

Observation of τ Lepton Pair Production in Ultraperipheral Pb-Pb Collisions at $\sqrt{s_{NN}} = 5.02$ TeV

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

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We present an observation of photon-photon production of τ lepton pairs in ultraperipheral lead-lead collisions. The measurement is based on a data sample with an integrated luminosity of $404 \mu\text{b}^{-1}$ collected by the CMS experiment at a center-of-mass energy per nucleon pair of $\sqrt{s_{NN}} = 5.02$ TeV. The $\gamma\gamma \rightarrow \tau^+\tau^-$ process is observed for $\tau^+\tau^-$ events with a muon and three charged hadrons in the final state. The measured fiducial cross section is $\sigma(\gamma\gamma \rightarrow \tau^+\tau^-) = 4.8 \pm 0.6(\text{stat}) \pm 0.5(\text{syst}) \mu\text{b}$, where the second (third) term corresponds to the statistical (systematic) uncertainty in $\sigma(\gamma\gamma \rightarrow \tau^+\tau^-)$ in agreement with leading-order QED predictions. Using $\sigma(\gamma\gamma \rightarrow \tau^+\tau^-)$, we estimate a model-dependent value of the anomalous magnetic moment of the τ lepton of $a_\tau = 0.001^{+0.055}_{-0.089}$.

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Ultraperipheral collisions (UPCs) of nuclei, where the impact parameter is larger than the sum of the nuclear radii, provide an extremely clean environment to study various photon-induced processes [1]. For the case of lead-lead (Pb-Pb) UPCs, the production cross section for two-photon fusion processes is enhanced by a factor of about Z^4 (where $Z = 82$ is the Pb charge number), relative to proton-proton collisions. The possibility of observing photon-induced τ lepton production in UPC events at a heavy ion collider was considered well before the LHC era [2]. Recently, theoretical studies [3,4] have proposed that kinematic properties of τ lepton pairs produced in heavy ion UPCs at the LHC can be used to constrain the electromagnetic couplings of the τ lepton. These constraints allow for fundamental tests of quantum electrodynamics (QED) and for probing beyond the standard model (BSM) physics.

A contributing factor in the coupling of the lepton (ℓ) to the photon (γ) is the anomalous magnetic moment $a_\ell = (g - 2)_\ell/2$, with the g factor being the proportionality constant that relates the magnetic moment to the spin of the lepton. With 12 significant digits, the electron anomalous magnetic moment a_e is among the most precisely measured quantities [5], and differs from the standard model (SM) expectation by either -2.4 or $+1.6$ standard deviations [5,6], depending on the input value of the fine structure constant, α_{QED} . The value of a_μ has been measured to nine significant figures [7]. It shows a tension of $+4.2$ standard

deviations with respect to SM predictions [8], although a calculation with a modified hadronic contribution [9] reduces the discrepancy between data and theory by a factor of more than 2, albeit with an uncertainty that is about 20% larger. While the predicted value of a_τ is $0.00117721(5)$ [10,11], with the number in parentheses denoting the uncertainty in the least significant figure, its best measured value is -0.018 ± 0.017 from the DELPHI Collaboration [12] (other existing limits on a_τ can be found in Ref. [13]). The larger uncertainty in a_τ compared with a_μ and a_e measurements primarily results from the short τ lepton lifetime, which is of the order of 10^{-13} s, such that τ leptons cannot be stored long enough to measure their a_τ -dependent precession in a magnetic field. A more precise a_τ determination would facilitate tighter constraints on BSM physics models [14,15], in which additional particles with mass M contribute with terms typically proportional to $(m_\ell/M)^2$. This motivates employing novel experimental approaches for measuring a_τ at current and potential future colliders, as undertaken in this Letter and in a recent measurement by the ATLAS Collaboration [16].

Here, we present an observation of τ lepton pairs in ultraperipheral Pb-Pb collisions, $\gamma\gamma \rightarrow \tau^+\tau^-$, in events that may contain excitations of the outgoing Pb ions. The analysis is based on a data sample with an integrated luminosity of $404 \mu\text{b}^{-1}$ collected by the CMS experiment in 2015 at a center-of-mass energy per nucleon pair of $\sqrt{s_{NN}} = 5.02$ TeV. One τ lepton is reconstructed through its decay to one muon and two neutrinos, while the other is reconstructed through its “3 pronged” decay into hadrons plus a neutrino [13]. This choice of final state offers a clean experimental signature, with the muon used for online selection and the hadronically decaying τ candidate providing discrimination against dimuon photoproduction and

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

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an unambiguous reconstruction of τ lepton decay. The reconstruction of the τ leptons is performed over a fiducial phase space, defined by the transverse momentum (p_T) and pseudorapidity (η) of each particle. Tabulated results are provided in the HEPData record for this analysis [17].

