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Searches for vector-like quarks with top quarks

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Searches for vector-like quarks at the ATLAS and CMS experiments in approximately 20 fb^{-1} of 8 TeV data from the LHC are presented. No significant excesses are reported, but analysis techniques developed in these searches are expected to play a role in increasing sensitivity in upcoming 13 TeV searches.

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1. Introduction

Vector-like quarks (VLQ's), fermions for which left-handed and right-handed fields transform in the same way under Standard Model gauge groups, are an attractive generic signature that arise in a number of models of physics beyond the Standard Model. The theory is described elsewhere in these proceedings, in particular by M. Peskin and A. Deandrea.

This article describes recent searches for VLQ's conducted by the ATLAS [1] and CMS [2] experiments at the Large Hadron Collider [3] operating at $\sqrt{s} = 8$ TeV. We denote the vector-like top partner with charge $+\frac{2}{3}e$ as T, and the bottom partner with charge $-\frac{1}{3}e$ as B. More exotically charged partners, $T_{5/3}$ and $B_{4/3}$, arise in some models. Assuming that these new particles couple primarily to third-generation quarks t and b, the most important decay channels include the $T \to bW$ and $B \to tW$ which may be expected for Standard Model-like chiral fourth-generation quarks, but also the flavor-changing neutral current decays $T \to tZ/H$ and $B \to bZ/H$. Different models give different branching fractions for these modes. While most searches assume pair production, it is expected that as mass limits are pushed higher, electroweak production of single VLQ's will become more important. Searches have also been conducted for decays of VLQ's of unspecified flavor Q to lighter-generation Standard Model quarks q. Due to space limitations, this article will focus on the most recent results and note developments in analysis techniques. In all the analyses touched upon below, readers are referred to the publications for full details.

2. Pair production with leptonic signatures

Both the ATLAS and CMS experiments have published a number of searches for pair-produced VLQ's where at least one of the daughter particles decays further to at least one isolated high-p_{T} lepton, usually an electron or muon. These leptons are expected to be accompanied by a number of high-p_{T} jets, some of which will be b-tagged, and gauge and Higgs bosons, depending on the particular VLQ and decay channel. The CMS experiment has consolidated its results into two papers, one focused on $B\overline{B}$ searches [4], and a more recent one focused on $T\overline{T}$ searches [5]. Both papers update and finalize previous analyses with the full 19.7 fb^{-1} dataset at 8 TeV, and calculate limits based on the combination of the analyses, taking into account correlated and uncorrelated systematic uncertainties. The ATLAS experiment, on the other hand, has published signature-based analyses on 20.3 fb^{-1} of data: single lepton+jets [6, 7], opposite-sign dileptonic Zt/b [8], same-sign dileptons with b quarks [9], and leptonic W with a light quark [10].

The ATLAS single-lepton search for $B\overline{B} \to tW + X$ [6] illustrates a typical analysis strategy: Fig. 1(left) shows unit-area-normalized Monte Carlo distributions of H_{T}, which is defined as the scalar sum of the p_{T}'s of the lepton, jets, and missing p_{T}, for the signal and the most important backgrounds, in this case $t\bar{t}$ and W+jets production. A clear separation is seen, and this variable is the most important single discriminant in this and other analyses (where H_{T} may sum over different ranges of objects, and is sometimes denoted S_{T}). More information, however, exists in other variables such as the angular separation between the lepton and the tagged b jet, and the transverse mass of the lepton and missing p_{T} system. In this analysis, this information is combined into a single discriminant using a Boosted Decision Tree (BDT) [11]. As shown in Fig. 1(right), the data distribution for the BDT discriminant is consistent with the background prediction from a combination of Monte Carlo and data-driven methods and validated in background-rich control regions. Limits for $B\overline{B}$ production are calculated as a function of B branching fractions to tW, bZ, and bH, and are shown combined with other ATLAS analyses in Sec. 5. This analysis can also be interpreted as a search for pair production of $T_{5/3}$ fermions. CMS has used a BDT in its $T\overline{T}$ search in single-lepton data [12, 13].

