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# Searches for Fourth Generation, Vector-like Quarks and Resonances with the ATLAS Detector

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**Abstract.** A summary of the searches for heavy quarks and heavy bosons decaying to top-antitop pairs ($t\bar{t}$ resonances) with 14.3 fb$^{-1}$ of the proton-proton collisions data at $\sqrt{s}$ = 8 TeV delivered by the LHC and recorded by the ATLAS detector is presented here. The searches for heavy quarks are performed in context of the chiral fourth generation and vector-like quarks. One of the searches is also sensitive to the production of four top quarks and positively-charged top quark pairs. The search for $t\bar{t}$ resonances is motivated by the narrow width topcolor leptophobic $Z'$ and broad width Kaluza-Klein gluon models.

## 1 Introduction

The fourth generation of chiral quarks is potentially addressing the baryon asymmetry by accommodating an additional source of the CP violation through extending the CKM matrix. It could provide a further insight into the forward-backward asymmetry in production of top-antitop pairs, the quark mass hierarchy and provide dark matter candidates [1]. The existence of the fourth generation is however highly disfavored as the properties of the resonance at about 126 GeV observed by the ATLAS detector [2] are compatible with those expected by the Higgs boson of the Standard Model of particle physics (SM).

Vector-like quarks are postulated by some models addressing the hierarchy problem without super-symmetry, such as Little Higgs models, extra dimension models etc [3]. The name refers to the feature that both chiralities transform in the same way under the weak symmetry group, which facilitates the generation of the vector-like quark masses without Yukawa coupling to the Higgs field. The existence of the vector-like quarks would cancel the quadratic divergences of the Higgs mass in the top loop. Vector-like quarks can appear with the SM charges (2/3, -1/3) or with exotic charges +5/3 and -4/3. They can form weak-isospin singlets, doublets and triplets.

At the current LHC center of mass energies the dominant production mechanism for both fourth generation and vector-like quarks is pair production via strong interaction, which is also the assumed production mechanism in all searches presented here.

The narrow width leptophobic topcolor $Z'$ boson with $\Gamma/m \approx 1.2\%$ explains the top quark mass and the electroweak symmetry breaking through top quark condensation associated with symmetry breaking of a new strong force [4]. The broad width Kaluza-klein gluons arise from the bulk Randall-Sundrum model involving an additional dimension with a warped geometry where the SM fields and matter are assumed to propagate in all five dimensions [5].

## 2 Search for Heavy top-like Quark $t'$ Decaying to a Higgs Boson and a top Quark

The observation of a Higgs boson opens up the space for new searches involving it in the final state as is the case for the vector-like quarks. These exotic fermions mix predominantly with the third SM generation quarks which allows for numerous decay modes. For the vector-like $t'$ three decay modes are predicted: $t' \to Wb$, $t' \to Zb$ and $t' \to Ht$. The branching ratios depend on the mass and the weak-isospin quantum number of the $t'$.

A search was presented for the production of $t'\bar{t}'$ pairs where at least one $t'$ quark decays into a Higgs boson and a top quark [6]. The search is optimized for the case where the Higgs boson decays into a $b\bar{b}$ par and the $W$ boson coming from the top quark decays into a lepton and a neutrino. Thus the signature which is searched for consists of exactly one isolated lepton, at least six jets, at least four of which are tagged as $b$ quarks, and significant missing transverse energy $E_{\mathrm{T}}^{\mathrm{miss}}$. Data is tested for presence of the $t'\bar{t}'$ by searching for the excess of events in the distribution of the total transverse momentum $H_{\mathrm{T}} = \sum_j p_{\mathrm{T}}^j + p_{\mathrm{T}}^l + E_{\mathrm{T}}^{\mathrm{miss}}$, where $p_{\mathrm{T}}^j$ stands for the $p_{\mathrm{T}}$ of the jets and $p_{\mathrm{T}}^l$ for the lepton $p_{\mathrm{T}}$.

The dominant background processes are the $t\bar{t}$ production in association with light and heavy flavor jets (Fig. 1). These two contributions are simultaneously fitted to data. The most significant systematic uncertainties come from the $b$ tagging efficiency, jet energy calibration and modeling of the included processes, especially of the dominant backgrounds.

