Abstract

We present results of searches for massive vector-like top and bottom quark partners using proton-proton collision data collected with the CMS detector at the CERN LHC at a center-of-mass energy of 13 TeV. Single and pair production of vector-like quarks are studied, with decays into a variety of final states, containing top and bottom quarks, electroweak gauge and Higgs bosons. We search using several categories of reconstructed objects, from multi-leptonic to fully-hadronic final states. We set exclusion limits on both the vector-like quark mass and cross sections, for combinations of the vector-like quark branching ratios.

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In Vector-Like Quark (VLQ) searches, there are two main areas depending on the production mode: the single electroweak production which is sensitive to the VLQ mass but also to mixing parameters and the pair production via gluon splitting which is mainly sensitive to the VLQ mass. Pair production is dominant at low VLQ mass. At high mass, the single production cross section can be large. Both production modes are complementary. The two generalist experiments on the LHC ring have two different approaches. Atlas works mainly on inclusive searches for pair production including single production channel while CMS focuses on dedicated analyses for each of the channels. Atlas has a few channels devoted to single production in which they can extract mixing parameters. CMS uses dedicated analysis with specific simulation for each various widths of the VLQ.

The results of the CMS analyses on the 2016 data taking period are reviewed for both the pair production and the single production cases.

1 Pair Production

The analysis strategy for the search of pair produced VLQ is to look for high energy deposits coming from the decay of the two massive particles. Some analyses also use VLQ mass reconstruction.

1.1 T/ Y^{4/3} pair search using kinematic fit reconstruction

In this analysis, the VLQ decay is into a W-boson and a b-quark. One of the Ws decays leptonically and the second hadronically. The final state consists of one lepton and at least 4 quarks, two of them come from b-quark. The lepton is defined as being either an electron or a muon. Missing transverse momentum is required to sign the presence of a neutrino. The jets are either standard ak4 jets or boosted ak8 jets identified as coming from a W-boson. Two loose b-tag jets are also requested. With this selection, the main background of the analysis is t¯t. The kinematic fit method is then used with the constraint that the invariant mass of the combination
of lepton, missing transverse momentum and one of b-tag jets should be equal to that of the combination made of from two remaining ak4 jets (or the ak8 W-tag jet) and the remaining b-tag jet. With this kinematic reconstruction, the invariant mass of the VLQ is reconstructed. In this distribution a resonance is looked for. No excess is seen so limits are set reaching 1.3 TeV when considering a branching fraction of the VLQ decaying into $Wb$ at 100% within the narrow width approximation.

1.2 T/B pair inclusive search

The VLQs (T/B) are searched in all decay channels: $Wb$, $\text{top}+H^0$ and $\text{top}+Z^0$ (or $\text{top}+W^{\pm}$, $b+H^0$ and $b+Z^0$ for B)\(^3\). The search is based on multi-lepton final state. The channel with one lepton (electron or muon) in the final state uses 16 final categories depending on the number of b-tag jets, the number of ak8 $H^0/W$-tag identified jets. The main background are $W+\text{jets}$ and $t\bar{t}$. Within these categories the main variable is scanned to look for presence of signal. The variable is the sum of transverse momenta of the leptons and all the jets contained in the event. Due to the pair produced and the high masses expected for VLQ, the signal would appear at high value of the sum. The dilepton channel focuses on the same sign dileptons coming from the mixture of the potential decays. Due to a low statistics in the expected background, a simple counting experiment is performed. The 3 or more lepton channel contains a relatively low level of background composed mainly of non prompt leptons and multiboson production. In this case, the sum of the transverse momenta of the leptons and jets is used as a main discriminating variable. In all the above channels, no sign of signal is seen, so limits on the VLQ mass are established. The limits are set depending on the model (according to the branching fraction for each decay channel) but also in a triangular frame to let each branching fraction vary. In the case of the doublet model a limit on the vector-like top quark mass of 1280 GeV is reached. For a vector-like bottom quark the limit goes down to 940 GeV.