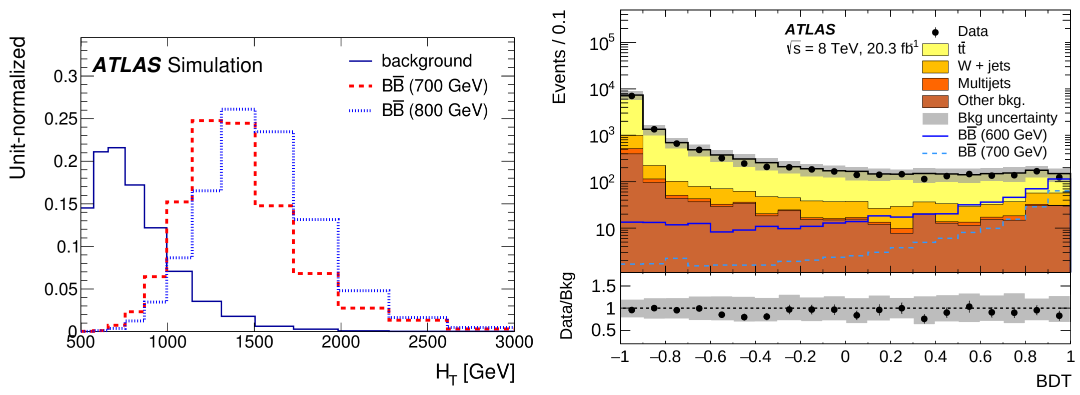

Figure 1: Left: Monte Carlo distributions of H_T for $t\bar{t}$ and W+jets production and vector-like $B\overline{B}$ production for B masses of 700 and 800 GeV. Right: Boosted Decision Tree discriminant distributions for data and backgrounds at ATLAS. Both Figures taken from Ref. [6].

Jet substructure techniques have been introduced in several searches in order to take advantage of non-leptonic decays. For instance, CMS has recently updated its $T\overline{T}$ search through its bW decay mode [5]. Hadronic W decays are reconstructed as pairs of "standard" anti-k_T jets [14] with $R = 0.5$ as well as single "fat" jets. In the latter case, the "fat" jet is a pruned [15, 16] Cambridge-Aachen jet [17] with $R = 0.8$, $p_T > 200$ GeV, and mass between 60 and 100 GeV. The leptonic and hadronic W candidates are paired with other jets, at least one of which is b-tagged, with a χ^2-like constraint used to prefer pairings with (putative $T \to bW$) masses close to one another. Both S_T and the fitted bW mass are used to discriminate signal from background. Fig. 2(left) shows the data and background distributions in the fitted mass in events with $S_T > 1240$ GeV. A similar analysis has been used in CMS to search for VLQ's of unspecified flavor, $Q\overline{Q} \to qWqW$, resulting in a preliminary lower mass limit of 788 GeV [18].

The ATLAS search for $Q\overline{Q} \to qWqW$ also reconstructs hadronic W decays using substructure-like techniques [10]. In this analysis, however, the daughter jets are "standard" ATLAS anti-k_T jets with $R = 0.4$, with a requirement that the two jets lie within $\Delta R < 1$ of one another, that the combined p_T exceeds 200 GeV, the combined mass m_{12} fall between 65 and 100 GeV, and the splitting scale $y_{12} \equiv \min(p_{T1}, p_{T2})^2 \Delta R^2 / m_{12}^2$ [19] is greater than 0.25. Two W candidates are paired with light-quark jets such that the mass difference between the two pairs is less than 120 GeV. The p_T sum of the lepton, missing momentum, and constituent jets is required to exceed 1100 GeV. Fig. 2(right) shows the resulting resolved qW mass distribution in data, compared with expected backgrounds and signals with different mass hypotheses and further assuming 100% branching fractions to qW. The data is consistent with the expected background, resulting in the published lower limit on the Q mass at 690 GeV under the 100% branching fraction assumption.

