Searches for Heavy Quarks at the ATLAS experiment

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Abstract. During 2011 the ATLAS experiment at CERN collected around 5 fb^{-1} of proton-proton collision data from the LHC at the center-of-mass energy of $\sqrt{s} = 7$ TeV. At such high energy frontier it is possible to explore possible new physics scenarios. Amongst the models of physics beyond the Standard Model (SM) some predict the existence of exotic heavy quarks, which would help to explain matter-antimatter asymmetry and to solve the hierarchy problem. Several analyses at ATLAS were performed to search for a chiral 4th generation of quarks with charges +2/3 and -1/3 (t' and b' respectively) and for vector-like quarks with charges of +2/3, -1/3, +5/3, -4/3, coming in singlets or doublets depending on the model. The recent discovery of a Higgs-like, SM-like boson with mass of ~ 125 GeV makes the vector-like quark scenario the most interesting one. The status of these searches and the limits set at 95% Confidence Level (CL) are presented.

1. Introduction

The ATLAS experiment [1] at CERN, Geneva, is a general purpose experiment equipped with a vertex detector (a silicon pixel detector and a silicon microstrip detector) and a central transition radiation tracker as the innermost three layers, surrounded by a superconducting solenoid which provides a magnetic field of 2 Tesla. Charged particle momenta are measured by this system for pseudorapidities $|\eta| < 2.5$[1]. The energy measurement is provided by the calorimeters, the electromagnetic sampling calorimeter (with lead and liquid-argon as passive and active material respectively) and the hadronic calorimeters, which use scintillating tiles alternated with steel in the central region and the liquid-argon technology in the end-cap and forward regions with, respectively, copper and tungsten as absorbers. Muons are detected in the muon spectrometer, a system of superconducting air-core toroids, trigger chambers and high-precision tracking chambers.

During 2011 data taking at the Large Hadron Collider (LHC), ATLAS showed excellent performance by collecting more than 5 fb^{-1} of data (see Figure 1). The full dataset available for analyses after data quality requirements is 4.7 fb^{-1}. At these values of integrated luminosity, a large amount of heavy quarks would be produced. An example of their production cross section as a function of the heavy quark mass $m_{q'}$ is shown in Figure 2, taken from [2]. Values for a

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[1] ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the centre of the detector and the z-axis along the beam pipe. The x-axis points from the IP to the centre of the LHC ring, and the y axis points upward. Cylindrical coordinates (r, ϕ) are used in the transverse (x, y) plane, ϕ being the azimuthal angle around the beam pipe. The pseudorapidity is defined in terms of the polar angle θ as $\eta = -\ln\tan(\theta/2)$.

Table 1. Summary of decay modes for vector-like quarks (VLQ) isosinglets and isodoublets. BRs depend on $m_{q'}$ and are very model dependent.

Singlets	Decay modes	Singlets	Decay modes	Doublets	Decay modes	Doublets	Decay modes	Doublets	Decay modes
$T(+2/3)$ $B(-1/3)$	W^+b, Ht, Zt W^-t, Hb, Zb	$X(+5/3)$ $Y(-4/3)$	W^+t W^-b	$\begin{pmatrix} T \\ B \end{pmatrix}$	W^+b, Ht, Zt W^-t, Hb, Zb	$\begin{pmatrix} T \\ X \end{pmatrix}$	Ht, Zt W^+t	$\begin{pmatrix} B \\ Y \end{pmatrix}$	Hb, Zb W^-b

