Generalization of exotic quark searches

F. Garberson and T. Golling

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F. Garberson, T. Golling
Yale University, New Haven CT, 06520, USA

General limits on exotic heavy quarks T, B and X with masses above 300 GeV are presented for arbitrary branching fractions of $T \to W^+b$, $T \to Zt$, $T \to Ht$, $B \to W^-t$, $B \to Zb$, $B \to Hb$ and $X \to W^+t$. The results are based on a CMS search in final states with three isolated leptons (e or μ) or two isolated leptons with the same electric charge. Exotic heavy quark pair production through the strong interaction is considered. In the context of vector-like quark models, T quarks with a mass $m_T < 480$ GeV and $m_T < 550$ GeV are excluded for weak isospin singlets and doublets, respectively, and B quarks with a mass $m_B < 480$ GeV are excluded for singlets, all at 95% confidence level. Mass limits at 95% confidence level for T and B singlets, (T,B) doublets and (X,T) doublets are presented as a function of the corresponding heavy quark masses. For equal mass $m_T = m_B$ and $m_X = m_T$ vector-like quarks are excluded at 95% confidence level with masses below 550 GeV for T and B singlets, 640 GeV for a (T,B) doublet and 640 GeV for a (X,T) doublet.

I. INTRODUCTION

Vector-like quarks [1–3] are new heavy quarks, in particular heavier than the top quark, which appear in many new physics models, such as extra dimensions, little Higgs, or composite Higgs models. Similar to a supersymmetric partner of the top quark, a vector-like top partner serves to stabilize the Higgs mass by cancelling the divergence of radiative corrections in the Higgs boson mass. Quarks are referred to as vector-like if their left- and right-handed chiralities transform in the same way under the electroweak group $SU(2) \times U(1)$. Vector-like quarks can be classified as weak isospin singlets, doublets or triplets. The mass eigenstates of these vector-like quarks are referred to as T and B, with charges 2/3 and $-1/3$, respectively, and X and Y, with charges 5/3 and $-4/3$, respectively. It is assumed that the new quarks mainly couple to the third generation [4] which leads to the following possible decay modes:

$$T \to W^+b, \quad T \to Zt, \quad T \to Ht,$$

$$B \to W^-t, \quad B \to Zb, \quad B \to Hb,$$

$$X \to W^+t,$$

$$Y \to W^-b.$$

For T and B singlets all decay modes are sizable. For doublets a reasonable assumption is that $V_{Tb} \ll V_{tB}$ so that only $T \to Zt$, $T \to Ht$ and $B \to W^-t$ contribute. In this paper we give special attention to this scenario but also present results that can be interpreted under any mixture of these decay modes. In addition, the branching fractions for the T and B decay modes vary with the heavy quark masses m_T and m_B, respectively. The total width of the new quarks is typically negligible as compared to the detector mass resolution in the probed mass range.

Exotic heavy quarks such as vector-like quarks are mainly produced in pairs through the strong interaction or singly via the electroweak interaction. We will only focus on the pair production. The cross section for this process is the same for each of these types of quarks and depends on the quark mass.

As has been proposed previously [5], analyses using two leptons with the same charge can have strong sensitivity when searching for heavy-quark partners. Using 4.9 fb^{-1} of pp collision data at $\sqrt{s} = 7$ TeV the CMS Collaboration excluded the existence of a fourth-generation b' quark with a mass below 611 GeV at 95% confidence level (CL) [6] by examining events with two isolated leptons (e or μ) with same electric charge or with three isolated leptons. The ATLAS collaboration used a same-sign dilepton data sample equivalent to 4.7 fb^{-1} of pp collisions at $\sqrt{s} = 7$ TeV to exclude both b' and vector-like quarks X with charge 5/3 (which they referred to as $T_{5/3}$) with masses below 670 GeV at 95% CL [7]. A similar analysis was performed by the CMS Collaboration using 5 fb^{-1} of pp collisions at $\sqrt{s} = 7$ TeV to exclude vector-like quarks X with charge 5/3 with masses below 645 GeV at 95% CL [8]. All three searches assume pair production through the strong interaction and branching ratios of unity $BR(b' \to W^-t) = 1$ and $BR(X \to W^+t) = 1$.

Same-sign-lepton or three-lepton signatures are also expected from many of the vector-like-quark final states discussed above. Accounting for all possible decay processes, for $T\bar{T}$ production the possible final states are W^+bW^-b,

$WbZt$, $WbHt$, $ZtZt$, $ZtHt$ and $HtHt$. For $B\bar{B}$ production the possible final states are W^-tW^+t, $WtZb$, $WtHb$, $ZbZb$, $ZbHb$ and $HbHb$. For $X\bar{X}$ production the only possible final state is W^+tW^-t. For simplicity, here b represents both b and $\bar{b}$, and analogously for top quarks. Among these, all final states except W^+bW^-b feature same-sign-lepton or three-lepton signatures. In this paper we exploit this feature and reinterpret the published CMS result [6] by relaxing the assumptions which determine the branching ratios as a function of mass to explore the entire space of possible branching ratios. A similar reinterpretation for arbitrary branching fractions was performed by ATLAS [9] for an analysis targeting the $T\bar{T} \to W^+bW^-b$ hypothesis in a single-lepton final state and excluding at 95% CL T quarks with a mass 400 GeV $< m_T <$ 500 GeV for weak isospin singlets. Reinterpretations of results of specific $T \to W^+b$ and $T \to Zt$ searches are also discussed in Ref. [10]. We show that these limits can be extended with the same-sign-lepton and three-lepton signatures, and we present limits for the T and B singlet and doublet, as well as for the (X,T) doublet hypotheses as a function of the corresponding heavy quark masses. These represent important generalizations of the existing limits.

