarks decaying to tV

This section presents the CMS search for pair-produced heavy quarks Q , decaying exclusively to a t -quark and a W or Z boson [6]. The analysis was performed using 5 fb^{-1} of data at $\sqrt{s} = 7$ TeV. For $Q \rightarrow tW$, the $Q\bar{Q}$ final state contains four W bosons and two b -quarks, while, for $Q \rightarrow tZ$, it contains two Z bosons, two W bosons and two b -quarks. In both cases, the search was performed with events where one of the W bosons decayed leptonically, while the other bosons decayed to jet pairs.

Events were requested to have exactly one muon (electron), with transverse momentum $p_T > 42$ (35) GeV, at least four jets with $p_T > 100, 60, 50, 35$ GeV and transverse missing energy $E_T^{miss} \geq 20$ GeV. They were then split into four exclusive categories according to the jet multiplicity (N_j): $N_j = 4, 5, 6$, and ≥ 7 jets. The search for the $Q\bar{Q}$ signal was performed by fitting the data S_T distribution as a function of the jet multiplicity, where S_T was defined as the scalar sum of the lepton and jets transverse momenta and the E_T^{miss} . Figure 1 left (right) shows the observed and expected 95% CL upper limits on the signal production cross-section, as a function of the Q quark mass (M_Q), for Q decaying exclusively to tW (tZ). Assuming a strong production mechanism for the signal model, masses below 675 (625) GeV were excluded for $Q \rightarrow tW$ ($Q \rightarrow tZ$).

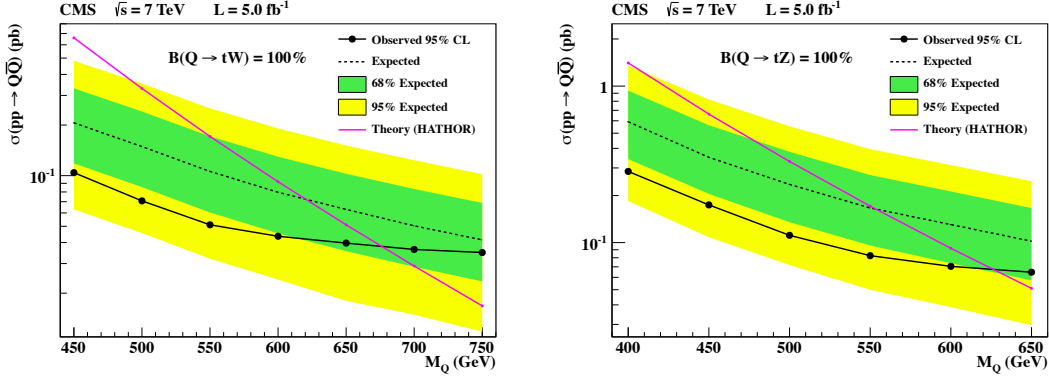


Figure 1: $Q \rightarrow tV$ search - Expected and observed 95% CL upper limits on the signal cross-section as a function of the Q quark mass, assuming $B(Q \rightarrow tW) = 100\%$ (left) and $B(Q \rightarrow tZ) = 100\%$ (right) [6].

3. Search for new heavy top partners with charge $5e/3$

In this section a summary of the CMS search for pair-produced heavy top partners with charge $5e/3$ ($T_{5/3}$), using 19.6 fb^{-1} of data at $\sqrt{s} = 8 \text{ TeV}$, is given [7]. A branching fraction of 100% for the decay $T_{5/3} \rightarrow tW$ was assumed, so that the considered signal final state contained two pairs of opposite-charge W bosons and two b -quarks. The search was performed with events where two same-sign W bosons decayed leptonically, while the other bosons decayed to jet pairs. For high values of the $T_{5/3}$ quark mass, the t -quarks and W bosons can be highly boosted and, consequently, jets from their hadronic decays could merge into one wide jet. For these cases, the analysis benefited from the use of dedicated reconstruction techniques, based on the Cambridge-Aachen (CA) clustering algorithm [10], which looked for substructures within wide jets and use them to identify boosted top quarks and W bosons [11] [12].

