Editors' Suggestion

Combination of the Searches for Pair-Produced Vectorlike Partners of the Third-Generation Quarks at $\sqrt{s} = 13$ TeV with the ATLAS Detector

M. Aaboud *et al.*[*]
(ATLAS Collaboration)

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A combination of the searches for pair-produced vectorlike partners of the top and bottom quarks in various decay channels ($T \to Zt/Wb/Ht$, $B \to Zb/Wt/Hb$) is performed using 36.1 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 vectorlike quark scenarios, significantly improving upon the reach of the individual searches. Model-independent limits are set assuming the vectorlike quarks decay to standard model particles. 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 and $|V_{Tb}| \ll |V_{tB}|$, T and B masses below 1.37 TeV are excluded.

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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 vectorlike 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 $T \to WB$. 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 to 2.0 fb for quark masses from 800 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 Fig. 1.

The branching ratio ($\mathcal{B}$) for each decay mode ($T \to Wb, Zt, Ht$ and $B \to Wt, Zb, Hb$) 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 $T \to Wb$ is absent if T is either in a (X, T) doublet, where X is a VLQ with a charge of $+5/3$, or in 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 $B \to Wt$ decay is forbidden. Conversely, for a (T, B) doublet with $|V_{Tb}| \ll |V_{tB}|$, $B \to Wt$ is the only allowed decay. Therefore, the specific B doublet scenario will be stated when interpreting the results.

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

[*]Full author list given at the end of the Letter.

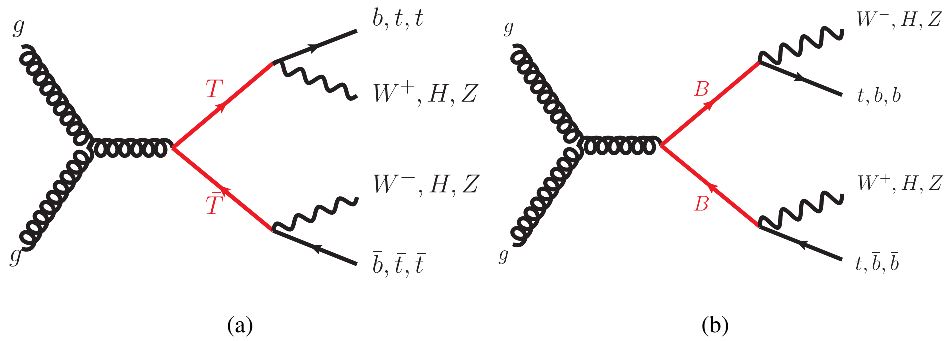

FIG. 1. Representative leading-order Feynman diagrams for (a) $T\bar{T}$ and (b) $B\bar{B}$ pair production. The studied VLQ decays are also displayed.

LHC at $\sqrt{s} = 13$ TeV. This Letter presents the full combination of the ATLAS searches using 36.1 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 $H \to b\bar{b}$. Events must have at least six jets [27] and either one lepton (electron [28] or muon [29]) or missing transverse momentum [30] $E_{\mathrm{T}}^{\mathrm{miss}} > 200$ 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 (S_{T}) of the transverse momenta of the selected jets, lepton, and missing transverse momentum. 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 $T\bar{T} \to WbWb$ events with one W decaying leptonically and the other hadronically. Event selection requires one lepton, ≥ 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 $T \to Wb \to \ell\nu b$ 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 $B \to Wt$. 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 $T\bar{T} \to ZtZt$ events with an invisible Z decay. Events must have $E_{\mathrm{T}}^{\mathrm{miss}} > 300$ GeV, one charged lepton from the decay of a top quark, and ≥ 4 small-radius jets, which are reclustered [34] into large-radius jets. The analysis defines a single-bin signal region that capitalizes on various $E_{\mathrm{T}}^{\mathrm{miss}}$-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 ($Z \to \ell^+\ell^-$) and at least two b-jets. The analysis has one trilepton signal region and three dilepton signal regions, depending on the number of large-radius jets (0, 1, or ≥ 2). The final discriminant depends on the signal region. The dominant backgrounds for the dilepton channels are Z + jets and/or $t\bar{t}$ and diboson, while the trilepton channels are dominated by diboson (WZ) and $t\bar{t}Z$ events, each modeled by MC simulation and validated with dedicated control regions.

Trilepton or 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 ("same sign"). 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 or nonprompt leptons and electrons with incorrectly measured charge) are estimated 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 $E_{\mathrm{T}}^{\mathrm{miss}}$, at least four (small-radius) high-p_{T} jets, and at least two b-tagged jets. This is the only analysis with significant sensitivity to $B\bar{B} \to HbH\bar{b}$. Small-radius jets are reclustered into large-radius jets, which may be identified as top quarks, W/Z, or H bosons using a multiclass 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.

TABLE I. The most sensitive decay channel for each analysis entering the combination. A "$\cdots$" 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]	$HtH\bar{t}$	$\cdots$
$W(\ell\nu)b+X$ [17]	$WbW\bar{b}$	$\cdots$
$W(\ell\nu)t+X$ [18]	$\cdots$	$WtW\bar{t}$
$Z(\nu\nu)t+X$ [19]	$ZtZ\bar{t}$	$\cdots$
$Z(\ell\ell)t/b+X$ [20]	$ZtZ\bar{t}$	$ZbZ\bar{b}$
Tril./s.s. dilepton [21]	$HtH\bar{t}$	$WtW\bar{t}$
Fully hadronic [22]	$HtH\bar{t}$	$HbH\bar{b}$

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 I. 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 ≥ 6 jets and ≥ 3 b-jets to avoid overlap with the $H(bb)t+X$ selection. The $Z(\nu\nu)t+X$ analysis also requires $S_{\mathrm{T}} < 1.8$ 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 or 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 fraction of events falling into more than one analysis region 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 Protos 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.