The CMS apparatus [18] is a multipurpose, nearly hermetic detector, designed to trigger on Refs. [19,20] and identify electrons, photons, muons, τ leptons, jets, and missing p_T [21–23]. A global reconstruction “particle-flow” algorithm [24] combines the information provided by the all-silicon inner tracker, the crystal electromagnetic calorimeter, and the brass and scintillator hadron calorimeter, operating inside a 3.8 T superconducting solenoid, with that from gas-ionization muon detectors embedded in the flux-return yoke outside the solenoid, to build τ lepton candidates and jets, and to measure the missing p_T [25–27]. Forward hadron (HF) calorimeters [28], made of steel and quartz-fibers, extend the $|\eta|$ coverage from 3.0, provided by the barrel and endcap detectors, to 5.2. The HF calorimeters are segmented to form $\Delta\eta \times \Delta\phi$ “towers” of width 0.175×0.175 , with ϕ being the azimuthal angle. Events are selected online using a two-tiered trigger system. The first level, composed of custom hardware processors, uses information from the calorimeters and muon detectors [19]. The second level, known as the high-level trigger [20], consists of a farm of processors running a version of the full event reconstruction software.

The UPCs producing two final-state τ leptons are uniquely characterized by low track multiplicity and the presence of very forward (i.e., high $|\eta|$) lead ions that are either scattered or dissociated in a direction so close to the beam as to be undetectable. Therefore, we select high-purity UPC events [29] by requiring in real time the presence of a single muon with no explicit p_T threshold requirement, at least one pixel detector track, and low event activity in the HF [19]. To further suppress background processes, such as hadronic Pb-Pb collisions, it is required offline that the maximum energy measured in an HF tower be below 4 GeV.

Furthermore, the fiducial phase space region is constrained offline by selecting events with one muon and exactly three additional tracks. For the muon defining the “ τ_μ ” candidate, a selection is applied requiring $|\eta| < 2.4$ and that the muon satisfy the “soft” identification criteria described in Ref. [22], with $p_T > 3.5$ GeV for $|\eta| < 1.2$ and $p_T > 2.5$ GeV for $|\eta| > 1.2$, following the acceptance of the muon detector system. The three tracks that form the “ $\tau_{3\text{prong}}$ ” candidate [25] are assumed to be pions and are required to be within the tracker acceptance ($|\eta| < 2.5$), along the direction of the two beams have a common vertex within 2.5 mm relative to the vertex corresponding to the hardest scattering in the event [30], and be identified as charged hadrons by the particle-flow algorithm. The transverse momentum of the leading (i.e., the highest p_T) and two subleading pions must be greater than 0.5 and 0.3 GeV, respectively. The selected tracks are required to

pass the “high-purity” requirements of Ref. [23]. The $\tau_{3\text{prong}}$ candidate is then required to be of opposite charge relative to the selected τ_μ , and to have $p_T^{\text{vis}} > 2$ GeV, where p_T^{vis} is the vector sum p_T of the three charged pions (the “visible” decay products of the $\tau_{3\text{prong}}$ candidate). Additionally, the invariant mass of the three pion candidates m_τ^{vis} is required to be less than 1.5 GeV. With these selections we identify 91 $\gamma\gamma \rightarrow \tau^+\tau^-$ candidate events.

Backgrounds arise from heavy quark photoproduction, UPC photon-photon and photon-pomeron interactions producing mesons that can decay to muons and charged hadrons. Dedicated samples of events from $\gamma\gamma \rightarrow \tau^+\tau^-$ [3], $\gamma\gamma \rightarrow c\bar{c}$, and $\gamma\gamma \rightarrow b\bar{b}$ processes are generated with MADGRAPH5_aMC@NLO (v2.6.5) [31], where PYTHIA8 (v2.1.2) [32] is used for the hadronization and decay, and GEANT4 [33] is used to emulate the full CMS detector response. All studied kinematic distributions of the muons and charged pions in simulated events are corrected using comparisons between the simulation and data, outside the signal region, as a function of the muon or track p_T and η . For muons, we use a “tag-and-probe” method with $J/\psi \rightarrow \mu^+\mu^-$ events [22]. For charged hadrons, we use the number of reconstructed D^0 meson decays to final states with four charged hadrons divided by those with two daughters. The simulated background processes produce a large number of tracks and hence sparsely populate the signal-dominated phase space region. They are only used to partly validate the expected $\gamma\gamma \rightarrow c\bar{c}$ and $\gamma\gamma \rightarrow b\bar{b}$ contributions to the background estimation as described in the following paragraph.