center-of-mass energy of 7 TeV for *e.g.* a vector-like quark with mass of 600 GeV are about 15 times lower. Pair production via the strong interaction is dominant up to $m_{q'} \sim \mathcal{O}(750 \text{ GeV})$ while for higher masses single production via the electroweak interaction dominates.
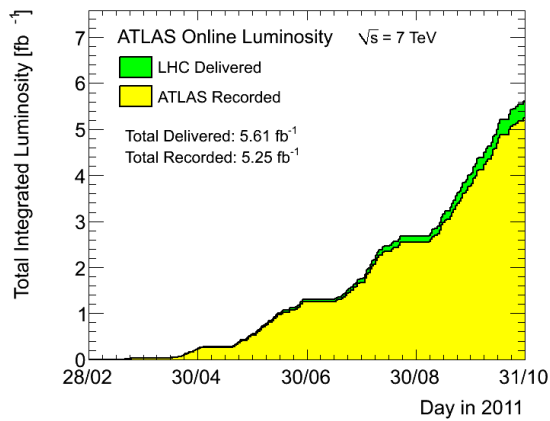
Figure 1. Performance of data acquisition of the ATLAS experiment for 2011. Of the 5.61 fb^{-1} delivered by the LHC, ATLAS recorded 5.25 fb^{-1} [3].
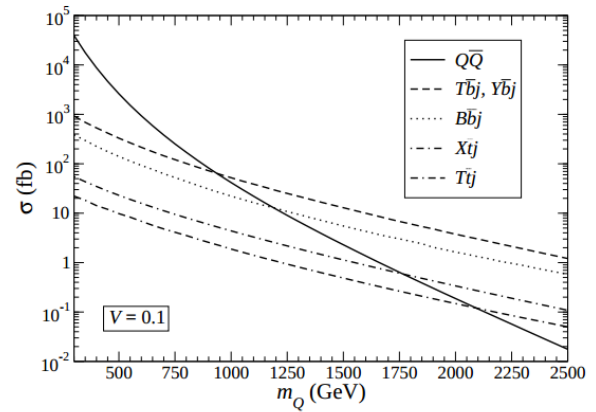
Figure 2. Pair and Single production cross sections for heavy quarks in proton-proton collisions at $\sqrt{s} = 14$ TeV [2].

The theoretical motivation for exotic heavy quarks searches is given by many models predicting their existence, see e.g. [2, 4, 5, 6]. Even though a new generation of quarks (whose families are constrained by asymptotic freedom to 9) would provide new sources of CP violation while staying consistent with precision electroweak measurements, it would also modify the SM predictions of the Higgs boson cross section and Branching Ratios (BR), which is in contraddiction with what was recently observed [7]. Still, some models allow for it, but the interest is now shifting towards vector-like quark models.

These heavy quarks with charges of +2/3, -1/3, +5/3, -4/3, named respectively T, B, X, Y, are weak-isospin singlets, doublets or triplets, whose left and right components transform the same under $SU(2) \times U(1)$. Table 1 shows the possible decay modes for isosinglets and isodoublets.

The analyses presented in the following have been performed using different fractions of the full 2011 dataset depending on the time of publication. Only pair produced heavy quarks are considered and events are selected in single lepton or dilepton channels.

2. Object definition

The searches for heavy quarks at the ATLAS experiment use common definitions for reconstructed objects. Jets are topological clusters reconstructed with the `AntikT4` algorithm [8] with transverse momentum p_T >25 GeV and pseudorapidity $|\eta|$ <2.5. Electrons are well isolated calorimeter deposits which are matched to tracks from the inner detector with transverse energy E_T >25 GeV and $|\eta|$ <2.47 after removing the pseudorapidity region [1.37,1.52], which corresponds to the transition region between barrel and endcap calorimeters. Muons are reconstructed from a segment in the tracker and muon detector matched to an isolated track in the inner detector with p_T > 20 GeV and $|\eta|$ <2.5. Some analyses use a b tagging algorithm [9] to identify jets coming from a b quark. The discriminant value is chosen as to get an efficiency of $\sim 70\%$ in simulated $t\bar{t}$ events.

2.1. Common selections
All the analyses require the primary vertex to have at least four tracks to reject background from cosmic radiation and to reject pileup events. Also, single lepton triggers are common to all the analyses.

For analyses in the lepton+jets channel, exactly one lepton is required and a veto is applied on any other lepton of the same or opposite flavor and the following cuts on missing transverse energy $\not{E}_T$ and transverse mass of the leptonically-decaying W, $m_T(W)^2$ are imposed:

- in the e+jets channel: $\not{E}_T$ >35 GeV, $m_T(W)$ >25 GeV
- in the μ+jets channel: $\not{E}_T$ >20 GeV, $\not{E}_T + m_T(W)$ >60 GeV

For analyses in the dilepton channel, at least two leptons are required. For same flavor $ee/\mu\mu$ analyses in general a Z veto $|m_{ll} - m_Z| < 10$ GeV is applied.