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 μ, a factor multiplying the theoretical signal cross section ($\mu \equiv \sigma/\sigma_{\mathrm{theory}}$), 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

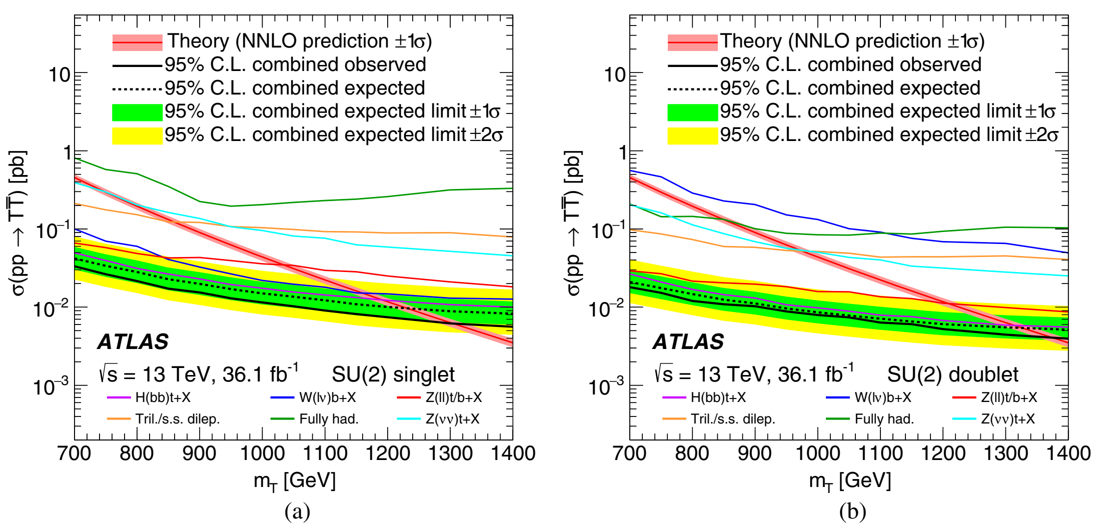

FIG. 2. Observed (solid lines) and expected (dashed line) 95% C.L. upper limits on the $T\bar{T}$ cross section versus mass for the combination and the standalone analyses in black and colored lines, respectively. The (a) singlet and (b) doublet scenarios [8] are displayed. The shaded bands correspond to ± 1 and ± 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.

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.

Results.—The behavior of the combination is consistent with the fits from the individual analyses. The postfit 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 (C.L.) 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

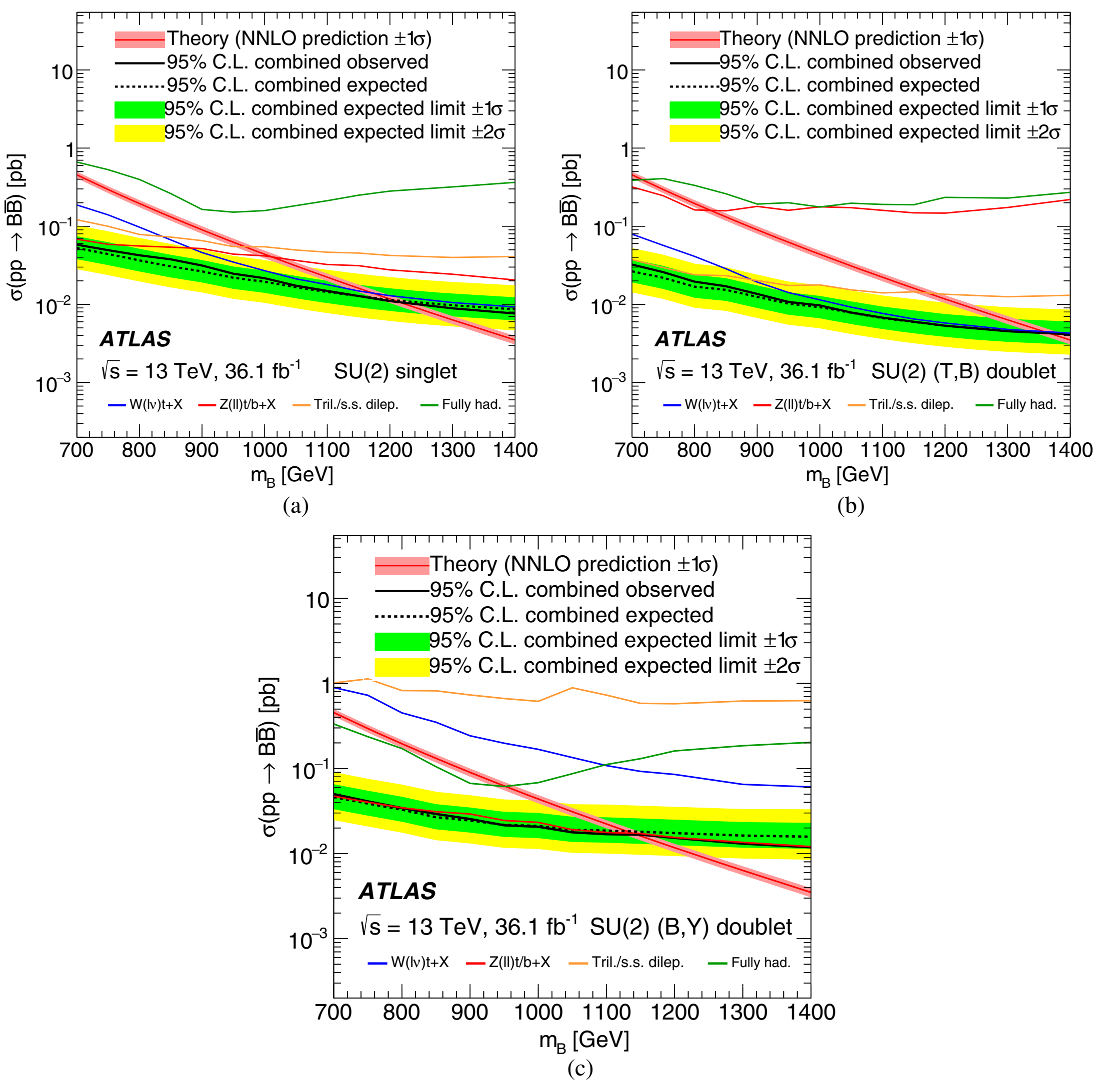

FIG. 3. Observed (solid lines) and expected (dashed line) 95% C.L. upper limits on the $B\bar{B}$ cross section versus mass for the combination and the standalone analyses in black and colored lines, respectively. The (a) singlet, (b) (T, B) doublet, and (c) (B, Y) doublet scenarios [8] are displayed. The shaded bands correspond to ±1 and ±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.