II. SAMPLES AND EVENT SELECTION

In this analysis the event selection of the CMS search is replicated as closely as possible. The selection is briefly described in Section II A. The details of how the selection is reproduced for this paper, and of how the signal samples are simulated, are discussed in Section II B.

A. The CMS event selection

As discussed above, CMS makes use of events that are selected under both same-sign and trilepton requirements (electron or muon). Events are selected if they pass a trigger that requires two leptons. Electrons are required to have $p_T > 20$ GeV and $|\eta| < 2.4$, excluding the region between the end-cap and barrel ($1.44 < |\eta| < 1.57$). Muons are required to have $p_T > 20$ GeV and $|\eta| < 2.4$. Jets are required to have $p_T > 25$ GeV and $|\eta| < 2.4$. For the same-sign analysis, CMS requires the presence of two isolated leptons with the same electric charge and at least four jets. For the trilepton analysis at least three isolated leptons must be identified, at least two of which must have an opposite charge, and at least two jets must be found. In all cases, at least one jet must be tagged as a b-jet using a tagger with roughly a 50% efficiency for identifying true b-jets, and events with two electrons or muons that are consistent with originating from a Z boson decay are rejected ($|m_{ll} - m_Z| > 10$ GeV). Finally, the scalar sum of the transverse momenta of the jets, leptons, and the missing transverse momentum is required to be at least 500 GeV.

B. Samples and event selection for the reinterpretation

For this analysis samples of singlet $T\bar{T}$ and $B\bar{B}$ production, and doublet $X\bar{X}$ production were generated. All samples were generated using Protos 2.0 [1, 11] and showered using Pythia 6.4.25 [12]. Past studies have determined cross-sections for these processes at NLO [13]. For this paper, however, we determine these cross-sections at approximate NNLO using the Hathor package [14]. 500,000 events were generated for each process and each mass hypothesis in 50 GeV intervals ranging from a lowest mass of 300 GeV to a highest mass of 900 GeV. In each case the Higgs mass was set to a value of 125 GeV.

The modeling of the CMS detector was performed using the Pretty Good Simulation (PGS) package [15], with the detailed detector descriptions taken from the default CMS detector card from the MadGraph [16] package. A few minor changes were then made to these defaults in order to improve the accuracy as discussed below. Some information, such as the CMS efficiencies for b-tagging and electron identification, is not provided in precise detail by the experiment. We document our assumptions below, and will show that we achieve good agreement with the published results.

All kinematic cuts on p_T and η of the leptons and jets are chosen to be identical to those of the experiment. PGS applies its own model for electron identification but it does not attempt to determine efficiency loss due to isolation cuts. In order to make the model more realistic we remove electrons if they are found to be within $\Delta R < 0.4$ of a jet with $p_T > 15$ GeV unless $\Delta R < 0.2$, in which case the jet is removed instead under the assumption that it is a misidentified electron.

As the CMS documentation [17] does not give precise numbers for the selection efficiencies, we assume that their electrons have the same isolation efficiencies as for ATLAS [7]. The calorimeter and tracker cuts are each 90% efficient for the electron isolation at ATLAS. As will be seen below, no significant bias is introduced by such an assumption.

Unlike for electrons, for muons PGS does not have a built-in muon identification model. Instead it only assumes a 2% inefficiency on all tracks in the analysis. This efficiency appears to be roughly correct for CMS, which has highly efficient muon selection and isolation requirements [18].

CMS has triggers that are highly efficient for electron identification, but less efficient for muon identification. CMS explicitly quotes their trigger efficiencies for their selected events as being 91% in the $\mu\mu$ channel, 96% in the $e\mu$ channel, and 99% in the ee channel [6]. When simulating the same-sign dilepton analysis for CMS, events are randomly thrown out according to these probabilities. For the CMS trilepton analysis the triggers are assumed to be 100% efficient.

The b-tagging efficiency for state-of-the-art CMS b-tagging algorithms is quite different from the efficiency that is assumed by PGS. The b-tagging efficiency is therefore set to more appropriate values.

For CMS a tagger was chosen that was tuned to be 50% efficient for real b-jets with a 1% mistagging efficiency for non-b jets [6]. In principle it would be best to account for the p_T and η-dependence of the tagging efficiencies. Unfortunately, none of the CMS public b-tagging documents [19, 20] provide the efficiencies of this particular operating point as a function of jet kinematics. This documentation does, however, indicate that the b-taggers in CMS tend to have less kinematic dependence than at many other experiments. We therefore instead use the average efficiency of 50% for real b-jets and 1% for non-b jets as quoted in the paper [6].