3. Searches for Heavy Tops

Two analyses are presented searching for $t' \to Wq$. The analysis in the lepton+jets channel assumes $q = b$ and interprets the search, performed using the full 2011 dataset, in terms of fourth generation quark as well as of vector like quarks $Y(-4/3)$ and $T(+2/3)$. The analysis in the dilepton channel uses 1.04 fb^{-1} of data and does not make assumptions on the quark flavor q, thus being extendable to heavy bottom final states. Both analyses use a binned maximum-likelihood ratio to probe Signal+Background and Background-only hypotheses with the CL_s method (see e.g. [10, 11]) and set 95% CL limits on the $t'\bar{t}'$ production cross section.

3.1. Lepton+jets analysis with 4.7 fb^{-1}
Assuming a 100% decay BR for $t' \to Wb$, this analysis [12] focused on the kinematical differences between a low mass boosted top quark and a high mass t' quark produced in pairs. Because of its high mass, the t' is produced almost at rest and will decay into highly boosted and energetic objects. A hadronically decaying boosted W boson can be detected as two light jets very close to each other or even merged into a single one. Two reconstructions are thus defined:

- W_{had}^{typeI}: a single jet with $p_T > 250$ GeV and mass in the [60,110] GeV window;
- W_{had}^{typeII}: a di-jet system with $\Delta R(j,j) < 0.8$, $p_T > 150$ GeV and mass in the [60,110] GeV window.

The following cuts are applied in addition to the common ones described in Section 2.1:

- e channel: cut on $m_T(W)$ substituted by $\not{E}_T + m_T(W)$ >60 GeV;

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[2] The defintion for the transverse mass is $m_T(W) = \sqrt{2p_T^l \not{E}_T (1 - \cos \Delta\phi)}$, where p_T^l is the p_T of the lepton and $\Delta\phi$ is the azimuthal angle separation between the lepton and $\not{E}_T$ directions.

- At least 3 jets and one W_{had}^{typeI} OR at least 4 jets and one W_{had}^{typeII} and no W_{had}^{typeI};
- $H_T > 750$ GeV[3];
- At least 1 b-tagged jet and, after identifying two b-jet candidates b_1, b_2 by looking at their discriminant weight, cut on the highest-p_T one and the second-hardest-p_T one, respectively, at $p_T > 160$ GeV, $p_T > 60$ GeV;
- $\Delta R(l, \nu) < 1.4$, where the neutrino is reconstructed by constraining the mass of the lepton-neutrino system to the W boson mass[4].

Further tight isolation requirements are applied to the previous "loose" selection, assuming the boosted top quark background will have close-by products: $min(\Delta R(l, b_{1,2})) > 1.4$ and $min(\Delta R(W_{had}, b_{1,2})) > 1.4$. Mass reconstruction is then performed by resolving the ambiguity from b-jet assigment and ν solutions by choosing the hadronic mass from the combination yielding the lower difference with leptonic side. Figure 3 shows the reconstructed mass after the "tight" selections for data, SM background and two different heavy quark signals: a chiral fourth generation t' and a vector-like t'.
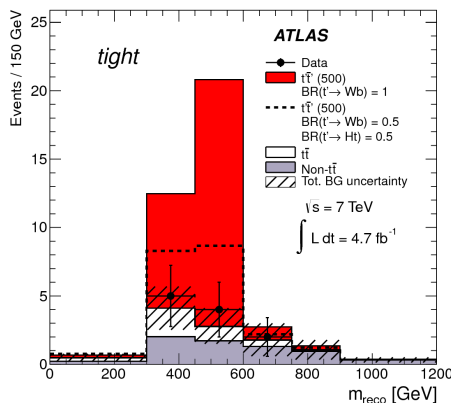
Figure 3. Distribution of reconstructed mass for the combined e+jets and μ+jets channels after the loose selection. The data (solid black points) are compared to the SM background prediction (stacked histograms). The total uncertainty on the background estimation is shown as a black hashed band. Also shown, stacked on top of the SM background, are the expected contributions from a signal with mass $m_{t'}$=500 GeV for the case of BR($t' \rightarrow Wb$)=1 (plain red histogram), corresponding to a fourth-generation t' quark, as well as the case of BR($t' \rightarrow Wb$)=BR($t' \rightarrow Ht$)=0.5 (dashed black histogram). The overflow has been added to the last bin [12].