To properly estimate the background, we use a technique based on control samples in data, referred to as the “ABCD method.” Three phase space regions (“categories”) are used to derive the background in the fourth region, from which the signal is extracted. The four categories, which have been found to be uncorrelated in data, are defined according to the value of the highest energy tower in HF, and the number of charged particle tracks per event (n_{ch}), excluding the track associated with the τ_μ candidate. The low- n_{ch} categories (B and D) are defined by $n_{\text{ch}} = 3$, whereas the high- n_{ch} categories (A and C) must have $5 \leq n_{\text{ch}} \leq 8$ to avoid signal contamination while being similar to the signal region. The low-HF (C and D) and high-HF (A and B) categories are defined by energies below and above 4 GeV, respectively. Consequently, category D is the signal region (low- n_{ch} and low-HF category), and the background estimation is $B_i C_i / A_i$, where each of the categories is evaluated per kinematic-variable and category-dependent bin, as indicated by the subscript i . Based on the simulated signal events, we find that the event selection described above removes all signal events from the control regions (A – C). The kinematic distributions showing the $\gamma\gamma \rightarrow \tau^+\tau^-$ signal process, scaled to match the QED prediction of Ref. [3], as well as the background model based on control

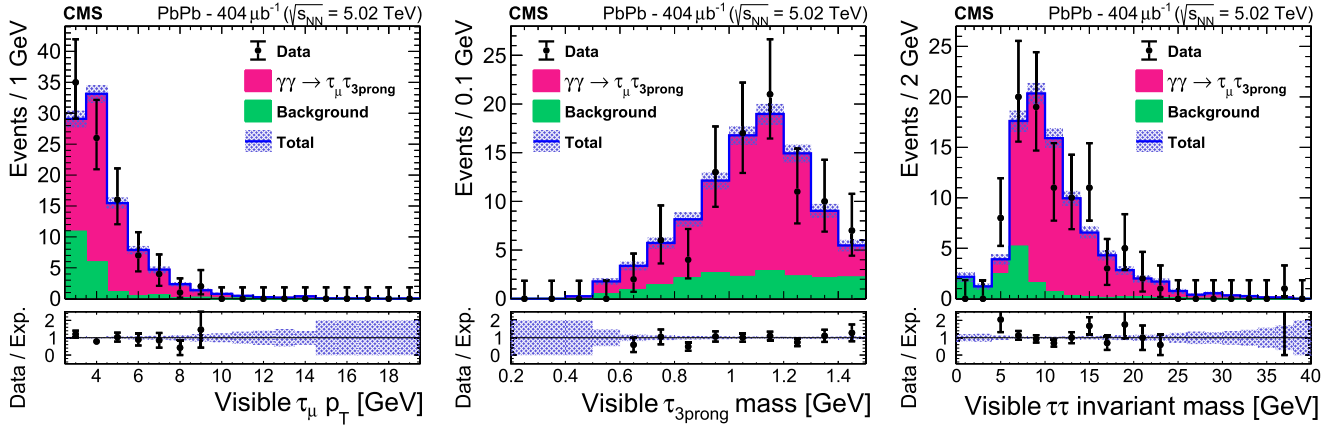


FIG. 1. Left: transverse momentum of the muon originating from the τ_μ candidate. Middle: invariant mass of the three pions forming the $\tau_{3\text{prong}}$ candidate. Right: $\tau^+\tau^-$ invariant mass. In all plots, the signal component (magenta histogram) is stacked on top of the background component (green histogram), considering their initial normalizations, as described in the text. The sum of signal and background is displayed by a blue line, and the shaded area shows the statistical uncertainty. The data are represented with black points, and the uncertainty is statistical only. The lower panels show the ratios of data to the signal-plus-background prediction, and the shaded bands represent the statistical uncertainty in the prefit expectation.

samples in data, are shown in Fig. 1. Good agreement is observed between the measured distributions and the sum of the signal simulation and background estimation.

A binned maximum likelihood fit of signal and background components is used for the signal extraction. The fit is performed on the binned distribution of the difference in azimuthal opening angle between the τ_μ and $\tau_{3\text{prong}}$ candidates, $\Delta\phi(\tau_\mu, \tau_{3\text{prong}})$, exploiting the fact that the two signal τ leptons are produced azimuthally back to back in UPCs [1,34]. The signal distribution is derived from the $\gamma\gamma \rightarrow \tau^+\tau^-$ simulation, while that of the background is obtained from the *ABCD* method described above, including its normalization as a constant parameter in the fit. The initial (“prefit”) number of signal events is taken from the QED prediction of Ref. [3]. Systematic uncertainties may affect both the normalization and the shape of the $\Delta\phi(\tau_\mu, \tau_{3\text{prong}})$ distributions. These uncertainties, in addition to the bin-by-bin variations of the signal and background templates, are represented by nuisance parameters in the fit. Rate-changing nuisance parameters are represented as log-normal probability distribution functions, while shape-changing ones are represented with Gaussian probability distribution functions. The negative of the log likelihood is minimized by varying the nuisance parameters according to their uncertainties and by scaling the signal by a multiplicative factor r .

