Search for pair production of scalar and vector leptoquarks decaying to muons and bottom quarks in proton-proton collisions at $\sqrt{s} = 13$ TeV

A. Hayrapetyan *et al.*[*]

(CMS Collaboration)

A search for pair production of scalar and vector leptoquarks (LQs) each decaying to a muon and a bottom quark is performed using proton-proton collision data collected at $\sqrt{s} = 13$ TeV with the CMS detector at the CERN LHC, corresponding to an integrated luminosity of 138 fb^{-1}. No excess above standard model expectation is observed. Scalar (vector) LQs with masses less than 1810 (2120) GeV are excluded at 95% confidence level, assuming a 100% branching fraction of the LQ decaying to a muon and a bottom quark. These limits represent the most stringent to date.

I. INTRODUCTION

The standard model (SM) of particle physics describes the interactions of elementary particles to high accuracy. There remain, however, observations of particle physics that are not fully explained, such as the similarities between the quark and lepton families. In some theoretical models of physics with extensions beyond the SM, these similarities are a manifestation of a deeper symmetry between the two types of particles, and there naturally arise particles that bridge the two families. Leptoquarks (LQs) are new bosons that would manifest this fundamental connection between quarks and leptons and are predicted by numerous extensions of the SM, such as grand unified theories [1–8], composite models with lepton and quark substructure [9], technicolor models [10–12], and superstring-inspired models [13]. Particles with similar decay modes are also found in *R*-parity violating supersymmetry [14–23]. Leptoquarks are color-triplet scalar or vector bosons carrying both lepton and baryon numbers. They generally decay either to a charged lepton and a quark, or to a neutrino and a quark. In recent years, there have been a number of observed tensions with the SM in measurements of *B*-meson decays and tests of lepton universality [24–35], often present in measurements of processes involving muons and third-generation quarks, as well as in precision measurements of the anomalous magnetic moment of the muon [36–38]. These tensions have increased interest in LQs and significant theoretical literature [39–43] has

re-examined the phenomenological and historical constraints of LQ models and searches, in particular removing the traditional constraint that LQs should decay within the same generation of quarks and leptons. Leptoquarks may provide a tree-level explanation of some anomalies in scenarios where the LQ-lepton-quark coupling is not restricted to remain in one generation [40]. At hadron colliders, LQs can be produced singly or in pairs. The dominant leading-order (LO) processes for pair production of LQs at the LHC involve gluon-gluon fusion and quark-antiquark annihilation, shown in Fig. 1. Pair production can also arise from so-called *t*-channel production, which does not provide a significant contribution for the model and parameters chosen in this analysis and is not considered [44].

Interpretations of direct searches for LQs are typically based on a general model where LQ-lepton-quark interactions are added to the SM Lagrangian [45]. The interactions of scalar LQs with SM particles are completely determined by three parameters [45]; the LQ mass m_{LQ}, the Yukawa coupling at the LQ-lepton-quark vertex λ_{LQ}, and the branching fraction β of the LQ decay to a charged lepton and a quark. Vector LQs are further dependent on an additional parameter κ that relates to their anomalous magnetic and electric quadrupole moments [46]. Values of $\kappa = 0$ and 1 are considered in this analysis, corresponding to the minimal coupling and Yang-Mills scenarios, respectively. Leptoquark pair production cross sections (σ) are independent of λ_{LQ} over many orders of magnitude [45]. In this analysis, λ_{LQ} has been set to 1, which will produce LQs that decay very close to the point of production [40] and ensures the pair production cross sections and results are independent of λ_{LQ}.

Pair production of LQs is characterized by final states with two leptons and two jets with large transverse momentum p_{T}. Previous limits on scalar LQ pair production decaying to muons and jets in proton-proton (pp) collisions have been published by the CMS and ATLAS

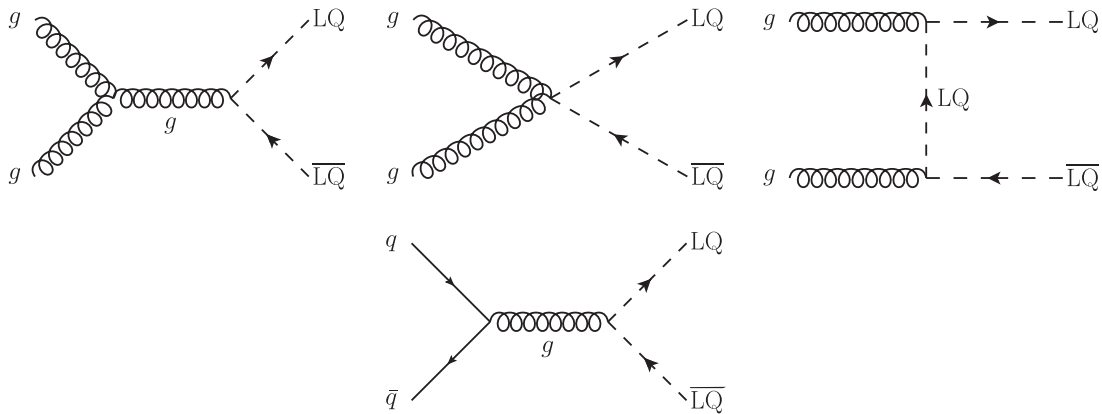[*]Full author list given at the end of the article.

FIG. 1. Dominant leading order Feynman diagrams for pair production of LQs at the LHC.

Collaborations [47–51]. The CMS result excludes, at 95% confidence level (CL), LQs decaying to muons and light (u, d, s) quarks with $m_{LQ} < 1.5$ (1.3) TeV for $\beta = 1$ (0.5) [48], and ATLAS excludes LQs decaying to muons and b quarks with $m_{LQ} < 1.7$ TeV for $\beta = 1$ [50,51]. Previous limits on vector LQs have been reported by CMS [47] and ATLAS [51], where CMS excludes vector LQs decaying to muons and light quarks with $m_{LQ} < 1.3$ (1.5) TeV for $\beta = 1$ in the minimal coupling (Yang-Mills) scenario, and ATLAS excludes vector LQs decaying to muons and b quarks with $m_{LQ} < 1.7$ (2.0) TeV for $\beta = 0.5$ in the minimal coupling (Yang-Mills) scenario. The present analysis searches for scalar and vector LQs that decay to a muon and a bottom quark, using data collected by the CMS detector during the 2016–2018 pp LHC runs at $\sqrt{s} = 13$ TeV. Results are presented for a value of $\beta = 1$, corresponding to maximal production of the $\mu\mu bb$ final state, as well as in the range $0 < \beta < 1$.

II. THE CMS DETECTOR

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 (ECAL), and a brass and scintillator hadron calorimeter (HCAL), 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 measured in gas-ionization detectors 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].

Events of interest are selected using a two-tiered trigger system. The first level (L1), composed of custom hardware processors, uses information from the calorimeters and muon detectors to select events at a rate of around 100 kHz within a fixed latency of about 4 µs [53]. The second level,

known as the high-level trigger, consists of a farm of processors running a version of the full event reconstruction software optimized for fast processing, and reduces the event rate to around 1 kHz before data storage [54].

III. EVENT RECONSTRUCTION

The primary vertex (PV) is taken to be the vertex corresponding to the hardest scattering in the event, evaluated using tracking information alone, as described in Sec. 9.4.1 of Ref. [55]. The global event reconstruction (also called particle-flow event reconstruction [56]) aims to reconstruct and identify each individual particle in an event, with an optimized combination of all subdetector information. In this process, the identification of the particle type (photon, electron, muon, charged or neutral hadron) plays an important role in the determination of the particle direction and energy. Photons (e.g., coming from π^0 decays or from electron bremsstrahlung) are identified as ECAL energy clusters not linked to the extrapolation of any charged particle trajectory to the ECAL. Electrons (e.g., coming from photon conversions in the tracker material or from B hadron semileptonic decays) are identified as primary charged particle tracks and potentially many ECAL energy clusters corresponding to these track extrapolations to the ECAL and to possible bremsstrahlung photons emitted along the way through the tracker material. Muons (e.g., from B hadron semileptonic decays) are identified as tracks in the central tracker consistent with either a track or several hits in the muon system, and associated with calorimeter deposits compatible with the muon hypothesis. Charged hadrons are identified as charged particle tracks neither identified as electrons, nor as muons. Finally, neutral hadrons are identified as HCAL energy clusters not linked to any charged hadron trajectory, or as a combined ECAL and HCAL energy excess with respect to the expected charged hadron energy deposit.

Jets originating from bottom quarks are identified using the DeepJet discriminator [57], a multiclass jet flavor tagging algorithm that uses deep learning and exploits low-

level features from a high number of jet constituents. A working point with a 75% efficiency to identify b jets and a 1% misidentification probability for light jets is used in this analysis [58,59].

The energy of photons is obtained from the ECAL measurement. The energy of electrons is determined from a combination of the track momentum at the main interaction vertex, the corresponding ECAL cluster energy, and the energy sum of all bremsstrahlung photons attached to the track. The energy of muons is obtained from the corresponding track momentum. The energy of charged hadrons is determined from a combination of the track momentum and the corresponding ECAL and HCAL energy deposits, corrected for the response function of the calorimeters to hadronic showers. Finally, the energy of neutral hadrons is obtained from the corresponding corrected ECAL and HCAL energy deposits.

For each event, hadronic jets are clustered from these reconstructed particles using the infrared and collinear safe anti-k_T algorithm [60,61] with a distance parameter of 0.4. Jet momentum is determined as the vectorial sum of all particle momenta in the jet, and is found from Monte Carlo (MC) simulation to be, on average, within 5–10% of the true momentum over the whole p_T spectrum and detector acceptance. Additional pp interactions within the same or nearby bunch crossings (pileup) can contribute additional tracks and calorimetric energy depositions to the jet momentum. To mitigate this effect, charged particles identified to be originating from pileup vertices are discarded and an offset correction is applied to correct for remaining contributions [62]. Jet energy corrections are derived from simulation to bring the measured response of jets to that of particle level jets on average. In situ measurements of the momentum balance in dijet, photon + jet, Z + jet, and multijet events are used to account for any residual differences in the jet energy scale between data and simulation [63]. The jet energy resolution amounts typically to 15–20% at 30 GeV, 10% at 100 GeV, and 5% at 1 TeV [63]. Additional selection criteria are applied to each jet to remove jets potentially dominated by anomalous contributions from various subdetector components or reconstruction failures [62].

Muons are measured in the range $|\eta| < 2.4$, with detection planes made using three technologies; drift tubes, cathode strip chambers, and resistive plate chambers. The single muon trigger efficiency exceeds 90% over the full η range, and the efficiency to reconstruct and identify muons is greater than 96%. Matching muons to tracks measured in the silicon tracker results in a relative p_T resolution of 1% in the barrel and 3% in the endcaps for muons with p_T up to 100 GeV, and of better than 7% in the barrel for muons with p_T up to 1 TeV [64]. Muons are required to be isolated from tracks arising from electromagnetic and hadronic activity in the event that may otherwise mimic muon signatures in the detector.

The missing transverse momentum vector $\vec{p}_T^{\mathrm{miss}}$ is computed as the negative vector p_T sum of all the particle-flow candidates in an event, and its magnitude is denoted as p_T^{miss} [65]. The $\vec{p}_T^{\mathrm{miss}}$ is modified to account for corrections to the energy scale of the reconstructed jets in the event.

IV. DATA AND SIMULATED SAMPLES

The dataset used in this paper was collected by the CMS detector during the 2016–2018 pp LHC runs at $\sqrt{s} = 13$ TeV and corresponds to an integrated luminosity of 138 fb^{-1} [66–68]. The integrated luminosities for the 2016, 2017, and 2018 data-taking years have 1.2–2.5% individual uncertainties [66–68], while the overall uncertainty for the 2016–2018 period is 1.6%. Events are selected using triggers that require at least one muon with $p_T > 50$ GeV, with no isolation requirements.

Signal samples are produced in 100 GeV steps for values of m_{LQ} between 300–3000 GeV at LO in quantum chromodynamics (QCD) with MadGraph5_aMC@NLO [69,70] versions 2.2.2 and 2.3.3 using the triplet scalar S3 model of Ref. [39]. For this analysis, the LQ ($\overline{\mathrm{LQ}}$) is forced to decay 100% to LQ $\rightarrow \mu^- b$ ($\overline{\mathrm{LQ}} \rightarrow \mu^+ \bar{b}$), giving rise to a $\mu^- \mu^+ b\bar{b}$ final state. These samples are used to study the signal efficiency.

The main SM background processes in this final state are $t\bar{t}$ + jets and Z/γ^* + jets production. Other minor contributions from SM processes include diboson ($WW/WZ/ZZ$) + jets, $t\bar{t} + Z/W/H$ ($t\bar{t}V$), single top quark production, and W + jets. Background from QCD multijets has been shown to be negligible [48] and is not considered in this analysis.

The Z/γ^* + jets and W + jets samples are generated at next-to-LO (NLO) using MadGraph5_aMC@NLO with FXFX merging [71]. Diboson samples are generated at NLO using MadGraph5_aMC@NLO. Single top quark, $t\bar{t}$ + jets, and $t\bar{t}V$ samples are generated at NLO using POWHEG v2 [72–75] and MadGraph5_aMC@NLO [76]. All of these samples are showered using PYTHIA 8.212 [77], to take into account the fragmentation and hadronization processes.

The parton distribution function (PDF) sets used for generating the 2016 (2017–2018) signal and background samples are NNPDF3.0 NLO (3.1 LO for signal, 3.1 NNLO for background) [78], with the full CMS detector geometry and response simulated using Geant4 [79,80]; all samples use the CUETP8M1 [81] (CP2 for signal, CP5 for SM backgrounds) [82]) underlying event tune, with additional pp interactions overlaid and corrected to match the distribution measured in data.

The scalar LQ pair production cross sections are calculated with MadGraph5_aMC@NLO using the tool from Ref. [83] with NLO QCD corrections [83–85] and the PDF4LHC15 [86] NLO PDF set, and are used for comparison with data and background estimations in the statistical analysis. For the vector LQ interpretation, LQ production cross sections are calculated at LO in QCD using a singlet

U1 model in which the LQ couples only to left-handed fermions [83]. The scalar LQ simulated samples are again used for the signal efficiency. It has been shown that relevant vector LQ pair production kinematic distributions agree within 10% with equivalent scalar pair production, for $m_{LQ} > 500$ GeV [40].

The simulated samples are corrected so that the detector response and resolution for both leptons and jets (including b tagged jets) and the trigger efficiency match those measured in data [63,64].

V. BACKGROUND ESTIMATION

The main SM processes that can mimic the LQ signal in this channel are $Z/\gamma^* +$ jets, $t\bar{t} +$ jets, and to a lesser extent diboson production. Backgrounds are estimated and validated using a selection dominated by background events, referred to as the preselection. This preselection requires two muons with $p_T > 53$ GeV, to remain fully efficient with respect to the trigger requirements, and at least two jets with $p_T > 50$ GeV, at least one of which is tagged as a bottom jet. Each event is required to have only two muons, and a veto on a third muon or an electron with $p_T > 20$ GeV is imposed. No requirement is placed on the muon charges. The muons are required to be separated from each other by $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} > 0.3$, where ϕ is the azimuthal angle (in radians) with respect to the counterclockwise beam axis. There are two requirements of $m_{\mu\mu} > 50$ GeV and $S_T^{\mu\mu ij} > 300$ GeV, where $m_{\mu\mu}$ is the invariant mass of the dimuon system, and $S_T^{\mu\mu ij}$ is defined as the scalar p_T sum of the two leading jets and two muons in the event.

The $Z/\gamma^* +$ jets, $t\bar{t} +$ jets, diboson, and $t\bar{t}V$ contribution estimates make use of background-dominated data control regions (CRs) after the preselection. Background shapes are taken from simulation, and show good shape agreement with the data in the CRs. For normalization, the simulation is compared to data in the different CRs, and the measured data normalization scale factors are applied to simulated events in the analysis. The $Z/\gamma^* +$ jets and $t\bar{t}$ normalizations are computed iteratively, then held constant to compute the simultaneous diboson and $t\bar{t}V$ normalization. For $Z/\gamma^* +$ jets, the CR is a $m_{\mu\mu}$ window of 80–100 GeV around the Z peak, and for $t\bar{t} +$ jets it is a window of 100–250 GeV. Both are computed at the preselection level. For diboson and $t\bar{t}V$ processes, the normalization is performed simultaneously, with a CR again $80 < m_{\mu\mu} < 100$ GeV around the Z peak, but with the preselection modified by the additional request of a third lepton (to remain orthogonal to the $Z/\gamma^* +$ jets CR) and no b tag requirement (to diminish the statistical uncertainty). Background contributions from single top quark and $W +$ jets events are estimated from simulation. The CR $m_{\mu\mu}$ distributions, after application of the data normalization scale factors, are shown in Fig. 2. The signal contribution in all control regions is negligible.

