

LHC searches for physics beyond the Standard Model with top quarks

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Abstract. Searches are presented for physics beyond the Standard Model involving top-quark and related signatures. The results are based on proton-proton collision data corresponding to integrated luminosities between 1 fb^{-1} and 5 fb^{-1} collected at a center-of-mass energy of 7 TeV with the ATLAS and CMS detectors at the Large Hadron Collider in 2011. The data are found to be consistent with the Standard Model. The non-observation of a signal is converted to limits at the 95% confidence level on the production cross section times branching ratio and on the masses of the hypothesized new particles for appropriate benchmark models.

1. Introduction

The Standard Model of particle physics is believed to be an effective theory valid up to energies close to 1 TeV. However, no new physics beyond the Standard Model (SM) has been observed yet, and it is critical to explore a wide range of possible signatures. A promising avenue lies in final states that involve the heaviest of the particles presumed to be elementary, the top quark. This document summarizes the status of these searches using the ATLAS [1] and CMS [2] detectors at the CERN Large Hadron Collider (LHC). The results are based on proton-proton collision data corresponding to integrated luminosities between 1 fb^{-1} and 5 fb^{-1} collected at a center-of-mass energy of 7 TeV in 2011.

The fact that the top quark is the heaviest elementary particle might be a hint that it plays a special role in the theory of electroweak symmetry breaking. The so-called hierarchy problem refers to the fact that the large quantum contributions to the square of the Higgs-boson mass should make the Higgs mass many orders of magnitude larger than the electroweak scale. Either there is an incredible, unnatural fine-tuning cancellation or nature chose another mechanism to protect the Higgs mass to keep it at the observed low value [3, 4]. Many models introduce top partners to cancel these quantum corrections. Finally, there are tantalizing hints of new physics in the forward-backward asymmetry in $t\bar{t}$ events at the Tevatron [5, 6].

Benchmark signal models are used to define signature-based searches in final states involving one or two leptons (electrons and muons), jets, of which typically one or more are required to be identified as b -jets, and missing transverse momentum (E_T^{miss}). The benchmarks include models of fourth-generation and vector-like quarks [7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20], top partners in little Higgs models [21, 22], as well as non-SM production of four top quarks [14], same-sign top-quark pair (tt) production [15], top+jet resonances in $t\bar{t}$ +jet events [23, 24], $W' \rightarrow t\bar{b}$ resonances [25, 26], and flavor changing neutral currents (FCNC) in single top-quark



production [27]. Searches for $t\bar{t}$ resonances, third generation supersymmetry and new physics in top-quark decays and properties are covered elsewhere in these proceedings [28].

2. Experimental techniques

The experimental approaches are similar between ATLAS and CMS. Searches are based on the 1+jets or dilepton $t\bar{t}$ channels. Jets are reconstructed from three-dimensional calorimeter energy clusters using the anti- k_t jet clustering algorithm [29] with a radius parameter of 0.4 for ATLAS and 0.5 for CMS. Leptons are required to pass quality criteria and to be isolated [30, 31, 32, 33]. The transverse momenta of jets and leptons are typically required to be larger than 20 or 25 GeV or more. Multivariate tagging algorithms [34, 35] are used to identify b -jets.

Typically, the statistical tool BumpHunter [36] is used to check for deviations, an excess or deficit, from the background hypothesis. In the absence of a signal, cross-section and mass limits are derived for benchmark models using CLs [37, 38] or occasionally Bayesian methods [39]. All limits quoted in this document are obtained at the 95% confidence level. Unless mentioned otherwise the new particles are assumed to decay with 100% branching fraction to the corresponding final state under study.

The largest background typically originates from SM $t\bar{t}$ production and is estimated from Monte Carlo (MC) simulation using MC@NLO [40, 41] or POWHEG [42] at ATLAS, and MADGRAPH [43, 44] at CMS. Data-driven multi-jet background estimates are based on the matrix method and on binned likelihood fits to the E_T^{miss} distribution. Data-driven W +jets estimates use the inherent W charge asymmetry in pp collisions. ALPGEN [45] (ATLAS) and MADGRAPH (CMS) are used to model W +jets in MC simulation. The composition of the flavor of the quarks produced in association with the W boson is measured in the low jet multiplicity bins and extrapolated using MC simulations. Small backgrounds, like the production of single top quarks, boson pairs, $t\bar{t}+W$, $t\bar{t}+Z$, and Z +jets are typically estimated from MC simulations.

