

Model independent analysis of heavy vector-like top partners ^a

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Abstract

Searches for new fermionic states heavier than the top quark are being pursued by the CMS & ATLAS collaborations, pushing the mass bounds towards the TeV scale. Although a chiral fourth generation of quarks is now excluded by the LHC results, models going beyond the Standard Model predict the existence of heavy vector-like top partners as potential smoking gun signatures. Relying on a model-independent parametrisation, we present the first results of a dedicated software called **XQCAT** (eXtra Quark Combined Analysis Tool), which recasts publicly available experimental data from direct and Supersymmetry inspired searches and computes the exclusion confidence level for New Physics scenarios with one or multiple top partners. The mass limits set on a T singlet scenario with general coupling assumptions are briefly discussed in this framework.

1 Theoretical overview

Despite the huge success of the Standard Model (SM), compelling arguments indicate that New Physics (NP) should appear at the TeV scale. In particular, the absence of any symmetries protecting the Brout-Englert-Higgs boson mass term leads to the expectation that the SM cannot be universally valid. As a possible solution to this puzzle, new regimes could be observed at that energy scale, with novel particles related to the top quark by a symmetry, therefore carrying similar quantum numbers. These new fermions may then contribute to stabilise the electroweak scale, and cancel the quadratically divergent contributions to the mass of the SM scalar boson.

Although a sequential fourth family of quarks is excluded by the current searches, models going beyond the SM now point at the possibility for Vector-Like Quarks (VLQs), *i.e.*, new fermionic resonances having their left- and right- handed components transforming identically under the electroweak gauge group. Referred to as “top partners”, these hypothetical quarks do not gain their masses from the breaking of the electroweak symmetry, and occur as a common feature of many NP scenarios such as extra-dimensional models, strongly interacting dynamics, models with extended gauge symmetries, Composite Higgs models, and so forth. Assuming that a single $SU(2)_L$ scalar doublet breaks the electroweak symmetry, minimal scenarios may allow these top partners to interact with the SM quarks through Yukawa interactions. After that the SM scalar boson develops its vacuum expectation value, the representations summarised in Table 1 are allowed by $SU(2)_L \times U(1)_Y$ gauge invariance. Vector-like quark singlets and

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Table 1: Vector-like multiplets have fixed quantum numbers under $SU(2)_L \times U(1)_Y$, assuming that they mix with the SM quarks through Yukawa couplings. The electric charge is the sum of the third component of the isospin T_3 , and of the hypercharge Y .

| Q_q | $T_{\frac{2}{3}}$ | $B_{-\frac{1}{3}}$ | $\begin{pmatrix} X_{\frac{5}{3}} \\ T_{\frac{2}{3}} \end{pmatrix}$ | $\begin{pmatrix} T_{\frac{2}{3}} \\ B_{-\frac{1}{3}} \end{pmatrix}$ | $\begin{pmatrix} B_{-\frac{1}{3}} \\ Y_{-\frac{4}{3}} \end{pmatrix}$ | $\begin{pmatrix} X_{\frac{5}{3}} \\ T_{\frac{2}{3}} \\ B_{-\frac{1}{3}} \end{pmatrix}$ | $\begin{pmatrix} T_{\frac{2}{3}} \\ B_{-\frac{1}{3}} \\ Y_{-\frac{4}{3}} \end{pmatrix}$ |
|-------|-------------------|--------------------|--|---|--|--|---|
| T_3 | 0 | 0 | 1/2 | 1/2 | 1/2 | 1 | 1 |
| Y | 2/3 | -1/3 | 7/6 | 1/6 | -5/6 | 2/3 | -1/3 |

triplets mix dominantly with the standard left-handed doublets, whereas doublets couple to the standard right-handed singlets.

