

Measurement of the Λ_b polarization and angular parameters in $\Lambda_b \rightarrow J/\psi\Lambda$ decays from pp collisions at $\sqrt{s}=7$ and 8 TeV

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

 (Received 13 February 2018; published 17 April 2018)

An analysis of the bottom baryon decay $\Lambda_b \rightarrow J/\psi(\rightarrow \mu^+\mu^-)\Lambda(\rightarrow p\pi^-)$ is performed to measure the Λ_b polarization and three angular parameters in data from pp collisions at $\sqrt{s}=7$ and 8 TeV, collected by the CMS experiment at the Large Hadron Collider. The Λ_b polarization is measured to be $0.00 \pm 0.06(\text{stat}) \pm 0.06(\text{syst})$ and the parity-violating asymmetry parameter is determined to be $0.14 \pm 0.14(\text{stat}) \pm 0.10(\text{syst})$. The measurements are compared to various theoretical predictions, including those from perturbative quantum chromodynamics.

DOI: 10.1103/PhysRevD.97.072010

I. INTRODUCTION

The decay $\Lambda_b \rightarrow J/\psi\Lambda$ is a rich source of information about the effect of strong interactions in hadronic decays. For this particular decay, perturbative quantum chromodynamics can be applied and therefore a systematic approach can be taken to study its characteristics. Several techniques [1–10] are used to study and calculate the decay amplitudes and the effect of the b quark polarization on this decay. The most interesting parameters that can be measured are the polarization, P , and the parity-violating decay asymmetry of the Λ_b , which is called α_b in some papers and is equal to $-\alpha_1$ in the notation used in this analysis. The LHCb and ATLAS experiments have reported measurements on this decay [11,12]. The LHCb Collaboration measured the Λ_b polarization and the decay amplitudes, while ATLAS assumed a Λ_b polarization of zero and measured the amplitudes. In this paper, a measurement of the Λ_b transverse polarization is presented using the decay $\Lambda_b \rightarrow J/\psi\Lambda$, with $J/\psi \rightarrow \mu^+\mu^-$ and $\Lambda \rightarrow p\pi^-$. Charge-conjugate modes are implied throughout this paper unless otherwise stated. The Λ_b baryons used in this measurement come from both direct production in pp collisions and decays of heavier b baryons [1,13–16]. The data were collected with the CMS detector in pp collisions at center-of-mass energies of 7 and 8 TeV, corresponding to integrated luminosities of 5.2 and 19.8 fb⁻¹, respectively.

II. ANGULAR DISTRIBUTION

The $\Lambda_b \rightarrow J/\psi\Lambda$ decay into the $\mu^+\mu^- p\pi^-$ final state is illustrated in Fig. 1. In pp collisions, we define the polarization of the Λ_b as the mean value of the Λ_b spin along the unit vector:

$$\hat{n} = \frac{\vec{p}_{\text{beam}} \times \vec{p}_{\Lambda_b}}{|\vec{p}_{\text{beam}} \times \vec{p}_{\Lambda_b}|}, \quad (1)$$

normal to its production plane, where \vec{p}_{beam} is in the direction of the counterclockwise proton beam direction [17], and \vec{p}_{Λ_b} is the Λ_b momentum. The decay is described by four complex helicity amplitudes $T_{\lambda_1\lambda_2}$, with $\lambda_1 = \pm 1/2$ and $\lambda_2 = \pm 1, 0$ referring to the helicities of the Λ and J/ψ particles, respectively. The angular distribution is a function of five decay angles ($\theta_\Lambda, \theta_p, \theta_\mu, \varphi_p, \varphi_\mu$) and has the form [8]

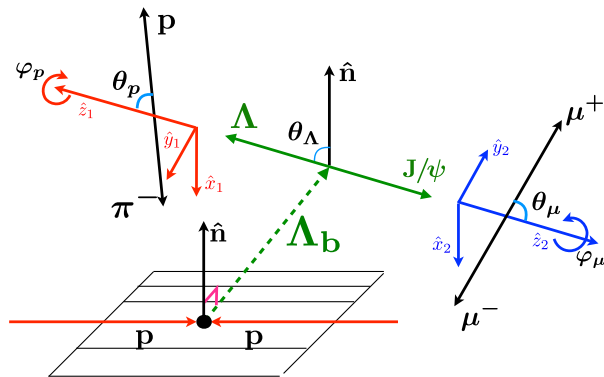


FIG. 1. Definition of the angles used to describe the $\Lambda_b \rightarrow J/\psi\Lambda$ decay into the $\mu^+\mu^- p\pi^-$ final state as explained in the text.

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

Published by the American Physical Society under the terms of the Creative Commons Attribution 4.0 International license. Further distribution of this work must maintain attribution to the author(s) and the published article's title, journal citation, and DOI. Funded by SCOAP³.

$$\begin{aligned} & \frac{d^5\Gamma}{d\cos\theta_\Lambda d\Omega_p d\Omega_\mu}(\theta_\Lambda, \theta_p, \theta_\mu, \varphi_p, \varphi_\mu) \\ &= \frac{1}{(4\pi)^3} \sum_{i=1}^{20} u_i(T_{\lambda_1\lambda_2}) v_i(P, \alpha_\Lambda) w_i(\theta_\Lambda, \theta_p, \theta_\mu, \varphi_p, \varphi_\mu), \end{aligned} \quad (2)$$

where w_i are trigonometric functions, u_i are bilinear combinations of the helicity amplitudes $T_{\lambda_1\lambda_2}$, and v_i stands for 1, P , α_Λ , or $P\alpha_\Lambda$; P is the Λ_b polarization and α_Λ is the asymmetry parameter in the decay $\Lambda \rightarrow p\pi^-$. The angle θ_Λ is the polar angle of the Λ momentum relative to \hat{n} in the Λ_b rest frame; θ_p and φ_p are the polar and azimuthal angles of the proton, respectively, defined with respect to the axes $\hat{z}_1 = \vec{p}_\Lambda/|\vec{p}_\Lambda|$ and $\hat{y}_1 = (\hat{n} \times \vec{p}_\Lambda)/|\hat{n} \times \vec{p}_\Lambda|$ in the rest frame of the Λ ; and the angles θ_μ and φ_μ are the polar and azimuthal angles, respectively, of the positively charged muon, defined with respect to the axes $\hat{z}_2 = \vec{p}_{J/\psi}/|\vec{p}_{J/\psi}|$ and $\hat{y}_2 = (\hat{n} \times \vec{p}_{J/\psi})/|\hat{n} \times \vec{p}_{J/\psi}|$ in the J/ψ rest frame. Here, \vec{p}_Λ and $\vec{p}_{J/\psi}$ are the momenta of the Λ and J/ψ , respectively, and $d\Omega_p = d(\cos\theta_p)d\varphi_p$ and $d\Omega_\mu = d(\cos\theta_\mu)d\varphi_\mu$ are differential solid angles. Assuming uniform detector acceptance over the azimuthal angles φ_p and φ_μ , the angular distribution can be simplified through an integration over these two angles:

$$\begin{aligned} & \frac{d^3\Gamma}{d\cos\theta_\Lambda d\cos\theta_p d\cos\theta_\mu}(\theta_\Lambda, \theta_p, \theta_\mu) \\ &= \int_{-\pi}^{\pi} \int_{-\pi}^{\pi} \frac{d^5\Gamma}{d\cos\theta_\Lambda d\Omega_p d\Omega_\mu}(\theta_\Lambda, \theta_p, \theta_\mu, \varphi_p, \varphi_\mu) d\varphi_p d\varphi_\mu \\ &\sim \sum_{i=1}^8 u_i(|T_{\lambda_1\lambda_2}|^2) v_i(P, \alpha_\Lambda) w_i(\theta_\Lambda, \theta_p, \theta_\mu). \end{aligned} \quad (3)$$

The eight functional forms of u_i , v_i , and w_i are listed in Table I. The u_i factors are written in terms of the three angular decay parameters α_1 , α_2 , and γ_0 proposed in Ref. [8], and the constant 1, which themselves can be written in terms of the $T_{\lambda_1\lambda_2}$ amplitudes as

$$\begin{aligned} 1 &= |T_{++}|^2 + |T_{+0}|^2 + |T_{-0}|^2 + |T_{--}|^2, \\ \alpha_1 &= |T_{++}|^2 - |T_{+0}|^2 + |T_{-0}|^2 - |T_{--}|^2, \\ \alpha_2 &= |T_{++}|^2 + |T_{+0}|^2 - |T_{-0}|^2 - |T_{--}|^2, \\ \gamma_0 &= |T_{++}|^2 - 2|T_{+0}|^2 - 2|T_{-0}|^2 + |T_{--}|^2, \end{aligned} \quad (4)$$

where α_1 is the asymmetry parameter for the decay $\Lambda_b \rightarrow J/\psi\Lambda$, α_2 represents the longitudinal polarization of the Λ , and γ_0 is a parameter that depends on the longitudinal and transverse polarizations of the J/ψ [9]. The CP invariance of Eq. (3) implies that the parameters for Λ_b and $\bar{\Lambda}_b$ are related as follows:

TABLE I. Functions used in Eq. (3) to describe the angular distribution in the decay $\Lambda_b \rightarrow J/\psi\Lambda$, with $J/\psi \rightarrow \mu^+\mu^-$ and $\Lambda \rightarrow p\pi^-$.

i	u_i	v_i	w_i
1	1	1	1
2	α_2	α_Λ	$\cos\theta_p$
3	$-\alpha_1$	P	$\cos\theta_\Lambda$
4	$-(1+2\gamma_0)/3$	$\alpha_\Lambda P$	$\cos\theta_\Lambda \cos\theta_p$
5	$\gamma_0/2$	1	$(3\cos^2\theta_\mu - 1)/2$
6	$(3\alpha_1 - \alpha_2)/4$	α_Λ	$\cos\theta_p(3\cos^2\theta_\mu - 1)/2$
7	$(\alpha_1 - 3\alpha_2)/4$	P	$\cos\theta_\Lambda(3\cos^2\theta_\mu - 1)/2$
8	$(\gamma_0 - 4)/6$	$\alpha_\Lambda P$	$\cos\theta_\Lambda \cos\theta_p(3\cos^2\theta_\mu - 1)/2$

$$\bar{P} = -P, \quad \bar{\alpha}_1 = -\alpha_1, \quad \bar{\alpha}_2 = -\alpha_2, \quad \bar{\gamma}_0 = \gamma_0. \quad (5)$$

In addition, CP conservation in $\Lambda \rightarrow p\pi^-$ decays implies that $\bar{\alpha}_\Lambda = -\alpha_\Lambda$ [18]. In this analysis, the four parameters ($P, \alpha_1, \alpha_2, \gamma_0$) are extracted from an analysis of the angular distribution given in Eq. (3), where α_Λ is fixed to its world-average value of 0.642 ± 0.013 [18].

III. THE CMS DETECTOR

The CMS detector is used to study a wide range of phenomena produced in high-energy collisions, with its central feature being a superconducting solenoid of 6m internal diameter, providing a magnetic field of 3.8 T. A silicon pixel and strip tracker, a lead tungstate scintillating crystal electromagnetic calorimeter, and a brass and scintillator sampling hadron calorimeter, including a central barrel and endcap detectors, are located within the magnetic volume.

The silicon tracker detects charged particles within the pseudorapidity range $|\eta| < 2.5$. It consists of 1440 silicon pixel and 15 148 silicon strip detector modules. For non-isolated particles with transverse momentum of $1 < p_T < 10$ GeV and $|\eta| < 1.4$, the track resolutions are typically 1.5% in p_T and 25–90 (45–150) μm in the transverse (longitudinal) impact parameter [19]. Muons are detected in gas-ionization chambers within the pseudorapidity range $|\eta| < 2.4$, with detection planes made using three technologies: drift tubes, cathode strip chambers, and resistive plate chambers [20]. The global event reconstruction (also called particle-flow event reconstruction [21]) consists of reconstructing and identifying each individual particle with an optimized combination of all subdetector information. In this process, muons are identified as a track in the silicon tracker consistent with either a track or several hits in the muon system, associated with an energy deficit in the calorimeters.

Events of interest are selected using a two-tiered trigger system [22]. 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 time interval of less than 4 μ s. The second level, known as the high-level trigger (HLT), 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.

A more detailed description of the CMS detector, a definition of the coordinate system used and the relevant kinematic variables, can be found in Ref. [17].

IV. DATA AND SIMULATED EVENTS

We use data collected with a trigger designed for events containing a J/ψ meson decaying to two muons that form a displaced vertex relative to the mean pp collision point (beamspot). The requirement on the displacement does not affect the angular distributions of the reconstructed Λ_b decay products. The dimuon trigger configurations were changed during the data taking at different center-of-mass energies, with increasingly stringent requirements to maintain an acceptable trigger rate as the instantaneous luminosity increased. The requirements of the different trigger versions are as follows: the J/ψ candidates are selected in the invariant mass window 2.5–4.0 GeV and 2.9–3.3 GeV depending on the version; the angle (β) between the reconstructed momentum vector of the dimuon system and the vector pointing from the beamspot position to the dimuon vertex must have a value of $\cos\beta > 0.9$; the distance between the beamspot and the dimuon vertex in the transverse plane must have a value that is at least a factor of 3 larger than its uncertainty (standard deviation or SD); the muon pair must satisfy $p_T^{\mu\mu} > 6.5$ or 6.9 GeV in the different versions; the χ^2 probability of the fit of the two muons to a common vertex must exceed 0.05, 0.10, or 0.15 from the earliest to the latest version; each muon must be in $|\eta(\mu)| < 2.2$ and have $p_T^\mu > 3.5$ or 4 GeV; and the distance of closest approach of each muon to the common vertex in the transverse plane must be less than 0.5 cm.

Simulated events of the signal decay are used to study the effects of detector acceptance and selection on the reconstructed angular distributions. The events are generated using PYTHIA 6.4[23] for production and hadronization, and EVTGEN [24] is used to describe the b and c hadron decays. The generated events are passed through the full CMS detector simulation based on GEANT4 [25]. The simulated event samples are generated to reproduce $\sqrt{s} = 7$ and 8 TeV data-taking conditions, where additional simulation of pp interactions in the same or nearby beam crossings and the impact of the HLT are included. Simulated events are reconstructed and selected using the same algorithms and requirements as used for data.

V. RECONSTRUCTION AND EVENT SELECTION

The offline selection requires pairs of oppositely charged muons originating from a common vertex to form the J/ψ

candidates. The standard CMS muon reconstruction procedure [20] is used to identify the muons. Since the trigger changed slightly over the different data-taking periods, the offline selection is required to be more restrictive than the most-stringent trigger, and is summarized as follows: (i) each muon must have $p_T^\mu > 4$ GeV and the dimuon transverse momentum must satisfy $p_T^{\mu\mu} > 8$ GeV; (ii) the χ^2 probability must exceed 0.15; and (iii) the dimuon invariant mass must lie within ± 150 MeV of the world-average J/ψ mass [18]. Additional requirements are the same as the trigger selection and, to reduce background, the J/ψ candidates must satisfy $\cos\beta > 0.99$.

The Λ candidates are constructed from pairs of oppositely charged tracks that have a successful fit to a common vertex. Since the default CMS algorithms cannot distinguish between pions and protons, the higher- and lower-momentum tracks are assumed to have the proton and pion masses [18], respectively. The selections used for Λ and K_S^0 particles are detailed in Ref. [26]. They are optimized to reduce background using the following additional requirements: (i) each track is required to have at least 6 hits in the silicon tracker and a χ^2 track fit per degree of freedom < 7 ; (ii) the tracks coming from the Λ decay are required to have $p_T^\pi > 0.3$ GeV, $p_T^p > 1.0$ GeV; (iii) the transverse impact parameter of the tracks relative to the beamspot is required to be greater than 3 SD; (iv) the probability of the two-track vertex fit must exceed 2%; (v) the transverse separation of the two-track vertex from the beamspot is required to be larger than 15 SD; (vi) the invariant mass of the Λ candidate is selected to lie within ± 9 MeV of the world-average value [18] and satisfy $p_T^{p\pi} > 1.3$ GeV; and (vii) to reduce the contamination of $K_S^0 \rightarrow \pi^+\pi^-$ decays, events are removed if their invariant mass falls within ± 20 MeV of the K_S^0 mass when the proton candidate is given the charged pion mass.

The Λ_b candidates are fitted to a common vertex by combining the J/ψ and Λ candidates, with the respective mass constraints to the world-average values of the J/ψ and Λ masses [18]. The selection of Λ_b candidates is optimized to reduce background with the additional requirements: $p_T^{J/\psi\Lambda} > 10$ GeV, a χ^2 probability of the fit to the $J/\psi\Lambda$ vertex $> 3\%$, and the $J/\psi\Lambda$ invariant mass $5.40 < m_{J/\psi\Lambda} < 5.84$ GeV.

To extract the number of signal and background events and to define the signal and sidebands regions, unbinned maximum likelihood fits to the reconstructed invariant mass ($m_{J/\psi\Lambda}$) distributions are performed, using separate data sets of the Λ_b and $\bar{\Lambda}_b$ candidates at $\sqrt{s} = 7$ and 8 TeV. The signal shape is modeled by two Gaussian functions with different SDs, σ_1 and σ_2 , but common mean $\mu_{J/\psi\Lambda}$, and the background by a first-order polynomial. We define in the four data sets the signal region as $\mu_{J/\psi\Lambda} \pm 16$ MeV, the lower sideband region as [5.46, 5.54] GeV, and the upper sideband region as

[5.70, 5.78] GeV. From the fits the Λ_b yields are 981 ± 39 and 2072 ± 55 signal events, and the $\bar{\Lambda}_b$ yields are 916 ± 40 and 1974 ± 53 signal events at $\sqrt{s} = 7$ and 8 TeV, respectively.

VI. MEASUREMENT OF THE POLARIZATION AND ANGULAR PARAMETERS

The analysis extracts the Λ_b polarization, P , and the angular decay parameters α_1 , α_2 , and γ_0 . The results are obtained from an unbinned maximum likelihood fit to the $J/\psi\Lambda$ invariant mass distribution and the three angular variables $\Theta_3 = (\cos\theta_\Lambda, \cos\theta_p, \cos\theta_\mu)$, using the extended likelihood function:

$$L = \exp(-N_{\text{sig}} - N_{\text{bkg}}) \prod_{i=1}^N [N_{\text{sig}} PDF_{\text{sig}} + N_{\text{bkg}} PDF_{\text{bkg}}], \quad (6)$$

where N is the total number of events, N_{sig} and N_{bkg} are the yields of signal and background events, respectively, determined from the fit in Sec. V, and PDF_{sig} and PDF_{bkg} represent the probability density functions (PDFs) for the signal and background, respectively. The PDF_{sig} has the form

$$PDF_{\text{sig}} = F_{\text{sig}}(\Theta_3) \epsilon(\Theta_3) G(m_{J/\psi\Lambda}), \quad (7)$$

where F_{sig} represents the theoretical angular distribution given by Eq. (3) and G is the sum of two Gaussian functions used to model the $J/\psi\Lambda$ invariant mass distribution, as mentioned in Sec. V. The effect of the detector on the angular distribution is taken into account by the factor ϵ that represents the efficiency as a function of the angles.