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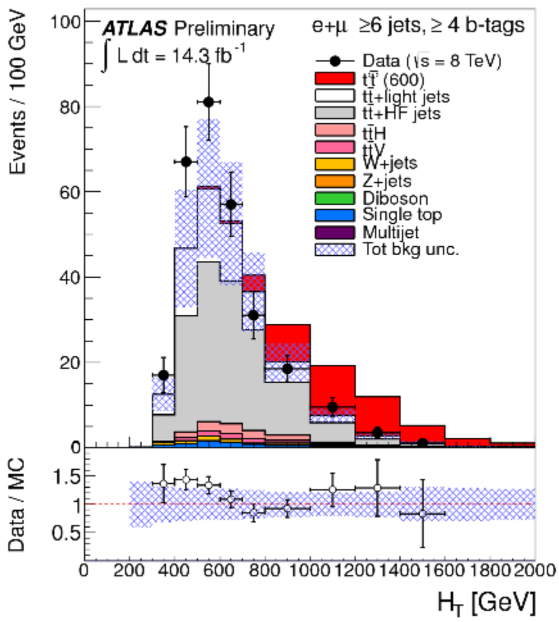



Figure 1: Discriminant $H_{\mathrm{T}}$ showing data and combined simulation samples [6].

Limits are set using $CL_s$ method with the log-likelihood ratio as test-statistics where the normalizations for the two dominant background processes are floating parameters. The observed exclusion limits are set in the plane $BR(t' \to Ht)$ versus $BR(t' \to Wb)$ for the $t'$ mass points between 350 GeV and 800 GeV in the steps of 50 GeV (Fig. 2). The result translates into a direct bound at 95% C.L. on the $t'$ mass of $m_{t'} > 790$ GeV for the doublet state and $m_{t'} > 640$ GeV for the singlet state.

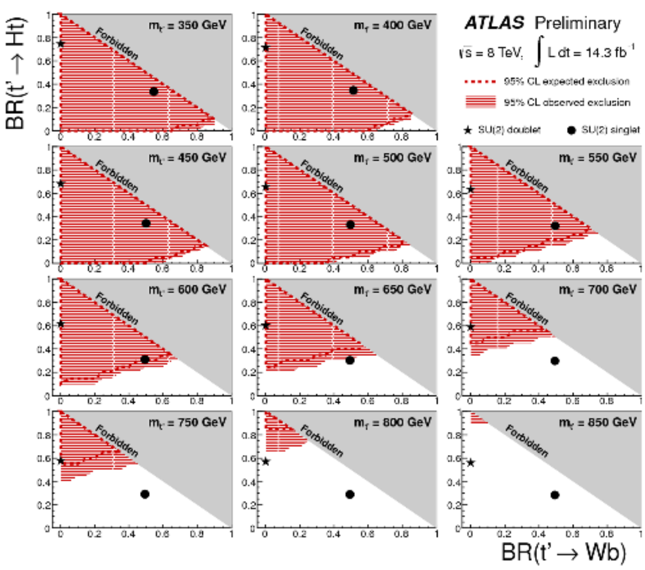



Figure 2: Observed and expected 95% CL exclusion in the branching ratio plain for different vector-like $t'$ mass points [6].

## 3 Search for Production of Same-Sign Dileptons with $b$ Jets

Production of events which contain leptons of the same electric charge in association with $b$ jets has a very low rate in the SM and thus a sensitivity to new physics. The search [7] is designed to be sensitive to several different new physics models: fourth generation bottom-like quark $b'$, vector-like bottom (B) and top (T), production of positively charged top quark pairs, and production of four top quarks within both the SM framework, and via contact interaction.

The final state considered in this search contains at least two leptons (electrons or muons) of the same electric charge. For the case of same flavored leptons, the dilepton mass $m_{ll}$ is required to be greater than 15 GeV to reject quarkonia decays and to fulfill $|m_{ll} - m_Z| > 10$ GeV, where $m_Z$ stands for the $Z$ boson mass, to veto the Drell-Yann background. The final selection in terms of the total transverse momentum $H_{\mathrm{T}}$, number of jets tagged as $b$ quarks $N_{b\text{-}jets}$ and the charge configuration of the lepton pair is optimized for every targeted model separately.

As the production cross sections of all SM processes that mimic this final state are very low, the major backgrounds originate from misreconstruction. The highest contribution comes from the events which are accepted because one or more jets is misreconstructed as lepton. It is followed by the contribution from the events in which one or more leptons are reconstructed with the wrong electric charge.

