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 $t\mu$ 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 $bv$, 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 $t\mu$, $tr$ and $bv$. 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 $B \to K^{(*)}\ell\ell$, 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, LQ → τμ, a decay mode that is essential to explain the anomalies in a_t and R_K [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 LQs coupled to heavy quarks, as it requires a heavy quark in the initial state. The pair production cross section depends on the mass of the scalar LQ and is known at leading order (LO) [51] and is much larger than the scalar production cross section for vector LQs has been calculated at next-to-leading order (NLO) precision [50]. The pair production cross section for vector LQs has been calculated at leading order (LO) [51] and is much larger than the scalar LQ cross section. The cross section for vector LQs depends on an additional parameter κ, which is a dimensionless coupling and takes a value of κ = 1 in the Yang-Mills case and κ = 0 in the minimal coupling case.

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the solenoid volume are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter, and a brass and scintillator hadron calorimeter, each composed of a barrel and two endcap sections. Forward calorimeters extend the pseudorapidity (η) coverage provided by the barrel and endcap detectors. Muons are detected in gas-ionization chambers embedded in the steel flux-return yoke outside the solenoid. A more detailed description of the CMS detector, together 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 τμ 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 ττ production at NLO. Single top quark production in the s channel, ττ production in association with a heavy gauge boson (ττ + V), and the production of a W boson with additional jet radiation are simulated with MADGRAPH 5_AMC@NLO (v2.2.2) [64] at NLO. Events from Drell-Yan (DY) production with additional jet radiation are simulated with MADGRAPH 5_AMC@NLO and POWHEG v2. Events in which jets are produced through the strong interaction only, referred to as quantum chromodynamic multijet events, are simulated with 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 FXFX [65] and MLM [66] algorithms, respectively. The parton shower and hadronization process is simulated with 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 CUETP8M1T4 [68] is used for the simulation of ττ and single top quark production via the t channel, all other processes are generated using CUETP8M1 [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 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 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 ≥ 30 GeV, |η| ≤ 2.4, and to be isolated. The isolation [77,78] is defined as the summed p_T of all neutral particles and charged hadrons in a cone with radius ΔR = \text{sqrt}(Δη^2 + Δφ^2), φ being the azimuthal angle in radians, of 0.4 (for muons) or 0.3 (for electrons) around the lepton. The sum is corrected for the contribution of neutral pileup inside the cone. Jets are clustered from charged and neutral PF candidates using the anti-k_T jet-clustering algorithm [74,75] with a distance parameter of 0.4. Charged PF candidates originating from vertices other than the primary vertex are not clustered. A jet energy correction (JEC) is applied [79] to account for remaining contributions arising from a different vertex than the primary one as well as for nonuniformity of the jet response in η and nonlinearity in p_T. 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 $p_T \geq 30 \text{ GeV}$ 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, the production of a $Z$ boson with additional jet radiation is suppressed. 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, the production of a $Z$ boson with additional jet radiation is suppressed. 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, the production of a $Z$ boson with additional jet radiation is suppressed.
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 $M_{\text{rec}}^{LQ}$ and $S_T$ after the background-only fit are shown in Fig. 1. A Bayesian method 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.

FIG. 1. Distributions for $M_{\text{rec}}^{LQ}$ (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.

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 $M_{\text{LQ}}$–$B(LQ \to t\mu)$ 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, \( B(LQ \rightarrow t\mu) = 1 \), 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 \( LQ \rightarrow t\tau \) and \( LQ \rightarrow b\nu \) [49] decay channels to set exclusions limits in the plane of \( M_{1LQ} \) and \( B(LQ \rightarrow t\mu) \). Figure 2 presents upper limits on the product of the production cross section and the branching fraction squared for \( B(LQ \rightarrow t\mu) = 1 - B(LQ \rightarrow t\tau) \) (upper) and \( B(LQ \rightarrow t\mu) = 1 - B(LQ \rightarrow b\nu) \) (lower). The values for \( B(LQ \rightarrow t\mu) = 0 \) correspond to the results of the search for pair-produced LQs in the \( LQ \rightarrow t\tau \) decay channel (upper) and the search for pair-produced LQs in the \( LQ \rightarrow b\nu \) channel (lower). These analyses excluded pair-produced scalar LQs in the targeted decay channels up to \( M_{1LQ} = 900 \) and 1080 GeV, respectively. In the upper (lower) part of Fig. 2 the sensitivity is driven by the present analysis for values of \( B(LQ \rightarrow t\mu) > 0.1 (0.3) \) and by the \( LQ \rightarrow t\tau(\nu\nu) \) 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 \( B(LQ \rightarrow t\mu) \), whereas LQs decaying either into a top quark and a muon or into a bottom quark and a neutrino are excluded up to \( M_{1LQ} = 980 \) 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 \( B(LQ \rightarrow t\mu) \) 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 \( \pm 1/3 \) 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);

