


Search for narrow resonances in the b -tagged dijet mass spectrum in proton-proton collisions at $\sqrt{s} = 13$ TeV

A. Tumasyan *et al.*^{*}
(CMS Collaboration)

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A search is performed for narrow resonances decaying to final states of two jets, with at least one jet originating from a b quark, in proton-proton collisions at $\sqrt{s} = 13$ TeV. The data set corresponds to an integrated luminosity of 138 fb^{-1} collected with the CMS detector at the LHC. Jets originating from energetic b hadrons are identified through a b -tagging algorithm that utilizes a deep neural network or the presence of a muon inside a jet. The invariant mass spectrum of jet pairs is well described by a smooth parametrization and no evidence for the production of new particles is observed. Upper limits on the production cross section are set for excited b quarks and other resonances decaying to dijet final states containing b quarks. These limits exclude at 95% confidence level models of Z' bosons with masses from 1.8 TeV to 2.4 TeV and of excited b quarks with masses from 1.8 TeV to 4.0 TeV. This is the most stringent exclusion of excited b quarks to date.

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I. INTRODUCTION

Searches for heavy resonances decaying into jet pairs provide a powerful tool with the potential for discovering new physics at hadron colliders. These resonances can be produced via parton-parton interactions, and then can decay to two partons. The final-state partons hadronize and are observed as two jets, referred to as dijets.

Such heavy resonances at the TeV scale are a feature of several models that extend the standard model (SM) to address some of its shortcomings, such as the extreme fine tuning required in quantum corrections to accommodate a Higgs boson observed at a mass of 125 GeV [1–4]. These models introduce heavy resonances that couple to the SM bosons and fermions [5,6]. A minimal extension of the SM is represented by the sequential standard model (SSM) [7], which introduces a spin-1 Z' boson with the same couplings to fermions as the SM Z boson, but with a much larger mass. The SSM, among many others, is generalized in the heavy vector triplet (HVT) framework [8], which extends the SM by introducing a triplet of heavy vector bosons, one neutral Z' and two oppositely charged W' , collectively referred to as V' . The heavy vector bosons couple to SM bosons and fermions with strengths $g_H = g_V c_H$ and $g_F = g^2 c_F / g_V$, respectively, where g_V is the strength of the new interaction; c_H is the coupling between

an HVT boson, the Higgs boson, and a longitudinally polarized SM vector boson; c_F is the coupling between an HVT boson and an SM fermion; and g is the electroweak coupling. In this search, we consider two benchmarks, defined in Ref. [8]. In the Model A scenario of the HVT framework, the coupling strengths of the heavy vector bosons to SM bosons and fermions are of the same order, and the new particles decay primarily to fermions. In the Model B scenario of the same framework, the couplings to fermions are suppressed with respect to the couplings to bosons, resulting in a branching fraction of the new particles to SM bosons that is close to unity.

Other models extending the SM postulate that leptons and quarks are composite objects, composed of more fundamental constituents. At an energy beyond the scale of constituent binding energies, the compositeness scale Λ , a new interaction should emerge [9–11]. Such models foresee the existence of excited states of quarks (q^*) and leptons (ℓ^*), which could be produced in high-energy collisions and then detected through their decays to SM particles. Excited states of composite quarks [12], which would be produced through a gauge interaction or via contact interactions (CI) [13], can result in large cross sections and could decay predominantly to a quark and a gluon (qg). In the model considered in this search, the compositeness scale Λ is set equal to the resonance mass and the couplings of excited quarks to other particles are assumed to be the same as for nonexcited fermions.

Since the early 1980s, searches for resonances in the dijet invariant mass spectrum [14] have been common at hadron colliders. From proton-proton (pp) collision data at $\sqrt{s} = 7$ and 8 TeV, the CMS Collaboration has published searches for dijet resonances where at least one of the two jets in the

^{*}Full author list given at the end of the article.

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final state arises from a b quark [15–17], based on a jet flavor identification commonly referred to as b tagging. The most recent search from the CMS Collaboration at $\sqrt{s} = 13$ TeV [18] did not attempt to identify the type of final-state parton that produced the jets, and considered resonance models where the final-state partons could be gluons or any flavor of SM quarks. Similar to a recent search from the ATLAS experiment [19], the present search identifies heavy-flavored quarks among the two final-state partons, and has increased sensitivity to models of dijet resonances that decay to b quarks. Examples are such models that predict an excited b quark (b^*), or a Z' where the couplings to the third generation are enhanced relative to the couplings to the first and second generations. Such enhanced couplings are also favored in models created to accommodate the possible anomalies observed in the low-energy heavy-flavor sector of the SM [20,21].

In this paper we report a search for Z' decaying into a b quark pair as well as b^* decaying into b quark and gluon, where two production modes are considered for the latter; $bg \rightarrow b^*$ and b^* via CI. Both resonances are assumed to be narrow. The data used for the analysis were collected by the CMS detector from pp collisions at a center-of-mass energy of 13 TeV during the LHC Run 2 (2016–2018), and correspond to a total integrated luminosity of 138 fb^{-1} .

Tabulated results are provided in the HEPData record for this analysis [22].

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. The ECAL and HCAL provide pseudorapidity coverage up to $|\eta| < 3.0$, which is further extended by forward calorimeters [23]. Muons are measured in gas-ionization detectors embedded in the steel flux-return yoke outside the solenoid. For nonisolated particles of transverse momentum $1 \text{ GeV} < p_T < 10 \text{ GeV}$ and $|\eta| < 1.4$, the reconstructed tracks have a p_T resolution of 1.5%, a transverse impact parameter resolution of 25–90 μm , and a longitudinal impact parameter resolution of 45–190 μm [24].

Events of interest are selected using a two-tiered trigger system. The first level, 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 [25]. 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 [26].

A 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. [23].

III. DATA AND SIMULATED SAMPLES

The data sample analyzed has been collected by the CMS experiment with trigger algorithms that require large hadronic activity in the event. In particular, two sets of trigger algorithms are used; single-jet triggers that require a jet with $p_T > 550 \text{ GeV}$ to be present in the event and triggers requiring the scalar p_T sum for all jets with $p_T > 30 \text{ GeV}$ and $|\eta| < 3.0$ in the event, to exceed 1050 GeV.

The $q\bar{q} \rightarrow Z' \rightarrow b\bar{b}$ signal Monte Carlo (MC) simulated events are produced at leading-order (LO) accuracy in quantum chromodynamics (QCD) with the MADGRAPH 5_amc@NLO v2.4.2 matrix element generator [27]. Various Z' mass hypotheses in the range of 1.6 TeV to 8 TeV are considered for these narrow resonance signals, which have a natural width smaller than the experimental dijet mass resolution (2–3%). This approximation is valid in a large fraction of the HVT parameter space, and is fulfilled in the Model A and Model B benchmarks discussed earlier [8].

For the b^* production processes, the signal samples are produced with PYTHIA 8.230 [28] for resonance masses up to 6 TeV. The characteristic dijet mass shape corresponding to the $bg \rightarrow b^* \rightarrow bg$ signal component is reported in Fig. 1 for resonance masses from 1 TeV to 6 TeV. The contribution of the low-mass tail to the signal shape becomes more dominant at large resonance masses. This is because the resonance natural mass shape coming from a Breit-Wigner distribution is convolved with falling parton distribution functions (PDFs), where for larger resonance masses the PDFs fall more steeply.

In all cases parton showering and hadronization processes are simulated by interfacing the event generators with PYTHIA 8.230 with the CUETP8M1 [29,30] tune. The

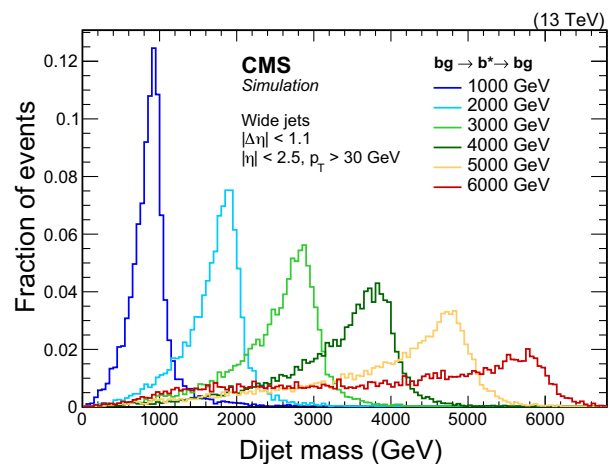


FIG. 1. Simulated signal shapes of b^* from the process $bg \rightarrow b^* \rightarrow bg$. Shown are the wide jets (see text) used to reconstruct the dijet mass spectra.

NNPDF2.3LO [31,32] PDFs are used to model the momentum distribution of the colliding partons inside the protons. The generated events include additional pp interactions (pileup) with a distribution that is chosen to match that observed in the data. These events are processed through a full detector simulation based on GEANT4 [33] and reconstructed with the same algorithms as those used for data.

IV. EVENT RECONSTRUCTION AND SELECTION

The event reconstruction is performed using a particle-flow (PF) algorithm [34], which uses an optimized combination of information from the various elements of the CMS detector to reconstruct and identify individual particles produced in each collision. The algorithm identifies each reconstructed particle either as an electron, a muon, a photon, or a charged or neutral hadron. The charged component of the pileup contribution is removed by applying the charged hadron subtraction mitigation algorithm. The momenta of neutral hadrons are rescaled according to their probability to originate from the primary interaction vertex deduced from the distribution of associated energy deposits in the calorimeters [35]. The PF candidates are then clustered into jets using the anti- k_T algorithm [36] implemented in the FASTJET package [37,38] with a distance parameter $R = 0.4$.

Jet energy corrections, extracted from simulation and data in multijet, γ + jets, and Z + jets events, are applied as a function of p_T and η to correct the jet response and to account for residual differences between data and simulation. Multijet events refer to SM events composed uniquely of jets produced through the strong interaction. The energy resolution for jets with $p_T \sim 1$ TeV is approximately 5% [39]. Jets are required to pass identification criteria, which have negligible impact on the signal efficiency, in order to remove spurious jets arising from detector noise [40].

Events are required to contain at least two jets, each with $p_T > 30$ GeV and $|\eta| < 2.5$, and each separated by $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} > 0.4$ from any electrons or muons. Here, ϕ is the azimuthal angle in radians. Geometrically close jets are combined into “wide jets”, and used to determine the dijet mass, as in our previous dijet searches [18]. In forming wide jets, the two jets with the largest p_T are used as seeds, and the four-momenta of jets within $\Delta R < 1.1$ of a seed jet are added to the seed jet’s four-momentum. The wide-jet algorithm, designed for dijet resonance event reconstruction, reduces the analysis sensitivity to gluon radiation from the final-state partons.

The pseudorapidity separation of the two wide jets is required to be $|\Delta\eta| < 1.1$. This requirement suppresses t -channel multijet production, and enhances the contribution to the signal from s -channel production.

In order to ensure the full efficiency of the trigger, only events with a dijet invariant mass m_{jj} larger than 1530 GeV

are considered. The trigger efficiency measurement is performed with a sample acquired with an independent trigger algorithm that requires the presence of a muon with $p_T > 50$ GeV at the high-level trigger.

Jets from b quarks are identified using a b -tagging DeepJet discriminator that relies on the application of convolutional neural networks on low-level objects, such as PF candidates and secondary vertex information, and improves the jet flavor identification capabilities of the CMS experiment, especially at high jet momenta [41,42]. The operation point of the discriminator was chosen in order to maximize the sensitivity to the Z' and b^* signal searches. It corresponds to a misidentification probability of 1% for jets from light (u, d, s) quarks and gluons with p_T of about 80 GeV. For this mistagging value, the efficiency of identifying genuine b quarks is approximately 75%, 45%, and 10% for a jet with p_T of 0.2 TeV, 1.0 TeV, and 3.0 TeV, respectively. The simulated event distributions passing the tagger are adjusted via scale factors such that they agree with the observed data.

Events are divided into independent categories, depending on the signal model considered. When searching for a b^* resonance decaying to a b quark and a gluon, only a single category with at least one b -tagged jet is needed. For a Z' signal, three categories are defined: $2b$, $1b$ and muon. Events are included in the $2b$ category if both jets fulfill the b -tagging requirements, and in the $1b$ category if only one of the two jets is b tagged. The muon category contains the events in which neither jet passes the b tag selection, but at least one jet contains a muon, identified within both the inner tracker and the muon detector. The presence of the muon naturally enriches the heavy-flavor component of the jets, mitigating the loss of signal efficiency of the b -tagging algorithm at very large p_T . This category dominates the signal sensitivity for Z' mass larger than 5 TeV, a region where the muon presence request has a roughly 50% larger signal efficiency than in the $2b$ category. The product of

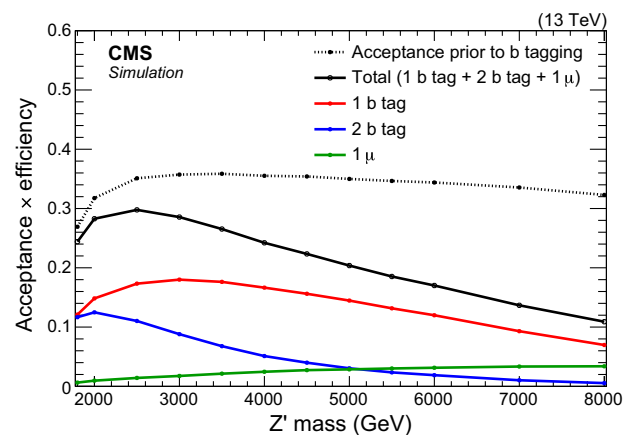


FIG. 2. The product of acceptance and efficiency of the event selection for a $Z' \rightarrow b\bar{b}$ resonance as a function of the resonance mass.