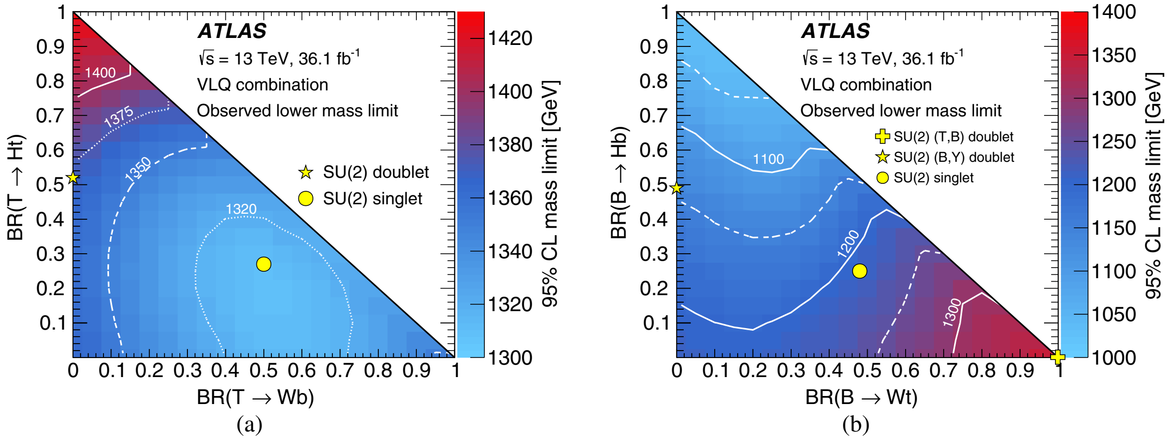

FIG. 4. Observed lower limits at 95% C.L. on the mass of the (a) T and (b) B as a function of branching ratio assuming $\mathcal{B}(T \to Ht) + \mathcal{B}(T \to Zt) + \mathcal{B}(T \to Wb) = 1$ and $\mathcal{B}(B \to Hb) + \mathcal{B}(B \to Zb) + \mathcal{B}(B \to Wt) = 1$. The yellow markers indicate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

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 $\mathrm{CL_s}$ 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 Fig. 2 for the benchmark scenarios of an isospin singlet or doublet T. Analogous limits on the $B\bar{B}$ cross section are shown in Fig. 3. 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, a B in a (T, B) doublet is excluded for masses below 1.37 TeV, and a 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 observed limit on the $T\bar{T}$ cross section is improved by up to a factor of ~1.7, which translates to an increase of 110 GeV in the observed mass limit.

In addition, model-independent lower limits are set on the VLQ mass for all combinations of branching ratios, assuming $\mathcal{B}(T \to Ht) + \mathcal{B}(T \to Zt) + \mathcal{B}(T \to Wb) = 1$ and $\mathcal{B}(B \to Hb) + \mathcal{B}(B \to Zb) + \mathcal{B}(B \to Wt) = 1$. The resulting lower limits on the VLQ mass as a function of branching ratio are presented in Fig. 4. Limits corresponding to $\mathcal{B}(T \to Wb) = 1$ and $\mathcal{B}(B \to Wt) = 1$ are found to also be applicable to $Y\bar{Y} \to WbWb$ and $X\bar{X} \to WtWt$, respectively. The high degree of complementarity between the analyses is clearly demonstrated in Fig. 4. For *any* combination of branching ratios, the combined analysis 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].

Conclusion.—The ATLAS Collaboration has performed a combination of seven analyses searching for pair-produced VLQs. Upper limits on the cross section are determined 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. Because of 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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Staroba,[137] P. Starovoitov,[59a] S. Stärz,[35] R. Staszewski,[82] M. Stegler,[44] P. Steinberg,[29] B. Stelzer,[149] H. J. Stelzer,[35] O. Stelzer-Chilton,[165a] H. Stenzel,[54] T. J. Stevenson,[90] G. A. Stewart,[55] M. C. Stockton,[35] G. Stoicea,[27b] P. Stolte,[51] S. Stonjek,[113] A. Straessner,[46] J. Strandberg,[151] S. Strandberg,[43a,43b] M. Strauss,[124] P. Strizenec,[28b] R. Ströhmer,[174] D. M. Strom,[127] R. Stroynowski,[41] A. Strubig,[48] S. A. Stucci,[29] B. Stugu,[17] J. Stupak,[124] N. A. Styles,[44] D. Su,[150] J. Su,[135] S. Suchek,[59a] Y. Sugaya,[129] M. Suk,[138] V. V. Sulin,[108] M. J. Sullivan,[88] D. M. S. Sultan,[52] S. Sultansoy,[4c] T. Sumida,[83] S. Sun,[103] X. Sun,[3] K. Suruliz,[153] C. J. E. Suster,[154] M. R. Sutton,[153] S. Suzuki,[79] M. Svatos,[137] M. Swiatlowski,[36] S. P. Swift,[2] A. Sydorenko,[97] I. Sykora,[28a] T. Sykora,[139] D. Ta,[97] K. Tackmann,[44,nn] J. Taenzer,[158] A. Taffard,[168] R. Tafirout,[165a] E. Tahirovic,[90] N. Taiblum,[158] H. Takai,[29] R. Takashima,[84] E. H. Takasugi,[113] K. Takeda,[80] T. Takeshita,[147] Y. Takubo,[79] M. Talby,[99] A. A. Talyshev,[120b,120a] J. Tanaka,[160] M. Tanaka,[162] R. Tanaka,[128] B. B. Tannenwald,[122] S. Tapia Araya,[144b] S. Tapprogge,[97] A. Tarek Abouelfadl Mohamed,[132] S. Tarem,[157] G. Tarna,[27b,p] G. F. Tartarelli,[66a] P. Tas,[139] M. Tasevsky,[137] T. Tashiro,[83] E. Tassi,[40b,40a] A. Tavares Delgado,[136a,136b] Y. Tayalati,[34e] A. C. Taylor,[116] A. J. Taylor,[48] G. N. Taylor,[102] P. T. E. Taylor,[102] W. Taylor,[165b] A. S. Tee,[87] P. Teixeira-Dias,[91] H. Ten Kate,[35] J. J. Teoh,[118] S. Terada,[79] K. Terashi,[160] J. Terron,[96] S. Terzo,[14] M. Testa,[49] R. J. Teuscher,[164,n] S. J. Thais,[180] T. Theveneaux-Pelzer,[44] F. Thiele,[39] D. W. Thomas,[91] J. P. Thomas,[21] A. S. Thompson,[55] P. D. Thompson,[21] L. A. Thomsen,[180] E. Thomson,[133] Y. Tian,[38] R. E. Ticse Torres,[51] V. O. Tikhomirov,[108,oo] Yu. A. Tikhonov,[120b,120a] S. Timoshenko,[110] P. Tipton,[180] S. Tisserant,[99] K. Todome,[162] S. Todorova-Nova,[5] S. Todt,[46] J. Tojo,[85] S. Tokár,[28a] K. Tokushuku,[79] E. Tolley,[122] K. G. Tomiwa,[32c] M. Tomoto,[115] L. Tompkins,[150] K. Toms,[116] B. Tong,[57] P. Tornambe,[50] E. Torrence,[127] H. Torres,[46] E. Torró Pastor,[145] C. Tosciri,[131] J. Toth,[99,pp] F. Touchard,[99] D. R. Tovey,[146] C. J. Treado,[121] T. Trefzger,[174] F. Tresoldi,[153] A. Tricoli,[29] I. M. Trigger,[165a] S. Trincaz-Duvoid,[132] M. F. Tripiana,[14] W. Trischuk,[164] B. Trocmé,[56] A. Trofymov,[128] C. Troncon,[66a] M. Trovatelli,[173] F. Trovato,[153] L. Truong,[32b] M. Trzebinski,[82] A. Trzupek,[82] F. Tsai,[44] J. C-L. Tseng,[131] P. V. Tsiareshka,[105] A. Tsirigotis,[159] N. Tsirintanis,[9] V. Tsiskaridze,[152] E. G. Tskhadadze,[156a] I. I. Tsukerman,[109] V. Tsulaia,[18] S. Tsuno,[79] D. Tsybychev,[152,163] Y. Tu,[61b] A. Tudorache,[27b] V. Tudorache,[27b] T. T. Tulbure,[27a] A. N. Tuna,[57] S. Turchikhin,[77] D. Turgeman,[177] I. Turk Cakir,[4b,qq] R. Turra,[66a] P. M. Tuts,[38] E. Tzovara,[97] G. Ucchielli,[23b,23a] I. Ueda,[79] M. Ughetto,[43a,43b] F. Ukegawa,[166] G. Unal,[35] A. Undrus,[29] G. Unel,[168] F. C. Ungaro,[102] Y. Unno,[79] K. Uno,[160] J. Urban,[28b] P. Urquijo,[102] P. Urrejola,[97] G. Usai,[8] J. Usui,[79] L. Vacavant,[99] V. Vacek,[138] B. Vachon,[101] K. O. H. Vadla,[130] A. Vaidya,[92] C. Valderanis,[112] E. Valdes Santurio,[43a,43b] M. Valente,[52] S. Valentinetti,[23b,23a] A. Valero,[171] L. Valéry,[44] R. A. Vallance,[21] A. Vallier,[5] J. A. Valls Ferrer,[171] T. R. Van Daalen,[14] H. Van der Graaf,[118] P. Van Gemmeren,[6] J. Van Nieuwkoop,[149] I. Van Vulpen,[118]

