



# Combination of the searches for pair-produced vector-like partners of the third-generation quarks at $\sqrt{s} = 13$ TeV with the ATLAS detector

The ATLAS Collaboration

A combination of the searches for pair-produced vector-like partners of the top and bottom quarks in various decay channels ( $T \rightarrow Zt/Wb/Ht$ ,  $B \rightarrow Zb/Wt/Hb$ ) is performed using  $36.1 \text{ fb}^{-1}$  of  $pp$  collision data at  $\sqrt{s} = 13$  TeV with the ATLAS detector at the Large Hadron Collider. The observed data are found to be in good agreement with the Standard Model background prediction in all individual searches. Therefore, combined 95% confidence-level upper limits are set on the production cross-section for a range of vector-like quark scenarios, significantly improving upon the reach of the individual searches. A singlet  $T$  is excluded for masses below 1.31 TeV and a singlet  $B$  is excluded for masses below 1.22 TeV. Assuming a weak isospin ( $T, B$ ) doublet,  $T$  and  $B$  masses below 1.37 TeV are excluded.

# 1 Introduction

Naturalness arguments [1] suggest there should be a mechanism that cancels out the quadratically divergent contributions to the Higgs boson mass caused by radiative corrections from Standard Model (SM) particles. Several explanations are proposed in theories beyond the SM. Little Higgs [2, 3] and Composite Higgs [4, 5] models introduce a spontaneously broken global symmetry, with the Higgs boson emerging as a pseudo Nambu–Goldstone boson [6]. Such models predict the existence of vector-like quarks (VLQs), color-triplet spin-1/2 fermions whose left- and right-handed chiralities transform in the same way under weak-isospin [7, 8]. In these models, VLQs are expected to couple preferentially to third-generation quarks [7, 9] and can have flavor-changing neutral-current decays in addition to charged-current decays. An up-type VLQ  $T$  with charge  $+2/3$  can decay into  $Wb$ ,  $Zt$ , or  $Ht$ . Similarly, a down-type quark  $B$  with charge  $-1/3$  can decay into  $Wt$ ,  $Zb$ , or  $Hb$ . In order to be consistent with results from precision electroweak measurements, the mass-splitting between VLQs belonging to the same  $SU(2)$  multiplet is required to be small [10], forbidding cascade decays such as  $T \rightarrow WB$ . Couplings between the VLQs and the first- and second-generation quarks, although not favored, are not excluded [11, 12].

At the Large Hadron Collider (LHC), VLQs with masses below approximately 1 TeV would mainly be pair-produced, a process dominated by the strong interaction. The corresponding predicted cross-section ranges from 195 fb to 2.0 fb for quark masses from 800 GeV to 1500 GeV [13] and depends only on the quark mass. Production of single VLQs via the electroweak interaction is also possible, but depends on the strength of the interaction between the new quarks and the weak gauge bosons. Representative Feynman diagrams for  $B\bar{B}$  and  $T\bar{T}$  production and decay are shown in Figure 1.

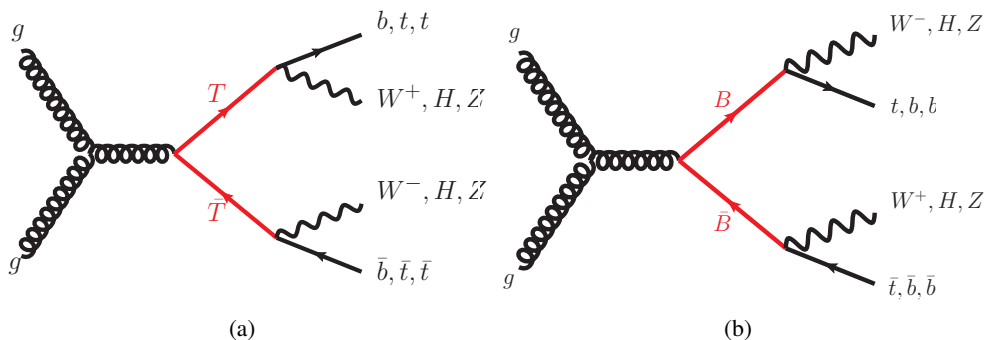


Figure 1: Representative leading-order Feynman diagrams for (a)  $T\bar{T}$  and (b)  $B\bar{B}$  pair production. The studied VLQ decays are also displayed.

