The following full text is a publisher's version.

For additional information about this publication click this link.
http://hdl.handle.net/2066/198821

Please be advised that this information was generated on 2019-09-13 and may be subject to change.
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)

(Received 9 August 2018; published 20 November 2018)

A combination of the searches for pair-produced vectorlike 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 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 $|V_{Tb}| \ll |V_{ib}|$, $T$ and $B$ masses below 1.37 TeV are excluded.

DOI: 10.1103/PhysRevLett.121.211801

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 $T \rightarrow WB$. 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 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 $BB$ and $TT$ production and decay are shown in Fig. 1.

The branching ratio $(B)$ 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 in a $(T, B)$ doublet with $|V_{Tb}| \ll |V_{ib}|$, 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 $|V_{Tb}| \ll |V_{ib}|$, $B \rightarrow Wt$ 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
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 $H \rightarrow bb$. 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 ($S_T$) 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.

$W(\ell\nu)t + X$ [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.

$Z(\ell\nu)t + X$ [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 ($Z \rightarrow \ell^+\ell^-$) 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 $\geq 2$). 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 $E_T^{\text{miss}}$, 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 $B \bar{B} \rightarrow Hb\bar{H}$. 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 “⋯” indicates that the analysis was not used for that signal process.

<table>
<thead>
<tr>
<th>Analysis</th>
<th>$T\bar{T}$ decay</th>
<th>$B\bar{B}$ decay</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H(b\bar{b}) + X$ [16]</td>
<td>$Hh\bar{h}$</td>
<td>⋯</td>
</tr>
<tr>
<td>$W(\ell\nu)b + X$ [17]</td>
<td>$Wb\bar{W}b$</td>
<td>⋯</td>
</tr>
<tr>
<td>$W(\ell\nu)t + X$ [18]</td>
<td>⋯</td>
<td>$Wt\bar{W}t$</td>
</tr>
<tr>
<td>$Z(\nu\nu)t + X$ [19]</td>
<td>$Zt\bar{Z}t$</td>
<td>⋯</td>
</tr>
<tr>
<td>$Z(\ell\ell)/b + X$ [20]</td>
<td>$Z\bar{b}Z\bar{b}$</td>
<td>⋯</td>
</tr>
<tr>
<td>Tril./s.s. dilepton [21]</td>
<td>$Hh\bar{h}$</td>
<td>$Wt\bar{W}t$</td>
</tr>
<tr>
<td>Fully hadronic [22]</td>
<td>$Hh\bar{h}$</td>
<td>$Hb\bar{H}b$</td>
</tr>
</tbody>
</table>

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 $\geq 6$ jets and $\geq 3$ $b$-jets to avoid overlap with the $H(b\bar{b})t + X$ 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 $Z(\ell\ell)/b + X$ 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 PROTON 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 $\mu$, a factor multiplying the theoretical signal cross section ($\mu = \sigma/\sigma_{\text{theory}}$), 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

![FIG. 2.](image-url) 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 $\pm 1$ 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.
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 $Z(\nu\bar{\nu})t+X$ 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 $Z(\nu\bar{\nu})t+X$ 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

![Graph of observed and expected 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.](image)

**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 $\pm 1$ 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.
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 $B(T \to Ht) + B(T \to Zt) + B(T \to Wb) = 1$ and $B(B \to Hb) + B(B \to Zb) + B(B \to Wt) = 1$. 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 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 $\sim$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 $B(T \to Ht) + B(T \to Zt) + B(T \to Wb) = 1$ and $B(B \to Hb) + B(B \to Zb) + B(B \to Wt) = 1$. The resulting lower limits on the VLQ mass as a function of branching ratio are presented in Fig. 4. Limits corresponding to $B(T \to Wb) = 1$ and $B(B \to Wt) = 1$ 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.