The background predictions are validated at the preselection level by comparing them with data in all relevant
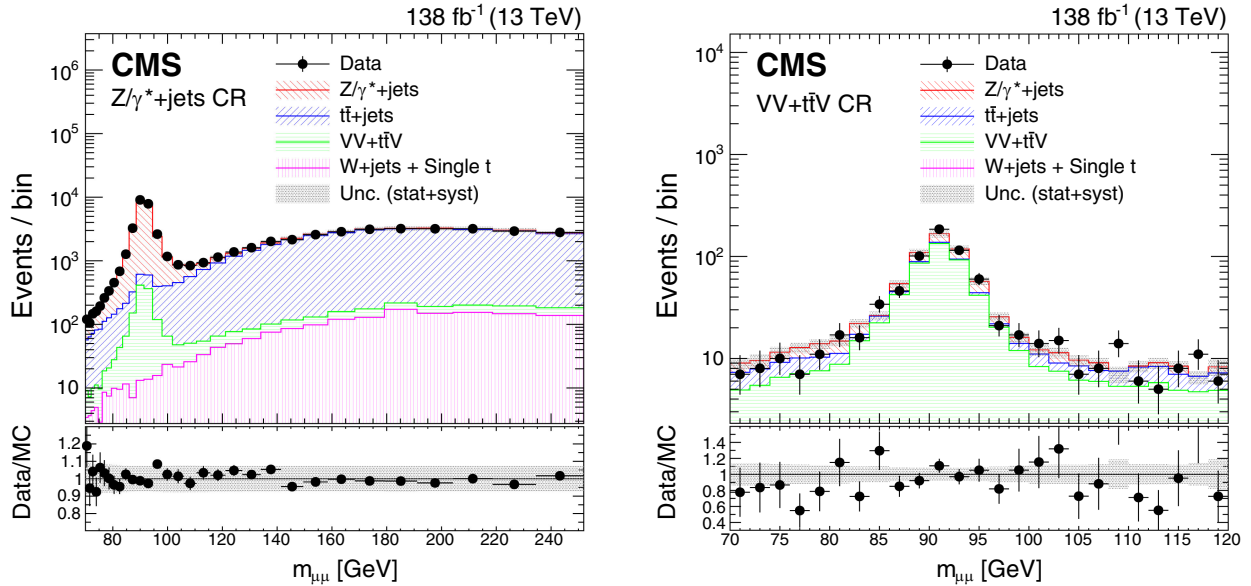

FIG. 2. Comparison of data and background $m_{\mu\mu}$ distribution at the preselection level for the $Z/\gamma^* +$ jets and $t\bar{t} +$ jets (left) and diboson and $t\bar{t}V$ (right) background control regions, with the corresponding data-to-background ratio shown below. For $Z/\gamma^* +$ jets, the control region is a $m_{\mu\mu}$ window of 80–100 GeV around the Z peak, and for $t\bar{t} +$ jets is a window of 100–250 GeV. For diboson and $t\bar{t}V$ processes, the normalization is performed simultaneously, with a control region again of 80–100 GeV around the Z peak, but with a third lepton requirement (to remain orthogonal to the $Z/\gamma^* +$ jets control region) and no b tag requirement (to diminish the statistical uncertainty). The error bars are the data statistical uncertainties, while the shaded band represents the combined statistical and systematic uncertainty in the full background estimate. The signal contribution in all control regions is negligible.
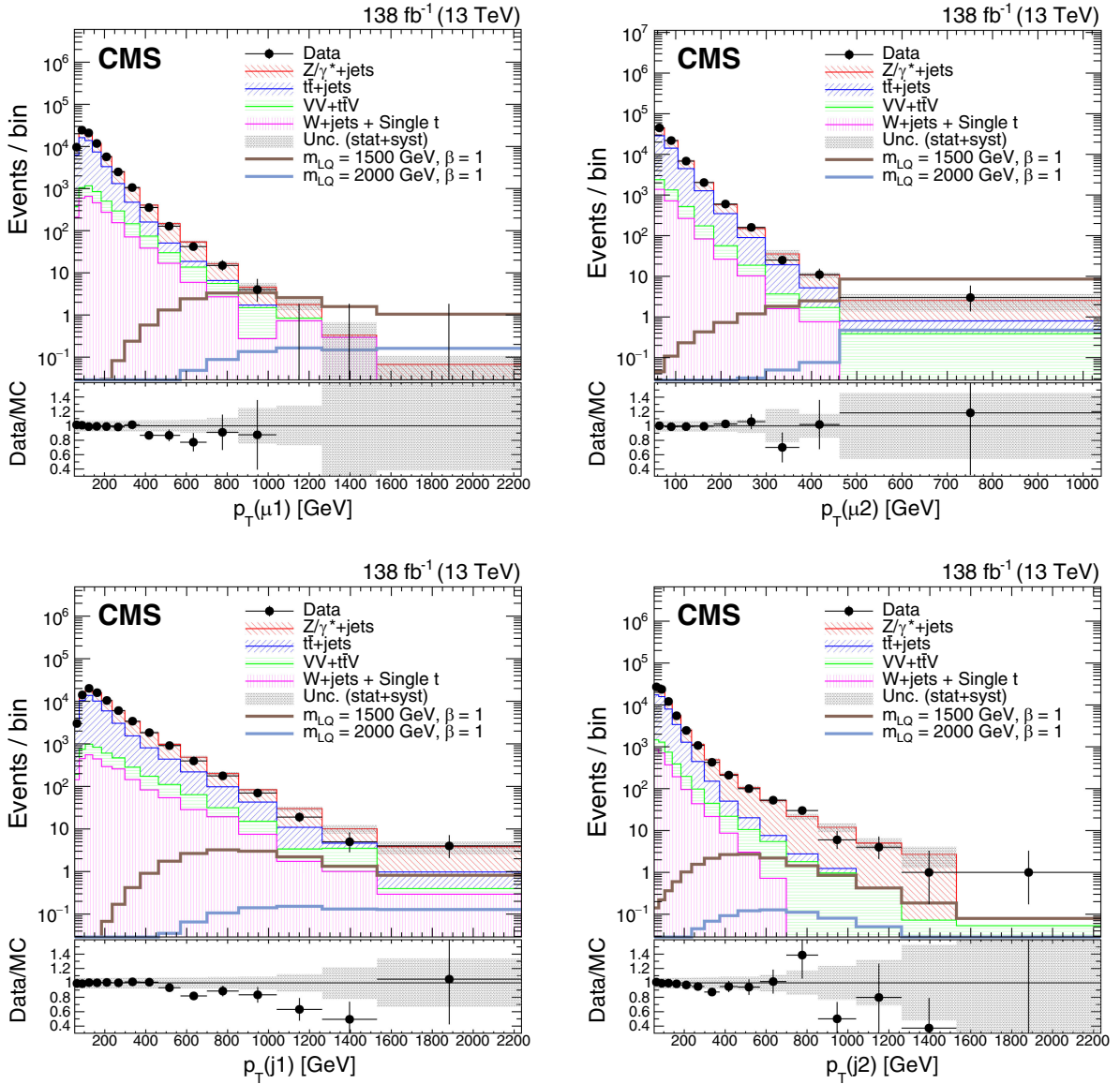
FIG. 3.　Comparison of data and background p_T distribution at the preselection level for the leading two muons and jets. The error bars are the data statistical uncertainties, while the shaded band represents the combined statistical and systematic uncertainty in the full background estimate.

kinematic distributions. Distributions at preselection of the muon and jet p_T spectra are shown in Fig. 3. There is good agreement apart from in the high-p_T regions of the jet spectra, where there is a tendency for the simulation to overestimate the rate. The small discrepancy is not important since the analysis sensitivity is dependent on the final selections discussed in Sec. VI A, and the jet p_T distributions play a limited role in the final selection.

VI. RESULTS

A. Final selection optimization

In order to separate signal from background, a final selection is defined for each m_{LQ} hypothesis. Multivariate techniques are used to increase the signal sensitivity compared to an analysis based on a set of independent selection criteria. A boosted decision tree (BDT) is trained on background and signal events at a modified preselection level for each m_{LQ} hypothesis. The modified preselection requires additional selection criteria of $m_{\mu\mu} > 250$ GeV and $m_{\mu\mu jj} > m_{LQ}$, to maintain the separation of the CR from the signal regions and reduce training bias in background-enriched and signal-depleted regions. An iterative procedure identifies eleven minimally-correlated kinematic variables with strong signal-to-background separation power to use as the input variables to the BDTs:

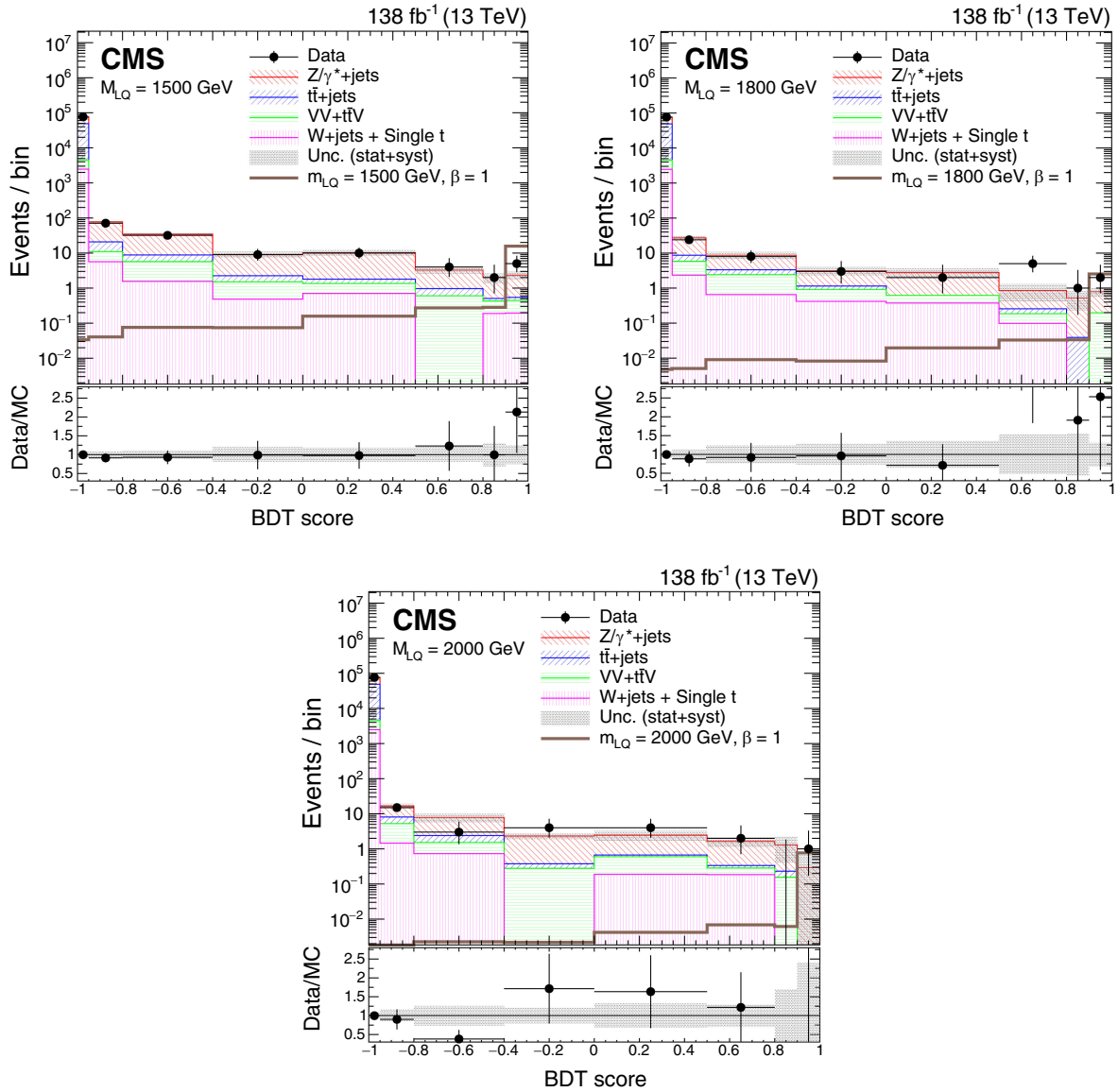 (i) invariant masses: $m_{\mu\mu}$ and $m_{\mu\mu jj}$;

FIG. 4. Comparison of data and background BDT discriminant distributions at the preselection level for LQ mass hypotheses of 1500 GeV (upper left), 1800 GeV (upper right), and 2000 GeV (lower). The error bars are the data statistical uncertainties, while the shaded band represents the combined statistical and systematic uncertainty in the full background estimate.

(ii) reconstructed LQ invariant masses $m_{\mu j1}$ and $m_{\mu j2}$, defined by pairing the two muons and jets such as to minimize the mass difference;

(iii) final-state momenta of muons and jets: $p_T(\mu 1)$, $p_T(\mu 2)$, $p_T(j1)$, and $p_T(j2)$;

(iv) combined momenta: $S_T^{\mu\mu jj}$ and p_T^{miss};

(v) ΔR separation between the dimuon pair and the leading-p_T jet momentum vectors.

Training samples are constructed using the full MC dataset, with random event sampling from the background and signal simulated samples. The gradient boost [87–89] algorithm is used for the BDT training, avoiding input variables that are too highly correlated, and studies of the independent training and testing events show no evidence

of overtraining. Examples of the BDT response at the preselection level are shown in Fig. 4.

The signal-to-background separation is optimized individually for each m_{LQ} using the relevant BDT discriminant as the sensitive variable. The figure of merit in the optimization is the Punzi significance [90] for a discovery potential of five standard deviations. This method is optimal for both making a discovery and for setting limits, and is valid in cases with low background event counts. A constant BDT discriminant selection is used for signal mass points $m_{LQ} > 1800$ GeV to avoid instabilities in the optimization due to a limited event count in the simulated samples. The signal efficiency for each m_{LQ} hypothesis, defined as the number of events passing final selection
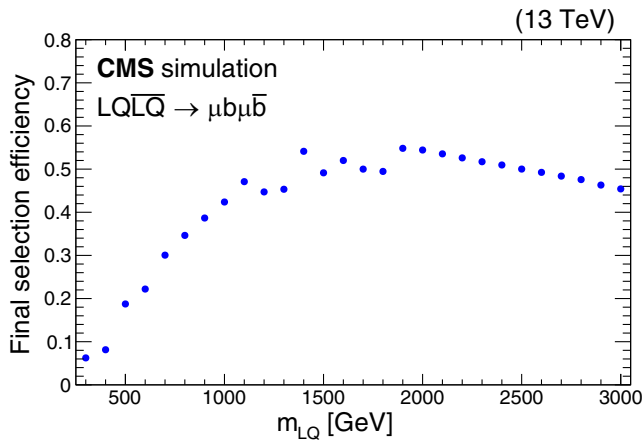
FIG. 5. Total signal selection efficiency, defined as the number of events passing the final selection divided by the number of generated events. The discrete nature of the individual BDT training and final selection for each LQ candidate mass produces the observed variation in the efficiency. Relative uncertainties are less than one percent in all cases.

FIG. 6. Data, background, and signal event yields after final selections, for each scalar m_{LQ} hypothesis. Each bin on the y axis represents an independent m_{LQ} hypothesis. The hatched band represents the combined statistical and systematic uncertainty in the full background estimate.

divided by the total number of generated events, is shown in Fig. 5. The discrete nature of the final selection for each LQ candidate mass produces the observed variation in the efficiency. The background rejection ranges from 55% to 96% and is above 90% for all $m_{LQ} > 600$ GeV.
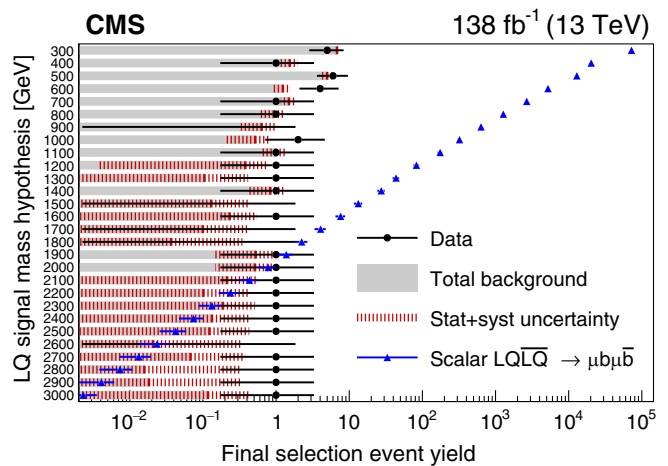
A detailed table of the event counts in data, expected background, and expected signal at final selection is available in the HEPData record for this analysis [91]. These data are also represented visually in Fig. 6. The x axis shows the final selection event yields for each of the

TABLE I. Systematic uncertainties in signal efficiency and background yields in the combined 2016–2018 dataset, shown as a range over all final selections (second and third columns) as well as for the $m_{LQ} = 1800$ GeV point (rightmost two columns). The last two rows show the total systematic and statistical uncertainties in the simulated samples.

Uncertainty	300 GeV $\leq m_{LQ} \leq$ 3000 GeV		$m_{LQ} = 1800$ GeV	
	Signal (%)	Background (%)	Signal (%)	Background (%)
b jet tagging efficiency	2–16	1–23	9	6
Jet-energy resolution	<1	1–17	<1	6
Jet-energy scale	0–2	1–22	<1	9
Integrated luminosity	4	0–1	4	1
Muon-energy resolution	<1	0–14	<0.1	5
Muon energy scale	0–3	3–32	<1	12
Muon identification	2	<1	2	1
Muon isolation	<1	<1	<1	<1
Muon reconstruction	1–63	0–8	17	2
Muon trigger	0–1	<1	1	<1
L1 prefire weighting	1	0–3	1	2
Pileup	<1	0–18	<1	4
PDF	⋯	5–29	⋯	16
Top quark p_T reweighting	⋯	3–4	⋯	4
$t\bar{t}$ normalization	⋯	1–2	⋯	1
$t\bar{t}$ shape	⋯	3–23	⋯	19
Diboson normalization	⋯	0–13	⋯	2
Diboson shape	⋯	0–10	⋯	1
$Z/\gamma^* +$ jets normalization	⋯	1–25	⋯	4
$Z/\gamma^* +$ jets shape	⋯	0–12	⋯	3
Total syst. uncertainty	5–65	7–72	20	32
Total stat. uncertainty	0–3	22–100	<1	100

individual m_{LQ} hypotheses shown on the y axis. Each bin on the y axis represents an independent m_{LQ} hypothesis. For example, the uppermost bin is a comparison of the yields after final selection in the $m_{LQ} = 300$ GeV signal mass hypothesis. The hatched band represents the combined statistical and systematic uncertainty in the full background estimate.

B. Systematic uncertainties

Theoretical uncertainties in the LQ signal production cross sections vary from 13% to 36% across the m_{LQ} range of 300–2500 GeV. They are estimated by varying the PDF eigenvectors within their uncertainties and the renormalization and factorization scales by factors of one-half and two [83].

Systematic uncertainties in the background yields and in the signal efficiency are calculated for each final selection by running the full analysis with separately varied detector conditions, particle momenta, or scale factors. These yields are compared to those for the nominal analysis, and the differences from nominal are used in the analysis of uncertainties.

Systematic uncertainties in the jet-energy resolution [63] and muon momentum resolution [64] are measured by smearing the jet and muon momenta, including high-p_T specific corrections for muons [92]. Uncertainties due to the jet energy scale and the muon momentum scale are estimated by propagating up and down the uncertainties in the applied jet and muon momentum corrections.

Shape uncertainties of the main background predictions are estimated by independently varying the factorization and normalization scales in the simulation by factors of one-half and two. The PDF uncertainty is estimated by varying the NNPDF eigenvectors within their uncertainties, following the PDF4LHC prescription [86,93].

The uncertainties in the $Z/\gamma^* +$ jets, $t\bar{t} +$ jets, diboson, and $t\bar{t}V$ background normalizations are estimated by varying the normalization scale factors described in Sec. V up and down by their statistical uncertainties.