The limits are extracted using the $CL_s$ method with the log-likelihood ratio as the test statistic. The likelihood function is derived with a single bin. The result is interpreted as a direct exclusion limit on the fourth generation $b'$ mass at $m_{b'} > 0.72$ TeV assuming $BR(b' \to Wt) = 1$ (Fig. 3 (a)). The limit on the $b'$ mass has also been set to $BR(b' \to Wt) \neq 1$ in order to test for the $b'$ decays into the first and second generation quarks (Fig. 3 (b)). Limits are further placed in the $BR(B \to Hb)$ versus $BR(B \to Wt)$ plain for the vector-like $B$ masses between 350 GeV and 850 GeV in steps of 50 GeV (Fig. 4 (a)) and in the analogous manner in the $BR(T \to Ht)$ versus $BR(T \to Wb)$ plain for the vector-like $T$ (Fig. 4 (b)). This translate into limits on the vector-like quark masses of $m_B > 0.59$ TeV and $m_T > 0.54$ TeV for the singlet model. The production cross section of the positively charged top quark pairs is found to be $\sigma_{tt} < 0.21$ pb and the cross section of four top quarks production $\sigma_{t\bar{t}t\bar{t}} < 85$ (59) fb in the SM (via four fermions contact interaction). Furthermore, the lower bound has been placed on the sgluon and Kaluza-Klein gluon masses at 0.80 TeV and 0.90 TeV respectively.

## 4 Search for Heavy Resonances decaying into $t\bar{t}$ Pairs in the Final State with a Lepton, Jets and missing $E_{\mathrm{T}}^{\mathrm{miss}}$

In this search [8] two event topologies were tested. In the case of highly boosted events, the decay products of the

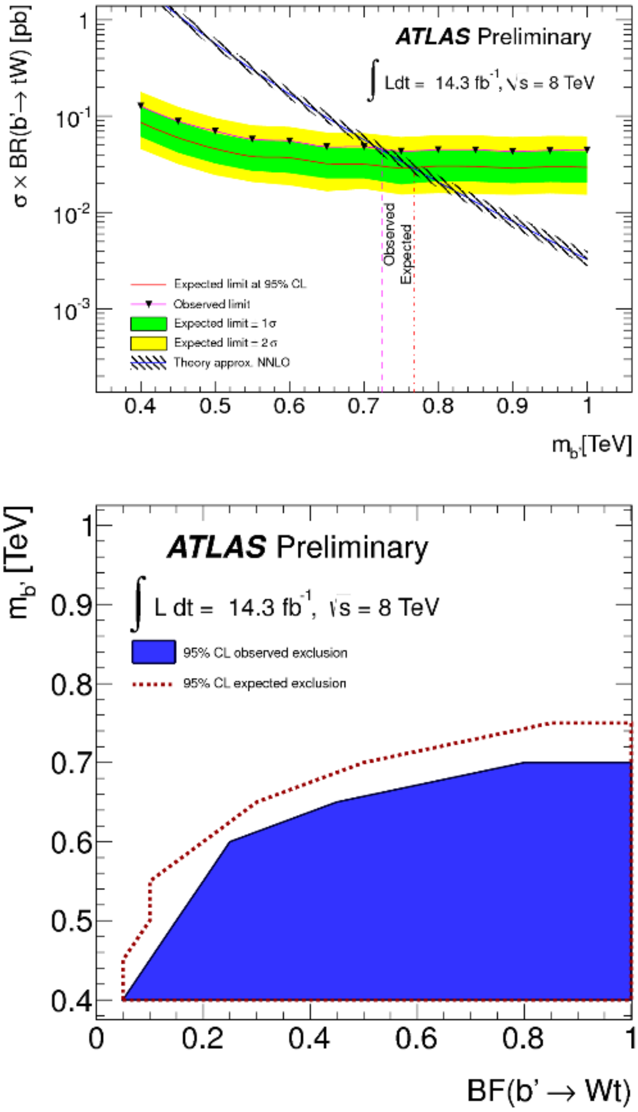



Figure 3: (a) Excluded cross section times branching ratio versus the $b'$ mass; (b) Excluded $b'$ mass as a function of $BR\,(b' \to Wt)$. Plots taken from [7].