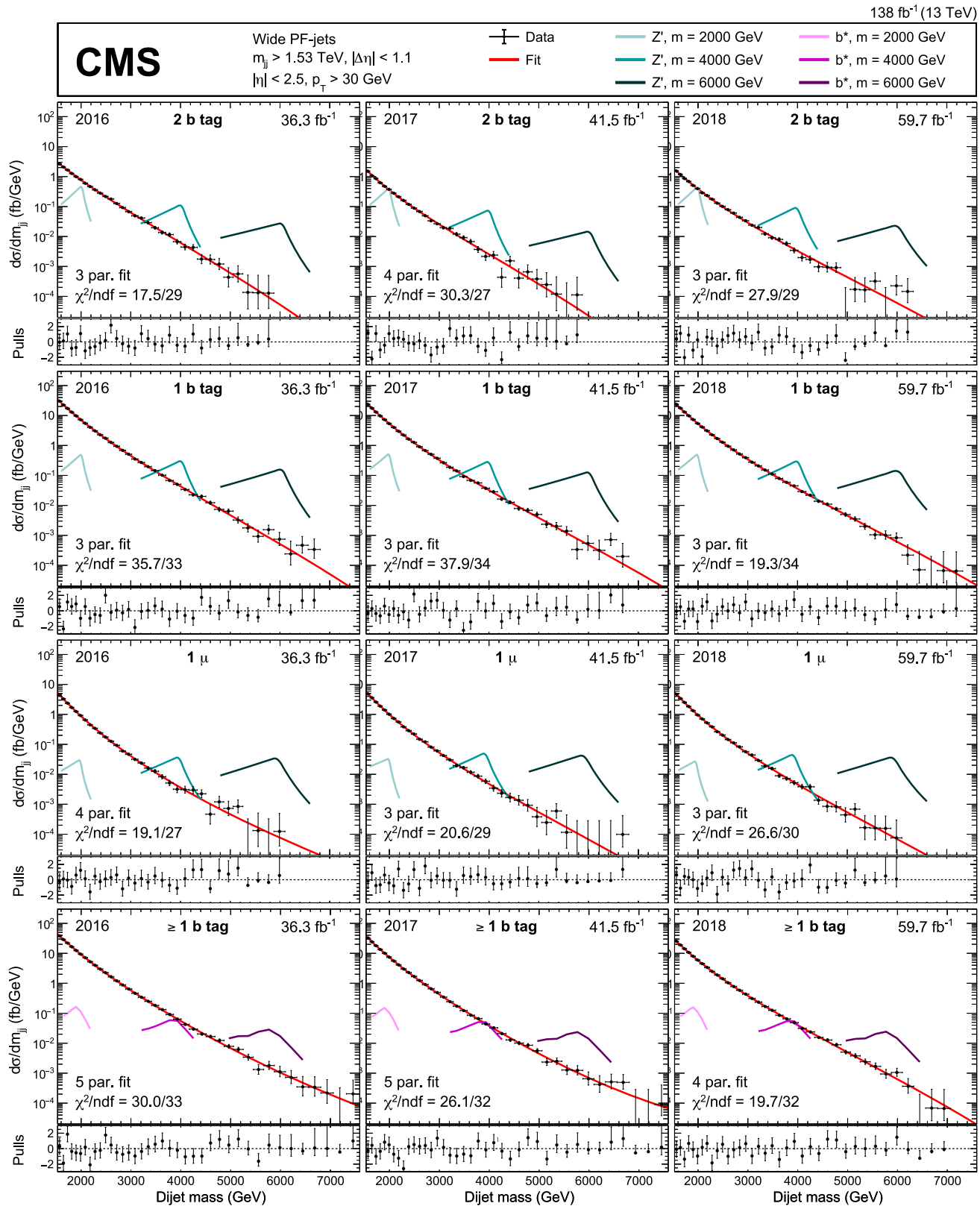


FIG. 3. The observed differential cross sections as a function of the dijet mass, shown as fit with the background functions, for the four tagging categories (rows) and the three data-taking periods (columns). The number of parameters in the fit, and the goodness of fit “ χ^2/ndf ”, are listed where “ndf” is the number of degrees of freedom. The lower panel within each row shows the pulls, (data-fit)/uncertainty, in units of the statistical uncertainty in data. The upper three rows are used to search for Z' models, the bottom row is used to search for the b^* model, and example shapes of these signal models are shown with the same arbitrary normalization for three choices of resonance mass.

acceptance and efficiency of the selections for the signal were very similar in all three data-taking years, and the average values are shown in Fig. 2. The dominant source of inefficiency is the requirement $|\Delta\eta| < 1.1$, which reduces the acceptance to approximately 41%.

V. BACKGROUND ESTIMATION

Background estimates based on simulated data predict that it is largely dominated by multijet production, which accounts for more than 95% of the total background. The contribution of top quark pair production is approximately 3–4% of the total background, depending on the b -tagging category. Production of vector bosons in association with partons, and production of boson pairs, contribute the remaining 1–2% of the total background.

The background is estimated directly from data assuming that it can be described by a smooth, monotonically decreasing function. The validity of this assumption is checked in simulation. The functions considered are power laws of the variable $x = m_{jj}/\sqrt{s}$, where $\sqrt{s} = 13$ TeV. Starting from the simplest functional form, an iterative procedure based on the Fisher F-test [43] is used to check at 90% confidence level (C.L.) if additional parameters are needed to model the individual background distributions. Depending on the dataset considered for the fit, a three-parameter ($p_0(1-x)^{p_1}/x^{p_2}$), four-parameter ($p_0(1-x)^{p_1}/x^{p_2+p_3 \log(x)}$) or five-parameter ($p_0(1-x)^{p_1}/x^{p_2+p_3 \log(x)+p_4 \log^2(x)}$) functional form is necessary to describe the data. The observed dijet mass spectra are well modeled by the background functional forms, as shown in Fig. 3, where the widths of the dijet mass bins correspond to the dijet mass resolution.

The expected shape of the reconstructed signal mass distribution is extracted from the simulated signal samples. The b^* signal shapes are dijet mass distributions obtained directly from the simulation, as shown in Fig. 1, while the Z' signal shapes are parametrizations that are fit separately to the simulation samples for each category, using a double-sided Crystal Ball function [44]. This functional form consists of a Gaussian distribution that models the core of the shape, and two power law functions that model the upper and lower tails, and requires a total of six parameters. The resolution of the reconstructed Z' is given by the width of the Gaussian core, and is found to be constant at 2% of the resonance mass. The signal shape, for a Z' of arbitrary mass, is then obtained by a spline interpolation of the simulated signal shape parameter values as a function of mass. Examples of the Z' and b^* shapes are shown in Fig. 3, with arbitrary normalizations.

Statistical tests have been performed to check the robustness of the fit method. Pseudoexperiments are generated after injecting a simulated signal with a range of values for the signal mass and cross section. The dijet mass distribution of the pseudodata is then fitted with the signal distribution combined with an alternate background

function containing one more parameter than the nominal function. The fitted signal yield is found to be compatible within one third of the statistical uncertainty to the injected yield, regardless of the injected signal strength and resonance mass. These tests confirm that the background estimation is insensitive both to the choice of the function used and to the possible presence of a signal in the data.

VI. SYSTEMATIC UNCERTAINTIES

The background shape is estimated from the fit to the data in the considered categories, and no assumption or constraint is applied to function parameters. These parameters are considered as uncorrelated among categories and data-taking periods. As described in Sec. V, different parametrizations of the fit function were studied and introduce no additional source of uncertainty.

The dominant uncertainties in the signal arise from the b tagging and the jet-reconstruction uncertainties. The uncertainty in the b -tagging scale factors [45] yields an uncertainty in the signal normalization of 2% and 4% in the $1b$ and $\geq 1b$ categories, respectively, and 15% in the $2b$ and muon categories. Uncertainties in the reconstruction of the hadronic jets affect mainly the shape of the reconstructed resonance mass. The four-momenta of the reconstructed jets are scaled and smeared according to the uncertainties in the jet p_T and momentum resolution. These effects result in a 2% uncertainty in the mean, and 10% in the width of the signal. The signal normalization is also affected by the uncertainty in the selection of the muons inside the jets. The efficiency of the identification of the muons inside jets is measured in a statistically independent and almost pure sample of high- p_T b jets, originating from the decay of pair-produced top quarks. This uncertainty is deduced from the statistical uncertainty in the efficiency measurement, ranging up to 43% for muons with $p_T < 100$ GeV. An uncertainty of 100% is assumed for jets with the p_T of an associated muon beyond this 100 GeV threshold, because no data was available in this region. Additional systematic uncertainties affecting the signal normalization include the vetoes for high- p_T leptons and missing transverse momenta (accounting for 1% each), pileup contributions (0.1%), and the integrated luminosity (1.2% in 2016 [46], 2.3% in 2017 [47], and 2.5% in 2018 [48]). The systematic uncertainty from the choice of PDFs [49] is estimated to be 8–41% of the normalization of the signal cross section, depending on the resonance mass. The factorization and renormalization scale uncertainties are estimated by varying the scales up and down by a factor of 2, both simultaneously and independently, using the maximum obtained value. The resulting effect is a variation of 6–14% of the normalization of the signal cross section.

VII. RESULTS AND INTERPRETATION

Exclusion limits are obtained by performing a background-only fit and a combined signal-plus-background fit

to the dijet mass distributions, separately by category and data-taking year. In the fit, based on a profile likelihood, the parameters and the normalization of the background in each category are left free to float. The systematic uncertainties in the signal are treated as nuisance parameters, with Gaussian constraints for the jet energy scale and resolution, and log-normal constraints for the integrated luminosity, and are profiled in the statistical interpretation [50]. The uncertainties that affect the signal normalization (PDFs and factorization and renormalization scales) are treated differently depending on how the exclusion is presented. When deriving upper limits on the cross section, these uncertainties are not varied in the fit, but are reported separately as the uncertainty in the theoretical cross sections from the model. When placing limits on the model parameters, these

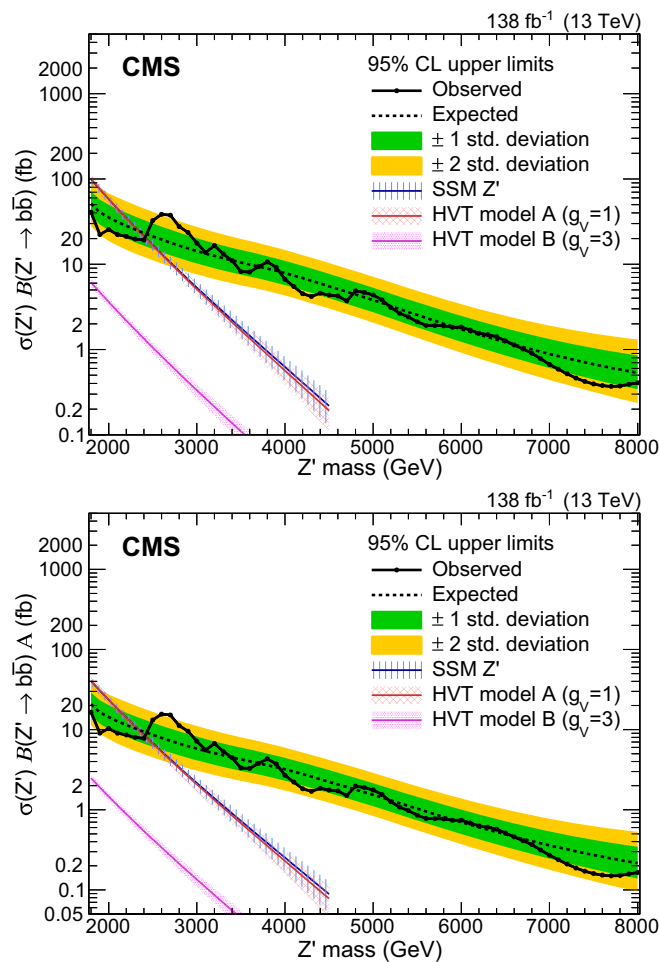


FIG. 4. The observed 95% C.L. upper limits (solid curve) on the product of the cross section and branching fraction (left), and multiplied by signal acceptance (right), for a resonance decaying to $b\bar{b}$. The corresponding expected limits (dashed curve) and their variations at the 1- and 2-standard deviation levels (shaded bands) are also shown. Limits are compared to predicted cross sections for Z' bosons from the sequential SM (SSM) and the heavy vector triplet (HVT) models A and B. The latter two models follow the parameter choices of $g_V = 1$ and $g_V = 3$, respectively.

nuisance parameters are fixed at the best-fit values, in the same manner as with the other systematic uncertainties. A more detailed description of the statistical treatment and the likelihood function is reported in Ref. [51]. Upper limits at 95% C.L. are set using the CL_s modified frequentist method [52,53], adopting the asymptotic approximation [54].

A model-independent representation of the observed upper limit on the product of cross section and branching fraction of a $b\bar{b}$ resonance, as well as the expected limit and its relative 68% and 95% uncertainty bands, are shown in Fig. 4. The acceptance, which is included in the product on the right side of Fig. 4, is defined exclusively via the geometric requirements $p_T > 30$ GeV, $|\eta| < 2.5$, and $|\Delta\eta| < 1.1$. This analysis sets an observed mass limit of 2.4 TeV, and an expected mass limit of 2.3 TeV, at 95% C.L., on a narrow Z' resonance in both the SSM and the HVT Model A. No upper limit can be set on Model B with suppressed fermionic coupling.

The cross section limit shown in Fig. 4 (left), is reinterpreted in Fig. 5 as limits on the coupling strengths of a heavy vector boson to SM bosons (g_H) and fermions (g_F). The subset of the parameter space where the natural width of the resonance is larger than the typical experimental resolution, and hence the narrow width approximation is invalid, is indicated in Fig. 5 with a gray shaded area.

For resonances that decay to a b quark and a gluon, upper limits are set by using the category where at least one of the two leading jets is b tagged. Upper limits on the joint product of cross section, branching fraction, and

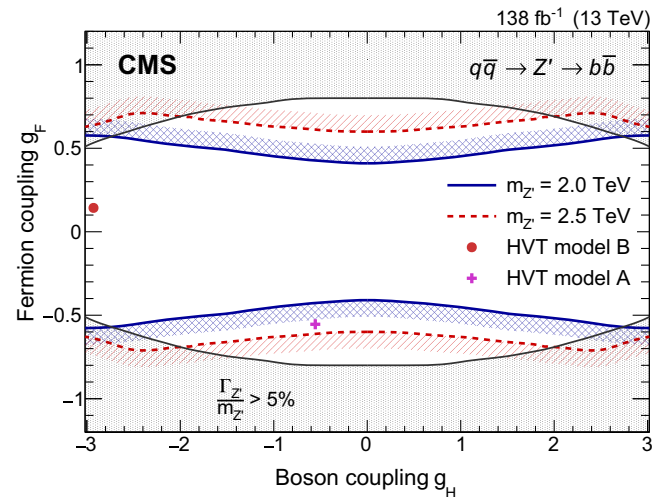


FIG. 5. The coupling strengths to SM bosons (g_H) and fermions (g_F) of a Z' boson with mass 2.0 TeV (blue) and 2.5 TeV (red) that are excluded at 95% C.L. for the HVT model. The shading indicates the excluded side of the contour. The benchmark scenarios corresponding to HVT models A and B are represented by a purple cross and a red point, respectively. The gray shaded area corresponds to the region where the resonance natural width is predicted to be larger than the typical experimental resolution, and thus the narrow-width approximation is not fulfilled.