M. Vanadia,[71a,71b] W. Vandelli,[35] A. Vaniachine,[163] P. Vankov,[118] R. Vari,[70a] E. W. Varnes,[7] C. Varni,[53b,53a] T. Varol,[41] D. Varouchas,[128] K. E. Varvell,[154] G. A. Vasquez,[144b] J. G. Vasquez,[180] F. Vazeille,[37] D. Vazquez Furelos,[14] T. Vazquez Schroeder,[35] J. Veatch,[51] V. Vecchio,[72a,72b] L. M. Veloce,[164] F. Veloso,[136a,136c] S. Veneziano,[70a] A. Ventura,[65a,65b] M. Venturi,[173] N. Venturi,[35] V. Vercesi,[68a] M. Verducci,[72a,72b] C. M. Vergel Infante,[76] C. Vergis,[24] W. Verkerke,[118] A. T. Vermeulen,[118] J. C. Vermeulen,[118] M. C. Vetterli,[149,e] N. Viaux Maira,[144b] M. Vicente Barreto Pinto,[52] I. Vichou,[170,a] T. Vickey,[146] O. E. Vickey Boeriu,[146] G. H. A. Viehhauser,[131] S. Viel,[18] L. Vigani,[131] M. Villa,[23b,23a] M. Villaplana Perez,[66a,66b] E. Vilucchi,[49] M. G. Vincter,[33] V. B. Vinogradov,[77] A. Vishwakarma,[44] C. Vittori,[23b,23a] I. Vivarelli,[153] S. Vlachos,[10] M. Vogel,[179] P. Vokac,[138] G. Volpi,[14] S. E. von Buddenbrock,[32c] E. Von Toerne,[24] V. Vorobel,[139] K. Vorobev,[110] M. Vos,[171] J. H. Vossebeld,[88] N. Vranjes,[16] M. Vranjes Milosavljevic,[16] V. Vrba,[138] M. Vreeswijk,[118] T. Šfiligoj,[89] R. Vuillermet,[35] I. Vukotic,[36] T. Ženiš,[28a] L. Živković,[16] P. Wagner,[24] W. Wagner,[179] J. Wagner-Kuhr,[112] H. Wahlberg,[86] S. Wahrmund,[46] K. Wakamiya,[80] V. M. Walbrecht,[113] J. Walder,[87] R. Walker,[112] S. D. Walker,[91] W. Walkowiak,[148] V. Wallangen,[43a,43b] A. M. Wang,[57] C. Wang,[58b,p] F. Wang,[178] H. Wang,[18] H. Wang,[3] J. Wang,[154] J. Wang,[59b] P. Wang,[41] Q. Wang,[124] R.-J. Wang,[132] R. Wang,[58a] R. Wang,[6] S. M. Wang,[155] W. T. Wang,[58a] W. Wang,[15c,rr] W. X. Wang,[58a,rr] Y. Wang,[58a] Z. Wang,[58c] C. Wanotayaroj,[44] A. Warburton,[101] C. P. Ward,[31] D. R. Wardrope,[92] A. Washbrook,[48] P. M. Watkins,[21] A. T. Watson,[21] M. F. Watson,[21] G. Watts,[145] S. Watts,[98] B. M. Waugh,[92] A. F. Webb,[11] S. Webb,[97] C. Weber,[180] M. S. Weber,[20] S. A. Weber,[33] S. M. Weber,[59a] A. R. Weidberg,[131] B. Weinert,[63] J. Weingarten,[51] M. Weirich,[97] C. Weiser,[50] P. S. Wells,[35] T. Wenaus,[29] T. Wengler,[35] S. Wenig,[35] N. Wermes,[24] M. D. Werner,[76] P. Werner,[35] M. Wessels,[59a] T. D. Weston,[20] K. Whalen,[127] N. L. Whallon,[145] A. M. Wharton,[87] A. S. White,[103] A. White,[8] M. J. White,[1] R. White,[144b] D. Whiteson,[168] B. W. Whitmore,[87] F. J. Wickens,[141] W. Wiedenmann,[178] M. Wielers,[141] C. Wiglesworth,[39] L. A. M. Wiik-Fuchs,[50] F. Wilk,[98] H. G. Wilkens,[35] L. J. Wilkins,[91] H. H. Williams,[133] S. Williams,[31] C. Willis,[104] S. Willocq,[100] J. A. Wilson,[21] I. Wingerter-Seez,[5] E. Winkels,[153] F. Winklmeier,[127] O. J. Winston,[153] B. T. Winter,[50] M. Wittgen,[150] M. Wobisch,[93] A. Wolf,[97] T. M. H. Wolf,[118] R. Wolff,[99] M. W. Wolter,[82] H. Wolters,[136a,136c] V. W. S. Wong,[172] N. L. Woods,[143] S. D. Worm,[21] B. K. Wosiek,[82] K. W. Woźniak,[82] K. Wraight,[55] M. Wu,[36] S. L. Wu,[178] X. Wu,[52] Y. Wu,[58a] T. R. Wyatt,[98] B. M. Wynne,[48] S. Xella,[39] Z. Xi,[103] L. Xia,[175] D. Xu,[15a] H. Xu,[58a] L. Xu,[29] T. Xu,[142] W. Xu,[103] B. Yabsley,[154] S. Yacoob,[32a] K. Yajima,[129] D. P. Yallup,[92] D. Yamaguchi,[162] Y. Yamaguchi,[162] A. Yamamoto,[79] T. Yamanaka,[160] F. Yamane,[80] M. Yamatani,[160] T. Yamazaki,[160] Y. Yamazaki,[80] Z. Yan,[25] H. J. Yang,[58c,58d] H. T. Yang,[18] S. Yang,[75] Y. Yang,[160] Z. Yang,[17] W-M. Yao,[18] Y. C. Yap,[44] Y. Yasu,[79] E. Yatsenko,[58c,58d] J. Ye,[41] S. Ye,[29] I. Yeletskikh,[77] E. Yigitbasi,[25] E. Yildirim,[97] K. Yorita,[176] K. Yoshihara,[133] C. J. S. Young,[35] C. Young,[150] J. Yu,[8] J. Yu,[76] X. Yue,[59a] S. P. Y. Yuen,[24] B. Zabinski,[82] G. Zacharis,[10] E. Zaffaroni,[52] R. Zaidan,[14] A. M. Zaitsev,[140,ii] T. Zakareishvili,[156b] N. Zakharchuk,[33] J. Zalieckas,[17] S. Zambito,[57] D. Zanzi,[35] D. R. Zaripovas,[55] S. V. Zeißner,[45] C. Zeitnitz,[179] G. Zemaityte,[131] J. C. Zeng,[170] Q. Zeng,[150] O. Zenin,[140] D. Zerwas,[128] M. Zgubič,[131] D. F. Zhang,[58b] D. Zhang,[103] F. Zhang,[178] G. Zhang,[58a] G. Zhang,[15b] H. Zhang,[15c] J. Zhang,[6] L. Zhang,[15c] L. Zhang,[58a] M. Zhang,[170] P. Zhang,[15c] R. Zhang,[58a] R. Zhang,[24] X. Zhang,[58b] Y. Zhang,[15d] Z. Zhang,[128] Y. Zhao,[58b,128,x] Z. Zhao,[58a] A. Zhemchugov,[77] Z. Zheng,[103] D. Zhong,[170] B. Zhou,[103] C. Zhou,[178] L. Zhou,[41] M. S. Zhou,[15d] M. Zhou,[152] N. Zhou,[58c] Y. Zhou,[7] C. G. Zhu,[58b] H. L. Zhu,[58a] H. Zhu,[15a] J. Zhu,[103] Y. Zhu,[58a] X. Zhuang,[15a] K. Zhukov,[108] V. Zhulanov,[120b,120a] A. Zibell,[174] D. Zieminska,[63] N. I. Zimine,[77] S. Zimmermann,[50] Z. Zinonos,[113] M. Zinser,[97] M. Ziolkowski,[148] G. Zobernig,[178] A. Zoccoli,[23b,23a] K. Zoch,[51] T. G. Zorbas,[146] R. Zou,[36] M. Zur Nedden,[19] and L. Zwalinski[35]