After applying all event selections, the PGS event yields are validated against the quoted CMS yields for the pair production of b' quarks. As shown in the ATLAS analysis [7], these yields are approximately identical to the X pair production yields. For purposes of this validation, since CMS assumes $BR(b' \to W^- t) = 1$ [6–8], we apply a filter to force the vector-like-quarks to decay in the same manner ($BR(B \to W^- t) = 1$). Very good agreement is found as shown in Table I. We therefore conclude that our signal modeling and event selection are sufficiently accurate.

	$m_{b'/B} = 450$ GeV	$m_{b'/B} = 500$ GeV	$m_{b'/B} = 550$ GeV	$m_{b'/B} = 600$ GeV	$m_{b'/B} = 650$ GeV
PGS same-sign	49.9 ± 1.4	25.1 ± 0.7	14 ± 0.4	7.9 ± 0.2	4.1 ± 0.1
CMS same-sign	49 ± 4.2	26 ± 2.2	14 ± 1.1	7.6 ± 0.6	4.3 ± 0.4
CMS SS Difference (%)	1.8 ± 9	-3.4 ± 8.9	0 ± 8.6	3.7 ± 8.7	-4.1 ± 9.1
PGS trilepton	16 ± 0.8	8.1 ± 0.4	4.5 ± 0.2	2.6 ± 0.1	1.5 ± 0.1
CMS trilepton	15 ± 1.6	8.2 ± 0.8	4.7 ± 0.4	2.7 ± 0.3	1.6 ± 0.2
CMS trilepton Difference (%)	6.6 ± 11.9	-0.6 ± 10.9	-3.5 ± 9.9	-5.3 ± 10.8	-8.3 ± 10.2

TABLE I: Here a comparison is made between the number of expected signal events passing the selection requirements of this paper and the selection requirements of the CMS paper. Results are shown for both the same-sign and the trilepton channels. In each case the first row shows the results using the generated samples and detector simulation of this paper (Protos $B\bar{B}$ production with PGS where both B quarks are forced to decay $B \to Wt$). The second row shows the quoted results from the CMS paper (MadGraph $b'\bar{b}'$ production with CMS simulation). All results are shown for an integrated luminosity of 4.9 fb^{-1}, with inclusive cross-sections determined using Hathor at NNLO. These cross-sections are verified to be identical to those of CMS. The CMS paper results include both statistical and systematic uncertainties, while the PGS result have statistical uncertainties only. The number of selected results appears to agree well with the CMS paper, suggesting that the samples and event selection used in this paper are sufficiently accurate for use in reinterpretations.

III. METHOD

This analysis proceeds in three steps. First, events are selected according to the prescriptions documented in Section II. It must be remembered that in the case of $B\bar{B}$ and $T\bar{T}$ events, the simulation assumes that the heavy quarks are singlets. When predictions for a model with alternate decays such as a doublet model are desired instead, a correction is needed to the appropriate decay branching fractions. This procedure is described in Section III A. Finally, the number of observed events is converted into exclusion limits. This procedure is discussed in Section III B.

A. Alternate decay-mode hypotheses

Depending on how each of the new heavy quarks decays, there are six possible combinations for each quark type as explained in Section I. The nominal $T\bar{T}$ and $B\bar{B}$ samples in this analysis are generated with the hypothesized branching fractions for the new heavy quark decays that is appropriate for singlets. In this section we explain how the expected number of signal events is converted to a value that is appropriate to more general branching fractions such as under a doublet model.

To achieve full generality, for each mass point a two dimensional grid of all possible branching fractions is scanned in 10% steps. The dimensions are chosen to be the branching ratio of the W-type decay modes, which we denote B_W, and the branching ratio of the Z-type decay modes, which we denote B_Z. The branching ratio of the Higgs-type decays follows from $B_H = 1 - B_W - B_Z$. The probability for the production of each of the six possible combinations of decays of the two new heavy quarks then depends upon these branching fractions that we are assuming. For a particular decay mode i, the probability is denoted $P_i(B_W, B_Z)$. After determining the acceptance times efficiency for our event selection for each decay, A_i, the number of signal events N that is expected for each hypothesis branching fraction is then determined according to Equation 1:

$$N = \sum_{i=1}^{6} P_i(B_W, B_Z) A_i \int \mathcal{L}\sigma, \tag{1}$$

where $\int \mathcal{L}$ is the integrated luminosity and σ is the corresponding heavy quark pair production cross section. We assume that the kinematic differences and consequently the differences in selection efficiency for singlets and doublets are negligible.

B. Limit setting

Limit setting is performed by running the MCLimit [21, 22] program simultaneously on the same-sign and the trilepton results. In order to run this limit setting the following inputs are needed: the number of expected background events from each source ($t\bar{t}$, diboson, etc.) with their associated uncertainties, the number of expected signal events with their associated uncertainty, and the number of observed data events.