Other sources of systematic uncertainty include: the luminosity measurement [66–68]; muon reconstruction; identification, and isolation [64]; b tagging efficiency [58,59]; pileup [94]; trigger efficiency and prefiring (L1 trigger incorrectly assigned to an earlier bunch crossing); top p_T reweighting (to account for differences in top quark p_T spectra observed in data and simulation) [95]; and track reconstruction efficiency. For LQ mass hypotheses above 1 TeV, the systematic uncertainties in the muon reconstruction efficiency become dominant and have a significant effect on the signal samples. These large uncertainties are due to limited numbers of very high momentum muons in the data control samples used to derive the data-to-simulation correction factors.

The effects of these systematic uncertainties in signal efficiency and total background yield are shown in Table I.

The maximum values given in Table I are only relevant for large values of m_{LQ}, where the total uncertainty is dominated by the statistical uncertainty in the simulated background samples. For most values of m_{LQ}, the systematic uncertainties are at the lower end of the range, as can be seen in the two rightmost columns of the table, which shows the uncertainties for the $m_{LQ} = 1800$ GeV signal point.

C. Limit setting

The data are compared to background predictions after the final selections have been applied. No significant excess above the predicted background is identified for any m_{LQ}. Limits are set on the LQ pair production cross section as a function of m_{LQ}, obtained using the asymptotic approximation [96] of the modified frequentist CL_s approach [97,98], which uses the ratio of the tail probabilities in the signal + background to background hypotheses. The systematic uncertainties described above are introduced as nuisance parameters in the limit setting procedure using log-normal probability functions. Uncertainties of a statistical nature are described by Γ distributions with widths determined by the number of events in simulated samples
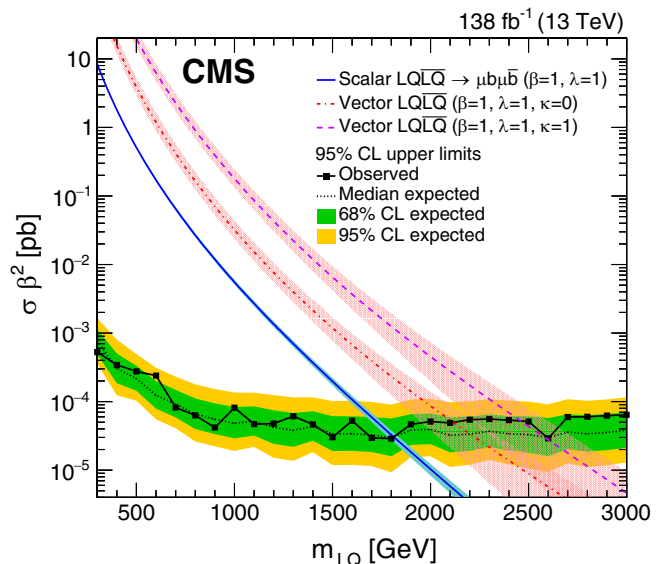

FIG. 7. The expected and observed upper limits at 95% CL on the product of the LQ pair production cross section and the branching fractions β^2 as a function of m_{LQ}. The black solid line represents the observed limits, the dotted line is for the median expected limits, and the inner dark-green and outer light-yellow bands are for the 68% and 95% CL intervals. The solid blue line and corresponding blue band represents the theoretical scalar LQ pair production cross sections and the uncertainties on the cross sections due to the PDF prediction and renormalization and factorization scales, respectively. Similarly, the dash-dotted (dashed) line and corresponding band represents the cross sections of theoretical vector LQ pair production and uncertainties in the minimal coupling (Yang-Mills) scenario.
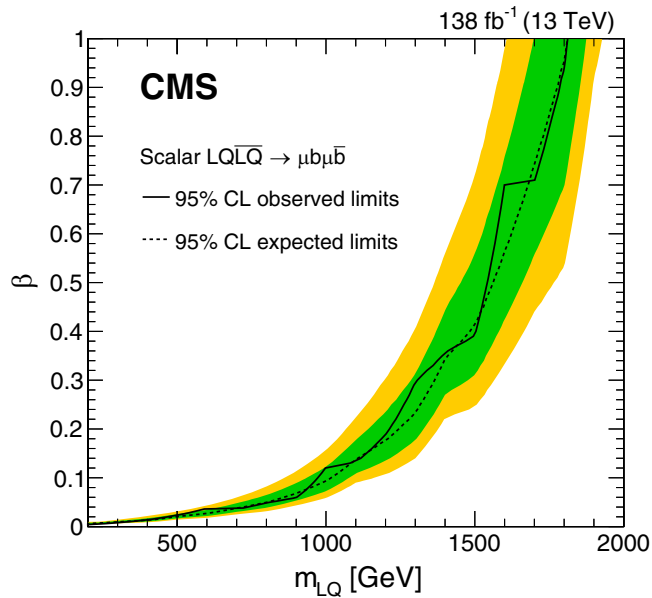
FIG. 8. The expected and observed exclusion limits at 95% CL as a function of the leptoquark mass and the branching fraction β. The solid line represents the observed limits, the dashed line represents the median expected limits, and the inner dark-green and outer light-yellow bands represent the 68% and 95% CL intervals. The area left of the observed limit is excluded.

or observed in data CRs. Individual datasets from different years are treated separately, then statistically combined into a single limit on the full dataset. Most systematic uncertainties are treated as fully uncorrelated across years in the combination, with the exception of PDF, pileup, and shape uncertainties, which are fully correlated, and the integrated luminosity uncertainty, which is partially correlated.

The 95% CL upper limits on $\sigma\beta^2$ as a function of m_{LQ} are shown in Fig. 7, together with the NLO (LO) predictions for the scalar (vector) LQ pair production cross sections. Theoretical uncertainties in the LQ signal production cross sections are shown as a band around the signal production cross section. Uncertainties in the vector model cross sections are larger than in the scalar model because of the LO assumptions in the interference of the helicity states of the vector model [83,99]. The discrete nature of the final selection for each LQ candidate mass produces the observed variation in the observed limit. By comparing the observed upper limit with the theoretical cross section values, scalar LQs with $m_{LQ} < 1810$ GeV are excluded under the assumption of $\beta = 1$, in agreement with the median expected limit of 1810 GeV. Vector LQs with $m_{LQ} < 2120$ (2460) GeV are excluded in the minimal coupling (Yang-Mills) scenario, under the assumption of $\beta = 1$, compared to the median expected limit of 2200 (2580) GeV.

Figure 8 shows the expected and observed exclusion limits at 95% CL as a function of the scalar LQ mass and β. Scalar LQs with $m_{LQ} < 1540$ GeV are excluded for $\beta = 0.5$, compared to the median expected limit of 1560 GeV.

VII. SUMMARY

A search has been performed for pair production of LQs decaying to muons and bottom quarks using proton-proton collision data collected at $\sqrt{s} = 13$ TeV in 2016–2018 with the CMS detector at the LHC, corresponding to an integrated luminosity of 138 fb^{-1}. Limits are set at 95% confidence level on the product of the scalar LQ pair production cross section and β^2, as a function of the LQ mass m_{LQ}, where β is the branching fraction of the LQ decaying to a muon and a bottom quark. Scalar LQs with $m_{LQ} < 1810$ GeV are excluded for $\beta = 1$. The results are also presented as a function of β, and scalar LQs with $m_{LQ} < 1540$ GeV are excluded for $\beta = 0.5$. A further interpretation is performed with a vector LQ model, and vector LQs with $m_{LQ} < 2120$ (2460) GeV are excluded in the minimal coupling (Yang-Mills) scenario for $\beta = 1$. These represent the most stringent limits to date on these models.

[1] J. C. Pati and A. Salam, Unified lepton-hadron symmetry and a gauge theory of the basic interactions, Phys. Rev. D **8,** 1240 (1973).

[2] J. C. Pati and A. Salam, Lepton number as the fourth color, Phys. Rev. D **10,** 275 (1974).

[3] H. Georgi and S. Glashow, Unity of all elementary-particle forces, Phys. Rev. Lett. **32,** 438 (1974).

[4] H. Fritzsch and P. Minkowski, United interactions of leptons and hadrons, Ann. Phys. (N.Y.) **93,** 193 (1975).

[5] G. Senjanović and A. Sokorac, Light lepto-quarks in SO (10), Z. Phys. C **20,** 255 (1983).

[6] P. H. Frampton and B.-H. Lee, SU(15) grand unification, Phys. Rev. Lett. **64,** 619 (1990).

[7] P. H. Frampton and T. W. Kephart, Higgs sector and proton decay in SU(15q) grand unification, Phys. Rev. D **42,** 3892 (1990).

[8] H. Murayama and T. Yanagida, A viable SU(5) GUT with light leptoquark bosons, Mod. Phys. Lett. A **07,** 147 (1992).

[9] B. Schrempp and F. Schrempp, Light leptoquarks, Phys. Lett. **153B,** 101 (1985).

[10] S. Dimopoulos and L. Susskind, Mass without scalars, Nucl. Phys. **B155,** 237 (1979).

[11] S. Dimopoulos, Technicolored signatures, Nucl. Phys. **B168,** 69 (1980).

[12] E. Eichten and K. Lane, Dynamical breaking of the weak interaction symmetries, Phys. Lett. **90B,** 85 (1980).

[13] J. L. Hewett and T. G. Rizzo, Low-energy phenomenology of superstring-inspired E$_6$ models, Phys. Rep. **183,** 193 (1989).

[14] P. Ramond, Dual theory for free fermions, Phys. Rev. D **3,** 2415 (1971).

[15] Y. A. Golfand and E. P. Likhtman, Extension of the algebra of Poincaré group generators and violation of p invariance, JETP Lett. **13,** 323 (1971).

[16] A. Neveu and J. H. Schwarz, Factorizable dual model of pions, Nucl. Phys. **B31,** 86 (1971).

[17] D. V. Volkov and V. P. Akulov, Possible universal neutrino interaction, JETP Lett. **16,** 438 (1972).

[18] J. Wess and B. Zumino, A Lagrangian model invariant under supergauge transformations, Phys. Lett. **49B,** 52 (1974).

[19] J. Wess and B. Zumino, Supergauge transformations in four dimensions, Nucl. Phys. **70B,** 39 (1974).

[20] P. Fayet, Supergauge invariant extension of the Higgs mechanism and a model for the electron and its neutrino, Nucl. Phys. **B90,** 104 (1975).

[21] G. R. Farrar and P. Fayet, Phenomenology of the production, decay, and detection of new hadronic states associated with supersymmetry, Phys. Lett. **76B,** 575 (1978).

[22] H. P. Nilles, Supersymmetry, supergravity and particle physics, Phys. Rep. **110,** 1 (1984).

[23] R. Barbier, C. Bérat, M. Besançon, M. Chemtob, A. Deandrea, E. Dudas, P. Fayet, S. Lavignac, G. Moreau, E. Perez, and Y. Sirois, R-parity violating supersymmetry, Phys. Rep. **420,** 1 (2005).

[24] J. P. Lees *et al.* (BABAR Collaboration), Evidence for an excess of $\bar{B} \to D^{(*)}\tau^-\bar{\nu}_\tau$ decays, Phys. Rev. Lett. **109,** 101802 (2012).

[25] J. P. Lees *et al.* (BABAR Collaboration), Measurement of an excess of $\bar{B} \to D^{(*)}\tau^-\bar{\nu}_\tau$ decays and implications for charged Higgs bosons, Phys. Rev. D **88,** 072012 (2013).

[26] M. Huschle *et al.* (Belle Collaboration), Measurement of the branching ratio of $\bar{B} \to D^{(*)}\tau^-\bar{\nu}_\tau$ relative to $\bar{B} \to D^{(*)}\ell^-\bar{\nu}_\ell$ decays with hadronic tagging at Belle, Phys. Rev. D **92,** 072014 (2015).

[27] S. Hirose *et al.* (Belle Collaboration), Measurement of the τ lepton polarization and $R(D^*)$ in the decay $\bar{B} \to D^*\tau^-\bar{\nu}_\tau$, Phys. Rev. Lett. **118,** 211801 (2017).

[28] S. Hirose *et al.* (Belle Collaboration), Measurement of the τ lepton polarization and $R(D^*)$ in the decay $\bar{B} \to D^*\tau^-\bar{\nu}_\tau$ with one-prong hadronic τ decays at Belle, Phys. Rev. D **97,** 012004 (2018).

[29] G. Caria *et al.* (Belle Collaboration), Measurement of $\mathcal{R}(D)$ and $\mathcal{R}(D^*)$ with a semileptonic tagging method, Phys. Rev. Lett. **124,** 161803 (2020).

[30] LHCb Collaboration, Measurement of the ratio of branching fractions $\mathcal{B}(\bar{B}^0 \to D^{*+}\tau^-\bar{\nu}_\tau)/\mathcal{B}(\bar{B}^0 \to D^{*+}\mu^-\bar{\nu}_\mu)$, Phys. Rev. Lett. **115,** 111803 (2015); **115,** 159901(E) (2015).

[31] LHCb Collaboration, Measurement of the ratio of the $B^0 \to D^{*-}\tau^+\nu_\tau$ and $B^0 \to D^{*-}\mu^+\nu_\mu$ branching fractions using three-prong τ-lepton decays, Phys. Rev. Lett. **120,** 171802 (2018).

[32] LHCb Collaboration, Test of lepton flavor universality by the measurement of the $B^0 \to D^{*-}\tau^+\nu_\tau$ branching fraction using three-prong τ decays, Phys. Rev. D **97,** 072013 (2018).

[33] LHCb Collaboration, Measurement of the ratio of branching fractions $\mathcal{B}(B_c^+ \to J/\psi\tau^+\nu_\tau)/\mathcal{B}(B_c^+ \to J/\psi\mu^+\nu_\mu)$, Phys. Rev. Lett. **120,** 121801 (2018).

[34] LHCb Collaboration, Test of lepton flavor universality using $B^0 \to D^{*-}\tau^+\nu_\tau$ decays with hadronic τ channels, Phys. Rev. D **108,** 012018 (2023).

[35] LHCb Collaboration, Measurement of the ratios of branching fractions $\mathcal{R}(D^*)$ and $\mathcal{R}(D^0)$, Phys. Rev. Lett. **131,** 111802 (2023).

[36] G. W. Bennett *et al.* (Muon g-2 Collaboration), Final report of the E821 muon anomalous magnetic moment measurement at BNL, Phys. Rev. D **73,** 072003 (2006).

[37] B. Abi *et al.* (Muon g-2 Collaboration), Measurement of the positive muon anomalous magnetic moment to 0.46 ppm, Phys. Rev. Lett. **126,** 141801 (2021).

[38] D. P. Aguillard *et al.* (Muon g-2 Collaboration), Measurement of the positive muon anomalous magnetic moment to 0.20 ppm, Phys. Rev. Lett. **131,** 161802 (2023).

[39] I. Doršner, S. Fajfer, A. Greljo, J. F. Kamenik, and N. Košnik, Physics of leptoquarks in precision experiments and at particle colliders, Phys. Rep. **641,** 1 (2016).

[40] B. Diaz, M. Schmaltz, and Y.-M. Zhong, The leptoquark Hunter's guide: Pair production, J. High Energy Phys. 10 (2017) 097.

[41] D. Buttazzo, A. Greljo, G. Isidori, and D. Marzocca, B-physics anomalies: A guide to combined explanations, J. High Energy Phys. 11 (2017) 044.

[42] L. Calibbi, A. Crivellin, and T. Li, Model of vector leptoquarks in view of the B-physics anomalies, Phys. Rev. D **98,** 115002 (2018).

[43] G. Hiller, D. Loose, and I. Nišandžić, Flavorful leptoquarks at hadron colliders, Phys. Rev. D **97,** 075004 (2018).

[44] I. Doršner, S. Fajfer, and A. Greljo, Cornering scalar leptoquarks at LHC, J. High Energy Phys. 10 (2014) 154.

[45] W. Buchmüller, R. Rückl, and D. Wyler, Leptoquarks in lepton-quark collisions, Phys. Lett. B **191,** 442 (1987).

[46] J. Blumlein, E. Boos, and A. Kryukov, Leptoquark pair production in hadronic interactions, Z. Phys. C **76,** 137 (1997).

[47] CMS Collaboration, Search for pair production of first and second generation leptoquarks in proton-proton collisions at $\sqrt{s} = 8$ TeV, Phys. Rev. D **93,** 032004 (2016).

[48] CMS Collaboration, Search for pair production of second-generation leptoquarks at $\sqrt{s} = 13$ TeV, Phys. Rev. D **99,** 032014 (2019).

[49] ATLAS Collaboration, Search for pairs of scalar leptoquarks decaying into quarks and electrons or muons in $\sqrt{s} = 13$ TeV pp collisions with the ATLAS detector, J. High Energy Phys. 10 (2020) 112.

[50] ATLAS Collaboration, Search for pair-produced scalar and vector leptoquarks decaying into third-generation quarks and first- or second-generation leptons in pp collisions with the ATLAS detector, J. High Energy Phys. 06 (2023) 188.

[51] ATLAS Collaboration, Combination of searches for pair-produced leptoquarks at $\sqrt{s} = 13$ TeV with the ATLAS detector, arXiv:2401.11928 [Phys. Lett. B (to be published)].

[52] CMS Collaboration, The CMS experiment at the CERN LHC, J. Instrum. **3,** S08004 (2008).

[53] CMS Collaboration, Performance of the CMS Level-1 trigger in proton-proton collisions at $\sqrt{s} = 13$ TeV, J. Instrum. **15,** P10017 (2020).

[54] CMS Collaboration, The CMS trigger system, J. Instrum. **12,** P01020 (2017).

[55] CMS Collaboration, Technical proposal for the Phase-II upgrade of the CMS detector, Technical Report No. CMS-TDR-15-02, 2015, https://cds.cern.ch/record/2020886.

[56] CMS Collaboration, Particle-flow reconstruction and global event description with the CMS detector, J. Instrum. **12,** P10003 (2017).

[57] E. Bols, J. Kieseler, M. Verzetti, M. Stoye, and A. Stakia, Jet flavour classification using DeepJet, J. Instrum. **15,** P12012 (2020).

[58] CMS Collaboration, Identification of heavy-flavour jets with the CMS detector in pp collisions at 13 TeV, J. Instrum. **13**, P05011 (2018).

[59] CMS Collaboration, Performance summary of AK4 jet b tagging with data from proton-proton collisions at 13 TeV with the CMS detector, CMS Detector Performance Note, Report No. CMS-DP-2023-005, 2023, http://cds.cern.ch/record/2854609.

