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Observation of the $J/\psi \rightarrow \mu^+ \mu^- \mu^+ \mu^-$ decay in proton-proton collisions at $\sqrt{s} = 13$ TeV

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



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The $J/\psi \rightarrow \mu^+ \mu^- \mu^+ \mu^-$ decay has been observed with a statistical significance in excess of five standard deviations. The analysis is based on an event sample of proton-proton collisions at a center-of-mass energy of 13 TeV, collected by the CMS experiment in 2018 and corresponding to an integrated luminosity of 33.6 fb^{-1} . Normalizing to the $J/\psi \rightarrow \mu^+ \mu^-$ decay mode leads to a branching fraction of $[10.1_{-2.7}^{+3.3}(\text{stat}) \pm 0.4(\text{syst})] \times 10^{-7}$, a value that is consistent with the standard model prediction.

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Decays of particles to leptons, especially muons, provide some of the cleanest signatures at hadron collider experiments. The large data sample collected by the CMS experiment [1,2] at the CERN LHC offers an excellent opportunity to explore rare decays to multilepton final states. The first such observation was the decay of the Z boson into four leptons [3]. Subsequently, the decays $Z \rightarrow J/\psi \ell^+ \ell^-$ (with the J/ψ decaying to two muons) and $\eta \rightarrow \mu^+ \mu^- \mu^+ \mu^-$ were also observed [4,5].

The BESIII collaboration recently reported the observation of the J/ψ decays $J/\psi \rightarrow e^+ e^- e^+ e^-$ and $J/\psi \rightarrow e^+ e^- \mu^+ \mu^-$, while for the $J/\psi \rightarrow \mu^+ \mu^- \mu^+ \mu^-$ branching fraction an upper limit was established, 1.6×10^{-6} at 90% confidence level [6]. In the standard model (SM), these processes occur via $\ell \rightarrow \ell \gamma^*/Z^*$ transitions, where the virtual photon or Z boson decays into a pair of leptons, as depicted in Fig. 1. These transitions provide opportunities to probe various beyond-SM scenarios, where new particles replace the γ^* or the Z^* boson [7–9]. Furthermore, such rare multilepton decays serve as a novel testing ground for quantum electrodynamics predictions [10,11].

This Letter presents the first observation of the $J/\psi \rightarrow \mu^+ \mu^- \mu^+ \mu^-$ decay and the measurement of its branching fraction, relative to the $J/\psi \rightarrow \mu^+ \mu^-$ decay mode. The analysis is based on a sample of proton-proton collisions at a center-of-mass energy of 13 TeV, collected by the CMS experiment and corresponding to an integrated luminosity of 33.6 fb^{-1} [12].

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the solenoid volume are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter, and a brass and scintillator hadron calorimeter, each composed of a barrel and two end cap sections. Forward calorimeters extend the pseudorapidity (η) coverage provided by the barrel and end cap detectors. Muons are measured in the $|\eta| < 2.4$ range, with detection planes made using three technologies: drift tubes, cathode strip chambers, and resistive plate chambers. A more detailed description of the CMS detector can be found in Ref. [1].

Events of interest are selected using a two-tiered trigger system. The first level, composed of custom hardware processors, uses information from the calorimeters and muon detectors to select events at a rate of around 100 kHz within a fixed latency of $4 \mu\text{s}$ [13]. The second level consists of a farm of processors running a version of the full event reconstruction software optimized for fast processing and reduces the event rate before data storage [14].

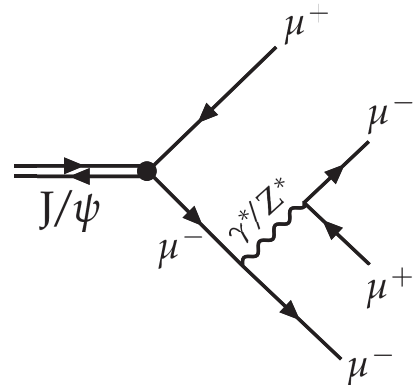


FIG. 1. Leading-order Feynman diagram representing the $J/\psi \rightarrow \mu^+ \mu^- \mu^+ \mu^-$ decay channel.

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

The single-muon trigger efficiency exceeds 90% over the full η range, and the efficiency to reconstruct and identify muons is larger than 96%. By matching muons to tracks measured in the silicon tracker, the transverse momentum, p_T , is measured with a relative resolution of 1% in the barrel and 3% in the end caps, for muons with p_T up to 100 GeV [15].

This study exploits the “B parking” data sample collected by the CMS experiment in 2018 [16]. A specialized trigger and data storage strategy was implemented to assemble a dataset enriched in b hadron decays [17]. The trigger selects events with at least one muon with $p_T > 9$ GeV and transverse impact parameter significance (distance of closest approach of the track to the beam line [18] divided by its uncertainty) larger than 6.

Two simulated event samples, used to evaluate the efficiency to reconstruct and select the $J/\psi \rightarrow \mu^+\mu^-\mu^+\mu^-$ and $J/\psi \rightarrow \mu^+\mu^-$ decays, are generated with the PYTHIA 8.230 Monte Carlo event generator [19], which includes modeling of the parton shower, fragmentation, and hadronization processes. The PYTHIA output is interfaced with EvtGen 1.3.0 [20], which simulates various b hadron decays. The samples are generated such that each event contains at least one b hadron decaying to a J/ψ meson plus other decay products, with the J/ψ meson decaying to either two or four muons using a phase space model. The underlying event is also modeled with PYTHIA 8, adopting the CP5 tune [21]. The NNPDF 3.1 [22] parton distribution functions are used. To account for additional proton-proton collisions in the same or adjacent bunch crossing (pileup), simulated minimum bias events are superimposed onto the hard scattering process, matching the multiplicity of reconstructed vertices observed in collision data. Final-state photon radiation is simulated using PHOTOS 3.61 [23]. The response of the CMS detector is emulated using Geant4 [24]. The simulated event samples are reconstructed using the same software packages as employed for collision data.

The events selected by the trigger need to comply with additional selection criteria, including the presence of four reconstructed muons with a net charge of zero and an invariant mass in the $2.6 < m_{\mu^+\mu^-\mu^+\mu^-} < 3.4$ GeV range. All the four selected muons are required to have $|\eta| < 1.5$ and $p_T > 3.5$ GeV. One of them must match the muon that triggered the event, which is ensured by requiring that it has $p_T > 9$ GeV and a small angular distance with respect to the trigger muon, $\sqrt{\Delta\eta^2 + \Delta\phi^2} < 0.1$, where $\Delta\eta$ and $\Delta\phi$ are the differences in pseudorapidity and azimuthal angle, respectively.

The four muons forming a J/ψ candidate are fitted to a common vertex, determined by a Kalman filter vertex fit [25]. Only candidates with a vertex-fit χ^2 probability exceeding 1% are kept. The p_T of the J/ψ meson candidate

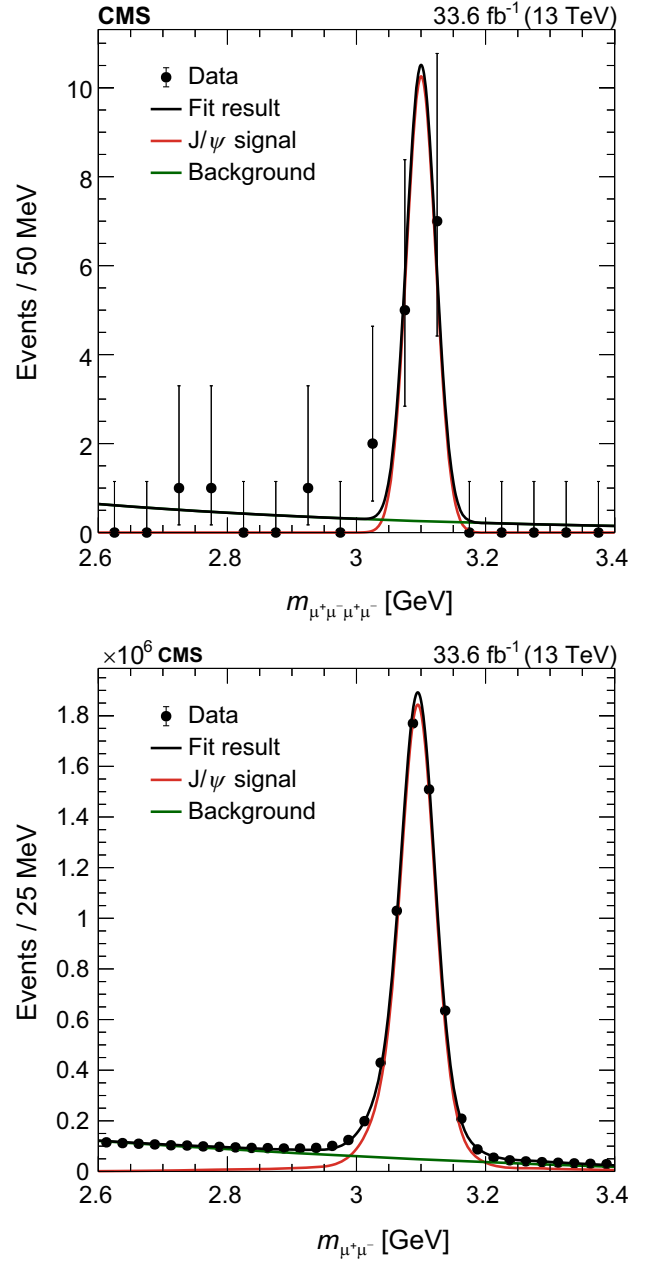


FIG. 2. Measured four-muon (left) and dimuon (right) mass distributions. The vertical bars represent the statistical uncertainties. The solid black line represents the result of the unbinned fit described in the text, while the red and green lines represent the signal and background terms, respectively.

must exceed 25 GeV and its absolute rapidity is restricted to be less than 2.2. No oppositely charged muon pair combination can have an invariant mass in the 0.75–0.80 or 0.98–1.05 GeV ranges, which are populated by dimuon decays of the ρ , ω , and ϕ mesons.

The branching fraction of the $J/\psi \rightarrow \mu^+\mu^-\mu^+\mu^-$ decay mode is measured relative to that of the $J/\psi \rightarrow \mu^+\mu^-$ decay. The selection criteria used in the $J/\psi \rightarrow \mu^+\mu^-$

events are the same as those applied to the two highest p_T muons of the $J/\psi \rightarrow \mu^+\mu^-\mu^+\mu^-$ decay.

Unbinned maximum likelihood fits are performed on the four-muon and dimuon invariant mass distributions to determine the two signal yields. The $\mu^+\mu^-\mu^+\mu^-$ invariant mass distribution is fitted by the superposition of two functions, one representing the $J/\psi \rightarrow \mu^+\mu^-\mu^+\mu^-$ signal and the other the underlying continuum background. The signal is modeled by a Crystal Ball function [26], with the mean fixed to the world-average J/ψ meson mass [27] and the width and tail parameters fixed to values determined from studies of simulated events. The background is modeled by a linear function. The $\mu^+\mu^-$ invariant mass distribution is fitted with essentially the same fit model, except that the signal is represented by the sum of a Crystal Ball function and a Gaussian function, without constraining any of the parameters. The fit models do not include

peaking background terms from hadronic J/ψ decay modes because the probability that a pion reaches the muon stations and is misidentified as a muon is below the per mil level [15], so that such contributions are negligible. The measured $m_{\mu^+\mu^-\mu^+\mu^-}$ and $m_{\mu^+\mu^-}$ distributions are shown in Fig. 2, together with the results of the fits.

The yields returned by the fits are $N(J/\psi \rightarrow \mu^+\mu^-\mu^+\mu^-) = 11.6^{+3.8}_{-3.1}$ and $N(J/\psi \rightarrow \mu^+\mu^-) = (5770 \pm 3) \times 10^3$. The significance of the $J/\psi \rightarrow \mu^+\mu^-\mu^+\mu^-$ signal is above 7 standard deviations, evaluated from the likelihood ratio of the default signal-plus-background fit and the background-only fit, imposing $N(J/\psi \rightarrow \mu^+\mu^-\mu^+\mu^-) = 0$, using the standard asymptotic formula [28].

The $J/\psi \rightarrow \mu^+\mu^-\mu^+\mu^-$ branching fraction relative to that of the $J/\psi \rightarrow \mu^+\mu^-$ is computed as

$$\frac{\mathcal{B}(J/\psi \rightarrow \mu^+\mu^-\mu^+\mu^-)}{\mathcal{B}(J/\psi \rightarrow \mu^+\mu^-)} = \frac{N(J/\psi \rightarrow \mu^+\mu^-\mu^+\mu^-)}{N(J/\psi \rightarrow \mu^+\mu^-)} \left/ \frac{\epsilon_{J/\psi \rightarrow \mu^+\mu^-\mu^+\mu^-}}{\epsilon_{J/\psi \rightarrow \mu^+\mu^-}} \right., \quad (1)$$

where $\mathcal{B}(J/\psi \rightarrow \mu^+\mu^-)$ is the branching fraction of the reference channel. The reconstruction efficiencies of each process are calculated as the fractions of generated events that are reconstructed, their ratio being $\epsilon_{J/\psi \rightarrow \mu^+\mu^-\mu^+\mu^-}/\epsilon_{J/\psi \rightarrow \mu^+\mu^-} = (11.92 \pm 0.02)\%$, where the uncertainty reflects the size of the simulated samples.