SENCYT (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); MSH and NSC (Poland); FCT (Portugal); JINR (Dubna); MON, RosAtom, RAS, RFBR and RAEP (Russia); MESTD (Serbia); SEIDI, CPAN, PCTI and FEDER (Spain); Swiss Funding Agencies (Switzerland); MST (Taipei); ThEPCenter, IPST, STAR, and NSTDA (Thailand); TUBITAK, TAEK (Turkey); NASU and SFFR (Ukraine); STFC (United Kingdom); DOE and NSF (USA).

[4] A. Bozek et al. (Belle Collaboration), Observation of \( B^+ \rightarrow \bar{D}^{*+}\tau^+\tilde{\nu}_\tau \), and evidence for \( B^+ \rightarrow \bar{D}^{0}\tau^+\nu_\tau \) at Belle, Phys. Rev. D 82, 072005 (2010).
[18] B. Dumont, K. Nishiwaki, and R. Watanabe, LHC constraints and prospects for \( S Yukawa \) scalar leptoquark explaining the \( B \to D^{(*)} \ell \bar{\nu} \) anomaly, Phys. Rev. D 94, 034001 (2016).
[19] A. Crivellin, D. Müller, and T. Ota, Simultaneous explanation of \( R(D^{(*)}) \) and \( b \to s \mu^+\mu^- \): the last scalar leptoquarks standing, J. High Energy Phys. 09 (2017) 040.
[23] D. Běčirević and O. Sumensari, A leptoquark model to accommodate \( R_{exp}^{D} < R_{SM}^{D} \) and \( R_{exp}^{K} < R_{SM}^{K} \), J. High Energy Phys. 08 (2017) 104.
[38] V. M. Abazov et al. (D0 Collaboration), Search for Third-Generation Leptoquarks in pp Collisions at \( \sqrt{s} = 1.96 \text{ TeV} \), Phys. Rev. Lett. 99, 061801 (2007).
[40] ATLAS Collaboration, Search for third generation scalar leptoquarks in pp collisions at \( \sqrt{s} = 7 \text{ TeV} \) with the ATLAS detector, J. High Energy Phys. 06 (2013) 033.
[45] CMS Collaboration, Search for heavy neutrinos or third-generation leptoquarks in final states with two hadronically decaying \( t \) leptons and two jets in proton-proton collisions at \( \sqrt{s} = 13 \text{ TeV} \), J. High Energy Phys. 03 (2017) 077.
[47] CMS Collaboration, Search for new phenomena with the \( M_{T2} \) variable in the all-hadronic final state produced in proton-proton collisions at \( \sqrt{s} = 13 \text{ TeV} \), Eur. Phys. J. C 77, 710 (2017).
A. M. Sirunyan,1 A. Tumasyan,1 W. Adam,2 F. Ambrogi,2 E. Asilar,2 T. Bergauer,2 J. Brandstetter,2 M. Dragicevic,2 J. Erö,2 A. Escalante Del Valle,2 M. Flechl,2 R. Frühwirth,2b V. M. Gheata,3 J. Hrubec,2 M. Jeitler,2b N. Krammer,2 I. Krätschmer,2 D. Liko,2 T. Madlener,2 I. Mikulec,2 N. Rad,2 H. Rohringer,2 J. Schieck,2b R. Schöfbeck,2 M. Spanning,2 D. Spizibart,2 A. Taurok,2 W. Waltenberger,2 J. Wittmann,2 C.-E. Wu,2b M. Zarucki,2 V. Chekhovsky,3 V. Mossolov,3 J. Suarez Gonzalez,3 E. A. De Wolf,3 D. Di Croce,3 X. Janssen,3 J. Lauwers,3 M. Pieters,3 H. Van Haevermaeta,3 P. Van Mechelen,4 N. Van Remortel,4 A. Abu Zeid,5 F. Blekman,5 J. D. Bourjose,6 T. Couron,6 C. Delaere,6 M. Delcourt,6 A. Giammanco,6 G. Krintiras,6 V. Lemaitre,6 A. Magitteri,6 A. Mertens,6 M. Musich,6 D. Liko,2 T. Madlener,2 I. Mikulec,2 N. Rad,2 H. Rohringer,2 J. Schieck,2b R. Schöfbeck,2 M. Spanning,2 D. Spizibart,2 A. Taurok,2 W. Waltenberger,2 J. Wittmann,2 C.