Depending on their charge assignments, these new quarks decay into a standard quark plus a standard gauge boson, such that

- $X_{5/3} \rightarrow W^+ u_i$,
- $T_{2/3} \rightarrow W^+ d_i, Z u_i, H u_i$,
- $B_{-1/3} \rightarrow W^- u_i, Z d_i, H d_i$,
- $Y_{-4/3} \rightarrow W^- d_i$,

where the index $i = 1, 2, 3$ denotes the three standard generations. The nominal branching fractions for T or B electroweak singlets are approximately 50% into W bosons, and 25% into Z and H bosons, in agreement with the Goldstone Boson Equivalence Theorem. The exotic states X and Y decay exclusively through charged currents to up- and down-type quarks, respectively.

As the guiding thread of this work, we point out that VLQs decaying to top and bottom quarks ($i = 3$) have been studied to a great extent at the LHC, while the constraints on top partners decaying to light jets ($i = 1, 2$) are still mild and require careful treatment. For this reason, we proposed in ² a model-independent framework to study the phenomenology of new top partners at the LHC, with general couplings to all three generations of SM quarks. Factoring out all model-dependent contributions, we performed a comprehensive analysis of all electroweak production channels for VLQs, relying on a minimal amount of parameters. Based on this parametrisation, we provided a compendium of the corresponding cross-section contributions, for benchmark points satisfying the experimental constraints. Our analysis allowed to highlight the potential relevance of scenarios which have been neglected in previous experimental searches, as well as of novel interesting channels to be studied at the LHC.

2 Reinterpretation of the searches for models with top partners

Since the start of its physics program, the LHC has delivered a large set of limits on new heavy coloured objects with spin 1/2. However, reinterpreting consistently the available bounds for specific NP scenarios requires dedicated strategies to account for all the allowed signals. In the presence of multiple resonances, events for a given final state may occur through different decay chains and topologies. Furthermore, the experimental efficiencies may be different depending on the considered model, affecting the rescaling of the mass bounds in a non-trivial way. Some studies and related codes like CheckMATE, SModelS and Fastlim ^{3,4,5} have already attempted to tackle this problem, however cannot be thoroughly applied to scenarios with multiple top partners.

In the following we present a dedicated software named **XQCAT**, for *eXtra Quark Combined Analysis Tool* ¹, that allows the user to determine the exclusion confidence level for any scenario

involving VLQs. Assuming strong pair-production as an input, the corresponding cross-sections are only sensitive to the masses of the new quarks. We simulated $pp \rightarrow Q\bar{Q} + \{0,1,2\}$ jets for each mass value with MadGraph5. The subsequent decays are then computed with BRIDGE, while hadronisation and showering are determined with PYTHIA. Detector simulation is performed through Delphes2. The full signal is reconstructed by combining, with the appropriate weights, the different model-independent topologies which generate the underlying final states and the corresponding kinematic distributions. We subsequently estimate the number of signal events passing the selection cuts for each signature and search, and extract the respective efficiencies for each subprocess contributing to the given final state. Finally, for each implemented search (or combination thereof), our analysis code evaluates the respective exclusion confidence level for a given input scenario.

To validate and apply our tool, we computed the 95% CL mass bounds for a T singlet under different hypotheses for its branching ratios into SM bosons and quarks, considering two selected subsets of searches:

1. *Direct searches:* a comprehensive number of final states was accounted for in ⁶. In this analysis, the CMS collaboration presented an inclusive search for $Q = 2/3$ top partners, at $\sqrt{s} = 8$ TeV and 19.5 fb^{-1} of integrated luminosity. Considering pair-produced objects mixing with third-generation quarks, CMS obtained 95% CL lower limits on T quark masses between 687 and 782 GeV.
2. *SUSY searches:* for the purpose of our analysis, we implemented the four Supersymmetry-inspired searches ^{7,8,9,10} at $\sqrt{s} = 7$ TeV considering the entire 2011 dataset, and characterised by large missing transverse energy and different numbers of leptons in the final state. The updated searches ^{11,12} at 8 TeV have been included as well. As we have checked that they are uncorrelated, these searches may be statistically combined.

