Search for Leptoquarks Coupled to Third-Generation Quarks in Proton-Proton Collisions at $\sqrt{s}=13$ TeV

A. M. Sirunyan et al.*
(CMS Collaboration)

(Received 14 September 2018; published 12 December 2018)

Three of the most significant measured deviations from standard model predictions, the enhanced decay rate for $B \to D^{(*)}\tau\nu$, hints of lepton universality violation in $B \to K^{(*)}\ell\ell$ decays, and the anomalous magnetic moment of the muon, can be explained by the existence of leptoquarks (LQs) with large couplings to third-generation quarks and masses at the TeV scale. The existence of these states can be probed at the LHC in high energy proton-proton collisions. A novel search is presented for pair production of LQs coupled to a top quark and a muon using data at a center-of-mass energy of 13 TeV, corresponding to an integrated luminosity of 35.9 fb$^{-1}$, recorded by the CMS experiment. No deviation from the standard model prediction has been observed and scalar LQs decaying exclusively into $\tau\mu$ are excluded up to masses of 1420 GeV. The results of this search are combined with those from previous searches for LQ decays into $tr$ and $bu$, which excluded scalar LQs below masses of 900 and 1080 GeV. Vector LQs are excluded up to masses of 1190 GeV for all possible combinations of branching fractions to $\tau\mu$, $tr$ and $bu$. With this analysis, all relevant couplings of LQs with an electric charge of $-1/3$ to third-generation quarks are probed for the first time.

DOI: 10.1103/PhysRevLett.121.241802

The standard model of particle physics has been outstandingly successful in describing most fundamental physical phenomena. However, significant deviations from the predictions of the standard model (SM) have been observed in measurements of rare decays of $B$ mesons. In particular, deviations have been seen in the values of the ratio $R_{D^{(*)}}$, defined as the ratio of the $B \to D^{(*)}\tau\nu$ branching fraction to the $B \to D^{(*)}\mu\nu$ branching fraction. These deviations from the SM were first reported by the BABAR [1,2] and Belle [3–5] Collaborations and have been confirmed by the LHCb Collaboration [6,7] with a combined significance of about four standard deviations [8]. The ratios of the branching fractions of $B \to K^{(*)}\mu\mu$ to $B \to K^{(*)}ee$, $R_K$ and $R_{K^*}$, as measured by the LHCb Collaboration [9–12], show departures from lepton universality by 2.6 and 2.4 standard deviations, respectively. The measurement of the muon anomalous magnetic moment $a_\mu$, one of the most precisely measured quantities in particle physics [13], also deviates from the SM prediction by 3.5 standard deviations [14]. These anomalies are among the most significant deviations from the SM observed so far.

The existence of leptoquarks (LQs) with masses at the TeV scale and large couplings to third-generation quarks [15–25] has been proposed as a possible explanation for one, two, or all of these deviations. Leptoquarks are hypothetical particles that can decay to SM quarks and leptons. They are triplets with respect to the strong interaction, have fractional electric charge, and can be either scalar (spin 0) or vector (spin 1) particles. Many extensions to the SM, among them grand unification [26–28], technicolor [29,30], and compositeness models [31,32], predict the existence of these particles. The effective Buchmüller-Rückl-Wyler model [33] incorporates the assumption that LQ interactions with SM fermions are renormalizable and gauge invariant, leading to restrictions on the allowed quantum numbers of LQs [34]. Depending on its quantum numbers and the coupling structure, a given LQ can decay to any one of a number of different combinations of SM fermions. The couplings of LQs to leptons and quarks of different generations introduce flavor changing neutral currents that may be observable in precision measurements [35]. While simultaneous couplings to the first and second generations are tightly constrained by experimental data, the bounds are weaker for couplings to the second and third generation, thus allowing the existence of leptoquarks with nondiagonal couplings in the generation matrix [19,24,36]. Collider searches for LQs with decays to third-generation quarks have been performed in the decay channels $LQ \to tr$, $LQ \to br$, and $LQ \to bv$ at $\sqrt{s}=8$ TeV [37–44] and recently at $\sqrt{s}=13$ TeV [45–49]. We present...
the first search for the pair production of LQs with decays to a top quark and a muon, \( t\mu \), a decay mode that is essential to explain the anomalies in \( a_\mu \) and \( R_{K^0}\) [19–25]. This search is combined with previous searches that target other decay modes [48,49]. The combination provides sensitivity to all relevant couplings of LQs with an electric charge of \(-1/3\) to third-generation quarks.