Uncertainties arising from the HF energy threshold are evaluated by varying the HF energy by 10% [35]. The effect on the measured cross section due to this variation is dominated by the resulting variation in the background shape from the *ABCD* procedure, and is found to be 0.9%. An additional systematic uncertainty coming from the background shape and yield estimation is considered by reevaluating the background using the *ABCD* procedure,

changing the high n_{ch} parameter to individual values of 5, 6, 7, and 8, as opposed to the range 5–8. The maximum variation with respect to the central value comes from the determination with $n_{\text{ch}} = 5$, resulting in a 0.2% variation of the fiducial cross section measurement.

The uncertainty in the muon efficiency, including the trigger response, identification and tracking efficiency, has an impact of 6.7%. The integrated luminosity is measured with the methods described in Refs. [36,37], and has an uncertainty of 5%, which affects the yield from the QED simulation to which the signal is normalized. The uncertainty in the pion tracking efficiency results in an uncertainty of 3.6%. The simulated signal distribution has a finite number of events, resulting in a 3% uncertainty due to bin-by-bin statistical fluctuations, and a 1.1% weighted binomial uncertainty on the efficiency. The uncertainty in the τ lepton branching fraction measurements is 0.6% [13].

The total uncertainty, obtained by adding them in quadrature while taking into account their correlation, is found to be 9.7%.

The best fit value of the signal strength multiplicative factor is $r = 0.99^{+0.16}_{-0.14}$ with $N_{\text{sig}} = 77 \pm 12$ signal events in the integral of the postfit signal component. The fit result is shown in Fig. 2, along with the data, and signal and background templates. The observed (expected) signal significance, computed using the asymptotic approximation [38], is found to be 14.2 (14.5) standard deviations. These values indicate a clear observation of the $\gamma\gamma \rightarrow \tau^+\tau^-$ process.

The cross section is measured in the fiducial phase space region, following the kinematic requirements previously described. The formula used is $\sigma(\gamma\gamma \rightarrow \tau^+\tau^-) = N_{\text{sig}} / (2\epsilon\mathcal{L}_{\text{int}}\mathcal{B}_{\tau_\mu}\mathcal{B}_{\tau_{3\text{prong}}})$, where N_{sig} is the number of signal events estimated by the fit process, ϵ is the total signal

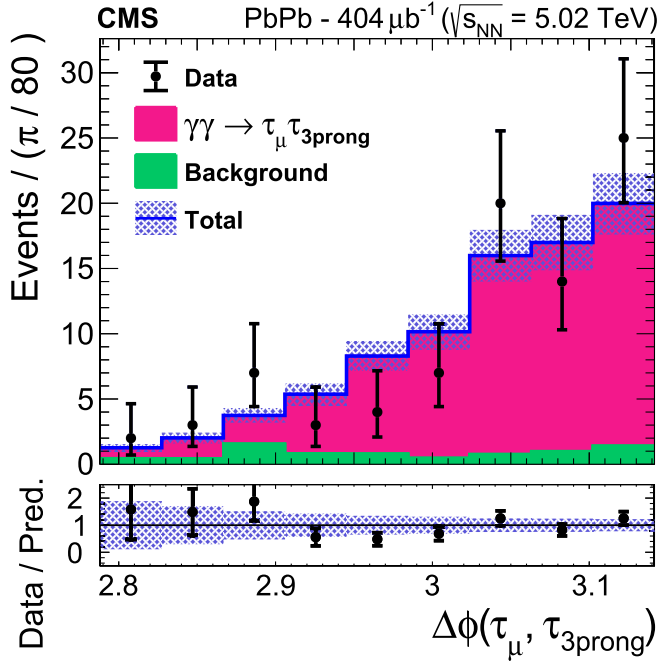


FIG. 2. Difference in azimuthal opening angle between the τ_μ and $\tau_{3\text{prong}}$ candidates. The data are represented by the points with the vertical bars showing the statistical uncertainties. The signal (background) contribution is given by the magenta (green) histogram, after the application of the fit procedure. The total is displayed by a blue line, and the shaded area shows the combined statistical and systematic uncertainties. The lower panel shows the ratio of data to the signal plus background prediction, and the shaded band represents the total uncertainty in the postfit prediction.