The branching ratio ( $\mathcal{B}$ ) for each decay mode ( $T \rightarrow Wb, Zt, Ht$  and  $B \rightarrow Wt, Zb, Hb$ ) depends on the VLQ mass and weak-isospin quantum numbers, as calculated in Ref. [8]. For a singlet  $T$ , all three decay modes have sizable branching ratios, while the charged-current decay mode  $T \rightarrow Wb$  is absent if  $T$  is either in a  $(X, T)$  doublet, where  $X$  is a VLQ with a charge of  $+5/3$ , or a  $(T, B)$  doublet with  $|V_{Tb}| \ll |V_{tB}|$ , where  $V_{ij}$  are the elements of a generalized Cabibbo–Kobayashi–Maskawa matrix [8, 14, 15]. Since the  $T$  quark branching ratios are identical in both doublets, no distinction is made between them when referring to the doublet  $T$  results. A singlet  $B$  will have a sizable branching ratio to all three decay channels, while the branching ratios in the doublet case depend on whether it is in a  $(T, B)$  doublet or  $(B, Y)$  doublet, where  $Y$  is a VLQ with a charge of  $-4/3$ . For a  $(B, Y)$  doublet, only neutral current couplings to SM quarks are allowed at leading order (LO), so the  $B \rightarrow Wt$  decay is forbidden. Conversely, for a  $(T, B)$  doublet with

$|V_{Tb}| \ll |V_{tB}|$ ,  $B \rightarrow Wt$  is the only allowed decay. Therefore, the specific  $B$  doublet scenario will be stated when interpreting the results.

## 2 Contributing analyses

Searches for pair-produced VLQ partners of the third-generation quarks have been performed by ATLAS [16–22] and CMS [23–25] at the LHC at  $\sqrt{s} = 13$  TeV. This Letter presents the full combination of the ATLAS searches using  $36.1 \text{ fb}^{-1}$  of data collected in 2015 and 2016. The ATLAS detector is described in Ref. [26]. Below is a brief description of each contributing analysis.

‘ $H(bb)t + X$ ’ [16]: The primary targets of this analysis are  $T\bar{T}$  events with at least one VLQ decaying into  $Ht$ , with  $H \rightarrow b\bar{b}$ . Events must have at least six jets [27] and either one lepton (electron [28] or muon [29]) or missing transverse momentum [30]  $E_T^{\text{miss}} > 200$  GeV with zero leptons. The analysis uses  $b$ -tagging [31, 32] as well as dedicated top and Higgs jet tagging to classify the events into 22 and 12 search regions for the zero-lepton and one-lepton selections, respectively. The final discriminant is the scalar sum of the transverse momenta of the selected jets, lepton, and missing transverse momentum ( $S_T$ ). The dominant background is the associated production of a  $t\bar{t}$  pair with  $b$ - and  $c$ -quark jets, which is modeled via Monte Carlo (MC) simulation and assigned dedicated modeling uncertainties.

‘ $W(\ell\nu)b + X$ ’ [17]: This analysis primarily targets  $T\bar{T} \rightarrow WbWb$  events with one  $W$  decaying leptonically and the other hadronically. Event selection requires one lepton,  $\geq 3$  jets, at least one of them being  $b$ -tagged, and a hadronically decaying  $W$  boson identified using jet substructure techniques [33]. The final discriminant is the reconstructed mass of the  $T \rightarrow Wb \rightarrow \ell\nu b$  candidate. The dominant background is from  $t\bar{t}$  pair production, which is modeled using MC simulation with dedicated modeling uncertainties.

‘ $W(\ell\nu)t + X$ ’ [18]: Very similar to the ‘ $W(\ell\nu)b + X$ ’ analysis, this analysis is optimized to target  $B\bar{B}$  signals, especially in the case where  $B \rightarrow Wt$ . This analysis discriminates between the signal and the dominant  $t\bar{t}$  background in the signal regions using either a boosted decision tree discriminant or the reconstructed mass of the  $B$  candidate.

‘ $Z(\nu\nu)t + X$ ’ [19]: This analysis targets  $T\bar{T} \rightarrow ZtZt$  events with an invisible  $Z$  decay. Events must have  $E_T^{\text{miss}} > 300$  GeV, one charged lepton from the decay of a top quark, and  $\geq 4$  small-radius jets, which are reclustered [34] into large-radius jets. The analysis defines a single-bin signal region that capitalizes on various  $E_T^{\text{miss}}$ -based variables and requires at least two high-mass large-radius jets due to hadronically decaying top quarks and/or heavy bosons from the VLQ decays. The dominant backgrounds are  $t\bar{t}$ +jets,  $W$ +jets and single-top events, which are estimated from MC simulation and normalized using dedicated control regions.