-E. Wu,2b M. Zarucki,2 V. Chekhovsky,3 V. Mossolov,3 J. Suarez Gonzalez,3 E. A. De Wolf,3 D. Di Croce,3 X. Janssen,3 J. Lauwers,3 M. Pieters,3 H. Van Haevermaeta,3 P. Van Mechelen,4 N. Van Remortel,4 A. Abu Zeid,5 F. Blekman,5 J. D. Bourjose,6 T. Couron,6 C. Delaere,6 M. Delcourt,6 A. Giammanco,6 G. Krintiras,6 V. Lemaitre,6 A. Magitteri,6 A. Mertens,6 M. Musich,6 D. Liko,2 T. Madlener,2 I. Mikulec,2 N. Rad,2 H. Rohringer,2 J. Schieck,2b R. Schöfbeck,2 M. Spanning,2 D. Spizibart,2 A. Taurok,2 W. Waltenberger,2 J. Wittmann,2 C.-E. Wu,2b M. Zarucki,2 V. Chekhovsky,3 V. Mossolov,3 J. Suarez Gonzalez,3 E. A. De Wolf,3 D. Di Croce,3 X. Janssen,3 J. Lauwers,3 M. Pieters,3 H. Van Haevermaeta,3 P. Van Mechelen,4 N. Van Remortel,4 A. Abu Zeid,5 F. Blekman,5 J. D. Bourjose,6 T. Couron,6 C. Delaere,6 M. Delcourt,6 A. Giammanco,6 G. Krintiras,6 V. Lemaitre,6 A. Magitteri,6 A. Mertens,6 M. Musich,6 D. Liko,2 T. Madlener,2 I. Mikulec,2 N. Rad,2 H. Rohringer,2 J. Schieck,2b R. Schöfbeck,2 M. Spanning,2 D. Spizibart,2 A. Taurok,2 W. Waltenberger,2 J. Wittmann,2 C.-E. Wu,2b M. Zarucki,2 V. Chekhovsky,3 V. Mossolov,3 J. Suarez Gonzalez,3 E. A. De Wolf,3 D. Di Croce,3 X. Janssen,3 J. Lauwers,3 M. Pieters,3 H. Van Haevermaeta,3 P. Van Mechelen,4 N. Van Remortel,4 A. Abu Zeid,5 F. Blekman,5 J. D. Bourjose,6 T. Couron,6 C. Delaere,6 M. Delcourt,6 A. Giammanco,6 G. Krintiras,6 V. Lemaitre,6 A. Magitteri,6 A. Mertens,6 M. Musich,6 D. Liko,2 T. Madlener,2 I. Mikulec,2 N. Rad,2 H. Rohringer,2 J. Schieck,2b R. Schöfbeck,2 M. Spanning,2 D. Spizibart,2 A. Taurok,2 W. Waltenberger,2 J. Wittmann,2 C.-E. Wu,2b M. Zarucki,2 V. Chekhovsky,3 V. Mossolov,3 J. Suarez Gonzalez,3 E. A. De Wolf,3 D. Di Croce,3 X. Janssen,3 J. Lauwers,3 M. Pieters,3 H. Van Haevermaeta,3 P. Van Mechelen,4 N. Van Remortel,4 A. Abu Zeid,5 F. Blekman,5 J. D. Bourjose,6 T. Couron,6 C. Delaere,6 M. Delcourt,6 A. Giammanco,6 G. Krintiras,6 V. Lemaitre,6 A. Magitteri,6 A. Mertens,6 M. Musich,6 D. Liko,2 T. Madlener,2 I. Mikulec,2 N. Rad,2 H. Rohringer,2 J. Schieck,2b R. Schöfbeck,2 M. Spanning,2 D. Spizibart,2 A. Taurok,2 W. Waltenberger,2 J. Wittmann,2 C.-E. Wu,2b M. Zarucki,2 V. Chekhovsky,3 V. Mossolov,3 J. Suarez Gonzalez,3 E. A. De Wolf,3 D. Di Croce,3 X. Janssen,3 J. Lauwers,3 M. Pieters,3 H. Van Haevermaeta,3 P. Van Mechelen,4 N. Van Remortel,4 A. Abu Zeid,5 F. Blekman,5 J. D. Bourjose,6 T. Couron,6 C. Delaere,6 M. Delcourt,6 A. Giammanco,6 G. Krintiras,6 V. Lemaitre,6 A. Magitteri,6 A. Mertens,6 M. Musich,6 D. Liko,2 T. Madlener,2 I. Mikulec,2 N. Rad,2 H. Rohringer,2 J. Schieck,2b R. Schöfbeck,2 M. Spanning,2 D. Spizibart,2 A. Taurok,2 W. Waltenberger,2 J. Wittmann,2 C.-E. Wu,2b M. Zarucki,2 V. Chekhovsky,3 V. Mossolov,3 J. Suarez Gonzalez,3 E. A. De Wolf,3 D. Di Croce,3 X. Janssen,3 J. Lauwers,3 M. Pieters,3 H. Van Haevermaeta,3 P. Van Mechelen,4 N. Van Remortel,4 A. Abu Zeid,5 F. Blekman,5 J. D. Bourjose,6 T. Couron,6 C. Delaere,6 M. Delcourt,6 A. Giammanco,6 G. Krintiras,6 V. Lemaitre,6 A. Magitteri,6 A. Mertens,6 M. Musich,6
INFIN Sezione di Torino, Torino, Italy
Universitá di Torino, Torino, Italy
Universitá del Piemonte Orientale, Novara, Italy
INFIN Sezione di Trieste, Trieste, Italy
Universitá di Trieste, Trieste, Italy
Kyungpook National University, Daegu, Korea