The leading systematic uncertainties typically originate from the uncertainty in the jet energy scale, the b -tagging efficiency, and the $t\bar{t}$ MC modeling. In certain cases the impact of systematic uncertainties on the sensitivity of the search is reduced by using Gaussian constraints or other marginalization techniques, see e.g. Ref. [10].

3. Results

An ATLAS analysis [7] searches for the pair production of heavy non-SM quarks Q with decays according to $Q\bar{Q} \rightarrow W^+qW^-\bar{q}$ with $q = d, s, b$ for up-type Q or $q = u, c$ for down-type Q . The search is performed with 1.04 fb^{-1} of integrated luminosity. Dilepton final states are selected, requiring large E_T^{miss} and at least two jets. No b -tagging is applied. Mass reconstruction of heavy quark candidates is performed by assuming that the W -boson decay products are nearly collinear. The resulting mass reconstruction is shown in Fig. 1. No deviation from the SM expectation is observed. Heavy non-SM quark masses below 350 GeV are excluded.

A similar CMS search [8] for pair production of heavy top-like quarks t' has been performed in the decay mode $t'\bar{t}' \rightarrow W^+bW^-\bar{b}$. The search uses 5.0 fb^{-1} of integrated luminosity. Again dilepton final states are selected, requiring large E_T^{miss} and at least two jets, but this time exactly two of the jets have to be identified as b -jets. The minimum value of the four possible masses of the system defined by one of the two leptons and one of the two b -jets (M_{lb}^{min}) is found to be a good variable for distinguishing $t'\bar{t}'$ from $t\bar{t}$ events, as can be seen in Fig. 2. The observed number of events agrees with the expectation from SM processes. Heavy t' quarks with a mass less than 557 GeV are excluded.

Searches for heavy top-like quarks t' given the hypothesized decay mode $t'\bar{t}' \rightarrow W^+bW^-\bar{b}$ are also conducted in final states with a single charged lepton, E_T^{miss} and, depending on the analysis, at least three or four jets, of which at least one must be identified as a b -jet [9, 10, 11].

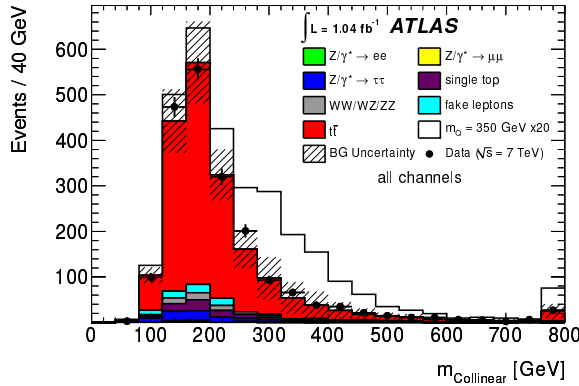


Figure 1. Expected and observed distributions of the collinear mass for the sum of ee , $\mu\mu$ and $e\mu$ channels [7]. The last bin contains overflow events. Samples are stacked. The signal has been amplified to 20 times the expected rate.

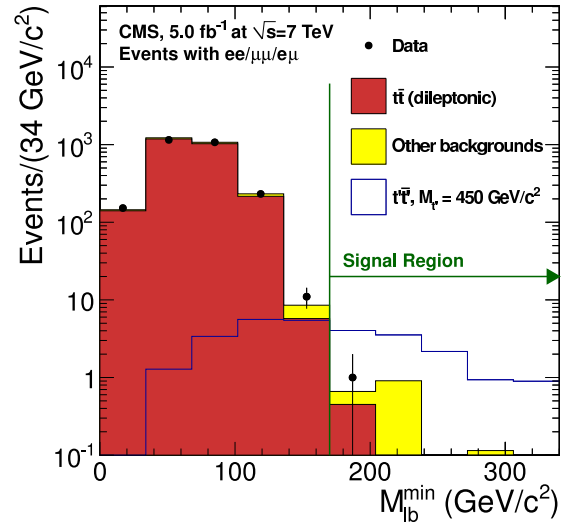


Figure 2. Comparison between the data and the simulated background for M_{lb}^{\min} [8]. The expected distribution for a signal with $m_{t'} = 450$ GeV is also shown. The signal region is defined by $M_{lb}^{\min} > 170$ GeV.