‘ $Z(\ell\ell)t/b + X$ ’ [20]: This analysis searches for  $T\bar{T}$  and  $B\bar{B}$  events containing a leptonically decaying  $Z$  boson ( $Z \rightarrow \ell^+\ell^-$ ). The analysis requires at least two  $b$ -jets and contains opposite-sign dilepton and trilepton channels. The dominant backgrounds for the dilepton channels are  $t\bar{t}$  and  $Z$ +jets, while the trilepton channels are dominated by diboson ( $WZ$ ) and  $t\bar{t}Z$  events, each modeled by MC simulation.

‘Trilepton/same-sign dilepton’ [21]: This analysis targets  $T\bar{T}$  and  $B\bar{B}$  decays with multilepton final states, with particular emphasis on events containing a pair of charged leptons with the same electric charge. Eight single-bin signal regions are defined in accord with the number of leptons and  $b$ -tagged jets. The background composition for this analysis varies between signal regions. Contributions from instrumental backgrounds (fake/non-prompt leptons and electrons with incorrectly measured charge) are estimated

Table 1: The most sensitive decay channel for each analysis entering the combination. A ‘-’ indicates that the analysis was not used for that signal process.

Analysis	$T\bar{T}$ decay	$B\bar{B}$ decay
$H(bb)t + X$ [16]	$HtH\bar{t}$	-
$W(\ell\nu)b + X$ [17]	$WbW\bar{b}$	-
$W(\ell\nu)t + X$ [18]	-	$WtW\bar{t}$
$Z(\nu\nu)t + X$ [19]	$ZtZ\bar{t}$	-
$Z(\ell\ell)t/b + X$ [20]	$ZtZ\bar{t}$	$ZbZ\bar{b}$
Tril./s.s. dilepton [21]	$HtH\bar{t}$	$WtW\bar{t}$
Fully hadronic [22]	$HtH\bar{t}$	$HbH\bar{b}$

using data-driven techniques, while background processes with prompt leptons, originating mostly from  $t\bar{t} + W$  and diboson events, are modeled with MC simulations.

‘Fully hadronic’ [22]: This analysis focuses on final states with zero leptons, low  $E_T^{\text{miss}}$ , and multiple jets and is the only analysis with significant sensitivity to  $B\bar{B} \rightarrow HbH\bar{b}$ . Small-radius jets are reclustered into large-radius jets, which may be identified as top quarks,  $W/Z$ , or  $H$  bosons using a multi-class deep neural network [35]. The final discriminant is the distribution of the signal likelihood calculated using the matrix-element method [36]. The dominant background is from multijet production, which is estimated using a data-driven technique.

Most of the analyses were designed to be complementary. While each analysis provides sensitivity to various decay configurations, the most sensitive is shown in Table 1. All analyses use consistent definitions for the reconstructed physics objects, so only a few additional selection requirements were needed to suppress overlap. Compared to the standalone analyses, the  $W(\ell\nu)b + X$  and  $Z(\nu\nu)t + X$  analyses removed events with  $\geq 6$  jets and  $\geq 3$   $b$ -jets to avoid overlap with the  $H(bb)t + X$  selection. The  $Z(\nu\nu)t + X$  analysis also requires  $S_T < 1.8$  TeV in a control region to mitigate the overlap with a signal region in the  $W(\ell\nu)b + X$  analysis. To reduce overlap with the  $Z(\ell\ell)t/b + X$  analysis, the trilepton/same-sign dilepton analysis removed events with more than three leptons or events with a lepton pair having an invariant mass compatible with a  $Z$  boson ( $Z$ -veto). This  $Z$ -veto is the only added selection requirement with significant impact on the individual analysis sensitivity; however, that sensitivity is recovered by the  $Z(\ell\ell)t/b + X$  analysis. After applying these additional selection requirements, the remaining fraction of overlapping events between analysis regions was evaluated to be less than 1% between any two signal regions and less than 3% between any pair of signal or control regions and has negligible impact on the results.