At the CERN LHC, pair production of LQs is possible via gluon-gluon fusion or quark-antiquark annihilation, allowing direct searches to be performed. Single LQ production via quark-gluon scattering is subdominant for allowing direct searches to be performed. Single LQ via gluon-gluon fusion or quark-antiquark annihilation, \( \kappa \) and production cross section for vector LQs has been calculated with a definition of the coordinate system used and the relevant kinematic variables, can be found in Ref.[52].

This analysis uses data recorded by the CMS detector in \( pp \) collisions at a center-of-mass energy of 13 TeV in 2016. Online, potential signal events are required to pass a single-muon trigger that selects isolated muon candidates with transverse momentum \( p_T > 24 \) GeV [53]. Data recorded by single electron triggers are used in background-enriched control regions (CRs). The data correspond to an integrated luminosity of 35.9 fb\(^{-1}\).

Signal events of pair-produced LQs with prompt decays to \( t\mu \) are simulated with the PYTHIA 8.205 [54,55] Monte Carlo program at LO for mass values ranging from 200 to 2000 GeV. The POWHEG [56–63] v1 generator is used to simulate background events resulting from the production of single top quarks in the \( tW \) channel at NLO. The POWHEG v2 generator is used for single top production in the \( t \) channel and for simulating \( t\bar{t} \) production at NLO. Single top quark production in the \( s \) channel, \( t\bar{t} \) production in association with a heavy gauge boson (\( t\bar{t} + V \)), and the production of a \( W \) boson with additional jet radiation are simulated with \textsc{MadGraph 5\_amc@nlo} (v2.2.2) [64] at NLO. Events from Drell-Yan (DY) production with additional jet radiation are simulated with \textsc{MadGraph 5\_amc@nlo} and \textsc{powheg v2}. Events in which jets are produced through the strong interaction only, referred to as quantum chromodynamic multijet events, are simulated with \textsc{pythia} at LO.

Parton showers in the simulated \( W \) boson production events and DY events with additional jet radiation are matched to the matrix element calculation with the \textsc{fxfx} [65] and MLM [66] algorithms, respectively. The parton shower and hadronization process is simulated with \textsc{pythia}. The NNPDF3.0 [67] parton distribution functions (PDFs) at LO and NLO are used for processes simulated at LO and NLO, respectively. The underlying event tune \textsc{cuetp8m2t4} [68] is used for the simulation of \( \bar{t}t \) and single top quark production via the \( t \) channel, all other processes are generated using \textsc{cuettpm1} [69,70]. All simulated event samples include the simulation of additional inelastic \( pp \) interactions within the same or adjacent bunch crossings (pileup). The detector response is simulated with the \textsc{geant4} package [71,72]. Simulated events are processed through the software chain used for collision data and are reweighted to match the observed distribution of the number of pileup interactions in data.

The CMS experiment uses a particle-flow (PF) event reconstruction algorithm [73], which makes use of an optimized combination of information from the various elements of the CMS detector. The reconstructed vertex with the largest value of summed physics object \( p_T^2 \) is taken to be the primary \( pp \) interaction vertex. The physics objects here are the objects returned by a jet finding algorithm [74,75] applied to all charged tracks associated with the vertex, plus the associated missing transverse momentum, taken as the negative vector \( p_T \) sum of those jets. More details are given in Ref. [76]. All detected particles are reconstructed either as electrons, muons, photons, charged hadrons, or neutral hadrons. In this analysis, electrons and muons are required to have \( p_T \geq 30 \) GeV, \( |\eta| \leq 2.4 \), and to be isolated. The isolation [77,78] is defined as the sum of those jets. More details are given in Ref. [76]. All detected particles are reconstructed either as electrons, muons, photons, charged hadrons, or neutral hadrons. In this analysis, electrons and muons are required to have \( p_T \geq 30 \) GeV, \( |\eta| \leq 2.4 \), and to be isolated. The isolation [77,78] is defined as the sum of those jets. More details are given in Ref. [76].