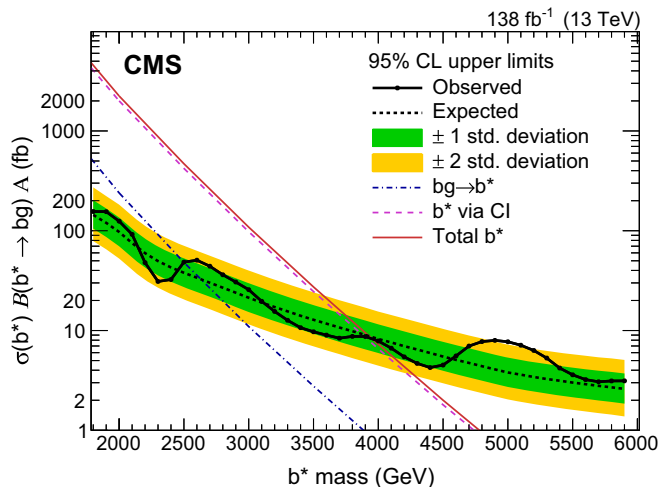


FIG. 6. The observed 95% C.L. upper limits on the product of the cross section, branching fraction, and acceptance for dijet resonances decaying to a b quark and a gluon (points). The corresponding expected limits (short dashed) and their variations at the 1- and 2-standard deviation levels (shaded bands) are also shown. Limits are compared to predictions for single b^* production (blue, dot dashed), the resonant component of the b^* production via contact interactions (magenta, long dashed), and the total b^* signal from the sum of these two production modes (red, solid).

acceptance are reported in Fig. 6. When considering the single b^* production process, $bg \rightarrow b^* \rightarrow bg$, with the cross section shown in Fig. 6, this analysis sets 95% C.L. mass limits of 2.5 TeV (observed) and 2.6 TeV (expected) for an excited b quark. Additionally the b^* production via contact interactions has been considered. Several processes contribute to the b^* production via CI [13], the dominant one being $q\bar{q} \rightarrow \bar{b}b^*$ (or $b\bar{b}^*$) $\rightarrow \bar{b}bg$ where three jets are present in the final state. In order to display the theory cross section for this new process on the same exclusion limit plot, only its resonant component has been considered. In particular events are selected when the reconstructed dijet originates from the b^* decay, and does not include the other qb quark in the event, which is the case for 50 (80)% of the events within the acceptance at 2 (4) TeV. Including both processes in the total signal cross section (single b^* production and the resonant component of the b^* production via CI) gives a significantly more stringent 95% C.L. mass limit of 4 TeV on excited b quarks.

VIII. SUMMARY

A search for heavy resonances decaying into b quarks has been presented and no excess has been found over the standard model (SM) expectations. The data were collected by the CMS experiment at $\sqrt{s} = 13$ TeV during 2016–2018 and correspond to an integrated luminosity of 138 fb^{-1} . Model-independent upper limits are set on the product of the cross section of the resonance and its

branching fraction to b quarks. Signals of Z' bosons decaying to pairs of b quarks are considered, for both the previously explored sequential standard model (SSM), and also for a new heavy vector triplet (HVT) model. The decays of Z' bosons in both the SSM and the HVT Model A are excluded at 95% confidence level for masses from 1.8 TeV to 2.4 TeV, and limits are set on the coupling strengths of the HVT boson to SM bosons and fermions. Signals of an excited b quark are considered for a previously explored channel, $bg \rightarrow b^* \rightarrow bg$, and a production mode via contact interactions. The excited b quark is excluded at 95% confidence level for masses from 1.8 TeV to 4.0 TeV. This is the most stringent exclusion of excited b quarks to date.

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H. Aarup Petersen⁴³, M. Aldaya Martin⁴³, P. Asmuss⁴³, S. Baxter⁴³, M. Bayatmakou⁴³, O. Behnke⁴³,
A. Bermúdez Martínez⁴³, S. Bhattacharya⁴³, A. A. Bin Anuar⁴³, K. Borrás^{43,w}, D. Brunner⁴³, A. Campbell⁴³,
A. Cardini⁴³, C. Cheng⁴³, F. Colombina⁴³, S. Consuegra Rodríguez⁴³, G. Correia Silva⁴³, V. Danilov⁴³,
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A. Geiser⁴³, A. Giraldi⁴³, A. Grohsjean⁴³, M. Guthoff⁴³, A. Jafari^{43,y}, N. Z. Jomhari⁴³, A. Kasem^{43,w},
M. Kasemann⁴³, H. Kaveh⁴³, C. Kleinwort⁴³, D. Krücker⁴³, W. Lange⁴³, J. Lidrych⁴³, K. Lipka⁴³,
W. Lohmann^{43,z}, R. Mankel⁴³, I.-A. Melzer-Pellmann⁴³, M. Mendizabal Morentin⁴³, J. Metwally⁴³, A. B. Meyer⁴³,
M. Meyer⁴³, J. Mnich⁴³, A. Mussgiller⁴³, Y. Otari⁴³, D. Pérez Adán⁴³, D. Pitzl⁴³, A. Raspereza⁴³,
B. Ribeiro Lopes⁴³, J. Rübenach⁴³, A. Saggio⁴³, A. Saibel⁴³, M. Savitskyi⁴³, M. Scham^{43,aa}, V. Scheurer⁴³,
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J. Bechtel⁴⁵, S. Brommer⁴⁵, M. Burkart⁴⁵, E. Butz⁴⁵, R. Caspart⁴⁵, T. Chwalek⁴⁵, W. De Boer^{45,a}, A. Dierlamm⁴⁵,
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M. Neukum⁴⁵, A. Nürnberg⁴⁵, G. Quast⁴⁵, K. Rabbertz⁴⁵, J. Rauser⁴⁵, D. Savoie⁴⁵, M. Schnepf⁴⁵, D. Seith⁴⁵,
I. Shvetsov⁴⁵, H. J. Simonis⁴⁵, R. Ulrich⁴⁵, J. Van Der Linden⁴⁵, R. F. Von Cube⁴⁵, M. Wassmer⁴⁵, M. Weber⁴⁵,
S. Wieland⁴⁵, R. Wolf⁴⁵, S. Wozniowski⁴⁵, S. Wunsch⁴⁵, G. Anagnostou⁴⁶, G. Daskalakis⁴⁶, T. Geralis⁴⁶,
A. Kyriakis⁴⁶, A. Stakia⁴⁶, M. Diamantopoulou⁴⁷, D. Karasavvas⁴⁷, G. Karathanasis⁴⁷, P. Kontaxakis⁴⁷,
C. K. Koraka⁴⁷, A. Manousakis-Katsikakis⁴⁷, A. Panagiotou⁴⁷, I. Papavergou⁴⁷, N. Saoulidou⁴⁷, K. Theofilatos⁴⁷,
E. Tziaferi⁴⁷, K. Vellidis⁴⁷, E. Vourliotis⁴⁷, G. Bakas⁴⁸, K. Kousouris⁴⁸, I. Papakrivopoulos⁴⁸, G. Tsipolitis⁴⁸,
A. Zacharopoulou⁴⁸, K. Adamidis⁴⁹, I. Bestintzanos⁴⁹, I. Evangelou⁴⁹, C. Foudas⁴⁹, P. Gianneios⁴⁹, P. Katsoulis⁴⁹,
P. Kokkas⁴⁹, N. Manthos⁴⁹, I. Papadopoulos⁴⁹, J. Strogas⁴⁹, M. Csanád⁵⁰, K. Farkas⁵⁰, M. M. A. Gadallah^{50,bb},
S. Lökös^{50,cc}, P. Major⁵⁰, K. Mandal⁵⁰, A. Mehta⁵⁰, G. Pásztor⁵⁰, A. J. Rádl⁵⁰, O. Surányi⁵⁰, G. I. Veres⁵⁰,
M. Bartók^{51,dd}, G. Bencze⁵¹, C. Hajdu⁵¹, D. Horvath^{51,ee}, F. Sikler⁵¹, V. Veszpremi⁵¹, S. Czellar⁵², J. Karancsi^{52,dd},
J. Molnar⁵², Z. Szillasi⁵², D. Teyssier⁵², P. Raics⁵³, Z. L. Trocsanyi^{53,ff}, B. Ujvari⁵³, T. Csorgo^{54,gg}, F. Nemes^{54,gg},
T. Novak⁵⁴, S. Choudhury⁵⁵, J. R. Komaragiri⁵⁵, D. Kumar⁵⁵, L. Panwar⁵⁵, P. C. Tiwari⁵⁵, S. Bansal⁵⁶,
S. B. Beri⁵⁶, V. Bhatnagar⁵⁶, G. Chaudhary⁵⁶, S. Chauhan⁵⁶, N. Dhingra^{56,hh}, R. Gupta⁵⁶, A. Kaur⁵⁶, M. Kaur⁵⁶,
S. Kaur⁵⁶, P. Kumari⁵⁶, M. Meena⁵⁶, K. Sandeep⁵⁶, J. B. Singh⁵⁶, A. K. Viridi⁵⁶, A. Ahmed⁵⁷, A. Bhardwaj⁵⁷,
B. C. Choudhary⁵⁷, M. Gola⁵⁷, S. Keshri⁵⁷, A. Kumar⁵⁷, M. Naimuddin⁵⁷, P. Priyanka⁵⁷, K. Ranjan⁵⁷, A. Shah⁵⁷,
M. Bharti^{58,ii}, R. Bhattacharya⁵⁸, S. Bhattacharya⁵⁸, D. Bhowmik⁵⁸, S. Dutta⁵⁸, S. Dutta⁵⁸, B. Gomber^{58,ii},
M. Maity^{58,kk}, P. Palit⁵⁸, P. K. Rout⁵⁸, G. Saha⁵⁸, B. Sahu⁵⁸, S. Sarkar⁵⁸, M. Sharan⁵⁸, B. Singh^{58,ii}, S. Thakur^{58,ii},
P. K. Behera⁵⁹, S. C. Behera⁵⁹, P. Kalbhor⁵⁹, A. Muhammad⁵⁹, R. Pradhan⁵⁹, P. R. Pujahari⁵⁹, A. Sharma⁵⁹,
A. K. Sikdar⁵⁹, D. Dutta⁶⁰, V. Jha⁶⁰, V. Kumar⁶⁰, D. K. Mishra⁶⁰, K. Naskar^{60,ll}, P. K. Netrakanti⁶⁰, L. M. Pant⁶⁰,
P. Shukla⁶⁰, T. Aziz⁶¹, S. Dugad⁶¹, M. Kumar⁶¹, G. B. Mohanty⁶¹, S. Banerjee⁶², R. Chudasama⁶², M. Guchait⁶²,
S. Karmakar⁶², S. Kumar⁶², G. Majumder⁶², K. Mazumdar⁶², S. Mukherjee⁶², S. Bahinipati^{63,mmm}, C. Kar⁶³,
P. Mal⁶³, T. Mishra⁶³, V. K. Muraleedharan Nair Bindhu^{63,nn}, A. Nayak^{63,nn}, P. Saha⁶³, N. Sur⁶³, S. K. Swain⁶³,
D. Vats^{63,nn}, K. Alpna⁶⁴, S. Dube⁶⁴, B. Kansal⁶⁴, A. Laha⁶⁴, S. Pandey⁶⁴, A. Rane⁶⁴, A. Rastogi⁶⁴,
S. Sharma⁶⁴, H. Bakhshiansohi^{65,oo}, E. Khazaie⁶⁵, M. Zeinali^{65,pp}, S. Chenarani^{66,qq}, S. M. Etesami⁶⁶,
M. Khakzad⁶⁶, M. Mohammadi Najafabadi⁶⁶, M. Grunewald⁶⁷, M. Abbrescia^{68a,68b}, R. Aly^{68a,68c,rr},
C. Aruta^{68a,68b}, A. Colaleo^{68a}, D. Creanza^{68a,68c}, N. De Filippis^{68a,68c}, M. De Palma^{68a,68b}, A. Di Florio^{68a,68b},
A. Di Pilato^{68a,68b}, W. Elmetenawee^{68a,68b}, L. Fiore^{68a}, A. Gelmi^{68a,68b}, M. Gul^{68a}, G. Iaselli^{68a,68c}, M. Ince^{68a,68b},
S. Lezki^{68a,68b}, G. Maggi^{68a,68c}, M. Maggi^{68a}, I. Margjeka^{68a,68b}, V. Mastrapasqua^{68a,68b}, S. My^{68a,68b},
S. Nuzzo^{68a,68b}, A. Pellecchia^{68a,68b}, A. Pompili^{68a,68b}, G. Pugliese^{68a,68c}, D. Ramos^{68a}, A. Ranieri^{68a}