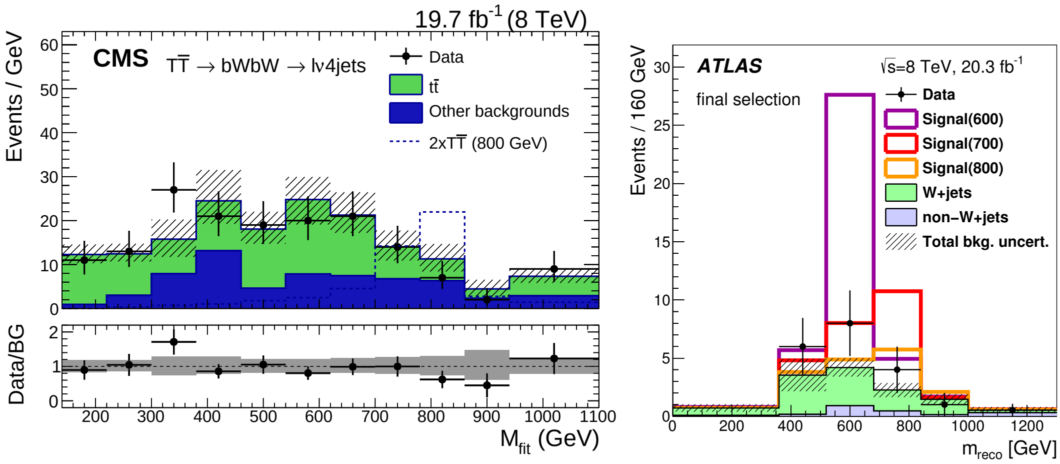

Figure 2: Left: fitted bW mass distributions for the CMS single-lepton $T\overline{T} \to bWbW$ search. The criterion $S_T > 1240$ GeV has been applied. Taken from Ref. [5]. Right: resolved qW mass distributions for the ATLAS single-lepton $Q\overline{Q}$ search. Taken from Ref. [10].

3. Forward single production

ATLAS has searched for single production of B quarks in the forward (large-$|\eta|$) region [20], to complement its earlier search for single T production [8]. The single-lepton search starts with a single high-p_T lepton and missing momentum, and requires two or three standard jets, one of which should be b-tagged. The presence of a further high-energy forward jet is required, consistent with the production mechanism. Events with a W or t candidate are tagged by reconstructing trimmed [21] "fat" ($R = 1$) anti-k_T jets with $p_T > 200$ GeV and $m > 50$ GeV, though the fat jet (which may overlap with the standard jets) plays no further role in the B reconstruction. The visible mass, consisting of the lepton, missing momentum, and the standard jets, is shown in Fig. 3(left) for the case where the lepton comes from the W daughter of the B decay.

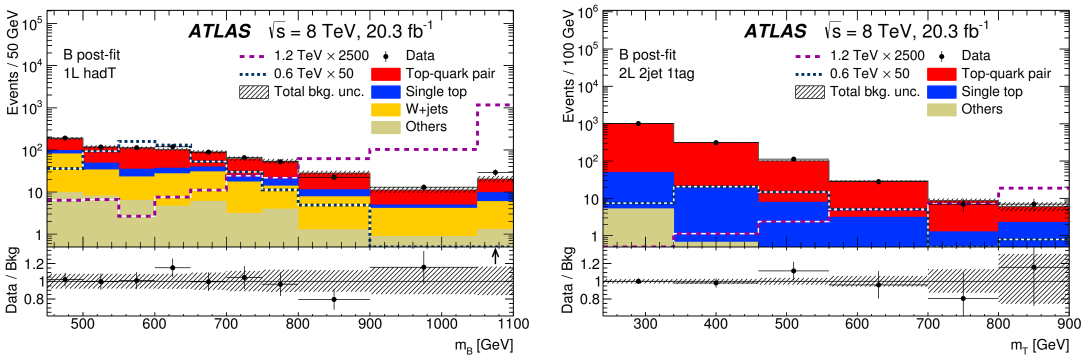

Figure 3: Left: visible mass in ATLAS single $B \to tW$ search with a single lepton and hadronic t decay. Right: visible mass in $B \to tW$ search with two leptons. Both Figures taken from Ref. [20].