To estimate the angular efficiency, simulated events of $\Lambda_b \rightarrow J/\psi\Lambda$ decays are generated with uniform distributions in $\cos\theta_\Lambda$, $\cos\theta_p$, and $\cos\theta_\mu$. After full detector simulation, reconstruction, and implementation of the final

selection requirements, the slight differences between the simulated events and the background-subtracted data are minimized through a weighting procedure where weights are assigned to the simulated events to match the data. The weights are computed with an iterative process in which, for each iteration, the histograms of a selection variable in background-subtracted data and simulated events are used to calculate the ratio bin by bin (weight) with its propagated statistical uncertainty. The final weight per event is the product of the weights in each iteration. The efficiency distributions as a function of the variables are fit with a product of Chebyshev polynomials, where the coefficients are obtained for Λ_b and $\bar{\Lambda}_b$ at $\sqrt{s} = 7$ and 8 TeV in separate likelihood fits. The simulated efficiency distributions and the results of these fits are shown in Fig. 2 for the Λ_b candidates at $\sqrt{s} = 8$ TeV.

The background PDF_{bkg} is given by the product of a first-order polynomial $\mathcal{P}(m_{J/\psi\Lambda})$ for the invariant mass and an angular distribution function $F_{\text{bkg}}(\Theta_3)$:

$$PDF_{\text{bkg}} = \mathcal{P}(m_{J/\psi\Lambda}) F_{\text{bkg}}(\Theta_3). \quad (8)$$

The background angular distributions $F_{\text{bkg}}(\Theta_3)$ are estimated using events from the $m_{J/\psi\Lambda}$ invariant mass sidebands. They are modeled using Chebyshev polynomials for $\cos\theta_\Lambda$ and $\cos\theta_p$, and a product of two complementary error functions for $\cos\theta_\mu$, as shown in Fig. 3 for Λ_b candidates at $\sqrt{s} = 8$ TeV.

The complete likelihood function in Eq. (6) is maximized by fitting simultaneously the four data sets for Λ_b and $\bar{\Lambda}_b$ at $\sqrt{s} = 7$ and 8 TeV, allowing for the extraction of the common parameters P , α_1 , α_2 , and γ_0 . The simultaneous fit is performed in the enriched signal mass range within 3.5 SDs of the mean Λ_b mass. This range contains more than 99.9% of the signal events, and significantly reduces the number of background events. As a result, the fit is less sensitive to the modeling discussed above. The fit parameters for the background and efficiency distributions

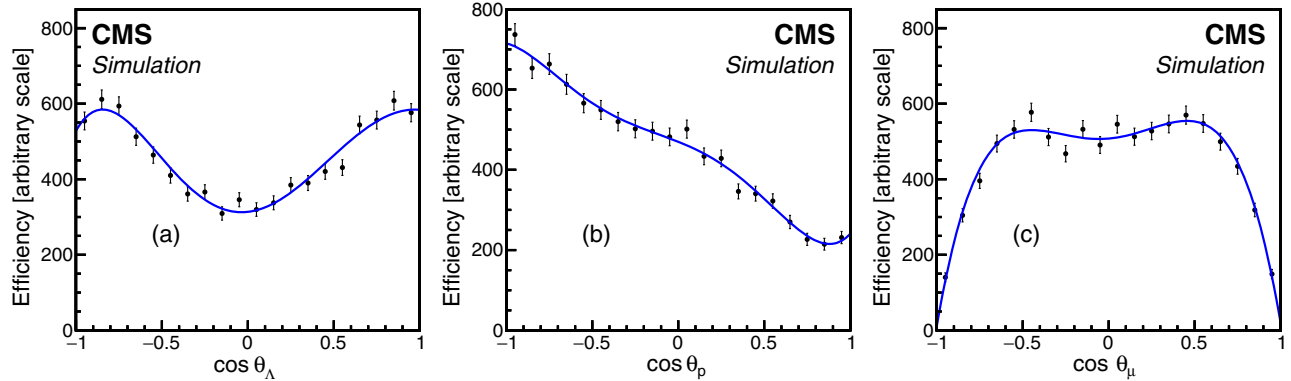


FIG. 2. The efficiencies as a function of (a) $\cos\theta_\Lambda$, (b) $\cos\theta_p$, and (c) $\cos\theta_\mu$ obtained from simulated $\Lambda_b \rightarrow J/\psi\Lambda$ decays at $\sqrt{s} = 8$ TeV. The vertical bars on the points are the statistical uncertainties in the simulated data, and the lines show the projections of a 3D fit to the distributions using Chebyshev polynomials. The scales of the vertical axes are arbitrary.

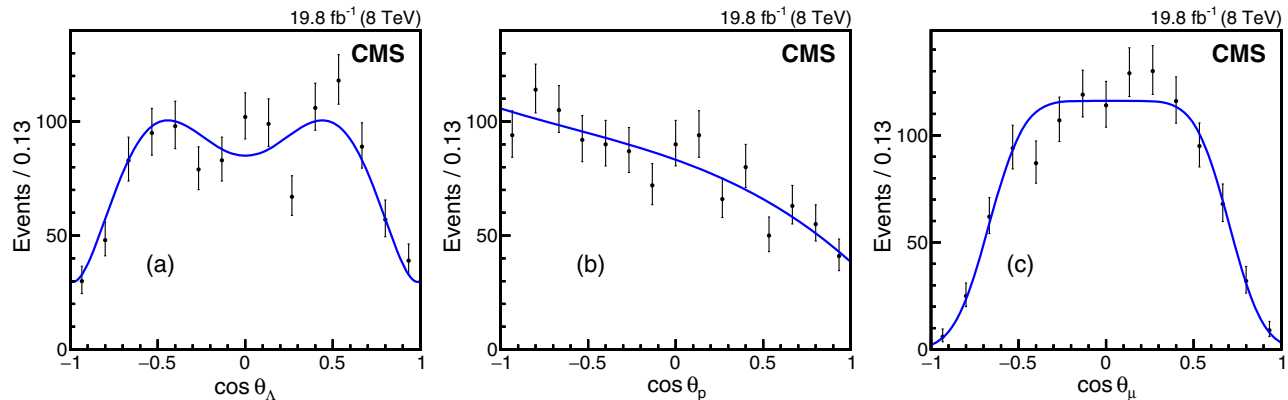


FIG. 3. The background angular distributions of (a) $\cos \theta_\Lambda$, (b) $\cos \theta_p$, and (c) $\cos \theta_\mu$ are shown, as obtained from the sidebands in the $J/\psi\Lambda$ invariant mass distribution at $\sqrt{s} = 8$ TeV. The vertical bars on the points represent the statistical uncertainties, and the solid lines are the results of the fits to data as described in the text.

are fixed to those found in the previous fits. The signal and background mass parameters are obtained from previous fits to the mass distribution within 10 SDs, and the numbers of signal and background events are fixed to the propagated values in the signal mass region. The resulting fit values of the polarization and the three angular decay parameters are

$$P = 0.00 \pm 0.06, \quad \alpha_1 = 0.14 \pm 0.14, \\ \alpha_2 = -1.11 \pm 0.04, \quad \gamma_0 = -0.27 \pm 0.08,$$

where the uncertainties are statistical only. The correlation matrix of the fitted parameters is shown in Table II. No strong correlations are found among these parameters. Translating these values to the squares of the helicity amplitudes, the results are

$$|T_{++}|^2 = 0.05 \pm 0.04, \quad |T_{+0}|^2 = -0.10 \pm 0.04, \\ |T_{-0}|^2 = 0.51 \pm 0.03, \quad |T_{--}|^2 = 0.52 \pm 0.04,$$

where the uncertainties are statistical only. The projections of the fit are shown in Figs. 4 and 5 for Λ_b and $\bar{\Lambda}_b$, respectively, using the combined data at $\sqrt{s} = 7$ and 8 TeV.

VII. SYSTEMATIC UNCERTAINTIES

Various sources of systematic uncertainty that affect the measurement of the parameters P , α_1 , α_2 , and γ_0 are discussed below.

TABLE II. Correlation matrix for the fitted parameters.

Parameter	P	α_1	α_2	γ_0
P	1	-0.039	-0.029	0.116
α_1		1	-0.207	-0.030
α_2			1	0.285
γ_0				1

Fit bias.—The bias introduced through the fitting procedure is studied by generating 1000 pseudoexperiments using the measured parameters as inputs. The difference between the input and the mean of the fitted values is taken as the systematic uncertainty.

Asymmetry parameter α_Λ .—This parameter is varied up and down by its uncertainty and the maximum deviation in the final result for each parameter is taken as the systematic uncertainty.

Model for the background $m_{J/\psi\Lambda}$ distribution.—An exponential function is used instead of the first-order polynomial in the likelihood fit. The parameter of the exponential and the background yield are varied by their uncertainties. The fit is redone taking into account this variation on the background model for the mass, and the differences between these results and the nominal fit results are taken as the systematic uncertainty for this source.

Model for the background angular distributions.—Alternative parametrizations of the background angular distributions are used to estimate the systematic uncertainty. For $\cos \theta_\Lambda$ and $\cos \theta_\mu$ the alternative models comprise a superposition of Gaussian kernels, as implemented in RooFit RooKeysPdf [27], while for $\cos \theta_p$ the alternative model is an error function. The differences relative to the nominal results are taken as the systematic uncertainties from the modeling of the background angular distributions.

Model for the signal $m_{J/\psi\Lambda}$ distribution.—We estimate this uncertainty by changing the parameters by their uncertainties, taking into account their correlations. In each sample of Λ_b and $\bar{\Lambda}_b$ at $\sqrt{s} = 7$ and 8 TeV, we use the parameter of the signal mass model with the largest global correlation and add 1 SD to its nominal value if the correlation is positive and subtract 1 SD if the correlation is negative. The difference relative to the nominal result is quoted as a systematic uncertainty.

Angular efficiencies.—The values of the Chebyshev polynomial coefficients that model the angular dependence of the efficiencies are changed by their uncertainties. The

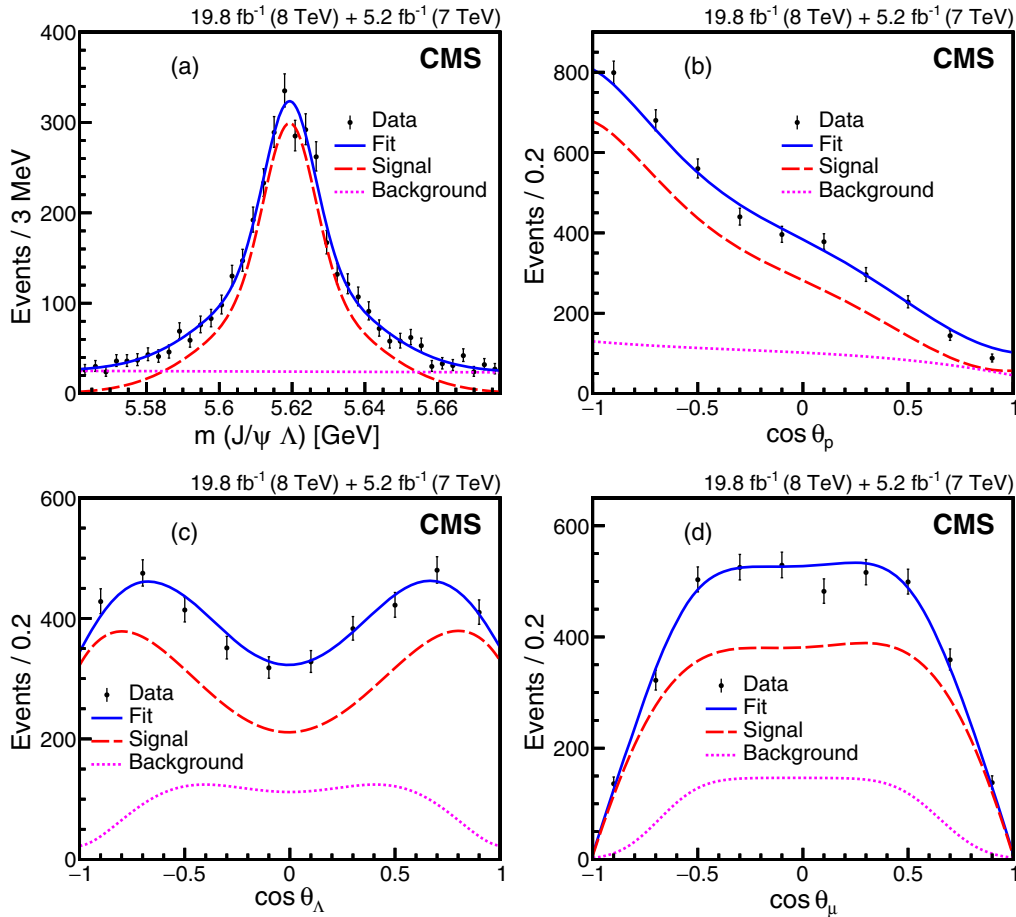


FIG. 4. Distributions in (a) $m_{J/\psi\Lambda}$, (b) $\cos\theta_p$, (c) $\cos\theta_\Lambda$, and (d) $\cos\theta_\mu$ for Λ_b candidates in the combined $\sqrt{s} = 7$ and 8 TeV data. The vertical bars on the points are the statistical uncertainties in the data, the solid line shows the result of the fit, and the dashed and dotted lines represent, respectively, the signal and background contributions from the fit.

difference relative to the nominal fitted result is taken as the systematic uncertainty.

Angular resolution.—We study the systematic uncertainty in the angular resolution of the measured observables $\cos\theta_\Lambda$, $\cos\theta_p$, and $\cos\theta_\mu$ by first determining the resolution using simulated events, then taking the difference between the generated (before detector simulation) and reconstructed (fully simulated) distributions of the cosines of the three polar angles, and fitting the resulting distributions to Gaussian functions. Using these models, we generate random numbers that are added to the three polar angles of the events at generation. The difference between the obtained parameters from the likelihood fits using the same events, with and without the added random terms, is quoted as the systematic uncertainty from the angular resolution.

Azimuthal angle efficiency.—Uniform azimuthal efficiencies are assumed throughout the analysis. Besides simplifying the measurement from a five- to a three-dimensional angular analysis, this assumption also reduces the number of angular parameters from 6 to 3. The effect of the nonuniformity in the φ_p and φ_μ efficiencies is investigated with 500 pseudoexperiments generated using the

five-dimensional angular distribution, multiplied by the polar and azimuthal efficiencies obtained from the full simulation, as well as initializing the 3 extra parameters to values away from the physical boundary. The resulting distributions are then fitted to the nominal three-dimensional angular model. Differences in the mean values of P , α_1 , α_2 , and γ_0 relative to the input values (set to the nominal results) are taken as the systematic uncertainties from the impact of the nonuniformity of the azimuthal efficiencies.

Weighting procedure.—To estimate the uncertainty from the weighting procedure, we vary each weight by its uncertainty and use this as a new weight to correct the efficiencies, then redo the fit with these new values. The differences between the results of this fit and the nominal values are taken as the systematic uncertainty in each parameter.

Reconstruction bias.—Possible unaccounted reconstruction biases are also considered. To estimate this systematic uncertainty, we use a simulated event sample with input values of the helicity amplitudes and polarization similar to those observed in data. Then, after reconstruction and selection as in data, we fit the simulated events and take

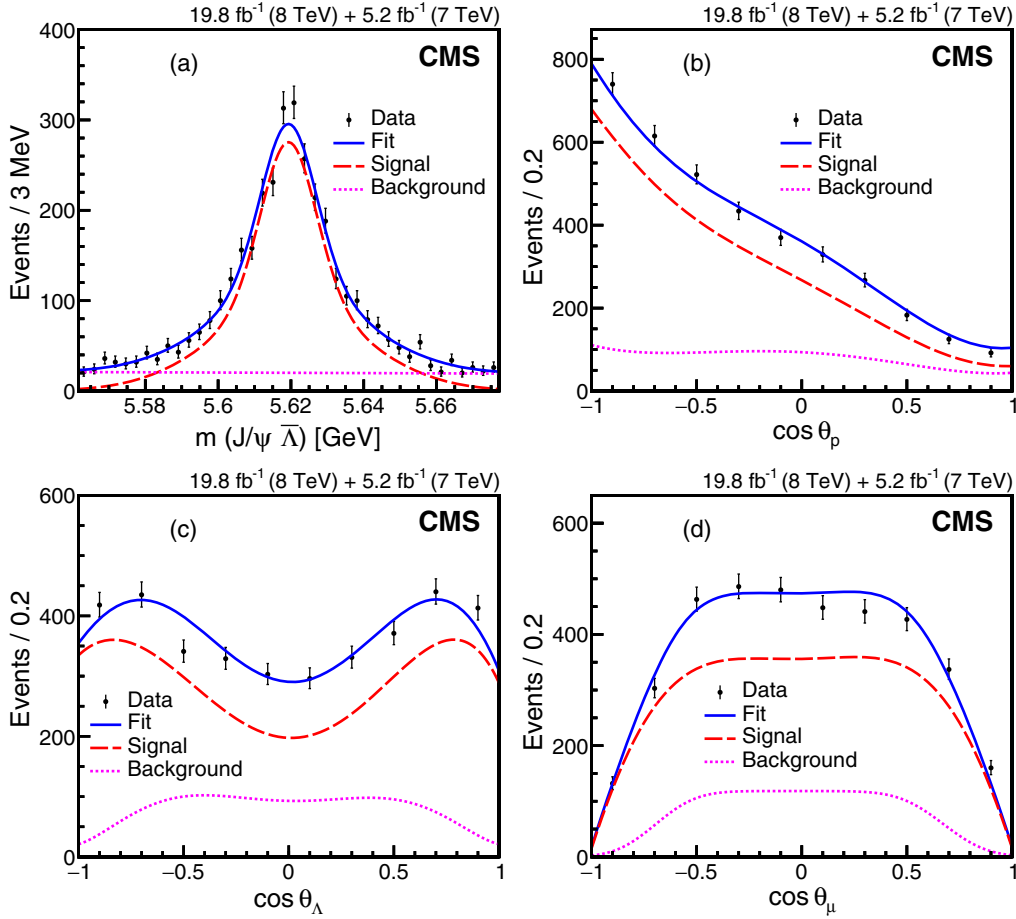


FIG. 5. Distributions in (a) $m_{J/\psi\bar{\Lambda}}$, (b) $\cos\theta_p$, (c) $\cos\theta_\Lambda$, and (d) $\cos\theta_\mu$ for $\bar{\Lambda}_b$ candidates in the combined $\sqrt{s} = 7$ and 8 TeV data. The vertical bars on the points are the statistical uncertainties in the data, the solid line shows the result of the fit, and the dashed and dotted lines represent, respectively, the signal and background contributions from the fit.

the differences between the input and fit values for every angular parameter and polarization. Since we are using the full reconstruction of the simulated events, we subtract in quadrature the systematic sources involved in the fit from those observed differences, and finally take the square root

of this subtraction as the estimate of the systematic uncertainty component due to reconstruction bias. This systematic uncertainty is by far the largest uncertainty; however, it is still smaller or comparable to the corresponding statistical uncertainty.