[60] M. Cacciari, G. P. Salam, and G. Soyez, The anti-k_T jet clustering algorithm, J. High Energy Phys. 04 (2008) 063.

[61] M. Cacciari, G. P. Salam, and G. Soyez, FastJet user manual, Eur. Phys. J. C **72**, 1896 (2012).

[62] CMS Collaboration, Pileup mitigation at CMS in 13 TeV data, J. Instrum. **15**, P09018 (2020).

[63] CMS Collaboration, Jet energy scale and resolution in the CMS experiment in pp collisions at 8 TeV, J. Instrum. **12**, P02014 (2017).

[64] CMS Collaboration, Performance of the CMS muon detector and muon reconstruction with proton-proton collisions at $\sqrt{s} = 13$ TeV, J. Instrum. **13**, P06015 (2018).

[65] CMS Collaboration, Performance of missing transverse momentum reconstruction in proton-proton collisions at $\sqrt{s} = 13$ TeV using the CMS detector, J. Instrum. **14**, P07004 (2019).

[66] CMS Collaboration, Precision luminosity measurement in proton-proton collisions at $\sqrt{s} = 13$ TeV in 2015 and 2016 at CMS, Eur. Phys. J. C **81**, 800 (2021).

[67] CMS Collaboration, CMS luminosity measurement for the 2017 data-taking period at $\sqrt{s} = 13$ TeV, CMS Physics Analysis Summary, Report No. CMS-PAS-LUM-17-004, 2018, http://cds.cern.ch/record/2621960.

[68] CMS Collaboration, CMS luminosity measurement for the 2018 data-taking period at $\sqrt{s} = 13$ TeV, CMS Physics Analysis Summary, Report No. CMS-PAS-LUM-18-002, 2019, http://cds.cern.ch/record/2676164.

[69] S. Frixione and B. R. Webber, Matching NLO QCD computations and parton shower simulations, J. High Energy Phys. 06 (2002) 029.

[70] J. Alwall, R. Frederix, S. Frixione, V. Hirschi, F. Maltoni, O. Mattelaer, H.-S. Shao, T. Stelzer, P. Torrielli, and M. Zaro, The automated computation of tree-level and next-to-leading order differential cross sections, and their matching to parton shower simulations, J. High Energy Phys. 07 (2014) 079.

[71] R. Frederix and S. Frixione, Merging meets matching in MC@NLO, J. High Energy Phys. 12 (2012) 061.

[72] S. Frixione, P. Nason, and C. Oleari, Matching NLO QCD computations with parton shower simulations: The POWHEG method, J. High Energy Phys. 11 (2007) 070.

[73] S. Alioli, P. Nason, C. Oleari, and E. Re, NLO vector-boson production matched with shower in POWHEG, J. High Energy Phys. 07 (2008) 060.

[74] S. Alioli, P. Nason, C. Oleari, and E. Re, NLO single-top production matched with shower in POWHEG: s- and t-channel contributions, J. High Energy Phys. 09 (2009) 111; 02 (2010) 11.

[75] S. Alioli, P. Nason, C. Oleari, and E. Re, A general framework for implementing NLO calculations in shower Monte Carlo programs: The POWHEG BOX, J. High Energy Phys. 06 (2010) 043.

[76] S. Frixione, E. Laenen, P. Motylinski, and B. R. Webber, Single-top production in MC@NLO, J. High Energy Phys. 03 (2006) 092.

[77] T. Sjöstrand, S. Ask, J. R. Christiansen, R. Corke, N. Desai, P. Ilten, S. Mrenna, S. Prestel, C. O. Rasmussen, and P. Z. Skands, An Introduction to PYTHIA 8.2, Comput. Phys. Commun. **191**, 159 (2015).

[78] R. D. Ball *et al.* (NNPDF Collaboration), Parton distributions for the LHC Run II, J. High Energy Phys. 04 (2015) 040.

[79] S. Agostinelli *et al.* (GEANT4 Collaboration), Geant4—A simulation toolkit, Nucl. Instrum. Methods Phys. Res., Sect. A **506**, 250 (2003).

[80] J. Allison *et al.*, Geant4 developments and applications, IEEE Trans. Nucl. Sci. **53**, 270 (2006).

[81] CMS Collaboration, Event generator tunes obtained from underlying event and multiparton scattering measurements, Eur. Phys. J. C **76**, 155 (2016).

[82] CMS Collaboration, Extraction and validation of a new set of CMS PYTHIA8 tunes from underlying-event measurements, Eur. Phys. J. C **80**, 4 (2020).

[83] I. Doršner and A. Greljo, Leptoquark toolbox for precision collider studies, J. High Energy Phys. 05 (2018) 126.

[84] M. Kramer, T. Plehn, M. Spira, and P. M. Zerwas, Pair production of scalar leptoquarks at the CERN LHC, Phys. Rev. D **71**, 057503 (2005).

[85] T. Mandal, S. Mitra, and S. Seth, Pair production of scalar leptoquarks at the LHC to NLO parton shower accuracy, Phys. Rev. D **93**, 035018 (2016).

[86] J. Butterworth *et al.*, PDF4LHC recommendations for LHC Run II, J. Phys. G **43**, 023001 (2016).

[87] L. Mason, J. Baxter, P. L. Bartlett, and M. Frean, Boosting algorithms as gradient descent, in *Advances in Neural Information Processing Systems* 12 (MIT Press, Cambridge, MA, 1999), p. 512, https://proceedings.neurips.cc/paper_files/paper/1999/file/96a93ba89a5b5c6c226e49b88973f46e-Paper.pdf.

[88] J. H. Friedman, Greedy function approximation: A gradient boosting machine, Ann. Stat. **29**, 1189 (2001).

[89] J. H. Friedman, Stochastic gradient boosting, Computational Statistics and Data Analysis **38**, 367 (2002).

[90] G. Punzi, Sensitivity of searches for new signals and its optimization, in Statistical Problems in Particle Physics, Astrophysics and Cosmology. Proceedings, Conference, PHYSTAT, Stanford, USA, 2003, arXiv:physics/0308063.

[91] HEPData record for this analysis (2024), http://dx.doi.org/10.17182/hepdata.146074.

[92] CMS Collaboration, Search for high-mass resonances in dilepton final states in proton-proton collisions at $\sqrt{s} = 13$ TeV, J. High Energy Phys. 06 (2018) 120.

[93] D. Bourilkov, R. C. Group, and M. R. Whalley, LHAPDF: PDF use from the Tevatron to the LHC, arXiv:hep-ph/0605240.

[94] CMS Collaboration, Measurement of the inelastic proton-proton cross section at $\sqrt{s} = 13$ TeV, J. High Energy Phys. 07 (2018) 161.

[95] CMS Collaboration, Measurement of differential cross sections for top quark pair production using the lepton + jets final state in proton-proton collisions at 13 TeV, Phys. Rev. D **95**, 092001 (2017).

[96] G. Cowan, K. Cranmer, E. Gross, and O. Vitells, Asymptotic formulae for likelihood-based tests of new physics, Eur. Phys. J. C **71**, 1554 (2011); **73**, 2501(E) (2013).

[97] T. Junk, Confidence level computation for combining searches with small statistics, Nucl. Instrum. Methods Phys. Res., Sect. A **434**, 435 (1999).

[98] A. L. Read, Presentation of search results: The CL_s technique, J. Phys. G **28**, 2693 (2002).

[99] J. B. Hammett and D. A. Ross, NLO leptoquark production and decay: The narrow-width approximation and beyond, J. High Energy Phys. 07 (2015) 148.

A. Hayrapetyan,[1] A. Tumasyan[1,b] W. Adam,[2] J. W. Andrejkovic,[2] T. Bergauer,[2] S. Chatterjee,[2] K. Damanakis,[2] M. Dragicevic,[2] P. S. Hussain,[2] M. Jeitler,[2,c] N. Krammer,[2] A. Li,[2] D. Liko,[2] I. Mikulec,[2] J. Schieck,[2,c] R. Schöfbeck,[2] D. Schwarz,[2] M. Sonawane,[2] S. Templ,[2] W. Waltenberger,[2] C.-E. Wulz,[2,c] M. R. Darwish,[3,d] T. Janssen,[3] P. Van Mechelen,[3] E. S. Bols,[4] J. D'Hondt,[4] S. Dansana,[4] A. De Moor,[4] M. Delcourt,[4] H. El Faham,[4] S. Lowette,[4] I. Makarenko,[4] D. Müller,[4] A. R. Sahasransu,[4] S. Tavernier,[4] M. Tytgat,[4,e] S. Van Putte,[4] D. Vannerom,[4] B. Clerbaux,[5] G. De Lentdecker,[5] L. Favart,[5] D. Hohov,[5] J. Jaramillo,[5] A. Khalilzadeh,[5] K. Lee,[5] M. Mahdavikhorrami,[5] A. Malara,[5] S. Paredes,[5] L. Pétré,[5] N. Postiau,[5] L. Thomas,[5] M. Vanden Bemden,[5] C. Vander Velde,[5] P. Vanlaer,[5] M. De Coen,[6] D. Dobur,[6] Y. Hong,[6] J. Knolle,[6] L. Lambrecht,[6] G. Mestdach,[6] C. Rendón,[6] A. Samalan,[6] K. Skovpen,[6] N. Van Den Bossche,[6] J. van der Linden,[6] L. Wezenbeek,[6] A. Benecke,[7] A. Bethani,[7] G. Bruno,[7] C. Caputo,[7] C. Delaere,[7] I. S. Donertas,[7] A. Giammanco,[7] K. Jaffel,[7] Sa. Jain,[7] V. Lemaitre,[7] J. Lidrych,[7] P. Mastrapasqua,[7] K. Mondal,[7] T. T. Tran,[7] S. Wertz,[7] G. A. Alves,[8] E. Coelho,[8] C. Hensel,[8] T. Menezes De Oliveira,[8] A. Moraes,[8] P. Rebello Teles,[8] M. Soeiro,[8] W. L. Aldá Júnior,[9] M. Alves Gallo Pereira,[9] M. Barroso Ferreira Filho,[9] H. Brandao Malbouisson,[9] W. Carvalho,[9] J. Chinellato,[9,f] E. M. Da Costa,[9] G. G. Da Silveira,[9,g] D. De Jesus Damiao,[9] S. Fonseca De Souza,[9] R. Gomes De Souza,[9] J. Martins,[9,h] C. Mora Herrera,[9] K. Mota Amarilo,[9] L. Mundim,[9] H. Nogima,[9] A. Santoro,[9] A. Sznajder,[9] M. Thiel,[9] A. Vilela Pereira,[9] C. A. Bernardes,[10,g] L. Calligaris,[10] T. R. Fernandez Perez Tomei,[10] E. M. Gregores,[10] P. G. Mercadante,[10] S. F. Novaes,[10] B. Orzari,[10] Sandra S. Padula,[10] A. Aleksandrov,[11] G. Antchev,[11] R. Hadjiiska,[11] P. Iaydjiev,[11] M. Misheva,[11] M. Shopova,[11] G. Sultanov,[11] A. Dimitrov,[12] L. Litov,[12] B. Pavlov,[12] P. Petkov,[12] A. Petrov,[12] E. Shumka,[12] S. Keshri,[13] S. Thakur,[13] T. Cheng,[14] Q. Guo,[14] T. Javaid,[14] L. Yuan,[14] Z. Hu,[15] J. Liu,[15] K. Yi,[15,i,j] G. M. Chen,[16,k] H. S. Chen,[16,k] M. Chen,[16,k] F. Iemmi,[16] C. H. Jiang,[16] A. Kapoor,[16,l] H. Liao,[16] Z.-A. Liu,[16,m] R. Sharma,[16,n] J. N. Song,[16,m] J. Tao,[16] C. Wang,[16,k] J. Wang,[16] Z. Wang,[16,k] H. Zhang,[16] A. Agapitos,[17] Y. Ban,[17] A. Levin,[17] C. Li,[17] Q. Li,[17] Y. Mao,[17] S. J. Qian,[17] X. Sun,[17] D. Wang,[17] H. Yang,[17] L. Zhang,[17] C. Zhou,[17] Z. You,[18] N. Lu,[19] G. Bauer,[20,o] X. Gao,[21,p] D. Leggat,[21] H. Okawa,[21] Z. Lin,[22] C. Lu,[22] M. Xiao,[22] C. Avila,[23] D. A. Barbosa Trujillo,[23] A. Cabrera,[23] C. Florez,[23] J. Fraga,[23] J. A. Reyes Vega,[23] J. Mejia Guisao,[24] F. Ramirez,[24] M. Rodriguez,[24] J. D. Ruiz Alvarez,[24] D. Giljanovic,[25] N. Godinovic,[25] D. Lelas,[25] A. Sculac,[25] M. Kovac,[26] T. Sculac,[26] P. Bargassa,[27] V. Brigljevic,[27] B. K. Chitroda,[27] D. Ferencek,[27] S. Mishra,[27] A. Starodumov,[27,q] T. Susa,[27] A. Attikis,[28] K. Christoforou,[28] S. Konstantinou,[28] J. Mousa,[28] C. Nicolaou,[28] F. Ptochos,[28] P. A. Razis,[28] H. Rykaczewski,[28] H. Saka,[28] A. Stepennov,[28] M. Finger,[29] M. Finger Jr.,[29] A. Kveton,[29] E. Ayala,[30] E. Carrera Jarrin,[31] A. A. Abdelalim,[32,r,s] E. Salama,[32,t,u] M. A. Mahmoud,[33] Y. Mohammed,[33] R. K. Dewanjee,[34,v] K. Ehataht,[34] M. Kadastik,[34] T. Lange,[34] S. Nandan,[34] C. Nielsen,[34] J. Pata,[34] M. Raidal,[34] L. Tani,[34] C. Veelken,[34] H. Kirschenmann,[35] K. Osterberg,[35] M. Voutilainen,[35] S. Bharthuar,[36] E. Brücken,[36] F. Garcia,[36] K. T. S. Kallonen,[36] R. Kinnunen,[36] T. Lampén,[36] K. Lassila-Perini,[36] S. Lehti,[36] T. Lindén,[36] L. Martikainen,[36] M. Myllymäki,[36] M. m. Rantanen,[36] H. Siikonen,[36] E. Tuominen,[36] J. Tuominiemi,[36] P. Luukka,[37] H. Petrow,[37] M. Besancon,[38] F. Couderc,[38] M. Dejardin,[38] D. Denegri,[38] J. L. Faure,[38] F. Ferri,[38] S. Ganjour,[38] P. Gras,[38] G. Hamel de Monchenault,[38] V. Lohezic,[38] J. Malcles,[38] J. Rander,[38] A. Rosowsky,[38] M. Ö. Sahin,[38] A. Savoy-Navarro,[38,w] P. Simkina,[38] M. Titov,[38] M. Tornago,[38] C. Baldenegro Barrera,[39] F. Beaudette,[39] A. Buchot Perraguin,[39] P. Busson,[39] A. Cappati,[39] C. Charlot,[39] F. Damas,[39] O. Davignon,[39] A. De Wit,[39] B. A. Fontana Santos Alves,[39] S. Ghosh,[39] A. Gilbert,[39] R. Granier de Cassagnac,[39] A. Hakimi,[39]