Using the reconstructed mass as discriminant variable, a log-likelihood ratio is built to derive limits with the CL_s technique [10, 11]. A chiral fourth generation quark (as well as a vector-like $Y(-4/3)$, which would have exactly the same final state if BR($t' \rightarrow Wb$)=1) is excluded at 95% CL for masses up to 656 GeV as shown in Figure 4. Re-interpreting the result also in terms of vector-like $T(2/3)$ is possible once the two additional possible decay channels $t' \rightarrow Zt$ and $t' \rightarrow Ht$ are considered. To be model-independent, a mixing plane is defined between $BR(T \rightarrow Wb)$ and $BR(T \rightarrow Ht)$, while $BR(T \rightarrow Zt)$ is given by $\sum BRs = 1$, and each point tested in the same way as before. The singlet scenario is excluded up to $m_T = 500$ GeV.

### 3.2. Opposite Sign Dilepton analysis with 1.04 fb^{-1}

This analysis [13] performs a search for a pair-produced fourth generation up quark decaying $t'\bar{t}' \rightarrow WqWq$ with $q = d, s, b$ and both W bosons decaying leptonically. By not requiring any additional information on the quark flavor, this analysis can be extended to searches for $b'\bar{b}' \rightarrow WqWq$ with $q = u, c$. The final state has two opposite sign leptons, either of same or different flavor. Under the boosted regime assumption for the heavy t', the leptons and their neutrinos are considered collinear. Additional analysis requirements with respect to the ones described in Section 2.1 are:

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[3] The H_T variable is defined as the sum of the first three or four leading jets p_T, the lepton p_T and the $\not{E}_T$.

[4] This gives rise to two possible solutions. If no real solution is found, assuming the neutrino will be collinear to the lepton in a boosted regime, pseudorapidity of the neutrino is set to that of the lepton.
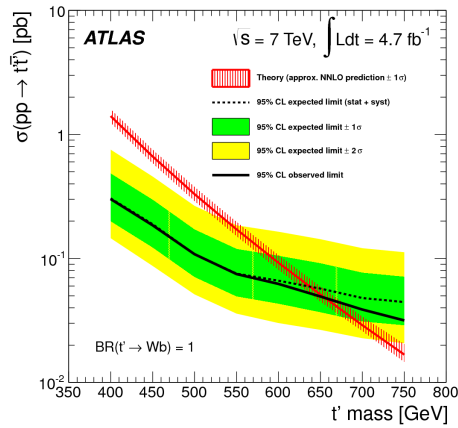
Figure 4. Observed (solid line) and expected (dashed line) 95% CL upper limits on the $t'\bar{t}'$ cross-section as a function of the t' quark mass. The surrounding shaded bands correspond to the ± 1 and ± 2 standard deviations around the expected limit. The thin red line and band show the theoretical prediction and its ± 1 standard deviation uncertainty [12].
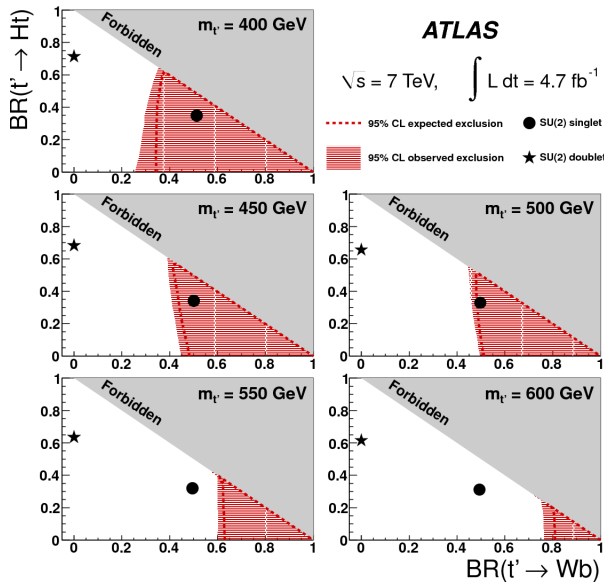