Finally, a correction is applied
to account for the residual differences in the jet response between data and simulated events. The jet energy resolution (JER) in simulated events is smeared to match the wider resolution in data. All jets are required to have $p_T \geq 30$ GeV and $|\eta| \leq 2.4$. The combined secondary vertex v2 [80] algorithm is used to identify jets originating from bottom quarks ($b$-tagged jets). The loose working point is chosen, which has an efficiency of about 90% and a mistag rate of approximately 10%. The missing transverse momentum $p_T^{\text{miss}}$ is calculated as the magnitude of the negative vectorial $p_T$ sum of all PF candidates in an event. Both the jet energy scale and resolution corrections are propagated to the calculation of $p_T^{\text{miss}}$.

Offline, events are required to contain at least two muons and at least two jets, of which at least one must be $b$ tagged. By requiring the invariant mass of each pair of muons in an event to exceed the $Z$ boson mass by at least 20 GeV, events arising from the production of a $Z$ boson with additional jet radiation are suppressed. As the decay of heavy LQs is expected to produce highly energetic leptons and jets, radiation are suppressed. As the decay of heavy LQs is expected to produce highly energetic leptons and jets, radiation are suppressed. The loose working point is chosen, which has an efficiency of about 90% and a mistag rate of approximately 10%. The missing transverse momentum $p_T^{\text{miss}}$ is calculated as the magnitude of the negative vectorial $p_T$ sum of all PF candidates in an event. Both the jet energy scale and resolution corrections are propagated to the calculation of $p_T^{\text{miss}}$.

Offline, events are required to contain at least two muons and at least two jets, of which at least one must be $b$ tagged. By requiring the invariant mass of each pair of muons in an event to exceed the $Z$ boson mass by at least 20 GeV, events arising from the production of a $Z$ boson with additional jet radiation are suppressed. As the decay of heavy LQs is expected to produce highly energetic leptons and jets, radiation are suppressed. The loose working point is chosen, which has an efficiency of about 90% and a mistag rate of approximately 10%. The missing transverse momentum $p_T^{\text{miss}}$ is calculated as the magnitude of the negative vectorial $p_T$ sum of all PF candidates in an event. Both the jet energy scale and resolution corrections are propagated to the calculation of $p_T^{\text{miss}}$.

Offline, events are required to contain at least two muons and at least two jets, of which at least one must be $b$ tagged. By requiring the invariant mass of each pair of muons in an event to exceed the $Z$ boson mass by at least 20 GeV, events arising from the production of a $Z$ boson with additional jet radiation are suppressed. As the decay of heavy LQs is expected to produce highly energetic leptons and jets, radiation are suppressed. The loose working point is chosen, which has an efficiency of about 90% and a mistag rate of approximately 10%. The missing transverse momentum $p_T^{\text{miss}}$ is calculated as the magnitude of the negative vectorial $p_T$ sum of all PF candidates in an event. Both the jet energy scale and resolution corrections are propagated to the calculation of $p_T^{\text{miss}}$.

Offline, events are required to contain at least two muons and at least two jets, of which at least one must be $b$ tagged. By requiring the invariant mass of each pair of muons in an event to exceed the $Z$ boson mass by at least 20 GeV, events arising from the production of a $Z$ boson with additional jet radiation are suppressed. As the decay of heavy LQs is expected to produce highly energetic leptons and jets, radiation are suppressed. The loose working point is chosen, which has an efficiency of about 90% and a mistag rate of approximately 10%. The missing transverse momentum $p_T^{\text{miss}}$ is calculated as the magnitude of the negative vectorial $p_T$ sum of all PF candidates in an event. Both the jet energy scale and resolution corrections are propagated to the calculation of $p_T^{\text{miss}}$.

Offline, events are required to contain at least two muons and at least two jets, of which at least one must be $b$ tagged. By requiring the invariant mass of each pair of muons in an event to exceed the $Z$ boson mass by at least 20 GeV, events arising from the production of a $Z$ boson with additional jet radiation are suppressed. As the decay of heavy LQs is expected to produce highly energetic leptons and jets, radiation are suppressed. The loose working point is chosen, which has an efficiency of about 90% and a mistag rate of approximately 10%. The missing transverse momentum $p_T^{\text{miss}}$ is calculated as the magnitude of the negative vectorial $p_T$ sum of all PF candidates in an event. Both the jet energy scale and resolution corrections are propagated to the calculation of $p_T^{\text{miss}}$.