CMS [9] uses the reconstructed t' mass m_{reco} , obtained from a kinematic fit of the reconstructed four-momenta to the decay hypothesis $t'\bar{t}' \rightarrow W^+bW^-\bar{b} \rightarrow l\nu b\bar{q}q'\bar{b}$, as well as H_T , defined as the scalar sum of the transverse momenta of the objects associated to the t' and \bar{t}' decay products. The two-dimensional distributions of H_T versus m_{reco} are fitted with analytic functions for the signal S and the background B. All two-dimensional bins are then sorted in increasing order of the expected S/B ratio, using the functions. The resulting distribution of this so-called S/B rank is shown in Fig. 3 and is used to exclude t' masses below 570 GeV with 5.0 fb^{-1} of integrated luminosity.

ATLAS [11] uses the reconstructed mass m_{reco} of the candidate t' as the discriminant. A tight selection is applied targeting t' masses above 400 GeV. In this mass range the decay products have large momenta. The reconstruction of hadronically-decaying W bosons W_{had} takes advantage of this. They are either defined as a single jet with $p_T > 250$ GeV and jet mass in the range of 60-110 GeV or as a dijet system with $p_T > 150$ GeV, angular separation $\Delta R(j, j) < 0.8$, and mass within the range of 60-110 GeV. Additional kinematic selection criteria include H_T (defined as the scalar sum of the transverse momenta of the lepton, E_T^{miss} , and the jets from the hypothesized t' decays) to be larger than 750 GeV, $\Delta R(l, \nu) < 1.4$, $\Delta R(W_{\text{had}}, b\text{-jet}) > 1.4$, and $\Delta R(l, b\text{-jet}) > 1.4$. With 4.7 fb^{-1} of integrated luminosity a t' quark with mass lower than 656 GeV is excluded.

In addition, in light of the recent discovery of a new boson of mass 126 GeV at the LHC, upper limits are derived, as shown in Fig. 4, for vector-like quarks of various masses in the two-dimensional plane of $\text{BR}(t' \rightarrow Wb)$ versus $\text{BR}(t' \rightarrow Ht)$, where H is the SM Higgs boson ($\text{BR}(t' \rightarrow Zt) = 1 - \text{BR}(t' \rightarrow Wb) - \text{BR}(t' \rightarrow Ht)$).

A search for pair-produced, heavy, vector-like charge-2/3 quarks is performed by CMS [12], assuming $\text{BR}(t' \rightarrow Zt) = 1$. Events are selected by requiring two charged leptons from the Z -boson decay, as well as an additional isolated charged lepton. Using 1.14 fb^{-1} of integrated luminosity t' quarks with a mass less than 475 GeV are excluded.

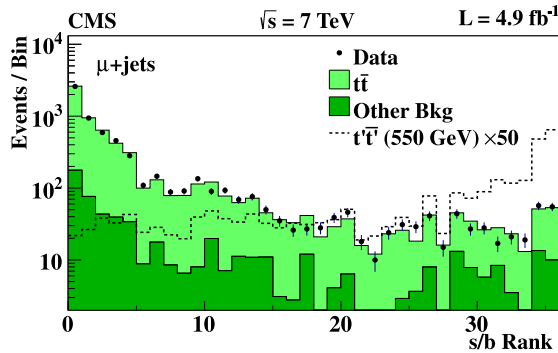


Figure 3. Number of events per bin in the two-dimensional H_T versus m_{reco} histogram, as a function of the S/B rank for the μ +jets channel [9].