Because the signal- and reference-channel events are recorded using the same trigger and share similar event topologies, many systematic uncertainties have been seen to cancel in Eq. (1). In the following, we only describe those that do not cancel.

We evaluate the sensitivity of $N(J/\psi \rightarrow \mu^+\mu^-\mu^+\mu^-)$ to the fit model by replacing the Crystal Ball function by a Gaussian function and the linear function by an exponential function. The corresponding systematic uncertainties are smaller than 0.1% when we replace the signal fit model and 0.4% when we replace the background model. For the alternative modeling of the reference channel we use a sum of two Crystal Ball functions for the signal and an exponential function for the background. The fitted value of $N(J/\psi \rightarrow \mu^+\mu^-)$ changes by 0.5% for each of the two variations. An additional 0.1% uncertainty reflects the size of the Monte Carlo samples used for calculating the reconstruction and selection efficiencies of the signal and reference channels. Differences between the reconstructed and simulated samples are accounted for through two scale factors, one reflecting the trigger efficiency and the other the reconstruction and event selection efficiencies. Varying these scale factors by their standard deviation uncertainties, we obtain the corresponding uncertainties on the branching fraction measurement: 1.9% and 1.4%, respectively. Recomputing the detection efficiencies with

conservative variations of the simulated J/ψ kinematical distributions leads to a systematic uncertainty of 2.8%. The total relative systematic uncertainty is 3.7%, computed as the quadratic sum of the individual terms, so that the final result is

$$\frac{\mathcal{B}(J/\psi \rightarrow \mu^+\mu^-\mu^+\mu^-)}{\mathcal{B}(J/\psi \rightarrow \mu^+\mu^-)} = [16.9^{+5.5}_{-4.6}(\text{stat}) \pm 0.6(\text{syst})] \times 10^{-6}.$$

Using the world's average $\mathcal{B}(J/\psi \rightarrow \mu^+\mu^-) = (5.961 \pm 0.033)\%$ [27], and propagating its uncertainty, we obtain

$$\mathcal{B}(J/\psi \rightarrow \mu^+\mu^-\mu^+\mu^-) = [10.1^{+3.3}_{-2.7}(\text{stat}) \pm 0.4(\text{syst})] \times 10^{-7},$$

a value consistent with the SM prediction, $(9.74 \pm 0.05) \times 10^{-7}$ [10].

The results reported in this paper are tabulated in the HEPData record for this analysis [29].

In summary, using a data sample of proton-proton collisions at $\sqrt{s} = 13$ TeV, collected in 2018 by the CMS collaboration and corresponding to an integrated luminosity of 33.6 fb^{-1} , the $J/\psi \rightarrow \mu^+\mu^-\mu^+\mu^-$ decay was observed for the first time, with a statistical significance exceeding five standard deviations. Taking the $J/\psi \rightarrow \mu^+\mu^-$ decay mode as normalization, its branching fraction was measured to be $\mathcal{B}(J/\psi \rightarrow \mu^+\mu^-\mu^+\mu^-) = [10.1^{+3.3}_{-2.7}(\text{stat}) \pm 0.4(\text{syst})] \times 10^{-7}$, a value consistent with the standard model prediction.

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

- B. Harikrishnan³⁹, L. Kalipoliti³⁹, G. Liu³⁹, M. Nguyen³⁹, C. Ochando³⁹, R. Salerno³⁹, J. B. Sauvan³⁹, Y. Sirois³⁹, L. Urda Gómez³⁹, E. Vernazza³⁹, A. Zabi³⁹, A. Zghiche³⁹, J.-L. Agram^{40,v}, J. Andrea⁴⁰, D. Apparu⁴⁰, D. Bloch⁴⁰, J.-M. Brom⁴⁰, E. C. Chabert⁴⁰, C. Collard⁴⁰, S. Falke⁴⁰, U. Goerlach⁴⁰, R. Haeblerle⁴⁰, A.-C. Le Bihan⁴⁰, M. Meena⁴⁰, O. Poncet⁴⁰, G. Saha⁴⁰, M. A. Sessini⁴⁰, P. Van Hove⁴⁰, P. Vaucelle⁴⁰, A. Di Florio⁴¹, D. Amram⁴², S. Beauceron⁴², B. Blancon⁴², G. Boudoul⁴², N. Chanon⁴², D. Contardo⁴², P. Depasse⁴², C. Dozen^{42,w}, H. El Mamouni⁴², J. Fay⁴², S. Gascon⁴², M. Gouzevitch⁴², C. Greenberg⁴², G. Grenier⁴², B. Ille⁴², E. Jourdain⁴², I. B. Laktineh⁴², M. Lethuillier⁴², L. Mirabito⁴², S. Perries⁴², A. Purohit⁴², M. Vander Donckt⁴², P. Verdier⁴², J. Xiao⁴², G. Adamov⁴³, I. Lomidze⁴³, Z. Tsamalaidze^{43,r}, V. Botta⁴⁴, L. Feld⁴⁴, K. Klein⁴⁴, M. Lipinski⁴⁴, D. Meuser⁴⁴, A. Pauls⁴⁴, D. Pérez Adán⁴⁴, N. Röwert⁴⁴, M. Teroerde⁴⁴, S. Diekmann⁴⁵, A. Dodonova⁴⁵, N. Eich⁴⁵, D. Eliseev⁴⁵, F. Engelke⁴⁵, J. Erdmann⁴⁵, M. Erdmann⁴⁵, P. Fackeldey⁴⁵, B. Fischer⁴⁵, T. Hebbeker⁴⁵, K. Hoepfner⁴⁵, F. Ivone⁴⁵, A. Jung⁴⁵, M. y. Lee⁴⁵, F. Mausolf⁴⁵, M. Merschmeyer⁴⁵, A. Meyer⁴⁵, S. Mukherjee⁴⁵, D. Noll⁴⁵, F. Nowotny⁴⁵, A. Pozdnyakov⁴⁵, Y. Rath⁴⁵, W. Redjeb⁴⁵, F. Rehm⁴⁵, H. Reithler⁴⁵, V. Sarkisovi⁴⁵, A. Schmidt⁴⁵, A. Sharma⁴⁵, J. L. Spah⁴⁵, A. Stein⁴⁵, F. Torres Da Silva De Araujo^{45,x}, S. Wiedenbeck⁴⁵, S. Zaleski⁴⁵, C. Dziwok⁴⁶, G. Flüge⁴⁶, T. Kress⁴⁶, A. Nowack⁴⁶, O. Pooth⁴⁶, A. Stahl⁴⁶, T. Ziemons⁴⁶, A. Zotz⁴⁶, H. Aarup Petersen⁴⁷, M. Aldaya Martin⁴⁷, J. Alimena⁴⁷, S. Amoroso⁴⁷, Y. An⁴⁷, J. Bach⁴⁷, S. Baxter⁴⁷, M. Bayatmakou⁴⁷, H. Becerril Gonzalez⁴⁷, O. Behnke⁴⁷, A. Belvedere⁴⁷, S. Bhattacharya⁴⁷, F. Blekman^{47,y}, K. Borras^{47,z}, A. Campbell⁴⁷, A. Cardini⁴⁷, C. Cheng⁴⁷, F. Colombina⁴⁷, S. Consuegra Rodríguez⁴⁷, M. De Silva⁴⁷, G. Eckerlin⁴⁷, D. Eckstein⁴⁷, L. I. Estevez Banos⁴⁷, O. Filatov⁴⁷, E. Gallo^{47,y}, A. Geiser⁴⁷, V. Guglielmi⁴⁷, M. Guthoff⁴⁷, A. Hinzmann⁴⁷, L. Jeppe⁴⁷, B. Kaech⁴⁷, M. Kasemann⁴⁷, C. Kleinwort⁴⁷, R. Kogler⁴⁷, M. Komm⁴⁷, D. Krücker⁴⁷, W. Lange⁴⁷, D. Leyva Pernia⁴⁷, K. Lipka^{47,aa}, W. Lohmann^{47,bb}, F. Lorkowski⁴⁷, R. Mankel⁴⁷, I.-A. Melzer-Pellmann⁴⁷, M. Mendizabal Morentin⁴⁷, A. B. Meyer⁴⁷, G. Milella⁴⁷, K. Moral Figueroa⁴⁷, A. Mussgiller⁴⁷, L. P. Nair⁴⁷, J. Niedziela⁴⁷, A. Nürnberg⁴⁷, Y. Otari⁴⁷, J. Park⁴⁷, E. Ranken⁴⁷, A. Raspereza⁴⁷, D. Rastorguev⁴⁷, J. Rübenach⁴⁷, L. Rygaard⁴⁷, A. Saggio⁴⁷, M. Scham^{47,cc,z}, S. Schnake^{47,z}, P. Schütze⁴⁷, C. Schwanenberger^{47,y}, D. Selivanova⁴⁷, K. Sharko⁴⁷, M. Shchedrolosiev⁴⁷, D. Stafford⁴⁷, F. Vazzoler⁴⁷, A. Ventura Barroso⁴⁷, R. Walsh⁴⁷, D. Wang⁴⁷, Q. Wang⁴⁷, Y. Wen⁴⁷, K. Wichmann⁴⁷, L. Wiens^{47,z}, C. Wissing⁴⁷, Y. Yang⁴⁷, A. Zimmermann Castro Santos⁴⁷, A. Albrecht⁴⁸, S. Albrecht⁴⁸, M. Antonello⁴⁸, S. Bein⁴⁸, L. Benato⁴⁸, S. Bollweg⁴⁸, M. Bonanomi⁴⁸, P. Connor⁴⁸, K. El Morabit⁴⁸, Y. Fischer⁴⁸, E. Garutti⁴⁸, A. Grohsjean⁴⁸, J. Haller⁴⁸, H. R. Jabusch⁴⁸, G. Kasieczka⁴⁸, P. Keicher⁴⁸, R. Klanner⁴⁸, W. Korcari⁴⁸, T. Kramer⁴⁸, C. c. Kuo⁴⁸, V. Kutzner⁴⁸, F. Labe⁴⁸, J. Lange⁴⁸, A. Lobanov⁴⁸, C. Matthies⁴⁸, L. Moureaux⁴⁸, M. Mrowietz⁴⁸, A. Nigamova⁴⁸, Y. Nissan⁴⁸, A. Paasch⁴⁸, K. J. Pena Rodriguez⁴⁸, T. Quadfasel⁴⁸, B. Raciti⁴⁸, M. Rieger⁴⁸, D. Savoie⁴⁸, J. Schindler⁴⁸, P. Schleper⁴⁸, M. Schröder⁴⁸, J. Schwandt⁴⁸, M. Sommerhalder⁴⁸, H. Stadie⁴⁸, G. Steinbrück⁴⁸, A. Tews⁴⁸, M. Wolf⁴⁸, S. Brommer⁴⁹, M. Burkart⁴⁹, E. Butz⁴⁹, T. Chwalek⁴⁹, A. Dierlamm⁴⁹, A. Droll⁴⁹, N. Faltermann⁴⁹, M. Giffels⁴⁹, A. Gottmann⁴⁹, F. Hartmann^{49,dd}, R. Hofsaess⁴⁹, M. Horzela⁴⁹, U. Husemann⁴⁹, J. Kieseler⁴⁹, M. Klute⁴⁹, R. Koppenhöfer⁴⁹, J. M. Lawhorn⁴⁹, M. Link⁴⁹, A. Lintuluoto⁴⁹, B. Maier⁴⁹, S. Maier⁴⁹, S. Mitra⁴⁹, M. Mormile⁴⁹, Th. Müller⁴⁹, M. Neukum⁴⁹, M. Oh⁴⁹, E. Pfeffer⁴⁹, M. Presilla⁴⁹, G. Quast⁴⁹, K. Rabbertz⁴⁹, B. Regnery⁴⁹, N. Shadskiy⁴⁹, I. Shvetsov⁴⁹, H. J. Simonis⁴⁹, L. Sowa⁴⁹, L. Stockmeier⁴⁹, K. Tauqeer⁴⁹, M. Toms⁴⁹, N. Trevisani⁴⁹, R. F. Von Cube⁴⁹, M. Wassmer⁴⁹, S. Wieland⁴⁹, F. Wittig⁴⁹, R. Wolf⁴⁹, X. Zuo⁴⁹, G. Anagnostou⁵⁰, G. Daskalakis⁵⁰, A. Kyriakis⁵⁰, A. Papadopoulos^{50,dd}, A. Stakia⁵⁰, P. Kontaxakis⁵¹, G. Melachroinos⁵¹, Z. Painesis⁵¹, I. Papavergou⁵¹, I. Paraskevas⁵¹, N. Saoulidou⁵¹, K. Theofilatos⁵¹, E. Tziaferi⁵¹, K. Vellidis⁵¹, I. Zisopoulos⁵¹, G. Bakas⁵², T. Chatzistavrou⁵², G. Karapostoli⁵², K. Kousouris⁵², I. Papakrivopoulos⁵², E. Siamarkou⁵², G. Tsipolitis⁵², A. Zacharopoulou⁵², K. Adamidis⁵³, I. Bestintzanos⁵³, I. Evangelou⁵³, C. Foudas⁵³, C. Kamtsikis⁵³, P. Katsoulis⁵³, P. Kokkas⁵³, P. G. Kosmoglou Kioseoglou⁵³, N. Manthos⁵³, I. Papadopoulos⁵³, J. Strologas⁵³, C. Hajdu⁵⁴, D. Horvath^{54,ee,ff}, K. Márton⁵⁴, A. J. Rádl^{54,gg}, F. Sikler⁵⁴, V. Veszpremi⁵⁴, M. Csanád⁵⁵, K. Farkas⁵⁵, A. Fehérkúti^{55,hh}, M. M. A. Gadallah^{55,ii}, Á. Kadlecik⁵⁵, P. Major⁵⁵, G. Pásztor⁵⁵, G. I. Veres⁵⁵, B. Ujvari⁵⁶, G. Zilizi⁵⁶, G. Bencze⁵⁷, S. Czellar⁵⁷, J. Molnar⁵⁷, Z. Szillasi⁵⁷, T. Csorgo^{58,hh}, T. Novak⁵⁸, J. Babbar⁵⁹, S. Bansal⁵⁹, S. B. Beri⁵⁹, V. Bhatnagar⁵⁹, G. Chaudhary⁵⁹, S. Chauhan⁵⁹, N. Dhingra^{59,jj}, A. Kaur⁵⁹, A. Kaur⁵⁹, H. Kaur⁵⁹, M. Kaur⁵⁹, S. Kumar⁵⁹, K. Sandeep⁵⁹, T. Sheokand⁵⁹, J. B. Singh⁵⁹, A. Singla⁵⁹, A. Ahmed⁶⁰, A. Bhardwaj⁶⁰