Chonnam National University, Institute for Universe and Elementary Particles, Kwangju, Korea
Hanyang University, Seoul, Korea
Korea University, Seoul, Korea
Sejong University, Seoul, Korea
Seoul National University, Seoul, Korea
University of Seoul, Seoul, Korea
Sungkyunkwan University, Suwon, Korea
Vilnius University, Vilnius, Lithuania
National Centre for Particle Physics, Universiti Malaya, Kuala Lumpur, Malaysia
Universidad de Sonora (UNISON), Hermosillo, Mexico
Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico
Universidad Iberoamericana, Mexico City, Mexico
Benemerita Universidad Autonoma de Puebla, Puebla, Mexico
Universidad Autónoma de San Luis Potosí, San Luis Potosí, Mexico
University of Auckland, Auckland, New Zealand
University of Canterbury, Christchurch, New Zealand
National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan
National Centre for Nuclear Research, Swierk, Poland
Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland
Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal
Joint Institute for Nuclear Research, Dubna, Russia
Petersburg Nuclear Physics Institute, Gatchina (St. Petersburg), Russia
Institute for Nuclear Research, Moscow, Russia
Institute for Theoretical and Experimental Physics, Moscow, Russia
Moscow Institute of Physics and Technology, Moscow, Russia
National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia
P.N. Lebedev Physical Institute, Moscow, Russia
Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia
Novosibirsk State University (NSU), Novosibirsk, Russia
Institute for High Energy Physics of National Research Centre 'Kurchatov Institute', Protvino, Russia
National Research Tomsk Polytechnic University, Tomsk, Russia
University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia
Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain
Universidad Autónoma de Madrid, Madrid, Spain
Universidad de Oviedo, Oviedo, Spain
Instituto de Física de Cantabria (IFCA), CSIC-Universidad de Cantabria, Santander, Spain
University of Ruhuna, Department of Physics, Matara, Sri Lanka
CERN, European Organization for Nuclear Research, Geneva, Switzerland
Paul Scherrer Institut, Villigen, Switzerland
ETH Zurich—Institute for Particle Physics and Astrophysics (IPA), Zurich, Switzerland
Universität Zürich, Zurich, Switzerland
National Central University, Chung-Li, Taiwan
National Taiwan University (NTU), Taipei, Taiwan
Chulalongkorn University, Faculty of Science, Department of Physics, Bangkok, Thailand
Çukurova University, Physics Department, Science and Art Faculty, Adana, Turkey
Middle East Technical University, Physics Department, Ankara, Turkey
Bogazici University, Istanbul, Turkey
Istanbul Technical University, Istanbul, Turkey
Institute for Scintillation Materials of National Academy of Science of Ukraine, Kharkov, Ukraine
National Scientific Center, Kharkov Institute of Physics and Technology, Kharkov, Ukraine
University of Bristol, Bristol, United Kingdom
Rutherford Appleton Laboratory, Didcot, United Kingdom
Imperial College, London, United Kingdom
Brunel University, Uxbridge, United Kingdom
Baylor University, Waco, Texas, USA