efficiency, $\mathcal{L}_{\text{int}} = 404 \pm 20 \text{ } \mu\text{b}^{-1}$ is the total integrated luminosity, and $\mathcal{B}_{\tau_\mu} = (17.39 \pm 0.04)\%$ and $\mathcal{B}_{\tau_{3\text{prong}}} = (14.55 \pm 0.06)\%$ [13] are the branching fractions for the two τ lepton decay modes. The factor of 2 accounts for the two potential τ lepton decay combinations yielding the same final state, whereas three-prong decays could include additional neutral pions. The efficiency is the product of the pion and muon reconstruction, the trigger, and the analysis selection efficiencies, and is evaluated using simulated signal events. The efficiency is calculated as the number of reconstructed events passing the analysis selection criteria divided by the number of generated events inside the fiducial phase space region, and is found to be $\epsilon = (78.5 \pm 0.8)\%$.

Combining all of the above, the fiducial cross section is found to be $\sigma(\gamma\gamma \rightarrow \tau^+\tau^-) = 4.8 \pm 0.6(\text{stat}) \pm 0.5(\text{syst}) \mu\text{b}$. The result, summarized in Fig. 3, is compared to leading-order QED predictions [3,4]. The analytical calculation from Ref. [4] results in a cross section which is 20% higher than that found in Ref. [3]. This is explained in Ref. [4] as mainly stemming from the different requirements applied in the modeling of single-photon fluxes. In both cases, although further theory advancements are needed for a proper uncertainty evaluation, a conservative uncertainty of 10% is considered following the approach

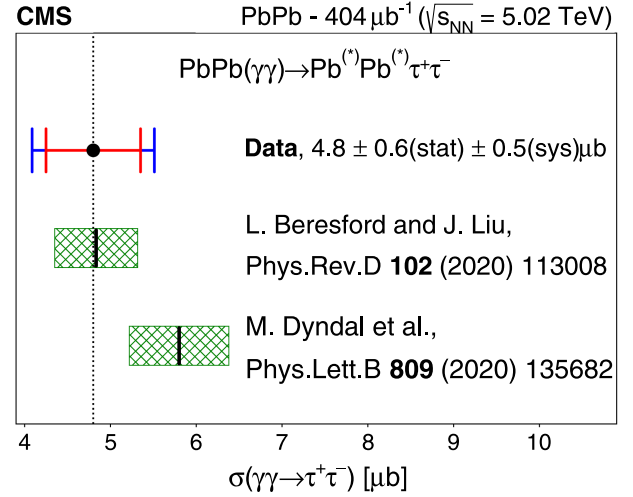


FIG. 3. The cross section, $\sigma(\gamma\gamma \rightarrow \tau^+\tau^-)$, measured in a fiducial phase space region at $\sqrt{s_{NN}} = 5.02 \text{ TeV}$. The theoretical predictions [3,4] are computed with leading-order accuracy in QED and are represented by the vertical solid lines that can be compared with the vertical dotted line representing this measurement. The outer blue (inner red) error bars surrounding the data point indicate the total (statistical) uncertainties, whereas the green hatched bands correspond to the uncertainty in the theoretical predictions as described in the main text. The potential electromagnetic excitation of the outgoing Pb ions is denoted by (*).

from Ref. [29] given the similarity of final states and phase-space volumes.

Recent calculations have evaluated the impact of BSM processes on the $\gamma\gamma \rightarrow \tau^+\tau^-$ cross section. The BSM coupling variations in a_τ can change the expected cross section and alter the τ lepton p_T spectrum [3,4]. We assume the correction factor of Ref. [3] to extrapolate the fiducial cross section measurement to the full phase space region, after taking into account an extra factor of $1/\sqrt{4\pi}$ for the electron charge in Heaviside-Lorentz units. We then use the dependency of the total $\sigma(\gamma\gamma \rightarrow \tau^+\tau^-)$ as a function of a_τ [3] to extract a model-dependent value of a_τ at the LHC. The measured value is $a_\tau = 0.001^{+0.055}_{-0.089}$, which is consistent with the current best measurement [12]. The ATLAS Collaboration has also recently reported a measurement of $\gamma\gamma \rightarrow \tau^+\tau^-$ using a larger Pb-Pb data sample with an integrated luminosity of 1.44 nb^{-1} [16]. With respect to the ATLAS measurement, we cover a larger phase space with muon $p_T > 2.5 \text{ GeV}$, while Ref. [16] uses $p_T > 4 \text{ GeV}$, and we make no restrictions on neutron emission. Because of the larger fiducial phase space region comprised by our measurement, the attained precision in r for the studied final state is comparable to that of $r = 0.98^{+0.14}_{-0.13}$ obtained in Ref. [16]. The approaches followed by the two collaborations in the measurement of a_τ are complementary to each other: we extract a_τ from $\sigma(\gamma\gamma \rightarrow \tau^+\tau^-)$, while Ref. [16] extracts a_τ from a shape analysis of the $\tau_\mu p_T$.