The number of data events, the number of background events from each source, and their respective uncertainties are input into MCLimit directly from the CMS paper [6]. The number of events in a given signal model are taken from the outputs of the PGS simulation, with any necessary corrections applied as discussed in Sections II B and III A to arrive at a given decay hypothesis.

In performing this limit setting there are certain approximations that are made. First, for a given signal model PGS does not predict the acceptance systematic uncertainties, only the central values. In the CMS paper these systematic uncertainties are shown to have very similar values for each of their signal masses, ranging from a total acceptance systematic of 8.6% to 9.0% for the same-sign channel, and 10% to 11% for the trilepton channel. We therefore assign the average uncertainties of 8.8% for the same-sign channel and 10.5% for the trilepton channel in our limit setting.

A second approximation that is made is related to the correlations between error sources in these analyses. Normally it would be necessary to split the uncertainties for each sample into their individual components in order to correctly handle the correlations between particular error sources. In this analysis, however, the systematic uncertainties that are correlated between samples are negligibly small and can be safely neglected. In particular, for the same-sign analysis the dominant background systematics are due to control-region estimations, which are not correlated to the signal uncertainties. Similarly, in the trilepton analysis the dominant background uncertainties are from data statistics, normalization of the theoretical backgrounds, and Monte Carlo sample statistics, which again are not correlated to the signal uncertainties. We therefore neglect correlations when running the limit-setting.

It should be pointed out that any biases that are introduced by either of these approximations would need to be quite sizable in order to lead to a significant change in the results of this paper due to the fact that statistical uncertainties on the signal play a larger role than systematic uncertainties. Nevertheless we perform one additional check by running the limit-setting on the published numbers for the b' model in the CMS paper and comparing with the expected results. The CMS paper sets 95% exclusion limits on the b' model of 611 GeV. Limit setting was run using the published CMS numbers for the expected b' events passing their event selection, and including all approximations. An exclusion level of 98.1% was determined for the 550 GeV mass point, an exclusion limit of 96.1% was determined for the 600 GeV mass point, and an exclusion limit of 80.5% was determined for the 650 GeV mass point. Under any reasonable interpolation between these points we would determine an expected 95% exclusion limit that is consistent with the CMS value of 611 GeV to well within 10 GeV. This cross-check therefore suggests that our limit setting approximations are not causing any appreciable bias.

IV. RESULTS

In Section IV A the results of the analysis assuming arbitrary branching fractions for heavy quark $T\bar{T}$ and $B\bar{B}$ decays are presented. In Section IV B these results are interpreted in the context of certain theoretically motivated values of heavy quark branching fractions, including the (X, T) doublet.

A. Results for arbitrary branching fractions for the new heavy quark decays

In this section results are presented for all possible branching fractions of heavy T and B quark decays. In each case we assume only the presence of a single $T\bar{T}$ or $B\bar{B}$ production process. Having both $T\bar{T}$ and $B\bar{B}$ present would of course lead to improved sensitivity. We discuss some models with both heavy quarks present later in Section IV B.

After selecting events from the signal samples that pass the selection requirements, the number of expected events as a function of the branching ratio of the decays of the new heavy quarks are determined according to the prescription of Section III A. These numbers are shown for example production processes in Figure 1. It should be noted that the numbers in Figures 1 (a) and (c) can be used to cross-check the reweighting procedure of Section III A. If this conversion is done correctly then these numbers should converge in their lower right corners to roughly the same values as were found when generated with a dedicated $B \to Wt$ filter for the 500 GeV mass sample as shown in Table I. For both the same-sign and the trilepton selections agreement is found within the uncertainties that are expected given limited Monte Carlo statistics.

The resulting exclusion values from running MCLimit are shown in Figures 2 and 3 for each signal hypothesis, depending on the branching ratios for each possible decay mode. In these figures the branching ratios for direct decays to W bosons are shown on the x-axes, and the branching ratios for direct decays to Z bosons are shown on the y-axes. The branching ratios for direct decays to Higgs (H) are then uniquely specified for each point on these grids by subtracting each of these probabilities ($\mathrm{BR}(H) = 1 - \mathrm{BR}(Z) - \mathrm{BR}(W)$). These results are also interpreted in terms of the standard singlet and doublet models. At 95% CL we exclude T quarks with a mass $m_T < 480$ GeV and $m_T < 550$ GeV and B quarks with a mass $m_B < 480$ GeV and $m_B < 610$ GeV for weak isospin singlets and doublets, respectively. These doublet-limits are quoted assuming $V_{Tb} \ll V_{tB}$. Production of $B\bar{B}$ and $T\bar{T}$ are both excluded at 95% CL for all possible branching ratios up to a mass of 360 GeV. When considering the results of the ATLAS search [9] in addition to those of this paper, the $T\bar{T}$ hypothesis is excluded for all branching ratios up to a mass of 450 GeV.

B. Results assuming nominal branching fractions for the new heavy quark decays

In this section results are presented under certain plausible models. After determining the number of events that are expected to pass selection for each signal hypothesis, the results are interpreted under the limit-setting framework described above.