Events were requested to have exactly two isolated same-sign leptons ($\mu\mu$, ee or $e\mu$) with $p_T > 30 \text{ GeV}$ and at least five constituents, where CA jets, identified to be originated from hadronically decays of boosted W bosons and t -quarks, counted as two and three constituents respectively. Events were also required to have $H_T > 900 \text{ GeV}$, with H_T defined as the scalar sum of the leptons and jets p_T . A counting experiment, using the total number of events in the three channels, was performed. Figure 2 shows the expected and observed limits on the signal production cross-section, as well as the theoretical prediction [13]: $T_{5/3}$ quarks with masses below 770 GeV were excluded.

4. Inclusive search for a sequential fourth generation of quarks

This section summarizes the inclusive CMS search for heavy b -quark and t -quark partners (b' and t'), using 5.0 fb^{-1} of data at $\sqrt{s} = 7 \text{ TeV}$ [8]. In presence of a 4th generation of quarks, an extension of the Cabibbo-Kobayashi-Maskawa (CKM) matrix is required. For simplicity, a model with only one free parameter A and degenerate masses for t' and b' ($m_{t'} = m_{b'}$) was assumed in the search. As a result, the 4×4 CKM matrix was rewritten as in Eq. 4.1, where $\sqrt{A} = |V_{tb}|$.

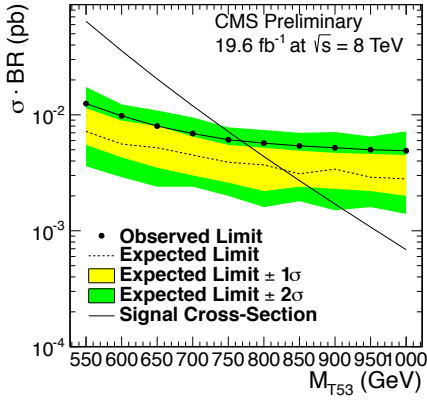


Figure 2: $T_{5/3}$ search - Expected and observed 95% C.L. limits on the signal cross-section times branching ratio as a function of $M_{T_{5/3}}$, [7].

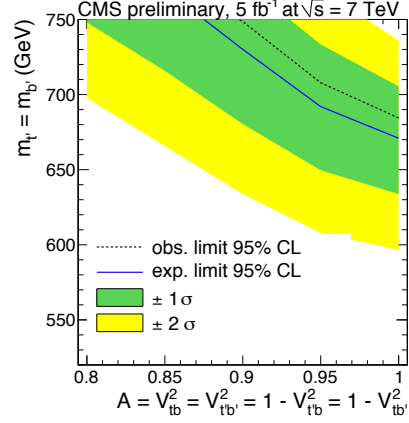


Figure 3: inclusive t' and b' search - 95% CL exclusion limit on $m_{t'} = m_{b'}$ as a function of the V_{CKM}^{4x4} parameter A [8].

$$V_{CKM}^{4x4} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} & V_{ub'} \\ V_{cd} & V_{cs} & V_{cb} & V_{cb'} \\ V_{td} & V_{ts} & V_{tb} & V_{tb'} \\ V_{t'd} & V_{t's} & V_{t'b} & V_{t'b'} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & \sqrt{A} & \sqrt{1-A} \\ 0 & 0 & -\sqrt{1-A} & \sqrt{A} \end{pmatrix} \quad (4.1)$$

Single ($t'b$ and $b't$) and pair ($t'\bar{t}'$, $t'b'$ and $b'\bar{b}'$) production processes for b' and t' quarks were considered. Under the analysis assumptions, the branching fractions of $t' \rightarrow bW$ and $b' \rightarrow tW \rightarrow bWW$ were almost equal to 100%, so that the considered final states contained two b -quarks and one to four W bosons, depending on the production mechanism. Three different channels were defined: the *single lepton channel*, the *same-sign dilepton channel* and the *three leptons channel*.