A. Chhetri⁶⁰, B. C. Choudhary⁶⁰, A. Kumar⁶⁰, A. Kumar⁶⁰, M. Naimuddin⁶⁰, K. Ranjan⁶⁰, M. K. Saini⁶⁰, S. Saumya⁶⁰, S. Baradia⁶¹, S. Barman^{61,kk}, S. Bhattacharya⁶¹, S. Das Gupta⁶¹, S. Dutta⁶¹, S. Dutta⁶¹, S. Sarkar⁶¹, M. M. Ameen⁶², P. K. Behera⁶², S. C. Behera⁶², S. Chatterjee⁶², G. Dash⁶², P. Jana⁶², P. Kalbhor⁶², S. Kamble⁶², J. R. Komaragiri^{62,ll}, D. Kumar^{62,ll}, P. R. Pujahari⁶², N. R. Saha⁶², A. Sharma⁶², A. K. Sikdar⁶², R. K. Singh⁶², P. Verma⁶², S. Verma⁶², A. Vijay⁶², S. Dugad⁶³, M. Kumar⁶³, G. B. Mohanty⁶³, B. Parida⁶³, M. Shelake⁶³, P. Suryadevara⁶³, A. Bala⁶⁴, S. Banerjee⁶⁴, R. M. Chatterjee⁶⁴, M. Guchait⁶⁴, Sh. Jain⁶⁴, A. Jaiswal⁶⁴, S. Kumar⁶⁴, G. Majumder⁶⁴, K. Mazumdar⁶⁴, S. Parolia⁶⁴, A. Thachayath⁶⁴, S. Bahinipati^{65,mm}, C. Kar⁶⁵, D. Maity^{65,nn}, P. Mal⁶⁵, T. Mishra⁶⁵, V. K. Muraleedharan Nair Bindhu^{65,nn}, K. Naskar^{65,nn}, A. Nayak^{65,nn}, S. Nayak⁶⁵, K. Pal⁶⁵, P. Sadangi⁶⁵, S. K. Swain⁶⁵, S. Varghese^{65,nn}, D. Vats^{65,nn}, S. Acharya^{66,oo}, A. Alpina⁶⁶, S. Dube⁶⁶, B. Gomber^{66,oo}, P. Hazarika⁶⁶, B. Kansal⁶⁶, A. Laha⁶⁶, B. Sahu^{66,oo}, S. Sharma⁶⁶, K. Y. Vaish⁶⁶, H. Bakhshiansohi^{67,pp}, A. Jafari^{67,qq}, M. Zeinali^{67,rr}, S. Bashiri⁶⁸, S. Chenarani^{68,ss}, S. M. Etesami⁶⁸, Y. Hosseini⁶⁸, M. Khakzad⁶⁸, E. Khazaie^{68,tt}, M. Mohammadi Najafabadi⁶⁸, S. Tizchang⁶⁸, M. Felcini⁶⁹, M. Grunewald⁶⁹, M. Abbrescia^{70a,70b}, A. Colaleo^{70a,70b}, D. Creanza^{70a,70c}, B. D'Anzi^{70a,70b}, N. De Filippis^{70a,70c}, M. De Palma^{70a,70b}, L. Fiore^{70a}, G. Iaselli^{70a,70c}, L. Longo^{70a}, M. Louka^{70a,70b}, G. Maggi^{70a,70c}, M. Maggi^{70a}, I. Margjeka^{70a}, V. Mastrapasqua^{70a,70b}, S. My^{70a,70b}, S. Nuzzo^{70a,70b}, A. Pellecchia^{70a,70b}, A. Pompili^{70a,70b}, G. Pugliese^{70a,70c}, R. Radogna^{70a,70b}, D. Ramos^{70a}, A. Ranieri^{70a}, L. Silvestris^{70a}, F. M. Simone^{70a,70c}, Ü. Sözbilir^{70a}, A. Stamerra^{70a,70b}, D. Troiano^{70a,70b}, R. Venditti^{70a,70b}, P. Verwilligen^{70a}, A. Zaza^{70a,70b}, G. Abbiendi^{71a}, C. Battilana^{71a,71b}, D. Bonacorsi^{71a,71b}, L. Borroni^{71a}, P. Capiluppi^{71a,71b}, A. Castro^{71a,71b,a}, F. R. Cavallo^{71a}, M. Cuffiani^{71a,71b}, G. M. Dallavalle^{71a}, T. Diotallevi^{71a,71b}, F. Fabbri^{71a}, A. Fanfani^{71a,71b}, D. Fasanella^{71a}, P. Giacomelli^{71a}, L. Giommi^{71a,71b}, C. Grandi^{71a}, L. Guiducci^{71a,71b}, S. Lo Meo^{71a,uu}, M. Lorusso^{71a,71b}, L. Lunerti^{71a}, S. Marcellini^{71a}, G. Masetti^{71a}, F. L. Navarria^{71a,71b}, G. Paggi^{71a,71b}, A. Perrotta^{71a}, F. Primavera^{71a,71b}, A. M. Rossi^{71a,71b}, S. Rossi Tisbeni^{71a,71b}, T. Rovelli^{71a,71b}, G. P. Siroli^{71a,71b}, S. Costa^{72a,72b,vv}, A. Di Mattia^{72a}, A. Lapertosa^{72a}, R. Potenza^{72a,72b}, A. Tricomi^{72a,72b,vv}, C. Tuve^{72a,72b}, P. Assiouras^{73a}, G. Barbagli^{73a}, G. Bardelli^{73a,73b}, B. Camaiani^{73a,73b}, A. Cassese^{73a}, R. Ceccarelli^{73a}, V. Ciulli^{73a,73b}, C. Civinini^{73a}, R. D'Alessandro^{73a,73b}, E. Focardi^{73a,73b}, T. Kello^{73a}, G. Latino^{73a,73b}, P. Lenzi^{73a,73b}, M. Lizzo^{73a}, M. Meschini^{73a}, S. Paoletti^{73a}, A. Papanastassiou^{73a,73b}, G. Sguazzoni^{73a}, L. Viliani^{73a}, L. Benussi⁷⁴, S. Bianco⁷⁴, S. Meola^{74,ww}, D. Piccolo⁷⁴, P. Chatagnon^{75a}, F. Ferro^{75a}, E. Robutti^{75a}, S. Tosi^{75a,75b}, A. Benaglia^{76a}, G. Boldrini^{76a,76b}, F. Brivio^{76a}, F. Cetorelli^{76a,76b}, F. De Guio^{76a,76b}, M. E. Dinardo^{76a,76b}, P. Dini^{76a}, S. Gennai^{76a}, R. Gerosa^{76a,76b}, A. Ghezzi^{76a,76b}, P. Govoni^{76a,76b}, L. Guzzi^{76a}, M. T. Lucchini^{76a,76b}, M. Malberti^{76a}, S. Malvezzi^{76a}, A. Massironi^{76a}, D. Menasce^{76a}, L. Moroni^{76a}, M. Paganoni^{76a,76b}, S. Palluotto^{76a,76b}, D. Pedrini^{76a}, A. Perego^{76a,76b}, B. S. Pinolini^{76a}, G. Pizzati^{76a,76b}, S. Ragazzi^{76a,76b}, T. Tabarelli de Fatis^{76a,76b}, S. Buontempo^{77a}, A. Cagnotta^{77a,77b}, F. Carnevali^{77a,77b}, N. Cavallo^{77a,77c}, F. Fabozzi^{77a,77c}, A. O. M. Iorio^{77a,77b}, L. Lista^{77a,77b,xx}, P. Paolucci^{77a,dd}, B. Rossi^{77a}, R. Ardino^{78a}, P. Azzi^{78a}, N. Bacchetta^{78a,yy}, D. Bisello^{78a,78b}, P. Bortignon^{78a}, G. Bortolato^{78a,78b}, A. Bragagnolo^{78a,78b}, A. C. M. Bulla^{78a}, R. Carlin^{78a,78b}, P. Checchia^{78a}, T. Dorigo^{78a}, F. Gasparini^{78a,78b}, U. Gasparini^{78a,78b}, E. Lusiani^{78a}, M. Margoni^{78a,78b}, A. T. Meneguzzo^{78a,78b}, M. Migliorini^{78a,78b}, F. Montecassiano^{78a}, J. Pazzini^{78a,78b}, P. Ronchese^{78a,78b}, R. Rossin^{78a,78b}, F. Simonetto^{78a,78b}, G. Strong^{78a}, M. Tosi^{78a,78b}, A. Triossi^{78a,78b}, S. Ventura^{78a}, P. Zotto^{78a,78b}, A. Zucchetta^{78a,78b}, G. Zumerle^{78a,78b}, C. Aimè^{79a}, A. Braghieri^{79a}, S. Calzaferri^{79a}, D. Fiorina^{79a}, P. Montagna^{79a,79b}, V. Re^{79a}, C. Riccardi^{79a,79b}, P. Salvini^{79a}, I. Vai^{79a,79b}, P. Vitulo^{79a,79b}, S. Ajmal^{80a,80b}, M. E. Ascioti^{80a,80b}, G. M. Bilei^{80a}, C. Carrivale^{80a,80b}, D. Ciangottini^{80a,80b}, L. Fanò^{80a,80b}, M. Magherini^{80a,80b}, V. Mariani^{80a,80b}, M. Menichelli^{80a}, F. Moscatelli^{80a,zz}, A. Rossi^{80a,80b}, A. Santocchia^{80a,80b}, D. Spiga^{80a}, T. Tedeschi^{80a,80b}, C. A. Alexe^{81a,81c}, P. Asenov^{81a,81b}, P. Azzurri^{81a}, G. Bagliesi^{81a}, R. Bhattacharya^{81a}, L. Bianchini^{81a,81b}, T. Boccali^{81a}, E. Bossini^{81a}, D. Bruschini^{81a,81c}, R. Castaldi^{81a}, M. A. Ciocci^{81a,81b}, M. Cipriani^{81a,81b}, V. D'Amante^{81a,81d}, R. Dell'Orso^{81a}, S. Donato^{81a}, A. Giassi^{81a}, F. Ligabue^{81a,81c}, D. Matos Figueiredo^{81a}, A. Messineo^{81a,81b}, M. Musich^{81a,81b}, F. Palla^{81a}, A. Rizzi^{81a,81b}, G. Rolandi^{81a,81c}, S. Roy Chowdhury^{81a}, T. Sarkar^{81a}, A. Scribano^{81a}, P. Spagnolo^{81a}, R. Tenchini^{81a}, G. Tonelli^{81a,81b}, N. Turini^{81a,81d}, F. Vaselli^{81a,81c}, A. Venturi^{81a}, P. G. Verdini^{81a}, C. Baldenegro Barrera^{82a,82b}, P. Barria^{82a}, C. Basile^{82a,82b}, M. Campana^{82a,82b}, F. Cavallari^{82a}, L. 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 J. F. Benitez¹⁰¹ A. Castaneda Hernandez¹⁰¹ H. A. Encinas Acosta¹⁰¹ L. G. Gallegos Maríñez¹⁰¹ M. León Coello¹⁰¹
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 C. Uribe Estrada¹⁰⁴ I. Bujanja¹⁰⁵ N. Raicevic¹⁰⁵ P. H. Butler¹⁰⁶ A. Ahmad¹⁰⁷ M. I. Asghar¹⁰⁷ A. Awais¹⁰⁷
 M. I. M. Awan¹⁰⁷ H. R. Hoorani¹⁰⁷ W. A. Khan¹⁰⁷ V. Avati¹⁰⁸ L. Grzanka¹⁰⁸ M. Malawski¹⁰⁸ H. Bialkowska¹⁰⁹
 M. Bluj¹⁰⁹ M. Górski¹⁰⁹ M. Kazana¹⁰⁹ M. Szleper¹⁰⁹ P. Zalewski¹⁰⁹ K. Bunkowski¹¹⁰ K. Doroba¹¹⁰
 A. Kalinowski¹¹⁰ M. Konecki¹¹⁰ J. Krolikowski¹¹⁰ A. Muhammad¹¹⁰ K. Pozniak¹¹¹ W. Zabolotny¹¹¹
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 M. Dordevic¹¹⁴ J. Milosevic¹¹⁴ L. Nadder¹¹⁴ V. Rekovic¹¹⁴ J. Alcaraz Maestre¹¹⁵ Cristina F. Bedoya¹¹⁵
 Oliver M. Carretero¹¹⁵ M. Cepeda¹¹⁵ M. Cerrada¹¹⁵ N. Colino¹¹⁵ B. De La Cruz¹¹⁵ A. Delgado Peris¹¹⁵
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 O. Gonzalez Lopez¹¹⁵ S. Goy Lopez¹¹⁵ J. M. Hernandez¹¹⁵ M. I. Josa¹¹⁵ E. Martin Viscasillas¹¹⁵ D. Moran¹¹⁵
 C. M. Morcillo Perez¹¹⁵ Á. Navarro Tobar¹¹⁵ C. Perez Dengra¹¹⁵ A. Pérez-Calero Yzquierdo¹¹⁵
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 G. Gomez¹¹⁸ C. Lasaosa García¹¹⁸ R. Lopez Ruiz¹¹⁸ C. Martinez Rivero¹¹⁸ P. Martinez Ruiz del Arbol¹¹⁸
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 J. M. Vizan Garcia¹¹⁸ B. Kailasapathy^{119,ccc} D. D. C. Wickramaratna¹¹⁹ W. G. D. Dharmaratna^{120,ddd}
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 B. Huber¹²¹ V. Innocente¹²¹ T. James¹²¹ P. Janot¹²¹ O. Kaluzinska¹²¹ S. Laurila¹²¹ P. Lecoq¹²¹