Figure 5. Observed (red filled area) and expected (red dashed line) 95% CL exclusion on the plane of $BR(t' \to Wb)$ vs $BR(t' \to Ht)$, for different values of the vector-like t' quark mass. The grey solid area corresponds to the unphysical region where the sum of branching ratios exceeds unity. The default branching ratio values from the PROTOS event generator for the weak-isospin singlet and doublet cases are shown as plain circle and star symbols, respectively. While the doublet scenario is not accessible, the singlet scenario is excluded up to $m_T = 500$ GeV [12].

- At least two jets, without any b-tagging requirement;
- For same flavor: $\not{E}_T > 60$ GeV;
- For different flavor: $H_T > 130$ GeV[5];
- $m_{ll} > 15$ GeV, with Z mass veto to remove most of the background.

The discriminant variable for the analysis is the collinear mass $m_{Collinear}$, defined as the average between the two masses recontructed by making the assumption that the lepton and the neutrino are collinear and the missing energy is the neutrino's energy. Events with mass difference $|\Delta m| > 25$ GeV are discarded. The efficiency of this cut for the signal is 99%.

Some additional cuts, optimized per t' mass, are applied for $t\bar{t}$ discrimination (see [13] for details). The resulting distibution for data, SM background and a signal is shown in Figure 6. This distribution is used to derive a binned maximum-likelihood ratio, and an observed 95% CL limit on fourth generation t' and b' masses is set at 350 GeV using the CL_s method [10, 11] (see Figure 7).

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[5] H_T is defined as the scalar sum of the transverse energy of each lepton and jet passing object selection cuts.
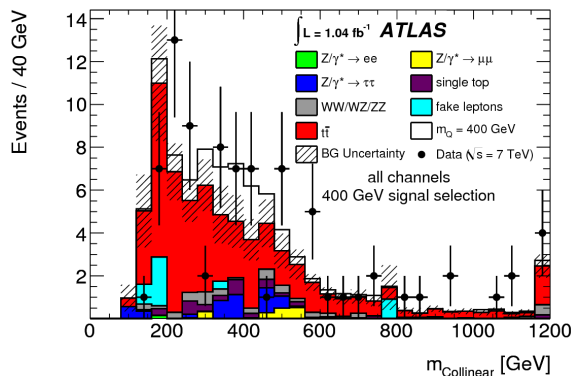
Figure 6. Distributions of $m_{Collinear}$ for the sum of ee, $\mu\mu$, and $e\mu$ channels after applying the final selection for $m_Q = 400$ GeV. The last bin contains overflow events. The uncertainty bands include all statistical and systematic background uncertainties [13].
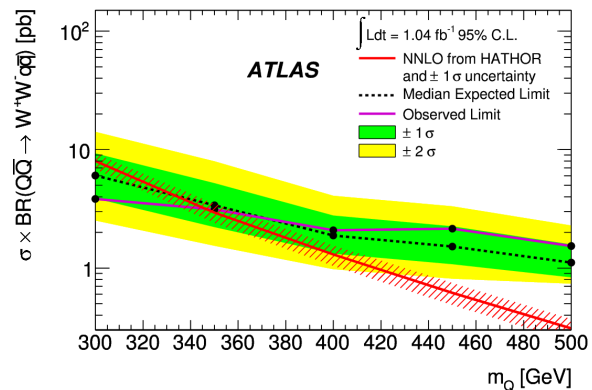
Figure 7. Observed and median expected 95% CL cross-section upper limits on $Q\bar{Q}$ production, compared to the theoretical prediction. The limit was calculated for five signal masses, and a linear interpolation has been made between mass points [13].