In the left plot of Fig.1, we show the exclusion confidence levels for a T singlet with $BR(Wb) = 50\%$ and $BR(Zt) = BR(Ht) = 25\%$. Through linear interpolation of the exclusion confidence levels, we obtain a 2σ mass bound of 614 GeV at 95% CL, whereas the linear interpolation of the efficiencies excludes masses below 634 GeV, slightly below the value of 668 GeV quoted in ⁶ (multilepton channels only). Yet, it is interesting to notice that the combination of the SUSY searches ^{7,8,9,10,11,12} set constraints in the same ballpark as the direct search ⁶.

This selection of searches allows to address an interesting complementarity between direct analyses for VLQs and others performed at the LHC. Although no specific search for pair-produced top partners decaying to light jets is currently available, it is shown that the SUSY searches already set significant bounds on these scenarios. On the right plot of Fig.1, we display the exclusion confidence levels for a T singlet mixing only with light quarks, such that $BR(Wj) = 0.5$ and $BR(Zj) = BR(Hj) = 0.25$. The bound provided by linearly interpolating the eCLs of the SUSY searches combination is 422 GeV (469 GeV if interpolating the efficiencies), while the direct search ⁶ does not provide limits above 400 GeV at the 2σ level. Considering that SUSY-inspired searches are not designed to probe such final states, it is remarkable that their combination is more sensitive than the analysis ⁶ for this specific scenario. This points at the interest of combining multiple topology searches so as to obtain more accurate bounds on New physics models.

3 Perspectives

Details on the ability of XQCAT to set bounds on realistic scenarios with more than one VLQs are given in ¹. Future developments will include further analyses such as recent searches by the ATLAS collaboration, searches for new bottom partners, and exotic phenomenologies. Finally, adding electroweak single production as a signal input within the context of our model-

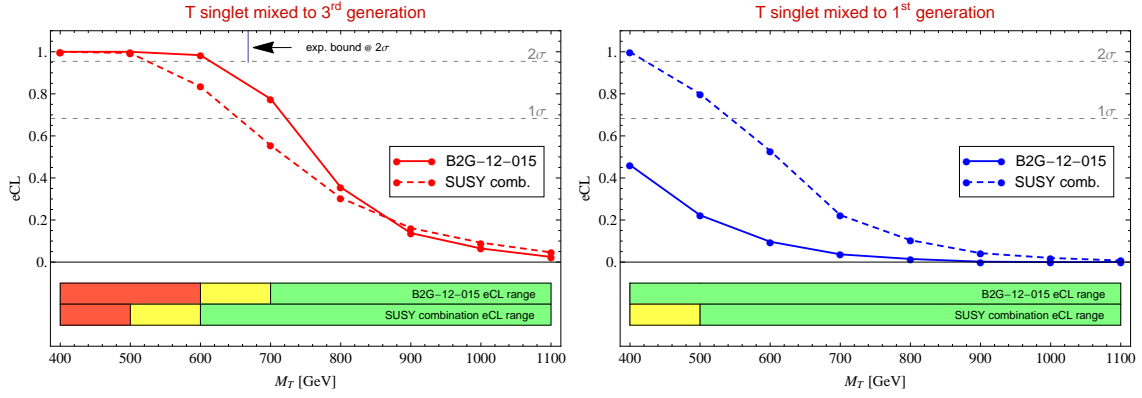


Figure 1 – Exclusion confidence levels for a T quark mixing only (left) with the SM top quark such that $BR(Wb) = 0.5$ and $BR(Zt) = BR(Ht) = 0.25$, and (right) to the SM up quark such that $BR(Wd) = 0.5$ and $BR(Zu) = BR(Hu) = 0.25$. The dots correspond to the simulated points, while the lines are linear interpolations of the eCLs. The solid line corresponds to the eCLs obtained using the direct searches, while the dashed line corresponds to the combination of the SUSY searches at $\sqrt{s} = 7$ and 8 TeV. The strips below the plot indicate in red the region where mass values can be excluded at 95% CL, in yellow the region where excluded mass limits can be expected, and in green the region where mass values cannot be excluded at the 2σ level.

independent framework² will allow us to probe the remaining allowed parameter space for VLQs below the TeV scale.

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