E. Leutgeb¹²¹, C. Lourenço¹²¹, L. Malgeri¹²¹, M. Mannelli¹²¹, A. C. Marini¹²¹, M. Matthewman¹²¹, A. Mehta¹²¹,
 F. Meijers¹²¹, S. Mersi¹²¹, E. Meschi¹²¹, V. Milosevic¹²¹, F. Monti¹²¹, F. Moortgat¹²¹, M. Mulders¹²¹,
 I. Neutelings¹²¹, S. Orfanelli¹²¹, F. Pantaleo¹²¹, G. Petrucciani¹²¹, A. Pfeiffer¹²¹, M. Pierini¹²¹, H. Qu¹²¹,
 D. Rabady¹²¹, B. Ribeiro Lopes¹²¹, M. Rovere¹²¹, H. Sakulin¹²¹, S. Sanchez Cruz¹²¹, S. Scarfi¹²¹, C. Schwick¹²¹,
 M. Selvaggi¹²¹, A. Sharma¹²¹, K. Shchelina¹²¹, P. Silva¹²¹, P. Sphicas^{121,eee}, A. G. Stahl Leiton¹²¹, A. Steen¹²¹,
 S. Summers¹²¹, D. Treille¹²¹, P. Tropea¹²¹, D. Walter¹²¹, J. Wanczyk^{121,fff}, J. Wang¹²¹, S. Wuchterl¹²¹,
 P. Zehetner¹²¹, P. Zejdl¹²¹, W. D. Zeuner¹²¹, T. Bevilacqua^{122,ggg}, L. Caminada^{122,ggg}, A. Ebrahimi¹²²,
 W. Erdmann¹²², R. Horisberger¹²², Q. Ingram¹²², H. C. Kaestli¹²², D. Kotlinski¹²², C. Lange¹²²,
 M. Missiroli^{122,ggg}, L. Nohte^{122,ggg}, T. Rohe¹²², T. K. Aarrestad¹²³, K. Androsov^{123,fff}, M. Backhaus¹²³,
 G. Bonomelli¹²³, A. Calandri¹²³, C. Cazzaniga¹²³, K. Datta¹²³, P. De Bryas Dexmiers D'archiac^{123,fff},
 A. De Cosa¹²³, G. Dissertori¹²³, M. Dittmar¹²³, M. Donega¹²³, F. Eble¹²³, M. Galli¹²³, K. Gedia¹²³,
 F. Glessgen¹²³, C. Grab¹²³, N. Härringer¹²³, T. G. Harte¹²³, D. Hits¹²³, W. Lustermann¹²³, A.-M. Lyon¹²³,
 R. A. Manzoni¹²³, M. Marchegiani¹²³, L. Marchese¹²³, C. Martin Perez¹²³, A. Mascellani^{123,fff},
 F. Nessi-Tedaldi¹²³, F. Pauss¹²³, V. Perovic¹²³, S. Pigazzini¹²³, C. Reissel¹²³, T. Reitenspiess¹²³, B. Ristic¹²³,
 F. Riti¹²³, R. Seidita¹²³, J. Steggemann^{123,fff}, A. Tarabini¹²³, D. Valsecchi¹²³, R. Wallny¹²³, C. Amsler^{124,hhh},
 P. Bärtshi¹²⁴, M. F. Canelli¹²⁴, K. Cormier¹²⁴, M. Huwiler¹²⁴, W. Jin¹²⁴, A. Jofrehel¹²⁴, B. Kilminster¹²⁴,
 S. Leontsinis¹²⁴, S. P. Liechti¹²⁴, A. Macchiolo¹²⁴, P. Meiring¹²⁴, F. Meng¹²⁴, U. Molinatti¹²⁴, J. Motta¹²⁴,
 A. Reimers¹²⁴, P. Robmann¹²⁴, M. Senger¹²⁴, E. Shokr¹²⁴, F. Stäger¹²⁴, R. Tramontano¹²⁴, C. Adloff^{125,iii},
 D. Bhowmik¹²⁵, C. M. Kuo¹²⁵, W. Lin¹²⁵, P. K. Rout¹²⁵, P. C. Tiwari^{125,ii}, S. S. Yu¹²⁵, L. Ceard¹²⁶, K. F. Chen¹²⁶,
 P. s. Chen¹²⁶, Z. g. Chen¹²⁶, A. De Iorio¹²⁶, W.-S. Hou¹²⁶, T. h. Hsu¹²⁶, Y. w. Kao¹²⁶, S. Karmakar¹²⁶, G. Kole¹²⁶,
 Y. y. Li¹²⁶, R.-S. Lu¹²⁶, E. Paganis¹²⁶, X. f. Su¹²⁶, J. Thomas-Wilsker¹²⁶, L. s. Tsai¹²⁶, H. y. Wu¹²⁶, E. Yazgan¹²⁶,
 C. Asawatangtrakuldee¹²⁷, N. Srimanobhas¹²⁷, V. Wachirapusanand¹²⁷, D. Agyel¹²⁸, F. Boran¹²⁸, F. Dolek¹²⁸,
 I. Dumanoglu^{128,jjj}, E. Eskut¹²⁸, Y. Guler^{128,kkk}, E. Gurpinar Guler^{128,kkk}, C. Isik¹²⁸, O. Kara¹²⁸,
 A. Kayis Topaksu¹²⁸, U. Kiminsu¹²⁸, G. Onengut¹²⁸, K. Ozdemir^{128,lll}, A. Polatoz¹²⁸, B. Tali^{128,mmm},
 U. G. Tok¹²⁸, S. Turkcapar¹²⁸, E. Uslan¹²⁸, I. S. Zorbakir¹²⁸, G. Sokmen¹²⁹, M. Yalvac^{129,nnn}, B. Akgun¹³⁰,
 I. O. Atakisi¹³⁰, E. Gülmez¹³⁰, M. Kaya^{130,ooo}, O. Kaya^{130,ppp}, S. Tekten^{130,qqq}, A. Cakir¹³¹, K. Cankocak^{131,jjj,rrr},
 G. G. Dincer^{131,jjj}, Y. Komurcu¹³¹, S. Sen^{131,sss}, O. Aydilek^{132,ttt}, B. Haciosahinoglu¹³², I. Hos^{132,uuu},
 B. Kaynak¹³², S. Ozkorucuklu¹³², O. Potok¹³², H. Sert¹³², C. Simsek¹³², C. Zorbilmez¹³², S. Cerci^{133,mmm},
 B. Isildak^{133,vvv}, D. Sunar Cerci¹³³, T. Yetkin¹³³, A. Boyaryntsev¹³⁴, B. Grynyov¹³⁴, L. Levchuk¹³⁵,
 D. Anthony¹³⁶, J. J. Brooke¹³⁶, A. Bundock¹³⁶, F. Bury¹³⁶, E. Clement¹³⁶, D. Cussans¹³⁶, H. Flacher¹³⁶,
 M. Glowacki¹³⁶, J. Goldstein¹³⁶, H. F. Heath¹³⁶, M.-L. Holmberg¹³⁶, L. Kreczko¹³⁶, S. Paramesvaran¹³⁶,
 L. Robertshaw¹³⁶, S. Seif El Nasr-Storey¹³⁶, V. J. Smith¹³⁶, N. Stylianou^{136,www}, K. Walkingshaw Pass¹³⁶, A. H. Ball¹³⁷,
 K. W. Bell¹³⁷, A. Belyaev^{137,xxx}, C. Brew¹³⁷, R. M. Brown¹³⁷, D. J. A. Cockerill¹³⁷, C. Cooke¹³⁷, A. Elliot¹³⁷,
 K. V. Ellis¹³⁷, K. Harder¹³⁷, S. Harper¹³⁷, J. Linacre¹³⁷, K. Manolopoulos¹³⁷, D. M. Newbold¹³⁷, E. Olaiya¹³⁷,
 D. Petyt¹³⁷, T. Reis¹³⁷, A. R. Sahasransu¹³⁷, G. Salvi¹³⁷, T. Schuh¹³⁷, C. H. Shepherd-Themistocleous¹³⁷,
 I. R. Tomalin¹³⁷, K. C. Whalen¹³⁷, T. Williams¹³⁷, I. Andreou¹³⁸, R. Bainbridge¹³⁸, P. Bloch¹³⁸, C. E. Brown¹³⁸,
 O. Buchmuller¹³⁸, V. Cacchio¹³⁸, C. A. Carrillo Montoya¹³⁸, G. S. Chahal^{138,yyy}, D. Colling¹³⁸, J. S. Dancu¹³⁸,
 I. Das¹³⁸, P. Dauncey¹³⁸, G. Davies¹³⁸, J. Davies¹³⁸, M. Della Negra¹³⁸, S. Fayer¹³⁸, G. Fedi¹³⁸, G. Hall¹³⁸,
 M. H. Hassanshahi¹³⁸, A. Howard¹³⁸, G. Iles¹³⁸, M. Knight¹³⁸, J. Langford¹³⁸, J. León Holgado¹³⁸, L. Lyons¹³⁸,
 A.-M. Magnan¹³⁸, S. Mallios¹³⁸, M. Mieskolainen¹³⁸, J. Nash^{138,zzz}, M. Pesaresi¹³⁸, P. B. Pradeep¹³⁸,
 B. C. Radburn-Smith¹³⁸, A. Richards¹³⁸, A. Rose¹³⁸, K. Savva¹³⁸, C. Seez¹³⁸, R. Shukla¹³⁸, A. Tapper¹³⁸,
 K. Uchida¹³⁸, G. P. Uttley¹³⁸, L. H. Vage¹³⁸, T. Virdee^{138,ddd}, M. Vojinovic¹³⁸, N. Wardle¹³⁸, D. Winterbottom¹³⁸,
 K. Coldham¹³⁹, J. E. Cole¹³⁹, A. Khan¹³⁹, P. Kyberd¹³⁹, I. D. Reid¹³⁹, S. Abdullin¹⁴⁰, A. Brinkerhoff¹⁴⁰,
 B. Caraway¹⁴⁰, E. Collins¹⁴⁰, J. Dittmann¹⁴⁰, K. Hatakeyama¹⁴⁰, J. Hiltbrand¹⁴⁰, B. McMaster¹⁴⁰,
 J. Samudio¹⁴⁰, S. Sawant¹⁴⁰, C. Sutantawibul¹⁴⁰, J. Wilson¹⁴⁰, R. Bartek¹⁴¹, A. Dominguez¹⁴¹,
 C. Huerta Escamilla¹⁴¹, A. E. Simsek¹⁴¹, R. Uniyal¹⁴¹, A. M. Vargas Hernandez¹⁴¹, B. Bam¹⁴²,
 A. Buchot Perraguin¹⁴², R. Chudasama¹⁴², S. I. Cooper¹⁴², C. Crovella¹⁴², S. V. Gleyzer¹⁴², E. Pearson¹⁴²,
 C. U. Perez¹⁴², P. Rumerio^{142,aaaa}, E. Usai¹⁴², R. Yi¹⁴², A. Akpinar¹⁴³, C. Cosby¹⁴³, G. De Castro¹⁴³,
 Z. Demiragli¹⁴³, C. Erice¹⁴³, C. Fangmeier¹⁴³, C. Fernandez Madrazo¹⁴³, E. Fontanesi¹⁴³, D. Gastler¹⁴³