TABLE III. The sources and values of the systematic uncertainties in each parameter and the total uncertainty. Each value in the table should be multiplied by 10^{-2} to obtain the corresponding systematic uncertainty.

Source	$P(\times 10^{-2})$	$\alpha_1(\times 10^{-2})$	$\alpha_2(\times 10^{-2})$	$\gamma_0(\times 10^{-2})$
Fit bias	0.1	0.3	0.1	0.2
Asymmetry parameter α_Λ	0.4	0.7	2.0	0.6
Background $m_{J/\psi\Lambda}$ distribution	0.01	0.5	1.0	0.9
Background angular distribution	0.4	0.5	0.9	5.0
Signal $m_{J/\psi\Lambda}$ distribution	0.01	0.3	1.0	1.0
Angular efficiencies	0.1	0.3	3.0	1.0
Angular resolution	1.0	0.1	2.6	0.8
Azimuthal angle efficiency	0.1	1.0	0.3	0.1
Weighting procedure	0.1	1.3	0.4	2.0
Reconstruction bias	5.7	9.8	2.0	9.1
Total (quadrature sum)	5.8	10.0	5.1	11.1

The contributions from the different uncertainty sources are assumed to be independent and the total systematic uncertainty is calculated as the quadrature sum of all uncertainties. The values of the systematic uncertainties in each parameter from the individual sources and their quadrature sum are given in Table III.

VIII. SUMMARY AND CONCLUSIONS

Based on an angular analysis of about 6000 $\Lambda_b \rightarrow J/\psi(\rightarrow\mu^+\mu^-)\Lambda(\rightarrow p\pi^-)$ events collected by the CMS experiment at $\sqrt{s}=7$ and 8 TeV, a measurement of the Λ_b polarization P , the parity-violating asymmetry parameter in the Λ_b decay α_1 , the Λ longitudinal polarization α_2 , and the parameter γ_0 has been performed. The obtained values are

$$\begin{aligned} P &= 0.00 \pm 0.06(\text{stat}) \pm 0.06(\text{syst}), \\ \alpha_1 &= 0.14 \pm 0.14(\text{stat}) \pm 0.10(\text{syst}), \\ \alpha_2 &= -1.11 \pm 0.04(\text{stat}) \pm 0.05(\text{syst}), \\ \gamma_0 &= -0.27 \pm 0.08(\text{stat}) \pm 0.11(\text{syst}), \end{aligned}$$

corresponding to the squares of the helicity amplitudes

$$\begin{aligned} |T_{++}|^2 &= 0.05 \pm 0.04(\text{stat}) \pm 0.04(\text{syst}), \\ |T_{+0}|^2 &= -0.10 \pm 0.04(\text{stat}) \pm 0.04(\text{syst}), \\ |T_{-0}|^2 &= 0.51 \pm 0.03(\text{stat}) \pm 0.04(\text{syst}), \\ |T_{--}|^2 &= 0.52 \pm 0.04(\text{stat}) \pm 0.04(\text{syst}). \end{aligned}$$

The measured Λ_b polarization value given above is consistent with the LHCb measurement [11] and theoretical predictions of 0.10 [5] and 0.20 [6]. Note that in our notation, α_1 is the negative value of α_b referred to in the theory [9,10,28–31], LHCb [11], and ATLAS [12] papers. To compare with the theoretical predictions and the other measurements, we use the negative of our measured value of α_1 . The many theoretical predictions for $-\alpha_1$ include -0.2 to -0.1 from quark model techniques [9,28–31], -0.17 to -0.14 from perturbative quantum chromodynamics calculations [10], and 0.78 from heavy-quark effective theory [4,6]. The measured value is inconsistent at more than 5 standard deviations with the heavy-quark effective theory prediction, but is consistent at less than one standard deviation with the other predictions. The presented measurement of α_1 is also consistent with the measurements $0.05 \pm 0.17(\text{stat}) \pm 0.07(\text{syst})$ and $0.30 \pm 0.16(\text{stat}) \pm 0.06(\text{syst})$ by LHCb [11] and ATLAS [12], respectively, and with no parity violation at the level of one standard deviation. The measurement of α_2 , compatible with -1 , indicates that the positive-helicity states of the Λ coming from the Λ_b decay are suppressed.

ACKNOWLEDGMENTS

We congratulate our colleagues in the CERN accelerator departments for the excellent performance of the LHC and thank the technical and administrative staffs at CERN and at other CMS institutes for their contributions to the success of the CMS effort. In addition, we gratefully acknowledge the computing centers and personnel of the Worldwide LHC Computing Grid for delivering so effectively the computing infrastructure essential to our analysis. Finally, we acknowledge the enduring support for the construction and operation of the LHC and the CMS detector provided by the following funding agencies: BMWF and FWF (Austria); FNRS and FWO (Belgium); CNPq, CAPES, FAPERJ, and FAPESP (Brazil); MES (Bulgaria); CERN; CAS, MoST, and NSFC (China); COLCIENCIAS (Colombia); MSES and CSF (Croatia); RPF (Cyprus); SENESCYT (Ecuador); MoER, ERC IUT, and ERDF (Estonia); Academy of Finland, MEC, and HIP (Finland); CEA and CNRS/IN2P3 (France); BMBF, DFG, and HGF (Germany); GSRT (Greece); OTKA and NIH (Hungary); DAE and DST (India); IPM (Iran); SFI (Ireland); INFN (Italy); MSIP and NRF (Republic of Korea); LAS (Lithuania); MOE and UM (Malaysia); BUAP, CINVESTAV, CONACYT, LNS, SEP, and UASLP-FAI (Mexico); MBIE (New Zealand); PAEC (Pakistan); MSHE and NSC (Poland); FCT (Portugal); JINR (Dubna); MON, RosAtom, RAS, RFBR and RAEP (Russia); MESTD (Serbia); SEIDI, CPAN, PCTI and FEDER (Spain); Swiss Funding Agencies (Switzerland); MST (Taipei); ThEPCenter, IPST, STAR, and NSTDA (Thailand); TUBITAK and TAEK (Turkey); NASU and SFFR (Ukraine); STFC (United Kingdom); DOE and NSF (USA). Individuals have received support from the Marie-Curie program and the European Research Council and Horizon 2020 Grant, Contract No. 675440 (European Union); the Leventis Foundation; the A. P. Sloan Foundation; the Alexander von Humboldt Foundation; the Belgian Federal Science Policy Office; the Fonds pour la Formation à la Recherche dans l'Industrie et dans l'Agriculture (FRIA-Belgium); the Agentschap voor Innovatie door Wetenschap en Technologie (IWT-Belgium); the Ministry of Education, Youth and Sports (MEYS) of the Czech Republic; the Council of Science and Industrial Research, India; the HOMING PLUS program of the Foundation for Polish Science, cofinanced from European Union, Regional Development Fund, the Mobility Plus program of the Ministry of Science and Higher Education, the National Science Center (Poland), Contracts No. Harmonia 2014/14/M/ST2/00428, Opus 2014/13/B/ST2/02543, 2014/15/B/ST2/03998, and 2015/19/B/ST2/02861, Sonata-bis 2012/07/E/ST2/01406; the National Priorities Research Program by Qatar National Research Fund; the program Severo Ochoa del Principado

de Asturias; the Thalys and Aristeia programs cofinanced by EU-ESF and the Greek NSRF; the Rachadapisek Sompot Fund for Postdoctoral Fellowship, Chulalongkorn University and the Chulalongkorn

Academic into Its 2nd Century Project Advancement Project (Thailand); the Welch Foundation, Contract No. C-1845; and the Weston Havens Foundation (USA).

-
- [1] A. F. Falk and M. E. Peskin, Production, decay, and polarization of excited heavy hadrons, *Phys. Rev. D* **49**, 3320 (1994).
- [2] B. Mele and G. Altarelli, Lepton spectra as a measure of b quark polarization at LEP, *Phys. Lett. B* **299**, 345 (1993).
- [3] D. Buskulic *et al.* (ALEPH Collaboration), Measurement of Λ_b polarization in Z decays, *Phys. Lett. B* **365**, 437 (1996).
- [4] Z. J. Ajaltouni, E. Conte, and O. Leitner, An angular distribution analysis of Λ_b decays, *Nucl. Phys. A* **755**, 435 (2005).
- [5] G. Hiller, M. Knecht, F. Legger, and T. Schietinger, Photon polarization from helicity suppression in radiative decays of polarized Λ_b to spin-3/2 baryons, *Phys. Lett. B* **649**, 152 (2007).
- [6] Z. J. Ajaltouni, E. Conte, and O. Leitner, Λ_b decays into Λ -vector, *Phys. Lett. B* **614**, 165 (2005).
- [7] P. Bialas, J. G. Korner, M. Kramer, and K. Zalewski, Joint angular decay distributions in exclusive weak decays of heavy mesons and baryons, *Z. Phys. C* **57**, 115 (1993).
- [8] M. Kramer and H. Simma, Angular correlations in $\Lambda_b \rightarrow \Lambda + V$: polarization measurements, HQET and CP violation, *Nucl. Phys. B, Proc. Suppl.* **50**, 125 (1996).
- [9] T. Gutsche, M. A. Ivanov, J. G. Körner, V. E. Lyubovitskij, and P. Santorelli, Polarization effects in the cascade decay $\Lambda_b \rightarrow \Lambda(\rightarrow p\pi^-) + J/\psi(l^+l^-)$ in the covariant confined quark model, *Phys. Rev. D* **88**, 114018 (2013).
- [10] C.-H. Chou, H.-H. Shih, S.-C. Lee, and H.-n. Li, $\Lambda_b \rightarrow \Lambda J/\psi$ decay in perturbative QCD, *Phys. Rev. D* **65**, 074030 (2002).
- [11] LHCb Collaboration, Measurements of the $\Lambda_b \rightarrow J/\psi\Lambda$ decay amplitudes and the Λ_b polarisation in pp collisions at $\sqrt{s} = 7\text{TeV}$, *Phys. Lett. B* **724**, 27 (2013).
- [12] ATLAS Collaboration, Measurement of the parity-violating asymmetry parameter α_b and the helicity amplitudes for the decay $\Lambda_b \rightarrow J/\psi\Lambda$ with the ATLAS detector, *Phys. Rev. D* **89**, 092009 (2014).
- [13] T. Aaltonen *et al.* (CDF Collaboration), Observation of the Heavy Baryons Σ_b and Σ_b^* , *Phys. Rev. Lett.* **99**, 202001 (2007).
- [14] T. Aaltonen *et al.* (CDF Collaboration), Measurement of the masses and widths of the bottom baryons Σ_b^\pm and $\Sigma_b^{*\pm}$, *Phys. Rev. D* **85**, 092011 (2012).
- [15] T. Aaltonen *et al.* (CDF Collaboration), Evidence for a bottom baryon resonance Λ_b^* in CDF data, *Phys. Rev. D* **88**, 071101 (2013).
- [16] R Aaij *et al.* (LHCb Collaboration), Observation of Excited Λ_b Baryons, *Phys. Rev. Lett.* **109**, 172003 (2012).
- [17] CMS Collaboration, The CMS experiment at the CERN LHC, *J. Instrum.* **3**, S08004 (2008).
- [18] C. Patrignani *et al.* (Particle Data Group Collaboration), Review of particle physics, *Chin. Phys. C* **40**, 100001 (2016).
- [19] CMS Collaboration, Description and performance of track and primary-vertex reconstruction with the CMS tracker, *J. Instrum.* **9**, P10009 (2014).
- [20] CMS Collaboration, Performance of CMS muon reconstruction in pp collision events at $\sqrt{s} = 7\text{TeV}$, *J. Instrum.* **7**, P10002 (2012).
- [21] CMS Collaboration, Particle-flow reconstruction and global event description with the CMS detector, *J. Instrum.* **12**, P10003 (2017).
- [22] CMS Collaboration, The CMS trigger system, *J. Instrum.* **12**, P01020 (2017).
- [23] T. Sjöstrand, S. Mrenna, and P.Z. Skands, PYTHIA 6.4 physics and manual, *J. High Energy Phys.* **05** (2006) 026.
- [24] D. J. Lange, The EVTGEN particle decay simulation package, Proceedings of the 7th International Conference on B physics at hadron machines (BEAUTY 2000), *Nucl. Instrum. Methods Phys. Res., Sect. A* **462**, 152 (2001).
- [25] S. Agostinelli *et al.* (GEANT4 Collaboration), GEANT4—a simulation toolkit, *Nucl. Instrum. Methods Phys. Res., Sect. A* **506**, 250 (2003).
- [26] CMS Collaboration, Strange particle production in pp collisions at $\sqrt{s} = 0.9$ and 7 TeV, *J. High Energy Phys.* **05** (2011) 064.
- [27] W. Verkerke and D. P. Kirkby, The RooFit toolkit for data modeling, eConference C0303241, MOLT007 (2003).
- [28] H.-Y. Cheng, Nonleptonic weak decays of bottom baryons, *Phys. Rev. D* **56**, 2799 (1997).
- [29] Fayyazuddin and Riazuddin, Two-body nonleptonic Λ_b decays in the quark model with factorization ansatz, *Phys. Rev. D* **58**, 014016 (1998).
- [30] R. Mohanta, A. K. Giri, M. P. Khanna, M. Ishida, S. Ishida, and M. Oda, Hadronic weak decays of Λ_b baryon in the covariant oscillator quark model, *Prog. Theor. Phys.* **101**, 959 (1999).
- [31] Z.-T. Wei, H.-W. Ke, and X.-Q. Li, Evaluating decay rates and asymmetries of Λ_b into light baryons in LFQM, *Phys. Rev. D* **80**, 094016 (2009).
-