The VLQ signal samples used by the analyses were generated with the LO generator PROTONS v2.2 [37] using the NNPDF2.3 LO [38] set of parton distribution functions (PDF) and passed to PYTHIA 8.186 [39] for parton showering and fragmentation. The samples are normalized using cross-sections computed with TOP++ v2.0 [13] at next-to-next-to-leading order (NNLO) in QCD, including resummation of next-to-next-to-leading logarithmic soft gluon terms [40–44], and using the MSTW 2008 NNLO [45, 46] PDF. Further information about simulated events and details of the background estimations for each analysis can be found in the respective publications.

### 3 Statistical analysis

The statistical analysis is the same as in the individual analyses and is based on a binned likelihood function constructed as the product of the Poisson probabilities of all bins entering the combination. This function depends on the signal-strength parameter  $\mu$ , a factor multiplying the theoretical signal cross-section ( $\mu \equiv \sigma/\sigma_{\text{theory}}$ ), and a set of nuisance parameters that encode the effect of the systematic uncertainties on the signal and background expectations. These parameters are included with Gaussian or log-normal constraints. Additional unconstrained nuisance parameters are included to control the normalization of the main backgrounds, following the settings used in the standalone searches. The combination is achieved by performing a fit with all bins from all the regions considered from each analysis.

The analysis is limited by statistical uncertainties, and the precise correlation model for the systematic uncertainties was found to not significantly affect the results. The detector-related uncertainties are treated as fully correlated across analyses, with the following exceptions. The central values and uncertainties of the  $b$ -tagging and the luminosity measurement were updated after the publication of the  $Z(\nu\nu)t + X$  and  $W(\ell\nu)b + X$  analyses. Therefore, to avoid propagating constraints caused by the change in the method, these uncertainties are correlated between the  $Z(\nu\nu)t + X$  and  $W(\ell\nu)b + X$  analyses, but uncorrelated with the other searches, which are correlated among themselves. The modeling uncertainties and background normalization parameters are treated as uncorrelated between analyses. Although some background processes are common to multiple analyses, the phase space and the techniques used to estimate those backgrounds can be quite different. Residual correlations are therefore expected to be negligible.

### 4 Results

The behavior of the combination is consistent with the fits from the individual analyses. The post-fit values of all nuisance parameters are compatible with the standalone analyses, with the constraints generally determined by the analysis most sensitive to the given nuisance parameter. Similarly, the background predictions in each analysis after the combined fit are very close to the results from the standalone analyses. After the combination, no significant excess is observed in the data, so 95% confidence level (CL) limits are set on the cross-section of a VLQ signal. To increase the applicability and usefulness of this combination, limits are evaluated both for benchmark scenarios with specific branching ratios and for general combinations of branching ratios.

For an assumed set of branching ratios, upper limits are set on the production cross-sections for  $T\bar{T}$  and  $B\bar{B}$  as a function of the VLQ mass using the  $\text{CL}_s$  method [47, 48] with the asymptotic approximation [49]. Observed and expected upper limits on the  $T\bar{T}$  cross-sections as a function of mass are shown in Figure 2 for the benchmark scenarios of an isospin singlet or doublet  $T$ . Analogous limits on the  $B\bar{B}$  cross-section are shown in Figure 3 for an isospin singlet  $B$  or  $B$  in a  $(T, B)$  doublet. The observed limits from the individual analyses, after the additional selections defined in this letter, are also shown. For a singlet  $T$ , masses below 1.31 TeV are excluded, while a  $T$  in an isospin doublet is excluded for masses below 1.37 TeV. A singlet  $B$  is excluded for masses below 1.22 TeV,  $B$  in a  $(T, B)$  doublet is excluded for masses below 1.37 TeV, and  $B$  in a  $(B, Y)$  doublet is excluded for masses below 1.14 TeV.

The combination is significantly more sensitive than any one analysis. For example, in the case of the SU(2) singlet, the limit on the  $T\bar{T}$  cross-section is improved by up to a factor of  $\sim 1.7$ , which translates to an increase of 110 GeV in the mass limit.