F. Golf¹⁴³, S. Jeon¹⁴³, J. O'cain¹⁴³, I. Reed¹⁴³, J. Rohlf¹⁴³, K. Salyer¹⁴³, D. Sperka¹⁴³, D. Spitzbart¹⁴³,
 I. Suarez¹⁴³, A. Tsatsos¹⁴³, A. G. Zecchinelli¹⁴³, G. Benelli¹⁴⁴, X. Coubez^{144,z}, D. Cutts¹⁴⁴, L. Gouskos¹⁴⁴,
 M. Hadley¹⁴⁴, U. Heintz¹⁴⁴, J. M. Hogan¹⁴⁴, T. Kwon¹⁴⁴, G. Landsberg¹⁴⁴, K. T. Lau¹⁴⁴, D. Li¹⁴⁴,
 J. Luo¹⁴⁴, S. Mondal¹⁴⁴, M. Narain^{144,a}, N. Pervan¹⁴⁴, T. Russell¹⁴⁴, S. Sagir^{144,cccc}, F. Simpson¹⁴⁴,
 M. Stamenkovic¹⁴⁴, N. Venkatasubramanian¹⁴⁴, X. Yan¹⁴⁴, W. Zhang¹⁴⁴, S. Abbott¹⁴⁵, C. Brainerd¹⁴⁵,
 R. Breedon¹⁴⁵, H. Cai¹⁴⁵, M. Calderon De La Barca Sanchez¹⁴⁵, M. Chertok¹⁴⁵, M. Citron¹⁴⁵, J. Conway¹⁴⁵,
 P. T. Cox¹⁴⁵, R. Erbacher¹⁴⁵, F. Jensen¹⁴⁵, O. Kukral¹⁴⁵, G. Mocellin¹⁴⁵, M. Mulhearn¹⁴⁵, S. Ostrom¹⁴⁵,
 W. Wei¹⁴⁵, Y. Yao¹⁴⁵, S. Yoo¹⁴⁵, F. Zhang¹⁴⁵, M. Bachtis¹⁴⁶, R. Cousins¹⁴⁶, A. Datta¹⁴⁶, G. Flores Avila¹⁴⁶,
 J. Hauser¹⁴⁶, M. Ignatenko¹⁴⁶, M. A. Iqbal¹⁴⁶, T. Lam¹⁴⁶, E. Manca¹⁴⁶, A. Nunez Del Prado¹⁴⁶, D. Saltzberg¹⁴⁶,
 V. Valuev¹⁴⁶, R. Clare¹⁴⁷, J. W. Gary¹⁴⁷, M. Gordon¹⁴⁷, G. Hanson¹⁴⁷, W. Si¹⁴⁷, S. Wimpenny^{147,a}, A. Aportela¹⁴⁸,
 A. Arora¹⁴⁸, J. G. Branson¹⁴⁸, S. Cittolin¹⁴⁸, S. Cooperstein¹⁴⁸, D. Diaz¹⁴⁸, J. Duarte¹⁴⁸, L. Giannini¹⁴⁸,
 Y. Gu¹⁴⁸, J. Guiang¹⁴⁸, R. Kansal¹⁴⁸, V. Krutelyov¹⁴⁸, R. Lee¹⁴⁸, J. Letts¹⁴⁸, M. Masciovecchio¹⁴⁸,
 F. Mokhtar¹⁴⁸, S. Mukherjee¹⁴⁸, M. Pieri¹⁴⁸, M. Quinlan¹⁴⁸, B. V. Sathia Narayanan¹⁴⁸, V. Sharma¹⁴⁸,
 M. Tadel¹⁴⁸, E. Vourliotis¹⁴⁸, F. Würthwein¹⁴⁸, Y. Xiang¹⁴⁸, A. Yagil¹⁴⁸, A. Barzdukas¹⁴⁹, L. Brennan¹⁴⁹,
 C. Campagnari¹⁴⁹, K. Downham¹⁴⁹, C. Grieco¹⁴⁹, J. Incandela¹⁴⁹, J. Kim¹⁴⁹, A. J. Li¹⁴⁹, P. Masterson¹⁴⁹,
 H. Mei¹⁴⁹, J. Richman¹⁴⁹, S. N. Santpur¹⁴⁹, U. Sarica¹⁴⁹, R. Schmitz¹⁴⁹, F. Setti¹⁴⁹, J. Shephlock¹⁴⁹,
 D. Stuart¹⁴⁹, T. Á. Vami¹⁴⁹, S. Wang¹⁴⁹, D. Zhang¹⁴⁹, A. Bornheim¹⁵⁰, O. Cerri¹⁵⁰, A. Latorre¹⁵⁰, J. Mao¹⁵⁰,
 H. B. Newman¹⁵⁰, G. Reales Gutiérrez¹⁵⁰, M. Spiropulu¹⁵⁰, J. R. Vlimant¹⁵⁰, C. Wang¹⁵⁰, S. Xie¹⁵⁰, R. Y. Zhu¹⁵⁰,
 J. Alison¹⁵¹, S. An¹⁵¹, M. B. Andrews¹⁵¹, P. Bryant¹⁵¹, M. Cremonesi¹⁵¹, V. Dutta¹⁵¹, T. Ferguson¹⁵¹,
 T. A. Gómez Espinosa¹⁵¹, A. Harilal¹⁵¹, A. Kallil Tharayil¹⁵¹, C. Liu¹⁵¹, T. Mudholkar¹⁵¹, S. Murthy¹⁵¹,
 P. Palit¹⁵¹, K. Park¹⁵¹, M. Paulini¹⁵¹, A. Roberts¹⁵¹, A. Sanchez¹⁵¹, W. Terrill¹⁵¹, J. P. Cumalat¹⁵², W. T. Ford¹⁵²,
 A. Hart¹⁵², A. Hassani¹⁵², G. Karathanasis¹⁵², N. Manganello¹⁵², A. Perloff¹⁵², C. Savard¹⁵², N. Schonbeck¹⁵²,
 K. Stenson¹⁵², K. A. Ulmer¹⁵², S. R. Wagner¹⁵², N. Zipper¹⁵², D. Zuolo¹⁵², J. Alexander¹⁵³,
 S. Bright-Thonney¹⁵³, X. Chen¹⁵³, D. J. Cranshaw¹⁵³, J. Fan¹⁵³, X. Fan¹⁵³, S. Hogan¹⁵³, P. Kotamnives¹⁵³,
 J. Monroy¹⁵³, M. Oshiro¹⁵³, J. R. Patterson¹⁵³, M. Reid¹⁵³, A. Ryd¹⁵³, J. Thom¹⁵³, P. Wittich¹⁵³, R. Zou¹⁵³,
 M. Albrow¹⁵⁴, M. Alyari¹⁵⁴, O. Amram¹⁵⁴, G. Apollinari¹⁵⁴, A. Apresyan¹⁵⁴, L. A. T. Bauerdick¹⁵⁴, D. Berry¹⁵⁴,
 J. Berryhill¹⁵⁴, P. C. Bhat¹⁵⁴, K. Burkett¹⁵⁴, J. N. Butler¹⁵⁴, A. Canepa¹⁵⁴, G. B. Cerati¹⁵⁴, H. W. K. Cheung¹⁵⁴,
 F. Chlebana¹⁵⁴, G. Cummings¹⁵⁴, J. Dickinson¹⁵⁴, I. Dutta¹⁵⁴, V. D. Elvira¹⁵⁴, Y. Feng¹⁵⁴, J. Freeman¹⁵⁴,
 A. Gandrakota¹⁵⁴, Z. Gece¹⁵⁴, L. Gray¹⁵⁴, D. Green¹⁵⁴, A. Grummer¹⁵⁴, S. Grünendahl¹⁵⁴, D. Guerrero¹⁵⁴,
 O. Gutsche¹⁵⁴, R. M. Harris¹⁵⁴, R. Heller¹⁵⁴, T. C. Herwig¹⁵⁴, J. Hirschauer¹⁵⁴, B. Jayatilaka¹⁵⁴, S. Jindariani¹⁵⁴,
 M. Johnson¹⁵⁴, U. Joshi¹⁵⁴, T. Klijnsma¹⁵⁴, B. Klima¹⁵⁴, K. H. M. Kwok¹⁵⁴, S. Lammel¹⁵⁴, D. Lincoln¹⁵⁴,
 R. Lipton¹⁵⁴, T. Liu¹⁵⁴, C. Madrid¹⁵⁴, K. Maeshima¹⁵⁴, C. Mantilla¹⁵⁴, D. Mason¹⁵⁴, P. McBride¹⁵⁴,
 P. Merkel¹⁵⁴, S. Mrenna¹⁵⁴, S. Nahn¹⁵⁴, J. Ngadiuba¹⁵⁴, D. Noonan¹⁵⁴, S. Norberg¹⁵⁴, V. Papadimitriou¹⁵⁴,
 N. Pastika¹⁵⁴, K. Pedro¹⁵⁴, C. Pena^{154,dddd}, F. Ravera¹⁵⁴, A. Reinsvold Hall^{154,eeee}, L. Ristori¹⁵⁴, M. Safdari¹⁵⁴,
 E. Sexton-Kennedy¹⁵⁴, N. Smith¹⁵⁴, A. Soha¹⁵⁴, L. Spiegel¹⁵⁴, S. Stoynev¹⁵⁴, J. Strait¹⁵⁴, L. Taylor¹⁵⁴,
 S. Tkaczyk¹⁵⁴, N. V. Tran¹⁵⁴, L. Uplegger¹⁵⁴, E. W. Vaandering¹⁵⁴, I. Zoi¹⁵⁴, C. Aruta¹⁵⁵, P. Avery¹⁵⁵,
 D. Bourilkov¹⁵⁵, P. Chang¹⁵⁵, V. Cherepanov¹⁵⁵, R. D. Field¹⁵⁵, E. Koenig¹⁵⁵, M. Kolosova¹⁵⁵, J. Konigsberg¹⁵⁵,
 A. Korytov¹⁵⁵, K. Matchev¹⁵⁵, N. Menendez¹⁵⁵, G. Mitselmakher¹⁵⁵, K. Mohrman¹⁵⁵,
 A. Muthirakalayil Madhu¹⁵⁵, N. Rawal¹⁵⁵, S. Rosenzweig¹⁵⁵, Y. Takahashi¹⁵⁵, J. Wang¹⁵⁵, T. Adams¹⁵⁶,
 A. Al Kadhimi¹⁵⁶, A. Askew¹⁵⁶, S. Bower¹⁵⁶, R. Habibullah¹⁵⁶, V. Hagopian¹⁵⁶, R. Hashmi¹⁵⁶, R. S. Kim¹⁵⁶,
 S. Kim¹⁵⁶, T. Kolberg¹⁵⁶, G. Martinez¹⁵⁶, H. Prosper¹⁵⁶, P. R. Prova¹⁵⁶, M. Wulansatiti¹⁵⁶, R. Yohay¹⁵⁶, J. Zhang¹⁵⁶,
 B. Alsufyani¹⁵⁷, M. M. Baarmand¹⁵⁷, S. Butalla¹⁵⁷, S. Das¹⁵⁷, T. Elkafrawy^{157,ffff}, M. Hohmann¹⁵⁷, M. Rahmani¹⁵⁷,
 E. Yanes¹⁵⁷, M. R. Adams¹⁵⁸, A. Baty¹⁵⁸, C. Bennett¹⁵⁸, R. Cavanaugh¹⁵⁸, R. Escobar Franco¹⁵⁸, O. Evdokimov¹⁵⁸,
 C. E. Gerber¹⁵⁸, M. Hawksworth¹⁵⁸, A. Hingrajiya¹⁵⁸, D. J. Hofman¹⁵⁸, J. h. Lee¹⁵⁸, D. S. Lemos¹⁵⁸,
 A. H. Merrit¹⁵⁸, C. Mills¹⁵⁸, S. Nanda¹⁵⁸, G. Oh¹⁵⁸, B. Ozek¹⁵⁸, D. Pilipovic¹⁵⁸, R. Pradhan¹⁵⁸, E. Prifti¹⁵⁸,
 T. Roy¹⁵⁸, S. Rudrabhatla¹⁵⁸, M. B. Tonjes¹⁵⁸, N. Varelas¹⁵⁸, M. A. Wadud¹⁵⁸, Z. Ye¹⁵⁸, J. Yoo¹⁵⁸,
 M. Alhusseini¹⁵⁹, D. Blend¹⁵⁹, K. Dilsiz^{159,gggg}, L. Emediato¹⁵⁹, G. Karaman¹⁵⁹, O. K. Köseyan¹⁵⁹, J.-P. Merlo¹⁵⁹,
 A. Mestvirishvili^{159,hhhh}, O. Neogi¹⁵⁹, H. Ogul^{159,iiiii}, Y. Onel¹⁵⁹, A. Penzo¹⁵⁹, C. Snyder¹⁵⁹, E. Tiras^{159,jjjj},
 B. Blumenfeld¹⁶⁰, L. Corcodilos¹⁶⁰, J. Davis¹⁶⁰, A. V. Gritsan¹⁶⁰, L. Kang¹⁶⁰, S. Kyriacou¹⁶⁰, P. Maksimovic¹⁶⁰