G. Selvaggi^{68a,68b} L. Silvestris^{68a} F. M. Simone^{68a,68b} R. Venditti^{68a} P. Verwilligen^{68a} G. Abbiendi^{69a}
C. Battilana^{69a,69b} D. Bonacorsi^{69a,69b} L. Borgonovi^{69a} L. Brigliadori^{69a} R. Campanini^{69a,69b} P. Capiluppi^{69a,69b}
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A. Fanfani^{69a,69b} P. Giacomelli^{69a} L. Giommi^{69a,69b} C. Grandi^{69a} L. Guiducci^{69a,69b} S. Lo Meo^{69a,ss}
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A. M. Rossi^{69a,69b} T. Rovelli^{69a,69b} G. P. Siroli^{69a,69b} S. Albergo^{70a,70b,tt} S. Costa^{70a,70b,tt} A. Di Mattia^{70a}
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M. Lizzo^{71a,71b} M. Meschini^{71a} S. Paoletti^{71a} R. Seidita^{71a,71b} G. Sguazzoni^{71a} L. Viliani^{71a} L. Benussi⁷²
S. Bianco⁷² D. Piccolo⁷² M. Bozzo^{73a,73b} F. Ferro^{73a} R. Mulargia^{73a,73b} E. Robutti^{73a} S. Tosi^{73a,73b}
A. Benaglia^{74a} G. Boldrini^{74a} F. Brivio^{74a,74b} F. Cetorelli^{74a,74b} F. De Guio^{74a,74b} M. E. Dinardo^{74a,74b}
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G. L. Pinna Angioni^{81a,81b} M. Ruspa^{81a,81c} K. Shchelina^{81a} F. Siviero^{81a,81b} V. Sola^{81a} A. Solano^{81a,81b}
D. Soldi^{81a,81b} A. Staiano^{81a} M. Tornago^{81a,81b} D. Trocino^{81a} A. Vagnerini^{81a,81b} S. Belforte^{82a}
V. Candelse^{82a,82b} M. Casarsa^{82a} F. Cossutti^{82a} A. Da Rold^{82a,82b} G. Della Ricca^{82a,82b} G. Sorrentino^{82a,82b}
F. Vazzoler^{82a,82b} S. Dogra⁸³ C. Huh⁸³ B. Kim⁸³ D. H. Kim⁸³ G. N. Kim⁸³ J. Kim⁸³ J. Lee⁸³ S. W. Lee⁸³
C. S. Moon⁸³ Y. D. Oh⁸³ S. I. Pak⁸³ B. C. Radburn-Smith⁸³ S. Sekmen⁸³ Y. C. Yang⁸³ H. Kim⁸⁴
D. H. Moon⁸⁴ B. Francois⁸⁵ T. J. Kim⁸⁵ J. Park⁸⁵ S. Cho⁸⁶ S. Choi⁸⁶ Y. Go⁸⁶ B. Hong⁸⁶ K. Lee⁸⁶
K. S. Lee⁸⁶ J. Lim⁸⁶ J. Park⁸⁶ S. K. Park⁸⁶ J. Yoo⁸⁶ J. Goh⁸⁷ A. Gurtu⁸⁷ H. S. Kim⁸⁸ Y. Kim⁸⁸ J. Almond⁸⁹
J. H. Bhyun⁸⁹ J. Choi⁸⁹ S. Jeon⁸⁹ J. Kim⁸⁹ J. S. Kim⁸⁹ S. Ko⁸⁹ H. Kwon⁸⁹ H. Lee⁸⁹ S. Lee⁸⁹ B. H. Oh⁸⁹
M. Oh⁸⁹ S. B. Oh⁸⁹ H. Seo⁸⁹ U. K. Yang⁸⁹ I. Yoon⁸⁹ W. Jang⁹⁰ D. Y. Kang⁹⁰ Y. Kang⁹⁰ S. Kim⁹⁰ B. Ko⁹⁰
J. S. H. Lee⁹⁰ Y. Lee⁹⁰ J. A. Merlin⁹⁰ I. C. Park⁹⁰ Y. Roh⁹⁰ M. S. Ryu⁹⁰ D. Song⁹⁰ I. J. Watson⁹⁰ S. Yang⁹⁰
S. Ha⁹¹ H. D. Yoo⁹¹ M. Choi⁹² H. Lee⁹² Y. Lee⁹² I. Yu⁹² T. Beyrouthy⁹³ Y. Maghrbi⁹³ K. Dreimanis⁹⁴
V. Veckalns⁹⁴ M. Ambrozys⁹⁵ A. Carvalho Antunes De Oliveira⁹⁵ A. Juodagalvis⁹⁵ A. Rinkevicius⁹⁵

G. Tamulaitis⁹⁵, N. Bin Norjoharuddeen⁹⁶, W. A. T. Wan Abdullah⁹⁶, M. N. Yusli⁹⁶, Z. Zolkapli⁹⁶, J. F. Benitez⁹⁷,
A. Castaneda Hernandez⁹⁷, M. León Coello⁹⁷, J. A. Murillo Quijada⁹⁷, A. Sehwat⁹⁷, L. Valencia Palomo⁹⁷,
G. Ayala⁹⁸, H. Castilla-Valdez⁹⁸, E. De La Cruz-Burelo⁹⁸, I. Heredia-De La Cruz⁹⁸, R. Lopez-Fernandez⁹⁸,
C. A. Mondragon Herrera⁹⁸, D. A. Perez Navarro⁹⁸, A. Sánchez Hernández⁹⁸, S. Carrillo Moreno⁹⁹,
C. Oropeza Barrera⁹⁹, F. Vazquez Valencia⁹⁹, I. Pedraza¹⁰⁰, H. A. Salazar Ibarguen¹⁰⁰, C. Uribe Estrada¹⁰⁰,
J. Mijuskovic^{101,xx}, N. Raicevic¹⁰¹, D. Krofcheck¹⁰², P. H. Butler¹⁰³, A. Ahmad¹⁰⁴, M. I. Asghar¹⁰⁴, A. Awais¹⁰⁴,
M. I. M. Awan¹⁰⁴, H. R. Hoorani¹⁰⁴, W. A. Khan¹⁰⁴, M. A. Shah¹⁰⁴, M. Shoaib¹⁰⁴, M. Waqas¹⁰⁴, V. Avati¹⁰⁵,
L. Grzanka¹⁰⁵, M. Malawski¹⁰⁵, H. Bialkowska¹⁰⁶, M. Bluj¹⁰⁶, B. Boimska¹⁰⁶, M. Górski¹⁰⁶, M. Kazana¹⁰⁶,
M. Szeleper¹⁰⁶, P. Zalewski¹⁰⁶, K. Bunkowski¹⁰⁷, K. Doroba¹⁰⁷, A. Kalinowski¹⁰⁷, M. Konecki¹⁰⁷,
J. Krolkowski¹⁰⁷, M. Araujo¹⁰⁸, P. Bargassa¹⁰⁸, D. Bastos¹⁰⁸, A. Boletti¹⁰⁸, P. Faccioli¹⁰⁸, M. Gallinaro¹⁰⁸,
J. Hollar¹⁰⁸, N. Leonardo¹⁰⁸, T. Niknejad¹⁰⁸, M. Pisano¹⁰⁸, J. Seixas¹⁰⁸, O. Toldaiev¹⁰⁸, J. Varela¹⁰⁸,
P. Adzic^{109,yy}, M. Dordevic¹⁰⁹, P. Milenovic¹⁰⁹, J. Milosevic¹⁰⁹, M. Aguilar-Benitez¹¹⁰, J. Alcaraz Maestre¹¹⁰,
A. Álvarez Fernández¹¹⁰, I. Bachiller¹¹⁰, M. Barrio Luna¹¹⁰, Cristina F. Bedoya¹¹⁰, C. A. Carrillo Montoya¹¹⁰,
M. Cepeda¹¹⁰, M. Cerrada¹¹⁰, N. Colino¹¹⁰, B. De La Cruz¹¹⁰, A. Delgado Peris¹¹⁰, J. P. Fernández Ramos¹¹⁰,
J. Flix¹¹⁰, M. C. Fouz¹¹⁰, O. Gonzalez Lopez¹¹⁰, S. Goy Lopez¹¹⁰, J. M. Hernandez¹¹⁰, M. I. Josa¹¹⁰,
J. León Holgado¹¹⁰, D. Moran¹¹⁰, Á. Navarro Tobar¹¹⁰, C. Perez Dengra¹¹⁰, A. Pérez-Calero Yzquierdo¹¹⁰,
J. Puerta Pelayo¹¹⁰, I. Redondo¹¹⁰, L. Romero¹¹⁰, S. Sánchez Navas¹¹⁰, L. Urda Gómez¹¹⁰, C. Willmott¹¹⁰,
J. F. de Trocóniz¹¹¹, R. Reyes-Almanza¹¹¹, B. Alvarez Gonzalez¹¹², J. Cuevas¹¹², C. Erice¹¹²,
J. Fernandez Menendez¹¹², S. Folgueras¹¹², I. Gonzalez Caballero¹¹², J. R. González Fernández¹¹²,
E. Palencia Cortezon¹¹², C. Ramón Álvarez¹¹², V. Rodríguez Bouza¹¹², A. Soto Rodríguez¹¹², A. Trapote¹¹²,
N. Trevisani¹¹², C. Vico Villalba¹¹², J. A. Brochero Cifuentes¹¹³, I. J. Cabrillo¹¹³, A. Calderon¹¹³,
J. Duarte Campderros¹¹³, M. Fernandez¹¹³, C. Fernandez Madrazo¹¹³, P. J. Fernández Manteca¹¹³,
A. García Alonso¹¹³, G. Gomez¹¹³, C. Martinez Rivero¹¹³, P. Martinez Ruiz del Arbol¹¹³, F. Matorras¹¹³,
P. Matorras Cuevas¹¹³, J. Piedra Gomez¹¹³, C. Prieels¹¹³, T. Rodrigo¹¹³, A. Ruiz-Jimeno¹¹³, L. Scodellaro¹¹³,
I. Vila¹¹³, J. M. Vizan Garcia¹¹³, M. K. Jayananda¹¹⁴, B. Kailasapathy^{114,zz}, D. U. J. Sonnadara¹¹⁴,
D. D. C. Wickramaratna¹¹⁴, W. G. D. Dharmaratna¹¹⁵, K. Liyanage¹¹⁵, N. Perera¹¹⁵, N. Wickramage¹¹⁵,
T. K. Aarrestad¹¹⁶, D. Abbaneo¹¹⁶, J. Alimena¹¹⁶, E. Auffray¹¹⁶, G. Auzinger¹¹⁶, J. Baechler¹¹⁶, P. Baillon^{116,a},
D. Barney¹¹⁶, J. Bendavid¹¹⁶, M. Bianco¹¹⁶, A. Bocci¹¹⁶, T. Camporesi¹¹⁶, M. Capeans Garrido¹¹⁶,
G. Cerminara¹¹⁶, N. Chernyavskaya¹¹⁶, S. S. Chhibra¹¹⁶, M. Cipriani¹¹⁶, L. Cristella¹¹⁶, D. d'Enterria¹¹⁶,
A. Dabrowski¹¹⁶, A. David¹¹⁶, A. De Roeck¹¹⁶, M. M. Defranchis¹¹⁶, M. Deile¹¹⁶, M. Dobson¹¹⁶, M. Dünser¹¹⁶,
N. Dupont¹¹⁶, A. Elliott-Peisert¹¹⁶, N. Emrskova¹¹⁶, F. Fallavollita^{116,aaa}, D. Fasanella¹¹⁶, A. Florent¹¹⁶,
G. Franzoni¹¹⁶, W. Funk¹¹⁶, S. Giani¹¹⁶, D. Gigi¹¹⁶, K. Gill¹¹⁶, F. Glege¹¹⁶, L. Gouskos¹¹⁶, M. Haranko¹¹⁶,
J. Hegeman¹¹⁶, V. Innocente¹¹⁶, T. James¹¹⁶, P. Janot¹¹⁶, J. Kaspar¹¹⁶, J. Kieseler¹¹⁶, M. Komm¹¹⁶,
N. Kratochwil¹¹⁶, C. Lange¹¹⁶, S. Laurila¹¹⁶, P. Lecoq¹¹⁶, A. Lintuluoto¹¹⁶, K. Long¹¹⁶, C. Lourenço¹¹⁶,
B. Maier¹¹⁶, L. Malgeri¹¹⁶, S. Mallios¹¹⁶, M. Mannelli¹¹⁶, A. C. Marini¹¹⁶, F. Meijers¹¹⁶, S. Mersi¹¹⁶,
E. Meschi¹¹⁶, F. Moortgat¹¹⁶, M. Mulders¹¹⁶, S. Orfanelli¹¹⁶, L. Orsini¹¹⁶, F. Pantaleo¹¹⁶, L. Pape¹¹⁶, E. Perez¹¹⁶,
M. Peruzzi¹¹⁶, A. Petrilli¹¹⁶, G. Petrucciani¹¹⁶, A. Pfeiffer¹¹⁶, M. Pierini¹¹⁶, D. Piparo¹¹⁶, M. Pitt¹¹⁶, H. Qu¹¹⁶,
T. Quast¹¹⁶, D. Rabady¹¹⁶, A. Racz¹¹⁶, G. Reales Gutiérrez¹¹⁶, M. Rieger¹¹⁶, M. Rovere¹¹⁶, H. Sakulin¹¹⁶,
J. Salfeld-Nebgen¹¹⁶, S. Scarfi¹¹⁶, C. Schäfer¹¹⁶, M. Selvaggi¹¹⁶, A. Sharma¹¹⁶, P. Silva¹¹⁶, W. Snoeys¹¹⁶,
P. Sphicas^{116,bbb}, S. Summers¹¹⁶, K. Tatar¹¹⁶, V. R. Tavolaro¹¹⁶, D. Treille¹¹⁶, P. Tropea¹¹⁶, A. Tsiros¹¹⁶,
G. P. Van Onsem¹¹⁶, J. Wanczyk^{116,ccc}, K. A. Wozniak¹¹⁶, W. D. Zeuner¹¹⁶, L. Caminada^{117,ddd}, A. Ebrahimi¹¹⁷,
W. Erdmann¹¹⁷, R. Horisberger¹¹⁷, Q. Ingram¹¹⁷, H. C. Kaestli¹¹⁷, D. Kotlinski¹¹⁷, M. Missiroli^{117,ddd},
L. Noehte^{117,ddd}, T. Rohe¹¹⁷, K. Androsov^{118,ccc}, M. Backhaus¹¹⁸, P. Berger¹¹⁸, A. Calandri¹¹⁸, A. De Cosa¹¹⁸,
G. Dissertori¹¹⁸, M. Dittmar¹¹⁸, M. Donegà¹¹⁸, C. Dorfer¹¹⁸, F. Eble¹¹⁸, K. Gedia¹¹⁸, F. Glessgen¹¹⁸,
T. A. Gómez Espinosa¹¹⁸, C. Grab¹¹⁸, D. Hits¹¹⁸, W. Lustermann¹¹⁸, A.-M. Lyon¹¹⁸, R. A. Manzoni¹¹⁸,
L. Marchese¹¹⁸, C. Martin Perez¹¹⁸, M. T. Meinhard¹¹⁸, F. Nessi-Tedaldi¹¹⁸, J. Niedziela¹¹⁸, F. Pauss¹¹⁸,
V. Perovic¹¹⁸, S. Pigazzini¹¹⁸, M. G. Ratti¹¹⁸, M. Reichmann¹¹⁸, C. Reissel¹¹⁸, T. Reitenspiess¹¹⁸, B. Ristic¹¹⁸,
D. Ruini¹¹⁸, D. A. Sanz Becerra¹¹⁸, V. Stampf¹¹⁸, J. Steggemann^{118,ccc}, R. Wallny¹¹⁸, D. H. Zhu¹¹⁸, C. Amsler^{119,ccc},
P. Bärtshi¹¹⁹, C. Botta¹¹⁹, D. Brzhechko¹¹⁹, M. F. Canelli¹¹⁹, K. Cormier¹¹⁹, A. De Wit¹¹⁹, R. Del Burgo¹¹⁹