In summary, an observation of τ lepton pair production in ultraperipheral nucleus-nucleus collisions is reported. Events with a final state of one muon and three charged hadrons assumed to be pions are reconstructed from a lead-lead data sample with an integrated luminosity of $404 \mu\text{b}^{-1}$ collected by the CMS experiment at $\sqrt{s_{NN}} = 5.02 \text{ TeV}$ in 2015. The statistical significance of the signal relative to the background-only expectation is far above 5 standard deviations. The cross section for the $\gamma\gamma \rightarrow \tau^+\tau^-$ process, within a fiducial phase space region, is $\sigma(\gamma\gamma \rightarrow \tau^+\tau^-) = 4.8 \pm 0.6(\text{stat}) \pm 0.5(\text{syst}) \mu\text{b}$, in agreement with leading-order quantum electrodynamics predictions. Using the measured cross section and its corresponding uncertainties, we estimate a model-dependent value of the anomalous magnetic moment of the τ lepton of $a_\tau = 0.001^{+0.055}_{-0.089}$. This measurement provides a novel experimental probe of the τ anomalous magnetic moment using heavy ion collisions at the LHC.

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A. Tumasyan^{1,b}, W. Adam², J. W. Andrejkovic², T. Bergauer², S. Chatterjee², K. Damanakis², M. Dragicevic², A. Escalante Del Valle², P. S. Hussain², M. Jeitler^{2,c}, N. Krammer², L. Lechner², D. Liko², I. Mikulec², P. Paulitsch², F. M. Pitters², J. Schieck^{2,c}, R. Schöfbeck², D. Schwarz², S. Templ², W. Waltenberger², C.-E. Wulz^{2,c}, M. R. Darwish^{3,d}, T. Janssen³, T. Kello^{3,e}, H. Rejeb Sfar³, P. Van Mechelen³, E. S. Bols⁴, J. D'Hondt⁴, A. De Moor⁴, M. Delcourt⁴, H. El Faham⁴, S. Lowette⁴, S. Moortgat⁴, A. Morton⁴, D. Müller⁴, A. R. Sahasransu⁴, S. Tavernier⁴, W. Van Doninck⁴, D. Vannerom⁴, B. Clerbaux⁵, G. De Lentdecker⁵, L. Favart⁵, D. Hohov⁵, J. Jaramillo⁵, K. Lee⁵, M. Mahdavihorrani⁵, I. Makarenko⁵, A. Malara⁵, S. Paredes⁵, L. Pétré⁵, N. Postiau⁵, E. Starling⁵, L. Thomas⁵, M. Vanden Bemden⁵, C. Vander Velde⁵, P. Vanlaer⁵, D. Dobur⁶, J. Knolle⁶, L. Lambrecht⁶, G. Mestdach⁶, M. Niedziela⁶, C. Rendón⁶, C. Roskas⁶, A. Samalan⁶, K. Skovpen⁶, M. Tytgat⁶, N. Van Den Bossche⁶, B. Vermassen⁶, L. Wezenbeek⁶, A. Benecke⁷, G. Bruno⁷, F. Bury⁷, C. Caputo⁷, P. David⁷, C. Delaere⁷, I. S. Donertas⁷, A. Giammanco⁷, K. Jaffel⁷, Sa. Jain⁷, V. Lemaitre⁷, K. Mondal⁷, J. Prisciandaro⁷, A. Taliencio⁷, T. T. Tran⁷, P. Vischia⁷, S. Wertz⁷, G. A. Alves⁸, E. Coelho⁸, C. Hensel⁸, A. Moraes⁸, P. Rebello Teles⁸, W. L. Aldá Júnior⁹, M. Alves Gallo Pereira⁹, M. Barroso Ferreira Filho⁹, H. Brandao Malbouisson⁹, W. Carvalho⁹, J. Chinellato^{9,f}, E. M. Da Costa⁹, G. G. Da Silveira^{9,g}, D. De Jesus Damiao⁹, V. Dos Santos Sousa⁹, S. Fonseca De Souza⁹, J. Martins^{9,h}, C. Mora Herrera⁹, K. Mota Amarilo⁹, L. Mundim⁹, H. Nogima⁹, A. Santoro⁹, S. M. Silva Do Amaral⁹, A. Sznajder⁹, M. Thiel⁹, F. Torres Da Silva De Araujo^{9,i}, A. Vilela Pereira⁹, C. A. Bernardes^{10,g}, L. Calligaris¹⁰, T. R. Fernandez Perez Tomei¹⁰, E. M. Gregores¹⁰, P. G. Mercadante¹⁰, S. F. Novaes¹⁰, Sandra S. Padula¹⁰, A. Aleksandrov¹¹, G. Antchev¹¹, R. Hadjiiska¹¹, P. Iaydjiev¹¹, M. Misheva¹¹, M. Rodozov¹¹, M. Shopova¹¹, G. Sultanov¹¹, A. Dimitrov¹², T. Ivanov¹², L. Litov¹², B. Pavlov¹², P. Petkov¹², A. Petrov¹², E. Shumka¹², T. Cheng¹³, T. Javaid^{13,j}, M. Mittal¹³, L. Yuan¹³, M. Ahmad¹⁴, G. Bauer^{14,k}, Z. Hu¹⁴, S. Lezki¹⁴, K. Yi^{14,l}