M. Roguljic¹⁶⁰, J. Roskes¹⁶⁰, S. Sekhar¹⁶⁰, M. Swartz¹⁶⁰, A. Abreu¹⁶¹, L. F. Alcerro Alcerro¹⁶¹, J. Anguiano¹⁶¹, S. Arteaga Escatel¹⁶¹, P. Baringer¹⁶¹, A. Bean¹⁶¹, Z. Flowers¹⁶¹, D. Grove¹⁶¹, J. King¹⁶¹, G. Krintiras¹⁶¹, M. Lazarovits¹⁶¹, C. Le Mahieu¹⁶¹, J. Marquez¹⁶¹, N. Minafra¹⁶¹, M. Murray¹⁶¹, M. Nickel¹⁶¹, M. Pitt¹⁶¹, S. Popescu^{161,kkkk}, C. Rogan¹⁶¹, C. Royon¹⁶¹, R. Salvatico¹⁶¹, S. Sanders¹⁶¹, C. Smith¹⁶¹, G. Wilson¹⁶¹, B. Allmond¹⁶², R. Gujju Gurunadha¹⁶², A. Ivanov¹⁶², K. Kaadze¹⁶², Y. Maravin¹⁶², J. Natoli¹⁶², D. Roy¹⁶², G. Sorrentino¹⁶², A. Baden¹⁶³, A. Belloni¹⁶³, J. Bistany-riebman¹⁶³, Y. M. Chen¹⁶³, S. C. Eno¹⁶³, N. J. Hadley¹⁶³, S. Jabeen¹⁶³, R. G. Kellogg¹⁶³, T. Koeth¹⁶³, B. Kronheim¹⁶³, Y. Lai¹⁶³, S. Lascio¹⁶³, A. C. Mignerey¹⁶³, S. Nabili¹⁶³, C. Palmer¹⁶³, C. Papageorgakis¹⁶³, M. M. Paranjpe¹⁶³, L. Wang¹⁶³, J. Bendavid¹⁶⁴, I. A. Cali¹⁶⁴, P. c. Chou¹⁶⁴, M. D'Alfonso¹⁶⁴, J. Eysermans¹⁶⁴, C. Freer¹⁶⁴, G. Gomez-Ceballos¹⁶⁴, M. Goncharov¹⁶⁴, G. Grosso¹⁶⁴, P. Harris¹⁶⁴, D. Hoang¹⁶⁴, D. Kovalskyi¹⁶⁴, J. Krupa¹⁶⁴, L. Lavezzo¹⁶⁴, Y.-J. Lee¹⁶⁴, K. Long¹⁶⁴, C. McGinn¹⁶⁴, A. Novak¹⁶⁴, C. Paus¹⁶⁴, D. Rankin¹⁶⁴, C. Roland¹⁶⁴, G. Roland¹⁶⁴, S. Rothman¹⁶⁴, G. S. F. Stephans¹⁶⁴, Z. Wang¹⁶⁴, B. Wyslouch¹⁶⁴, T. J. Yang¹⁶⁴, B. Crossman¹⁶⁵, B. M. Joshi¹⁶⁵, C. Kapsiak¹⁶⁵, M. Krohn¹⁶⁵, D. Mahon¹⁶⁵, J. Mans¹⁶⁵, B. Marzocchi¹⁶⁵, M. Revering¹⁶⁵, R. Rusack¹⁶⁵, R. Saradhy¹⁶⁵, N. Strobbe¹⁶⁵, K. Bloom¹⁶⁶, D. R. Claes¹⁶⁶, G. Haza¹⁶⁶, J. Hossain¹⁶⁶, C. Joo¹⁶⁶, I. Kravchenko¹⁶⁶, J. E. Siado¹⁶⁶, W. Tabb¹⁶⁶, A. Vagnerini¹⁶⁶, A. Wightman¹⁶⁶, F. Yan¹⁶⁶, D. Yu¹⁶⁶, H. Bandyopadhyay¹⁶⁷, L. Hay¹⁶⁷, H. w. Hsia¹⁶⁷, I. Iashvili¹⁶⁷, A. Kalogeropoulos¹⁶⁷, A. Kharchilava¹⁶⁷, M. Morris¹⁶⁷, D. Nguyen¹⁶⁷, S. Rappoccio¹⁶⁷, H. Rejeb Sfar¹⁶⁷, A. Williams¹⁶⁷, P. Young¹⁶⁷, G. Alverson¹⁶⁸, E. Barberis¹⁶⁸, J. Bonilla¹⁶⁸, J. Dervan¹⁶⁸, Y. Haddad¹⁶⁸, Y. Han¹⁶⁸, A. Krishna¹⁶⁸, J. Li¹⁶⁸, M. Lu¹⁶⁸, G. Madigan¹⁶⁸, R. McCarthy¹⁶⁸, D. M. Morse¹⁶⁸, V. Nguyen¹⁶⁸, T. Orimoto¹⁶⁸, A. Parker¹⁶⁸, L. Skinnari¹⁶⁸, D. Wood¹⁶⁸, J. Bueghly¹⁶⁹, S. Dittmer¹⁶⁹, K. A. Hahn¹⁶⁹, Y. Liu¹⁶⁹, Y. Miao¹⁶⁹, D. G. Monk¹⁶⁹, M. H. Schmitt¹⁶⁹, A. Taliercio¹⁶⁹, M. Velasco¹⁶⁹, G. Agarwal¹⁷⁰, R. Band¹⁷⁰, R. Bucci¹⁷⁰, S. Castells¹⁷⁰, A. Das¹⁷⁰, R. Goldouzian¹⁷⁰, M. Hildreth¹⁷⁰, K. W. Ho¹⁷⁰, K. Hurtado Anampa¹⁷⁰, T. Ivanov¹⁷⁰, C. Jessop¹⁷⁰, K. Lannon¹⁷⁰, J. Lawrence¹⁷⁰, N. Loukas¹⁷⁰, L. Lutton¹⁷⁰, J. Mariano¹⁷⁰, N. Marinelli¹⁷⁰, I. Mcalister¹⁷⁰, T. McCauley¹⁷⁰, C. Mcgrady¹⁷⁰, C. Moore¹⁷⁰, Y. Musienko^{170,r}, H. Nelson¹⁷⁰, M. Osherson¹⁷⁰, A. Piccinelli¹⁷⁰, R. Ruchti¹⁷⁰, A. Townsend¹⁷⁰, Y. Wan¹⁷⁰, M. Wayne¹⁷⁰, H. Yockey¹⁷⁰, M. Zarucki¹⁷⁰, L. Zygala¹⁷⁰, A. Basnet¹⁷¹, B. Bylsma¹⁷¹, M. Carrigan¹⁷¹, L. S. Durkin¹⁷¹, C. Hill¹⁷¹, M. Joyce¹⁷¹, M. Nunez Ornelas¹⁷¹, K. Wei¹⁷¹, B. L. Winer¹⁷¹, B. R. Yates¹⁷¹, H. Bouchamaoui¹⁷², P. Das¹⁷², G. Dezoort¹⁷², P. Elmer¹⁷², A. Frankenthal¹⁷², B. Greenberg¹⁷², N. Haubrich¹⁷², K. Kennedy¹⁷², G. Kopp¹⁷², S. Kwan¹⁷², D. Lange¹⁷², A. Loeliger¹⁷², D. Marlow¹⁷², I. Ojalvo¹⁷², J. Olsen¹⁷², A. Shevelev¹⁷², D. Stickland¹⁷², C. Tully¹⁷², S. Malik¹⁷³, A. S. Bakshi¹⁷⁴, S. Chandra¹⁷⁴, R. Chawla¹⁷⁴, A. Gu¹⁷⁴, L. Gutay¹⁷⁴, M. Jones¹⁷⁴, A. W. Jung¹⁷⁴, A. M. Koshy¹⁷⁴, M. Liu¹⁷⁴, G. Negro¹⁷⁴, N. Neumeister¹⁷⁴, G. Paspalaki¹⁷⁴, S. Piperov¹⁷⁴, V. Scheurer¹⁷⁴, J. F. Schulte¹⁷⁴, M. Stojanovic¹⁷⁴, J. Thieman¹⁷⁴, A. K. Virdi¹⁷⁴, F. Wang¹⁷⁴, W. Xie¹⁷⁴, J. Dolen¹⁷⁵, N. Parashar¹⁷⁵, A. Pathak¹⁷⁵, D. Acosta¹⁷⁶, T. Carnahan¹⁷⁶, K. M. Ecklund¹⁷⁶, P. J. Fernández Manteca¹⁷⁶, S. Freed¹⁷⁶, P. Gardner¹⁷⁶, F. J. M. Geurts¹⁷⁶, W. Li¹⁷⁶, J. Lin¹⁷⁶, O. Miguel Colin¹⁷⁶, B. P. Padley¹⁷⁶, R. Redjimi¹⁷⁶, J. Rotter¹⁷⁶, E. Yigitbasi¹⁷⁶, Y. Zhang¹⁷⁶, A. Bodek¹⁷⁷, P. de Barbaro¹⁷⁷, R. Demina¹⁷⁷, J. L. Dulemba¹⁷⁷, A. Garcia-Bellido¹⁷⁷, O. Hindrichs¹⁷⁷, A. Khukhunaishvili¹⁷⁷, N. Parmar¹⁷⁷, P. Parygin^{177,x}, E. Popova^{177,x}, R. Taus¹⁷⁷, B. Chiarito¹⁷⁸, J. P. Chou¹⁷⁸, S. V. Clark¹⁷⁸, D. Gadkari¹⁷⁸, Y. Gershtein¹⁷⁸, E. Halkiadakis¹⁷⁸, M. Heindl¹⁷⁸, C. Houghton¹⁷⁸, D. Jaroslawski¹⁷⁸, O. Karacheban^{178,bb}, S. Konstantinou¹⁷⁸, I. Laflotte¹⁷⁸, A. Lath¹⁷⁸, R. Montalvo¹⁷⁸, K. Nash¹⁷⁸, J. Reichert¹⁷⁸, H. Routray¹⁷⁸, P. Saha¹⁷⁸, S. Salur¹⁷⁸, S. Schnetzer¹⁷⁸, S. Somalwar¹⁷⁸, R. Stone¹⁷⁸, S. A. Thayil¹⁷⁸, S. Thomas¹⁷⁸, J. Vora¹⁷⁸, H. Wang¹⁷⁸, H. Acharya¹⁷⁹, D. Ally¹⁷⁹, A. G. Delannoy¹⁷⁹, S. Fiorendi¹⁷⁹, S. Higginbotham¹⁷⁹, T. Holmes¹⁷⁹, A. R. Kanuganti¹⁷⁹, N. Karunaratna¹⁷⁹, L. Lee¹⁷⁹, E. Nibigira¹⁷⁹, S. Spanier¹⁷⁹, D. Aebi¹⁸⁰, M. Ahmad¹⁸⁰, T. Akhter¹⁸⁰, O. Bouhali^{180,llll}, R. Eusebi¹⁸⁰, J. Gilmore¹⁸⁰, T. Huang¹⁸⁰, T. Kamon^{180,mmmm}, H. Kim¹⁸⁰, S. Luo¹⁸⁰, R. Mueller¹⁸⁰, D. Overton¹⁸⁰, D. Rathjens¹⁸⁰, A. Safonov¹⁸⁰, N. Akchurin¹⁸¹, J. Damgov¹⁸¹, N. Gogate¹⁸¹, V. Hegde¹⁸¹, A. Hussain¹⁸¹, Y. Kazhykarim¹⁸¹, K. Lamichhane¹⁸¹, S. W. Lee¹⁸¹, A. Mankel¹⁸¹, T. Peltola¹⁸¹, I. Volobouev¹⁸¹, E. Appelt¹⁸², Y. Chen¹⁸², S. Greene¹⁸², A. Gurrola¹⁸², W. Johns¹⁸², R. Kunnawalkam Elayavalli¹⁸², A. Melo¹⁸², F. Romeo¹⁸², P. Sheldon¹⁸², S. Tuo¹⁸², J. Velkovska¹⁸², J. Viinikainen¹⁸², B. Cardwell¹⁸³, B. Cox¹⁸³, J. Hakala¹⁸³, R. Hirosky¹⁸³, A. Ledovskoy¹⁸³, C. Neu¹⁸³, S. Bhattacharya¹⁸⁴, P. E. Karchin¹⁸⁴, A. Aravind¹⁸⁵, S. Banerjee¹⁸⁵, K. Black¹⁸⁵, T. Bose¹⁸⁵, S. Dasu¹⁸⁵, I. De Bruyn¹⁸⁵, P. Everaerts¹⁸⁵, C. Galloni¹⁸⁵, H. He¹⁸⁵, M. Herndon¹⁸⁵, A. Herve¹⁸⁵, C. K. Koraka¹⁸⁵