Offline, events are required to contain at least two muons and at least two jets, of which at least one must be $b$ tagged. By requiring the invariant mass of each pair of muons in an event to exceed the $Z$ boson mass by at least 20 GeV, events arising from the production of a $Z$ boson with additional jet radiation are suppressed. As the decay of heavy LQs is expected to produce highly energetic leptons and jets, radiation are suppressed. The loose working point is chosen, which has an efficiency of about 90% and a mistag rate of approximately 10%. The missing transverse momentum $p_T^{\text{miss}}$ is calculated as the magnitude of the negative vectorial $p_T$ sum of all PF candidates in an event. Both the jet energy scale and resolution corrections are propagated to the calculation of $p_T^{\text{miss}}$.
the SM backgrounds and the signal, as well as all systematic uncertainties, are taken into account as nuisance parameters in the fit. The uncertainty in the luminosity is assigned a log-normal prior distribution, for all other systematic uncertainties a Gaussian prior is used. The statistical uncertainty in the predicted background and the signal is taken into account by defining one additional nuisance parameter with a Gaussian distribution for each bin. A flat prior distribution is assumed for the signal cross section. The data are found to be compatible with the SM prediction in both categories. The distributions of $M_{\ell Q}$ and $S_T$ after the background-only fit are shown in Fig. 1. A Bayesian method [93–95] is used to set upper limits at 95% confidence level (C.L.) on the cross section for pair production of LQs decaying into a top quark and a muon. Pseudoexperiments are performed to determine the median along with the regions expected to contain 68% and 95% of the distribution of limits under the background-only hypothesis.

![Graph](image1.png)

**FIG. 1.** Distributions for $M_{\ell Q}$ (category A, left) and $S_T$ (category B, right) after applying the full selection and estimating the $t\bar{t}$ and DY + jets background contributions from data in category B. All backgrounds are normalized according to the post-fit nuisance parameters based on the corresponding SM cross sections. In the upper panels, the hatched areas correspond to the total uncertainty. In the lower panels, the gray bands indicate the total uncertainty.

![Graph](image2.png)

**FIG. 2.** Observed upper limits on the production cross section for pair production of LQs decaying into a top quark and a muon or a $\tau$ lepton (upper) and LQs decaying into a top quark and a muon or into a bottom quark and a neutrino (lower) at 95% C.L. in the $M_{\ell Q} - B(LQ \rightarrow t\mu)$ plane. The lines show the lower mass exclusion limits for scalar (black) and vector (colored) LQs. They are derived by using the prediction for the scalar and vector LQ signal calculated at NLO [50] and LO [51], respectively.
Pair-produced scalar LQs decaying exclusively into a top quark and a muon, \( B(LQ \to \mu t) = 1 \), are excluded at 95% C.L. for LQ masses up to 1420 GeV, exceeding the best previous limit, obtained from a reinterpretation [36] of a search for supersymmetry [96], by more than 600 GeV. These results are combined with results from the LQ \( \to t\tau \) decay channel to set exclusions limits in the plane of \( M_{LQ} \) and \( B(LQ \to \mu t) \). Figure 2 presents upper limits on the product of the production cross section and the branching fraction squared for \( B(LQ \to \mu t) = 1 - B(LQ \to \tau \tau) \) (upper) and \( B(LQ \to \mu t) = 1 - B(LQ \to b \nu) \) (lower). The values for \( B(LQ \to \mu t) = 0 \) correspond to the results of the search for pair-produced LQs in the LQ \( t\tau \) decay channel (upper) and the search for pair-produced LQs in the LQ \( b \nu \) channel (lower). These analyses excluded pair-produced scalar LQs in the targeted decay channels up to \( M_{LQ} = 900 \) and 1080 GeV, respectively. In the upper (lower) part of Fig. 2 the sensitivity is driven by the present analysis for values of \( B(LQ \to \mu t) > 0.1(0.3) \) and by the LQ \( \to \tau \tau(b \nu) \) search for smaller values. Scalar LQs decaying into a top quark and either a muon or a \( \tau \) lepton are excluded below masses of 900 GeV for all values of \( B(LQ \to \mu t) \), whereas LQs decaying either into a top quark and a muon or into a bottom quark and a neutrino are excluded up to \( M_{LQ} = 980 \) GeV. The simulated samples of scalar LQ pair production are also used to derive mass exclusion limits for pair-produced vector LQs, as the acceptance for both types of LQs is similar. The lower limit of excluded vector LQ masses is shown in Fig. 2 for the two coupling cases \( \kappa = 1 \) and \( \kappa = 0 \). Vector LQs are excluded up to masses of 1190 GeV for all values of \( B(LQ \to \mu t) \) and \( \kappa \) considered.