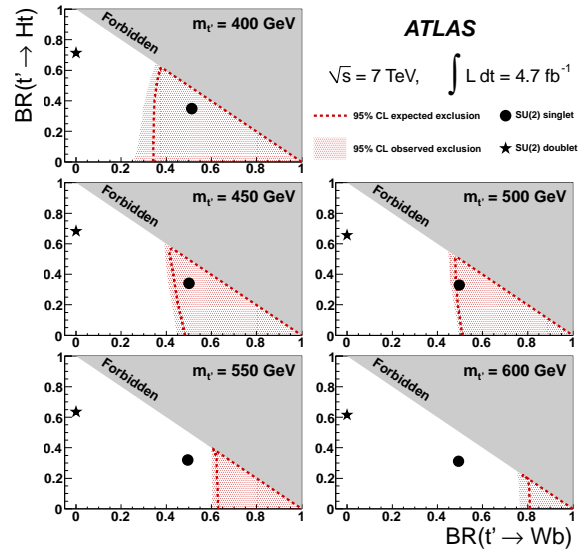


Figure 4. Observed (red filled area) and expected (red dashed line) exclusion limits in the plane of $\text{BR}(t' \rightarrow Wb)$ vs $\text{BR}(t' \rightarrow Ht)$ for different values of the vector-like t' quark mass [11]. The grey solid area corresponds to the unphysical region where the sum of the branching ratios exceeds unity.

Both ATLAS and CMS conduct searches for heavy pair-produced bottom-like quarks. These b' quarks are assumed to decay exclusively to Wt . The $W^+tW^-\bar{t}$ final state has the distinctive signature of three or more leptons or two leptons of same charge which is exploited.

CMS uses 4.9 fb^{-1} of integrated luminosity to select trilepton and same-sign-dilepton events with E_T^{miss} [13]. At least one jet must be identified as a b -jet. Events are rejected where any two leptons of the same flavor have an invariant mass consistent with the Z -boson mass. Furthermore, S_T , defined as the scalar sum of the transverse momenta of the leptons, E_T^{miss} , and the jets, is used to reject background, as shown in Fig. 5. b' quarks with mass below 611 GeV are excluded.

A similar analysis by ATLAS focuses on same-sign-dilepton events using 4.7 fb^{-1} of integrated luminosity [14]. The most important background is the contribution arising from fake leptons. Another significant background is from various SM processes where two real leptons are produced, but in which one of the leptons has a mis-identified charge. Additional signal hypotheses are considered for the interpretation of the results. Both single and pair production of new heavy quarks $T_{5/3}$, with charge $5/3$, are considered with $T_{5/3} \rightarrow W^+t$. For the single production the assumed coupling constant λ of the $tWT_{5/3}$ vertex is varied as shown in Fig. 6. Assuming only $b'\bar{b}'$ or $T_{5/3}\bar{T}_{5/3}$ production quark masses below 670 GeV are excluded. In addition, first limits are set on non-SM production of four top quarks, yielding $\sigma_{4\text{tops}} < 61 \text{ fb}$. In an earlier version of the ATLAS same-sign-dilepton search [15] using 1.04 fb^{-1} of integrated luminosity the results are also interpreted for same-sign top-quark pair production. The results leave little room to explain the measurement of the forward-backward asymmetry in top-quark pair production at the Tevatron by a flavor-changing Z' boson.

CMS excludes $T_{5/3}$ masses below 645 GeV by analyzing very similar same-sign-dilepton final states, assuming $T_{5/3}\bar{T}_{5/3}$ production and using 5.0 fb^{-1} of integrated luminosity [16].

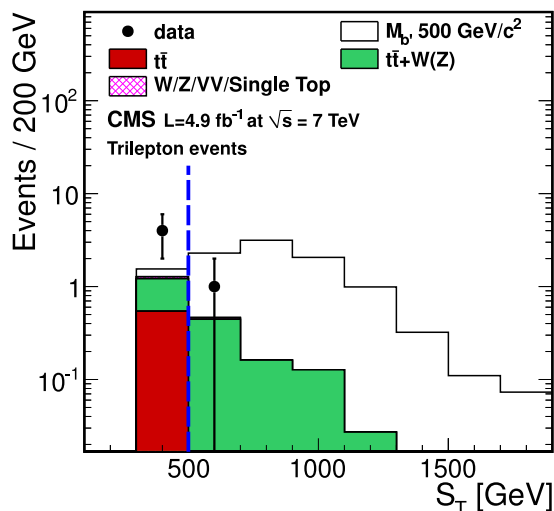


Figure 5. The S_T distributions for the trilepton channel [13]. The vertical dotted line indicates the lower S_T threshold used in the analysis.