A search using opposite-sign $e\mu$ pairs is considerably cleaner, and has correspondingly looser requirements. No missing momentum requirement is made, and since both W's decay leptonically, only one central b-tagged jet near one of the leptons is required, in addition to the forward jet with $1.5 < |\eta| < 4.5$. Fig. 3 shows the visible transverse mass distributions. With 20.3 fb^{-1} of data, the search yields an upper limit on the product of the cross section and branching fraction rather than a lower limit on the mass.

4. Non-leptonic signatures

CMS has conducted several searches for VLQ's in non-leptonic datasets. The search for $T\overline{T} \to tH + X$ with $H \to \gamma\gamma$ takes advantage of the narrow Higgs peak in the diphoton mass spectrum, resulting in a nearly background-free search [5]. The all-hadronic $T\overline{T} \to bWbW$ search reconstructs two single-jet W's using pruned fat jets with an additional mass drop criterion, which requires that a splitting is found within the jet where the daughter subjet masses are less than 40% of the mass of the parent [19]. Opposite T quarks are resolved by requiring a back-to-back topology and a small mass difference between the two bW candidate pairings. The distribution of the scalar sum of the four jets' transverse energy $H_{\mathrm{T}}{}^{4\mathrm{jet}}$ is shown in Fig. 4(left). A similar analysis is used to search for $B\overline{B} \to bHbH$, followed by $H \to b\overline{b}$ decays.

Both top and Higgs jet tagging are employed on filtered Cambridge-Aachen jets with $R = 1.5$ in order to search for $T\overline{T} \to tHtH$ decays [13]. HEPTOPTAGGER [22], which attempts to distinguish the t decay products inside the fat jet, is used for top tagging, while Higgs tagging looks for two b-tagged filtered subjets [19] with mass exceeding 60 GeV. The $b\overline{b}$ mass distribution in the best signal region is shown in Fig. 4(right).

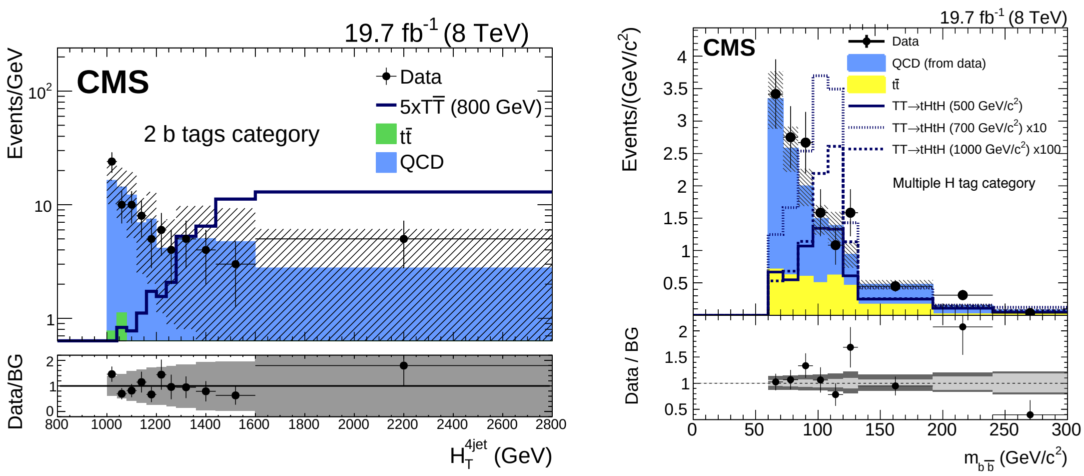

Figure 4: Left: 4-jet H_{T} distibution for the CMS search for all-hadronic $T \to bW$ decays. Taken from Ref. [5]. Right: $b\overline{b}$ mass distribution for the CMS search for all-hadronic $T \to tH$ decays. Taken from Ref. [13].