(ATLAS Collaboration)

[1]*Department of Physics, University of Adelaide, Adelaide, Australia*
[2]*Physics Department, SUNY Albany, Albany New York, USA*
[3]*Department of Physics, University of Alberta, Edmonton, Alberta, Canada*
[4a]*Department of Physics, Ankara University, Ankara, Turkey*
[4b]*Istanbul Aydin University, Istanbul, Turkey*
[4c]*Division of Physics, TOBB University of Economics and Technology, Ankara, Turkey*
[5]*LAPP, Université Grenoble Alpes, Université Savoie Mont Blanc, CNRS/IN2P3, Annecy, France*
[6]*High Energy Physics Division, Argonne National Laboratory, Argonne, Illinois, USA*
[7]*Department of Physics, University of Arizona, Tucson, Arizona, USA*
[8]*Department of Physics, University of Texas at Arlington, Arlington, Texas, USA*

[9]*Physics Department, National and Kapodistrian University of Athens, Athens, Greece*
[10]*Physics Department, National Technical University of Athens, Zografou, Greece*
[11]*Department of Physics, University of Texas at Austin, Austin, Texas, USA*
[12a]*Bahcesehir University, Faculty of Engineering and Natural Sciences, Istanbul, Turkey*
[12b]*Istanbul Bilgi University, Faculty of Engineering and Natural Sciences, Istanbul, Turkey*
[12c]*Department of Physics, Bogazici University, Istanbul, Turkey*
[12d]*Department of Physics Engineering, Gaziantep University, Gaziantep, Turkey*
[13]*Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan*
[14]*Institut de Física d'Altes Energies (IFAE), Barcelona Institute of Science and Technology, Barcelona, Spain*
[15a]*Institute of High Energy Physics, Chinese Academy of Sciences, Beijing, China*
[15b]*Physics Department, Tsinghua University, Beijing, China*
[15c]*Department of Physics, Nanjing University, Nanjing, China*
[15d]*University of Chinese Academy of Science (UCAS), Beijing, China*
[16]*Institute of Physics, University of Belgrade, Belgrade, Serbia*
[17]*Department for Physics and Technology, University of Bergen, Bergen, Norway*
[18]*Physics Division, Lawrence Berkeley National Laboratory and University of California, Berkeley, California, USA*
[19]*Institut für Physik, Humboldt Universität zu Berlin, Berlin, Germany*
[20]*Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern, Switzerland*
[21]*School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom*
[22]*Centro de Investigaciónes, Universidad Antonio Nariño, Bogota, Colombia*
[23a]*Dipartimento di Fisica e Astronomia, Università di Bologna, Bologna, Italy*
[23b]*INFN Sezione di Bologna, Italy*
[24]*Physikalisches Institut, Universität Bonn, Bonn, Germany*
[25]*Department of Physics, Boston University, Boston, Massachusetts, USA*
[26]*Department of Physics, Brandeis University, Waltham, Massachusetts, USA*
[27a]*Transilvania University of Brasov, Brasov, Romania*
[27b]*Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest, Romania*
[27c]*Department of Physics, Alexandru Ioan Cuza University of Iasi, Iasi, Romania*
[27d]*National Institute for Research and Development of Isotopic and Molecular Technologies, Physics Department, Cluj-Napoca, Romania*
[27e]*University Politehnica Bucharest, Bucharest, Romania*
[27f]*West University in Timisoara, Timisoara, Romania*
[28a]*Faculty of Mathematics, Physics and Informatics, Comenius University, Bratislava, Slovak Republic*
[28b]*Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice, Slovak Republic*
[29]*Physics Department, Brookhaven National Laboratory, Upton, New York, USA*
[30]*Departamento de Física, Universidad de Buenos Aires, Buenos Aires, Argentina*
[31]*Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom*
[32a]*Department of Physics, University of Cape Town, Cape Town, South Africa*
[32b]*Department of Mechanical Engineering Science, University of Johannesburg, Johannesburg, South Africa*
[32c]*School of Physics, University of the Witwatersrand, Johannesburg, South Africa*
[33]*Department of Physics, Carleton University, Ottawa, Ontario, Canada*
[34a]*Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Energies—Université Hassan II, Casablanca, Morocco*
[34b]*Centre National de l'Energie des Sciences Techniques Nucleaires (CNESTEN), Rabat, Morocco*
[34c]*Faculté des Sciences Semlalia, Université Cadi Ayyad, LPHEA-Marrakech, Morocco*
[34d]*Faculté des Sciences, Université Mohamed Premier and LPTPM, Oujda, Morocco*
[34e]*Faculté des sciences, Université Mohammed V, Rabat, Morocco*
[35]*CERN, Geneva, Switzerland*
[36]*Enrico Fermi Institute, University of Chicago, Chicago, Illinois, USA*
[37]*LPC, Université Clermont Auvergne, CNRS/IN2P3, Clermont-Ferrand, France*
[38]*Nevis Laboratory, Columbia University, Irvington, New York, USA*