A. Lanaro,¹⁸⁵ R. Loveless¹⁸⁵ , J. Madhusudanan Sreekala¹⁸⁵ , A. Mallampalli¹⁸⁵ , A. Mohammadi¹⁸⁵ , S. Mondal,¹⁸⁵
G. Parida¹⁸⁵ , L. Pétré¹⁸⁵ , D. Pinna,¹⁸⁵ A. Savin,¹⁸⁵ V. Shang¹⁸⁵ , V. Sharma¹⁸⁵ , W. H. Smith¹⁸⁵ , D. Teague,¹⁸⁵
H. F. Tsoi¹⁸⁵ , W. Vetens¹⁸⁵ , A. Warden¹⁸⁵ , S. Afanasiev¹⁸⁶ , V. Alexakhin¹⁸⁶ , V. Andreev¹⁸⁶ , Yu. Andreev¹⁸⁶ ,
T. Aushev¹⁸⁶ , M. Azarkin¹⁸⁶ , A. Babaev¹⁸⁶ , V. Blinov,^{186,r} E. Boos¹⁸⁶ , V. Borshch¹⁸⁶ , D. Budkouski¹⁸⁶ ,
V. Bunichev¹⁸⁶ , V. Chekhovsky,¹⁸⁶ R. Chistov^{186,r} , M. Danilov^{186,r} , A. Dermenev¹⁸⁶ , T. Dimova^{186,r} ,
D. Druzhkin^{186,nnnn} , M. Dubinin^{186,dddd} , L. Dudko¹⁸⁶ , A. Ershov¹⁸⁶ , G. Gavrilo¹⁸⁶ , V. Gavrilo¹⁸⁶ ,
S. Gninenko¹⁸⁶ , V. Golovtsov¹⁸⁶ , N. Golubev¹⁸⁶ , I. Golutvin^{186,a} , I. Gorbunov¹⁸⁶ , Y. Ivanov¹⁸⁶ , V. Kachanov¹⁸⁶ ,
V. Karjavine¹⁸⁶ , A. Karneyev¹⁸⁶ , V. Kim^{186,r} , M. Kirakosyan,¹⁸⁶ D. Kirpichnikov¹⁸⁶ , M. Kirsanov¹⁸⁶ ,
V. Klyukhin¹⁸⁶ , O. Kodolova^{186,oooo} , D. Konstantinov¹⁸⁶ , V. Korenkov¹⁸⁶ , A. Kozyrev^{186,r} , N. Krasnikov¹⁸⁶ ,
A. Lanev¹⁸⁶ , P. Levchenko^{186,pppp} , N. Lychkovskaya¹⁸⁶ , V. Makarenko¹⁸⁶ , A. Malakhov¹⁸⁶ , V. Matveev^{186,r} ,
V. Murzin¹⁸⁶ , A. Nikitenko^{186,qqqq,oooo} , S. Obraztsov¹⁸⁶ , V. Oreshkin¹⁸⁶ , V. Palichik¹⁸⁶ , V. Perelygin¹⁸⁶ ,
M. Perfilov,¹⁸⁶ S. Petrushanko¹⁸⁶ , S. Polikarpov^{186,r} , V. Popov¹⁸⁶ , O. Radchenko^{186,r} , M. Savina¹⁸⁶ , V. Savrin¹⁸⁶ ,
V. Shalaev¹⁸⁶ , S. Shmatov¹⁸⁶ , S. Shulha¹⁸⁶ , Y. Skovpen^{186,r} , S. Slabospitskii¹⁸⁶ , V. Smirnov¹⁸⁶ , D. Sosnov¹⁸⁶ ,
V. Sulimov¹⁸⁶ , E. Tcherniaev¹⁸⁶ , A. Terkulov¹⁸⁶ , O. Teryaev¹⁸⁶ , I. Tlisova¹⁸⁶ , A. Toropin¹⁸⁶ , L. Uvarov¹⁸⁶ ,
A. Uzunian¹⁸⁶ , A. Vorobyev,^{186,a} G. Vorotnikov¹⁸⁶ , N. Voytishin¹⁸⁶ , B. S. Yuldashev,^{186,rrrr} , A. Zarubin¹⁸⁶ ,
I. Zhizhin¹⁸⁶ , and A. Zhokin¹⁸⁶ 

(CMS Collaboration)

¹*Yerevan Physics Institute, Yerevan, Armenia*

²*Institut für Hochenergiephysik, Vienna, Austria*

³*Universiteit Antwerpen, Antwerpen, Belgium*

⁴*Vrije Universiteit Brussel, Brussel, Belgium*

⁵*Université Libre de Bruxelles, Bruxelles, Belgium*

⁶*Ghent University, Ghent, Belgium*

⁷*Université Catholique de Louvain, Louvain-la-Neuve, Belgium*

⁸*Centro Brasileiro de Pesquisas Físicas, Rio de Janeiro, Brazil*

⁹*Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil*

¹⁰*Universidade Estadual Paulista, Universidade Federal do ABC, São Paulo, Brazil*

¹¹*Institute for Nuclear Research and Nuclear Energy, Bulgarian Academy of Sciences, Sofia, Bulgaria*

¹²*University of Sofia, Sofia, Bulgaria*

¹³*Instituto De Alta Investigación, Universidad de Tarapacá, Casilla 7 D, Arica, Chile*

¹⁴*Beihang University, Beijing, China*

¹⁵*Department of Physics, Tsinghua University, Beijing, China*

¹⁶*Institute of High Energy Physics, Beijing, China*

¹⁷*State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China*

¹⁸*Guangdong Provincial Key Laboratory of Nuclear Science and Guangdong-Hong Kong Joint Laboratory of Quantum Matter, South China Normal University, Guangzhou, China*

¹⁹*Sun Yat-Sen University, Guangzhou, China*

²⁰*University of Science and Technology of China, Hefei, China*

²¹*Nanjing Normal University, Nanjing, China*

²²*Institute of Modern Physics and Key Laboratory of Nuclear Physics and Ion-beam Application (MOE)—Fudan University, Shanghai, China*

²³*Zhejiang University, Hangzhou, Zhejiang, China*

²⁴*Universidad de Los Andes, Bogota, Colombia*

²⁵*Universidad de Antioquia, Medellin, Colombia*

²⁶*University of Split, Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, Split, Croatia*

²⁷*University of Split, Faculty of Science, Split, Croatia*

²⁸*Institute Rudjer Boskovic, Zagreb, Croatia*

²⁹*University of Cyprus, Nicosia, Cyprus*

³⁰*Charles University, Prague, Czech Republic*

³¹*Universidad San Francisco de Quito, Quito, Ecuador*

³²*Academy of Scientific Research and Technology of the Arab Republic of Egypt, Egyptian Network of High Energy Physics, Cairo, Egypt*

³³*Center for High Energy Physics (CHEP-FU), Fayoum University, El-Fayoum, Egypt*

- ³⁴National Institute of Chemical Physics and Biophysics, Tallinn, Estonia
³⁵Department of Physics, University of Helsinki, Helsinki, Finland
³⁶Helsinki Institute of Physics, Helsinki, Finland
³⁷Lappeenranta-Lahti University of Technology, Lappeenranta, Finland
³⁸IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France
³⁹Laboratoire Leprince-Ringuet, CNRS/IN2P3, Ecole Polytechnique, Institut Polytechnique de Paris, Palaiseau, France
⁴⁰Université de Strasbourg, CNRS, IPHC UMR 7178, Strasbourg, France
⁴¹Centre de Calcul de l'Institut National de Physique Nucleaire et de Physique des Particules, CNRS/IN2P3, Villeurbanne, France
⁴²Institut de Physique des 2 Infinis de Lyon (IP2I), Villeurbanne, France
⁴³Georgian Technical University, Tbilisi, Georgia
⁴⁴RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany
⁴⁵RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
⁴⁶RWTH Aachen University, III. Physikalisches Institut B, Aachen, Germany
⁴⁷Deutsches Elektronen-Synchrotron, Hamburg, Germany
⁴⁸University of Hamburg, Hamburg, Germany
⁴⁹Karlsruher Institut fuer Technologie, Karlsruhe, Germany
⁵⁰Institute of Nuclear and Particle Physics (INPP), NCSR Demokritos, Aghia Paraskevi, Greece
⁵¹National and Kapodistrian University of Athens, Athens, Greece
⁵²National Technical University of Athens, Athens, Greece
⁵³University of Ioánnina, Ioánnina, Greece
⁵⁴HUN-REN Wigner Research Centre for Physics, Budapest, Hungary
⁵⁵MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary
⁵⁶Faculty of Informatics, University of Debrecen, Debrecen, Hungary
⁵⁷Institute of Nuclear Research ATOMKI, Debrecen, Hungary
⁵⁸Karoly Robert Campus, MATE Institute of Technology, Gyongyos, Hungary
⁵⁹Panjab University, Chandigarh, India
⁶⁰University of Delhi, Delhi, India
⁶¹Saha Institute of Nuclear Physics, HBNI, Kolkata, India
⁶²Indian Institute of Technology Madras, Madras, India
⁶³Tata Institute of Fundamental Research-A, Mumbai, India
⁶⁴Tata Institute of Fundamental Research-B, Mumbai, India
⁶⁵National Institute of Science Education and Research, An OCC of Homi Bhabha National Institute, Bhubaneswar, Odisha, India
⁶⁶Indian Institute of Science Education and Research (IISER), Pune, India
⁶⁷Isfahan University of Technology, Isfahan, Iran
⁶⁸Institute for Research in Fundamental Sciences (IPM), Tehran, Iran
⁶⁹University College Dublin, Dublin, Ireland
^{70a}INFN Sezione di Bari, Bari, Italy
^{70b}Università di Bari, Bari, Italy
^{70c}Politecnico di Bari, Bari, Italy
^{71a}INFN Sezione di Bologna, Bologna, Italy
^{71b}Università di Bologna, Bologna, Italy
^{72a}INFN Sezione di Catania, Catania, Italy
^{72b}Università di Catania, Catania, Italy
^{73a}INFN Sezione di Firenze, Firenze, Italy
^{73b}Università di Firenze, Firenze, Italy
⁷⁴INFN Laboratori Nazionali di Frascati, Frascati, Italy
^{75a}INFN Sezione di Genova, Genova, Italy
^{75b}Università di Genova, Genova, Italy
^{76a}INFN Sezione di Milano-Bicocca, Milano, Italy
^{76b}Università di Milano-Bicocca, Milano, Italy
^{77a}INFN Sezione di Napoli, Napoli, Italy
^{77b}Università di Napoli "Federico II," Napoli, Italy
^{77c}Università della Basilicata, Potenza, Italy
^{77d}Scuola Superiore Meridionale (SSM), Napoli, Italy
^{78a}INFN Sezione di Padova, Padova, Italy
^{78b}Università di Padova, Padova, Italy

- ^{78c}Università di Trento, Trento, Italy
^{79a}INFN Sezione di Pavia, Pavia, Italy
^{79b}Università di Pavia, Pavia, Italy
^{80a}INFN Sezione di Perugia, Perugia, Italy
^{80b}Università di Perugia, Perugia, Italy
^{81a}INFN Sezione di Pisa, Pisa, Italy
^{81b}Università di Pisa, Pisa, Italy
^{81c}Scuola Normale Superiore di Pisa, Pisa, Italy
^{81d}Università di Siena, Siena, Italy
^{82a}INFN Sezione di Roma, Roma, Italy
^{82b}Sapienza Università di Roma, Roma, Italy
^{83a}INFN Sezione di Torino, Torino, Italy
^{83b}Università di Torino, Torino, Italy
^{83c}Università del Piemonte Orientale, Novara, Italy
^{84a}INFN Sezione di Trieste, Trieste, Italy
^{84b}Università di Trieste, Trieste, Italy
⁸⁵Kyungpook National University, Daegu, Korea
⁸⁶Department of Mathematics and Physics—GWNu, Gangneung, Korea
⁸⁷Chonnam National University, Institute for Universe and Elementary Particles, Kwangju, Korea
⁸⁸Hanyang University, Seoul, Korea
⁸⁹Korea University, Seoul, Korea
⁹⁰Kyung Hee University, Department of Physics, Seoul, Korea
⁹¹Sejong University, Seoul, Korea
⁹²Seoul National University, Seoul, Korea
⁹³University of Seoul, Seoul, Korea
⁹⁴Yonsei University, Department of Physics, Seoul, Korea
⁹⁵Sungkyunkwan University, Suwon, Korea
⁹⁶College of Engineering and Technology, American University of the Middle East (AUM),
 Dasman, Kuwait
⁹⁷Riga Technical University, Riga, Latvia
⁹⁸University of Latvia (LU), Riga, Latvia
⁹⁹Vilnius University, Vilnius, Lithuania
¹⁰⁰National Centre for Particle Physics, Universiti Malaya, Kuala Lumpur, Malaysia
¹⁰¹Universidad de Sonora (UNISON), Hermosillo, Mexico
¹⁰²Centro de Investigación y de Estudios Avanzados del IPN, Mexico City, Mexico
¹⁰³Universidad Iberoamericana, Mexico City, Mexico
¹⁰⁴Benemerita Universidad Autónoma de Puebla, Puebla, Mexico
¹⁰⁵University of Montenegro, Podgorica, Montenegro
¹⁰⁶University of Canterbury, Christchurch, New Zealand
¹⁰⁷National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan
¹⁰⁸AGH University of Krakow, Faculty of Computer Science, Electronics and Telecommunications,
 Krakow, Poland
¹⁰⁹National Centre for Nuclear Research, Swierk, Poland
¹¹⁰Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland
¹¹¹Warsaw University of Technology, Warsaw, Poland
¹¹²Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal
¹¹³Faculty of Physics, University of Belgrade, Belgrade, Serbia
¹¹⁴VINCA Institute of Nuclear Sciences, University of Belgrade, Belgrade, Serbia
¹¹⁵Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain
¹¹⁶Universidad Autónoma de Madrid, Madrid, Spain
¹¹⁷Universidad de Oviedo, Instituto Universitario de Ciencias y Tecnologías Espaciales de Asturias
 (ICTEA), Oviedo, Spain
¹¹⁸Instituto de Física de Cantabria (IFCA), CSIC-Universidad de Cantabria, Santander, Spain
¹¹⁹University of Colombo, Colombo, Sri Lanka
¹²⁰University of Ruhuna, Department of Physics, Matara, Sri Lanka
¹²¹CERN, European Organization for Nuclear Research, Geneva, Switzerland
¹²²Paul Scherrer Institut, Villigen, Switzerland
¹²³ETH Zurich—Institute for Particle Physics and Astrophysics (IPA), Zurich, Switzerland
¹²⁴Universität Zürich, Zurich, Switzerland
¹²⁵National Central University, Chung-Li, Taiwan