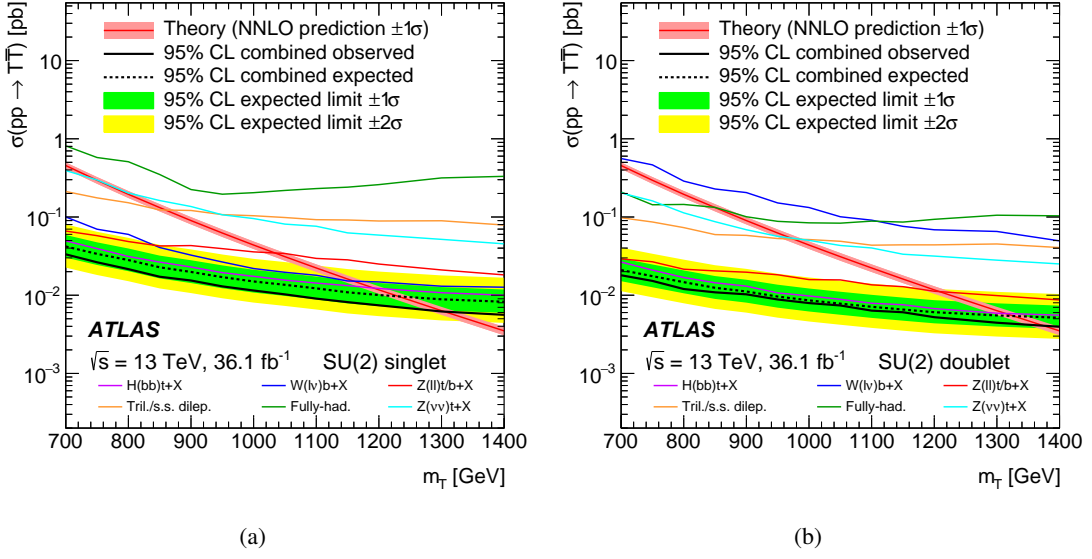


Figure 2: Observed (solid line) and expected (dashed line) 95% CL upper limits on the  $T\bar{T}$  cross-section versus mass for the combination and the standalone analyses in black and colored lines, respectively. The (a) singlet and (b) doublet scenarios [8] are displayed. The shaded bands correspond to  $\pm 1$  and  $\pm 2$  standard deviations around the combined expected limit. The rapidly falling thin red line and band show the theory prediction and corresponding uncertainty [13], respectively.

In addition, model-independent lower limits are set on the VLQ mass for all combinations of branching ratios, assuming  $\mathcal{B}(T \rightarrow Ht) + \mathcal{B}(T \rightarrow Zt) + \mathcal{B}(T \rightarrow Wb) = 1$  and  $\mathcal{B}(B \rightarrow Hb) + \mathcal{B}(B \rightarrow Zb) + \mathcal{B}(B \rightarrow Wt) = 1$ . The resulting lower limits on the VLQ mass as a function of branching ratio are presented in Figure 4. Limits corresponding to  $\mathcal{B}(T \rightarrow Wb) = 1$  and  $\mathcal{B}(B \rightarrow Wt) = 1$  are found to also be applicable to  $Y\bar{Y} \rightarrow WbWb$  and  $X\bar{X} \rightarrow WtWt$ , respectively. The high degree of complementarity between the analyses is clearly demonstrated in Figure 4. For *any* combination of branching ratios, the combination leads to observed (expected) lower mass limits of 1.31 (1.22) TeV for  $T$  and 1.03 (0.98) TeV for  $B$ . Limits on the signal strength, which can be used to interpret the results in scenarios with additional VLQ decays that escape detection [50], are available in the HEPData repository [51, 52].