4. Searches for Heavy Bottoms

Two analyses are presented searching for pair-produced $b'\bar{b}'$, one looking for $b' \to Wt$ decays and one looking for $b' \to Zb$ decays. In the case of a chiral fourth-generation b' the neutral current mode would occur through loop diagrams, being then highly disfavored once the phase space allows the tree-level decay into a top and a W (i.e. $m_{b'} > 255$ GeV). For a vector-like b' on the contrary, $b' \to Zb$ would be a tree-level decay, thus leaving the branching ratio to this channel to be determined by the specific model. The analysis with the full 2011 dataset in the same-sign dilepton channel performs a search for a chiral b' decaying into Wt re-interpreting the result in terms of vector like quarks $X(+5/3)$ and $B(-1/3)$. The analysis in the opposite-sign dilepton channel searches for vector-like b' decaying into Zb, using 2.0 fb^{-1} of data. Both the analyses use the CL_s method (see e.g. [10, 11]) and set 95% CL limits on $b'\bar{b}'$ production cross section.

4.1. Same-sign Dilepton analysis with 4.7 fb^{-1}

For this analysis [14] the interesting decays have four W bosons (pair-produced chiral fourth-generation b' or vector-like $X(5/3)$) or two same sign W bosons (singly-produced vector-like $X(5/3)$). The resulting final state of two isolated same-sign leptons has the advantage of having very few SM processes as possible background, which consists mainly of fakes and charge flips.

Additional analysis requirements with respect to the ones presented in Section 2.1 are:

- At least two jets of which at least one b-tagged
- Leading lepton $p_T > 25$ GeV
- For same flavor leptons $m_{ll} > 15$ GeV with Z mass veto
- $\not{E}_T > 40$ GeV and $H_T > 550$ GeV[6]

Four events have been observed in the signal region out of 5.6±1.7 expected background events. For the three different models considered limits are then derived using the CL_s technique [10, 11]. For pair production of chiral b' and vector-like $X(5/3)$ masses up to 670 GeV are excluded at 95% CL (see Figure 8). In case of $X(5/3)$ single production, the cross section depends on the coupling constant λ of the $tWX_{5/3}$ vertex. Three values for λ are explored:

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[6] H_T is defined as the scalar sum of all leptons and jets transverse momenta.

$\lambda \ll 1$ (equivalent to pair production), $\lambda = 1$ and $\lambda = 3$, and the observed limits are set at 680 GeV and 700 GeV for the last two, respectively (see Figure 9).
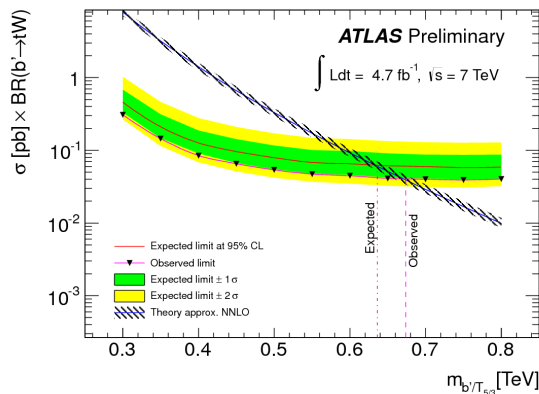
Figure 8. Expected and observed upper limits on the pair production cross section of the b' and $X(+5/3)$, as a function of their mass [14].
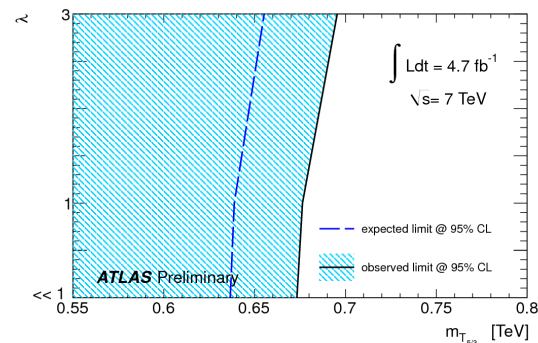
Figure 9. Expected and observed lower limits on the $X(+5/3)$ signal, as a function of the $X(+5/3)$ mass and the coupling constant λ. The shaded area is excluded at 95% CL [14].