In summary, this analysis represents the first search for leptoquarks decaying to top quarks and muons, reaching LQ masses of \( \mathcal{O}(1 \text{ TeV}) \) and placing direct constraints on the corresponding LQ coupling, thus probing the region of interest of models including LQs. With this result, all relevant couplings of LQs with an electric charge of \(-1/3\) to third-generation quarks are examined for the first time.

We congratulate our colleagues in the CERN accelerator departments for the excellent performance of the LHC and thank the technical and administrative staffs at CERN and at other CMS institutes for their contributions to the success of the CMS effort. In addition, we gratefully acknowledge the computing centers and personnel of the Worldwide LHC Computing Grid for delivering so effectively the computing infrastructure essential to our analyses. Finally, we acknowledge the enduring support for the construction and operation of the LHC and the CMS detector provided by the following funding agencies: BMWFW and FWF (Austria); FNRS and FWO (Belgium); CNPq, CAPES, FAPERJ, and FAPESP (Brazil); MES (Bulgaria); CERN; CAS, MoST, and NSFC (China); COLCIENCIAS (Colombia); MSES and CSF (Croatia); RPF (Cyprus); SENESCYT (Ecuador); MoER, ERC IUT, and ERDF (Estonia); Academy of Finland, MEC, and HIP (Finland); CEA and CNRS/IN2P3 (France); BMBF, DFG, and HGF (Germany); GSRT (Greece); OTKA and NIH (Hungary); DAE and DST (India); IPM (Iran); SFI (Ireland); INFN (Italy); MSIP and NRF (Republic of Korea); LAS (Lithuania); MOE and UM (Malaysia); BUAP, CINVESTAV, CONACYT, LNS, SEP, and UASLP-FAI (Mexico); MBIE (New Zealand); PAEC (Pakistan); MSHE and NSC (Poland); FCT (Portugal); JINR (Dubna); MON, RosAtom, RAS, and RAEP (Russia); MESTD (Serbia); SEIDI, CPAN, PCTI and FEDER (Spain); Swiss Funding Agencies (Switzerland); MST (Taipei); ThEPCenter, IPST, STAR, and NSTDA (Thailand); TUBITAK and TAEK (Turkey); NASU and SFFR (Ukraine); STFC (United Kingdom); DOE and NSF (USA).

[4] A. Bozek et al. (Belle Collaboration), Observation of \( B^+ \to D^{(*)0}\mu^+\nu_\mu \) and evidence for \( B^+ \to D^{(*)0}\tau^+\nu_\tau \) at Belle, Phys. Rev. D 82, 072005 (2010).
[5] M. Huschle et al. (Belle Collaboration), Measurement of the branching ratio of \( \bar{B} \to D^{(*)+}\tau^-\bar{\nu}_\tau \) relative to \( \bar{B} \to D^{(*)-}\bar{\nu}_\tau \) decays with hadronic tagging at Belle, Phys. Rev. D 92, 072014 (2015).
[7] LHCB Collaboration, Test of lepton flavor universality by the measurement of the \( B^0 \to D^-\tau^+\nu_\tau \) branching fraction using three-prong \( \tau \) decays, Phys. Rev. D 97, 072013 (2018).
[12] LHCB Collaboration, Test of lepton universality with \( B^0 \to K^{(*)}\ell^+\ell^- \) decays, J. High Energy Phys. 08 (2017) 055.