B. Harikrishnan,[39] L. Kalipoliti,[39] G. Liu,[39] J. Motta,[39] M. Nguyen,[39] C. Ochando,[39] L. Portales,[39]
R. Salerno,[39] J. B. Sauvan,[39] Y. Sirois,[39] A. Tarabini,[39] E. Vernazza,[39] A. Zabi,[39] A. Zghiche,[39]
J.-L. Agram,[40,x] J. Andrea,[40] D. Apparu,[40] D. Bloch,[40] J.-M. Brom,[40] E. C. Chabert,[40] C. Collard,[40] S. Falke,[40]
U. Goerlach,[40] C. Grimault,[40] R. Haeberle,[40] A.-C. Le Bihan,[40] M. Meena,[40] G. Saha,[40] M. A. Sessini,[40]
P. Van Hove,[40] S. Beauceron,[41] B. Blancon,[41] G. Boudoul,[41] N. Chanon,[41] J. Choi,[41] D. Contardo,[41]
P. Depasse,[41] C. Dozen,[41,y] H. El Mamouni,[41] J. Fay,[41] S. Gascon,[41] M. Gouzevitch,[41] C. Greenberg,[41]
G. Grenier,[41] B. Ille,[41] I. B. Laktineh,[41] M. Lethuillier,[41] L. Mirabito,[41] S. Perries,[41] A. Purohit,[41]
M. Vander Donckt,[41] P. Verdier,[41] J. Xiao,[41] I. Lomidze,[42] T. Toriashvili,[42,z] Z. Tsamalaidze,[42,q] V. Botta,[43]
L. Feld,[43] K. Klein,[43] M. Lipinski,[43] D. Meuser,[43] A. Pauls,[43] N. Röwert,[43] M. Teroerde,[43] S. Diekmann,[44]
A. Dodonova,[44] N. Eich,[44] D. Eliseev,[44] F. Engelke,[44] J. Erdmann,[44] M. Erdmann,[44] P. Fackeldey,[44]
B. Fischer,[44] T. Hebbeker,[44] K. Hoepfner,[44] F. Ivone,[44] A. Jung,[44] M. y. Lee,[44] L. Mastrolorenzo,[44]
F. Mausolf,[44] M. Merschmeyer,[44] A. Meyer,[44] S. Mukherjee,[44] D. Noll,[44] A. Novak,[44] F. Nowotny,[44]
A. Pozdnyakov,[44] Y. Rath,[44] W. Redjeb,[44] F. Rehm,[44] H. Reithler,[44] U. Sarkar,[44] V. Sarkisovi,[44] A. Schmidt,[44]
A. Sharma,[44] J. L. Spah,[44] A. Stein,[44] F. Torres Da Silva De Araujo,[44,aa] L. Vigilante,[44] S. Wiedenbeck,[44]
S. Zaleski,[44] C. Dziwok,[45] G. Flügge,[45] W. Haj Ahmad,[45,bb] T. Kress,[45] A. Nowack,[45] O. Pooth,[45] A. Stahl,[45]
T. Ziemons,[45] A. Zotz,[45] H. Aarup Petersen,[46] M. Aldaya Martin,[46] J. Alimena,[46] S. Amoroso,[46] Y. An,[46]
S. Baxter,[46] M. Bayatmakou,[46] H. Becerril Gonzalez,[46] O. Behnke,[46] A. Belvedere,[46] S. Bhattacharya,[46]
F. Blekman,[46,cc] K. Borras,[46,dd] A. Campbell,[46] A. Cardini,[46] C. Cheng,[46] F. Colombina,[46]
S. Consuegra Rodríguez,[46] G. Correia Silva,[46] M. De Silva,[46] G. Eckerlin,[46] D. Eckstein,[46] L. I. Estevez Banos,[46]
O. Filatov,[46] E. Gallo,[46,cc] A. Geiser,[46] A. Giraldi,[46] G. Greau,[46] V. Guglielmi,[46] M. Guthoff,[46] A. Hinzmann,[46]
A. Jafari,[46,ee] L. Jeppe,[46] N. Z. Jomhari,[46] B. Kaech,[46] M. Kasemann,[46] C. Kleinwort,[46] R. Kogler,[46]
M. Komm,[46] D. Krücker,[46] W. Lange,[46] D. Leyva Pernia,[46] K. Lipka,[46,ff] W. Lohmann,[46,gg] R. Mankel,[46]
I.-A. Melzer-Pellmann,[46] M. Mendizabal Morentin,[46] A. B. Meyer,[46] G. Milella,[46] A. Mussgiller,[46] L. P. Nair,[46]
A. Nürnberg,[46] Y. Otarid,[46] J. Park,[46] D. Pérez Adán,[46] E. Ranken,[46] A. Raspereza,[46] B. Ribeiro Lopes,[46]
J. Rübenach,[46] A. Saggio,[46] M. Scham,[46,hh,dd] S. Schnake,[46,dd] P. Schütze,[46] C. Schwanenberger,[46,cc]
D. Selivanova,[46] M. Shchedrolosiev,[46] R. E. Sosa Ricardo,[46] D. Stafford,[46] F. Vazzoler,[46] A. Ventura Barroso,[46]
R. Walsh,[46] Q. Wang,[46] Y. Wen,[46] K. Wichmann,[46] L. Wiens,[46,dd] C. Wissing,[46] Y. Yang,[46]
A. Zimermmane Castro Santos,[46] A. Albrecht,[47] S. Albrecht,[47] M. Antonello,[47] S. Bein,[47] L. Benato,[47]
M. Bonanomi,[47] P. Connor,[47] M. Eich,[47] K. El Morabit,[47] Y. Fischer,[47] A. Fröhlich,[47] C. Garbers,[47] E. Garutti,[47]
A. Grohsjean,[47] M. Hajheidari,[47] J. Haller,[47] H. R. Jabusch,[47] G. Kasieczka,[47] P. Keicher,[47] R. Klanner,[47]
W. Korcari,[47] T. Kramer,[47] V. Kutzner,[47] F. Labe,[47] J. Lange,[47] A. Lobanov,[47] C. Matthies,[47] A. Mehta,[47]
L. Moureaux,[47] M. Mrowietz,[47] A. Nigamova,[47] Y. Nissan,[47] A. Paasch,[47] K. J. Pena Rodriguez,[47] T. Quadfasel,[47]
B. Raciti,[47] M. Rieger,[47] D. Savoiu,[47] J. Schindler,[47] P. Schleper,[47] M. Schröder,[47] J. Schwandt,[47]
M. Sommerhalder,[47] H. Stadie,[47] G. Steinbrück,[47] A. Tews,[47] M. Wolf,[47] S. Brommer,[48] M. Burkart,[48] E. Butz,[48]
T. Chwalek,[48] A. Dierlamm,[48] A. Droll,[48] N. Faltermann,[48] M. Giffels,[48] A. Gottmann,[48] F. Hartmann,[48,ii]
R. Hofsaess,[48] M. Horzela,[48] U. Husemann,[48] J. Kieseler,[48] M. Klute,[48] R. Koppenhöfer,[48] J. M. Lawhorn,[48]
M. Link,[48] A. Lintuluoto,[48] S. Maier,[48] S. Mitra,[48] M. Mormile,[48] Th. Müller,[48] M. Neukum,[48] M. Oh,[48]
M. Presilla,[48] G. Quast,[48] K. Rabbertz,[48] B. Regnery,[48] N. Shadskiy,[48] I. Shvetsov,[48] H. J. Simonis,[48]
M. Toms,[48,q] N. Trevisani,[48] R. Ulrich,[48] R. F. Von Cube,[48] M. Wassmer,[48] S. Wieland,[48] F. Wittig,[48] R. Wolf,[48]
X. Zuo,[48] G. Anagnostou,[49] G. Daskalakis,[49] A. Kyriakis,[49] A. Papadopoulos,[49,ii] A. Stakia,[49] P. Kontaxakis,[50]
G. Melachroinos,[50] A. Panagiotou,[50] I. Papavergou,[50] I. Paraskevas,[50] N. Saoulidou,[50] K. Theofilatos,[50]
E. Tziaferi,[50] K. Vellidis,[50] I. Zisopoulos,[50] G. Bakas,[51] T. Chatzistavrou,[51] G. Karapostoli,[51] K. Kousouris,[51]
I. Papakrivopoulos,[51] E. Siamarkou,[51] G. Tsipolitis,[51] A. Zacharopoulou,[51] K. Adamidis,[52] I. Bestintzanos,[52]
I. Evangelou,[52] C. Foudas,[52] P. Gianneios,[52] C. Kamtsikis,[52] P. Katsoulis,[52] P. Kokkas,[52]
P. G. Kosmoglou Kioseoglou,[52] N. Manthos,[52] I. Papadopoulos,[52] J. Strologas,[52] M. Bartók,[53,jj] C. Hajdu,[53]
D. Horvath,[53,kk,ll] F. Sikler,[53] V. Veszpremi,[53] M. Csanád,[54] K. Farkas,[54] M. M. A. Gadallah,[54,mm]
Á. Kadlecsik,[54] P. Major,[54] K. Mandal,[54] G. Pásztor,[54] A. J. Rádl,[54,nn] G. I. Veres,[54] P. Raics,[55] B. Ujvari,[55]
G. Zilizi,[55] G. Bencze,[56] S. Czellar,[56] J. Molnar,[56] Z. Szillasi,[56] T. Csorgo,[57,nn] F. Nemes,[57,nn] T. Novak,[57]
J. Babbar,[58] S. Bansal,[58] S. B. Beri,[58] V. Bhatnagar,[58] G. Chaudhary,[58] S. Chauhan,[58] N. Dhingra,[58,oo]

A. Kaur,[58] A. Kaur,[58] H. Kaur,[58] M. Kaur,[58] S. Kumar,[58] K. Sandeep,[58] T. Sheokand,[58] J. B. Singh,[58] A. Singla,[58] A. Ahmed,[59] A. Bhardwaj,[59] A. Chhetri,[59] B. C. Choudhary,[59] A. Kumar,[59] A. Kumar,[59] M. Naimuddin,[59] K. Ranjan,[59] S. Saumya,[59] S. Baradia,[60] S. Barman,[60,pp] S. Bhattacharya,[60] S. Dutta,[60] S. Dutta,[60] P. Palit,[60] S. Sarkar,[60] M. M. Ameen,[61] P. K. Behera,[61] S. C. Behera,[61] S. Chatterjee,[61] P. Jana,[61] P. Kalbhor,[61] J. R. Komaragiri,[61,qq] D. Kumar,[61,qq] L. Panwar,[61,qq] P. R. Pujahari,[61] N. R. Saha,[61] A. Sharma,[61] A. K. Sikdar,[61] S. Verma,[61] S. Dugad,[62] M. Kumar,[62] G. B. Mohanty,[62] P. Suryadevara,[62] A. Bala,[63] S. Banerjee,[63] R. M. Chatterjee,[63] M. Guchait,[63] Sh. Jain,[63] S. Karmakar,[63] S. Kumar,[63] G. Majumder,[63] K. Mazumdar,[63] S. Parolia,[63] A. Thachayath,[63] S. Bahinipati,[64,rr] A. K. Das,[64] C. Kar,[64] D. Maity,[64,ss] P. Mal,[64] T. Mishra,[64] V. K. Muraleedharan Nair Bindhu,[64,ss] K. Naskar,[64,ss] A. Nayak,[64,ss] P. Sadangi,[64] P. Saha,[64] S. K. Swain,[64] S. Varghese,[64,ss] D. Vats,[64,ss] S. Acharya,[65,tt] A. Alpana,[65] S. Dube,[65] B. Gomber,[65,tt] B. Kansal,[65] A. Laha,[65] B. Sahu,[65,tt] S. Sharma,[65] H. Bakhshiansohi,[66,uu] E. Khazaie,[66,vv] M. Zeinali,[66,ww] S. Chenarani,[67,xx] S. M. Etesami,[67] M. Khakzad,[67] M. Mohammadi Najafabadi,[67] M. Grunewald,[68] M. Abbrescia,[69a,69b] R. Aly,[69a,69c,r] A. Colaleo,[69a,69b] D. Creanza,[69a,69c] B. D'Anzi,[69a,69b] N. De Filippis,[69a,69c] M. De Palma,[69a,69b] A. Di Florio,[69a,69c] W. Elmetenawee,[69a,69b,r] L. Fiore,[69a] G. Iaselli,[69a,69c] M. Louka,[69a,69b] G. Maggi,[69a,69c] M. Maggi,[69a] I. Margjeka,[69a,69b] V. Mastrapasqua,[69a,69b] S. My,[69a,69b] S. Nuzzo,[69a,69b] A. Pellecchia,[69a,69b] A. Pompili,[69a,69b] G. Pugliese,[69a,69c] R. Radogna,[69a] G. Ramirez-Sanchez,[69a,69c] D. Ramos,[69a] A. Ranieri,[69a] L. Silvestris,[69a] F. M. Simone,[69a,69b] Ü. Sözbilir,[69a] A. Stamerra,[69a] R. Venditti,[69a] P. Verwilligen,[69a] A. Zaza,[69a,69b] C. Battilana,[70a,70b] D. Bonacorsi,[70a,70b] L. Borgonovi,[70a] R. Campanini,[70a,70b] P. Capiluppi,[70a,70b] A. Castro,[70a,70b] F. R. Cavallo,[70a] M. Cuffiani,[70a,70b] G. M. Dallavalle,[70a] T. Diotalevi,[70a,70b] F. Fabbri,[70a] A. Fanfani,[70a,70b] D. Fasanella,[70a,70b] P. Giacomelli,[70a] L. Giommi,[70a,70b] C. Grandi,[70a] L. Guiducci,[70a,70b] S. Lo Meo,[70a,yy] L. Lunerti,[70a,70b] S. Marcellini,[70a] G. Masetti,[70a] F. L. Navarria,[70a,70b] A. Perrotta,[70a] F. Primavera,[70a,70b] A. M. Rossi,[70a,70b] T. Rovelli,[70a,70b] G. P. Siroli,[70a,70b] S. Costa,[71a,71b,zz] A. Di Mattia,[71a] R. Potenza,[71a,71b] A. Tricomi,[71a,71b,zz] C. Tuve,[71a,71b] P. Assiouras,[72a] G. Barbagli,[72a] G. Bardelli,[72a,72b] B. Camaiani,[72a,72b] A. Cassese,[72a] R. Ceccarelli,[72a] V. Ciulli,[72a,72b] C. Civinini,[72a] R. D'Alessandro,[72a,72b] E. Focardi,[72a,72b] T. Kello,[72a] G. Latino,[72a,72b] P. Lenzi,[72a,72b] M. Lizzo,[72a] M. Meschini,[72a] S. Paoletti,[72a] A. Papanastassiou,[72a,72b] G. Sguazzoni,[72a] L. Viliani,[72a] L. Benussi,[73] S. Bianco,[73] S. Meola,[73,aaa] D. Piccolo,[73] P. Chatagnon,[74a] F. Ferro,[74a] E. Robutti,[74a] S. Tosi,[74a,74b] A. Benaglia,[75a] G. Boldrini,[75a,75b] F. Brivio,[75a] F. Cetorelli,[75a] F. De Guio,[75a,75b] M. E. Dinardo,[75a,75b] P. Dini,[75a] S. Gennai,[75a] R. Gerosa,[75a,75b] A. Ghezzi,[75a,75b] P. Govoni,[75a,75b] L. Guzzi,[75a] M. T. Lucchini,[75a,75b] M. Malberti,[75a] S. Malvezzi,[75a] A. Massironi,[75a] D. Menasce,[75a] L. Moroni,[75a] M. Paganoni,[75a,75b] D. Pedrini,[75a] B. S. Pinolini,[75a] S. Ragazzi,[75a,75b] T. Tabarelli de Fatis,[75a,75b] D. Zuolo,[75a] S. Buontempo,[76a] A. Cagnotta,[76a,76b] F. Carnevali,[76a,76b] N. Cavallo,[76a,76c] A. De Iorio,[76a,76b] F. Fabozzi,[76a,76c] A. O. M. Iorio,[76a,76b] L. Lista,[76a,76b,bbb] P. Paolucci,[76a,ii] B. Rossi,[76a] C. Sciacca,[76a,76b] R. Ardino,[77a] P. Azzi,[77a] N. Bacchetta,[77a,ccc] P. Bortignon,[77a] A. Bragagnolo,[77a,77b] R. Carlin,[77a,77b] P. Checchia,[77a] T. Dorigo,[77a] F. Gasparini,[77a,77b] E. Lusiani,[77a] M. Margoni,[77a,77b] A. T. Meneguzzo,[77a,77b] M. Migliorini,[77a,77b] F. Montecassiano,[77a] M. Passaseo,[77a] J. Pazzini,[77a,77b] P. Ronchese,[77a,77b] R. Rossin,[77a,77b] F. Simonetto,[77a,77b] G. Strong,[77a] M. Tosi,[77a,77b] A. Triossi,[77a,77b] S. Ventura,[77a] H. Yarar,[77a,77b] M. Zanetti,[77a,77b] P. Zotto,[77a,77b] A. Zucchetta,[77a,77b] G. Zumerle,[77a,77b] S. Abu Zeid,[78a,u] C. Aimè,[78a,78b] A. Braghieri,[78a] S. Calzaferri,[78a] D. Fiorina,[78a] P. Montagna,[78a,78b] V. Re,[78a] C. Riccardi,[78a,78b] P. Salvini,[78a] I. Vai,[78a,78b] P. Vitulo,[78a,78b] S. Ajmal,[79a,79b] P. Asenov,[79a,ddd] G. M. Bilei,[79a] D. Ciangottini,[79a,79b] L. Fanò,[79a,79b] M. Magherini,[79a,79b] G. Mantovani,[79a,79b] V. Mariani,[79a,79b] M. Menichelli,[79a] F. Moscatelli,[79a,ddd] A. Rossi,[79a,79b] A. Santocchia,[79a,79b] D. Spiga,[79a] T. Tedeschi,[79a,79b] P. Azzurri,[80a] G. Bagliesi,[80a] R. Bhattacharya,[80a] L. Bianchini,[80a,80b] T. Boccali,[80a] E. Bossini,[80a] D. Bruschini,[80a,80c] R. Castaldi,[80a] M. A. Ciocci,[80a,80b] M. Cipriani,[80a,80b] V. D'Amante,[80a,80d] R. Dell'Orso,[80a] S. Donato,[80a] A. Giassi,[80a] F. Ligabue,[80a,80c] D. Matos Figueiredo,[80a] A. Messineo,[80a,80b] M. Musich,[80a,80b] F. Palla,[80a] A. Rizzi,[80a,80b] G. Rolandi,[80a,80c] S. Roy Chowdhury,[80a] T. Sarkar,[80a] A. Scribano,[80a] P. Spagnolo,[80a] R. Tenchini,[80a] G. Tonelli,[80a,80b] N. Turini,[80a,80d] A. Venturi,[80a] P. G. Verdini,[80a] P. Barria,[81a] M. Campana,[81a,81b] F. Cavallari,[81a] L. Cunqueiro Mendez,[81a,81b] D. Del Re,[81a,81b] E. Di Marco,[81a] M. Diemoz,[81a] F. Errico,[81a,81b] E. Longo,[81a,81b] P. Meridiani,[81a] J. Mijuskovic,[81a,81b] G. Organtini,[81a,81b] F. Pandolfi,[81a] R. Paramatti,[81a,81b] C. Quaranta,[81a,81b] S. Rahatlou,[81a,81b] C. Rovelli,[81a] F. Santanastasio,[81a,81b] L. Soffi,[81a] N. Amapane,[82a,82b]