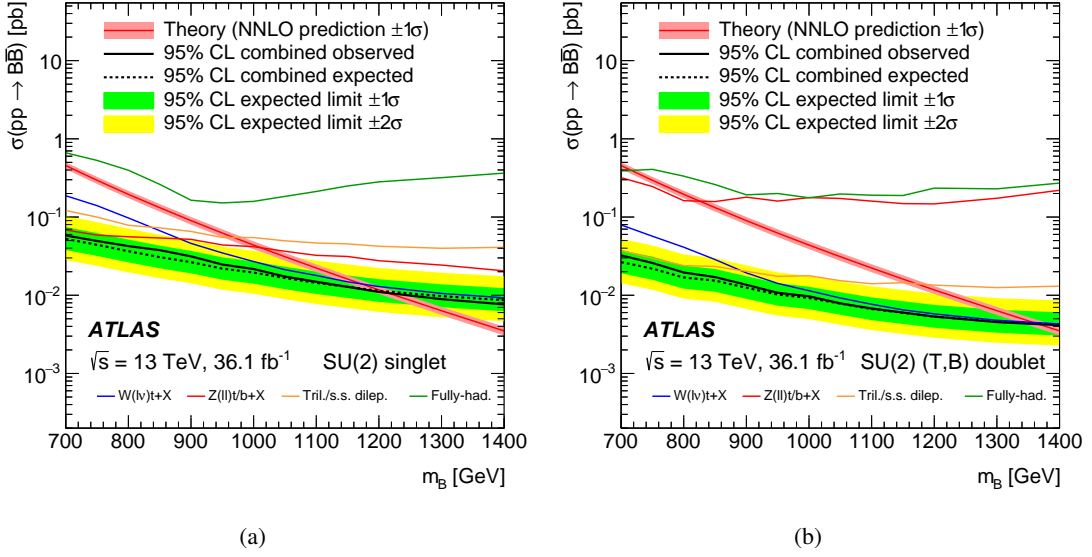


Figure 3: Observed (solid line) and expected (dashed line) 95% CL upper limits on the  $B\bar{B}$  cross-section versus mass for the combination and the standalone analyses in black and colored lines, respectively. The (a) singlet and (b)  $(T, B)$  doublet scenarios [8] are displayed. The shaded bands correspond to  $\pm 1$  and  $\pm 2$  standard deviations around the combined expected limit. The rapidly falling thin red line and band show the theory prediction and corresponding uncertainty [13], respectively.

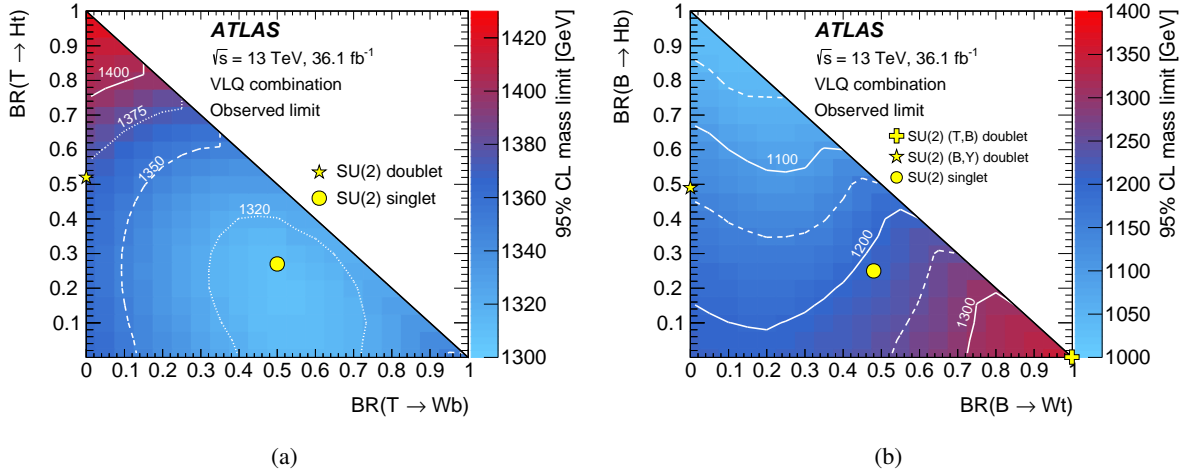


Figure 4: Observed lower limits at 95% CL on the mass of the (a)  $T$  and (b)  $B$  as a function of branching ratio assuming  $\mathcal{B}(T \rightarrow Ht) + \mathcal{B}(T \rightarrow Zt) + \mathcal{B}(T \rightarrow Wb) = 1$  and  $\mathcal{B}(B \rightarrow Hb) + \mathcal{B}(B \rightarrow Zb) + \mathcal{B}(B \rightarrow Wt) = 1$ . The yellow markers indicate the branching ratios for the SU(2) singlet and doublet scenarios for VLQ masses above 800 GeV where the branching ratios become approximately independent of the VLQ mass [8].

## 5 Conclusion

The ATLAS Collaboration has performed a combination of seven analyses searching for pair-produced VLQs. Upper limits on the cross-section are calculated and used to set lower limits on the VLQ mass for various benchmark scenarios and for general combinations of branching ratios. This combination results in the most stringent limits to date on VLQ pair production. Due to the high degree of complementarity between the analyses, the combination has significantly better sensitivity than the standalone analyses, for the first time excluding  $T$  ( $B$ ) masses below 1.31 (1.03) TeV for *any* combination of decays into SM particles.

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