J. K. Heikkilä,¹¹⁹ M. Huwiler,¹¹⁹ W. Jin,¹¹⁹ A. Jofrehei,¹¹⁹ B. Kilminster,¹¹⁹ S. Leontsinis,¹¹⁹ S. P. Liechi,¹¹⁹ A. Macchiolo,¹¹⁹ P. Meiring,¹¹⁹ V. M. Mikuni,¹¹⁹ U. Molinatti,¹¹⁹ I. Neutelings,¹¹⁹ A. Reimers,¹¹⁹ P. Robmann,¹¹⁹ S. Sanchez Cruz,¹¹⁹ K. Schweiger,¹¹⁹ M. Senger,¹¹⁹ Y. Takahashi,¹¹⁹ C. Adloff,^{120,fff} C. M. Kuo,¹²⁰ W. Lin,¹²⁰ A. Roy,¹²⁰ T. Sarkar,^{120,kk} S. S. Yu,¹²⁰ L. Ceard,¹²¹ Y. Chao,¹²¹ K. F. Chen,¹²¹ P. H. Chen,¹²¹ W.-S. Hou,¹²¹ Y. y. Li,¹²¹ R.-S. Lu,¹²¹ E. Paganis,¹²¹ A. Psallidas,¹²¹ A. Steen,¹²¹ H. y. Wu,¹²¹ E. Yazgan,¹²¹ P. r. Yu,¹²¹ B. Asavapibhop,¹²² C. Asawatangtrakuldee,¹²² N. Srimanobhas,¹²² F. Boran,¹²³ S. Damarseckin,^{123,ggg} Z. S. Demiroglu,¹²³ F. Dolek,¹²³ I. Dumanoglu,^{123,hhh} E. Eskut,¹²³ Y. Guler,^{123,iii} E. Gurpinar Guler,^{123,iii} C. Isik,¹²³ O. Kara,¹²³ A. Kayis Topaksu,¹²³ U. Kiminsu,¹²³ G. Onengut,¹²³ K. Ozdemir,^{123,iii} A. Polatoz,¹²³ A. E. Simsek,¹²³ B. Tali,^{123,kkk} U. G. Tok,¹²³ S. Turkcapar,¹²³ I. S. Zorbakir,¹²³ B. Isildak,^{124,iii} G. Karapinar,¹²⁴ K. Ocalan,^{124,mmm} M. Yalvac,^{124,nnn} B. Akgun,¹²⁵ I. O. Atakisi,¹²⁵ E. Gülmez,¹²⁵ M. Kaya,^{125,ooo} O. Kaya,^{125,ppp} Ö. Özçelik,¹²⁵ S. Tekten,^{125,qqq} E. A. Yetkin,^{125,rrr} A. Cakir,¹²⁶ K. Cankocak,^{126,hhh} Y. Komurcu,¹²⁶ S. Sen,^{126,sss} S. Cerci,^{127,kkk} I. Hos,^{127,ttt} B. Kaynak,¹²⁷ S. Ozkorucuklu,¹²⁷ D. Sunar Cerci,^{127,kkk} C. Zorbilmez,¹²⁷ B. Grynyov,¹²⁸ L. Levchuk,¹²⁹ D. Anthony,¹³⁰ E. Bhal,¹³⁰ S. Bologna,¹³⁰ J. J. Brooke,¹³⁰ A. Bundock,¹³⁰ E. Clement,¹³⁰ D. Cussans,¹³⁰ H. Flacher,¹³⁰ J. Goldstein,¹³⁰ G. P. Heath,¹³⁰ H. F. Heath,¹³⁰ L. Kreczko,¹³⁰ B. Krikler,¹³⁰ S. Paramesvaran,¹³⁰ S. Seif El Nasr-Storey,¹³⁰ V. J. Smith,¹³⁰ N. Stylianou,^{130,uuu} K. Walkingshaw Pass,¹³⁰ R. White,¹³⁰ K. W. Bell,¹³¹ A. Belyaev,^{131,vvv} C. Brew,¹³¹ R. M. Brown,¹³¹ D. J. A. Cockerill,¹³¹ C. Cooke,¹³¹ K. V. Ellis,¹³¹ K. Harder,¹³¹ S. Harper,¹³¹ M.-L. Holmberg,¹³¹ J. Linacre,¹³¹ K. Manolopoulos,¹³¹ D. M. Newbold,¹³¹ E. Olaiya,¹³¹ D. Petyt,¹³¹ T. Reis,¹³¹ T. Schuh,¹³¹ C. H. Shepherd-Themistocleous,¹³¹ I. R. Tomalin,¹³¹ T. Williams,¹³¹ R. Bainbridge,¹³² P. Bloch,¹³² S. Bonomally,¹³² J. Borg,¹³² S. Breeze,¹³² O. Buchmuller,¹³² V. Cepaitis,¹³² G. S. Chahal,^{132,www} D. Colling,¹³² P. Dauncey,¹³² G. Davies,¹³² M. Della Negra,¹³² S. Fayer,¹³² G. Fedi,¹³² G. Hall,¹³² M. H. Hassanshahi,¹³² G. Iles,¹³² J. Langford,¹³² L. Lyons,¹³² A.-M. Magnan,¹³² S. Malik,¹³² A. Martelli,¹³² D. G. Monk,¹³² J. Nash,^{132,xxx} M. Pesaresi,¹³² D. M. Raymond,¹³² A. Richards,¹³² A. Rose,¹³² E. Scott,¹³² C. Seez,¹³² A. Shtiplijski,¹³² A. Tapper,¹³² K. Uchida,¹³² T. Virdee,^{132,v} M. Vojinovic,¹³² N. Wardle,¹³² S. N. Webb,¹³² D. Winterbottom,¹³² K. Coldham,¹³³ J. E. Cole,¹³³ A. Khan,¹³³ P. Kyberd,¹³³ I. D. Reid,¹³³ L. Teodorescu,¹³³ S. Zahid,¹³³ S. Abdullin,¹³⁴ A. Brinkerhoff,¹³⁴ B. Caraway,¹³⁴ J. Dittmann,¹³⁴ K. Hatakeyama,¹³⁴ A. R. Kanuganti,¹³⁴ B. McMaster,¹³⁴ N. Pastika,¹³⁴ M. Saunders,¹³⁴ S. Sawant,¹³⁴ C. Sutantawibul,¹³⁴ J. Wilson,¹³⁴ R. Bartek,¹³⁵ A. Dominguez,¹³⁵ R. Uniyal,¹³⁵ A. M. Vargas Hernandez,¹³⁵ A. Buccilli,¹³⁶ S. I. Cooper,¹³⁶ D. Di Croce,¹³⁶ S. V. Gleyzer,¹³⁶ C. Henderson,¹³⁶ C. U. Perez,¹³⁶ P. Rumerio,^{136,yyy} C. West,¹³⁶ A. Akpinar,¹³⁷ A. Albert,¹³⁷ D. Arcaro,¹³⁷ C. Cosby,¹³⁷ Z. Demiragli,¹³⁷ E. Fontanesi,¹³⁷ D. Gastler,¹³⁷ S. May,¹³⁷ J. Rohlf,¹³⁷ K. Salyer,¹³⁷ D. Sperka,¹³⁷ D. Spitzbart,¹³⁷ I. Suarez,¹³⁷ A. Tsatsos,¹³⁷ S. Yuan,¹³⁷ D. Zou,¹³⁷ G. Benelli,¹³⁸ B. Burkle,¹³⁸ X. Coubez,^{138,w} D. Cutts,¹³⁸ M. Hadley,¹³⁸ U. Heintz,¹³⁸ J. M. Hogan,^{138,zzz} T. KWON,¹³⁸ G. Landsberg,¹³⁸ K. T. Lau,¹³⁸ D. Li,¹³⁸ M. Lukasik,¹³⁸ J. Luo,¹³⁸ M. Narain,¹³⁸ N. Pervan,¹³⁸ S. Sagir,^{138,aaaa} F. Simpson,¹³⁸ E. Usai,¹³⁸ W. Y. Wong,¹³⁸ X. Yan,¹³⁸ D. Yu,¹³⁸ W. Zhang,¹³⁸ J. Bonilla,¹³⁹ C. Brainerd,¹³⁹ R. Breedon,¹³⁹ M. Calderon De La Barca Sanchez,¹³⁹ M. Chertok,¹³⁹ J. Conway,¹³⁹ P. T. Cox,¹³⁹ R. Erbacher,¹³⁹ G. Haza,¹³⁹ F. Jensen,¹³⁹ O. Kukral,¹³⁹ R. Lander,¹³⁹ M. Mulhearn,¹³⁹ D. Pellett,¹³⁹ B. Regnery,¹³⁹ D. Taylor,¹³⁹ Y. Yao,¹³⁹ F. Zhang,¹³⁹ M. Bachtis,¹⁴⁰ R. Cousins,¹⁴⁰ A. Datta,¹⁴⁰ D. Hamilton,¹⁴⁰ J. Hauser,¹⁴⁰ M. Ignatenko,¹⁴⁰ M. A. Iqbal,¹⁴⁰ T. Lam,¹⁴⁰ W. A. Nash,¹⁴⁰ S. Regnard,¹⁴⁰ D. Saltzberg,¹⁴⁰ B. Stone,¹⁴⁰ V. Valuev,¹⁴⁰ K. Burt,¹⁴¹ Y. Chen,¹⁴¹ R. Clare,¹⁴¹ J. W. Gary,¹⁴¹ M. Gordon,¹⁴¹ G. Hanson,¹⁴¹ G. Karapostoli,¹⁴¹ O. R. Long,¹⁴¹ N. Manganelli,¹⁴¹ M. Olmedo Negrete,¹⁴¹ W. Si,¹⁴¹ S. Wimpenny,¹⁴¹ Y. Zhang,¹⁴¹ J. G. Branson,¹⁴² P. Chang,¹⁴² S. Cittolin,¹⁴² S. Cooperstein,¹⁴² N. Deelen,¹⁴² D. Diaz,¹⁴² J. Duarte,¹⁴² R. Gerosa,¹⁴² L. Giannini,¹⁴² J. Guiang,¹⁴² R. Kansal,¹⁴² V. Krutelyov,¹⁴² R. Lee,¹⁴² J. Letts,¹⁴² M. Masciovecchio,¹⁴² F. Mokhtar,¹⁴² M. Pieri,¹⁴² B. V. Sathia Narayanan,¹⁴² V. Sharma,¹⁴² M. Tadel,¹⁴² A. Vartak,¹⁴² F. Würthwein,¹⁴² Y. Xiang,¹⁴² A. Yagil,¹⁴² N. Amin,¹⁴³ C. Campagnari,¹⁴³ M. Citron,¹⁴³ A. Dorsett,¹⁴³ V. Dutta,¹⁴³ J. Incandela,¹⁴³ M. Kilpatrick,¹⁴³ J. Kim,¹⁴³ B. Marsh,¹⁴³ H. Mei,¹⁴³ M. Oshiro,¹⁴³ M. Quinnan,¹⁴³ J. Richman,¹⁴³ U. Sarica,¹⁴³ F. Setti,¹⁴³ J. Sheplock,¹⁴³ D. Stuart,¹⁴³ S. Wang,¹⁴³ A. Bornheim,¹⁴⁴ O. Cerri,¹⁴⁴ I. Dutta,¹⁴⁴ J. M. Lawhorn,¹⁴⁴ N. Lu,¹⁴⁴ J. Mao,¹⁴⁴ H. B. Newman,¹⁴⁴ T. Q. Nguyen,¹⁴⁴ M. Spiropulu,¹⁴⁴ J. R. Vlimant,¹⁴⁴ C. Wang,¹⁴⁴ S. Xie,¹⁴⁴ Z. Zhang,¹⁴⁴ R. Y. Zhu,¹⁴⁴ J. Alison,¹⁴⁵ S. An,¹⁴⁵ M. B. Andrews,¹⁴⁵ P. Bryant,¹⁴⁵ T. Ferguson,¹⁴⁵ A. Harilal,¹⁴⁵ C. Liu,¹⁴⁵ T. Mudholkar,¹⁴⁵ M. Paulini,¹⁴⁵ A. Sanchez,¹⁴⁵ W. Terrill,¹⁴⁵ J. P. Cumalat,¹⁴⁶