R. Arcidiacono[82a,82c] S. Argiro[82a,82b] M. Arneodo[82a,82c] N. Bartosik,[82a] R. Bellan[82a,82b] A. Bellora[82a,82b] C. Biino[82a] N. Cartiglia[82a] M. Costa[82a,82b] R. Covarelli[82a,82b] N. Demaria[82a] L. Finco[82a] M. Grippo[82a,82b] B. Kiani[82a,82b] F. Legger[82a] F. Luongo[82a,82b] C. Mariotti[82a] S. Maselli[82a] A. Mecca[82a,82b] E. Migliore[82a,82b] M. Monteno[82a] R. Mulargia[82a] M. M. Obertino[82a,82b] G. Ortona[82a] L. Pacher[82a,82b] N. Pastrone[82a] M. Pelliccioni[82a] M. Ruspa[82a,82c] F. Siviero[82a,82b] V. Sola[82a,82b] A. Solano[82a,82b] A. Staiano[82a] C. Tarricone[82a,82b] D. Trocino[82a] G. Umoret[82a,82b] E. Vlasov[82a,82b] S. Belforte[83a] V. Candelise[83a,83b] M. Casarsa[83a] F. Cossutti[83a] K. De Leo[83a,83b] G. Della Ricca[83a,83b] S. Dogra,[84] J. Hong[84] C. Huh[84] B. Kim[84] D. H. Kim[84] J. Kim,[84] H. Lee,[84] S. W. Lee,[84] C. S. Moon,[84] Y. D. Oh[84] M. S. Ryu[84] S. Sekmen[84] Y. C. Yang[84] M. S. Kim[85] G. Bak[86] P. Gwak[86] H. Kim[86] D. H. Moon[86] E. Asilar[87] D. Kim[87] T. J. Kim[87] J. A. Merlin,[87] S. Choi[88] S. Han,[88] B. Hong[88] K. Lee,[88] K. S. Lee[88] S. Lee,[88] J. Park,[88] S. K. Park,[88] J. Yoo[88] J. Goh[89] S. Yang[89] H. S. Kim[90] Y. Kim,[90] S. Lee,[90] J. Almond,[91] J. H. Bhyun,[91] J. Choi[91] W. Jun,[91] J. Kim,[91] S. Ko[91] H. Kwon[91] H. Lee[91] J. Lee,[91] J. Lee[91] B. H. Oh[91] S. B. Oh[91] H. Seo[91] U. K. Yang,[91] I. Yoon[91] W. Jang[92] D. Y. Kang,[92] Y. Kang[92] S. Kim[92] B. Ko,[92] J. S. H. Lee[92] Y. Lee[92] I. C. Park[92] Y. Roh,[92] I. J. Watson[92] S. Ha[93] H. D. Yoo[93] M. Choi[94] M. R. Kim[94] H. Lee,[94] Y. Lee[94] I. Yu[94] T. Beyrouthy,[95] Y. Maghrbi[95] K. Dreimanis[96] A. Gaile[96] G. Pikurs,[96] A. Potrebko[96] M. Seidel[96] V. Veckalns[96,eee] N. R. Strautnieks[97] M. Ambrozas[98] A. Juodagalvis[98] A. Rinkevicius[98] G. Tamulaitis[98] N. Bin Norjoharuddeen[99] I. Yusuff[99,fff] Z. Zolkapli,[99] J. F. Benitez[100] A. Castaneda Hernandez[100] H. A. Encinas Acosta,[100] L. G. Gallegos Maríñez,[100] M. León Coello[100] J. A. Murillo Quijada[100] A. Sehrawat[100] L. Valencia Palomo[100] G. Ayala[101] H. Castilla-Valdez[101] E. De La Cruz-Burelo[101] I. Heredia-De La Cruz[101,ggg] R. Lopez-Fernandez[101] C. A. Mondragon Herrera,[101] A. Sánchez Hernández[101] C. Oropeza Barrera[102] M. Ramírez García[102] I. Bautista[103] I. Pedraza[103] H. A. Salazar Ibarguen[103] C. Uribe Estrada[103] I. Bubanja,[104] N. Raicevic[104] P. H. Butler[105] A. Ahmad[106] M. I. Asghar,[106] A. Awais[106] M. I. M. Awan,[106] H. R. Hoorani[106] W. A. Khan[106] V. Avati,[107] L. Grzanka[107] M. Malawski[107] H. Bialkowska[108] M. Bluj[108] B. Boimska[108] M. Górski[108] M. Kazana[108] M. Szleper[108] P. Zalewski[108] K. Bunkowski[109] K. Doroba[109] A. Kalinowski[109] M. Konecki[109] J. Krolikowski[109] A. Muhammad[109] K. Pozniak[110] W. Zabolotny[110] M. Araujo[111] D. Bastos[111] C. Beirão Da Cruz E Silva[111] A. Boletti[111] M. Bozzo[111] T. Camporesi[111] G. Da Molin[111] P. Faccioli[111] M. Gallinaro[111] J. Hollar[111] N. Leonardo[111] T. Niknejad[111] A. Petrilli[111] M. Pisano[111] J. Seixas[111] J. Varela[111] J. W. Wulff,[111] P. Adzic[112] P. Milenovic[112] M. Dordevic[113] J. Milosevic[113] V. Rekovic,[113] M. Aguilar-Benitez,[114] J. Alcaraz Maestre[114] Cristina F. Bedoya[114] M. Cepeda[114] M. Cerrada[114] N. Colino[114] B. De La Cruz[114] A. Delgado Peris[114] A. Escalante Del Valle[114] D. Fernández Del Val[114] J. P. Fernández Ramos[114] J. Flix[114] M. C. Fouz[114] O. Gonzalez Lopez[114] S. Goy Lopez[114] J. M. Hernandez[114] M. I. Josa[114] D. Moran[114] C. M. Morcillo Perez[114] Á. Navarro Tobar[114] C. Perez Dengra[114] A. Pérez-Calero Yzquierdo[114] J. Puerta Pelayo[114] I. Redondo[114] D. D. Redondo Ferrero[114] L. Romero,[114] S. Sánchez Navas[114] L. Urda Gómez[114] J. Vazquez Escobar[114] C. Willmott,[114] J. F. de Trocóniz[115] B. Alvarez Gonzalez[116] J. Cuevas[116] J. Fernandez Menendez[116] S. Folgueras[116] I. Gonzalez Caballero[116] J. R. González Fernández[116] E. Palencia Cortezon[116] C. Ramón Álvarez[116] V. Rodríguez Bouza[116] A. Soto Rodríguez[116] A. Trapote[116] C. Vico Villalba[116] P. Vischia[116] S. Bhowmik[117] S. Blanco Fernández[117] J. A. Brochero Cifuentes[117] I. J. Cabrillo[117] A. Calderon[117] J. Duarte Campderros[117] M. Fernandez[117] G. Gomez[117] C. Lasaosa García[117] C. Martinez Rivero[117] P. Martinez Ruiz del Arbol[117] F. Matorras[117] P. Matorras Cuevas[117] E. Navarrete Ramos[117] J. Piedra Gomez[117] L. Scodellaro[117] I. Vila[117] J. M. Vizan Garcia[117] M. K. Jayananda[118] B. Kailasapathy[118,hhh] D. U. J. Sonnadara[118] D. D. C. Wickramarathna[118] W. G. D. Dharmaratna[119,iii] K. Liyanage[119] N. Perera[119] N. Wickramage[119] D. Abbaneo[120] C. Amendola[120] E. Auffray[120] G. Auzinger[120] J. Baechler,[120] D. Barney[120] A. Bermúdez Martínez[120] M. Bianco[120] B. Bilin[120] A. A. Bin Anuar[120] A. Bocci[120] C. Botta[120] E. Brondolin[120] C. Caillol[120] G. Cerminara[120] N. Chernyavskaya[120] D. d'Enterria[120] A. Dabrowski[120] A. David[120] A. De Roeck[120] M. M. Defranchis[120] M. Deile[120] M. Dobson[120] L. Forthomme[120] G. Franzoni[120] W. Funk[120] S. Giani,[120] D. Gigi,[120] K. Gill[120] F. Glege[120] L. Gouskos[120] M. Haranko[120] J. Hegeman[120] B. Huber,[120] V. Innocente[120] T. James[120] P. Janot[120] S. Laurila[120] P. Lecoq[120] E. Leutgeb[120] C. Lourenço[120] B. Maier[120] L. Malgeri[120] M. Mannelli[120] A. C. Marini[120] M. Matthewman,[120] F. Meijers[120]

S. Mersi[120] E. Meschi[120] V. Milosevic[120] F. Monti[120] F. Moortgat[120] M. Mulders[120] I. Neutelings[120] S. Orfanelli[120] F. Pantaleo[120] G. Petrucciani[120] A. Pfeiffer[120] M. Pierini[120] D. Piparo[120] H. Qu[120] D. Rabady[120] G. Reales Gutiérrez[120] M. Rovere[120] H. Sakulin[120] S. Scarfi[120] C. Schwick[120] M. Selvaggi[120] A. Sharma[120] K. Shchelina[120] P. Silva[120] P. Sphicas[120,jjj] A. G. Stahl Leiton[120] A. Steen[120] S. Summers[120] D. Treille[120] P. Tropea[120] A. Tsirou[120] D. Walter[120] J. Wanczyk[120,kkk] J. Wang[120] S. Wuchterl[120] P. Zehetner[120] P. Zejdl[120] W. D. Zeuner[120] T. Bevilacqua[121,lll] L. Caminada[121,lll] A. Ebrahimi[121] W. Erdmann[121] R. Horisberger[121] Q. Ingram[121] H. C. Kaestli[121] D. Kotlinski[121] C. Lange[121] M. Missiroli[121,lll] L. Noehte[121,lll] T. Rohe[121] T. K. Aarrestad[122] K. Androsov[122,kkk] M. Backhaus[122] A. Calandri[122] C. Cazzaniga[122] K. Datta[122] A. De Cosa[122] G. Dissertori[122] M. Dittmar[122] M. Donegà[122] F. Eble[122] M. Galli[122] K. Gedia[122] F. Glessgen[122] C. Grab[122] D. Hits[122] W. Lustermann[122] A.-M. Lyon[122] R. A. Manzoni[122] M. Marchegiani[122] L. Marchese[122] C. Martin Perez[122] A. Mascellani[122,kkk] F. Nessi-Tedaldi[122] F. Pauss[122] V. Perovic[122] S. Pigazzini[122] C. Reissel[122] T. Reitenspiess[122] B. Ristic[122] F. Riti[122] D. Ruini[122] R. Seidita[122] J. Steggemann[122,kkk] D. Valsecchi[122] R. Wallny[122] C. Amsler[123,mmm] P. Bärtschi[123] D. Brzhechko[123] M. F. Canelli[123] K. Cormier[123] J. K. Heikkilä[123] M. Huwiler[123] W. Jin[123] A. Jofrehei[123] B. Kilminster[123] S. Leontsinis[123] S. P. Liechti[123] A. Macchiolo[123] P. Meiring[123] U. Molinatti[123] A. Reimers[123] P. Robmann[123] S. Sanchez Cruz[123] M. Senger[123] Y. Takahashi[123] R. Tramontano[123] C. Adloff[124,nnn] D. Bhowmik[124] C. M. Kuo[124] W. Lin[124] P. K. Rout[124] P. C. Tiwari[124,qq] S. S. Yu[124] L. Ceard[125] Y. Chao[125] K. F. Chen[125] P. s. Chen[125] Z. g. Chen[125] W.-S. Hou[125] T. h. Hsu,[125] Y. w. Kao,[125] R. Khurana[125] G. Kole[125] Y. y. Li[125] R.-S. Lu[125] E. Paganis[125] X. f. Su[125] J. Thomas-Wilsker[125] L. s. Tsai,[125] H. y. Wu,[125] E. Yazgan[125] C. Asawatangtrakuldee[126] N. Srimanobhas[126] V. Wachirapusitanand[126] D. Agyel[127] F. Boran[127] Z. S. Demiroglu[127] F. Dolek[127] I. Dumanoglu[127,ooo] E. Eskut[127] Y. Guler[127,ppp] E. Gurpinar Guler[127,ppp] C. Isik[127] O. Kara,[127] A. Kayis Topaksu[127] U. Kiminsu[127] G. Onengut[127] K. Ozdemir[127,qqq] A. Polatoz[127] B. Tali[127,rrr] U. G. Tok[127] S. Turkcapar[127] E. Uslan[127] I. S. Zorbakir[127] M. Yalvac[128,sss] B. Akgun[129] I. O. Atakisi[129] E. Gülmez[129] M. Kaya[129,ttt] O. Kaya[129,uuu] S. Tekten[129,vvv] A. Cakir[130] K. Cankocak[130,ooo,www] Y. Komurcu[130] S. Sen[130,xxx] O. Aydilek[131] S. Cerci[131,rrr] V. Epshteyn[131] B. Hacisahinoglu[131] I. Hos[131,yyy] B. Kaynak[131] S. Ozkorucuklu[131] O. Potok[131] H. Sert[131] C. Simsek[131] D. Sunar Cerci[131,rrr] C. Zorbilmez[131] B. Isildak[132,zzz] A. Boyaryntsev[133] B. Grynyov[133] L. Levchuk[134] D. Anthony[135] J. J. Brooke[135] A. Bundock[135] F. Bury[135] E. Clement[135] D. Cussans[135] H. Flacher[135] M. Glowacki[135] J. Goldstein[135] H. F. Heath[135] L. Kreczko[135] S. Paramesvaran[135] S. Seif El Nasr-Storey,[135] V. J. Smith[135] N. Stylianou[135,aaaa] K. Walkingshaw Pass[135] R. White[135] A. H. Ball[136] K. W. Bell[136] A. Belyaev[136,bbbb] C. Brew[136] R. M. Brown[136] D. J. A. Cockerill[136] C. Cooke[136] K. V. Ellis[136] K. Harder[136] S. Harper[136] M.-L. Holmberg[136,cccc] J. Linacre[136] K. Manolopoulos[136] D. M. Newbold[136] E. Olaiya,[136] D. Petyt[136] T. Reis[136] G. Salvi[136] T. Schuh,[136] C. H. Shepherd-Themistocleous[136] I. R. Tomalin[136] T. Williams[136] R. Bainbridge[137] P. Bloch[137] C. E. Brown[137] O. Buchmuller,[137] V. Cacchio,[137] C. A. Carrillo Montoya[137] G. S. Chahal[137,dddd] D. Colling[137] J. S. Dancu[137] I. Das[137] P. Dauncey[137] G. Davies[137] J. Davies,[137] M. Della Negra[137] S. Fayer,[137] G. Fedi[137] G. Hall[137] M. H. Hassanshahi[137] A. Howard,[137] G. Iles[137] M. Knight[137] J. Langford[137] J. León Holgado[137] L. Lyons[137] A.-M. Magnan[137] S. Malik,[137] M. Mieskolainen[137] J. Nash[137,eeee] M. Pesaresi[137] B. C. Radburn-Smith[137] A. Richards,[137] A. Rose[137] C. Seez[137] R. Shukla[137] A. Tapper[137] K. Uchida[137] G. P. Uttley[137] L. H. Vage[137] T. Virdee[137,ii] M. Vojinovic[137] N. Wardle[137] D. Winterbottom[137] K. Coldham,[138] J. E. Cole[138] A. Khan,[138] P. Kyberd[138] I. D. Reid[138] S. Abdullin[139] A. Brinkerhoff[139] B. Caraway[139] J. Dittmann[139] K. Hatakeyama[139] J. Hiltbrand[139] B. McMaster[139] M. Saunders[139] S. Sawant[139] C. Sutantawibul[139] J. Wilson[139] R. Bartek[140] A. Dominguez[140] C. Huerta Escamilla,[140] A. E. Simsek[140] R. Uniyal[140] A. M. Vargas Hernandez[140] B. Bam[141] R. Chudasama[141] S. I. Cooper[141] S. V. Gleyzer[141] C. U. Perez[141] P. Rumerio[141,ffff] E. Usai[141] R. Yi[141] A. Akpinar[142] D. Arcaro[142] C. Cosby[142] Z. Demiragli[142] C. Erice[142] C. Fangmeier[142] C. Fernandez Madrazo[142] E. Fontanesi[142] D. Gastler[142] F. Golf[142] S. Jeon[142] I. Reed[142] J. Rohlf[142] K. Salyer[142] D. Sperka[142] D. Spitzbart[142] I. Suarez[142] A. Tsatsos[142] S. Yuan[142] A. G. Zecchinelli[142] G. Benelli[143] X. Coubez[143,dd] D. Cutts[143] M. Hadley[143] U. Heintz[143] J. M. Hogan[143,gggg] T. Kwon[143] G. Landsberg[143] K. T. Lau[143] D. Li[143] J. Luo[143] S. Mondal[143] M. Narain[143,a] N. Pervan[143] S. Sagir[143,hhhh]