We thank CERN for the very successful operation of the LHC, as well as the support staff from our institutions without whom ATLAS could not be operated efficiently. We acknowledge the support of ANPCyT, Argentina; YerPhI, Armenia; ARC, Australia; BMWFW and FWF, Austria; ANAS, Azerbaijan; SSTC, Belarus; CNPq and FAPESP, Brazil; NSERC, NRC and CFI, Canada; CERN; CONICYT, Chile; CAS, MOST and NSFC, China; COLCIENCIAS, Colombia; MSMT CR, MPO CR and VSC CR, Czech Republic; DNRF and DNSRC, Denmark; IN2P3-CNRS, CEA-DRF/IRFU, France; SRNSFG, Georgia; BMBF, HGF, and MPG, Germany; GSRT, Greece; RGC, Hong Kong SAR, China; ISF, I-CORE and Benoziyo Center, Israel; INFN, Italy; MEXT and JSPS, Japan; CNRST, Morocco; NWO, Netherlands; RCN, Norway; MNiSW and NCN, Poland; FCT, Portugal; MNE/IFA, Romania; MES of Russia and NRC KI, Russian Federation; JINR; MESTD, Serbia; MSSR, Slovakia; ARRS and MIZŠ, Slovenia; DST/NRF, South Africa; MINECO, Spain; SRC and Wallenberg Foundation, Sweden; SERI, SNSF and Cantons of Bern and Geneva, Switzerland; MOST, Taiwan; TAEK, Turkey; STFC,
United Kingdom; DOE and NSF, United States of America. In addition, individual groups and members have received support from BCKDF, the Canada Council, CANARIE, CRC, Compute Canada, FORNT, and the Ontario Innovation Trust, Canada; EPLANET, ERC, ERDF, FP7, Horizon 2020 and Marie Skłodowska-Curie Actions, European Union; Investissements d’Avenir Labex and Idex, ANR, Région Auvergne and Fondation Partager le Savoir, France; DFG and AvH Foundation, Germany; Herakleitos, Thales and Aristeia programmes co-financed by EU-ESF and the Greek NSRF; BSF, GIF and Minerva, Israel; BRF, Norway; CERCA Programme Generalitat de Catalunya, Generalitat Valenciana, Spain; the Royal Society and Leverhulme Trust, United Kingdom. The crucial computing support from all WLCG partners is acknowledged gratefully, in particular from CERN, the ATLAS Tier-1 facilities at TRIUMF (Canada), NDGF (Denmark, Norway, Sweden), CC-IN2P3 (France), KIT/GridKA (Germany), INFN-CNAF (Italy), NL-T1 (Netherlands), PIC (Spain), ASGC (Taiwan), RAL (UK) and BNL (USA), the Tier-2 facilities worldwide and large non-WLCG resource providers. Major contributors of computing resources are listed in Ref. [53].


[41] P. Bärnreuther, M. Czakon, A. Mitov, Percent-Level-Precision Physics at the Tevatron: Next-to-Next-to-Leading Order QCD Corrections to $q\bar{q} \rightarrow t\bar{t} + X$, Phys. Rev. Lett. 109, 132001 (2012).


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

211801-16
Centre de Calcul de l’Institut National de Physique Nucléaire et de Physique des Particules (IN2P3), Villeurbanne, France

Department of Physics and Astronomy, University of Oklahoma, Norman, Oklahoma, USA

Research Center for Advanced Particle Physics and Department of Physics, Kyushu University, Fukuoka, Japan

Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata, Argentina

Physics Department, Lancaster University, Lancaster, United Kingdom

Department of Experimental Particle Physics, Jožef Stefan Institute and Department of Physics, University of Ljubljana, Ljubljana, Slovenia

School of Physics and Astronomy, Queen Mary University of London, London, United Kingdom

Department of Physics, Royal Holloway University of London, Egham, United Kingdom

Department of Physics and Astronomy, University College London, London, United Kingdom