W. T. Ford¹⁴⁶, A. Hassani¹⁴⁶, E. MacDonald¹⁴⁶, R. Patel¹⁴⁶, A. Perloff¹⁴⁶, C. Savard¹⁴⁶, K. Stenson¹⁴⁶,
 K. A. Ulmer¹⁴⁶, S. R. Wagner¹⁴⁶, J. Alexander¹⁴⁷, S. Bright-Thonney¹⁴⁷, X. Chen¹⁴⁷, Y. Cheng¹⁴⁷,
 D. J. Cranshaw¹⁴⁷, S. Hogan¹⁴⁷, J. Monroy¹⁴⁷, J. R. Patterson¹⁴⁷, D. Quach¹⁴⁷, J. Reichert¹⁴⁷, M. Reid¹⁴⁷,
 A. Ryd¹⁴⁷, W. Sun¹⁴⁷, J. Thom¹⁴⁷, P. Wittich¹⁴⁷, R. Zou¹⁴⁷, M. Albrow¹⁴⁸, M. Alyari¹⁴⁸, G. Apollinari¹⁴⁸,
 A. Apresyan¹⁴⁸, A. Apyan¹⁴⁸, S. Banerjee¹⁴⁸, L. A. T. Bauerdick¹⁴⁸, D. Berry¹⁴⁸, J. Berryhill¹⁴⁸, P. C. Bhat¹⁴⁸,
 K. Burkett¹⁴⁸, J. N. Butler¹⁴⁸, A. Canepa¹⁴⁸, G. B. Cerati¹⁴⁸, H. W. K. Cheung¹⁴⁸, F. Chlebana¹⁴⁸,
 K. F. Di Petrillo¹⁴⁸, V. D. Elvira¹⁴⁸, Y. Feng¹⁴⁸, J. Freeman¹⁴⁸, Z. Gecse¹⁴⁸, L. Gray¹⁴⁸, D. Green¹⁴⁸,
 S. Grünendahl¹⁴⁸, O. Gutsche¹⁴⁸, R. M. Harris¹⁴⁸, R. Heller¹⁴⁸, T. C. Herwig¹⁴⁸, J. Hirschauer¹⁴⁸, B. Jayatilaka¹⁴⁸,
 S. Jindariani¹⁴⁸, M. Johnson¹⁴⁸, U. Joshi¹⁴⁸, T. Klijsma¹⁴⁸, B. Klima¹⁴⁸, K. H. M. Kwok¹⁴⁸, S. Lammel¹⁴⁸,
 D. Lincoln¹⁴⁸, R. Lipton¹⁴⁸, T. Liu¹⁴⁸, C. Madrid¹⁴⁸, K. Maeshima¹⁴⁸, C. Mantilla¹⁴⁸, D. Mason¹⁴⁸,
 P. McBride¹⁴⁸, P. Merkel¹⁴⁸, S. Mrenna¹⁴⁸, S. Nahn¹⁴⁸, J. Ngadiuba¹⁴⁸, V. O'Dell¹⁴⁸, V. Papadimitriou¹⁴⁸,
 K. Pedro¹⁴⁸, C. Pena^{148,bbbb}, O. Prokofyev¹⁴⁸, F. Ravera¹⁴⁸, A. Reinsvold Hall¹⁴⁸, L. Ristori¹⁴⁸,
 E. Sexton-Kennedy¹⁴⁸, N. Smith¹⁴⁸, A. Soha¹⁴⁸, W. J. Spalding¹⁴⁸, L. Spiegel¹⁴⁸, J. Strait¹⁴⁸, L. Taylor¹⁴⁸,
 S. Tkaczyk¹⁴⁸, N. V. Tran¹⁴⁸, L. Uplegger¹⁴⁸, E. W. Vaandering¹⁴⁸, H. A. Weber¹⁴⁸, D. Acosta¹⁴⁹, P. Avery¹⁴⁹,
 D. Bourilkov¹⁴⁹, L. Cadamuro¹⁴⁹, V. Cherepanov¹⁴⁹, F. Errico¹⁴⁹, R. D. Field¹⁴⁹, D. Guerrero¹⁴⁹, B. M. Joshi¹⁴⁹,
 M. Kim¹⁴⁹, E. Koenig¹⁴⁹, J. Konigsberg¹⁴⁹, A. Korytov¹⁴⁹, K. H. Lo¹⁴⁹, K. Matchev¹⁴⁹, N. Menendez¹⁴⁹,
 G. Mitselmakher¹⁴⁹, A. Muthirakalayil Madhu¹⁴⁹, N. Rawal¹⁴⁹, D. Rosenzweig¹⁴⁹, S. Rosenzweig¹⁴⁹,
 J. Rotter¹⁴⁹, K. Shi¹⁴⁹, J. Sturdy¹⁴⁹, J. Wang¹⁴⁹, E. Yigitbasi¹⁴⁹, X. Zuo¹⁴⁹, T. Adams¹⁵⁰, A. Askew¹⁵⁰,
 R. Habibullah¹⁵⁰, V. Hagopian¹⁵⁰, K. F. Johnson¹⁵⁰, R. Khurana¹⁵⁰, T. Kolberg¹⁵⁰, G. Martinez¹⁵⁰, H. Prosper¹⁵⁰,
 C. Schiber¹⁵⁰, O. Viazlo¹⁵⁰, R. Yohay¹⁵⁰, J. Zhang¹⁵⁰, M. M. Baarmand¹⁵¹, S. Butalla¹⁵¹, T. Elkafray^{151,cccc},
 M. Hohlmann¹⁵¹, R. Kumar Verma¹⁵¹, D. Noonan¹⁵¹, M. Rahmani¹⁵¹, F. Yumiceva¹⁵¹, M. R. Adams¹⁵²,
 H. Becerril Gonzalez¹⁵², R. Cavanaugh¹⁵², S. Dittmer¹⁵², O. Evdokimov¹⁵², C. E. Gerber¹⁵², D. A. Hangal¹⁵²,
 D. J. Hofman¹⁵², A. H. Merrit¹⁵², C. Mills¹⁵², G. Oh¹⁵², T. Roy¹⁵², S. Rudrabhatla¹⁵², M. B. Tonjes¹⁵²,
 N. Varelas¹⁵², J. Viinikainen¹⁵², X. Wang¹⁵², Z. Wu¹⁵², Z. Ye¹⁵², M. Alhousseini¹⁵³, K. Dilsiz^{153,dddd},
 R. P. Gandrajula¹⁵³, O. K. Köseyan¹⁵³, J.-P. Merlo¹⁵³, A. Mestvirishvili^{153,eeee}, J. Nachtman¹⁵³, H. Ogul^{153,ffff},
 Y. Onel¹⁵³, A. Penzo¹⁵³, C. Snyder¹⁵³, E. Tiras^{153,gggg}, O. Amram¹⁵⁴, B. Blumenfeld¹⁵⁴, L. Corcodilos¹⁵⁴,
 J. Davis¹⁵⁴, M. Eminizer¹⁵⁴, A. V. Gritsan¹⁵⁴, S. Kyriacou¹⁵⁴, P. Maksimovic¹⁵⁴, J. Roskes¹⁵⁴, M. Swartz¹⁵⁴,
 T. Á. Vámi¹⁵⁴, A. Abreu¹⁵⁵, J. Anguiano¹⁵⁵, C. Baldenegro Barrera¹⁵⁵, P. Baringer¹⁵⁵, A. Bean¹⁵⁵, A. Bylinkin¹⁵⁵,
 Z. Flowers¹⁵⁵, T. Isidori¹⁵⁵, S. Khalil¹⁵⁵, J. King¹⁵⁵, G. Krintiras¹⁵⁵, A. Kropivnitskaya¹⁵⁵, M. Lazarovits¹⁵⁵,
 C. Le Mahieu¹⁵⁵, C. Lindsey¹⁵⁵, J. Marquez¹⁵⁵, N. Minafra¹⁵⁵, M. Murray¹⁵⁵, M. Nickel¹⁵⁵, C. Rogan¹⁵⁵,
 C. Royon¹⁵⁵, R. Salvatico¹⁵⁵, S. Sanders¹⁵⁵, E. Schmitz¹⁵⁵, C. Smith¹⁵⁵, J. D. Tapia Takaki¹⁵⁵, Q. Wang¹⁵⁵,
 Z. Warner¹⁵⁵, J. Williams¹⁵⁵, G. Wilson¹⁵⁵, S. Duric¹⁵⁶, A. Ivanov¹⁵⁶, K. Kaadze¹⁵⁶, D. Kim¹⁵⁶, Y. Maravin¹⁵⁶,
 T. Mitchell¹⁵⁶, A. Modak¹⁵⁶, K. Nam¹⁵⁶, F. Rebassoo¹⁵⁷, D. Wright¹⁵⁷, E. Adams¹⁵⁸, A. Baden¹⁵⁸, O. Baron¹⁵⁸,
 A. Belloni¹⁵⁸, S. C. Eno¹⁵⁸, N. J. Hadley¹⁵⁸, S. Jabeen¹⁵⁸, R. G. Kellogg¹⁵⁸, T. Koeth¹⁵⁸, A. C. Mignerey¹⁵⁸,
 S. Nabili¹⁵⁸, C. Palmer¹⁵⁸, M. Seidel¹⁵⁸, A. Skuja¹⁵⁸, L. Wang¹⁵⁸, K. Wong¹⁵⁸, D. Abercrombie¹⁵⁹,
 G. Andreassi¹⁵⁹, R. Bi¹⁵⁹, W. Busza¹⁵⁹, I. A. Cali¹⁵⁹, Y. Chen¹⁵⁹, M. D'Alfonso¹⁵⁹, J. Eysermans¹⁵⁹, C. Freer¹⁵⁹,
 G. Gomez-Ceballos¹⁵⁹, M. Goncharov¹⁵⁹, P. Harris¹⁵⁹, M. Hu¹⁵⁹, M. Klute¹⁵⁹, D. Kovalskyi¹⁵⁹, J. Krupa¹⁵⁹,
 Y.-J. Lee¹⁵⁹, C. Mironov¹⁵⁹, C. Paus¹⁵⁹, D. Rankin¹⁵⁹, C. Roland¹⁵⁹, G. Roland¹⁵⁹, Z. Shi¹⁵⁹,
 G. S. F. Stephens¹⁵⁹, J. Wang¹⁵⁹, Z. Wang¹⁵⁹, B. Wyslouch¹⁵⁹, R. M. Chatterjee¹⁶⁰, A. Evans¹⁶⁰, J. Hiltbrand¹⁶⁰,
 Sh. Jain¹⁶⁰, M. Krohn¹⁶⁰, Y. Kubota¹⁶⁰, J. Mans¹⁶⁰, M. Revering¹⁶⁰, R. Rusack¹⁶⁰, R. Saradhy¹⁶⁰,
 N. Schroeder¹⁶⁰, N. Strobbe¹⁶⁰, M. A. Wadud¹⁶⁰, K. Bloom¹⁶¹, M. Bryson¹⁶¹, S. Chauhan¹⁶¹, D. R. Claes¹⁶¹,
 C. Fangmeier¹⁶¹, L. Finco¹⁶¹, F. Golf¹⁶¹, C. Joo¹⁶¹, I. Kravchenko¹⁶¹, M. Musich¹⁶¹, I. Reed¹⁶¹, J. E. Siado¹⁶¹,
 G. R. Snow^{161,a}, W. Tabb¹⁶¹, F. Yan¹⁶¹, A. G. Zecchinelli¹⁶¹, G. Agarwal¹⁶², H. Bandyopadhyay¹⁶², L. Hay¹⁶²,
 I. Iashvili¹⁶², A. Kharchilava¹⁶², C. McLean¹⁶², D. Nguyen¹⁶², J. Pekkanen¹⁶², S. Rappoccio¹⁶², A. Williams¹⁶²,
 G. Alverson¹⁶³, E. Barberis¹⁶³, Y. Haddad¹⁶³, A. Hortiangtham¹⁶³, J. Li¹⁶³, G. Madigan¹⁶³, B. Marzocchi¹⁶³,
 D. M. Morse¹⁶³, V. Nguyen¹⁶³, T. Orimoto¹⁶³, A. Parker¹⁶³, L. Skinnari¹⁶³, A. Tishelman-Charny¹⁶³,
 T. Wamorkar¹⁶³, B. Wang¹⁶³, A. Wisecarver¹⁶³, D. Wood¹⁶³, S. Bhattacharya¹⁶⁴, J. Bueghly¹⁶⁴, Z. Chen¹⁶⁴,
 A. Gilbert¹⁶⁴, T. Gunter¹⁶⁴, K. A. Hahn¹⁶⁴, Y. Liu¹⁶⁴, N. Odell¹⁶⁴, M. H. Schmitt¹⁶⁴, M. Velasco¹⁶⁴, R. Band¹⁶⁵,
 R. Bucci¹⁶⁵, M. Cremonesi¹⁶⁵, A. Das¹⁶⁵, N. Dev¹⁶⁵, R. Goldouzian¹⁶⁵, M. Hildreth¹⁶⁵, K. Hurtado Anampa¹⁶⁵