The first hypothesis is that both a B and a T singlet are present with the expected branching ratios. In this case the default Protos model has the correct branching fractions and no corrections are required. Alternately, we consider the presence of a (B, T) (with $V_{Tb} \ll V_{tB}$) or a (X, T) doublet. For each of these models, the limit results are presented in Figure 4 in a two-dimensional grid depending on the hypothesized mass of the new heavy quarks. It should be noted that in the case of the singlet model there is no reason to assume that both a B and a T quark must be present. In case only a single quark is present, the limits can be extracted by considering the high-mass limit for the other quark in Figure 4.

Assuming identical masses for the new heavy quarks in the singlets and doublets, the 95% CL limits can be interpreted as $m_Q < 550$ GeV for the case of a singlet T and a singlet B, $m_Q < 640$ GeV for the case of a doublet (T, B), and $m_Q < 640$ GeV for the case of a doublet (X, T).

V. CONCLUSION

We demonstrate in this paper that searches in final states with three isolated leptons (e or μ) or two isolated leptons with same electric charge have a very good sensitivity to exotic heavy quarks T, B and X for all possible decay modes $T \to W^+b$, $T \to Zt$, $T \to Ht$, $B \to W^-t$, $B \to Zb$, $B \to Hb$ and $X \to W^+t$. ATLAS and CMS searches in these final states have previously set limits assuming $BR(b' \to W^-t) = 1$ and $BR(X \to W^+t) = 1$. We reinterpret CMS results and generalize their limits for arbitrary branching ratios for heavy quark masses above 300 GeV.

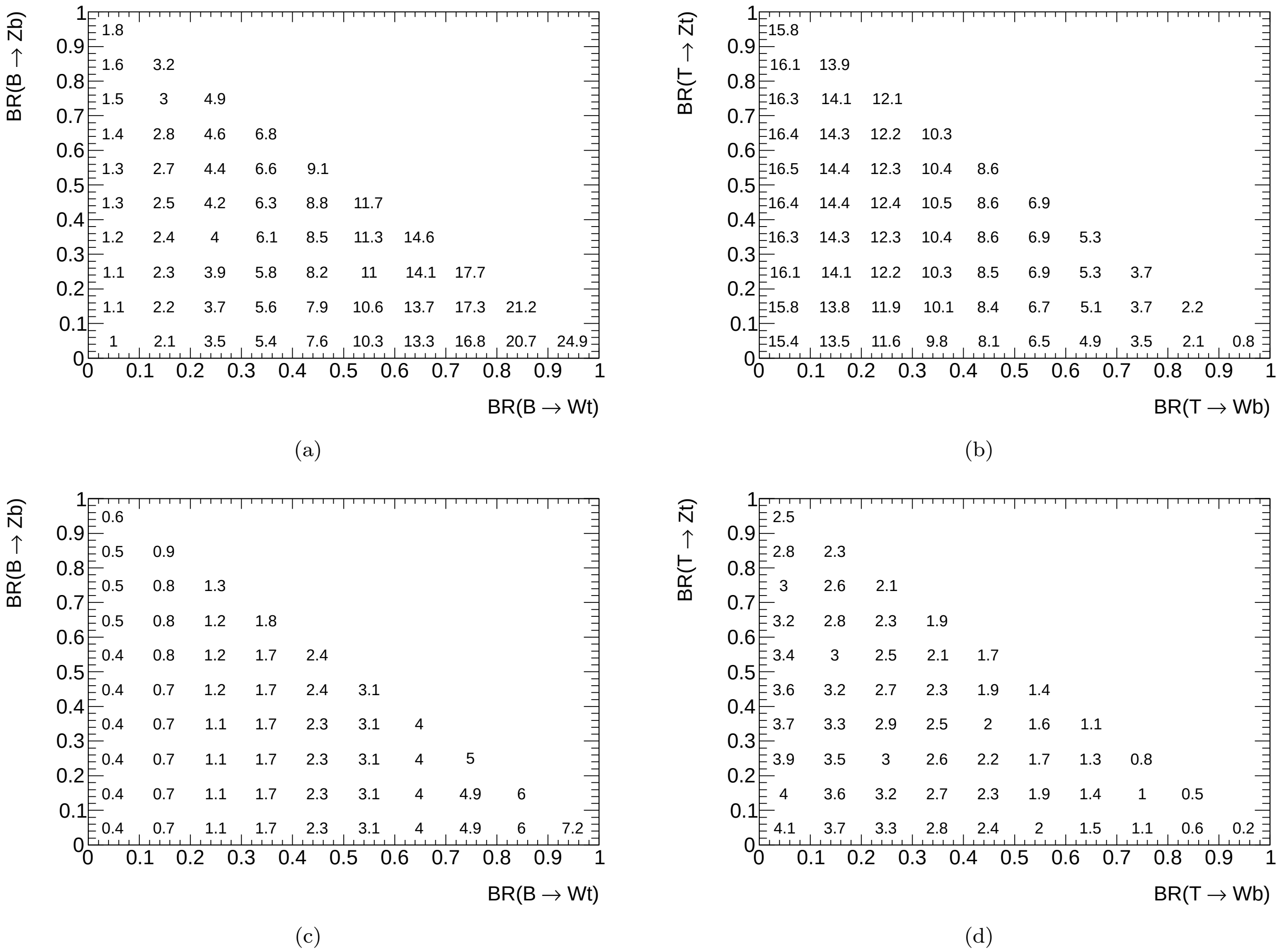
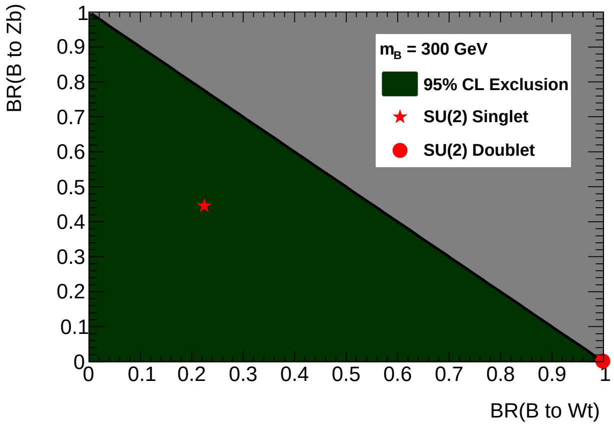
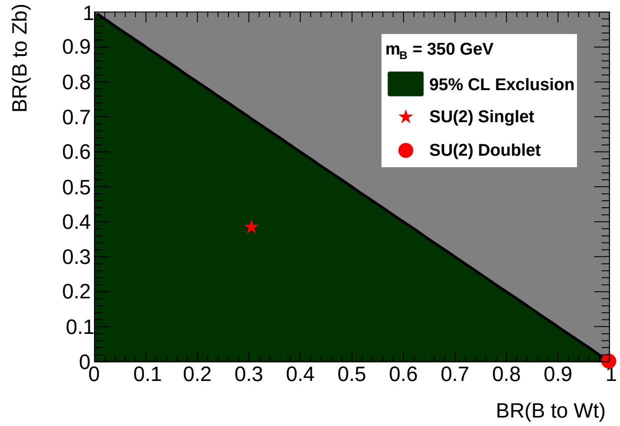