A. M. Sirunyan,¹ A. Tumasyan,¹ W. Adam,² F. Ambrogio,² E. Asilar,² T. Bergauer,² J. Brandstetter,² E. Brondolin,² M. Dragicevic,² J. Erö,² A. Escalante Del Valle,² M. Flechl,² M. Friedl,² R. Frühwirth,^{2,b} V. M. Ghete,² J. Grossmann,² J. Hrubec,² M. Jeitler,^{2,b} A. König,² N. Krammer,² I. Krätschmer,² D. Liko,² T. Madlener,² I. Mikulec,² E. Pree,² N. Rad,² H. Rohringer,² J. Schieck,^{2,b} R. Schöffbeck,² M. Spanring,² D. Spitzbart,² A. Taurok,² W. Waltenberger,² J. Wittmann,² C.-E. Wulz,^{2,b} M. Zarucki,² V. Chekhovskiy,³ V. Mossolov,³ J. Suarez Gonzalez,³ E. A. De Wolf,⁴ D. Di Croce,⁴ X. Janssen,⁴ J. Lauwers,⁴ H. Van Haevermaet,⁴ P. Van Mechelen,⁴ N. Van Remortel,⁴ S. Abu Zeid,⁵ F. Blekman,⁵ J. D'Hondt,⁵ I. De Bruyn,⁵ J. De Clercq,⁵ K. Deroover,⁵ G. Flouris,⁵ D. Lontkovskiy,⁵ S. Lowette,⁵ I. Marchesini,⁵ S. Moortgat,⁵ L. Moreels,⁵ Q. Python,⁵ K. Skovpen,⁵ S. Tavernier,⁵ W. Van Doninck,⁵ P. Van Mulders,⁵ I. Van Parijs,⁵ D. Beghin,⁶ B. Bilin,⁶ H. Brun,⁶ B. Clerbaux,⁶ G. De Lentdecker,⁶ H. Delannoy,⁶ B. Dorney,⁶ G. Fasanella,⁶ L. Favart,⁶ R. Goldouzian,⁶ A. Grebenyuk,⁶ A. K. Kalsi,⁶ T. Lenzi,⁶ J. Luetic,⁶ T. Maerschalk,⁶ A. Marinov,⁶ T. Seva,⁶ E. Starling,⁶ C. Vander Velde,⁶ P. Vanlaer,⁶ D. Vannerom,⁶ R. Yonamine,⁶ F. Zenoni,⁶ T. Cornelis,⁷ D. Dobur,⁷ A. Fagot,⁷ M. Gul,⁷ I. Khvastunov,^{7,c} D. Poyraz,⁷ C. Roskas,⁷ S. Salva,⁷ D. Trocino,⁷ M. Tytgat,⁷ W. Verbeke,⁷ N. Zaganidis,⁷ H. Bakhshiansohi,⁸ O. Bondu,⁸ S. Brochet,⁸ G. Bruno,⁸ C. Caputo,⁸ A. Caudron,⁸ P. David,⁸ S. De Visscher,⁸ C. Delaere,⁸ M. Delcourt,⁸ B. Francois,⁸ A. Giammanco,⁸ M. Komm,⁸ G. Krintiras,⁸ V. Lemaître,⁸ A. Magitteri,⁸ A. Mertens,⁸ M. Musich,⁸ K. Piotrkowski,⁸ L. Quertenmont,⁸ A. Saggio,⁸ M. Vidal Marono,⁸ S. Wertz,⁸ J. Zobec,⁸ W. L. Aldá Júnior,⁹ F. L. Alves,⁹ G. A. Alves,⁹ L. Brito,⁹ G. Correia Silva,⁹ C. Hensel,⁹ A. Moraes,⁹ M. E. Pol,⁹ P. Rebello Teles,⁹ E. Belchior Batista Das Chagas,¹⁰ W. Carvalho,¹⁰ J. Chinellato,^{10,d} E. Coelho,¹⁰ E. M. Da Costa,¹⁰ G. G. Da Silveira,^{10,e} D. De Jesus Damiao,¹⁰ S. Fonseca De Souza,¹⁰ L. M. Huertas Guativa,¹⁰ H. Malbouisson,¹⁰ M. Melo De Almeida,¹⁰ C. Mora Herrera,¹⁰ L. Mundim,¹⁰ H. Nogima,¹⁰ L. J. Sanchez Rosas,¹⁰ A. Santoro,¹⁰ A. Sznajder,¹⁰ M. Thiel,¹⁰ E. J. Tonelli Manganote,^{10,d} F. Torres Da Silva De Araujo,¹⁰ A. Vilela Pereira,¹⁰ S. Ahuja,^{11a} C. A. Bernardes,^{11a} T. R. Fernandez Perez Tomei,^{11a} E. M. Gregores,^{11b} P. G. Mercadante,^{11b} S. F. Novaes,^{11a} Sandra S. Padula,^{11a} D. Romero Abad,^{11b} J. C. Ruiz Vargas,^{11a} A. Aleksandrov,¹² R. Hadjiiska,¹² P. Iaydjiev,¹² M. Misheva,¹² M. Rodozov,¹² M. Shopova,¹² G. Sultanov,¹² A. Dimitrov,¹³ L. Litov,¹³ B. Pavlov,¹³ P. Petkov,¹³ W. Fang,^{14,f} X. Gao,^{14,f} L. Yuan,¹⁴ M. Ahmad,¹⁵ J. G. Bian,¹⁵ G. M. Chen,¹⁵ H. S. Chen,¹⁵ M. Chen,¹⁵ Y. Chen,¹⁵ C. H. Jiang,¹⁵ D. Leggat,¹⁵ H. Liao,¹⁵ Z. Liu,¹⁵ F. Romeo,¹⁵ S. M. Shaheen,¹⁵ A. Spiezia,¹⁵ J. Tao,¹⁵ C. Wang,¹⁵ Z. Wang,¹⁵ E. Yazgan,¹⁵ T. Yu,¹⁵ H. Zhang,¹⁵ J. Zhao,¹⁵ Y. Ban,¹⁶ G. Chen,¹⁶ J. Li,¹⁶ Q. Li,¹⁶ S. Liu,¹⁶ Y. Mao,¹⁶ S. J. Qian,¹⁶ D. Wang,¹⁶ Z. Xu,¹⁶ F. Zhang,^{16,f} Y. Wang,¹⁷ C. Avila,¹⁸ A. Cabrera,¹⁸ L. F. Chaparro Sierra,¹⁸ C. Florez,¹⁸ C. F. González Hernández,¹⁸ J. D. Ruiz Alvarez,¹⁸ M. A. Segura Delgado,¹⁸ B. Courbon,¹⁹ N. Godinovic,¹⁹ D. Lelas,¹⁹ I. Puljak,¹⁹ P. M. Ribeiro Cipriano,¹⁹ T. Sculac,¹⁹ Z. Antunovic,²⁰ M. Kovac,²⁰ V. Brigljevic,²¹ D. Ferencek,²¹ K. Kadija,²¹ B. Mesic,²¹ A. Starodumov,^{21,g} T. Susa,²¹ M. W. Ather,²² A. Attikis,²² G. Mavromanolakis,²² J. Mousa,²² C. Nicolaou,²² F. Ptochos,²² P. A. Razis,²² H. Rykaczewski,²² M. Finger,^{23,h} M. Finger Jr.,^{23,h} E. Carrera Jarrin,²⁴ A. Mohamed,^{25,i} Y. Mohammed,^{25,j} E. Salama,^{25,k,l} S. Bhowmik,²⁶ R. K. Dewanjee,²⁶ M. Kadastik,²⁶ L. Perrini,²⁶ M. Raidal,²⁶ A. Tiko,²⁶ C. Veelken,²⁶ P. Eerola,²⁷ H. Kirschenmann,²⁷ J. Pekkanen,²⁷ M. Voutilainen,²⁷ J. Havukainen,²⁸ J. K. Heikkilä,²⁸ T. Järvinen,²⁸ V. Karimäki,²⁸ R. Kinnunen,²⁸ T. Lampén,²⁸ K. Lassila-Perini,²⁸ S. Laurila,²⁸ S. Lehti,²⁸ T. Lindén,²⁸ P. Luukka,²⁸ T. Mäenpää,²⁸ H. Siikonen,²⁸ E. Tuominen,²⁸ J. Tuominiemi,²⁸ T. Tuuva,²⁹ M. Besancon,³⁰ F. Couderc,³⁰ M. Dejardin,³⁰ D. Denegri,³⁰ J. L. Faure,³⁰ F. Ferri,³⁰ S. Ganjour,³⁰ S. Ghosh,³⁰ A. Givernaud,³⁰ P. Gras,³⁰ G. Hamel de Monchenault,³⁰ P. Jarry,³⁰ I. Kucher,³⁰ C. Leloup,³⁰ E. Locci,³⁰ M. Machet,³⁰ J. Malcles,³⁰ G. Negro,³⁰ J. Rander,³⁰ A. Rosowsky,³⁰ M. Ö. Sahin,³⁰ M. Titov,³⁰ A. Abdulsalam,^{31,m} C. Amendola,³¹ I. Antropov,³¹ S. Baffioni,³¹ F. Beaudette,³¹ P. Busson,³¹ L. Cadamuro,³¹ C. Charlot,³¹ R. Granier de Cassagnac,³¹ M. Jo,³¹ S. Lisniak,³¹ A. Lobanov,³¹ J. Martin Blanco,³¹ M. Nguyen,³¹ C. Ochando,³¹ G. Ortona,³¹ P. Paganini,³¹ P. Pigard,³¹ R. Salerno,³¹ J. B. Sauvan,³¹ Y. Sirois,³¹ A. G. Stahl Leitner,³¹ T. Streblter,³¹ Y. Yilmaz,³¹ A. Zabi,³¹ A. Zghiche,³¹ J.-L. Agram,^{32,n} J. Andrea,³² D. Bloch,³² J.-M. Brom,³² M. Buttignol,³² E. C. Chabert,³² N. Chanon,³² C. Collard,³² E. Conte,^{32,n} X. Coubez,³² F. Drouhin,^{32,n} J.-C. Fontaine,^{32,n} D. Gelé,³² U. Goerlach,³² M. Jansová,³² P. Juillot,³² A.-C. Le Bihan,³² N. Tonon,³² P. Van Hove,³² S. Gadrat,³³ S. Beauceron,³⁴ C. Bernet,³⁴ G. Boudoul,³⁴ R. Chierici,³⁴ D. Contardo,³⁴ P. Depasse,³⁴ H. El Mamouni,³⁴ J. Fay,³⁴ L. Finco,³⁴ S. Gascon,³⁴ M. Gouzevitch,³⁴ G. Grenier,³⁴ B. Ille,³⁴ F. Lagarde,³⁴ I. B. Laktineh,³⁴ M. Lethuillier,³⁴ L. Mirabito,³⁴ A. L. Pequegnot,³⁴ S. Perries,³⁴ A. Popov,^{34,o} V. Sordini,³⁴ M. Vander Donckt,³⁴ S. Viret,³⁴ S. Zhang,³⁴ T. Toriashvili,^{35,p} Z. Tsamalaidze,^{36,h} C. Autermann,³⁷ L. Feld,³⁷ M. K. Kiesel,³⁷ K. Klein,³⁷ M. Lipinski,³⁷ M. Preuten,³⁷ C. Schomakers,³⁷ J. Schulz,³⁷ M. Teroerde,³⁷ B. Wittmer,³⁷ V. Zhukov,^{37,o} A. Albert,³⁸ D. Duchardt,³⁸ M. Endres,³⁸ M. Erdmann,³⁸ S. Erdweg,³⁸ T. Esch,³⁸ R. Fischer,³⁸ A. Güth,³⁸ M. Hamer,³⁸ T. Hebbeker,³⁸ C. Heidemann,³⁸ K. Hoepfner,³⁸ S. Knutzen,³⁸ M. Merschmeyer,³⁸

A. Meyer,³⁸ P. Millet,³⁸ S. Mukherjee,³⁸ T. Pook,³⁸ M. Radziej,³⁸ H. Reithler,³⁸ M. Rieger,³⁸ F. Scheuch,³⁸ D. Teyssier,³⁸ S. Thüer,³⁸ G. Flügge,³⁹ B. Kargoll,³⁹ T. Kress,³⁹ A. Künsken,³⁹ T. Müller,³⁹ A. Nehr Korn,³⁹ A. Nowack,³⁹ C. Pistone,³⁹ O. Pooth,³⁹ A. Stahl,^{39,q} M. Aldaya Martin,⁴⁰ T. Arndt,⁴⁰ C. Asawatangtrakuldee,⁴⁰ K. Beernaert,⁴⁰ O. Behnke,⁴⁰ U. Behrens,⁴⁰ A. Bermúdez Martínez,⁴⁰ A. A. Bin Anuar,⁴⁰ K. Borrás,^{40,r} V. Botta,⁴⁰ A. Campbell,⁴⁰ P. Connor,⁴⁰ C. Contreras-Campana,⁴⁰ F. Costanza,⁴⁰ C. Diez Pardos,⁴⁰ G. Eckerlin,⁴⁰ D. Eckstein,⁴⁰ T. Eichhorn,⁴⁰ E. Eren,⁴⁰ E. Gallo,^{40,s} J. Garay Garcia,⁴⁰ A. Geiser,⁴⁰ J. M. Grados Luyando,⁴⁰ A. Grohsjean,⁴⁰ P. Gunnellini,⁴⁰ M. Guthoff,⁴⁰ A. Harb,⁴⁰ J. Hauk,⁴⁰ M. Hempel,^{40,t} H. Jung,⁴⁰ M. Kasemann,⁴⁰ J. Keaveney,⁴⁰ C. Kleinwort,⁴⁰ I. Korol,⁴⁰ D. Krücker,⁴⁰ W. Lange,⁴⁰ A. Lelek,⁴⁰ T. Lenz,⁴⁰ J. Leonard,⁴⁰ K. Lipka,⁴⁰ W. Lohmann,^{40,t} R. Mankel,⁴⁰ I.-A. Melzer-Pellmann,⁴⁰ A. B. Meyer,⁴⁰ M. Missiroli,⁴⁰ G. Mittag,⁴⁰ J. Mnich,⁴⁰ A. Mussgiller,⁴⁰ E. Ntomari,⁴⁰ D. Pitzl,⁴⁰ A. Raspereza,⁴⁰ M. Savitskiy,⁴⁰ P. Saxena,⁴⁰ R. Shevchenko,⁴⁰ N. Stefaniuk,⁴⁰ G. P. Van Onsem,⁴⁰ R. Walsh,⁴⁰ Y. Wen,⁴⁰ K. Wichmann,⁴⁰ C. Wissing,⁴⁰ O. Zenaiev,⁴⁰ R. Aggleton,⁴¹ S. Bein,⁴¹ V. Blobel,⁴¹ M. Centis Vignali,⁴¹ T. Dreyer,⁴¹ E. Garutti,⁴¹ D. Gonzalez,⁴¹ J. Haller,⁴¹ A. Hinemann,⁴¹ M. Hoffmann,⁴¹ A. Karavdina,⁴¹ R. Klanner,⁴¹ R. Kogler,⁴¹ N. Kovalchuk,⁴¹ S. Kurz,⁴¹ T. Lapsien,⁴¹ D. Marconi,⁴¹ M. Meyer,⁴¹ M. Niedziela,⁴¹ D. Nowatschin,⁴¹ F. Pantaleo,^{41,q} T. Peiffer,⁴¹ A. Perieanu,⁴¹ C. Scharf,⁴¹ P. Schleper,⁴¹ A. Schmidt,⁴¹ S. Schumann,⁴¹ J. Schwandt,⁴¹ J. Sonneveld,⁴¹ H. Stadie,⁴¹ G. Steinbrück,⁴¹ F. M. Stober,⁴¹ M. Stöver,⁴¹ H. Tholen,⁴¹ D. Troendle,⁴¹ E. Usai,⁴¹ A. Vanhoefer,⁴¹ B. Vormwald,⁴¹ M. Akbiyik,⁴² C. Barth,⁴² M. Baselga,⁴² S. Baur,⁴² E. Butz,⁴² R. Caspart,⁴² T. Chwalek,⁴² F. Colombo,⁴² W. De Boer,⁴² A. Dierlamm,⁴² N. Faltermann,⁴² B. Freund,⁴² R. Friese,⁴² M. Giffels,⁴² M. A. Harrendorf,⁴² F. Hartmann,^{42,q} S. M. Heindl,⁴² U. Husemann,⁴² F. Kassel,^{42,q} S. Kudella,⁴² H. Mildner,⁴² M. U. Mozer,⁴² Th. Müller,⁴² M. Plagge,⁴² G. Quast,⁴² K. Rabbertz,⁴² M. Schröder,⁴² I. Shvetsov,⁴² G. Sieber,⁴² H. J. Simonis,⁴² R. Ulrich,⁴² S. Wayand,⁴² M. Weber,⁴² T. Weiler,⁴² S. Williamson,⁴² C. Wöhrmann,⁴² R. Wolf,⁴² G. Anagnostou,⁴³ G. Daskalakis,⁴³ T. Geralis,⁴³ A. Kyriakis,⁴³ D. Loukas,⁴³ I. Topsis-Giotis,⁴³ G. Karathanasis,⁴⁴ S. Kesisoglou,⁴⁴ A. Panagiotou,⁴⁴ N. Saoulidou,⁴⁴ K. Kousouris,⁴⁵ I. Evangelou,⁴⁶ C. Foudas,⁴⁶ P. Giannelos,⁴⁶ P. Katsoulis,⁴⁶ P. Kokkas,⁴⁶ S. Mallios,⁴⁶ N. Manthos,⁴⁶ I. Papadopoulos,⁴⁶ E. Paradas,⁴⁶ J. Strolgas,⁴⁶ F. A. Triantis,⁴⁶ D. Tsitsonis,⁴⁶ M. Csanad,⁴⁷ N. Filipovic,⁴⁷ G. Pasztor,⁴⁷ O. Surányi,⁴⁷ G. I. Veres,^{47,u} G. Bencze,⁴⁸ C. Hajdu,⁴⁸ D. Horvath,^{48,v} Á. Hunyadi,⁴⁸ F. Sikler,⁴⁸ V. Veszpremi,⁴⁸ G. Vesztergombi,^{48,u} N. Beni,⁴⁹ S. Czellar,⁴⁹ J. Karancsi,^{49,w} A. Makovec,⁴⁹ J. Molnar,⁴⁹ Z. Szillasi,⁴⁹ M. Bartók,^{50,u} P. Raics,⁵⁰ Z. L. Trocsanyi,⁵⁰ B. Ujvari,⁵⁰ S. Choudhury,⁵¹ J. R. Komaragiri,⁵¹ S. Bahinipati,^{52,x} P. Mal,⁵² K. Mandal,⁵² A. Nayak,^{52,y} D. K. Sahoo,^{52,x} N. Sahoo,⁵² S. K. Swain,⁵² S. Bansal,⁵³ S. B. Beri,⁵³ V. Bhatnagar,⁵³ R. Chawla,⁵³ N. Dhingra,⁵³ A. Kaur,⁵³ M. Kaur,⁵³ S. Kaur,⁵³ R. Kumar,⁵³ P. Kumari,⁵³ A. Mehta,⁵³ J. B. Singh,⁵³ G. Walia,⁵³ Ashok Kumar,⁵⁴ Aashaq Shah,⁵⁴ A. Bhardwaj,⁵⁴ S. Chauhan,⁵⁴ B. C. Choudhary,⁵⁴ R. B. Garg,⁵⁴ S. Keshri,⁵⁴ A. Kumar,⁵⁴ S. Malhotra,⁵⁴ M. Naimuddin,⁵⁴ K. Ranjan,⁵⁴ R. Sharma,⁵⁴ R. Bhardwaj,⁵⁵ R. Bhattacharya,⁵⁵ S. Bhattacharya,⁵⁵ U. Bhawandeep,⁵⁵ S. Dey,⁵⁵ S. Dutt,⁵⁵ S. Dutta,⁵⁵ S. Ghosh,⁵⁵ N. Majumdar,⁵⁵ A. Modak,⁵⁵ K. Mondal,⁵⁵ S. Mukhopadhyay,⁵⁵ S. Nandan,⁵⁵ A. Purohit,⁵⁵ A. Roy,⁵⁵ S. Roy Chowdhury,⁵⁵ S. Sarkar,⁵⁵ M. Sharan,⁵⁵ S. Thakur,⁵⁵ P. K. Behera,⁵⁶ R. Chudasama,⁵⁷ D. Dutta,⁵⁷ V. Jha,⁵⁷ V. Kumar,⁵⁷ A. K. Mohanty,^{57,q} P. K. Netrakanti,⁵⁷ L. M. Pant,⁵⁷ P. Shukla,⁵⁷ A. Topkar,⁵⁷ T. Aziz,⁵⁸ S. Dugad,⁵⁸ B. Mahakud,⁵⁸ S. Mitra,⁵⁸ G. B. Mohanty,⁵⁸ N. Sur,⁵⁸ B. Sutar,⁵⁸ S. Banerjee,⁵⁹ S. Bhattacharya,⁵⁹ S. Chatterjee,⁵⁹ P. Das,⁵⁹ M. Guchait,⁵⁹ Sa. Jain,⁵⁹ S. Kumar,⁵⁹ M. Maity,^{59,z} G. Majumder,⁵⁹ K. Mazumdar,⁵⁹ T. Sarkar,^{59,z} N. Wickramage,^{59,aa} S. Chauhan,⁶⁰ S. Dube,⁶⁰ V. Hegde,⁶⁰ A. Kapoor,⁶⁰ K. Kotheekar,⁶⁰ S. Pandey,⁶⁰ A. Rane,⁶⁰ S. Sharma,⁶⁰ S. Chenarani,^{61,bb} E. Eskandari Tadavani,⁶¹ S. M. Etesami,^{61,bb} M. Khakzad,⁶¹ M. Mohammadi Najafabadi,⁶¹ M. Naseri,⁶¹ S. Paktinat Mehdiabadi,^{61,cc} F. Rezaei Hosseinabadi,⁶¹ B. Safarzadeh,^{61,dd} M. Zeinali,⁶¹ M. Felcini,⁶² M. Grunewald,⁶² M. Abbrescia,^{63a,63b} C. Calabria,^{63a,63b} A. Colaleo,^{63a} D. Creanza,^{63a,63c} L. Cristella,^{63a,63b} N. De Filippis,^{63a,63c} M. De Palma,^{63a,63b} F. Errico,^{63a,63b} L. Fiore,^{63a} G. Iaselli,^{63a,63c} S. Lezki,^{63a,63b} G. Maggi,^{63a,63c} M. Maggi,^{63a} G. Miniello,^{63a,63b} S. My,^{63a,63b} S. Nuzzo,^{63a,63b} A. Pompili,^{63a,63b} G. Pugliese,^{63a,63c} R. Radogna,^{63a} A. Ranieri,^{63a} G. Selvaggi,^{63a,63b} A. Sharma,^{63a} L. Silvestris,^{63a,q} R. Venditti,^{63a} P. Verwilligen,^{63a} G. Abbiendi,^{64a} C. Battilana,^{64a,64b} D. Bonacorsi,^{64a,64b} L. Borgonovi,^{64a,64b} S. Braibant-Giacomelli,^{64a,64b} R. Campanini,^{64a,64b} P. Capiluppi,^{64a,64b} A. Castro,^{64a,64b} F. R. Cavallo,^{64a} S. S. Chhibra,^{64a,64b} G. Codispoti,^{64a,64b} M. Cuffiani,^{64a,64b} G. M. Dallavalle,^{64a} F. Fabbri,^{64a} A. Fanfani,^{64a,64b} D. Fasanella,^{64a,64b} P. Giacomelli,^{64a} C. Grandi,^{64a} L. Guiducci,^{64a,64b} S. Marcellini,^{64a} G. Masetti,^{64a} A. Montanari,^{64a} F. L. Navarria,^{64a,64b} A. Perrotta,^{64a} A. M. Rossi,^{64a,64b} T. Rovelli,^{64a,64b} G. P. Siroli,^{64a,64b} N. Tosi,^{64a} S. Albergo,^{65a,65b} S. Costa,^{65a,65b} A. Di Mattia,^{65a} F. Giordano,^{65a,65b} R. Potenza,^{65a,65b} A. Tricoli,^{65a,65b} C. Tuve,^{65a,65b} G. Barbagli,^{66a} K. Chatterjee,^{66a,66b} V. Ciulli,^{66a,66b} C. Civinini,^{66a} R. D'Alessandro,^{66a,66b} E. Focardi,^{66a,66b} P. Lenzi,^{66a,66b} M. Meschini,^{66a} S. Paoletti,^{66a} L. Russo,^{66a,ee} G. Sguazzoni,^{66a} D. Strom,^{66a} L. Viliani,^{66a} L. Benussi,⁶⁷ S. Bianco,⁶⁷