[17] I. Došner, S. Faider, N. Košnik, and I. Nišandžić, Minimally flavored colored scalar in $\bar{B} \to D^{(*)} \tau\bar{\nu}$ and the mass matrices constraints, J. High Energy Phys. 11 (2013) 084.

[18] B. Dumont, K. Nishiwaki, and R. Watanabe, LHC constraints and prospects for $S_1$ scalar leptoquark explaining the $\bar{B} \to D^{(*)} \tau \bar{\nu}$ anomaly, Phys. Rev. D 94, 034001 (2016).


[38] V. M. Abazov et al. (DO Collaboration), Search for Third-Generation Leptoquarks in $p\bar{p}$ Collisions at $\sqrt{s}=1.96$ TeV, Phys. Rev. Lett. 99, 061801 (2007).


[91] CMS Collaboration (CMS Collaboration), CMS Luminosity Measurements for the 2016 Data Taking Period,


77a INFN Sezione di Torino, Torino, Italy
77b Università di Torino, Torino, Italy
77c Università del Piemonte Orientale, Novara, Italy
78a INFN Sezione di Trieste, Trieste, Italy
78b Università di Trieste, Trieste, Italy
79 Kyungpook National University, Daegu, Korea
80 Chonnam National University, Institute for Universe and Elementary Particles, Kwangju, Korea
81 Hanyang University, Seoul, Korea
82 Korea University, Seoul, Korea
83 Sejong University, Seoul, Korea
84 Seoul National University, Seoul, Korea
85 University of Seoul, Seoul, Korea
86 Sungkyunkwan University, Suwon, Korea
87 Vilnius University, Vilnius, Lithuania
88 National Centre for Particle Physics, Universiti Malaya, Kuala Lumpur, Malaysia
89 Universidad de Sonora (UNISON), Hermosillo, Mexico
90 Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico
91 Universidad Iberoamericana, Mexico City, Mexico
92 Benemerita Universidad Autonoma de Puebla, Puebla, Mexico
93 Universidad Autonoma de San Luis Potosi, San Luis Potosi, Mexico
94 University of Auckland, Auckland, New Zealand
95 University of Canterbury, Christchurch, New Zealand
96 National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan
97 National Centre for Nuclear Research, Swierk, Poland
98 Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland
99 Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal
100 Joint Institute for Nuclear Research, Duhna, Russia
101 Petersburg Nuclear Physics Institute, Gatchina (St. Petersburg), Russia
102 Institute for Nuclear Research, Moscow, Russia
103 Institute for Theoretical and Experimental Physics, Moscow, Russia
104 Moscow Institute of Physics and Technology, Moscow, Russia
105 National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia
106 P.N. Lebedev Physical Institute, Moscow, Russia
107 Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia
108 Novosibirsk State University (NSU), Novosibirsk, Russia
109 Institute for High Energy Physics of National Research Centre 'Kurchatov Institute', Protvino, Russia
110 National Research Tomsk Polytechnic University, Tomsk, Russia
111 University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia
112 Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain
113 Universidad Autónoma de Madrid, Madrid, Spain
114 Universidad de Oviedo, Oviedo, Spain
115 Instituto de Física de Cantabria (IFCA), CSIC-Universidad de Cantabria, Santander, Spain
116 University of Ruhuna, Department of Physics, Matara, Sri Lanka
117 CERN, European Organization for Nuclear Research, Geneva, Switzerland
118 Paul Scherrer Institut, Villigen, Switzerland
119 ETH Zurich—Institute for Particle Physics and Astrophysics (IPA), Zurich, Switzerland
120 Universitàt Zürich, Zurich, Switzerland
121 National Central University, Chung-Li, Taiwan
122 National Taiwan University (NTU), Taipei, Taiwan