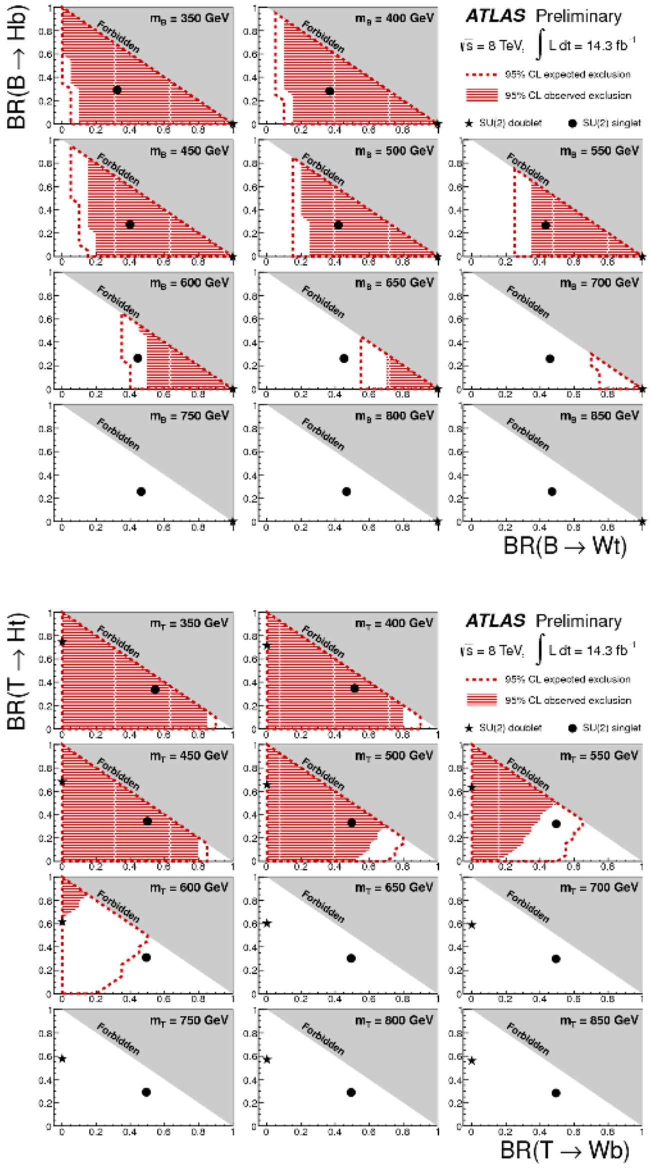



Figure 4: Exclusion area in the branching ratio plane for individual signal mass point of (a) vector-like $B$; (b) vector-like (T). Plots taken from [7].

hadronically decaying top quark are expected to be collimated so that they all fall within a single fat jet ($R = 1.0$). Such events should also contain one small jet ($R = 0.4$) close to the lepton, at least one small jet tagged as $b$ quark and sizable $E_{\rm T}^{\rm miss}$.

Further acceptance is gained by considering in addition the resolved event topology, that consists of four small jets (or three small jets if one of them has mass greater than 60 GeV), two of which are tagged as a $b$, a lepton and sizable $E_{\rm T}$.

In both cases the invariant mass of the top pair is used as a discriminant (Fig. 5). In the boosted case the longitudinal neutrino momentum $p_z^\nu$ is obtained by imposing an on-shell mass of the leptonically decaying $W$ boson, whereas in the resolved case a $\chi^2$ function is constructed to calculate the $p_z^\nu$ and assign the jets to one or the other top quark.

This search results in excluding the leptophobic topcolor $Z'$ boson with the mass in the range 0.5 TeV $< {\rm m}_{Z'} <$ 1.8 TeV (Fig. 6 (a)) and the Kaluza-Klein gluon in the mass range 0.5 TeV $< {\rm m}_{\rm gKK} <$ 2.0 TeV (Fig. 6 (b)).

## 5 Conclusions

All searches presented here were carried out with 14.3 fb$^{-1}$ of the ATLAS detector data at the center of mass energy of 8 TeV. The absence of any excess of events above the SM expectation resulted in a set of exclusion limits summarized in the Table 1.

## References


[1] B. Holdom et al., PMC Physics **A3, 4** (2009) and references therein.