F. Fabbri,⁶⁷ D. Piccolo,⁶⁷ F. Primavera,^{67,q} V. Calvelli,^{68a,68b} F. Ferro,^{68a} F. Ravera,^{68a,68b} E. Robutti,^{68a} S. Tosi,^{68a,68b}
A. Benaglia,^{69a} A. Beschi,^{69b} L. Brianza,^{69a,69b} F. Brivio,^{69a,69b} V. Ciriolo,^{69a,69b,q} M. E. Dinardo,^{69a,69b} S. Fiorendi,^{69a,69b}
S. Gennai,^{69a} A. Ghezzi,^{69a,69b} P. Govoni,^{69a,69b} M. Malberti,^{69a,69b} S. Malvezzi,^{69a} R. A. Manzoni,^{69a,69b} D. Menasce,^{69a}
L. Moroni,^{69a} M. Paganoni,^{69a,69b} K. Pauwels,^{69a,69b} D. Pedrini,^{69a} S. Pigazzini,^{69a,69b,ff} S. Ragazzi,^{69a,69b}
T. Tabarelli de Fatis,^{69a,69b} S. Buontempo,^{70a} N. Cavallo,^{70a,70c} S. Di Guida,^{70a,70d,q} F. Fabozzi,^{70a,70c} F. Fienga,^{70a,70b}
A. O. M. Iorio,^{70a,70b} W. A. Khan,^{70a} L. Lista,^{70a} S. Meola,^{70a,70d,q} P. Paolucci,^{70a,q} C. Sciacca,^{70a,70b} F. Thyssen,^{70a} P. Azzi,^{71a}
N. Bacchetta,^{71a} L. Benato,^{71a,71b} D. Bisello,^{71a,71b} A. Boletti,^{71a,71b} R. Carlin,^{71a,71b} A. Carvalho Antunes De Oliveira,^{71a,71b}
P. Checchia,^{71a} M. Dall'Osso,^{71a,71b} P. De Castro Manzano,^{71a} T. Dorigo,^{71a} U. Dosselli,^{71a} F. Fanzago,^{71a} F. Gasparini,^{71a,71b}
A. Gozzelino,^{71a} S. Lacaprara,^{71a} P. Lujan,^{71a} M. Margoni,^{71a,71b} N. Pozzobon,^{71a,71b} P. Ronchese,^{71a,71b} R. Rossin,^{71a,71b}
F. Simonetto,^{71a,71b} E. Torassa,^{71a} M. Zanetti,^{71a,71b} P. Zotto,^{71a,71b} G. Zumerle,^{71a,71b} A. Braghieri,^{72a} A. Magnani,^{72a}
P. Montagna,^{72a,72b} S. P. Ratti,^{72a,72b} V. Re,^{72a} M. Ressegotti,^{72a,72b} C. Riccardi,^{72a,72b} P. Salvini,^{72a} I. Vai,^{72a,72b} P. Vitulo,^{72a,72b}
L. Alunni Solestizi,^{73a,73b} M. Biasini,^{73a,73b} G. M. Bilei,^{73a} C. Cecchi,^{73a,73b} D. Ciangottini,^{73a,73b} L. Fanò,^{73a,73b}
P. Lariccia,^{73a,73b} R. Leonardi,^{73a,73b} E. Manoni,^{73a} G. Mantovani,^{73a,73b} V. Mariani,^{73a,73b} M. Menichelli,^{73a} A. Rossi,^{73a,73b}
A. Santocchia,^{73a,73b} D. Spiga,^{73a} K. Androsov,^{74a} P. Azzurri,^{74a,q} G. Bagliesi,^{74a} T. Boccali,^{74a} L. Borrello,^{74a} R. Castaldi,^{74a}
M. A. Ciocci,^{74a,74b} R. Dell'Orso,^{74a} G. Fedi,^{74a} L. Giannini,^{74a,74c} A. Giassi,^{74a} M. T. Grippo,^{74a,ee} F. Ligabue,^{74a,74c}
T. Lomtadze,^{74a} E. Manca,^{74a,74c} G. Mandorli,^{74a,74c} A. Messineo,^{74a,74b} F. Palla,^{74a} A. Rizzi,^{74a,74b} A. Savoy-Navarro,^{74a,gg}
P. Spagnolo,^{74a} R. Tenchini,^{74a} G. Tonelli,^{74a,74b} A. Venturi,^{74a} P. G. Verdini,^{74a} L. Barone,^{75a,75b} F. Cavallari,^{75a}
M. Cipriani,^{75a,75b} N. Daci,^{75a} D. Del Re,^{75a,75b} E. Di Marco,^{75a,75b} M. Diemoz,^{75a} S. Gelli,^{75a,75b} E. Longo,^{75a,75b}
F. Margaroli,^{75a,75b} B. Marzocchi,^{75a,75b} P. Meridiani,^{75a} G. Organtini,^{75a,75b} R. Paramatti,^{75a,75b} F. Priato,^{75a,75b}
S. Rahatlou,^{75a,75b} C. Rovelli,^{75a} F. Santanastasio,^{75a,75b} N. Amapane,^{76a,76b} R. Arcidiacono,^{76a,76c} S. Argiro,^{76a,76b}
M. Arneodo,^{76a,76c} N. Bartosik,^{76a} R. Bellan,^{76a,76b} C. Biino,^{76a} N. Cartiglia,^{76a} F. Cenna,^{76a,76b} M. Costa,^{76a,76b}
R. Covarelli,^{76a,76b} A. Degano,^{76a,76b} N. Demaria,^{76a} B. Kiani,^{76a,76b} C. Mariotti,^{76a} S. Maselli,^{76a} E. Migliore,^{76a,76b}
V. Monaco,^{76a,76b} E. Monteil,^{76a,76b} M. Monteno,^{76a} M. M. Obertino,^{76a,76b} L. Pacher,^{76a,76b} N. Pastrone,^{76a} M. Pelliccioni,^{76a}
G. L. Pinna Angioni,^{76a,76b} A. Romero,^{76a,76b} M. Ruspa,^{76a,76c} R. Sacchi,^{76a,76b} K. Shchelina,^{76a,76b} V. Sola,^{76a}
A. Solano,^{76a,76b} A. Staiano,^{76a} P. Traczyk,^{76a,76b} S. Belforte,^{77a} M. Casarsa,^{77a} F. Cossutti,^{77a} G. Della Ricca,^{77a,77b}
A. Zanetti,^{77a} D. H. Kim,⁷⁸ G. N. Kim,⁷⁸ M. S. Kim,⁷⁸ J. Lee,⁷⁸ S. Lee,⁷⁸ S. W. Lee,⁷⁸ C. S. Moon,⁷⁸ Y. D. Oh,⁷⁸ S. Sekmen,⁷⁸
D. C. Son,⁷⁸ Y. C. Yang,⁷⁸ H. Kim,⁷⁹ D. H. Moon,⁷⁹ G. Oh,⁷⁹ J. A. Brochero Cifuentes,⁸⁰ J. Goh,⁸⁰ T. J. Kim,⁸⁰ S. Cho,⁸¹
S. Choi,⁸¹ Y. Go,⁸¹ D. Gyun,⁸¹ S. Ha,⁸¹ B. Hong,⁸¹ Y. Jo,⁸¹ Y. Kim,⁸¹ K. Lee,⁸¹ K. S. Lee,⁸¹ S. Lee,⁸¹ J. Lim,⁸¹ S. K. Park,⁸¹
Y. Roh,⁸¹ J. Almond,⁸² J. Kim,⁸² J. S. Kim,⁸² H. Lee,⁸² K. Lee,⁸² K. Nam,⁸² S. B. Oh,⁸² B. C. Radburn-Smith,⁸² S. h. Seo,⁸²
U. K. Yang,⁸² H. D. Yoo,⁸² G. B. Yu,⁸² H. Kim,⁸³ J. H. Kim,⁸³ J. S. H. Lee,⁸³ I. C. Park,⁸³ Y. Choi,⁸⁴ C. Hwang,⁸⁴ J. Lee,⁸⁴
I. Yu,⁸⁴ V. Dudenias,⁸⁵ A. Juodagalvis,⁸⁵ J. Vaitkus,⁸⁵ I. Ahmed,⁸⁶ Z. A. Ibrahim,⁸⁶ M. A. B. Md Ali,^{86,hh}
F. Mohamad Idris,^{86,ii} W. A. T. Wan Abdullah,⁸⁶ M. N. Yusli,⁸⁶ Z. Zolkapli,⁸⁶ R. Reyes-Almanza,⁸⁷ G. Ramirez-Sanchez,⁸⁷
M. C. Duran-Osuna,⁸⁷ H. Castilla-Valdez,⁸⁷ E. De La Cruz-Burelo,⁸⁷ I. Heredia-De La Cruz,^{87,jj} R. I. Rabadan-Trejo,⁸⁷
R. Lopez-Fernandez,⁸⁷ J. Mejia Guisao,⁸⁷ A. Sanchez-Hernandez,⁸⁷ S. Carrillo Moreno,⁸⁸ C. Oropeza Barrera,⁸⁸
F. Vazquez Valencia,⁸⁸ J. Eysermans,⁸⁹ I. Pedraza,⁸⁹ H. A. Salazar Ibarquen,⁸⁹ C. Uribe Estrada,⁸⁹ A. Morelos Pineda,⁹⁰
D. Krofcheck,⁹¹ P. H. Butler,⁹² A. Ahmad,⁹³ M. Ahmad,⁹³ Q. Hassan,⁹³ H. R. Hoorani,⁹³ A. Saddique,⁹³ M. A. Shah,⁹³
M. Shoaib,⁹³ M. Waqas,⁹³ H. Bialkowska,⁹⁴ M. Bluj,⁹⁴ B. Boimska,⁹⁴ T. Frueboes,⁹⁴ M. Górski,⁹⁴ M. Kazana,⁹⁴
K. Nawrocki,⁹⁴ M. Szleper,⁹⁴ P. Zalewski,⁹⁴ K. Bunkowski,⁹⁵ A. Byszuk,^{95,kk} K. Doroba,⁹⁵ A. Kalinowski,⁹⁵ M. Konecki,⁹⁵
J. Krolikowski,⁹⁵ M. Misiura,⁹⁵ M. Olszewski,⁹⁵ A. Pyskir,⁹⁵ M. Walczak,⁹⁵ P. Bargassa,⁹⁶ C. Beirão Da Cruz E Silva,⁹⁶
A. Di Francesco,⁹⁶ P. Faccioli,⁹⁶ B. Galinhas,⁹⁶ M. Gallinaro,⁹⁶ J. Hollar,⁹⁶ N. Leonardo,⁹⁶ L. Lloret Iglesias,⁹⁶
M. V. Nemallapudi,⁹⁶ J. Seixas,⁹⁶ G. Strong,⁹⁶ O. Toldaiev,⁹⁶ D. Vadrucchio,⁹⁶ J. Varela,⁹⁶ I. Golutvin,⁹⁷ V. Karjavin,⁹⁷
I. Kashunin,⁹⁷ V. Korenkov,⁹⁷ G. Kozlov,⁹⁷ A. Lanev,⁹⁷ A. Malakhov,⁹⁷ V. Matveev,^{97,ll,mmm} V. V. Mitsyn,⁹⁷ P. Moisenz,⁹⁷
V. Palichik,⁹⁷ V. Perelygin,⁹⁷ S. Shmatov,⁹⁷ N. Skatchkov,⁹⁷ V. Smirnov,⁹⁷ V. Trofimov,⁹⁷ B. S. Yuldashev,^{97,nn} A. Zarubin,⁹⁷
V. Zhiltsov,⁹⁷ Y. Ivanov,⁹⁸ V. Kim,^{98,oo} E. Kuznetsova,^{98,pp} P. Levchenko,⁹⁸ V. Murzin,⁹⁸ V. Oreshkin,⁹⁸ I. Smirnov,⁹⁸
D. Sosnov,⁹⁸ V. Sulimov,⁹⁸ L. Uvarov,⁹⁸ S. Vavilov,⁹⁸ A. Vorobyev,⁹⁸ Yu. Andreev,⁹⁹ A. Dermenev,⁹⁹ S. Gninenko,⁹⁹
N. Golubev,⁹⁹ A. Karneyev,⁹⁹ M. Kirsanov,⁹⁹ N. Krasnikov,⁹⁹ A. Pashenkov,⁹⁹ D. Tlisov,⁹⁹ A. Toropin,⁹⁹ V. Epshteyn,¹⁰⁰
V. Gavrilov,¹⁰⁰ N. Lychkovskaya,¹⁰⁰ V. Popov,¹⁰⁰ I. Pozdnyakov,¹⁰⁰ G. Safronov,¹⁰⁰ A. Spiridonov,¹⁰⁰ A. Stepenov,¹⁰⁰
V. Stolin,¹⁰⁰ M. Toms,¹⁰⁰ E. Vlasov,¹⁰⁰ A. Zhokin,¹⁰⁰ T. Aushev,¹⁰¹ A. Bylinkin,^{101,mmm} R. Chistov,^{102,qq} M. Danilov,^{102,qq}
P. Parygin,¹⁰² D. Philippov,¹⁰² S. Polikarpov,¹⁰² E. Tarkovskii,¹⁰² V. Andreev,¹⁰³ M. Azarkin,^{103,mmm} I. Dremin,^{103,mmm}