F. Simpson,[143] M. Stamenkovic,[143] W. Y. Wong,[143] X. Yan,[143] W. Zhang,[143] S. Abbott,[144] J. Bonilla,[144] C. Brainerd,[144] R. Breedon,[144] M. Calderon De La Barca Sanchez,[144] M. Chertok,[144] M. Citron,[144] J. Conway,[144] P. T. Cox,[144] R. Erbacher,[144] F. Jensen,[144] O. Kukral,[144] G. Mocellin,[144] M. Mulhearn,[144] D. Pellett,[144] W. Wei,[144] Y. Yao,[144] F. Zhang,[144] M. Bachtis,[145] R. Cousins,[145] A. Datta,[145] G. Flores Avila,[145] J. Hauser,[145] M. Ignatenko,[145] M. A. Iqbal,[145] T. Lam,[145] E. Manca,[145] A. Nunez Del Prado,[145] D. Saltzberg,[145] V. Valuev,[145] R. Clare,[146] J. W. Gary,[146] M. Gordon,[146] G. Hanson,[146] W. Si,[146] S. Wimpenny,[146,a] J. G. Branson,[147] S. Cittolin,[147] S. Cooperstein,[147] D. Diaz,[147] J. Duarte,[147] L. Giannini,[147] J. Guiang,[147] R. Kansal,[147] V. Krutelyov,[147] R. Lee,[147] J. Letts,[147] M. Masciovecchio,[147] F. Mokhtar,[147] S. Mukherjee,[147] M. Pieri,[147] M. Quinnan,[147] B. V. Sathia Narayanan,[147] V. Sharma,[147] M. Tadel,[147] E. Vourliotis,[147] F. Würthwein,[147] Y. Xiang,[147] A. Yagil,[147] A. Barzdukas,[148] L. Brennan,[148] C. Campagnari,[148] A. Dorsett,[148] J. Incandela,[148] J. Kim,[148] A. J. Li,[148] P. Masterson,[148] H. Mei,[148] J. Richman,[148] U. Sarica,[148] R. Schmitz,[148] F. Setti,[148] J. Sheplock,[148] D. Stuart,[148] T. Á. Vámi,[148] S. Wang,[148] A. Bornheim,[149] O. Cerri,[149] A. Latorre,[149] J. Mao,[149] H. B. Newman,[149] M. Spiropulu,[149] J. R. Vlimant,[149] C. Wang,[149] S. Xie,[149] R. Y. Zhu,[149] J. Alison,[150] S. An,[150] M. B. Andrews,[150] P. Bryant,[150] M. Cremonesi,[150] V. Dutta,[150] T. Ferguson,[150] A. Harilal,[150] C. Liu,[150] T. Mudholkar,[150] S. Murthy,[150] M. Paulini,[150] A. Roberts,[150] A. Sanchez,[150] W. Terrill,[150] J. P. Cumalat,[151] W. T. Ford,[151] A. Hassani,[151] G. Karathanasis,[151] E. MacDonald,[151] N. Manganelli,[151] F. Marini,[151] A. Perloff,[151] C. Savard,[151] N. Schonbeck,[151] K. Stenson,[151] K. A. Ulmer,[151] S. R. Wagner,[151] N. Zipper,[151] J. Alexander,[152] S. Bright-Thonney,[152] X. Chen,[152] D. J. Cranshaw,[152] J. Fan,[152] X. Fan,[152] D. Gadkari,[152] S. Hogan,[152] P. Kotamnives,[152] J. Monroy,[152] M. Oshiro,[152] J. R. Patterson,[152] J. Reichert,[152] M. Reid,[152] A. Ryd,[152] J. Thom,[152] P. Wittich,[152] R. Zou,[152] M. Albrow,[153] M. Alyari,[153] O. Amram,[153] G. Apollinari,[153] A. Apresyan,[153] L. A. T. Bauerdick,[153] D. Berry,[153] J. Berryhill,[153] P. C. Bhat,[153] K. Burkett,[153] J. N. Butler,[153] A. Canepa,[153] G. B. Cerati,[153] H. W. K. Cheung,[153] F. Chlebana,[153] G. Cummings,[153] J. Dickinson,[153] I. Dutta,[153] V. D. Elvira,[153] Y. Feng,[153] J. Freeman,[153] A. Gandrakota,[153] Z. Gecse,[153] L. Gray,[153] D. Green,[153] A. Grummer,[153] S. Grünendahl,[153] D. Guerrero,[153] O. Gutsche,[153] R. M. Harris,[153] R. Heller,[153] T. C. Herwig,[153] J. Hirschauer,[153] L. Horyn,[153] B. Jayatilaka,[153] S. Jindariani,[153] M. Johnson,[153] U. Joshi,[153] T. Klijnsma,[153] B. Klima,[153] K. H. M. Kwok,[153] S. Lammel,[153] D. Lincoln,[153] R. Lipton,[153] T. Liu,[153] C. Madrid,[153] K. Maeshima,[153] C. Mantilla,[153] D. Mason,[153] P. McBride,[153] P. Merkel,[153] S. Mrenna,[153] S. Nahn,[153] J. Ngadiuba,[153] D. Noonan,[153] V. Papadimitriou,[153] N. Pastika,[153] K. Pedro,[153] C. Pena,[153,iiii] F. Ravera,[153] A. Reinsvold Hall,[153,jjjj] L. Ristori,[153] E. Sexton-Kennedy,[153] N. Smith,[153] A. Soha,[153] L. Spiegel,[153] S. Stoynev,[153] J. Strait,[153] L. Taylor,[153] S. Tkaczyk,[153] N. V. Tran,[153] L. Uplegger,[153] E. W. Vaandering,[153] I. Zoi,[153] C. Aruta,[154] P. Avery,[154] D. Bourilkov,[154] L. Cadamuro,[154] P. Chang,[154] V. Cherepanov,[154] R. D. Field,[154] E. Koenig,[154] M. Kolosova,[154] J. Konigsberg,[154] A. Korytov,[154] K. H. Lo,[154] K. Matchev,[154] N. Menendez,[154] G. Mitselmakher,[154] K. Mohrman,[154] A. Muthirakalayil Madhu,[154] N. Rawal,[154] D. Rosenzweig,[154] S. Rosenzweig,[154] K. Shi,[154] J. Wang,[154] T. Adams,[155] A. Al Kadhim,[155] A. Askew,[155] N. Bower,[155] R. Habibullah,[155] V. Hagopian,[155] R. Hashmi,[155] R. S. Kim,[155] S. Kim,[155] T. Kolberg,[155] G. Martinez,[155] H. Prosper,[155] P. R. Prova,[155] M. Wulansatiti,[155] R. Yohay,[155] J. Zhang,[155] B. Alsufyani,[156] M. M. Baarmand,[156] S. Butalla,[156] T. Elkafrawy,[156,u] M. Hohlmann,[156] R. Kumar Verma,[156] M. Rahmani,[156] E. Yanes,[156] M. R. Adams,[157] A. Baty,[157] C. Bennett,[157] R. Cavanaugh,[157] S. Dittmer,[157] R. Escobar Franco,[157] O. Evdokimov,[157] C. E. Gerber,[157] D. J. Hofman,[157] J. h. Lee,[157] D. S. Lemos,[157] A. H. Merrit,[157] C. Mills,[157] S. Nanda,[157] G. Oh,[157] B. Ozek,[157] D. Pilipovic,[157] R. Pradhan,[157] T. Roy,[157] S. Rudrabhatla,[157] M. B. Tonjes,[157] N. Varelas,[157] Z. Ye,[157] J. Yoo,[157] M. Alhusseini,[158] D. Blend,[158] K. Dilsiz,[158,kkkk] L. Emediato,[158] G. Karaman,[158] O. K. Köseyan,[158] J.-P. Merlo,[158] A. Mestvirishvili,[158,llll] J. Nachtman,[158] O. Neogi,[158] H. Ogul,[158,mmmm] Y. Onel,[158] A. Penzo,[158] C. Snyder,[158] E. Tiras,[158,nnnn] B. Blumenfeld,[159] L. Corcodilos,[159] J. Davis,[159] A. V. Gritsan,[159] L. Kang,[159] S. Kyriacou,[159] P. Maksimovic,[159] M. Roguljic,[159] J. Roskes,[159] S. Sekhar,[159] M. Swartz,[159] A. Abreu,[160] L. F. Alcerro Alcerro,[160] J. Anguiano,[160] P. Baringer,[160] A. Bean,[160] Z. Flowers,[160] D. Grove,[160] J. King,[160] G. Krintiras,[160] M. Lazarovits,[160] C. Le Mahieu,[160] C. Lindsey,[160] J. Marquez,[160] N. Minafra,[160] M. Murray,[160] M. Nickel,[160] M. Pitt,[160] S. Popescu,[160,oooo] C. Rogan,[160] C. Royon,[160] R. Salvatico,[160] S. Sanders,[160] C. Smith,[160] Q. Wang,[160] G. Wilson,[160] B. Allmond,[161] A. Ivanov,[161] K. Kaadze,[161] A. Kalogeropoulos,[161] D. Kim,[161] Y. Maravin,[161] K. Nam,[161]

J. Natoli[161] D. Roy[161] G. Sorrentino[161] F. Rebassoo[162] D. Wright[162] A. Baden[163] A. Belloni[163] Y. M. Chen[163] S. C. Eno[163] N. J. Hadley[163] S. Jabeen[163] R. G. Kellogg[163] T. Koeth[163] Y. Lai[163] S. Lascio[163] A. C. Mignerey[163] S. Nabili[163] C. Palmer[163] C. Papageorgakis[163] M. M. Paranjpe,[163] L. Wang[163] J. Bendavid[164] W. Busza[164] I. A. Cali[164] Y. Chen[164] M. D'Alfonso[164] J. Eysermans[164] C. Freer[164] G. Gomez-Ceballos[164] M. Goncharov,[164] G. Grosso[164] P. Harris,[164] D. Hoang[164] D. Kovalskyi[164] J. Krupa[164] L. Lavezzo[164] Y.-J. Lee[164] K. Long[164] C. Mironov[164] C. Paus[164] D. Rankin[164] C. Roland[164] G. Roland[164] S. Rothman[164] G. S. F. Stephans[164] Z. Wang,[164] B. Wyslouch[164] T. J. Yang[164] B. Crossman[165] B. M. Joshi[165] C. Kapsiak[165] M. Krohn[165] D. Mahon[165] J. Mans[165] B. Marzocchi[165] S. Pandey[165] M. Revering[165] R. Rusack[165] R. Saradhy[165] N. Schroeder[165] N. Strobbe[165] M. A. Wadud[165] L. M. Cremaldi[166] K. Bloom[167] D. R. Claes[167] G. Haza[167] J. Hossain[167] C. Joo[167] I. Kravchenko[167] J. E. Siado[167] W. Tabb[167] A. Vagnerini[167] A. Wightman[167] F. Yan[167] D. Yu[167] H. Bandyopadhyay[168] L. Hay[168] I. Iashvili[168] A. Kharchilava[168] M. Morris[168] D. Nguyen[168] S. Rappoccio[168] H. Rejeb Sfar,[168] A. Williams[168] G. Alverson[169] E. Barberis[169] J. Dervan,[169] Y. Haddad[169] Y. Han[169] A. Krishna[169] J. Li[169] M. Lu[169] G. Madigan[169] R. Mccarthy[169] D. M. Morse[169] V. Nguyen[169] T. Orimoto[169] A. Parker[169] L. Skinnari[169] A. Tishelman-Charny[169] B. Wang[169] D. Wood[169] S. Bhattacharya[170] J. Bueghly,[170] Z. Chen[170] K. A. Hahn[170] Y. Liu[170] Y. Miao[170] D. G. Monk[170] M. H. Schmitt[170] A. Taliercio[170] M. Velasco,[170] G. Agarwal[171] R. Band,[171] R. Bucci,[171] S. Castells[171] A. Das[171] R. Goldouzian[171] M. Hildreth[171] K. W. Ho[171] K. Hurtado Anampa[171] T. Ivanov[171] C. Jessop[171] K. Lannon[171] J. Lawrence[171] N. Loukas[171] L. Lutton[171] J. Mariano,[171] N. Marinelli,[171] I. Mcalister,[171] T. McCauley[171] C. Mcgrady[171] C. Moore[171] Y. Musienko,[171,q] H. Nelson[171] M. Osherson[171] A. Piccinelli[171] R. Ruchti[171] A. Townsend[171] Y. Wan,[171] M. Wayne[171] H. Yockey,[171] M. Zarucki[171] L. Zygala[171] A. Basnet[172] B. Bylsma,[172] M. Carrigan[172] L. S. Durkin[172] C. Hill[172] M. Joyce[172] M. Nunez Ornelas[172] K. Wei,[172] B. L. Winer[172] B. R. Yates[172] F. M. Addesa[173] H. Bouchamaoui[173] P. Das,[173] G. Dezoort[173] P. Elmer[173] A. Frankenthal[173] B. Greenberg[173] N. Haubrich[173] G. Kopp[173] S. Kwan[173] D. Lange[173] A. Loeliger[173] D. Marlow[173] I. Ojalvo[173] J. Olsen[173] A. Shevelev[173] D. Stickland[173] C. Tully[173] S. Malik[174] A. S. Bakshi[175] V. E. Barnes[175] S. Chandra[175] R. Chawla[175] S. Das[175] A. Gu[175] L. Gutay,[175] M. Jones[175] A. W. Jung[175] D. Kondratyev[175] A. M. Koshy,[175] M. Liu[175] G. Negro[175] N. Neumeister[175] G. Paspalaki[175] S. Piperov[175] V. Scheurer,[175] J. F. Schulte[175] M. Stojanovic[175] J. Thieman[175] A. K. Virdi[175] F. Wang[175] W. Xie[175] J. Dolen[176] N. Parashar[176] A. Pathak[176] D. Acosta[177] T. Carnahan[177] K. M. Ecklund[177] P. J. Fernández Manteca[177] S. Freed,[177] P. Gardner,[177] F. J. M. Geurts[177] W. Li[177] O. Miguel Colin[177] B. P. Padley[177] R. Redjimi,[177] J. Rotter[177] E. Yigitbasi[177] Y. Zhang[177] A. Bodek[178] P. de Barbaro[178] R. Demina[178] J. L. Dulemba[178] A. Garcia-Bellido[178] O. Hindrichs[178] A. Khukhunaishvili[178] N. Parmar,[178] P. Parygin[178,q] E. Popova[178,q] R. Taus[178] G. P. Van Onsem[178] K. Goulianos[179] B. Chiarito[180] J. P. Chou[180] Y. Gershtein[180] E. Halkiadakis[180] A. Hart[180] M. Heindl[180] D. Jaroslawski[180] O. Karacheban[180,gg] I. Laflotte[180] A. Lath[180] R. Montalvo,[180] K. Nash,[180] H. Routray[180] S. Salur[180] S. Schnetzer,[180] S. Somalwar[180] R. Stone[180] S. A. Thayil[180] S. Thomas,[180] J. Vora[180] H. Wang[180] H. Acharya,[181] D. Ally[181] A. G. Delannoy[181] S. Fiorendi[181] S. Higginbotham[181] T. Holmes[181] A. R. Kanuganti[181] N. Karunarathna[181] L. Lee[181] E. Nibigira[181] S. Spanier[181] D. Aebi[182] M. Ahmad[182] O. Bouhali[182,pppp] R. Eusebi[182] J. Gilmore[182] T. Huang[182] T. Kamon[182,qqqq] H. Kim[182] S. Luo[182] R. Mueller[182] D. Overton[182] D. Rathjens[182] A. Safonov[182] N. Akchurin[183] J. Damgov[183] V. Hegde[183] A. Hussain[183] Y. Kazhykarim,[183] K. Lamichhane[183] S. W. Lee[183] A. Mankel[183] T. Peltola[183] I. Volobouev[183] A. Whitbeck[183] E. Appelt[184] S. Greene,[184] A. Gurrola[184] W. Johns[184] R. Kunnawalkam Elayavalli[184] A. Melo[184] F. Romeo[184] P. Sheldon[184] S. Tuo[184] J. Velkovska[184] J. Viinikainen[184] B. Cardwell[185] B. Cox[185] J. Hakala[185] R. Hirosky[185] A. Ledovskoy[185] C. Neu[185] C. E. Perez Lara[185] P. E. Karchin[186] A. Aravind,[187] S. Banerjee[187] K. Black[187] T. Bose[187] S. Dasu[187] I. De Bruyn[187] P. Everaerts[187] C. Galloni,[187] H. He[187] M. Herndon[187] A. Herve[187] C. K. Koraka[187] A. Lanaro,[187] R. Loveless[187] J. Madhusudanan Sreekala,[187] A. Mallampalli[187] A. Mohammadi[187] S. Mondal,[187] G. Parida[187] D. Pinna,[187] A. Savin,[187] V. Shang[187] V. Sharma[187] W. H. Smith[187] D. Teague,[187] H. F. Tsoi[187] W. Vetens[187] A. Warden[187] S. Afanasiev,[188] V. Andreev,[188] Yu. Andreev,[188] T. Aushev,[188] M. Azarkin,[188] A. Babaev,[188] A. Belyaev,[188] V. Blinov,[188,q] E. Boos[188] V. Borshch[188] D. Budkouski,[188] V. Chekhovsky,[188] R. Chistov[188,q] M. Danilov[188,q]

A. Dermenev[188] T. Dimova[188,q] D. Druzhkin[188,rrrr] M. Dubinin[188,iiii] L. Dudko[188] A. Ershov[188]
G. Gavrilov[188] V. Gavrilov[188] S. Gninenko[188] V. Golovtcov[188] N. Golubev[188] I. Golutvin[188] I. Gorbunov[188]
A. Gribushin[188] Y. Ivanov[188] V. Kachanov[188] V. Karjavine[188] A. Karneyeu[188] V. Kim[188,q] M. Kirakosyan[188]
D. Kirpichnikov[188] M. Kirsanov[188] V. Klyukhin[188] O. Kodolova[188,ssss] V. Korenkov[188] A. Kozyrev[188,q]
N. Krasnikov[188] A. Lanev[188] P. Levchenko[188,tttt] N. Lychkovskaya[188] V. Makarenko[188] A. Malakhov[188]
V. Matveev[188,q] V. Murzin[188] A. Nikitenko[188,uuuu,ssss] S. Obraztsov[188] V. Oreshkin[188] V. Palichik[188]
V. Perelygin[188] S. Petrushanko[188] S. Polikarpov[188,q] V. Popov[188] O. Radchenko[188,q] M. Savina[188]
V. Savrin[188] V. Shalaev[188] S. Shmatov[188] S. Shulha[188] Y. Skovpen[188,q] S. Slabospitskii[188] V. Smirnov[188]
A. Snigirev[188] D. Sosnov[188] V. Sulimov[188] E. Tcherniaev[188] A. Terkulov[188] O. Teryaev[188] I. Tlisova[188]
A. Toropin[188] L. Uvarov[188] A. Uzunian[188] A. Vorobyev,[188,a] N. Voytishin[188] B. S. Yuldashev[188,vvvv]
A. Zarubin[188] I. Zhizhin[188] and A. Zhokin[188]

(CMS Collaboration)

[1]*Yerevan Physics Institute, Yerevan, Armenia*
[2]*Institut für Hochenergiephysik, Vienna, Austria*
[3]*Universiteit Antwerpen, Antwerpen, Belgium*
[4]*Vrije Universiteit Brussel, Brussel, Belgium*
[5]*Université Libre de Bruxelles, Bruxelles, Belgium*
[6]*Ghent University, Ghent, Belgium*
[7]*Université Catholique de Louvain, Louvain-la-Neuve, Belgium*
[8]*Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil*
[9]*Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil*
[10]*Universidade Estadual Paulista, Universidade Federal do ABC, São Paulo, Brazil*
[11]*Institute for Nuclear Research and Nuclear Energy, Bulgarian Academy of Sciences, Sofia, Bulgaria*
[12]*University of Sofia, Sofia, Bulgaria*
[13]*Instituto De Alta Investigación, Universidad de Tarapacá, Casilla 7 D, Arica, Chile*
[14]*Beihang University, Beijing, China*
[15]*Department of Physics, Tsinghua University, Beijing, China*
[16]*Institute of High Energy Physics, Beijing, China*
[17]*State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China*
[18]*Sun Yat-Sen University, Guangzhou, China*
[19]*University of Science and Technology of China, Hefei, China*
[20]*Nanjing Normal University, Nanjing, China*
[21]*Institute of Modern Physics and Key Laboratory of Nuclear Physics and Ion-beam Application (MOE)-Fudan University, Shanghai, China*
[22]*Zhejiang University, Hangzhou, Zhejiang, China*
[23]*Universidad de Los Andes, Bogota, Colombia*
[24]*Universidad de Antioquia, Medellin, Colombia*
[25]*University of Split, Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, Split, Croatia*
[26]*University of Split, Faculty of Science, Split, Croatia*
[27]*Institute Rudjer Boskovic, Zagreb, Croatia*
[28]*University of Cyprus, Nicosia, Cyprus*
[29]*Charles University, Prague, Czech Republic*
[30]*Escuela Politecnica Nacional, Quito, Ecuador*
[31]*Universidad San Francisco de Quito, Quito, Ecuador*
[32]*Academy of Scientific Research and Technology of the Arab Republic of Egypt, Egyptian Network of High Energy Physics, Cairo, Egypt*
[33]*Center for High Energy Physics (CHEP-FU), Fayoum University, El-Fayoum, Egypt*
[34]*National Institute of Chemical Physics and Biophysics, Tallinn, Estonia*
[35]*Department of Physics, University of Helsinki, Helsinki, Finland*
[36]*Helsinki Institute of Physics, Helsinki, Finland*
[37]*Lappeenranta-Lahti University of Technology, Lappeenranta, Finland*
[38]*IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France*
[39]*Laboratoire Leprince-Ringuet, CNRS/IN2P3, Ecole Polytechnique, Institut Polytechnique de Paris, Palaiseau, France*

[40]Université de Strasbourg, CNRS, IPHC UMR 7178, Strasbourg, France

[41]Institut de Physique des 2 Infinis de Lyon (IP2I), Villeurbanne, France

[42]Georgian Technical University, Tbilisi, Georgia

[43]RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany

[44]RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany

[45]RWTH Aachen University, III. Physikalisches Institut B, Aachen, Germany

[46]Deutsches Elektronen-Synchrotron, Hamburg, Germany

[47]University of Hamburg, Hamburg, Germany

[48]Karlsruher Institut fuer Technologie, Karlsruhe, Germany

[49]Institute of Nuclear and Particle Physics (INPP), NCSR Demokritos, Aghia Paraskevi, Greece