Louisiana Tech University, Ruston, Louisiana, USA

Fysiska institutionen, Lunds universitet, Lund, Sweden

Department of Physics, Royal Holloway University of London, Egham, United Kingdom

School of Physics, University of Manchester, Manchester, United Kingdom

School of Physics and Astronomy, University of New Mexico, Albuquerque, New Mexico, USA

Graduate School of Science and Kobayashi-Maskawa Institute, Nagoya University, Nagoya, Japan

Department of Physics, University of North Carolina at Chapel Hill, Chapel Hill, North Carolina, USA

Louisiana Tech University, Ruston, Louisiana, USA

Research Institute for Nuclear Problems of Byelorussian State University, Minsk, Belarus

B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Minsk, Belarus

Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan, USA

School of Physics, University of Melbourne, Victoria, Australia

Institut National de Physique Nucléaire et de Physique des Particules (IN2P3), Villeurbanne, France

Institut für Physik, Universität Mainz, Mainz, Germany

School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom

CPPM, Aix-Marseille Université, CNRS/IN2P3, Marseille, France

Department of Physics, University of Massachusetts, Amherst, Massachusetts, USA

Department of Physics, McGill University, Montreal, Quebec, Canada

School of Physics, University of Melbourne, Victoria, Australia

Department of Physics, University of Michigan, Ann Arbor, Michigan, USA

B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Minsk, Belarus

Research Institute for Nuclear Problems of Byelorussian State University, Minsk, Belarus

Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan, USA

Graduate School of Science, Osaka University, Osaka, Japan

Department of Physics and Astronomy, University of New Mexico, Albuquerque, New Mexico, USA

Research Institute for Nuclear Problems of Byelorussian State University, Minsk, Belarus

School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom

Department of Physics and Astronomy, University of New Mexico, Albuquerque, New Mexico, USA

Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München, Germany

Nagasaki Institute of Applied Science, Nagasaki, Japan

Graduate School of Science and Kobayashi-Maskawa Institute, Nagoya University, Nagoya, Japan

Fakultät für Physik, Ludwig-Maximilians-Universität München, München, Germany

Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München, Germany

Department of Physics and Astronomy, University of New Mexico, Albuquerque, New Mexico, USA

Department of Physics, Northern Illinois University, DeKalb, Illinois, USA

Budker Institute of Nuclear Physics, SB RAS, Novosibirsk, Russia

Novosibirsk State University Novosibirsk, Russia

Department of Physics, New York University, New York, New York, USA

Ohio State University, Columbus, Ohio, USA

Faculty of Science, Okayama University, Okayama, Japan

Department of Physics and Astronomy, University of Oklahoma, Norman, Oklahoma, USA

Department of Physics, Oklahoma State University, Stillwater, Oklahoma, USA

Palacký University, RCPTM, Joint Laboratory of Optics, Olomouc, Czech Republic

Center for High Energy Physics, University of Oregon, Eugene, Oregon, USA

Université Paris-Sud, CNRS/IN2P3, Université Paris-Saclay, Orsay, France

Graduate School of Science, Osaka University, Osaka, Japan

Department of Physics, University of Oslo, Oslo, Norway

Department of Physics, Oxford University, Oxford, United Kingdom

LPNHE, Sorbonne Université, Paris Diderot Sorbonne Paris Cité, CNRS/IN2P3, Paris, France

Department of Physics, University of Pennsylvania, Philadelphia, Pennsylvania, USA

Konstantinov Nuclear Physics Institute of National Research Centre “Kurchatov Institute”, PNPI, St. Petersburg, Russia

Department of Physics and Astronomy, National Academy of Sciences of Belarus, Minsk, Belarus

Department of Physics, University of Pennsylvania, Philadelphia, Pennsylvania, USA

Laboratório de Instrumentação e Física Experimental de Partículas—LIP, Portugal

Departamento de Física, Faculdade de Ciências, Universidade de Lisboa, Lisboa, Portugal

Departamento de Física, Universidade de Coimbra, Coimbra, Portugal