For the single lepton channel, events were requested to have exactly one isolated lepton (μ or e) with $p_T > 40$ and $E_T^{miss} > 40$ GeV. They were then classified according to the number of b -jets and hadronically decaying W boson candidates. The S_T distribution (defined in Section 2) and the reconstructed mass of the hadronic bW system were used to look for the signal. For the dilepton (trilepton) channel, events were requested to have two same-sign leptons (three leptons) with $p_T > 20$ GeV, at least four (two) b -jets and $E_T^{miss} > 40$ GeV. A counting experiment was performed in both the dilepton and trilepton channels. Figure 3 shows the expected and observed 95% CL exclusion limits on $m_{t'} = m_{b'}$, as a function of A , for the combination of the three channels. For $A = 1$, the observed (expected) limit was found to be 683 (670) GeV.

5. Search for b' quarks with three or more leptons and b -tags

This section summarizes the inclusive CMS search for anomalous production of events with three or more leptons, focusing on the interpretation of the results in the context of heavy b' quarks decaying to tW or bZ [9]. The analysis was performed using $9.2 fb^{-1}$ of data at $\sqrt{s} = 8$ TeV.

Events were requested to have at least three isolated leptons with $p_T > 10$ GeV (20 GeV for the leading), including at most one hadronic τ . They were then classified according to several quan-

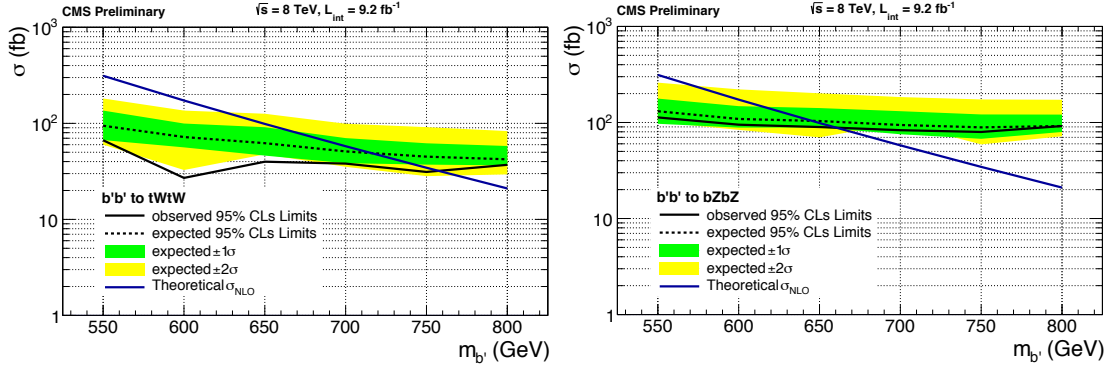


Figure 4: $b' \rightarrow tW (tZ)$ search - Expected and observed 95% C.L. limits on the signal production cross-section, as a function of the b' mass, for b' decaying exclusively to tW (left) and bZ (right) [9].

ities: the number of opposite-sign same-flavor (OSSF) lepton pairs; the number of reconstructed hadronic τ and b -jets; the event S_T ; the number of OSSF pairs with dilepton mass in the Z mass window ([75 GeV, 105 GeV]). This classification resulted in 90 (150) channels with 3 (4) leptons.

Channels with four (three) leptons, one (two) OSSF, no hadronic τ , at least one b -jets and no (≥ 1) OSSF pairs compatible with the Z boson were used to search for pair-produced b' , decaying to tW (bZ). Expected and observed yields in the considered signal regions were combined to set exclusion limits. Figure 4 left (right) shows the 95% CL upper limits on the signal production cross-section, as a function of the b' quark mass ($m_{b'}$), for b' decaying exclusively to tW (bZ). The exclusion limit on $m_{b'}$ was found to be 760 (660) GeV for $b' \rightarrow tW$ ($b' \rightarrow bZ$).

6. Conclusions

A summary of CMS searches for new heavy quarks has been presented. Results were produced using $p-p$ collision data at $\sqrt{s} = 7$ TeV and 8 TeV, with integrated luminosities ranging between 5.0 and 19.6 fb^{-1} . A fourth generation of heavy quarks was searched for considering different production mechanisms and final states, with no evidence of its existence.

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