M. Kirakosyan,^{103,mm} S. V. Rusakov,¹⁰³ A. Terkulov,¹⁰³ A. Baskakov,¹⁰⁴ A. Belyaev,¹⁰⁴ E. Boos,¹⁰⁴ M. Dubinin,^{104,rr} L. Dudko,¹⁰⁴ A. Ershov,¹⁰⁴ A. Gribushin,¹⁰⁴ V. Klyukhin,¹⁰⁴ O. Kodolova,¹⁰⁴ I. Lokhtin,¹⁰⁴ I. Miagkov,¹⁰⁴ S. Obraztsov,¹⁰⁴ S. Petrushanko,¹⁰⁴ V. Savrin,¹⁰⁴ A. Snigirev,¹⁰⁴ V. Blinov,^{105,ss} D. Shtol,^{105,ss} Y. Skovpen,^{105,ss} I. Azhgirey,¹⁰⁶ I. Bayshev,¹⁰⁶ S. Bitioukov,¹⁰⁶ D. Elumakhov,¹⁰⁶ A. Godizov,¹⁰⁶ V. Kachanov,¹⁰⁶ A. Kalinin,¹⁰⁶ D. Konstantinov,¹⁰⁶ P. Mandrik,¹⁰⁶ V. Petrov,¹⁰⁶ R. Ryutin,¹⁰⁶ A. Sobol,¹⁰⁶ S. Troshin,¹⁰⁶ N. Tyurin,¹⁰⁶ A. Uzunian,¹⁰⁶ A. Volkov,¹⁰⁶ P. Adzic,^{107,tt} P. Cirkovic,¹⁰⁷ D. Devetak,¹⁰⁷ M. Dordevic,¹⁰⁷ J. Milosevic,¹⁰⁷ V. Rekovic,¹⁰⁷ J. Alcaraz Maestre,¹⁰⁸ I. Bachiller,¹⁰⁸ M. Barrio Luna,¹⁰⁸ M. Cerrada,¹⁰⁸ N. Colino,¹⁰⁸ B. De La Cruz,¹⁰⁸ A. Delgado Peris,¹⁰⁸ C. Fernandez Bedoya,¹⁰⁸ J. P. Fernández Ramos,¹⁰⁸ J. Flix,¹⁰⁸ M. C. Fouz,¹⁰⁸ O. Gonzalez Lopez,¹⁰⁸ S. Goy Lopez,¹⁰⁸ J. M. Hernandez,¹⁰⁸ M. I. Josa,¹⁰⁸ D. Moran,¹⁰⁸ A. Pérez-Calero Yzquierdo,¹⁰⁸ J. Puerta Pelayo,¹⁰⁸ I. Redondo,¹⁰⁸ L. Romero,¹⁰⁸ M. S. Soares,¹⁰⁸ A. Triossi,¹⁰⁸ A. Álvarez Fernández,¹⁰⁸ C. Albajar,¹⁰⁹ J. F. de Trocóniz,¹⁰⁹ J. Cuevas,¹¹⁰ C. Erice,¹¹⁰ J. Fernandez Menendez,¹¹⁰ I. Gonzalez Caballero,¹¹⁰ J. R. González Fernández,¹¹⁰ E. Palencia Cortezon,¹¹⁰ S. Sanchez Cruz,¹¹⁰ P. Vischia,¹¹⁰ J. M. Vizán García,¹¹⁰ I. J. Cabrillo,¹¹¹ A. Calderon,¹¹¹ B. Chazin Quero,¹¹¹ E.urras,¹¹¹ J. Duarte Campderros,¹¹¹ M. Fernandez,¹¹¹ J. Garcia-Ferrero,¹¹¹ G. Gomez,¹¹¹ A. Lopez Virto,¹¹¹ J. Marco,¹¹¹ C. Martinez Rivero,¹¹¹ P. Martinez Ruiz del Arbol,¹¹¹ F. Matorras,¹¹¹ J. Piedra Gomez,¹¹¹ T. Rodrigo,¹¹¹ A. Ruiz-Jimeno,¹¹¹ L. Scodellaro,¹¹¹ N. Trevisani,¹¹¹ I. Vila,¹¹¹ R. Vilar Cortabitarte,¹¹¹ D. Abbaneo,¹¹² B. Akgun,¹¹² E. Auffray,¹¹² P. Baillon,¹¹² A. H. Ball,¹¹² D. Barney,¹¹² J. Bendavid,¹¹² M. Bianco,¹¹² P. Bloch,¹¹² A. Bocci,¹¹² C. Botta,¹¹² T. Camporesi,¹¹² R. Castello,¹¹² M. Cepeda,¹¹² G. Cerminara,¹¹² E. Chapon,¹¹² Y. Chen,¹¹² D. d'Enterria,¹¹² A. Dabrowski,¹¹² V. Daponte,¹¹² A. David,¹¹² M. De Gruttola,¹¹² A. De Roeck,¹¹² N. Deelen,¹¹² M. Dobson,¹¹² T. du Pree,¹¹² M. Dünser,¹¹² N. Dupont,¹¹² A. Elliott-Peisert,¹¹² P. Everaerts,¹¹² F. Fallavollita,¹¹² G. Franzoni,¹¹² J. Fulcher,¹¹² W. Funk,¹¹² D. Gigi,¹¹² A. Gilbert,¹¹² K. Gill,¹¹² F. Glege,¹¹² D. Gulhan,¹¹² P. Harris,¹¹² J. Hegeman,¹¹² V. Innocente,¹¹² A. Jafari,¹¹² P. Janot,¹¹² O. Karacheban,^{112,t} J. Kieseler,¹¹² V. Knünz,¹¹² A. Kornmayer,¹¹² M. J. Kortelainen,¹¹² M. Kramer,^{112,b} C. Lange,¹¹² P. Lecoq,¹¹² C. Lourenço,¹¹² M. T. Lucchini,¹¹² L. Malgeri,¹¹² M. Mannelli,¹¹² A. Martelli,¹¹² F. Meijers,¹¹² J. A. Merlin,¹¹² S. Mersi,¹¹² E. Meschi,¹¹² P. Milenovic,^{112,uu} F. Moortgat,¹¹² M. Mulders,¹¹² H. Neugebauer,¹¹² J. Ngadiuba,¹¹² S. Orfanelli,¹¹² L. Orsini,¹¹² L. Pape,¹¹² E. Perez,¹¹² M. Peruzzi,¹¹² A. Petrilli,¹¹² G. Petrucciani,¹¹² A. Pfeiffer,¹¹² M. Pierini,¹¹² D. Rabady,¹¹² A. Racz,¹¹² T. Reis,¹¹² G. Rolandi,^{112,vv} M. Rovere,¹¹² H. Sakulin,¹¹² C. Schäfer,¹¹² C. Schwick,¹¹² M. Seidel,¹¹² M. Selvaggi,¹¹² A. Sharma,¹¹² P. Silva,¹¹² P. Sphicas,^{112,ww} A. Stakia,¹¹² J. Stegmann,¹¹² M. Stoye,¹¹² M. Tosi,¹¹² D. Treille,¹¹² A. Tsiros,¹¹² V. Veckalns,^{112,xx} M. Verweij,¹¹² W. D. Zeuner,¹¹² W. Bertl,^{113,a} L. Caminada,^{113,yy} K. Deiters,¹¹³ W. Erdmann,¹¹³ R. Horisberger,¹¹³ Q. Ingram,¹¹³ H. C. Kaestli,¹¹³ D. Kotlinski,¹¹³ U. Langenegger,¹¹³ T. Rohe,¹¹³ S. A. Wiederkehr,¹¹³ M. Backhaus,¹¹⁴ L. Bäni,¹¹⁴ P. Berger,¹¹⁴ L. Bianchini,¹¹⁴ B. Casal,¹¹⁴ G. Dissertori,¹¹⁴ M. Dittmar,¹¹⁴ M. Donegà,¹¹⁴ C. Dorfer,¹¹⁴ C. Grab,¹¹⁴ C. Heidegger,¹¹⁴ D. Hits,¹¹⁴ J. Hoss,¹¹⁴ G. Kasieczka,¹¹⁴ T. Kljnsma,¹¹⁴ W. Lustermaun,¹¹⁴ B. Mangano,¹¹⁴ M. Marionneau,¹¹⁴ M. T. Meinhard,¹¹⁴ D. Meister,¹¹⁴ F. Micheli,¹¹⁴ P. Musella,¹¹⁴ F. Nessi-Tedaldi,¹¹⁴ F. Pandolfi,¹¹⁴ J. Pata,¹¹⁴ F. Pauss,¹¹⁴ G. Perrin,¹¹⁴ L. Perrozzi,¹¹⁴ M. Quittnat,¹¹⁴ M. Reichmann,¹¹⁴ D. A. Sanz Becerra,¹¹⁴ M. Schönenberger,¹¹⁴ L. Shchutska,¹¹⁴ V. R. Tavolaro,¹¹⁴ K. Theofilatos,¹¹⁴ M. L. Vesterbacka Olsson,¹¹⁴ R. Wallny,¹¹⁴ D. H. Zhu,¹¹⁴ T. K. Aarrestad,¹¹⁵ C. Amsler,^{115,zz} M. F. Canelli,¹¹⁵ A. De Cosa,¹¹⁵ R. Del Burgo,¹¹⁵ S. Donato,¹¹⁵ C. Galloni,¹¹⁵ T. Hreus,¹¹⁵ B. Kilminster,¹¹⁵ D. Pinna,¹¹⁵ G. Rauco,¹¹⁵ P. Robmann,¹¹⁵ D. Salerno,¹¹⁵ K. Schweiger,¹¹⁵ C. Seitz,¹¹⁵ Y. Takahashi,¹¹⁵ A. Zucchetta,¹¹⁵ V. Candelise,¹¹⁶ Y. H. Chang,¹¹⁶ K. y. Cheng,¹¹⁶ T. H. Doan,¹¹⁶ Sh. Jain,¹¹⁶ R. Khurana,¹¹⁶ C. M. Kuo,¹¹⁶ W. Lin,¹¹⁶ A. Pozdnyakov,¹¹⁶ S. S. Yu,¹¹⁶ Arun Kumar,¹¹⁷ P. Chang,¹¹⁷ Y. Chao,¹¹⁷ K. F. Chen,¹¹⁷ P. H. Chen,¹¹⁷ F. Fiori,¹¹⁷ W.-S. Hou,¹¹⁷ Y. Hsiung,¹¹⁷ Y. F. Liu,¹¹⁷ R.-S. Lu,¹¹⁷ E. Paganis,¹¹⁷ A. Psallidas,¹¹⁷ A. Steen,¹¹⁷ J. f. Tsai,¹¹⁷ B. Asavapibhop,¹¹⁸ K. Kovitanggoon,¹¹⁸ G. Singh,¹¹⁸ N. Srimanobhas,¹¹⁸ M. N. Bakirci,^{119,aaa} A. Bat,¹¹⁹ F. Boran,¹¹⁹ S. Damarseekin,¹¹⁹ Z. S. Demiroglu,¹¹⁹ C. Dozen,¹¹⁹ E. Eskut,¹¹⁹ S. Girgis,¹¹⁹ G. Gokbulut,¹¹⁹ Y. Guler,¹¹⁹ I. Hos,^{119,bbb} E. E. Kangal,^{119,ccc} O. Kara,¹¹⁹ U. Kiminsu,¹¹⁹ M. Oglakci,¹¹⁹ G. Onengut,^{119,ddd} K. Ozdemir,^{119,eee} A. Polatoz,¹¹⁹ B. Tali,^{119,fff} U. G. Tok,¹¹⁹ H. Topakli,^{119,aaa} S. Turkcapar,¹¹⁹ I. S. Zorbakir,¹¹⁹ C. Zorbilmez,¹¹⁹ G. Karapinar,^{120,ggg} K. Ocalan,^{120,hhh} M. Yalvac,¹²⁰ M. Zeyrek,¹²⁰ E. Gülmez,¹²¹ M. Kaya,^{121,iii} O. Kaya,^{121,jjj} S. Tekten,¹²¹ E. A. Yetkin,^{121,kkk} M. N. Agaras,¹²² S. Atay,¹²² A. Cakir,¹²² K. Cankocak,¹²² Y. Komurcu,¹²² B. Grynyov,¹²³ L. Levchuk,¹²⁴ F. Ball,¹²⁵ L. Beck,¹²⁵ J. J. Brooke,¹²⁵ D. Burns,¹²⁵ E. Clement,¹²⁵ D. Cussans,¹²⁵ O. Davignon,¹²⁵ H. Flacher,¹²⁵ J. Goldstein,¹²⁵ G. P. Heath,¹²⁵ H. F. Heath,¹²⁵ L. Kreczko,¹²⁵ D. M. Newbold,^{125,lll} S. Paramesvaran,¹²⁵ T. Sakuma,¹²⁵ S. Seif El Nasr-storey,¹²⁵ D. Smith,¹²⁵ V. J. Smith,¹²⁵ K. W. Bell,¹²⁶ A. Belyaev,^{126,mmm} C. Brew,¹²⁶ R. M. Brown,¹²⁶ L. Calligaris,¹²⁶ D. Cieri,¹²⁶ D. J. A. Cockerill,¹²⁶ J. A. Coughlan,¹²⁶ K. Harder,¹²⁶ S. Harper,¹²⁶ J. Linacre,¹²⁶ E. Olaiya,¹²⁶ D. Petyt,¹²⁶ C. H. Shepherd-Themistocleous,¹²⁶

A. Thea,¹²⁶ I. R. Tomalin,¹²⁶ T. Williams,¹²⁶ W. J. Womersley,¹²⁶ G. Auzinger,¹²⁷ R. Bainbridge,¹²⁷ J. Borg,¹²⁷ S. Breeze,¹²⁷
 O. Buchmuller,¹²⁷ A. Bundock,¹²⁷ S. Casasso,¹²⁷ M. Citron,¹²⁷ D. Colling,¹²⁷ L. Corpe,¹²⁷ P. Dauncey,¹²⁷ G. Davies,¹²⁷
 A. De Wit,¹²⁷ M. Della Negra,¹²⁷ R. Di Maria,¹²⁷ A. Elwood,¹²⁷ Y. Haddad,¹²⁷ G. Hall,¹²⁷ G. Iles,¹²⁷ T. James,¹²⁷ R. Lane,¹²⁷
 C. Laner,¹²⁷ L. Lyons,¹²⁷ A.-M. Magnan,¹²⁷ S. Malik,¹²⁷ L. Mastrolorenzo,¹²⁷ T. Matsushita,¹²⁷ J. Nash,¹²⁷ A. Nikitenko,^{127,g}
 V. Palladino,¹²⁷ M. Pesaresi,¹²⁷ D. M. Raymond,¹²⁷ A. Richards,¹²⁷ A. Rose,¹²⁷ E. Scott,¹²⁷ C. Seez,¹²⁷ A. Shtipliyski,¹²⁷
 S. Summers,¹²⁷ A. Tapper,¹²⁷ K. Uchida,¹²⁷ M. Vazquez Acosta,^{127,nnn} T. Virdee,^{127,q} N. Wardle,¹²⁷ D. Winterbottom,¹²⁷
 J. Wright,¹²⁷ S. C. Zenz,¹²⁷ J. E. Cole,¹²⁸ P. R. Hobson,¹²⁸ A. Khan,¹²⁸ P. Kyberd,¹²⁸ I. D. Reid,¹²⁸ L. Teodorescu,¹²⁸
 S. Zahid,¹²⁸ A. Borzou,¹²⁹ K. Call,¹²⁹ J. Dittmann,¹²⁹ K. Hatakeyama,¹²⁹ H. Liu,¹²⁹ N. Pastika,¹²⁹ C. Smith,¹²⁹ R. Bartek,¹³⁰
 A. Dominguez,¹³⁰ A. Buccilli,¹³¹ S. I. Cooper,¹³¹ C. Henderson,¹³¹ P. Rumerio,¹³¹ C. West,¹³¹ D. Arcaro,¹³² A. Avetisyan,¹³²
 T. Bose,¹³² D. Gastler,¹³² D. Rankin,¹³² C. Richardson,¹³² J. Rohlf,¹³² L. Sulak,¹³² D. Zou,¹³² G. Benelli,¹³³ D. Cutts,¹³³
 M. Hadley,¹³³ J. Hakala,¹³³ U. Heintz,¹³³ J. M. Hogan,¹³³ K. H. M. Kwok,¹³³ E. Laird,¹³³ G. Landsberg,¹³³ J. Lee,¹³³
 Z. Mao,¹³³ M. Narain,¹³³ J. Pazzini,¹³³ S. Piperov,¹³³ S. Sagir,¹³³ R. Syarif,¹³³ D. Yu,¹³³ R. Band,¹³⁴ C. Brainerd,¹³⁴
 R. Breedon,¹³⁴ D. Burns,¹³⁴ M. Calderon De La Barca Sanchez,¹³⁴ M. Chertok,¹³⁴ J. Conway,¹³⁴ R. Conway,¹³⁴ P. T. Cox,¹³⁴
 R. Erbacher,¹³⁴ C. Flores,¹³⁴ G. Funk,¹³⁴ W. Ko,¹³⁴ R. Lander,¹³⁴ C. Mclean,¹³⁴ M. Mulhearn,¹³⁴ D. Pellett,¹³⁴ J. Pilot,¹³⁴
 S. Shalhout,¹³⁴ M. Shi,¹³⁴ J. Smith,¹³⁴ D. Stolp,¹³⁴ K. Tos,¹³⁴ M. Tripathi,¹³⁴ Z. Wang,¹³⁴ M. Bachtis,¹³⁵ C. Bravo,¹³⁵
 R. Cousins,¹³⁵ A. Dasgupta,¹³⁵ A. Florent,¹³⁵ J. Hauser,¹³⁵ M. Ignatenko,¹³⁵ N. Mccoll,¹³⁵ S. Regnard,¹³⁵ D. Saltzberg,¹³⁵
 C. Schnaible,¹³⁵ V. Valuev,¹³⁵ E. Bouvier,¹³⁶ K. Burt,¹³⁶ R. Clare,¹³⁶ J. Ellison,¹³⁶ J. W. Gary,¹³⁶ S. M. A. Ghiasi Shirazi,¹³⁶
 G. Hanson,¹³⁶ J. Heilman,¹³⁶ G. Karapostoli,¹³⁶ E. Kennedy,¹³⁶ F. Lacroix,¹³⁶ O. R. Long,¹³⁶ M. Olmedo Negrete,¹³⁶
 M. I. Paneva,¹³⁶ W. Si,¹³⁶ L. Wang,¹³⁶ H. Wei,¹³⁶ S. Wimpenny,¹³⁶ B. R. Yates,¹³⁶ J. G. Branson,¹³⁷ S. Cittolin,¹³⁷
 M. Derdzinski,¹³⁷ R. Gerosa,¹³⁷ D. Gilbert,¹³⁷ B. Hashemi,¹³⁷ A. Holzner,¹³⁷ D. Klein,¹³⁷ G. Kole,¹³⁷ V. Krutelyov,¹³⁷
 J. Letts,¹³⁷ M. Masciovecchio,¹³⁷ D. Olivito,¹³⁷ S. Padhi,¹³⁷ M. Pieri,¹³⁷ M. Sani,¹³⁷ V. Sharma,¹³⁷ S. Simon,¹³⁷ M. Tadel,¹³⁷
 A. Vartak,¹³⁷ S. Wasserbaech,^{137,ooo} J. Wood,¹³⁷ F. Würthwein,¹³⁷ A. Yagil,¹³⁷ G. Zevi Della Porta,¹³⁷ N. Amin,¹³⁸
 R. Bhandari,¹³⁸ J. Bradmiller-Feld,¹³⁸ C. Campagnari,¹³⁸ A. Dishaw,¹³⁸ V. Dutta,¹³⁸ M. Franco Sevilla,¹³⁸ L. Gouskos,¹³⁸
 R. Heller,¹³⁸ J. Incandela,¹³⁸ A. Ovcharova,¹³⁸ H. Qu,¹³⁸ J. Richman,¹³⁸ D. Stuart,¹³⁸ I. Suarez,¹³⁸ J. Yoo,¹³⁸ D. Anderson,¹³⁹
 A. Bornheim,¹³⁹ J. Bunn,¹³⁹ J. M. Lawhorn,¹³⁹ H. B. Newman,¹³⁹ T. Q. Nguyen,¹³⁹ C. Pena,¹³⁹ M. Spiropulu,¹³⁹
 J. R. Vlimant,¹³⁹ R. Wilkinson,¹³⁹ S. Xie,¹³⁹ Z. Zhang,¹³⁹ R. Y. Zhu,¹³⁹ M. B. Andrews,¹⁴⁰ T. Ferguson,¹⁴⁰ T. Mudholkar,¹⁴⁰
 M. Paulini,¹⁴⁰ J. Russ,¹⁴⁰ M. Sun,¹⁴⁰ H. Vogel,¹⁴⁰ I. Vorobiev,¹⁴⁰ M. Weinberg,¹⁴⁰ J. P. Cumalat,¹⁴¹ W. T. Ford,¹⁴¹
 F. Jensen,¹⁴¹ A. Johnson,¹⁴¹ M. Krohn,¹⁴¹ S. Leontsinis,¹⁴¹ T. Mulholland,¹⁴¹ K. Stenson,¹⁴¹ K. A. Ulmer,¹⁴¹ S. R. Wagner,¹⁴¹
 J. Alexander,¹⁴² J. Chaves,¹⁴² J. Chu,¹⁴² S. Dittmer,¹⁴² K. Mcdermott,¹⁴² N. Mirman,¹⁴² J. R. Patterson,¹⁴² D. Quach,¹⁴²
 A. Rinkevicius,¹⁴² A. Ryd,¹⁴² L. Skinnari,¹⁴² L. Soffi,¹⁴² S. M. Tan,¹⁴² Z. Tao,¹⁴² J. Thom,¹⁴² J. Tucker,¹⁴² P. Wittich,¹⁴²
 M. Zientek,¹⁴² S. Abdullin,¹⁴³ M. Albrow,¹⁴³ M. Alyari,¹⁴³ G. Apollinari,¹⁴³ A. Apresyan,¹⁴³ A. Apyan,¹⁴³ S. Banerjee,¹⁴³
 L. A. T. Bauerdick,¹⁴³ A. Beretvas,¹⁴³ J. Berryhill,¹⁴³ P. C. Bhat,¹⁴³ G. Bolla,^{143,a} K. Burkett,¹⁴³ J. N. Butler,¹⁴³ A. Canepa,¹⁴³
 G. B. Cerati,¹⁴³ H. W. K. Cheung,¹⁴³ F. Chlebana,¹⁴³ M. Cremonesi,¹⁴³ J. Duarte,¹⁴³ V. D. Elvira,¹⁴³ J. Freeman,¹⁴³
 Z. Gecse,¹⁴³ E. Gottschalk,¹⁴³ L. Gray,¹⁴³ D. Green,¹⁴³ S. Grünendahl,¹⁴³ O. Gutsche,¹⁴³ J. Hanlon,¹⁴³ R. M. Harris,¹⁴³
 S. Hasegawa,¹⁴³ J. Hirschauer,¹⁴³ Z. Hu,¹⁴³ B. Jayatilaka,¹⁴³ S. Jindariani,¹⁴³ M. Johnson,¹⁴³ U. Joshi,¹⁴³ B. Klima,¹⁴³
 B. Kreis,¹⁴³ S. Lammel,¹⁴³ D. Lincoln,¹⁴³ R. Lipton,¹⁴³ M. Liu,¹⁴³ T. Liu,¹⁴³ R. Lopes De Sá,¹⁴³ J. Lykken,¹⁴³
 K. Maeshima,¹⁴³ N. Magini,¹⁴³ J. M. Marraffino,¹⁴³ D. Mason,¹⁴³ P. McBride,¹⁴³ P. Merkel,¹⁴³ S. Mrenna,¹⁴³ S. Nahn,¹⁴³
 V. O'Dell,¹⁴³ K. Pedro,¹⁴³ O. Prokofyev,¹⁴³ G. Rakness,¹⁴³ L. Ristori,¹⁴³ B. Schneider,¹⁴³ E. Sexton-Kennedy,¹⁴³ A. Soha,¹⁴³
 W. J. Spalding,¹⁴³ L. Spiegel,¹⁴³ S. Stoynev,¹⁴³ J. Strait,¹⁴³ N. Strobbe,¹⁴³ L. Taylor,¹⁴³ S. Tkaczyk,¹⁴³ N. V. Tran,¹⁴³
 L. Uplegger,¹⁴³ E. W. Vaandering,¹⁴³ C. Vernieri,¹⁴³ M. Verzocchi,¹⁴³ R. Vidal,¹⁴³ M. Wang,¹⁴³ H. A. Weber,¹⁴³
 A. Whitbeck,¹⁴³ W. Wu,¹⁴³ D. Acosta,¹⁴⁴ P. Avery,¹⁴⁴ P. Bortignon,¹⁴⁴ D. Bourilkov,¹⁴⁴ A. Brinkerhoff,¹⁴⁴ A. Carnes,¹⁴⁴
 M. Carver,¹⁴⁴ D. Curry,¹⁴⁴ R. D. Field,¹⁴⁴ I. K. Furic,¹⁴⁴ S. V. Gleyzer,¹⁴⁴ B. M. Joshi,¹⁴⁴ J. Konigsberg,¹⁴⁴ A. Korytov,¹⁴⁴
 K. Kotov,¹⁴⁴ P. Ma,¹⁴⁴ K. Matchev,¹⁴⁴ H. Mei,¹⁴⁴ G. Mitselmakher,¹⁴⁴ K. Shi,¹⁴⁴ D. Sperka,¹⁴⁴ N. Terentyev,¹⁴⁴ L. Thomas,¹⁴⁴
 J. Wang,¹⁴⁴ S. Wang,¹⁴⁴ J. Yelton,¹⁴⁴ Y. R. Joshi,¹⁴⁵ S. Linn,¹⁴⁵ P. Markowitz,¹⁴⁵ J. L. Rodriguez,¹⁴⁵ A. Ackert,¹⁴⁶
 T. Adams,¹⁴⁶ A. Askew,¹⁴⁶ S. Hagopian,¹⁴⁶ V. Hagopian,¹⁴⁶ K. F. Johnson,¹⁴⁶ T. Kolberg,¹⁴⁶ G. Martinez,¹⁴⁶ T. Perry,¹⁴⁶
 H. Prosper,¹⁴⁶ A. Saha,¹⁴⁶ A. Santra,¹⁴⁶ V. Sharma,¹⁴⁶ R. Yohay,¹⁴⁶ M. M. Baarmand,¹⁴⁷ V. Bhopatkar,¹⁴⁷
 S. Colafranceschi,¹⁴⁷ M. Hohmann,¹⁴⁷ D. Noonan,¹⁴⁷ T. Roy,¹⁴⁷ F. Yumiceva,¹⁴⁷ M. R. Adams,¹⁴⁸ L. Apanasevich,¹⁴⁸
 D. Berry,¹⁴⁸ R. R. Betts,¹⁴⁸ R. Cavanaugh,¹⁴⁸ X. Chen,¹⁴⁸ O. Evdokimov,¹⁴⁸ C. E. Gerber,¹⁴⁸ D. A. Hangal,¹⁴⁸
 D. J. Hofman,¹⁴⁸ K. Jung,¹⁴⁸ J. Kamin,¹⁴⁸ I. D. Sandoval Gonzalez,¹⁴⁸ M. B. Tonjes,¹⁴⁸ H. Trauger,¹⁴⁸ N. Varelas,¹⁴⁸