1.3 $X^{5/3}$/B pair search

This search is composed of two analyses being combined. The decay channel studied here is purely $\text{top}+W^{\pm}$. The first analysis requests one lepton (electron or muon)\(^4\), some missing transverse momentum and at least 4 ak4 jets (or 1 ak8 jet and 2 ak4 jets, etc). As previously, various categories are created depending on the number of b-tag jets, the number of ak8 $W$/top-tag identified jets. The main background for this search is $t\bar{t}+\text{jets}$. The variable studied is the minimum invariant mass of the lepton and a b-tag jet. The background tends to stay at low value while the signal expends to high value. The second analysis\(^5\) uses the same sign dilepton final state which has a low background mainly coming from non prompt leptons and $t\bar{t}$. Due to the low statistics, a counting experiment is performed. In the two analysis no sign of signal is observed. Limits are defined and this analysis is sensitive to the chirality of the VLQ. The sensitivity of the combination under preparation excludes masses up to around 1.3 TeV for both chiralities.

2 Single Production

In CMS, Monte Carlo samples are produced with various widths: 10%, 20% and 30%. On top of the narrow width approximation studies performed by the pair production searches, further model parameters are investigating in the single production searches. The analyses reconstruct the VLQ invariant mass and use the forward jet coming from the production mode to further categorize the events.
2.1 Single $B \rightarrow b+H^0$

The search is divided into two regimes: low mass and high mass regime. The two regimes differ by $H_T$, corresponding to the sum of transverse momentum of jets in the event, of 900 GeV for the low mass and 1.25 TeV for the high mass. The analysis relies on the presence of a boosted Higgs boson candidate with double b-tagging applied. Moreover, at least 3 ak4 jets and a third b-tag jet are requested. The events are split in two categories depending on the presence or not of a forward jet. The main background, multijets, is estimated from the data via a side band region around the Higgs invariant mass. No excess is observed in the distribution of the invariant mass of the Higgs boson candidate and b-tag jet and limits are set for each of the width hypotheses.

2.2 Single $T \rightarrow top+Z^0$

The Z-boson is searched for with a decay into two leptons. The top quark is reconstructed either fully resolved or partially resolved or boosted. These regimes for the top-quark define categories together with the presence of a forward jet. The selected events must contain two isolated opposite sign electrons or muons, at least 3 ak4 jets with one b-tag one for the fully resolved category, at least one ak4jets b-tag and one W-tag ak8 jets for the partially resolved category and at least one top-tag ak8 jets for the boosted category. The main background of this search are $Z+jets$ and $t\bar{t}$. The invariant mass of the top and Z candidates is used to look for a potential resonance. Nothing is observed and limits are established for the various width hypotheses. A large range of exclusion in the case of a singlet model is reached.

2.3 Single $X^{5/3}/B \rightarrow top+W^\pm$

This search is performed in lepton+jets final state where the lepton is either an electron or a muon. The analysis also uses the various reconstruction modes: resolved to fully boosted and categorize the events depending on the reconstruction. In order to fully reconstruct the mass of the VLQ, a $\chi^2$ is built to associate the jets. The neutrino energy is determined via $W$ constraints. The analysis fits together the region with no forward jet and at least one forward jet for signal and background and for the various reconstruction categories. No excess is found. The limits for the different width in the case of a left handed B are presented in figure 1. For a width larger than 10% most of the masses below 1.4 TeV are excluded.
Figure 2 – Summary of the current limits as function of the VLQ mass for pair production (left) and for single production (right)\(^3\).

3 Conclusion

CMS has a variety of complementary searches in place for both pair production and single production. The pair production begins to reach the high mass regime where as the single production starts to dominate. The single production is getting up to speed with the studies of the various widths and allows to exclude model parameters. A summary of the current results is presented in figure 2 as a function of the VLQ mass. The complementary approach of the searches will either give us a stringent constraint on the model when the full Run 2 data will be analysed or a first sign of new physics.

References

9. CMS Collaboration, [twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsB2G](http://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsB2G)