5. Mass Limits

Figures 5 and 6 summarize the 95% CL lower mass limits for T and B quarks as a function of branching fractions to channels involving W and Higgs bosons, assuming that they couple primarily

PoS(TOP2015)046

to third-generation Standard Model quarks. Both figures include analyses reported previously and not summarized here. The CMS limits combine the different searches with their systematic uncertainties to obtain Bayesian limits [4, 5], while the ATLAS summary plots show the most stringent lower limit, calculated in each analysis using the $\mathrm{CL_s}$ method, for a given set of branching fractions [7]. Within the above assumptions, the current mass limits push above 700 GeV irrespective of model. The single-lepton ATLAS $B\overline{B} \to tW + X$ search has also yielded the most stringent single mass limit on $T_{5/3}$ at 840 GeV.

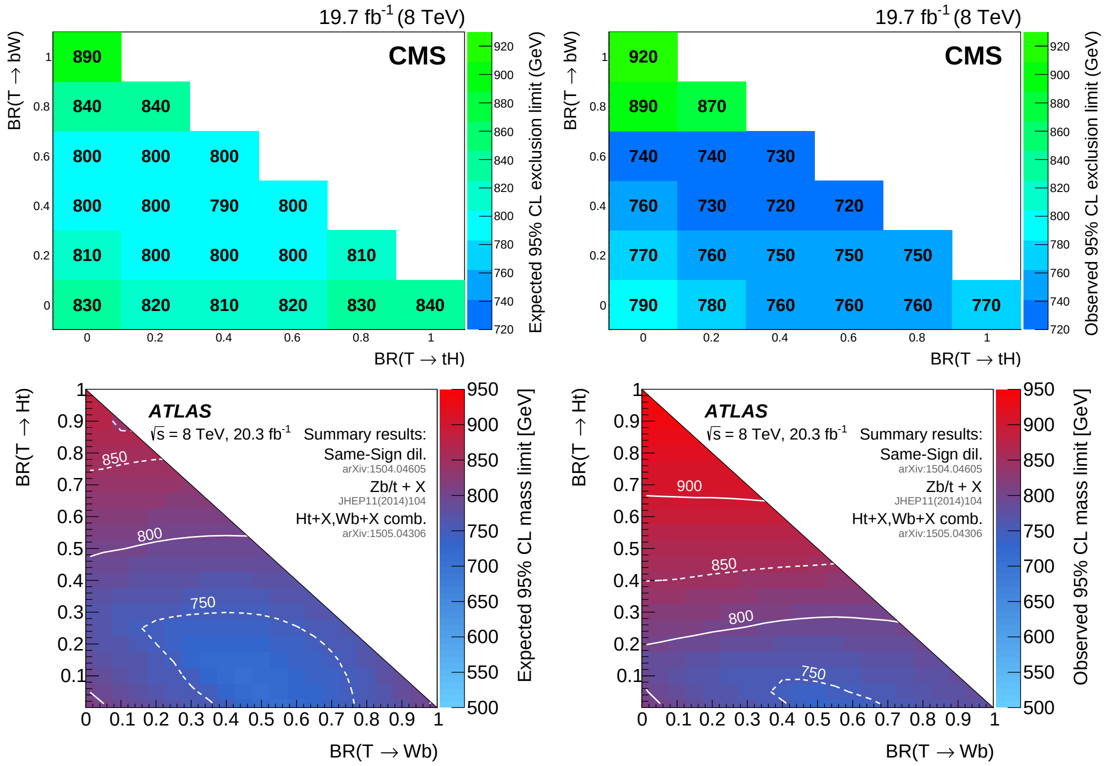

Figure 5: Combined expected (left) and observed (right) 95% CL lower T mass limits for CMS (top, taken from Ref. [5]) and ATLAS (bottom, taken from Ref. [7]). Note that the axes for the two collaborations are swapped relative to one another.