123 Chulalongkorn University, Faculty of Science, Department of Physics, Bangkok, Thailand
124 Çukurova University, Physics Department, Science and Art Faculty, Adana, Turkey
125 Middle East Technical University, Physics Department, Ankara, Turkey
126 Bogazici University, Istanbul, Turkey
127 Istanbul Technical University, Istanbul, Turkey
128 Institute for Scintillation Materials of National Academy of Science of Ukraine, Kharkov, Ukraine
129 National Scientific Center, Kharkov Institute of Physics and Technology, Kharkov, Ukraine
130 University of Bristol, Bristol, United Kingdom
131 Rutherford Appleton Laboratory, Didcot, United Kingdom
132 Imperial College, London, United Kingdom
133 Brunel University, Uxbridge, United Kingdom
134 Baylor University, Waco, Texas, USA
135 Catholic University of America, Washington DC, USA
136 The University of Alabama, Tuscaloosa, USA
137 Boston University, Boston, Massachusetts, USA
138 Brown University, Providence, Rhode Island, USA
139 University of California, Davis, Davis, California, USA
140 University of California, Los Angeles, California, USA
141 University of California, Riverside, Riverside, California, USA
142 University of California, San Diego, La Jolla, California, USA
143 University of California, Santa Barbara—Department of Physics, Santa Barbara, California, USA
144 California Institute of Technology, Pasadena, California, USA
145 Carnegie Mellon University, Pittsburgh, Pennsylvania, USA
146 University of Colorado Boulder, Boulder, Colorado, USA
147 Cornell University, Ithaca, New York, USA
148 Fermi National Accelerator Laboratory, Batavia, Illinois, USA
149 University of Florida, Gainesville, Florida, USA
150 Florida International University, Miami, Florida, USA
151 Florida State University, Tallahassee, Florida, USA
152 Florida Institute of Technology, Melbourne, Florida, USA
153 University of Illinois at Chicago (UIC), Chicago, Illinois, USA
154 The University of Iowa, Iowa City, Iowa, USA
155 Johns Hopkins University, Baltimore, Maryland, USA
156 The University of Kansas, Lawrence, Kansas, USA
157 Kansas State University, Manhattan, Kansas, USA
158 Lawrence Livermore National Laboratory, Livermore, California, USA
159 University of Maryland, College Park, Maryland, USA
160 Massachusetts Institute of Technology, Cambridge, Massachusetts, USA
161 University of Minnesota, Minneapolis, Minnesota, USA
162 University of Mississippi, Oxford, Mississippi, USA
163 University of Nebraska-Lincoln, Lincoln, Nebraska, USA
164 State University of New York at Buffalo, Buffalo, New York, USA
165 Northeastern University, Boston, Massachusetts, USA
166 Northwestern University, Evanston, Illinois, USA
167 University of Notre Dame, Notre Dame, Indiana, USA
168 The Ohio State University, Columbus, Ohio, USA
169 Princeton University, Princeton, New Jersey, USA
170 University of Puerto Rico, Mayaguez, Puerto Rico
171 Purdue University, West Lafayette, Indiana, USA
172 Purdue University Northwest, Hammond, Indiana, USA
173 Rice University, Houston, Texas, USA
174 University of Rochester, Rochester, New York, USA
175 Rutgers, The State University of New Jersey, Piscataway, New Jersey, USA
176 University of Tennessee, Knoxville, Tennessee, USA
177 Texas A&M University, College Station, Texas, USA
178 Texas Tech University, Lubbock, Texas, USA
179 Vanderbilt University, Nashville, Tennessee, USA
180 University of Virginia, Charlottesville, Virginia, USA
181 Wayne State University, Detroit, Michigan, USA
182 University of Wisconsin—Madison, Madison, Wisconsin, USA