FIG. 1: Here we show the number of expected signal events passing full event selection requirements depending on the branching ratios of the heavy quark decays for a given VLQ model for pair production of quarks with a mass of 500 GeV. Branching ratios for direct decays to Higgs are uniquely specified for each point on these grids as $\mathrm{BR}(T \to Ht) = 1 - \mathrm{BR}(T \to Zt) - \mathrm{BR}(T \to Wb)$. The figures shown here are same-sign yields for $B\bar{B}$ (a) and $T\bar{T}$ (b) production, and trilepton yields for $B\bar{B}$ (c) and $T\bar{T}$ (d) production.

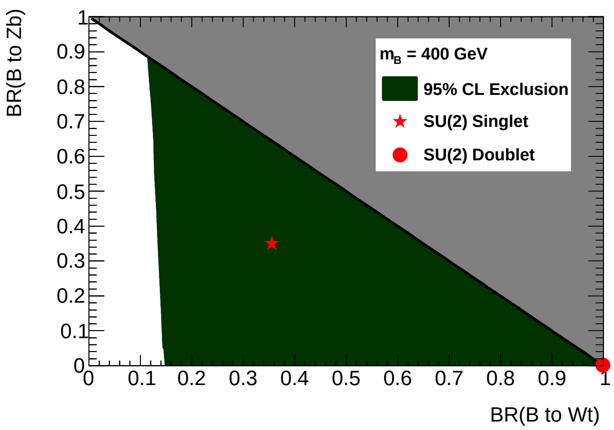
At 95% CL we exclude T quarks with a mass $m_T < 480$ GeV and $m_T < 550$ GeV and B quarks with a mass $m_B < 480$ GeV and $m_B < 610$ GeV for weak isospin singlets and doublets, respectively. Mass limits at 95% CL for T and B singlets, (T,B) doublets and (X,T) doublets are presented as a function of the corresponding heavy quark masses. Under an equal mass hypothesis ($m_T = m_B$ and $m_X = m_T$) vector-like quarks are excluded at 95% CL with masses below 550 GeV for T and B singlets, 640 GeV for (T,B) doublets (assuming $V_{Tb} \ll V_{tB}$) and 640 GeV for (X,T) doublets.