Catholic University of America, Washington DC, USA

The University of Alabama, Tuscaloosa, USA

Boston University, Boston, Massachusetts, USA

Brown University, Providence, Rhode Island, USA

University of California, Davis, Davis, California, USA

University of California, Los Angeles, California, USA

University of California, Riverside, Riverside, California, USA

University of California, San Diego, La Jolla, California, USA

University of California, Santa Barbara—Department of Physics, Santa Barbara, California, USA

California Institute of Technology, Pasadena, California, USA

Carnegie Mellon University, Pittsburgh, Pennsylvania, USA

University of Colorado Boulder, Boulder, Colorado, USA

Cornell University, Ithaca, New York, USA

Fermi National Accelerator Laboratory, Batavia, Illinois, USA

University of Florida, Gainesville, Florida, USA

Florida International University, Miami, Florida, USA

Florida State University, Tallahassee, Florida, USA

Florida Institute of Technology, Melbourne, Florida, USA

University of Illinois at Chicago (UIC), Chicago, Illinois, USA

The University of Iowa, Iowa City, Iowa, USA

Johns Hopkins University, Baltimore, Maryland, USA

The University of Kansas, Lawrence, Kansas, USA

Kansas State University, Manhattan, Kansas, USA

Lawrence Livermore National Laboratory, Livermore, California, USA

University of Maryland, College Park, Maryland, USA

Massachusetts Institute of Technology, Cambridge, Massachusetts, USA

University of Minnesota, Minneapolis, Minnesota, USA

University of Mississippi, Oxford, Mississippi, USA

University of Nebraska-Lincoln, Lincoln, Nebraska, USA

State University of New York at Buffalo, Buffalo, New York, USA

Northeastern University, Boston, Massachusetts, USA

Northwestern University, Evanston, Illinois, USA

University of Notre Dame, Notre Dame, Indiana, USA

The Ohio State University, Columbus, Ohio, USA

Princeton University, Princeton, New Jersey, USA

University of Puerto Rico, Mayagüez, Puerto Rico

Purdue University, West Lafayette, Indiana, USA

Purdue University Northwest, Hammond, Indiana, USA

Rice University, Houston, Texas, USA

University of Rochester, Rochester, New York, USA

Rutgers, The State University of New Jersey, Piscataway, New Jersey, USA

University of Tennessee, Knoxville, Tennessee, USA

Texas A&M University, College Station, Texas, USA

Texas Tech University, Lubbock, Texas, USA

Vanderbilt University, Nashville, Tennessee, USA

University of Virginia, Charlottesville, Virginia, USA

Wayne State University, Detroit, Michigan, USA

University of Wisconsin—Madison, Madison, Wisconsin, USA

*Deceased.

Also at Vienna University of Technology, Vienna, Austria.

Also at IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France.

Also at Universidade Estadual de Campinas, Campinas, Brazil.

Also at Federal University of Rio Grande do Sul, Porto Alegre, Brazil.

Also at Université Libre de Bruxelles, Bruxelles, Belgium.

Also at University of Chinese Academy of Sciences.

Also at Institute for Theoretical and Experimental Physics, Moscow, Russia.

Also at Joint Institute for Nuclear Research, Dubna, Russia.

Also at Helwan University, Cairo, Egypt.
Also at Beykent University, Istanbul, Turkey.
Also at Bingol University, Bingol, Turkey.
Also at Sinop University, Sinop, Turkey.
Also at Mimar Sinan University, Istanbul, Istanbul, Turkey.
Also at Texas A&M University at Qatar, Doha, Qatar.
Also at Kyungpook National University, Daegu, Korea.