[39]*Niels Bohr Institute, University of Copenhagen, Copenhagen, Denmark*
[40a]*Dipartimento di Fisica, Università della Calabria, Rende, Italy*
[40b]*INFN Gruppo Collegato di Cosenza, Laboratori Nazionali di Frascati, Italy*
[41]*Physics Department, Southern Methodist University, Dallas, Texas, USA*
[42]*Physics Department, University of Texas at Dallas, Richardson, Texas, USA*
[43a]*Department of Physics, Stockholm University, Sweden*
[43b]*Oskar Klein Centre, Stockholm, Sweden*
[44]*Deutsches Elektronen-Synchrotron DESY, Hamburg and Zeuthen, Germany*
[45]*Lehrstuhl für Experimentelle Physik IV, Technische Universität Dortmund, Dortmund, Germany*

[46]Institut für Kern- und Teilchenphysik, Technische Universität Dresden, Dresden, Germany
[47]Department of Physics, Duke University, Durham, North Carolina, USA
[48]SUPA—School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom
[49]INFN e Laboratori Nazionali di Frascati, Frascati, Italy
[50]Physikalisches Institut, Albert-Ludwigs-Universität Freiburg, Freiburg, Germany
[51]II. Physikalisches Institut, Georg-August-Universität Göttingen, Göttingen, Germany
[52]Département de Physique Nucléaire et Corpusculaire, Université de Genève, Genève, Switzerland
[53a]Dipartimento di Fisica, Università di Genova, Genova, Italy
[53b]INFN Sezione di Genova, Italy
[54]II. Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen, Germany
[55]SUPA—School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom
[56]LPSC, Université Grenoble Alpes, CNRS/IN2P3, Grenoble INP, Grenoble, France
[57]Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge, Massachusetts, USA
[58a]Department of Modern Physics and State Key Laboratory of Particle Detection and Electronics, University of Science and Technology of China, Hefei, China
[58b]Institute of Frontier and Interdisciplinary Science and Key Laboratory of Particle Physics and Particle Irradiation (MOE), Shandong University, Qingdao, China
[58c]School of Physics and Astronomy, Shanghai Jiao Tong University, KLPPAC-MoE, SKLPPC, Shanghai, China
[58d]Tsung-Dao Lee Institute, Shanghai, China
[59a]Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany
[59b]Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany
[60]Faculty of Applied Information Science, Hiroshima Institute of Technology, Hiroshima, Japan
[61a]Department of Physics, Chinese University of Hong Kong, Shatin, N.T., Hong Kong, China
[61b]Department of Physics, University of Hong Kong, Hong Kong, China
[61c]Department of Physics and Institute for Advanced Study, Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong, China
[62]Department of Physics, National Tsing Hua University, Hsinchu, Taiwan
[63]Department of Physics, Indiana University, Bloomington, Indiana, USA
[64a]INFN Gruppo Collegato di Udine, Sezione di Trieste, Udine, Italy
[64b]ICTP, Trieste, Italy
[64c]Dipartimento di Chimica, Fisica e Ambiente, Università di Udine, Udine, Italy
[65a]INFN Sezione di Lecce, Italy
[65b]Dipartimento di Matematica e Fisica, Università del Salento, Lecce, Italy
[66a]INFN Sezione di Milano, Italy
[66b]Dipartimento di Fisica, Università di Milano, Milano, Italy
[67a]INFN Sezione di Napoli, Italy
[67b]Dipartimento di Fisica, Università di Napoli, Napoli, Italy
[68a]INFN Sezione di Pavia, Italy
[68b]Dipartimento di Fisica, Università di Pavia, Pavia, Italy
[69a]INFN Sezione di Pisa, Italy
[69b]Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy
[70a]INFN Sezione di Roma, Italy
[70b]Dipartimento di Fisica, Sapienza Università di Roma, Roma, Italy
[71a]INFN Sezione di Roma Tor Vergata, Italy
[71b]Dipartimento di Fisica, Università di Roma Tor Vergata, Roma, Italy
[72a]INFN Sezione di Roma Tre, Italy
[72b]Dipartimento di Matematica e Fisica, Università Roma Tre, Roma, Italy
[73a]INFN-TIFPA, Italy
[73b]Università degli Studi di Trento, Trento, Italy
[74]Institut für Astro- und Teilchenphysik, Leopold-Franzens-Universität, Innsbruck, Austria
[75]University of Iowa, Iowa City, Iowa, USA
[76]Department of Physics and Astronomy, Iowa State University, Ames, Iowa, USA
[77]Joint Institute for Nuclear Research, Dubna, Russia
[78a]Departamento de Engenharia Elétrica, Universidade Federal de Juiz de Fora (UFJF), Juiz de Fora, Brazil
[78b]Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro, Brazil
[78c]Universidade Federal de São João del Rei (UFSJ), São João del Rei, Brazil
[78d]Instituto de Física, Universidade de São Paulo, São Paulo, Brazil
[79]KEK, High Energy Accelerator Research Organization, Tsukuba, Japan
[80]Graduate School of Science, Kobe University, Kobe, Japan
[81a]AGH University of Science and Technology, Faculty of Physics and Applied Computer Science, Krakow, Poland