C. Jessop¹⁶⁵, K. Lannon¹⁶⁵, J. Lawrence¹⁶⁵, N. Loukas¹⁶⁵, L. Lutton¹⁶⁵, N. Marinelli¹⁶⁵, I. Mcalister¹⁶⁵, T. McCauley¹⁶⁵, C. Mcgrady¹⁶⁵, K. Mohrman¹⁶⁵, C. Moore¹⁶⁵, Y. Musienko^{165,n}, R. Ruchti¹⁶⁵, P. Siddireddy¹⁶⁵, A. Townsend¹⁶⁵, M. Wayne¹⁶⁵, A. Wightman¹⁶⁵, M. Zarucki¹⁶⁵, L. Zygala¹⁶⁵, B. Bylsma¹⁶⁶, B. Cardwell¹⁶⁶, L. S. Durkin¹⁶⁶, B. Francis¹⁶⁶, C. Hill¹⁶⁶, M. Nunez Ornelas¹⁶⁶, K. Wei¹⁶⁶, B. L. Winer¹⁶⁶, B. R. Yates¹⁶⁶, F. M. Addesa¹⁶⁷, B. Bonham¹⁶⁷, P. Das¹⁶⁷, G. Dezoort¹⁶⁷, P. Elmer¹⁶⁷, A. Frankenthal¹⁶⁷, B. Greenberg¹⁶⁷, N. Haubrich¹⁶⁷, S. Higginbotham¹⁶⁷, A. Kalogeropoulos¹⁶⁷, G. Kopp¹⁶⁷, S. Kwan¹⁶⁷, D. Lange¹⁶⁷, D. Marlow¹⁶⁷, K. Mei¹⁶⁷, I. Ojalvo¹⁶⁷, J. Olsen¹⁶⁷, D. Stickland¹⁶⁷, C. Tully¹⁶⁷, S. Malik¹⁶⁸, S. Norberg¹⁶⁸, A. S. Bakshi¹⁶⁹, V. E. Barnes¹⁶⁹, R. Chawla¹⁶⁹, S. Das¹⁶⁹, L. Gutay¹⁶⁹, M. Jones¹⁶⁹, A. W. Jung¹⁶⁹, S. Karmarkar¹⁶⁹, D. Kondratyev¹⁶⁹, M. Liu¹⁶⁹, G. Negro¹⁶⁹, N. Neumeister¹⁶⁹, G. Paspalaki¹⁶⁹, S. Piperov¹⁶⁹, A. Purohit¹⁶⁹, J. F. Schulte¹⁶⁹, M. Stojanovic¹⁶⁹, J. Thieman¹⁶⁹, F. Wang¹⁶⁹, R. Xiao¹⁶⁹, W. Xie¹⁶⁹, J. Dolen¹⁷⁰, N. Parashar¹⁷⁰, A. Baty¹⁷¹, T. Carnahan¹⁷¹, M. Decaro¹⁷¹, S. Dildick¹⁷¹, K. M. Ecklund¹⁷¹, S. Freed¹⁷¹, P. Gardner¹⁷¹, F. J. M. Geurts¹⁷¹, A. Kumar¹⁷¹, W. Li¹⁷¹, B. P. Padley¹⁷¹, R. Redjimi¹⁷¹, W. Shi¹⁷¹, A. G. Stahl Leiton¹⁷¹, S. Yang¹⁷¹, L. Zhang^{171, hhhh}, Y. Zhang¹⁷¹, A. Bodek¹⁷², P. de Barbaro¹⁷², R. Demina¹⁷², J. L. Dulemba¹⁷², C. Fallon¹⁷², T. Ferbel¹⁷², M. Galanti¹⁷², A. Garcia-Bellido¹⁷², O. Hindrichs¹⁷², A. Khukhunaishvili¹⁷², E. Ranken¹⁷², R. Taus¹⁷², B. Chiarito¹⁷³, J. P. Chou¹⁷³, A. Gandrakota¹⁷³, Y. Gershtein¹⁷³, E. Halkiadakis¹⁷³, A. Hart¹⁷³, M. Heindl¹⁷³, O. Karacheban^{173,z}, I. Laflotte¹⁷³, A. Lath¹⁷³, R. Montalvo¹⁷³, K. Nash¹⁷³, M. Osherson¹⁷³, S. Salur¹⁷³, S. Schnetzer¹⁷³, S. Somalwar¹⁷³, R. Stone¹⁷³, S. A. Thayil¹⁷³, S. Thomas¹⁷³, H. Wang¹⁷³, H. Acharya¹⁷⁴, A. G. Delannoy¹⁷⁴, S. Fiorendi¹⁷⁴, S. Spanier¹⁷⁴, O. Bouhali^{175, iii}, M. Dalchenko¹⁷⁵, A. Delgado¹⁷⁵, R. Eusebi¹⁷⁵, J. Gilmore¹⁷⁵, T. Huang¹⁷⁵, T. Kamon^{175, jiii}, H. Kim¹⁷⁵, S. Luo¹⁷⁵, S. Malhotra¹⁷⁵, R. Mueller¹⁷⁵, D. Overton¹⁷⁵, D. Rathjens¹⁷⁵, A. Safonov¹⁷⁵, N. Akchurin¹⁷⁶, J. Damgov¹⁷⁶, V. Hegde¹⁷⁶, S. Kunori¹⁷⁶, K. Lamichhane¹⁷⁶, S. W. Lee¹⁷⁶, T. Mengke¹⁷⁶, S. Muthumuni¹⁷⁶, T. Peltola¹⁷⁶, I. Volobouev¹⁷⁶, Z. Wang¹⁷⁶, A. Whitbeck¹⁷⁶, E. Appelt¹⁷⁷, S. Greene¹⁷⁷, A. Gurrola¹⁷⁷, W. Johns¹⁷⁷, A. Melo¹⁷⁷, H. Ni¹⁷⁷, K. Padeken¹⁷⁷, F. Romeo¹⁷⁷, P. Sheldon¹⁷⁷, S. Tuo¹⁷⁷, J. Velkovska¹⁷⁷, M. W. Arenton¹⁷⁸, B. Cox¹⁷⁸, G. Cummings¹⁷⁸, J. Hakala¹⁷⁸, R. Hirosky¹⁷⁸, M. Joyce¹⁷⁸, A. Ledovskoy¹⁷⁸, A. Li¹⁷⁸, C. Neu¹⁷⁸, C. E. Perez Lara¹⁷⁸, B. Tannenwald¹⁷⁸, S. White¹⁷⁸, E. Wolfe¹⁷⁸, N. Poudyal¹⁷⁹, K. Black¹⁸⁰, T. Bose¹⁸⁰, C. Caillol¹⁸⁰, S. Dasu¹⁸⁰, I. De Bruyn¹⁸⁰, P. Everaerts¹⁸⁰, F. Fienga¹⁸⁰, C. Galloni¹⁸⁰, H. He¹⁸⁰, M. Herndon¹⁸⁰, A. Hervé¹⁸⁰, U. Hussain¹⁸⁰, A. Lanaro¹⁸⁰, A. Loeliger¹⁸⁰, R. Loveless¹⁸⁰, J. Madhusudanan Sreekala¹⁸⁰, A. Mallampalli¹⁸⁰, A. Mohammadi¹⁸⁰, D. Pinna¹⁸⁰, A. Savin¹⁸⁰, V. Shang¹⁸⁰, V. Sharma¹⁸⁰, W. H. Smith¹⁸⁰, D. Teague¹⁸⁰, S. Trembath-Reichert¹⁸⁰, W. Vetens¹⁸⁰, S. Afanasiev¹⁸¹, V. Andreev¹⁸¹, Yu. Andreev¹⁸¹, T. Aushev¹⁸¹, M. Azarkin¹⁸¹, A. Babaev¹⁸¹, A. Belyaev¹⁸¹, V. Blinov^{181,n}, E. Boos¹⁸¹, V. Borshch¹⁸¹, D. Budkouski¹⁸¹, V. Bunichev¹⁸¹, O. Bychkova¹⁸¹, V. Chekhovsky¹⁸¹, R. Chistov^{181,n}, M. Danilov^{181,n}, A. Dermenev¹⁸¹, T. Dimova^{181,n}, I. Dremin¹⁸¹, M. Dubinin^{181, bbbb}, L. Dudko¹⁸¹, V. Epshteyn^{181, kkkk}, G. Gavrilo¹⁸¹, V. Gavrilo¹⁸¹, S. Gninenko¹⁸¹, V. Golovtsov¹⁸¹, N. Golubev¹⁸¹, I. Golutvin¹⁸¹, I. Gorbunov¹⁸¹, A. Gribushin¹⁸¹, V. Ivanchenko¹⁸¹, Y. Ivanov¹⁸¹, V. Kachanov¹⁸¹, L. Kardapoltsev^{181,n}, V. Karjavine¹⁸¹, A. Karneyev¹⁸¹, V. Kim^{181,n}, M. Kirakosyan¹⁸¹, D. Kirpichnikov¹⁸¹, M. Kirsanov¹⁸¹, V. Klyukhin¹⁸¹, O. Kodolova^{181, llll}, D. Konstantinov¹⁸¹, V. Korenkov¹⁸¹, A. Kozyrev^{181,n}, N. Krasnikov¹⁸¹, E. Kuznetsova^{181, mmmm}, A. Lanev¹⁸¹, A. Litomin¹⁸¹, N. Lychkovskaya¹⁸¹, V. Makarenko¹⁸¹, A. Malakhov¹⁸¹, V. Matveev^{181,n}, V. Murzin¹⁸¹, A. Nikitenko^{181, nnnn}, S. Obraztsov¹⁸¹, V. Okhotnikov¹⁸¹, V. Oreshkin¹⁸¹, A. Oskin¹⁸¹, I. Ovtin^{181,n}, V. Palichik¹⁸¹, P. Parygin^{181, oooo}, A. Pashenkov¹⁸¹, V. Perelygin¹⁸¹, M. Perfilov¹⁸¹, S. Petrushanko¹⁸¹, G. Pivovarov¹⁸¹, S. Polikarpov^{181,n}, V. Popov¹⁸¹, O. Radchenko^{181,n}, M. Savina¹⁸¹, V. Savrin¹⁸¹, D. Seitova¹⁸¹, V. Shalae¹⁸¹, S. Shmatov¹⁸¹, S. Shulha¹⁸¹, Y. Skovpen^{181,n}, S. Slabospitskii¹⁸¹, I. Smirnov¹⁸¹, V. Smirnov¹⁸¹, D. Sosnov¹⁸¹, A. Stepenov¹⁸¹, V. Sulimov¹⁸¹, E. Tcherniaev¹⁸¹, A. Terkulov¹⁸¹, O. Teryaev¹⁸¹, M. Toms^{181, pppp}, A. Toropin¹⁸¹, L. Uvarov¹⁸¹, A. Uzunian¹⁸¹, E. Vlasov^{181, qqqq}, S. Volkov¹⁸¹, A. Vorobyev¹⁸¹, N. Voytishin¹⁸¹, B. S. Yuldashev^{181, rrrr}, A. Zarubin¹⁸¹, I. Zhizhin¹⁸¹ and A. Zhokin¹⁸¹

(CMS Collaboration)

¹Yerevan Physics Institute, Yerevan, Armenia²Institut für Hochenergiephysik, Vienna, Austria³Universiteit 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 Físicas, 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*Beihang University, Beijing, China*
¹⁴*Department of Physics, Tsinghua University, Beijing, China*
¹⁵*Institute of High Energy Physics, Beijing, China*
¹⁶*State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China*
¹⁷*Sun Yat-Sen University, Guangzhou, China*
¹⁸*Institute of Modern Physics and Key Laboratory of Nuclear Physics and Ion-beam Application (MOE)—Fudan University, Shanghai, China*
¹⁹*Zhejiang University, Hangzhou, Zhejiang, China*
²⁰*Universidad de Los Andes, Bogota, Colombia*
²¹*Universidad de Antioquia, Medellin, Colombia*
²²*University of Split, Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, Split, Croatia*
²³*University of Split, Faculty of Science, Split, Croatia*
²⁴*Institute Rudjer Boskovic, Zagreb, Croatia*
²⁵*University of Cyprus, Nicosia, Cyprus*
²⁶*Charles University, Prague, Czech Republic*
²⁷*Escuela Politecnica Nacional, Quito, Ecuador*
²⁸*Universidad San Francisco de Quito, Quito, Ecuador*
²⁹*Academy of Scientific Research and Technology of the Arab Republic of Egypt, Egyptian Network of High Energy Physics, Cairo, Egypt*
³⁰*Center for High Energy Physics (CHEP-FU), Fayoum University, El-Fayoum, Egypt*
³¹*National Institute of Chemical Physics and Biophysics, Tallinn, Estonia*
³²*Department of Physics, University of Helsinki, Helsinki, Finland*
³³*Helsinki Institute of Physics, Helsinki, Finland*
³⁴*Lappeenranta-Lahti University of Technology, Lappeenranta, Finland*
³⁵*IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France*
³⁶*Laboratoire Leprince-Ringuet, CNRS/IN2P3, Ecole Polytechnique, Institut Polytechnique de Paris, Palaiseau, France*
³⁷*Université de Strasbourg, CNRS, IPHC UMR 7178, Strasbourg, France*
³⁸*Institut de Physique des 2 Infinis de Lyon (IP2I), Villeurbanne, France*
³⁹*Georgian Technical University, Tbilisi, Georgia*
⁴⁰*RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany*
⁴¹*RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany*
⁴²*RWTH Aachen University, III. Physikalisches Institut B, Aachen, Germany*
⁴³*Deutsches Elektronen-Synchrotron, Hamburg, Germany*
⁴⁴*University of Hamburg, Hamburg, Germany*
⁴⁵*Karlsruher Institut fuer Technologie, Karlsruhe, Germany*
⁴⁶*Institute of Nuclear and Particle Physics (INPP), NCSR Demokritos, Aghia Paraskevi, Greece*
⁴⁷*National and Kapodistrian University of Athens, Athens, Greece*
⁴⁸*National Technical University of Athens, Athens, Greece*
⁴⁹*University of Ioánnina, Ioánnina, Greece*
⁵⁰*MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary*
⁵¹*Wigner Research Centre for Physics, Budapest, Hungary*
⁵²*Institute of Nuclear Research ATOMKI, Debrecen, Hungary*
⁵³*Institute of Physics, University of Debrecen, Debrecen, Hungary*
⁵⁴*Karoly Robert Campus, MATE Institute of Technology, Gyongyos, Hungary*
⁵⁵*Indian Institute of Science (IISc), Bangalore, India*
⁵⁶*Panjab University, Chandigarh, India*
⁵⁷*University of Delhi, Delhi, India*
⁵⁸*Saha Institute of Nuclear Physics, HBNI, Kolkata, India*

- ⁵⁹*Indian Institute of Technology Madras, Madras, India*
⁶⁰*Bhabha Atomic Research Centre, Mumbai, India*
⁶¹*Tata Institute of Fundamental Research-A, Mumbai, India*
⁶²*Tata Institute of Fundamental Research-B, Mumbai, India*
⁶³*National Institute of Science Education and Research, An OCC of Homi Bhabha National Institute, Bhubaneswar, Odisha, India*
⁶⁴*Indian Institute of Science Education and Research (IISER), Pune, India*
⁶⁵*Isfahan University of Technology, Isfahan, Iran*
⁶⁶*Institute for Research in Fundamental Sciences (IPM), Tehran, Iran*
⁶⁷*University College Dublin, Dublin, Ireland*
^{68a}*INFN Sezione di Bari, Bari, Italy*
^{68b}*Università di Bari, Bari, Italy*
^{68c}*Politecnico di Bari, Bari, Italy*
^{69a}*INFN Sezione di Bologna, Bologna, Italy*
^{69b}*Università di Bologna, Bologna, Italy*
^{70a}*INFN Sezione di Catania, Catania, Italy*
^{70b}*Università di Catania, Catania, Italy*
^{71a}*INFN Sezione di Firenze, Firenze, Italy*
^{71b}*Università di Firenze, Firenze, Italy*
⁷²*INFN Laboratori Nazionali di Frascati, Frascati, Italy*
^{73a}*INFN Sezione di Genova, Genova, Italy*
^{73b}*Università di Genova, Genova, Italy*
^{74a}*INFN Sezione di Milano-Bicocca, Milano, Italy*
^{74b}*Università di Milano-Bicocca, Milano, Italy*
^{75a}*INFN Sezione di Napoli, Napoli, Italy*
^{75b}*Università di Napoli 'Federico II', Napoli, Italy*
^{75c}*Università della Basilicata, Potenza, Italy*
^{75d}*Università G. Marconi, Roma, Italy*
^{76a}*INFN Sezione di Padova, Padova, Italy*
^{76b}*Università di Padova, Padova, Italy*
^{76c}*Università di Trento, Trento, Italy*
^{77a}*INFN Sezione di Pavia, Pavia, Italy*
^{77b}*Università di Pavia, Pavia, Italy*
^{78a}*INFN Sezione di Perugia, Perugia, Italy*
^{78b}*Università di Perugia, Perugia, Italy*
^{79a}*INFN Sezione di Pisa, Pisa, Italy*
^{79b}*Università di Pisa, Pisa, Italy*
^{79c}*Scuola Normale Superiore di Pisa, Pisa, Italy*
^{79d}*Università di Siena, Siena, Italy*
^{80a}*INFN Sezione di Roma, Roma, Italy*
^{80b}*Sapienza Università di Roma, Roma, Italy*
^{81a}*INFN Sezione di Torino, Torino, Italy*
^{81b}*Università di Torino, Torino, Italy*
^{81c}*Università del Piemonte Orientale, Novara, Italy*
^{82a}*INFN Sezione di Trieste, Trieste, Italy*
^{82b}*Università di Trieste, Trieste, Italy*
⁸³*Kyungpook National University, Daegu, Korea*
⁸⁴*Chonnam National University, Institute for Universe and Elementary Particles, Kwangju, Korea*
⁸⁵*Hanyang University, Seoul, Korea*
⁸⁶*Korea University, Seoul, Korea*
⁸⁷*Kyung Hee University, Department of Physics, Seoul, Korea*
⁸⁸*Sejong University, Seoul, Korea*
⁸⁹*Seoul National University, Seoul, Korea*
⁹⁰*University of Seoul, Seoul, Korea*
⁹¹*Yonsei University, Department of Physics, Seoul, Korea*
⁹²*Sungkyunkwan University, Suwon, Korea*
⁹³*College of Engineering and Technology, American University of the Middle East (AUM), Dasman, Kuwait*
⁹⁴*Riga Technical University, Riga, Latvia*
⁹⁵*Vilnius University, Vilnius, Lithuania*