H. Wang,¹⁴⁸ Z. Wu,¹⁴⁸ J. Zhang,¹⁴⁸ B. Bilki,^{149,ppp} W. Clarida,¹⁴⁹ K. Dilsiz,^{149,qqq} S. Durgut,¹⁴⁹ R. P. Gandrajula,¹⁴⁹ M. Haytmyradov,¹⁴⁹ V. Khristenko,¹⁴⁹ J.-P. Merlo,¹⁴⁹ H. Mermerkaya,^{149,rrr} A. Mestvirishvili,¹⁴⁹ A. Moeller,¹⁴⁹ J. Nachtman,¹⁴⁹ H. Ogul,^{149,sss} Y. Onel,¹⁴⁹ F. Ozok,^{149,ttt} A. Penzo,¹⁴⁹ C. Snyder,¹⁴⁹ E. Tiras,¹⁴⁹ J. Wetzel,¹⁴⁹ K. Yi,¹⁴⁹ B. Blumenfeld,¹⁵⁰ A. Cocoros,¹⁵⁰ N. Eminizer,¹⁵⁰ D. Fehling,¹⁵⁰ L. Feng,¹⁵⁰ A. V. Gritsan,¹⁵⁰ P. Maksimovic,¹⁵⁰ J. Roskes,¹⁵⁰ U. Sarica,¹⁵⁰ M. Swartz,¹⁵⁰ M. Xiao,¹⁵⁰ C. You,¹⁵⁰ A. Al-bataineh,¹⁵¹ P. Baringer,¹⁵¹ A. Bean,¹⁵¹ S. Boren,¹⁵¹ J. Bowen,¹⁵¹ J. Castle,¹⁵¹ S. Khalil,¹⁵¹ A. Kropivnitskaya,¹⁵¹ D. Majumder,¹⁵¹ W. Mcbrayer,¹⁵¹ M. Murray,¹⁵¹ C. Rogan,¹⁵¹ C. Royon,¹⁵¹ S. Sanders,¹⁵¹ E. Schmitz,¹⁵¹ J. D. Tapia Takaki,¹⁵¹ Q. Wang,¹⁵¹ A. Ivanov,¹⁵² K. Kaadze,¹⁵² Y. Maravin,¹⁵² A. Mohammadi,¹⁵² L. K. Saini,¹⁵² N. Skhirtladze,¹⁵² F. Rebassoo,¹⁵³ D. Wright,¹⁵³ A. Baden,¹⁵⁴ O. Baron,¹⁵⁴ A. Belloni,¹⁵⁴ S. C. Eno,¹⁵⁴ Y. Feng,¹⁵⁴ C. Ferraioli,¹⁵⁴ N. J. Hadley,¹⁵⁴ S. Jabeen,¹⁵⁴ G. Y. Jeng,¹⁵⁴ R. G. Kellogg,¹⁵⁴ J. Kunkle,¹⁵⁴ A. C. Mignerey,¹⁵⁴ F. Ricci-Tam,¹⁵⁴ Y. H. Shin,¹⁵⁴ A. Skuja,¹⁵⁴ S. C. Tonwar,¹⁵⁴ D. Abercrombie,¹⁵⁵ B. Allen,¹⁵⁵ V. Azzolini,¹⁵⁵ R. Barbieri,¹⁵⁵ A. Baty,¹⁵⁵ G. Bauer,¹⁵⁵ R. Bi,¹⁵⁵ S. Brandt,¹⁵⁵ W. Busza,¹⁵⁵ I. A. Cali,¹⁵⁵ M. D'Alfonso,¹⁵⁵ Z. Demiragli,¹⁵⁵ G. Gomez Ceballos,¹⁵⁵ M. Goncharov,¹⁵⁵ D. Hsu,¹⁵⁵ M. Hu,¹⁵⁵ Y. Iiyama,¹⁵⁵ G. M. Innocenti,¹⁵⁵ M. Klute,¹⁵⁵ D. Kovalskiy,¹⁵⁵ Y.-J. Lee,¹⁵⁵ A. Levin,¹⁵⁵ P. D. Luckey,¹⁵⁵ B. Maier,¹⁵⁵ A. C. Marini,¹⁵⁵ C. McGinn,¹⁵⁵ C. Mironov,¹⁵⁵ S. Narayanan,¹⁵⁵ X. Niu,¹⁵⁵ C. Paus,¹⁵⁵ C. Roland,¹⁵⁵ G. Roland,¹⁵⁵ J. Salfeld-Nebgen,¹⁵⁵ G. S. F. Stephans,¹⁵⁵ K. Sumorok,¹⁵⁵ K. Tatar,¹⁵⁵ D. Velicanu,¹⁵⁵ J. Wang,¹⁵⁵ T. W. Wang,¹⁵⁵ B. Wyslouch,¹⁵⁵ A. C. Benvenuti,¹⁵⁶ R. M. Chatterjee,¹⁵⁶ A. Evans,¹⁵⁶ P. Hansen,¹⁵⁶ J. Hiltbrand,¹⁵⁶ S. Kalafut,¹⁵⁶ Y. Kubota,¹⁵⁶ Z. Lesko,¹⁵⁶ J. Mans,¹⁵⁶ S. Nourbakhsh,¹⁵⁶ N. Ruckstuhl,¹⁵⁶ R. Rusack,¹⁵⁶ J. Turkewitz,¹⁵⁶ M. A. Wadud,¹⁵⁶ J. G. Acosta,¹⁵⁷ S. Oliveros,¹⁵⁷ E. Avdeeva,¹⁵⁸ K. Bloom,¹⁵⁸ D. R. Claes,¹⁵⁸ C. Fangmeier,¹⁵⁸ F. Golf,¹⁵⁸ R. Gonzalez Suarez,¹⁵⁸ R. Kamalieddin,¹⁵⁸ I. Kravchenko,¹⁵⁸ J. Monroy,¹⁵⁸ J. E. Siado,¹⁵⁸ G. R. Snow,¹⁵⁸ B. Stieger,¹⁵⁸ J. Dolen,¹⁵⁹ A. Godshalk,¹⁵⁹ C. Harrington,¹⁵⁹ I. Iashvili,¹⁵⁹ D. Nguyen,¹⁵⁹ A. Parker,¹⁵⁹ S. Rappoccio,¹⁵⁹ B. Roobahani,¹⁵⁹ G. Alverson,¹⁶⁰ E. Barberis,¹⁶⁰ C. Freer,¹⁶⁰ A. Hortiangtham,¹⁶⁰ A. Massironi,¹⁶⁰ D. M. Morse,¹⁶⁰ T. Orimoto,¹⁶⁰ R. Teixeira De Lima,¹⁶⁰ T. Wamorkar,¹⁶⁰ B. Wang,¹⁶⁰ A. Wisecarver,¹⁶⁰ D. Wood,¹⁶⁰ S. Bhattacharya,¹⁶¹ O. Charaf,¹⁶¹ K. A. Hahn,¹⁶¹ N. Mucia,¹⁶¹ N. Odell,¹⁶¹ M. H. Schmitt,¹⁶¹ K. Sung,¹⁶¹ M. Trovato,¹⁶¹ M. Velasco,¹⁶¹ R. Bucci,¹⁶² N. Dev,¹⁶² M. Hildreth,¹⁶² K. Hurtado Anampa,¹⁶² C. Jessop,¹⁶² D. J. Karmgard,¹⁶² N. Kellams,¹⁶² K. Lannon,¹⁶² W. Li,¹⁶² N. Loukas,¹⁶² N. Marinelli,¹⁶² F. Meng,¹⁶² C. Mueller,¹⁶² Y. Musienko,^{162,II} M. Planer,¹⁶² A. Reinsvold,¹⁶² R. Ruchti,¹⁶² P. Siddireddy,¹⁶² G. Smith,¹⁶² S. Taroni,¹⁶² M. Wayne,¹⁶² A. Wightman,¹⁶² M. Wolf,¹⁶² A. Woodard,¹⁶² J. Alimena,¹⁶³ L. Antonelli,¹⁶³ B. Bylsma,¹⁶³ L. S. Durkin,¹⁶³ S. Flowers,¹⁶³ B. Francis,¹⁶³ A. Hart,¹⁶³ C. Hill,¹⁶³ W. Ji,¹⁶³ T. Y. Ling,¹⁶³ B. Liu,¹⁶³ W. Luo,¹⁶³ B. L. Winer,¹⁶³ H. W. Wulsin,¹⁶³ S. Cooperstein,¹⁶⁴ O. Driga,¹⁶⁴ P. Elmer,¹⁶⁴ J. Hardenbrook,¹⁶⁴ P. Hebda,¹⁶⁴ S. Higginbotham,¹⁶⁴ A. Kalogeropoulos,¹⁶⁴ D. Lange,¹⁶⁴ J. Luo,¹⁶⁴ D. Marlow,¹⁶⁴ K. Mei,¹⁶⁴ I. Ojalvo,¹⁶⁴ J. Olsen,¹⁶⁴ C. Palmer,¹⁶⁴ P. Piroué,¹⁶⁴ D. Stickland,¹⁶⁴ C. Tully,¹⁶⁴ S. Malik,¹⁶⁵ S. Norberg,¹⁶⁵ A. Barker,¹⁶⁶ V. E. Barnes,¹⁶⁶ S. Das,¹⁶⁶ S. Folgueras,¹⁶⁶ L. Gutay,¹⁶⁶ M. Jones,¹⁶⁶ A. W. Jung,¹⁶⁶ A. Khatiwada,¹⁶⁶ D. H. Miller,¹⁶⁶ N. Neumeister,¹⁶⁶ C. C. Peng,¹⁶⁶ H. Qiu,¹⁶⁶ J. F. Schulte,¹⁶⁶ J. Sun,¹⁶⁶ F. Wang,¹⁶⁶ R. Xiao,¹⁶⁶ W. Xie,¹⁶⁶ T. Cheng,¹⁶⁷ N. Parashar,¹⁶⁷ J. Stupak,¹⁶⁷ Z. Chen,¹⁶⁸ K. M. Ecklund,¹⁶⁸ S. Freed,¹⁶⁸ F. J. M. Geurts,¹⁶⁸ M. Guilbaud,¹⁶⁸ M. Kilpatrick,¹⁶⁸ W. Li,¹⁶⁸ B. Michlin,¹⁶⁸ B. P. Padley,¹⁶⁸ J. Roberts,¹⁶⁸ J. Rorie,¹⁶⁸ W. Shi,¹⁶⁸ Z. Tu,¹⁶⁸ J. Zabel,¹⁶⁸ A. Zhang,¹⁶⁸ A. Bodek,¹⁶⁹ P. de Barbaro,¹⁶⁹ R. Demina,¹⁶⁹ Y. t. Duh,¹⁶⁹ T. Ferbel,¹⁶⁹ M. Galanti,¹⁶⁹ A. Garcia-Bellido,¹⁶⁹ J. Han,¹⁶⁹ O. Hindrichs,¹⁶⁹ A. Khukhunaishvili,¹⁶⁹ K. H. Lo,¹⁶⁹ P. Tan,¹⁶⁹ M. Verzetti,¹⁶⁹ R. Ciesielski,¹⁷⁰ K. Goulianos,¹⁷⁰ C. Mesropian,¹⁷⁰ A. Agapitos,¹⁷¹ J. P. Chou,¹⁷¹ Y. Gershtein,¹⁷¹ T. A. Gómez Espinosa,¹⁷¹ E. Halkiadakis,¹⁷¹ M. Heindl,¹⁷¹ E. Hughes,¹⁷¹ S. Kaplan,¹⁷¹ R. Kunnawalkam Elayavalli,¹⁷¹ S. Kyriacou,¹⁷¹ A. Lath,¹⁷¹ R. Montalvo,¹⁷¹ K. Nash,¹⁷¹ M. Osherson,¹⁷¹ H. Saka,¹⁷¹ S. Salur,¹⁷¹ S. Schnetzer,¹⁷¹ D. Sheffield,¹⁷¹ S. Somalwar,¹⁷¹ R. Stone,¹⁷¹ S. Thomas,¹⁷¹ P. Thomassen,¹⁷¹ M. Walker,¹⁷¹ A. G. Delannoy,¹⁷² J. Heideman,¹⁷² G. Riley,¹⁷² K. Rose,¹⁷² S. Spanier,¹⁷² K. Thapa,¹⁷² O. Bouhali,^{173,uuu} A. Castaneda Hernandez,^{173,uuu} A. Celik,¹⁷³ M. Dalchenko,¹⁷³ M. De Mattia,¹⁷³ A. Delgado,¹⁷³ S. Dildick,¹⁷³ R. Eusebi,¹⁷³ J. Gilmore,¹⁷³ T. Huang,¹⁷³ T. Kamon,^{173,vvv} R. Mueller,¹⁷³ Y. Pakhotin,¹⁷³ R. Patel,¹⁷³ A. Perloff,¹⁷³ L. Pemiè,¹⁷³ D. Rathjens,¹⁷³ A. Safonov,¹⁷³ A. Tatarinov,¹⁷³ N. Akchurin,¹⁷⁴ J. Damgov,¹⁷⁴ F. De Guio,¹⁷⁴ P. R. Duerdo,¹⁷⁴ J. Faulkner,¹⁷⁴ E. Gурpinar,¹⁷⁴ S. Kunori,¹⁷⁴ K. Lamichhane,¹⁷⁴ S. W. Lee,¹⁷⁴ T. Libeiro,¹⁷⁴ T. Mengke,¹⁷⁴ S. Muthumuni,¹⁷⁴ T. Peltola,¹⁷⁴ S. Undleeb,¹⁷⁴ I. Volobouev,¹⁷⁴ Z. Wang,¹⁷⁴ S. Greene,¹⁷⁵ A. Gurrola,¹⁷⁵ R. Janjam,¹⁷⁵ W. Johns,¹⁷⁵ C. Maguire,¹⁷⁵ A. Melo,¹⁷⁵ H. Ni,¹⁷⁵ K. Padeken,¹⁷⁵ P. Sheldon,¹⁷⁵ S. Tuo,¹⁷⁵ J. Velkovska,¹⁷⁵ Q. Xu,¹⁷⁵ M. W. Arenton,¹⁷⁶ P. Barria,¹⁷⁶ B. Cox,¹⁷⁶ R. Hirosky,¹⁷⁶ M. Joyce,¹⁷⁶ A. Ledovsky,¹⁷⁶ H. Li,¹⁷⁶ C. Neu,¹⁷⁶ T. Sinthuprasith,¹⁷⁶ Y. Wang,¹⁷⁶ E. Wolfe,¹⁷⁶ F. Xia,¹⁷⁶ R. Harr,¹⁷⁷ P. E. Karchin,¹⁷⁷ N. Poudyal,¹⁷⁷ J. Sturdy,¹⁷⁷ P. Thapa,¹⁷⁷ S. Zaleski,¹⁷⁷ M. Brodski,¹⁷⁸ J. Buchanan,¹⁷⁸ C. Caillol,¹⁷⁸ D. Carlsmith,¹⁷⁸ S. Dasu,¹⁷⁸ L. Dodd,¹⁷⁸ S. Duric,¹⁷⁸ B. Gomber,¹⁷⁸ M. Grothe,¹⁷⁸ M. Herndon,¹⁷⁸ A. Hervé,¹⁷⁸

U. Hussain,¹⁷⁸ P. Klabbbers,¹⁷⁸ A. Lanaro,¹⁷⁸ A. Levine,¹⁷⁸ K. Long,¹⁷⁸ R. Loveless,¹⁷⁸ T. Ruggles,¹⁷⁸ A. Savin,¹⁷⁸
 N. Smith,¹⁷⁸ W. H. Smith,¹⁷⁸ D. Taylor,¹⁷⁸ and N. Woods¹⁷⁸

(CMS Collaboration)