[81b]Marian Smoluchowski Institute of Physics, Jagiellonian University, Krakow, Poland
[82]Institute of Nuclear Physics Polish Academy of Sciences, Krakow, Poland
[83]Faculty of Science, Kyoto University, Kyoto, Japan
[84]Kyoto University of Education, Kyoto, Japan
[85]Research Center for Advanced Particle Physics and Department of Physics, Kyushu University, Fukuoka, Japan
[86]Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata, Argentina
[87]Physics Department, Lancaster University, Lancaster, United Kingdom
[88]Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom
[89]Department of Experimental Particle Physics, Jožef Stefan Institute and Department of Physics, University of Ljubljana, Ljubljana, Slovenia
[90]School of Physics and Astronomy, Queen Mary University of London, London, United Kingdom
[91]Department of Physics, Royal Holloway University of London, Egham, United Kingdom
[92]Department of Physics and Astronomy, University College London, London, United Kingdom
[93]Louisiana Tech University, Ruston, Louisiana, USA
[94]Fysiska institutionen, Lunds universitet, Lund, Sweden
[95]Centre de Calcul de l'Institut National de Physique Nucléaire et de Physique des Particules (IN2P3), Villeurbanne, France
[96]Departamento de Física Teorica C-15 and CIAFF, Universidad Autónoma de Madrid, Madrid, Spain
[97]Institut für Physik, Universität Mainz, Mainz, Germany
[98]School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom
[99]CPPM, Aix-Marseille Université, CNRS/IN2P3, Marseille, France
[100]Department of Physics, University of Massachusetts, Amherst, Massachusetts, USA
[101]Department of Physics, McGill University, Montreal, Quebec, Canada
[102]School of Physics, University of Melbourne, Victoria, Australia
[103]Department of Physics, University of Michigan, Ann Arbor, Michigan, USA
[104]Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan, USA
[105]B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Minsk, Belarus
[106]Research Institute for Nuclear Problems of Byelorussian State University, Minsk, Belarus
[107]Group of Particle Physics, University of Montreal, Montreal, Quebec, Canada
[108]P.N. Lebedev Physical Institute of the Russian Academy of Sciences, Moscow, Russia
[109]Institute for Theoretical and Experimental Physics (ITEP), Moscow, Russia
[110]National Research Nuclear University MEPhI, Moscow, Russia
[111]D.V. Skobeltsyn Institute of Nuclear Physics, M.V. Lomonosov Moscow State University, Moscow, Russia
[112]Fakultät für Physik, Ludwig-Maximilians-Universität München, München, Germany
[113]Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München, Germany
[114]Nagasaki Institute of Applied Science, Nagasaki, Japan
[115]Graduate School of Science and Kobayashi-Maskawa Institute, Nagoya University, Nagoya, Japan
[116]Department of Physics and Astronomy, University of New Mexico, Albuquerque, New Mexico, USA
[117]Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands
[118]Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam, Netherlands
[119]Department of Physics, Northern Illinois University, DeKalb, Illinois, USA
[120a]Budker Institute of Nuclear Physics, SB RAS, Novosibirsk, Russia
[120b]Novosibirsk State University Novosibirsk, Russia
[121]Department of Physics, New York University, New York, New York, USA
[122]The Ohio State University, Columbus, Ohio, USA
[123]Faculty of Science, Okayama University, Okayama, Japan
[124]Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman, Oklahoma, USA
[125]Department of Physics, Oklahoma State University, Stillwater, Oklahoma, USA
[126]Palacký University, RCPTM, Joint Laboratory of Optics, Olomouc, Czech Republic
[127]Center for High Energy Physics, University of Oregon, Eugene, Oregon, USA
[128]LAL, Université Paris-Sud, CNRS/IN2P3, Université Paris-Saclay, Orsay, France
[129]Graduate School of Science, Osaka University, Osaka, Japan
[130]Department of Physics, University of Oslo, Oslo, Norway
[131]Department of Physics, Oxford University, Oxford, United Kingdom
[132]LPNHE, Sorbonne Université, Paris Diderot Sorbonne Paris Cité, CNRS/IN2P3, Paris, France
[133]Department of Physics, University of Pennsylvania, Philadelphia, Pennsylvania, USA
[134]Konstantinov Nuclear Physics Institute of National Research Centre "Kurchatov Institute", PNPI, St. Petersburg, Russia
[135]Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh, Pennsylvania, USA
[136a]Laboratório de Instrumentação e Física Experimental de Partículas—LIP, Portugal
[136b]Departamento de Física, Faculdade de Ciências, Universidade de Lisboa, Lisboa, Portugal
[136c]Departamento de Física, Universidade de Coimbra, Coimbra, Portugal