- ⁹⁶*National Centre for Particle Physics, Universiti Malaya, Kuala Lumpur, Malaysia*
⁹⁷*Universidad de Sonora (UNISON), Hermosillo, Mexico*
⁹⁸*Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico*
⁹⁹*Universidad Iberoamericana, Mexico City, Mexico*
¹⁰⁰*Benemerita Universidad Autonoma de Puebla, Puebla, Mexico*
¹⁰¹*University of Montenegro, Podgorica, Montenegro*
¹⁰²*University of Auckland, Auckland, New Zealand*
¹⁰³*University of Canterbury, Christchurch, New Zealand*
¹⁰⁴*National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan*
¹⁰⁵*AGH University of Science and Technology Faculty of Computer Science, Electronics and Telecommunications, Krakow, Poland*
¹⁰⁶*National Centre for Nuclear Research, Swierk, Poland*
¹⁰⁷*Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland*
¹⁰⁸*Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal*
¹⁰⁹*VINCA Institute of Nuclear Sciences, University of Belgrade, Belgrade, Serbia*
¹¹⁰*Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain*
¹¹¹*Universidad Autónoma de Madrid, Madrid, Spain*
¹¹²*Universidad de Oviedo, Instituto Universitario de Ciencias y Tecnologías Espaciales de Asturias (ICTEA), Oviedo, Spain*
¹¹³*Instituto de Física de Cantabria (IFCA), CSIC-Universidad de Cantabria, Santander, Spain*
¹¹⁴*University of Colombo, Colombo, Sri Lanka*
¹¹⁵*University of Ruhuna, Department of Physics, Matara, Sri Lanka*
¹¹⁶*CERN, European Organization for Nuclear Research, Geneva, Switzerland*
¹¹⁷*Paul Scherrer Institut, Villigen, Switzerland*
¹¹⁸*ETH Zurich—Institute for Particle Physics and Astrophysics (IPA), Zurich, Switzerland*
¹¹⁹*Universität Zürich, Zurich, Switzerland*
¹²⁰*National Central University, Chung-Li, Taiwan*
¹²¹*National Taiwan University (NTU), Taipei, Taiwan*
¹²²*Chulalongkorn University, Faculty of Science, Department of Physics, Bangkok, Thailand*
¹²³*Çukurova University, Physics Department, Science and Art Faculty, Adana, Turkey*
¹²⁴*Middle East Technical University, Physics Department, Ankara, Turkey*
¹²⁵*Bogazici University, Istanbul, Turkey*
¹²⁶*Istanbul Technical University, Istanbul, Turkey*
¹²⁷*Istanbul University, Istanbul, Turkey*
¹²⁸*Institute for Scintillation Materials of National Academy of Science of Ukraine, Kharkiv, Ukraine*
¹²⁹*National Science Centre, Kharkiv Institute of Physics and Technology, Kharkiv, Ukraine*
¹³⁰*University of Bristol, Bristol, United Kingdom*
¹³¹*Rutherford Appleton Laboratory, Didcot, United Kingdom*
¹³²*Imperial College, London, United Kingdom*
¹³³*Brunel University, Uxbridge, United Kingdom*
¹³⁴*Baylor University, Waco, Texas, USA*
¹³⁵*Catholic University of America, Washington, DC, USA*
¹³⁶*The University of Alabama, Tuscaloosa, Alabama, USA*
¹³⁷*Boston University, Boston, Massachusetts, USA*
¹³⁸*Brown University, Providence, Rhode Island, USA*
¹³⁹*University of California, Davis, Davis, California, USA*
¹⁴⁰*University of California, Los Angeles, California, USA*
¹⁴¹*University of California, Riverside, Riverside, California, USA*
¹⁴²*University of California, San Diego, La Jolla, California, USA*
¹⁴³*University of California, Santa Barbara—Department of Physics, Santa Barbara, California, USA*
¹⁴⁴*California Institute of Technology, Pasadena, California, USA*
¹⁴⁵*Carnegie Mellon University, Pittsburgh, Pennsylvania, USA*
¹⁴⁶*University of Colorado Boulder, Boulder, Colorado, USA*
¹⁴⁷*Cornell University, Ithaca, New York, USA*
¹⁴⁸*Fermi National Accelerator Laboratory, Batavia, Illinois, USA*
¹⁴⁹*University of Florida, Gainesville, Florida, USA*
¹⁵⁰*Florida State University, Tallahassee, Florida, USA*
¹⁵¹*Florida Institute of Technology, Melbourne, Florida, USA*
¹⁵²*University of Illinois at Chicago (UIC), Chicago, Illinois, USA*
¹⁵³*The University of Iowa, Iowa City, Iowa, USA*

- ¹⁵⁴*Johns Hopkins University, Baltimore, Maryland, USA*
¹⁵⁵*The University of Kansas, Lawrence, Kansas, USA*
¹⁵⁶*Kansas State University, Manhattan, Kansas, USA*
¹⁵⁷*Lawrence Livermore National Laboratory, Livermore, California, USA*
¹⁵⁸*University of Maryland, College Park, Maryland, USA*
¹⁵⁹*Massachusetts Institute of Technology, Cambridge, Massachusetts, USA*
¹⁶⁰*University of Minnesota, Minneapolis, Minnesota, USA*
¹⁶¹*University of Nebraska-Lincoln, Lincoln, Nebraska, USA*
¹⁶²*State University of New York at Buffalo, Buffalo, New York, USA*
¹⁶³*Northeastern University, Boston, Massachusetts, USA*
¹⁶⁴*Northwestern University, Evanston, Illinois, USA*
¹⁶⁵*University of Notre Dame, Notre Dame, Indiana, USA*
¹⁶⁶*The Ohio State University, Columbus, Ohio, USA*
¹⁶⁷*Princeton University, Princeton, New Jersey, USA*
¹⁶⁸*University of Puerto Rico, Mayaguez, Puerto Rico, USA*
¹⁶⁹*Purdue University, West Lafayette, Indiana, USA*
¹⁷⁰*Purdue University Northwest, Hammond, Indiana, USA*
¹⁷¹*Rice University, Houston, Texas, USA*
¹⁷²*University of Rochester, Rochester, New York, USA*
¹⁷³*Rutgers, The State University of New Jersey, Piscataway, New Jersey, USA*
¹⁷⁴*University of Tennessee, Knoxville, Tennessee, USA*
¹⁷⁵*Texas A&M University, College Station, Texas, USA*
¹⁷⁶*Texas Tech University, Lubbock, Texas, USA*
¹⁷⁷*Vanderbilt University, Nashville, Tennessee, USA*
¹⁷⁸*University of Virginia, Charlottesville, Virginia, USA*
¹⁷⁹*Wayne State University, Detroit, Michigan, USA*
¹⁸⁰*University of Wisconsin—Madison, Madison, Wisconsin, USA*
¹⁸¹*An institute or international laboratory covered by a cooperation agreement with CERN*

^aDeceased.

^bAlso at Yerevan State University, Yerevan, Armenia.

^cAlso at TU Wien, Vienna, Austria.

^dAlso at Institute of Basic and Applied Sciences, Faculty of Engineering, Arab Academy for Science, Technology and Maritime Transport, Alexandria, Egypt.

^eAlso at Université Libre de Bruxelles, Bruxelles, Belgium.

^fAlso at Universidade Estadual de Campinas, Campinas, Brazil.

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

^hAlso at The University of the State of Amazonas, Manaus, Brazil.

ⁱAlso at University of Chinese Academy of Sciences, Beijing, China.

^jAlso at UFMS, Nova Andradina, Brazil.

^kAlso at The University of Iowa, Iowa City, Iowa, USA.

^lAlso at Nanjing Normal University Department of Physics, Nanjing, China.

^mAlso at University of Chinese Academy of Sciences, Beijing, China.

ⁿAlso at Another institute or international laboratory covered by a cooperation agreement with CERN.

^oAlso at Cairo University, Cairo, Egypt.

^pAlso at British University in Egypt, Cairo, Egypt.

^qAlso at Suez University, Suez, Egypt.

^rAlso at Purdue University, West Lafayette, Indiana, USA.

^sAlso at Université de Haute Alsace, Mulhouse, France.

^tAlso at Ilia State University, Tbilisi, Georgia.

^uAlso at Erzincan Binali Yildirim University, Erzincan, Turkey.

^vAlso at CERN, European Organization for Nuclear Research, Geneva, Switzerland.

^wAlso at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany.

^xAlso at University of Hamburg, Hamburg, Germany.

^yAlso at Isfahan University of Technology, Isfahan, Iran.

^zAlso at Brandenburg University of Technology, Cottbus, Germany.

^{aa}Also at Forschungszentrum Jülich, Juelich, Germany.

^{bb}Also at Physics Department, Faculty of Science, Assiut University, Assiut, Egypt.

^{cc}Also at Karoly Robert Campus, MATE Institute of Technology, Gyongyos, Hungary.

^{dd}Also at Institute of Physics, University of Debrecen, Debrecen, Hungary.

- ^{ce} Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary.
- ^{ff} Also at MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary.
- ^{eg} Also at Wigner Research Centre for Physics, Budapest, Hungary.
- ^{hh} Also at Punjab Agricultural University, Ludhiana, India.
- ⁱⁱ Also at Shoolini University, Solan, India.
- ^{jj} Also at University of Hyderabad, Hyderabad, India.
- ^{kk} Also at University of Visva-Bharati, Santiniketan, India.
- ^{ll} Also at Indian Institute of Technology (IIT), Mumbai, India.
- ^{mm} Also at IIT Bhubaneswar, Bhubaneswar, India.
- ⁿⁿ Also at Institute of Physics, Bhubaneswar, India.
- ^{oo} Also at Deutsches Elektronen-Synchrotron, Hamburg, Germany.
- ^{pp} Also at Sharif University of Technology, Tehran, Iran.
- ^{qq} Also at Department of Physics, University of Science and Technology of Mazandaran, Behshahr, Iran.
- ^{rr} Also at Helwan University, Cairo, Egypt.
- ^{ss} Also at Italian National Agency for New Technologies, Energy and Sustainable Economic Development, Bologna, Italy.
- ^{tt} Also at Centro Siciliano di Fisica Nucleare e di Struttura Della Materia, Catania, Italy.
- ^{uu} Also at Università di Napoli 'Federico II', Napoli, Italy.
- ^{vv} Also at Consiglio Nazionale delle Ricerche—Istituto Officina dei Materiali, Perugia, Italy.
- ^{ww} Also at Consejo Nacional de Ciencia y Tecnología, Mexico City, Mexico.
- ^{xx} Also at IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France.
- ^{yy} Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia.
- ^{zz} Also at Trincomalee Campus, Eastern University, Sri Lanka, Nilaveli, Sri Lanka.
- ^{aaa} Also at INFN Sezione di Pavia, Università di Pavia, Pavia, Italy.
- ^{bbb} Also at National and Kapodistrian University of Athens, Athens, Greece.
- ^{ccc} Also at Ecole Polytechnique Fédérale Lausanne, Lausanne, Switzerland.
- ^{ddd} Also at Universität Zürich, Zurich, Switzerland.
- ^{eee} Also at Stefan Meyer Institute for Subatomic Physics, Vienna, Austria.
- ^{fff} Also at Laboratoire d'Annecy-le-Vieux de Physique des Particules, IN2P3-CNRS, Annecy-le-Vieux, France.
- ^{ggg} Also at Şirnak University, Şirnak, Turkey.
- ^{hhh} Also at Near East University, Research Center of Experimental Health Science, Mersin, Turkey.
- ⁱⁱⁱ Also at Konya Technical University, Konya, Turkey.
- ^{jjj} Also at Izmir Bakircay University, Izmir, Turkey.
- ^{kkk} Also at Adiyaman University, Adiyaman, Turkey.
- ^{lll} Also at Ozyegin University, Istanbul, Turkey.
- ^{mmm} Also at Necmettin Erbakan University, Konya, Turkey.
- ⁿⁿⁿ Also at Bozok Universitetesi Rektörlüğü, Yozgat, Turkey.
- ^{ooo} Also at Marmara University, Istanbul, Turkey.
- ^{ppp} Also at Milli Savunma University, Istanbul, Turkey.
- ^{qqq} Also at Kafkas University, Kars, Turkey.
- ^{rrr} Also at Istanbul Bilgi University, Istanbul, Turkey.
- ^{sss} Also at Hacettepe University, Ankara, Turkey.
- ^{ttt} Also at Istanbul University—Cerrahpasa, Faculty of Engineering, Istanbul, Turkey.
- ^{uuu} Also at Vrije Universiteit Brussel, Brussel, Belgium.
- ^{vvv} Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom.
- ^{www} Also at IPPP Durham University, Durham, United Kingdom.
- ^{xxx} Also at Monash University, Faculty of Science, Clayton, Australia.
- ^{yyy} Also at Università di Torino, Torino, Italy.
- ^{zzz} Also at Bethel University, St. Paul, Minnesota, USA.
- ^{aaaa} Also at Karamanoğlu Mehmetbey University, Karaman, Turkey.
- ^{bbbb} Also at California Institute of Technology, Pasadena, California, USA.
- ^{cccc} Also at Ain Shams University, Cairo, Egypt.
- ^{dddd} Also at Bingol University, Bingol, Turkey.
- ^{eeee} Also at Georgian Technical University, Tbilisi, Georgia.
- ^{fff} Also at Sinop University, Sinop, Turkey.
- ^{ggg} Also at Erciyes University, Kayseri, Turkey.
- ^{hhh} Also at Institute of Modern Physics and Key Laboratory of Nuclear Physics and Ion-beam Application (MOE)—Fudan University, Shanghai, China.
- ⁱⁱⁱ Also at Texas A&M University at Qatar, Doha, Qatar.
- ^{jjj} Also at Kyungpook National University, Daegu, Korea.
- ^{kkk} Also at Istanbul University, Istanbul, Turkey.

^{llll}Also at Yerevan Physics Institute, Yerevan, Armenia.

^{mmmm}Also at University of Florida, Gainesville, Florida, USA.

ⁿⁿⁿⁿAlso at Imperial College, London, United Kingdom.

^{oooo}Also at University of Rochester, Rochester, New York, USA.

^{pppp}Also at Baylor University, Waco, Texas, USA.

^{qqqq}Also at INFN Sezione di Torino, Università di Torino, Torino, Italy, Università del Piemonte Orientale, Novara, Italy.

^{rrrr}Also at Institute of Nuclear Physics of the Uzbekistan Academy of Sciences, Tashkent, Uzbekistan.