- ¹*Yerevan Physics Institute, Yerevan, Armenia*
²*Institut für Hochenergiephysik, Wien, Austria*
³*Institute for Nuclear Problems, Minsk, Belarus*
⁴*Universiteit Antwerpen, Antwerpen, Belgium*
⁵*Vrije Universiteit Brussel, Brussel, Belgium*
⁶*Université Libre de Bruxelles, Bruxelles, Belgium*
⁷*Ghent University, Ghent, Belgium*
⁸*Université Catholique de Louvain, Louvain-la-Neuve, Belgium*
⁹*Centro Brasileiro de Pesquisas Físicas, Rio de Janeiro, Brazil*
¹⁰*Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil*
^{11a}*Universidade Estadual Paulista, São Paulo, Brazil*
^{11b}*Universidade Federal do ABC, São Paulo, Brazil*
¹²*Institute for Nuclear Research and Nuclear Energy, Bulgarian Academy of Sciences, Sofia, Bulgaria*
¹³*University of Sofia, Sofia, Bulgaria*
¹⁴*Beihang 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*Tsinghua University, Beijing, China*
¹⁸*Universidad de Los Andes, Bogota, Colombia*
¹⁹*University of Split, Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, Split, Croatia*
²⁰*University of Split, Faculty of Science, Split, Croatia*
²¹*Institute Rudjer Boskovic, Zagreb, Croatia*
²²*University of Cyprus, Nicosia, Cyprus*
²³*Charles University, Prague, Czech Republic*
²⁴*Universidad San Francisco de Quito, Quito, Ecuador*
²⁵*Academy of Scientific Research and Technology of the Arab Republic of Egypt, Egyptian Network of High Energy Physics, Cairo, Egypt*
²⁶*National Institute of Chemical Physics and Biophysics, Tallinn, Estonia*
²⁷*Department of Physics, University of Helsinki, Helsinki, Finland*
²⁸*Helsinki Institute of Physics, Helsinki, Finland*
²⁹*Lappeenranta University of Technology, Lappeenranta, Finland*
³⁰*IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France*
³¹*Laboratoire Leprince-Ringuet, Ecole polytechnique, CNRS/IN2P3, Université Paris-Saclay, Palaiseau, France*
³²*Université de Strasbourg, CNRS, IPHC UMR 7178, Strasbourg, France*
³³*Centre de Calcul de l'Institut National de Physique Nucleaire et de Physique des Particules, CNRS/IN2P3, Villeurbanne, France*
³⁴*Université de Lyon, Université Claude Bernard Lyon 1, CNRS-IN2P3, Institut de Physique Nucléaire de Lyon, Villeurbanne, France*
³⁵*Georgian Technical University, Tbilisi, Georgia*
³⁶*Tbilisi State University, Tbilisi, Georgia*
³⁷*RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany*
³⁸*RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany*
³⁹*RWTH Aachen University, III. Physikalisches Institut B, Aachen, Germany*
⁴⁰*Deutsches Elektronen-Synchrotron, Hamburg, Germany*
⁴¹*University of Hamburg, Hamburg, Germany*
⁴²*Institut für Experimentelle Teilchenphysik, Karlsruhe, Germany*
⁴³*Institute of Nuclear and Particle Physics (INPP), NCSR Demokritos, Aghia Paraskevi, Greece*
⁴⁴*National and Kapodistrian University of Athens, Athens, Greece*
⁴⁵*National Technical University of Athens, Athens, Greece*
⁴⁶*University of Ioánnina, Ioánnina, Greece*
⁴⁷*MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary*

- ⁴⁸Wigner Research Centre for Physics, Budapest, Hungary
⁴⁹Institute of Nuclear Research ATOMKI, Debrecen, Hungary
⁵⁰Institute of Physics, University of Debrecen, Debrecen, Hungary
⁵¹Indian Institute of Science (IISc), Bangalore, India
⁵²National Institute of Science Education and Research, Bhubaneswar, India
⁵³Panjab University, Chandigarh, India
⁵⁴University of Delhi, Delhi, India
⁵⁵Saha Institute of Nuclear Physics, HBNI, Kolkata, India
⁵⁶Indian Institute of Technology Madras, Madras, India
⁵⁷Bhabha Atomic Research Centre, Mumbai, India
⁵⁸Tata Institute of Fundamental Research-A, Mumbai, India
⁵⁹Tata Institute of Fundamental Research-B, Mumbai, India
⁶⁰Indian Institute of Science Education and Research (IISER), Pune, India
⁶¹Institute for Research in Fundamental Sciences (IPM), Tehran, Iran
⁶²University College Dublin, Dublin, Ireland
^{63a}INFN Sezione di Bari, Bari, Italy
^{63b}Università di Bari, Bari, Italy
^{63c}Politecnico di Bari, Bari, Italy
^{64a}INFN Sezione di Bologna, Bologna, Italy
^{64b}Università di Bologna, Bologna, Italy
^{65a}INFN Sezione di Catania, Catania, Italy
^{65b}Università di Catania, Catania, Italy
^{66a}INFN Sezione di Firenze, Firenze, Italy
^{66b}Università di Firenze, Firenze, Italy
⁶⁷INFN Laboratori Nazionali di Frascati, Frascati, Italy
^{68a}INFN Sezione di Genova, Genova, Italy
^{68b}Università di Genova, Genova, Italy
^{69a}INFN Sezione di Milano-Bicocca, Milano, Italy
^{69b}Università di Milano-Bicocca, Milano, Italy
^{70a}INFN Sezione di Napoli, Roma, Italy
^{70b}Università di Napoli 'Federico II', Roma, Italy
^{70c}Università della Basilicata, Roma, Italy
^{70d}Università G. Marconi, Roma, Italy
^{71a}INFN Sezione di Padova, Trento, Italy
^{71b}Università di Padova, Trento, Italy
^{71c}Università di Trento, Trento, Italy
^{72a}INFN Sezione di Pavia, Pavia, Italy
^{72b}Università di Pavia, Pavia, Italy
^{73a}INFN Sezione di Perugia, Perugia, Italy
^{73b}Università di Perugia, Perugia, Italy
^{74a}INFN Sezione di Pisa, Pisa, Italy
^{74b}Università di Pisa, Pisa, Italy
^{74c}Scuola Normale Superiore di Pisa, Pisa, Italy
^{75a}INFN Sezione di Roma, Rome, Italy
^{75b}Sapienza Università di Roma, Rome, Italy
^{76a}INFN Sezione di Torino, Torino, Italy
^{76b}Università di Torino, Torino, Italy
^{76c}Università del Piemonte Orientale, Novara, Italy
^{77a}INFN Sezione di Trieste, Trieste, Italy
^{77b}Università di Trieste, Trieste, Italy
⁷⁸Kyungpook National University, Daegu, Korea
⁷⁹Chonnam National University, Institute for Universe and Elementary Particles, Kwangju, Korea
⁸⁰Hanyang University, Seoul, Korea
⁸¹Korea University, Seoul, Korea
⁸²Seoul National University, Seoul, Korea
⁸³University of Seoul, Seoul, Korea
⁸⁴Sungkyunkwan University, Suwon, Korea
⁸⁵Vilnius University, Vilnius, Lithuania
⁸⁶National Centre for Particle Physics, Universiti Malaya, Kuala Lumpur, Malaysia
⁸⁷Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico

- ⁸⁸*Universidad Iberoamericana, Mexico City, Mexico*
- ⁸⁹*Benemerita Universidad Autonoma de Puebla, Puebla, Mexico*
- ⁹⁰*Universidad Autónoma de San Luis Potosí, San Luis Potosí, Mexico*
- ⁹¹*University of Auckland, Auckland, New Zealand*
- ⁹²*University of Canterbury, Christchurch, New Zealand*
- ⁹³*National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan*
- ⁹⁴*National Centre for Nuclear Research, Swierk, Poland*
- ⁹⁵*Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland*
- ⁹⁶*Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal*
- ⁹⁷*Joint Institute for Nuclear Research, Dubna, Russia*
- ⁹⁸*Petersburg Nuclear Physics Institute, Gatchina (St. Petersburg), Russia*
- ⁹⁹*Institute for Nuclear Research, Moscow, Russia*
- ¹⁰⁰*Institute for Theoretical and Experimental Physics, Moscow, Russia*
- ¹⁰¹*Moscow Institute of Physics and Technology, Moscow, Russia*
- ¹⁰²*National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia*
- ¹⁰³*P. N. Lebedev Physical Institute, Moscow, Russia*
- ¹⁰⁴*Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia*
- ¹⁰⁵*Novosibirsk State University (NSU), Novosibirsk, Russia*
- ¹⁰⁶*State Research Center of Russian Federation, Institute for High Energy Physics of NRC "Kurchatov Institute", Protvino, Russia*
- ¹⁰⁷*University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia*
- ¹⁰⁸*Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain*
- ¹⁰⁹*Universidad Autónoma de Madrid, Madrid, Spain*
- ¹¹⁰*Universidad de Oviedo, Oviedo, Spain*
- ¹¹¹*Instituto de Física de Cantabria (IFCA), CSIC-Universidad de Cantabria, Santander, Spain*
- ¹¹²*CERN, European Organization for Nuclear Research, Geneva, Switzerland*
- ¹¹³*Paul Scherrer Institut, Villigen, Switzerland*
- ¹¹⁴*ETH Zurich - Institute for Particle Physics and Astrophysics (IPA), Zurich, Switzerland*
- ¹¹⁵*Universität Zürich, Zurich, Switzerland*
- ¹¹⁶*National Central University, Chung-Li, Taiwan*
- ¹¹⁷*National Taiwan University (NTU), Taipei, Taiwan*
- ¹¹⁸*Chulalongkorn University, Faculty of Science, Department of Physics, Bangkok, Thailand*
- ¹¹⁹*Çukurova University, Physics Department, Science and Art Faculty, Adana, Turkey*
- ¹²⁰*Middle East Technical University, Physics Department, Ankara, Turkey*
- ¹²¹*Bogazici University, Istanbul, Turkey*
- ¹²²*Istanbul Technical University, Istanbul, Turkey*
- ¹²³*Institute for Scintillation Materials of National Academy of Science of Ukraine, Kharkov, Ukraine*
- ¹²⁴*National Scientific Center, Kharkov Institute of Physics and Technology, Kharkov, Ukraine*
- ¹²⁵*University of Bristol, Bristol, United Kingdom*
- ¹²⁶*Rutherford Appleton Laboratory, Didcot, United Kingdom*
- ¹²⁷*Imperial College, London, United Kingdom*
- ¹²⁸*Brunel University, Uxbridge, United Kingdom*
- ¹²⁹*Baylor University, Waco, Texas, USA*
- ¹³⁰*Catholic University of America, Washington, DC, USA*
- ¹³¹*The University of Alabama, Tuscaloosa, Alabama, USA*
- ¹³²*Boston University, Boston, Massachusetts, USA*
- ¹³³*Brown University, Providence, Rhode Island, USA*
- ¹³⁴*University of California, Davis, Davis, California, USA*
- ¹³⁵*University of California, Los Angeles, Los Angeles, California, USA*
- ¹³⁶*University of California, Riverside, Riverside, California, USA*
- ¹³⁷*University of California, San Diego, La Jolla, California, USA*
- ¹³⁸*University of California, Santa Barbara, Department of Physics, Santa Barbara, California, USA*
- ¹³⁹*California Institute of Technology, Pasadena, California, USA*
- ¹⁴⁰*Carnegie Mellon University, Pittsburgh, Pennsylvania, USA*
- ¹⁴¹*University of Colorado Boulder, Boulder, Colorado, USA*
- ¹⁴²*Cornell University, Ithaca, New York, USA*
- ¹⁴³*Fermi National Accelerator Laboratory, Batavia, Illinois, USA*
- ¹⁴⁴*University of Florida, Gainesville, Florida, USA*
- ¹⁴⁵*Florida International University, Miami, Florida, USA*

- ¹⁴⁶Florida State University, Tallahassee, Florida, USA
¹⁴⁷Florida Institute of Technology, Melbourne, Florida, USA
¹⁴⁸University of Illinois at Chicago (UIC), Chicago, Illinois, USA
¹⁴⁹The University of Iowa, Iowa City, Iowa, USA
¹⁵⁰Johns Hopkins University, Baltimore, Maryland, USA
¹⁵¹The University of Kansas, Lawrence, Kansas, USA
¹⁵²Kansas State University, Manhattan, Kansas, USA
¹⁵³Lawrence Livermore National Laboratory, Livermore, California, USA
¹⁵⁴University of Maryland, College Park, Maryland, USA
¹⁵⁵Massachusetts Institute of Technology, Cambridge, Massachusetts, USA
¹⁵⁶University of Minnesota, Minneapolis, Minnesota, USA
¹⁵⁷University of Mississippi, Oxford, Mississippi, USA
¹⁵⁸University of Nebraska-Lincoln, Lincoln, Nebraska, USA
¹⁵⁹State University of New York at Buffalo, Buffalo, New York, USA
¹⁶⁰Northeastern University, Boston, Massachusetts, USA
¹⁶¹Northwestern University, Evanston, Illinois, USA
¹⁶²University of Notre Dame, Notre Dame, Indiana, USA
¹⁶³The Ohio State University, Columbus, Ohio, USA
¹⁶⁴Princeton University, Princeton, New Jersey, USA
¹⁶⁵University of Puerto Rico, Mayaguez, Puerto Rico
¹⁶⁶Purdue University, West Lafayette, Indiana, USA
¹⁶⁷Purdue University Northwest, Hammond, Indiana, USA
¹⁶⁸Rice University, Houston, Texas, USA
¹⁶⁹University of Rochester, Rochester, New York, USA
¹⁷⁰The Rockefeller University, New York, New York, USA
¹⁷¹Rutgers, The State University of New Jersey, Piscataway, New Jersey, USA
¹⁷²University of Tennessee, Knoxville, Tennessee, USA
¹⁷³Texas A&M University, College Station, Texas, USA
¹⁷⁴Texas Tech University, Lubbock, Texas, USA
¹⁷⁵Vanderbilt University, Nashville, Tennessee, USA
¹⁷⁶University of Virginia, Charlottesville, Virginia, USA
¹⁷⁷Wayne State University, Detroit, Michigan, USA
¹⁷⁸University of Wisconsin - Madison, Madison, Wisconsin, USA

^aDeceased.

^bAlso at Vienna University of Technology, Vienna, Austria.

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

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

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

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

^gAlso at Institute for Theoretical and Experimental Physics, Moscow, Russia.

^hAlso at Joint Institute for Nuclear Research, Dubna, Russia.

ⁱAlso at Zewail City of Science and Technology, Zewail, Egypt.

^jAlso at Fayoum University, El-Fayoum, Egypt.

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

^lAlso at Ain Shams University, Cairo, Egypt.

^mAlso at Department of Physics, King Abdulaziz University, Jeddah, Saudi Arabia.

ⁿAlso at Université de Haute Alsace, Mulhouse, France.

^oAlso at Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia.

^pAlso at Tbilisi State University, Tbilisi, Georgia.

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

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

^sAlso at University of Hamburg, Hamburg, Germany.

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

^uAlso at MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary.

^vAlso at Institute of Nuclear Research ATOMKI, Debrecen, Hungary.

^wAlso at Institute of Physics, University of Debrecen, Debrecen, Hungary.

^xAlso at IIT Bhubaneswar, Bhubaneswar, India.

^yAlso at Institute of Physics, Bhubaneswar, India.

^zAlso at University of Visva-Bharati, Santiniketan, India.

- ^{aa} Also at University of Ruhuna, Matara, Sri Lanka.
- ^{bb} Also at Isfahan University of Technology, Isfahan, Iran.
- ^{cc} Also at Yazd University, Yazd, Iran.
- ^{dd} Also at Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, Tehran, Iran.
- ^{ee} Also at Università degli Studi di Siena, Siena, Italy.
- ^{ff} Also at INFN Sezione di Milano-Bicocca, Università di Milano-Bicocca, Milano, Italy.
- ^{gg} Also at Purdue University, West Lafayette, IN, USA.
- ^{hh} Also at International Islamic University of Malaysia, Kuala Lumpur, Malaysia.
- ⁱⁱ Also at Malaysian Nuclear Agency, MOSTI, Kajang, Malaysia.
- ^{jj} Also at Consejo Nacional de Ciencia y Tecnología, Mexico city, Mexico.
- ^{kk} Also at Warsaw University of Technology, Institute of Electronic Systems, Warsaw, Poland.
- ^{ll} Also at Institute for Nuclear Research, Moscow, Russia.
- ^{mm} Also at National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia.
- ⁿⁿ Also at Institute of Nuclear Physics of the Uzbekistan Academy of Sciences, Tashkent, Uzbekistan.
- ^{oo} Also at St. Petersburg State Polytechnical University, St. Petersburg, Russia.
- ^{pp} Also at University of Florida, Gainesville, FL, USA.
- ^{qq} Also at P. N. Lebedev Physical Institute, Moscow, Russia.
- ^{rr} Also at California Institute of Technology, Pasadena, CA, USA.
- ^{ss} Also at Budker Institute of Nuclear Physics, Novosibirsk, Russia.
- ^{tt} Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia.
- ^{uu} Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia.
- ^{vv} Also at Scuola Normale e Sezione dell'INFN, Pisa, Italy.
- ^{ww} Also at National and Kapodistrian University of Athens, Athens, Greece.
- ^{xx} Also at Riga Technical University, Riga, Latvia.
- ^{yy} Also at Universität Zürich, Zurich, Switzerland.
- ^{zz} Also at Stefan Meyer Institute for Subatomic Physics.
- ^{aaa} Also at Gaziosmanpasa University, Tokat, Turkey.
- ^{bbb} Also at Istanbul Aydin University, Istanbul, Turkey.
- ^{ccc} Also at Mersin University, Mersin, Turkey.
- ^{ddd} Also at Cag University, Mersin, Turkey.
- ^{eee} Also at Piri Reis University, Istanbul, Turkey.
- ^{fff} Also at Adiyaman University, Adiyaman, Turkey.
- ^{ggg} Also at Izmir Institute of Technology, Izmir, Turkey.
- ^{hhh} Also at Necmettin Erbakan University, Konya, Turkey.
- ⁱⁱⁱ Also at Marmara University, Istanbul, Turkey.
- ^{jjj} Also at Kafkas University, Kars, Turkey.
- ^{kkk} Also at Istanbul Bilgi University, Istanbul, Turkey.
- ^{lll} Also at Rutherford Appleton Laboratory, Didcot, United Kingdom.
- ^{mmm} Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom.
- ⁿⁿⁿ Also at Instituto de Astrofísica de Canarias, La Laguna, Spain.
- ^{ooo} Also at Utah Valley University, Orem, UT, USA.
- ^{ppp} Also at Beykent University.
- ^{qqq} Also at Bingol University, Bingol, Turkey.
- ^{rrr} Also at Erzincan University, Erzincan, Turkey.
- ^{sss} Also at Sinop University, Sinop, Turkey.
- ^{ttt} Also at Mimar Sinan University, Istanbul, Turkey.
- ^{uuu} Also at Texas A&M University at Qatar, Doha, Qatar.
- ^{vvv} Also at Kyungpook National University.