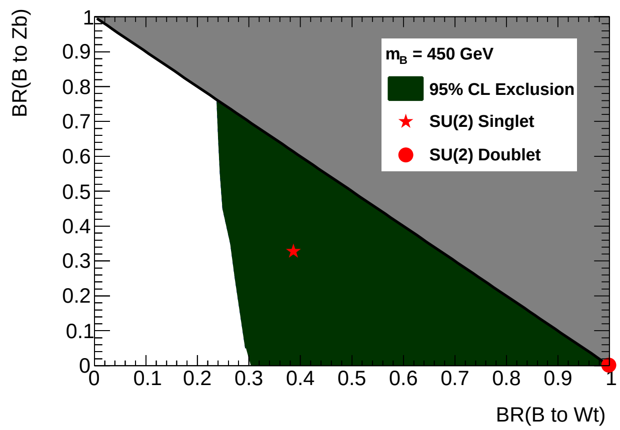
(a)



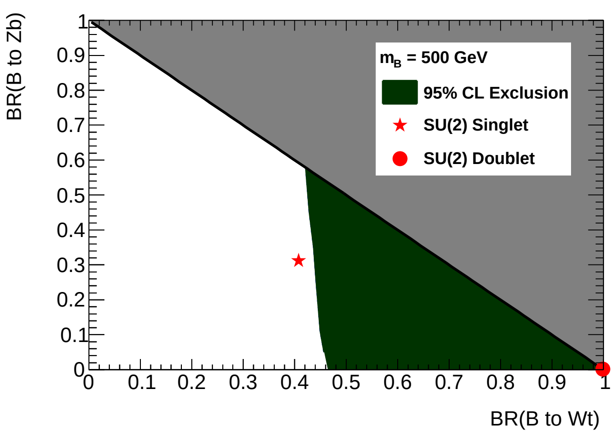
(b)



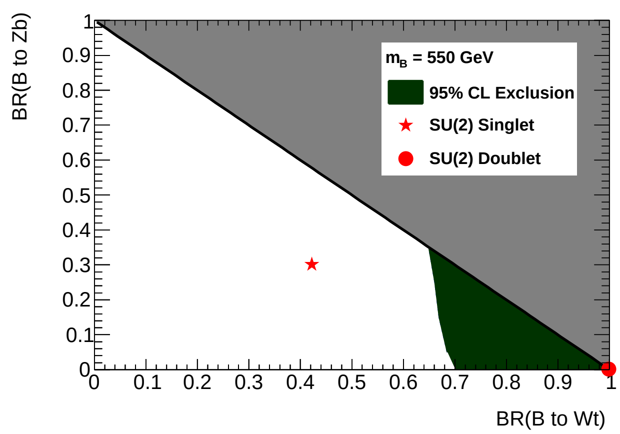
(c)



(d)



(e)



(f)

FIG. 2: Here we show the 95% CL exclusion regions for $B\bar{B}$ pair production depending on the assumed branching ratios. Branching ratios for direct decays to Higgs are uniquely specified for each point on these grids as $\mathrm{BR}(T \to Ht) = 1 - \mathrm{BR}(T \to Zt) - \mathrm{BR}(T \to Wb)$. The actual branching fractions of course depend on the parameters of a given VLQ model. In each case the branching fractions of the singlet model are indicated by a star. For the doublet model, the branching ratios depend on the CKM parameters. Branching fractions under the reasonable scenario of $V_{Tb} \ll V_{tB}$ are shown as a circle. Results are shown assuming a B mass of 300 GeV (a), 350 GeV (b), 400 GeV. (c), 450 GeV (d), 500 GeV (e) and 550 GeV (f).