4.2. Opposite-sign electron pair analysis with 2.0 fb^{-1}
This analysis [15] looks for pair production of vector-like b' decaying in the channel $b' \to Zb$. In addition to the common cuts presented in Section 2.1 the following conditions are required in order to fully reconstruct the Z boson and the b':

- At least one b-jet
- $|m_{ee} - m_Z| < 15$ GeV
- $p_T(Zb) > 150$ GeV

The b' candidate is reconstructed from an electron positron pair e^+e^- and the highest-p_T b-jet of the event and its invariant mass (show in Figure 10) used as a discriminant variable to compute the binned likelihood. Defining $\beta = 2 \times BR(b' \to Zb) - BR(b' \to Zb)^2$, this variable describes the fraction of signal events with at least one $b' \to Zb$ decay as a function of the BR, meaning that $\beta = 1$ is equal to $BR(b' \to Zb) = 1$ while for vector-like singlet $B(-1/3)$ β varies with the mass (e.g. $m_B = 200 - 700$ GeV corresponds to $\beta = 0.9 - 0.5$). Figure 11 shows the cross section limits obtained using the CL_s technique [10, 11] for two scenarios: the 100% decay into Zb and the singlet model. Observed limits are set respectively at 400 GeV and 358 GeV at 95% CL.

5. Conclusions
The ATLAS experiment is active in investigating new physics models with exotic heavy quarks. The latest searches have excluded various scenarios at 95% CL using data collected in 2011: chiral 4th generation t' (100% to Wb) and vector like $Y(-4/3)$ are excluded up to 656 GeV [12]; chiral 4th generation t' (to Wq, $q = d, s, b$) are excluded up to 350 GeV [13]; chiral 4th generation b' (100% to Wt) and vector like $X(5/3)$ are excluded up to 670 GeV [14]; vector like b' (100% to Zb) are excluded up to 400 GeV [15]; vector like $B(-1/3)$ singlet model is excluded up to 358 GeV [15]; vector like $T(2/3)$ singlet model is excluded up to 500 GeV [12].
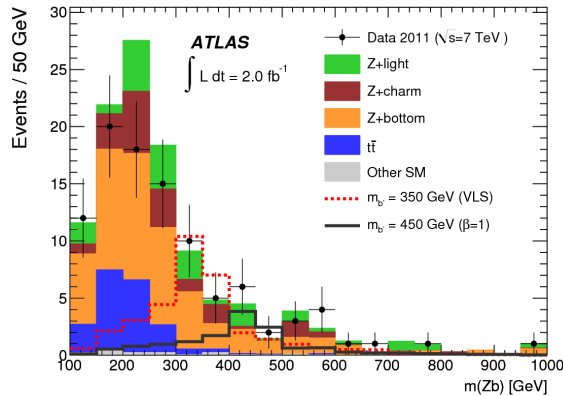
Figure 10. Mass distribution of the b' candidate in events passing the selection. The predicted contributions of the SM background sources are stacked, while the distributions for the two signal scenarios described in the text are overlaid. The highest mass bin also includes the data and prediction for $m(Zb) > 1$ TeV [15].
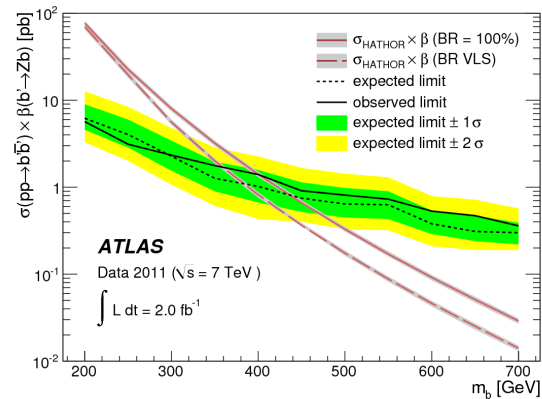
Figure 11. The expected and observed 95% CL cross section limits as a function of b' mass. The signal cross section is shown with uncertainties arising from PDFs and renormalization and factorization scale choice. The prediction is also multiplied by the beta factors described in the text [15].

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