[2] ATLAS Collaboration, Phys. Lett. **B 716** (2012) 1-29

[3] J. A. Aguilar-Saavedra, JHEP **0911** (2009) 030

[4] Robert M. Harris and Supriya Jain, Eur.Phys.J. **C72** (2012) 2072

[5] Ben Lillie, Lisa Randall, Lian-Tao Wang, JHEP **0709** (2007) 074

[6] ATLAS Collaboration, ATLAS-CONF-2013-018, http://cds.cern.ch/record/1525525

[7] ATLAS Collaboration, ATLAS-CONF-2013-051, http://cds.cern.ch/record/1547567

[8] ATLAS Collaboration, ATLAS-CONF-2013-052, http://cds.cern.ch/record/1547568

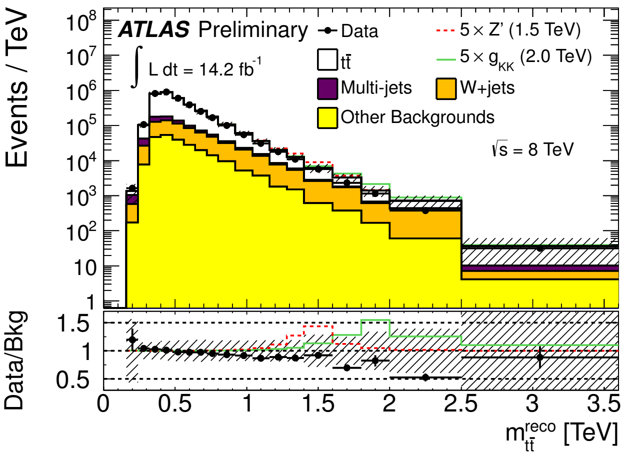
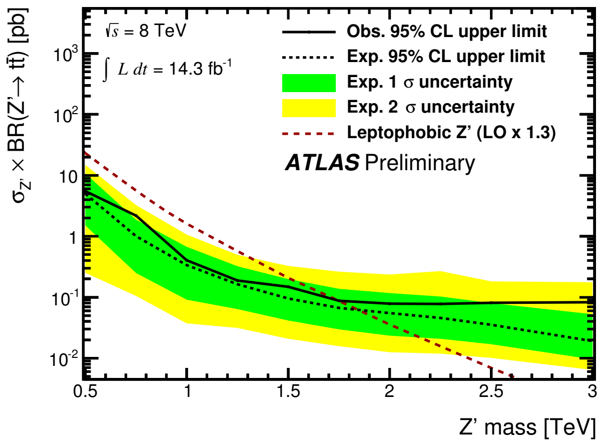



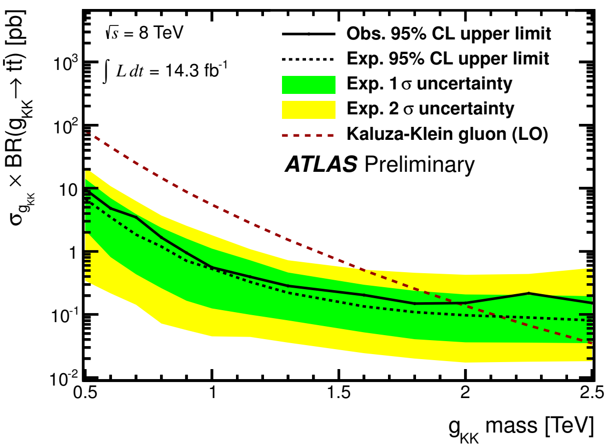

Figure 5: Reconstructed $t\bar{t}$ mass for boosted and resolved channel combined [8].

| Particle/Process | Limit |
|---|---|
| $b'$ | $m_{b'} > 720$ GeV |
| $B$ singlet | $m_B > 590$ GeV |
| $T$ singlet | $m_T > 640$ GeV |
| $T$ doublet | $m_T > 790$ GeV |
| leptophobic $Z'$ | $m_{Z'} < 0.5$ or $m_{Z'} > 1.8$ TeV |
| Kaluza-Klein gluon | $m_{gKK} < 0.5$ or $m_{gKK} > 2.0$ TeV |
| $t\bar{t}t\bar{t}$ production | $\sigma\,(t\bar{t}t\bar{t}) < 85$ fb in the SM |
| | $\sigma\,(t\bar{t}t\bar{t}) < 59$ fb via contact interaction |
| $tt$ production | $\sigma\,(t\bar{t}) < 210$ fb |

Table 1: Summary of the exclusion limits presented [6–8].




(a)




(b)

Figure 6: Observed and expected exclusion limit on the production cross section times branching ratio versus the particle mass of (a) leptophobic $Z'$ boson; (b) Kaluza-Klein gluon. Plots taken from [8].