a Deceased.
b Also at Vienna University of Technology, Vienna, Austria.
c Also at IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France.
d Also at Universidade Estadual de Campinas, Campinas, Brazil.
e Also at Federal University of Rio Grande do Sul, Porto Alegre, Brazil.
f Also at Université Libre de Bruxelles, Bruxelles, Belgium.
g Also at University of Chinese Academy of Sciences.
h Also at Institute for Theoretical and Experimental Physics, Moscow, Russia.
i Also at Joint Institute for Nuclear Research, Dubna, Russia.
j Also at Helwan University, Cairo, Egypt.
\textsuperscript{Also at Zewail City of Science and Technology, Zewail, Egypt.}
\textsuperscript{Also at Ain Shams University, Cairo, Egypt.}
\textsuperscript{Also at British University in Egypt, Cairo, Egypt.}
\textsuperscript{Also at Department of Physics, King Abdulaziz University, Jeddah, Saudi Arabia.}
\textsuperscript{Also at Université de Haute Alsace, Mulhouse, France.}
\textsuperscript{Also at Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia.}
\textsuperscript{Also at Tbilisi State University, Tbilisi, Georgia.}
\textsuperscript{Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland.}
\textsuperscript{Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany.}
\textsuperscript{Also at University of Hamburg, Hamburg, Germany.}
\textsuperscript{Also at Brandenburg University of Technology, Cottbus, Germany.}
\textsuperscript{Also at MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary.}
\textsuperscript{Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary.}
\textsuperscript{Also at Institute of Physics, University of Debrecen, Debrecen, Hungary.}
\textsuperscript{Also at IIT Bhubaneswar, Bhubaneswar, India.}
\textsuperscript{Also at Shoolini University, Solan, India.}
\textsuperscript{Also at University of Visva-Bharati, Santiniketan, India.}
\textsuperscript{Also at Isfahan University of Technology, Isfahan, Iran.}
\textsuperscript{Also at Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, Tehran, Iran.}
\textsuperscript{Also at Università degli Studi di Siena, Siena, Italy.}
\textsuperscript{Also at Kyunghee University, Seoul, Korea.}
\textsuperscript{Also at International Islamic University of Malaysia, Kuala Lumpur, Malaysia.}
\textsuperscript{Also at Malaysian Nuclear Agency, MOSTI, Kajang, Malaysia.}
\textsuperscript{Also at Consejo Nacional de Ciencia y Tecnología, Mexico city, Mexico.}
\textsuperscript{Also at Warsaw University of Technology, Institute of Electronic Systems, Warsaw, Poland.}
\textsuperscript{Also at National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia.}
\textsuperscript{Also at St. Petersburg State Polytechnical University, St. Petersburg, Russia.}
\textsuperscript{Also at University of Florida, Gainesville, Florida, USA.}
\textsuperscript{Also at P.N. Lebedev Physical Institute, Moscow, Russia.}
\textsuperscript{Also at California Institute of Technology, Pasadena, California, USA.}
\textsuperscript{Also at Budker Institute of Nuclear Physics, Novosibirsk, Russia.}
\textsuperscript{Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia.}
\textsuperscript{Also at INFN Sezione di Pavia, Università di Pavia, Pavia, Italy.}
\textsuperscript{Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia.}
\textsuperscript{Also at Scuola Normale e Sezione dell'INFN, Pisa, Italy.}
\textsuperscript{Also at National and Kapodistrian University of Athens, Athens, Greece.}
\textsuperscript{Also at Riga Technical University, Riga, Latvia.}
\textsuperscript{Also at Universität Zürich, Zurich, Switzerland.}
\textsuperscript{Also at Stefan Meyer Institute for Subatomic Physics, Vienna, Austria.}
\textsuperscript{Also at Gaziosmanpasa University, Tokat, Turkey.}
\textsuperscript{Also at Adiyaman University, Adiyaman, Turkey.}
\textsuperscript{Also at Istanbul Aydin University, Istanbul, Turkey.}
\textsuperscript{Also at Mersin University, Mersin, Turkey.}
\textsuperscript{Also at Piri Reis University, Istanbul, Turkey.}
\textsuperscript{Also at Ozyegin University, Istanbul, Turkey.}
\textsuperscript{Also at Istanbul Institute of Technology, Izmir, Turkey.}
\textsuperscript{Also at Marmara University, Istanbul, Turkey.}
\textsuperscript{Also at Kafkas University, Kars, Turkey.}
\textsuperscript{Also at Istanbul University, Faculty of Science, Istanbul, Turkey.}
\textsuperscript{Also at Istanbul Bilgi University, Istanbul, Turkey.}
\textsuperscript{Also at Hacettepe University, Ankara, Turkey.}
\textsuperscript{Also at Rutherford Appleton Laboratory, Didcot, United Kingdom.}
\textsuperscript{Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom.}
\textsuperscript{Also at Monash University, Faculty of Science, Clayton, Australia.}
\textsuperscript{Also at Bethel University, St. Paul, USA.}
\textsuperscript{Also at Karamanoğlu Mehmetbey University, Karaman, Turkey.}
\textsuperscript{Also at Utah Valley University, Orem, Utah, USA.}
\textsuperscript{Also at Purdue University, West Lafayette, Indiana, USA.}