- ¹²⁶National Taiwan University (NTU), Taipei, Taiwan
- ¹²⁷High Energy Physics Research Unit, Department of Physics, Faculty of Science,
Chulalongkorn University, Bangkok, Thailand
- ¹²⁸Çukurova University, Physics Department, Science and Art Faculty, Adana, Turkey
- ¹²⁹Middle East Technical University, Physics Department, Ankara, Turkey
- ¹³⁰Bogazici University, Istanbul, Turkey
- ¹³¹Istanbul Technical University, Istanbul, Turkey
- ¹³²Istanbul University, Istanbul, Turkey
- ¹³³Yildiz Technical University, Istanbul, Turkey
- ¹³⁴Institute for Scintillation Materials of National Academy of Science of Ukraine, Kharkiv, Ukraine
- ¹³⁵National Science Centre, Kharkiv Institute of Physics and Technology, Kharkiv, Ukraine
- ¹³⁶University of Bristol, Bristol, United Kingdom
- ¹³⁷Rutherford Appleton Laboratory, Didcot, United Kingdom
- ¹³⁸Imperial College, London, United Kingdom
- ¹³⁹Brunel University, Uxbridge, United Kingdom
- ¹⁴⁰Baylor University, Waco, Texas, USA
- ¹⁴¹Catholic University of America, Washington, DC, USA
- ¹⁴²The University of Alabama, Tuscaloosa, Alabama, USA
- ¹⁴³Boston University, Boston, Massachusetts, USA
- ¹⁴⁴Brown University, Providence, Rhode Island, USA
- ¹⁴⁵University of California, Davis, Davis, California, USA
- ¹⁴⁶University of California, Los Angeles, California, USA
- ¹⁴⁷University of California, Riverside, Riverside, California, USA
- ¹⁴⁸University of California, San Diego, La Jolla, California, USA
- ¹⁴⁹University of California, Santa Barbara—Department of Physics, Santa Barbara, California, USA
- ¹⁵⁰California Institute of Technology, Pasadena, California, USA
- ¹⁵¹Carnegie Mellon University, Pittsburgh, Pennsylvania, USA
- ¹⁵²University of Colorado Boulder, Boulder, Colorado, USA
- ¹⁵³Cornell University, Ithaca, New York, USA
- ¹⁵⁴Fermi National Accelerator Laboratory, Batavia, Illinois, USA
- ¹⁵⁵University of Florida, Gainesville, Florida, USA
- ¹⁵⁶Florida State University, Tallahassee, Florida, USA
- ¹⁵⁷Florida Institute of Technology, Melbourne, Florida, USA
- ¹⁵⁸University of Illinois Chicago, Chicago, USA, Chicago, USA
- ¹⁵⁹The University of Iowa, Iowa City, Iowa, USA
- ¹⁶⁰Johns Hopkins University, Baltimore, Maryland, USA
- ¹⁶¹The University of Kansas, Lawrence, Kansas, USA
- ¹⁶²Kansas State University, Manhattan, Kansas, USA
- ¹⁶³University of Maryland, College Park, Maryland, USA
- ¹⁶⁴Massachusetts Institute of Technology, Cambridge, Massachusetts, USA
- ¹⁶⁵University of Minnesota, Minneapolis, Minnesota, USA
- ¹⁶⁶University of Nebraska-Lincoln, Lincoln, Nebraska, USA
- ¹⁶⁷State University of New York at Buffalo, Buffalo, New York, USA
- ¹⁶⁸Northeastern University, Boston, Massachusetts, USA
- ¹⁶⁹Northwestern University, Evanston, Illinois, USA
- ¹⁷⁰University of Notre Dame, Notre Dame, Indiana, USA
- ¹⁷¹The Ohio State University, Columbus, Ohio, USA
- ¹⁷²Princeton University, Princeton, New Jersey, USA
- ¹⁷³University of Puerto Rico, Mayaguez, Puerto Rico, USA
- ¹⁷⁴Purdue University, West Lafayette, Indiana, USA
- ¹⁷⁵Purdue University Northwest, Hammond, Indiana, USA
- ¹⁷⁶Rice University, Houston, Texas, USA
- ¹⁷⁷University of Rochester, Rochester, New York, USA
- ¹⁷⁸Rutgers, The State University of New Jersey, Piscataway, New Jersey, USA
- ¹⁷⁹University of Tennessee, Knoxville, Tennessee, USA
- ¹⁸⁰Texas A&M University, College Station, Texas, USA
- ¹⁸¹Texas Tech University, Lubbock, Texas, USA
- ¹⁸²Vanderbilt University, Nashville, Tennessee, USA
- ¹⁸³University of Virginia, Charlottesville, Virginia, USA
- ¹⁸⁴Wayne State University, Detroit, Michigan, USA

¹⁸⁵*University of Wisconsin—Madison, Madison, Wisconsin, USA*¹⁸⁶*An institute or international laboratory covered by a cooperation agreement with CERN*^aDeceased.^bAlso at Yerevan State University, Yerevan, Armenia.^cAlso at TU Wien, Vienna, Austria.^dAlso at Institute of Basic and Applied Sciences, Faculty of Engineering, Arab Academy for Science, Technology and Maritime Transport, Alexandria, Egypt.^eAlso at Ghent University, Ghent, Belgium.^fAlso at Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil.^gAlso at Universidade Estadual de Campinas, Campinas, Brazil.^hAlso at Federal University of Rio Grande do Sul, Porto Alegre, Brazil.ⁱAlso at UFMS, Nova Andradina, Brazil.^jAlso at Nanjing Normal University, Nanjing, China.^kAlso at The University of Iowa, Iowa City, Iowa, USA.^lAlso at University of Chinese Academy of Sciences, Beijing, China.^mAlso at China Center of Advanced Science and Technology, Beijing, China.ⁿAlso at University of Chinese Academy of Sciences, Beijing, China.^oAlso at China Spallation Neutron Source, Guangdong, China.^pAlso at Henan Normal University, Xinxiang, China.^qAlso at Université Libre de Bruxelles, Bruxelles, Belgium.^rAlso at Another institute or international laboratory covered by a cooperation agreement with CERN.^sAlso at Suez University, Suez, Egypt.^tAlso at British University in Egypt, Cairo, Egypt.^uAlso at Purdue University, West Lafayette, Indiana, USA.^vAlso at Université de Haute Alsace, Mulhouse, France.^wAlso at Department of Physics, Tsinghua University, Beijing, China.^xAlso at The University of the State of Amazonas, Manaus, Brazil.^yAlso at University of Hamburg, Hamburg, Germany.^zAlso at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany.^{aa}Also at Bergische University Wuppertal (BUW), Wuppertal, Germany.^{bb}Also at Brandenburg University of Technology, Cottbus, Germany.^{cc}Also at Forschungszentrum Jülich, Jülich, Germany.^{dd}Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland.^{ee}Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary.^{ff}Also at Universitatea Babes-Bolyai—Facultatea de Fizica, Cluj-Napoca, Romania.^{gg}Also at MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary.^{hh}Also at HUN-REN Wigner Research Centre for Physics, Budapest, Hungary.ⁱⁱAlso at Physics Department, Faculty of Science, Assiut University, Assiut, Egypt.^{jj}Also at Punjab Agricultural University, Ludhiana, India.^{kk}Also at University of Visva-Bharati, Santiniketan, India.^{ll}Also at Indian Institute of Science (IISc), Bangalore, India.^{mm}Also at IIT Bhubaneswar, Bhubaneswar, India.ⁿⁿAlso at Institute of Physics, Bhubaneswar, India.^{oo}Also at University of Hyderabad, Hyderabad, India.^{pp}Also at Deutsches Elektronen-Synchrotron, Hamburg, Germany.^{qq}Also at Isfahan University of Technology, Isfahan, Iran.^{rr}Also at Sharif University of Technology, Tehran, Iran.^{ss}Also at Department of Physics, University of Science and Technology of Mazandaran, Behshahr, Iran.^{tt}Also at Department of Physics, Isfahan University of Technology, Isfahan, Iran.^{uu}Also at Italian National Agency for New Technologies, Energy and Sustainable Economic Development, Bologna, Italy.^{vv}Also at Centro Siciliano di Fisica Nucleare e di Struttura Della Materia, Catania, Italy.^{ww}Also at Università degli Studi Guglielmo Marconi, Roma, Italy.^{xx}Also at Scuola Superiore Meridionale, Università di Napoli “Federico II,” Napoli, Italy.^{yy}Also at Fermi National Accelerator Laboratory, Batavia, Illinois, USA.^{zz}Also at Consiglio Nazionale delle Ricerche—Istituto Officina dei Materiali, Perugia, Italy.^{aaa}Also at Department of Applied Physics, Faculty of Science and Technology, Universiti Kebangsaan Malaysia, Bangi, Malaysia.^{bbb}Also at Consejo Nacional de Ciencia y Tecnología, Mexico City, Mexico.^{ccc}Also at Trincomalee Campus, Eastern University, Sri Lanka, Nilaveli, Sri Lanka.^{ddd}Also at Saegis Campus, Nugegoda, Sri Lanka.

- ^{eee} Also at National and Kapodistrian University of Athens, Athens, Greece.
- ^{fff} Also at Ecole Polytechnique Fédérale Lausanne, Lausanne, Switzerland.
- ^{ggg} Also at Universität Zürich, Zurich, Switzerland.
- ^{hhh} Also at Stefan Meyer Institute for Subatomic Physics, Vienna, Austria.
- ⁱⁱⁱ Also at Laboratoire d'Annecy-le-Vieux de Physique des Particules, IN2P3-CNRS, Annecy-le-Vieux, France.
- ^{jjj} Also at Near East University, Research Center of Experimental Health Science, Mersin, Turkey.
- ^{kkk} Also at Konya Technical University, Konya, Turkey.
- ^{lll} Also at Izmir Bakircay University, Izmir, Turkey.
- ^{mmm} Also at Adiyaman University, Adiyaman, Turkey.
- ⁿⁿⁿ Also at Bozok Universitetesi Rektörlüğü, Yozgat, Turkey.
- ^{ooo} Also at Marmara University, Istanbul, Turkey.
- ^{ppp} Also at Milli Savunma University, Istanbul, Turkey.
- ^{qqq} Also at Kafkas University, Kars, Turkey.
- ^{rrr} Also at Istanbul Okan University, Istanbul, Turkey.
- ^{sss} Also at Hacettepe University, Ankara, Turkey.
- ^{ttt} Also at Erzincan Binali Yildirim University, Erzincan, Turkey.
- ^{uuu} Also at Istanbul University—Cerrahpasa, Faculty of Engineering, Istanbul, Turkey.
- ^{vvv} Also at Yildiz Technical University, Istanbul, Turkey.
- ^{www} Also at Vrije Universiteit Brussel, Brussel, Belgium.
- ^{xxx} Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom.
- ^{yyy} Also at IPPP Durham University, Durham, United Kingdom.
- ^{zzz} Also at Monash University, Faculty of Science, Clayton, Australia.
- ^{aaaa} Also at Università di Torino, Torino, Italy.
- ^{bbbb} Also at Bethel University, St. Paul, Minnesota, USA.
- ^{cccc} Also at Karamanoğlu Mehmetbey University, Karaman, Turkey.
- ^{dddd} Also at California Institute of Technology, Pasadena, California, USA.
- ^{eeee} Also at United States Naval Academy, Annapolis, Maryland, USA.
- ^{fff} Also at Ain Shams University, Cairo, Egypt.
- ^{ggg} Also at Bingol University, Bingol, Turkey.
- ^{hhh} Also at Georgian Technical University, Tbilisi, Georgia.
- ⁱⁱⁱ Also at Sinop University, Sinop, Turkey.
- ^{jjj} Also at Erciyes University, Kayseri, Turkey.
- ^{kkk} Also at Horia Hulubei National Institute of Physics and Nuclear Engineering (IFIN-HH), Bucharest, Romania.
- ^{lll} Also at Texas A&M University at Qatar, Doha, Qatar.
- ^{mmm} Also at Kyungpook National University, Daegu, Korea.
- ⁿⁿⁿ Also at Universiteit Antwerpen, Antwerpen, Belgium.
- ^{ooo} Also at Yerevan Physics Institute, Yerevan, Armenia.
- ^{ppp} Also at Northeastern University, Boston, Massachusetts, USA.
- ^{qqq} Also at Imperial College, London, United Kingdom.
- ^{rrr} Also at Institute of Nuclear Physics of the Uzbekistan Academy of Sciences, Tashkent, Uzbekistan.