Both experiments have searched for decay modes involving lighter quark generations, with ATLAS publishing a lower limit of 690 GeV and CMS releasing a preliminary limt of 788 GeV, in both cases assuming for the calculation a 100% branching fraction for $Q \to qW$. Limits have not been calculated for couplings involving exotic charges, such as $B \to Z'b \to b\bar{b}b$ [23].

6. Conclusion

Vector-like quarks remain a promising signature of physics beyond the Standard Model and arise as a generic feature in a number of classes of such models. ATLAS and CMS have searched for these new particles in roughly 20 fb^{-1} each of data taken at $\sqrt{s} = 8$ TeV under a number of different model assumptions. No searches have yielded significant excesses, but with both experiments

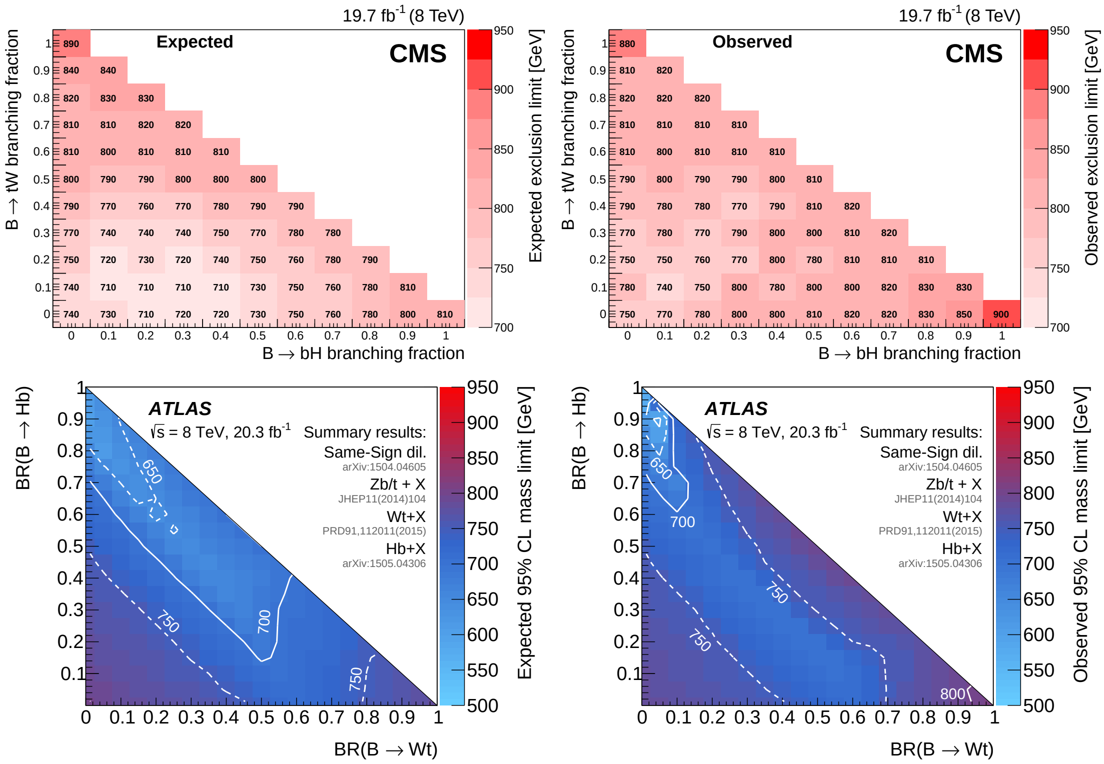

Figure 6: Combined expected (left) and observed (right) 95% CL lower B mass limits for CMS (top, taken from Ref. [4]) and ATLAS (bottom, taken from Ref. [7]). Note that the axes for the two collaborations are swapped relative to one another.

pursuing and adding new techniques to increase sensitivity, there is eager expectation for data analysis at 13 TeV.

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