[136d]*Centro de Física Nuclear da Universidade de Lisboa, Lisboa, Portugal*
[136e]*Departamento de Física, Universidade do Minho, Braga, Portugal*
[136f]*Departamento de Física Teorica y del Cosmos, Universidad de Granada, Granada (Spain), Spain*
[136g]*Dep Física and CEFITEC of Faculdade de Ciências e Tecnologia, Universidade Nova de Lisboa, Caparica, Portugal*
[137]*Institute of Physics, Academy of Sciences of the Czech Republic, Prague, Czech Republic*
[138]*Czech Technical University in Prague, Prague, Czech Republic*
[139]*Charles University, Faculty of Mathematics and Physics, Prague, Czech Republic*
[140]*State Research Center Institute for High Energy Physics, NRC KI, Protvino, Russia*
[141]*Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom*
[142]*IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France*
[143]*Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz, California, USA*
[144a]*Departamento de Física, Pontificia Universidad Católica de Chile, Santiago, Chile*
[144b]*Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso, Chile*
[145]*Department of Physics, University of Washington, Seattle, Washington, USA*
[146]*Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom*
[147]*Department of Physics, Shinshu University, Nagano, Japan*
[148]*Department Physik, Universität Siegen, Siegen, Germany*
[149]*Department of Physics, Simon Fraser University, Burnaby, British Columbia, Canada*
[150]*SLAC National Accelerator Laboratory, Stanford, California, USA*
[151]*Physics Department, Royal Institute of Technology, Stockholm, Sweden*
[152]*Departments of Physics and Astronomy, Stony Brook University, Stony Brook NY, USA*
[153]*Department of Physics and Astronomy, University of Sussex, Brighton, United Kingdom*
[154]*School of Physics, University of Sydney, Sydney, Australia*
[155]*Institute of Physics, Academia Sinica, Taipei, Taiwan*
[156a]*E. Andronikashvili Institute of Physics, Iv. Javakhishvili Tbilisi State University, Tbilisi, Georgia*
[156b]*High Energy Physics Institute, Tbilisi State University, Tbilisi, Georgia*
[157]*Department of Physics, Technion, Israel Institute of Technology, Haifa, Israel*
[158]*Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel*
[159]*Department of Physics, Aristotle University of Thessaloniki, Thessaloniki, Greece*
[160]*International Center for Elementary Particle Physics and Department of Physics, University of Tokyo, Tokyo, Japan*
[161]*Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo, Japan*
[162]*Department of Physics, Tokyo Institute of Technology, Tokyo, Japan*
[163]*Tomsk State University, Tomsk, Russia*
[164]*Department of Physics, University of Toronto, Toronto, Ontario, Canada*
[165a]*TRIUMF, Vancouver, British Columbia, Canada*
[165b]*Department of Physics and Astronomy, York University, Toronto, Ontario, Canada*
[166]*Division of Physics and Tomonaga Center for the History of the Universe, Faculty of Pure and Applied Sciences, University of Tsukuba, Tsukuba, Japan*
[167]*Department of Physics and Astronomy, Tufts University, Medford, Massachusetts, USA*
[168]*Department of Physics and Astronomy, University of California Irvine, Irvine, California, USA*
[169]*Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden*
[170]*Department of Physics, University of Illinois, Urbana, Illinois, USA*
[171]*Instituto de Física Corpuscular (IFIC), Centro Mixto Universidad de Valencia—CSIC, Valencia, Spain*
[172]*Department of Physics, University of British Columbia, Vancouver, British Columbia, Canada*
[173]*Department of Physics and Astronomy, University of Victoria, Victoria, British Columbia, Canada*
[174]*Fakultät für Physik und Astronomie, Julius-Maximilians-Universität Würzburg, Würzburg, Germany*
[175]*Department of Physics, University of Warwick, Coventry, United Kingdom*
[176]*Waseda University, Tokyo, Japan*
[177]*Department of Particle Physics, Weizmann Institute of Science, Rehovot, Israel*
[178]*Department of Physics, University of Wisconsin, Madison, Wisconsin, USA*
[179]*Fakultät für Mathematik und Naturwissenschaften, Fachgruppe Physik, Bergische Universität Wuppertal, Wuppertal, Germany*
[180]*Department of Physics, Yale University, New Haven, Connecticut, USA*
[181]*Yerevan Physics Institute, Yerevan, Armenia*

[a]Deceased.
[b]Also at Department of Physics, King's College London, London, United Kingdom.
[c]Also at Istanbul University, Dept. of Physics, Istanbul, Turkey.
[d]Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan.
[e]Also at TRIUMF, Vancouver, British Columbia, Canada.
[f]Also at Department of Physics and Astronomy, University of Louisville, Louisville, Kentucky, USA.

[g]Also at Department of Physics, California State University, Fresno, California, USA.
[h]Also at Department of Physics, University of Fribourg, Fribourg, Switzerland.
[i]Also at II. Physikalisches Institut, Georg-August-Universität Göttingen, Göttingen, Germany.
[j]Also at Departament de Fisica de la Universitat Autonoma de Barcelona, Barcelona, Spain.
[k]Also at Tomsk State University, Tomsk, and Moscow Institute of Physics and Technology State University, Dolgoprudny, Russia.
[l]Also at The Collaborative Innovation Center of Quantum Matter (CICQM), Beijing, China.
[m]Also at Universita di Napoli Parthenope, Napoli, Italy.
[n]Also at Institute of Particle Physics (IPP), Canada.
[o]Also at Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest, Romania.
[p]Also at CPPM, Aix-Marseille Université, CNRS/IN2P3, Marseille, France.
[q]Also at Department of Physics, St. Petersburg State Polytechnical University, St. Petersburg, Russia.
[r]Also at Borough of Manhattan Community College, City University of New York, New York, USA.
[s]Also at Department of Financial and Management Engineering, University of the Aegean, Chios, Greece.
[t]Also at Centre for High Performance Computing, CSIR Campus, Rosebank, Cape Town, South Africa.
[u]Also at Louisiana Tech University, Ruston, Louisiana, USA.
[v]Also at Institucio Catalana de Recerca i Estudis Avancats, ICREA, Barcelona, Spain.
[w]Also at Department of Physics, University of Michigan, Ann Arbor, Michigan, USA.
[x]Also at LAL, Université Paris-Sud, CNRS/IN2P3, Université Paris-Saclay, Orsay, France.
[y]Also at Graduate School of Science, Osaka University, Osaka, Japan.
[z]Also at Physikalisches Institut, Albert-Ludwigs-Universität Freiburg, Freiburg, Germany.
[aa]Also at Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands.
[bb]Also at Institute of Theoretical Physics, Ilia State University, Tbilisi, Georgia.
[cc]Also at CERN, Geneva, Switzerland.
[dd]Also at Manhattan College, New York, New York, USA.
[ee]Also at Hellenic Open University, Patras, Greece.
[ff]Also at The City College of New York, New York, New York, USA.
[gg]Also at Departamento de Física Teorica y del Cosmos, Universidad de Granada, Granada (Spain), Spain.
[hh]Also at Department of Physics, California State University, Sacramento, California, USA.
[ii]Also at Moscow Institute of Physics and Technology State University, Dolgoprudny, Russia.
[jj]Also at Département de Physique Nucléaire et Corpusculaire, Université de Genève, Genève, Switzerland.
[kk]Also at Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom.
[ll]Also at School of Physics, Sun Yat-sen University, Guangzhou, China.
[mm]Also at Department of Applied Physics and Astronomy, University of Sharjah, Sharjah, United Arab Emirates.
[nn]Also at Institut für Experimentalphysik, Universität Hamburg, Hamburg, Germany.
[oo]Also at National Research Nuclear University MEPhI, Moscow, Russia.
[pp]Also at Institute for Particle and Nuclear Physics, Wigner Research Centre for Physics, Budapest, Hungary.
[qq]Also at Giresun University, Faculty of Engineering, Giresun, Turkey.
[rr]Also at Institute of Physics, Academia Sinica, Taipei, Taiwan.