[50]National and Kapodistrian University of Athens, Athens, Greece

[51]National Technical University of Athens, Athens, Greece

[52]University of Ioánnina, Ioánnina, Greece

[53]HUN-REN Wigner Research Centre for Physics, Budapest, Hungary

[54]MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University,
Budapest, Hungary

[55]Faculty of Informatics, University of Debrecen, Debrecen, Hungary

[56]Institute of Nuclear Research ATOMKI, Debrecen, Hungary

[57]Karoly Robert Campus, MATE Institute of Technology, Gyongyos, Hungary

[58]Panjab University, Chandigarh, India

[59]University of Delhi, Delhi, India

[60]Saha Institute of Nuclear Physics, HBNI, Kolkata, India

[61]Indian Institute of Technology Madras, Madras, India

[62]Tata Institute of Fundamental Research-A, Mumbai, India

[63]Tata Institute of Fundamental Research-B, Mumbai, India

[64]National Institute of Science Education and Research, An OCC of Homi Bhabha National Institute,
Bhubaneswar, Odisha, India

[65]Indian Institute of Science Education and Research (IISER), Pune, India

[66]Isfahan University of Technology, Isfahan, Iran

[67]Institute for Research in Fundamental Sciences (IPM), Tehran, Iran

[68]University College Dublin, Dublin, Ireland

[69a]INFN Sezione di Bari, Bari, Italy

[69b]Università di Bari, Bari, Italy

[69c]Politecnico di Bari, Bari, Italy

[70a]INFN Sezione di Bologna, Bologna, Italy

[70b]Università di Bologna, Bologna, Italy

[71a]INFN Sezione di Catania, Catania, Italy

[71b]Università di Catania, Catania, Italy

[72a]INFN Sezione di Firenze, Firenze, Italy

[72b]Università di Firenze, Firenze, Italy

[73]INFN Laboratori Nazionali di Frascati, Frascati, Italy

[74a]INFN Sezione di Genova, Genova, Italy

[74b]Università di Genova, Genova, Italy

[75a]INFN Sezione di Milano-Bicocca, Milano, Italy

[75b]Università di Milano-Bicocca, Milano, Italy

[76a]INFN Sezione di Napoli, Napoli, Italy

[76b]Università di Napoli 'Federico II', Napoli, Italy

[76c]Università della Basilicata, Potenza, Italy

[76d]Scuola Superiore Meridionale (SSM), Napoli, Italy

[77a]INFN Sezione di Padova, Padova, Italy

[77b]Università di Padova, Padova, Italy

[77c]Università di Trento, Trento, Italy

[78a]INFN Sezione di Pavia, Pavia, Italy

[78b]Università di Pavia, Pavia, Italy

[79a]INFN Sezione di Perugia, Perugia, Italy

[79b]Università di Perugia, Perugia, Italy

[80a]INFN Sezione di Pisa, Pisa, Italy

[80b]Università di Pisa, Pisa, Italy

[80c]Scuola Normale Superiore di Pisa, Pisa, Italy

[80d]Università di Siena, Siena, Italy

[81a]*INFN Sezione di Roma, Roma, Italy*
[81b]*Sapienza Università di Roma, Roma, Italy*
[82a]*INFN Sezione di Torino, Torino, Italy*
[82b]*Università di Torino, Torino, Italy*
[82c]*Università del Piemonte Orientale, Novara, Italy*
[83a]*INFN Sezione di Trieste, Trieste, Italy*
[83b]*Università di Trieste, Trieste, Italy*
[84]*Kyungpook National University, Daegu, Korea*
[85]*Department of Mathematics and Physics-GWNU, Gangneung, Korea*
[86]*Chonnam National University, Institute for Universe and Elementary Particles, Kwangju, Korea*
[87]*Hanyang University, Seoul, Korea*
[88]*Korea University, Seoul, Korea*
[89]*Kyung Hee University, Department of Physics, Seoul, Korea*
[90]*Sejong University, Seoul, Korea*
[91]*Seoul National University, Seoul, Korea*
[92]*University of Seoul, Seoul, Korea*
[93]*Yonsei University, Department of Physics, Seoul, Korea*
[94]*Sungkyunkwan University, Suwon, Korea*
[95]*College of Engineering and Technology, American University of the Middle East (AUM),
Dasman, Kuwait*
[96]*Riga Technical University, Riga, Latvia*
[97]*University of Latvia (LU), Riga, Latvia*
[98]*Vilnius University, Vilnius, Lithuania*
[99]*National Centre for Particle Physics, Universiti Malaya, Kuala Lumpur, Malaysia*
[100]*Universidad de Sonora (UNISON), Hermosillo, Mexico*
[101]*Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico*
[102]*Universidad Iberoamericana, Mexico City, Mexico*
[103]*Benemerita Universidad Autonoma de Puebla, Puebla, Mexico*
[104]*University of Montenegro, Podgorica, Montenegro*
[105]*University of Canterbury, Christchurch, New Zealand*
[106]*National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan*
[107]*AGH University of Krakow, Faculty of Computer Science, Electronics and Telecommunications,
Krakow, Poland*
[108]*National Centre for Nuclear Research, Swierk, Poland*
[109]*Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland*
[110]*Warsaw University of Technology, Warsaw, Poland*
[111]*Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal*
[112]*Faculty of Physics, University of Belgrade, Belgrade, Serbia*
[113]*VINCA Institute of Nuclear Sciences, University of Belgrade, Belgrade, Serbia*
[114]*Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain*
[115]*Universidad Autónoma de Madrid, Madrid, Spain*
[116]*Universidad de Oviedo, Instituto Universitario de Ciencias y Tecnologías Espaciales de Asturias (ICTEA),
Oviedo, Spain*
[117]*Instituto de Física de Cantabria (IFCA), CSIC-Universidad de Cantabria, Santander, Spain*
[118]*University of Colombo, Colombo, Sri Lanka*
[119]*University of Ruhuna, Department of Physics, Matara, Sri Lanka*
[120]*CERN, European Organization for Nuclear Research, Geneva, Switzerland*
[121]*Paul Scherrer Institut, Villigen, Switzerland*
[122]*ETH Zurich-Institute for Particle Physics and Astrophysics (IPA), Zurich, Switzerland*
[123]*Universität Zürich, Zurich, Switzerland*
[124]*National Central University, Chung-Li, Taiwan*
[125]*National Taiwan University (NTU), Taipei, Taiwan*
[126]*High Energy Physics Research Unit, Department of Physics, Faculty of Science,
Chulalongkorn University, Bangkok, Thailand*
[127]*Çukurova University, Physics Department, Science and Art Faculty, Adana, Turkey*
[128]*Middle East Technical University, Physics Department, Ankara, Turkey*
[129]*Bogazici University, Istanbul, Turkey*
[130]*Istanbul Technical University, Istanbul, Turkey*
[131]*Istanbul University, Istanbul, Turkey*
[132]*Yildiz Technical University, Istanbul, Turkey*

[133] *Institute for Scintillation Materials of National Academy of Science of Ukraine, Kharkiv, Ukraine*

[134] *National Science Centre, Kharkiv Institute of Physics and Technology, Kharkiv, Ukraine*

[135] *University of Bristol, Bristol, United Kingdom*

[136] *Rutherford Appleton Laboratory, Didcot, United Kingdom*

[137] *Imperial College, London, United Kingdom*

[138] *Brunel University, Uxbridge, United Kingdom*

[139] *Baylor University, Waco, Texas, USA*

[140] *Catholic University of America, Washington, DC, USA*

[141] *The University of Alabama, Tuscaloosa, Alabama, USA*

[142] *Boston University, Boston, Massachusetts, USA*

[143] *Brown University, Providence, Rhode Island, USA*

[144] *University of California, Davis, Davis, California, USA*

[145] *University of California, Los Angeles, California, USA*

[146] *University of California, Riverside, Riverside, California, USA*

[147] *University of California, San Diego, La Jolla, California, USA*

[148] *University of California, Santa Barbara - Department of Physics, Santa Barbara, California, USA*

[149] *California Institute of Technology, Pasadena, California, USA*

[150] *Carnegie Mellon University, Pittsburgh, Pennsylvania, USA*

[151] *University of Colorado Boulder, Boulder, Colorado, USA*

[152] *Cornell University, Ithaca, New York, USA*

[153] *Fermi National Accelerator Laboratory, Batavia, Illinois, USA*

[154] *University of Florida, Gainesville, Florida, USA*

[155] *Florida State University, Tallahassee, Florida, USA*

[156] *Florida Institute of Technology, Melbourne, Florida, USA*

[157] *University of Illinois Chicago, Chicago, USA, Chicago, USA*

[158] *The University of Iowa, Iowa City, Iowa, USA*

[159] *Johns Hopkins University, Baltimore, Maryland, USA*

[160] *The University of Kansas, Lawrence, Kansas, USA*

[161] *Kansas State University, Manhattan, Kansas, USA*

[162] *Lawrence Livermore National Laboratory, Livermore, California, USA*

[163] *University of Maryland, College Park, Maryland, USA*

[164] *Massachusetts Institute of Technology, Cambridge, Massachusetts, USA*

[165] *University of Minnesota, Minneapolis, Minnesota, USA*

[166] *University of Mississippi, Oxford, Mississippi, USA*

[167] *University of Nebraska-Lincoln, Lincoln, Nebraska, USA*

[168] *State University of New York at Buffalo, Buffalo, New York, USA*

[169] *Northeastern University, Boston, Massachusetts, USA*

[170] *Northwestern University, Evanston, Illinois, USA*

[171] *University of Notre Dame, Notre Dame, Indiana, USA*

[172] *The Ohio State University, Columbus, Ohio, USA*

[173] *Princeton University, Princeton, New Jersey, USA*

[174] *University of Puerto Rico, Mayaguez, Puerto Rico, USA*

[175] *Purdue University, West Lafayette, Indiana, USA*

[176] *Purdue University Northwest, Hammond, Indiana, USA*

[177] *Rice University, Houston, Texas, USA*

[178] *University of Rochester, Rochester, New York, USA*

[179] *The Rockefeller University, New York, New York, USA*

[180] *Rutgers, The State University of New Jersey, Piscataway, New Jersey, USA*

[181] *University of Tennessee, Knoxville, Tennessee, USA*

[182] *Texas A&M University, College Station, Texas, USA*

[183] *Texas Tech University, Lubbock, Texas, USA*

[184] *Vanderbilt University, Nashville, Tennessee, USA*

[185] *University of Virginia, Charlottesville, Virginia, USA*

[186] *Wayne State University, Detroit, Michigan, USA*

[187] *University of Wisconsin - Madison, Madison, Wisconsin, USA*

[188] *An institute or international laboratory covered by a cooperation agreement with CERN*

[a] Deceased.

[b] Also at Yerevan State University, Yerevan, Armenia.

[c] Also at TU Wien, Vienna, Austria.

[d] Also at Institute of Basic and Applied Sciences, Faculty of Engineering, Arab Academy for Science, Technology and Maritime Transport, Alexandria, Egypt.

[e] Also at Ghent University, Ghent, Belgium.

[f] Also at Universidade Estadual de Campinas, Campinas, Brazil.

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

[h] Also at UFMS, Nova Andradina, Brazil.

[i] Also at Nanjing Normal University, Nanjing, China.

[j] Also at The University of Iowa, Iowa City, Iowa, USA.

[k] Also at University of Chinese Academy of Sciences, Beijing, China.

[l] Also at China Center of Advanced Science and Technology, Beijing, China.

[m] Also at University of Chinese Academy of Sciences, Beijing, China.

[n] Also at China Spallation Neutron Source, Guangdong, China.

[o] Also at Henan Normal University, Xinxiang, China.

[p] Also at Université Libre de Bruxelles, Bruxelles, Belgium.

[q] Also at Another institute or international laboratory covered by a cooperation agreement with CERN.

[r] Also at Helwan University, Cairo, Egypt.

[s] Also at Zewail City of Science and Technology, Zewail, Egypt.

[t] Also at British University in Egypt, Cairo, Egypt.

[u] Also at Ain Shams University, Cairo, Egypt.

[v] Also at Birla Institute of Technology, Mesra, Mesra, India.

[w] Also at Purdue University, West Lafayette, Indiana, USA.

[x] Also at Université de Haute Alsace, Mulhouse, France.

[y] Also at Department of Physics, Tsinghua University, Beijing, China.

[z] Also at Tbilisi State University, Tbilisi, Georgia.

[aa] Also at The University of the State of Amazonas, Manaus, Brazil.

[bb] Also at Erzincan Binali Yildirim University, Erzincan, Turkey.

[cc] Also at University of Hamburg, Hamburg, Germany.

[dd] Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany.

[ee] Also at Isfahan University of Technology, Isfahan, Iran.

[ff] Also at Bergische University Wuppertal (BUW), Wuppertal, Germany.

[gg] Also at Brandenburg University of Technology, Cottbus, Germany.

[hh] Also at Forschungszentrum Jülich, Juelich, Germany.

[ii] Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland.

[jj] Also at Institute of Physics, University of Debrecen, Debrecen, Hungary.

[kk] Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary.

[ll] Also at Universitatea Babes-Bolyai—Facultatea de Fizica, Cluj-Napoca, Romania.

[mm] Also at Physics Department, Faculty of Science, Assiut University, Assiut, Egypt.

[nn] Also at HUN-REN Wigner Research Centre for Physics, Budapest, Hungary.

[oo] Also at Punjab Agricultural University, Ludhiana, India.

[pp] Also at University of Visva-Bharati, Santiniketan, India.

[qq] Also at Indian Institute of Science (IISc), Bangalore, India.

[rr] Also at IIT Bhubaneswar, Bhubaneswar, India.

[ss] Also at Institute of Physics, Bhubaneswar, India.

[tt] Also at University of Hyderabad, Hyderabad, India.

[uu] Also at Deutsches Elektronen-Synchrotron, Hamburg, Germany.

[vv] Also at Department of Physics, Isfahan University of Technology, Isfahan, Iran.

[ww] Also at Sharif University of Technology, Tehran, Iran.

[xx] Also at Department of Physics, University of Science and Technology of Mazandaran, Behshahr, Iran.

[yy] Also at Italian National Agency for New Technologies, Energy and Sustainable Economic Development, Bologna, Italy.

[zz] Also at Centro Siciliano di Fisica Nucleare e di Struttura Della Materia, Catania, Italy.

[aaa] Also at Università degli Studi Guglielmo Marconi, Roma, Italy.

[bbb] Also at Scuola Superiore Meridionale, Università di Napoli ’Federico II’, Napoli, Italy.

[ccc] Also at Fermi National Accelerator Laboratory, Batavia, Illinois, USA.

[ddd] Also at Consiglio Nazionale delle Ricerche—Istituto Officina dei Materiali, Perugia, Italy.

[eee] Also at Riga Technical University, Riga, Latvia.

[fff] Also at Department of Applied Physics, Faculty of Science and Technology, Universiti Kebangsaan Malaysia, Bangi, Malaysia.

[ggg] Also at Consejo Nacional de Ciencia y Tecnología, Mexico City, Mexico.

[hhh] Also at Trincomalee Campus, Eastern University, Sri Lanka, Nilaveli, Sri Lanka.

[iii] Also at Saegis Campus, Nugegoda, Sri Lanka.

[jjj] Also at National and Kapodistrian University of Athens, Athens, Greece.

[kkk]Also at Ecole Polytechnique Fédérale Lausanne, Lausanne, Switzerland.

[lll]Also at Universität Zürich, Zurich, Switzerland.

[mmm]Also at Stefan Meyer Institute for Subatomic Physics, Vienna, Austria.

[nnn]Also at Laboratoire d'Annecy-le-Vieux de Physique des Particules, IN2P3-CNRS, Annecy-le-Vieux, France.

[ooo]Also at Near East University, Research Center of Experimental Health Science, Mersin, Turkey.

[ppp]Also at Konya Technical University, Konya, Turkey.

[qqq]Also at Izmir Bakircay University, Izmir, Turkey.

[rrr]Also at Adiyaman University, Adiyaman, Turkey.

[sss]Also at Bozok Universitetesi Rektörlügü, Yozgat, Turkey.

[ttt]Also at Marmara University, Istanbul, Turkey.

[uuu]Also at Milli Savunma University, Istanbul, Turkey.

[vvv]Also at Kafkas University, Kars, Turkey.

[www]Also at stanbul Okan University, Istanbul, Turkey.

[xxx]Also at Hacettepe University, Ankara, Turkey.

[yyy]Also at Istanbul University—Cerrahpasa, Faculty of Engineering, Istanbul, Turkey.

[zzz]Also at Yildiz Technical University, Istanbul, Turkey.

[aaaa]Also at Vrije Universiteit Brussel, Brussel, Belgium.

[bbbb]Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom.

[cccc]Also at University of Bristol, Bristol, United Kingdom.

[dddd]Also at IPPP Durham University, Durham, United Kingdom.

[eeee]Also at Monash University, Faculty of Science, Clayton, Australia.

[ffff]Also at Università di Torino, Torino, Italy.

[gggg]Also at Bethel University, St. Paul, Minnesota, USA.

[hhhh]Also at Karamanoğlu Mehmetbey University, Karaman, Turkey.

[iiii]Also at California Institute of Technology, Pasadena, California, USA.

[jjjj]Also at United States Naval Academy, Annapolis, Maryland, USA.

[kkkk]Also at Bingol University, Bingol, Turkey.

[llll]Also at Georgian Technical University, Tbilisi, Georgia.

[mmmm]Also at Sinop University, Sinop, Turkey.

[nnnn]Also at Erciyes University, Kayseri, Turkey.

[oooo]Also at Horia Hulubei National Institute of Physics and Nuclear Engineering (IFIN-HH), Bucharest, Romania.

[pppp]Also at Texas A&M University at Qatar, Doha, Qatar.

[qqqq]Also at Kyungpook National University, Daegu, Korea.

[rrrr]Also at Universiteit Antwerpen, Antwerpen, Belgium.

[ssss]Also at Yerevan Physics Institute, Yerevan, Armenia.

[tttt]Also at Northeastern University, Boston, Massachusetts, USA.

[uuuu]Also at Imperial College, London, United Kingdom.

[vvvv]Also at Institute of Nuclear Physics of the Uzbekistan Academy of Sciences, Tashkent, Uzbekistan.