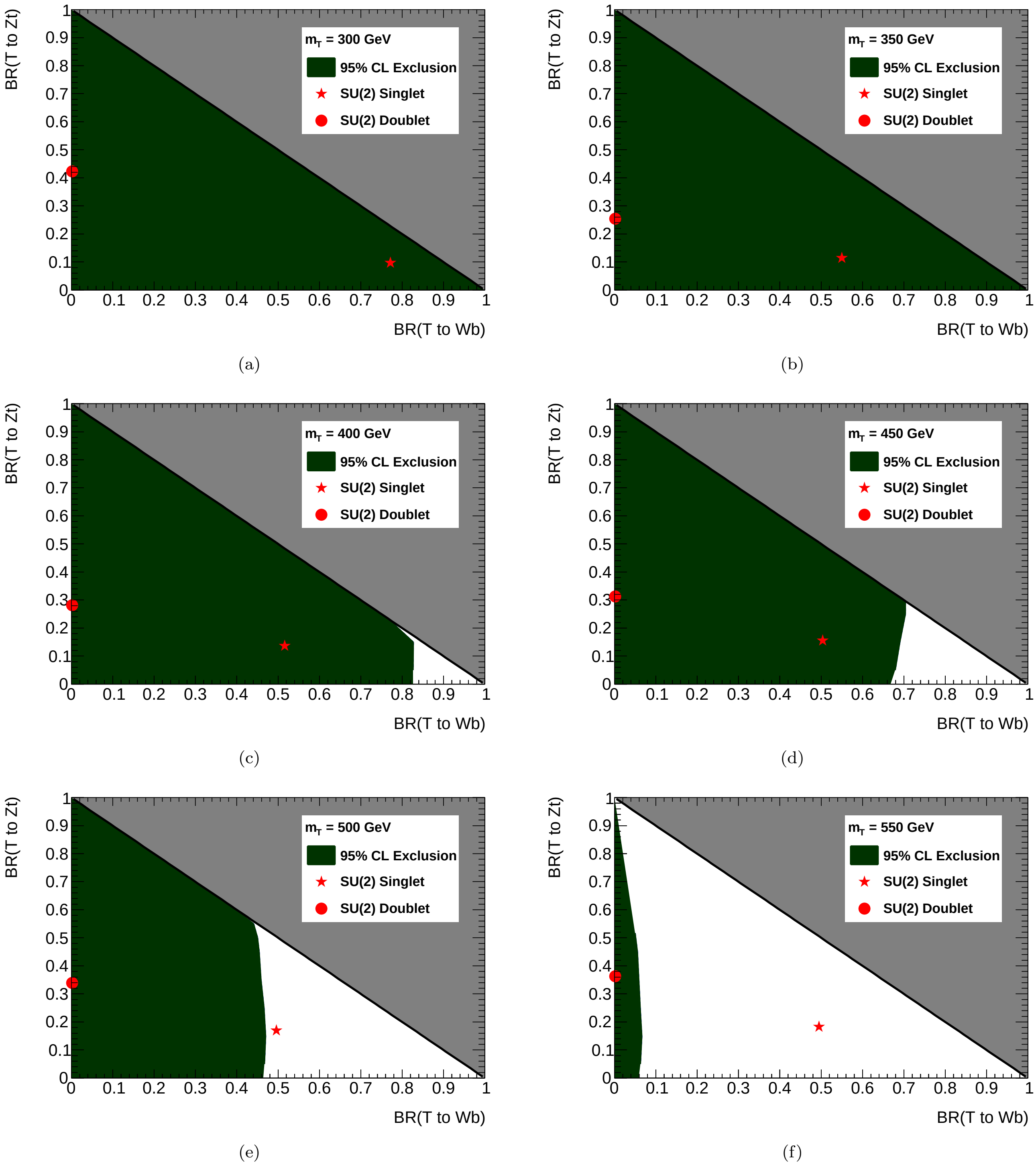
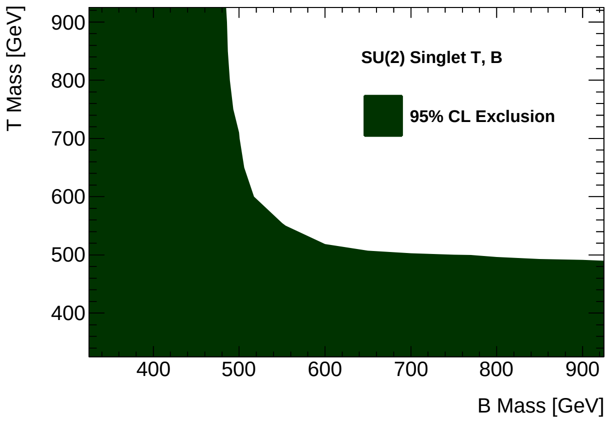
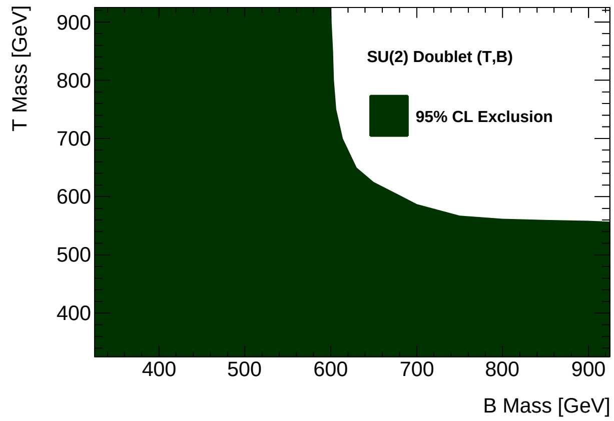


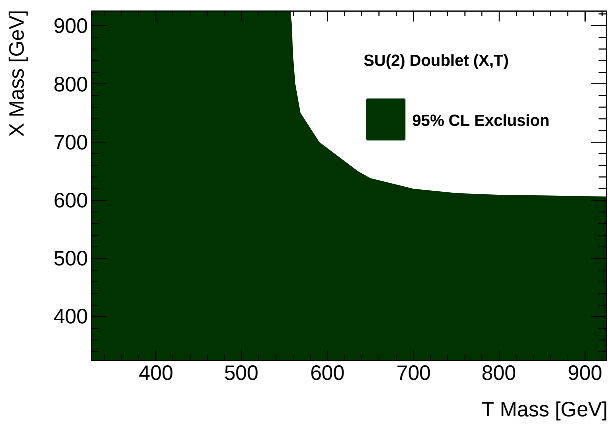
FIG. 3: Similar results to those of Figure 2 are shown here for each possible decay-mode of $T\bar{T}$ (instead of $B\bar{B}$).



(a)



(b)



(c)

FIG. 4: Here 95% CL exclusion limits are shown depending on the mass of each quark and the model. Figure (a) shows results assuming the presence of two singlets, T and B. Figure (b) shows results assuming the presence of a (T, B) doublet under the assumption $V_{Tb} \ll V_{tB}$. Figure (c) shows results assuming the presence of a (X, T) doublet.

VI. ACKNOWLEDGMENTS

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