- G. M. Chen^{15,j}, H. S. Chen^{15,j}, M. Chen^{15,j}, F. Iemmi¹⁵, C. H. Jiang¹⁵, A. Kapoor¹⁵, H. Liao¹⁵, Z.-A. Liu^{15,m},
 V. Milosevic¹⁵, F. Monti¹⁵, R. Sharma¹⁵, J. Tao¹⁵, J. Thomas-Wilsker¹⁵, J. Wang¹⁵, H. Zhang¹⁵, J. Zhao¹⁵,
 A. Agapitos¹⁶, Y. An¹⁶, Y. Ban¹⁶, C. Chen¹⁶, A. Levin¹⁶, C. Li¹⁶, Q. Li¹⁶, X. Lyu¹⁶, Y. Mao¹⁶, S. J. Qian¹⁶,
 X. Sun¹⁶, D. Wang¹⁶, J. Xiao¹⁶, H. Yang¹⁶, M. Lu¹⁷, Z. You¹⁷, X. Gao^{18,e}, D. Leggat¹⁸, H. Okawa¹⁸,
 Y. Zhang¹⁸, Z. Lin¹⁹, C. Lu¹⁹, M. Xiao¹⁹, C. Avila²⁰, D. A. Barbosa Trujillo²⁰, A. Cabrera²⁰, C. Florez²⁰,
 J. Fraga²⁰, J. Mejia Guisao²¹, F. Ramirez²¹, M. Rodriguez²¹, J. D. Ruiz Alvarez²¹, D. Giljanovic²²,
 N. Godinovic²², D. Lelas²², I. Puljak²², Z. Antunovic²³, M. Kovac²³, T. Sculac²³, V. Brigljevic²⁴,
 B. K. Chitroda²⁴, D. Ferencek²⁴, D. Majumder²⁴, M. Roguljic²⁴, A. Starodumov^{24,n}, T. Susa²⁴, A. Attikis²⁵,
 K. Christoforou²⁵, G. Kole²⁵, M. Kolosova²⁵, S. Konstantinou²⁵, J. Mousa²⁵, C. Nicolaou²⁵, F. Ptochos²⁵,
 P. A. Razis²⁵, H. Rykaczewski²⁵, H. Saka²⁵, M. Finger^{26,n}, M. Finger Jr.^{26,n}, A. Kveton²⁶, E. Ayala²⁷,
 E. Carrera Jarrin²⁸, Y. Assran^{29,o,p}, S. Elgammal^{29,o}, A. Lotfy³⁰, M. A. Mahmoud³⁰, S. Bhowmik³¹,
 R. K. Dewanjee³¹, K. Ehataht³¹, M. Kadastik³¹, T. Lange³¹, S. Nandan³¹, C. Nielsen³¹, J. Pata³¹, M. Raidal³¹,
 L. Tani³¹, C. Veelken³¹, P. Eerola³², H. Kirschenmann³², K. Osterberg³², M. Voutilainen³², S. Bharthuar³³,
 E. Brücken³³, F. Garcia³³, J. Havukainen³³, M. S. Kim³³, R. Kinnunen³³, T. Lampén³³, K. Lassila-Perini³³,
 S. Lehti³³, T. Lindén³³, M. Lotti³³, L. Martikainen³³, M. Myllymäki³³, J. Ott³³, M. m. Rantanen³³,
 H. Siikonen³³, E. Tuominen³³, J. Tuominiemi³³, P. Luukka³⁴, H. Petrow³⁴, T. Tuuva³⁴, C. Amendola³⁵,
 M. Besancon³⁵, F. Couderc³⁵, M. Dejardin³⁵, D. Denegri³⁵, J. L. Faure³⁵, F. Ferri³⁵, S. Ganjour³⁵, P. Gras³⁵,
 G. Hamel de Monchenault³⁵, P. Jarry³⁵, V. Lohezic³⁵, J. Malcles³⁵, J. Rander³⁵, A. Rosowsky³⁵, M. Ö. Sahin³⁵,