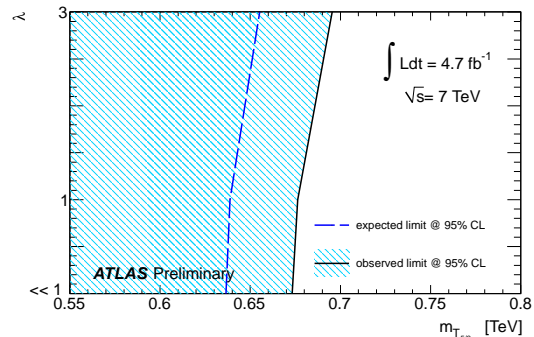


Figure 6. Expected and observed lower limits on the $T_{5/3}$ signal as a function of the $T_{5/3}$ mass and the coupling constant λ [14]. The shaded area is excluded.

Also the 1-lepton channel is used by ATLAS to set limits on $b'\bar{b}'$ production with $b' \rightarrow W^+t$ [17]. Similar to Ref. [11] hadronically decaying W bosons are reconstructed. The limits are not competitive since only 1.04 fb^{-1} of integrated luminosity was used for these results.

A combined search in the 1-lepton, same-sign-dilepton and trilepton final states is presented by CMS by assuming both single and pair production of both t' and b' [18]. By analyzing S_T and the invariant bW mass in bins of number of reconstructed hadronically decaying W bosons and b -jets, limits are presented as a function of the mass difference between t' and b' and as a function of the matrix element V_{tb} .

Both ATLAS [19] and CMS [20] set limits on $b'\bar{b}'$ production with at least one b' decaying to a Z boson and a bottom quark. Using 2.0 fb^{-1} of integrated luminosity ATLAS excludes vector-like singlet b' quarks mixing solely with the third SM generation with masses below 358 GeV. Assuming $\text{BR}(b' \rightarrow Zb) = 1$ CMS excludes b' masses below 550 GeV using 4.9 fb^{-1} .

Searches for signatures of pair production of supersymmetric top partners also have sensitivity to spin-1/2 top partners in little Higgs models as shown by ATLAS analyses presented in Refs. [21, 22].

Searches for new heavy resonances, a color singlet W' or a color triplet ϕ , produced in association with a top quark are motivated by top-flavor violating processes designed to explain the $t\bar{t}$ forward-backward asymmetry observed at the Tevatron. Two-dimensional limits are set on the mass and the coupling of W' and ϕ by ATLAS [23] by analyzing the \bar{t} +jet and the t +jet invariant mass, respectively, in $t\bar{t}$ +jet candidate events. Similar limits are set by CMS [24]. The limits leave little room for top-flavor violating processes to explain the $t\bar{t}$ forward-backward asymmetry observed at the Tevatron.

Both ATLAS [25] and CMS [26] search for resonances in the $t\bar{b}$ (and c.c.) spectrum and set lower limits on the mass of right handed $W' \rightarrow t\bar{b}$ of 1.85 TeV. ATLAS uses the invariant $t\bar{b}$ mass as the discriminant, while CMS makes use of boosted decision trees.

ATLAS uses a neural network analysis to search for FCNC single top-quark production [27]. Two-dimensional limits are set in the plane of $\text{BR}(t \rightarrow ug)$ and $\text{BR}(t \rightarrow cg)$.

4. Conclusions

Top quarks play an important role in ATLAS and CMS searches for physics beyond the SM. No hints of new phenomena could be established yet. Results from LHC pp collisions at a center-of-mass energy of 8 TeV and eventually close to 14 TeV are anticipated with great suspense.

Acknowledgments

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