 A. Savoy-Navarro^{35,q}, P. Simkina³⁵, M. Titov³⁵, C. Baldenegro Barrera³⁶, F. Beaudette³⁶, A. Buchot Perraguin³⁶,
 P. Busson³⁶, A. Cappati³⁶, C. Charlot³⁶, F. Damas³⁶, O. Davignon³⁶, B. Diab³⁶, G. Falmagne³⁶,
 B. A. Fontana Santos Alves³⁶, S. Ghosh³⁶, R. Granier de Cassagnac³⁶, A. Hakimi³⁶, B. Harikrishnan³⁶, G. Liu³⁶,
 J. Motta³⁶, M. Nguyen³⁶, C. Ochando³⁶, L. Portales³⁶, R. Salerno³⁶, U. Sarkar³⁶, J. B. Sauvan³⁶, Y. Sirois³⁶,
 A. Tarabini³⁶, E. Vernazza³⁶, A. Zabi³⁶, A. Zghiche³⁶, J.-L. Agram^{37,r}, J. Andrea³⁷, D. Appar³⁷, D. Bloch³⁷,
 G. Bourgatte³⁷, J.-M. Brom³⁷, E. C. Chabert³⁷, C. Collard³⁷, D. Darej³⁷, U. Goerlach³⁷, C. Grimault³⁷,
 A.-C. Le Bihan³⁷, P. Van Hove³⁷, S. Beauceron³⁸, C. Bernet³⁸, B. Blancon³⁸, G. Boudoul³⁸, A. Carle³⁸,
 N. Chanon³⁸, J. Choi³⁸, D. Contardo³⁸, P. Depasse³⁸, C. Dozen^{38,s}, H. El Mamouni³⁸, J. Fay³⁸, S. Gascon³⁸,
 M. Gouzevitch³⁸, G. Grenier³⁸, B. Ille³⁸, I. B. Laktineh³⁸, M. Lethuillier³⁸, L. Mirabito³⁸, S. Perries³⁸,
 L. Torterotot³⁸, M. Vander Donckt³⁸, P. Verdier³⁸, S. Viret³⁸, I. Bagaturia^{39,t}, I. Lomidze³⁹, Z. Tsamalaidze^{39,n},
 V. Botta⁴⁰, L. Feld⁴⁰, K. Klein⁴⁰, M. Lipinski⁴⁰, D. Meuser⁴⁰, A. Pauls⁴⁰, N. Röwert⁴⁰, M. Teroerde⁴⁰,
 S. Diekmann⁴¹, A. Dodonova⁴¹, N. Eich⁴¹, D. Eliseev⁴¹, M. Erdmann⁴¹, P. Fackeldey⁴¹, D. Fasanella⁴¹,
 B. Fischer⁴¹, T. Hebbeker⁴¹, K. Hoepfner⁴¹, F. Ivone⁴¹, M. y. Lee⁴¹, L. Mastrolorenzo⁴¹, M. Merschmeyer⁴¹,
 A. Meyer⁴¹, S. Mondal⁴¹, S. Mukherjee⁴¹, D. Noll⁴¹, A. Novak⁴¹, F. Nowotny⁴¹, A. Pozdnyakov⁴¹, Y. Rath⁴¹,
 W. Redjeb⁴¹, H. Reithler⁴¹, A. Schmidt⁴¹, S. C. Schuler⁴¹, A. Sharma⁴¹, L. Vigilante⁴¹, S. Wiedenbeck⁴¹,
 S. Zaleski⁴¹, C. Dziwok⁴², G. Flüge⁴², W. Haj Ahmad^{42,u}, O. Hlushchenko⁴², T. Kress⁴², A. Nowack⁴²,
 O. Pooth⁴², A. Stahl^{42,v}, T. Ziemons⁴², A. Zotz⁴², H. Aarup Petersen⁴³, M. Aldaya Martin⁴³, P. Asmuss⁴³,
 S. Baxter⁴³, M. Bayatmakou⁴³, O. Behnke⁴³, A. Bermúdez Martínez⁴³, S. Bhattacharya⁴³, A. A. Bin Anuar⁴³,
 F. Blekman^{43,w}, K. Borrás^{43,x}, D. Brunner⁴³, A. Campbell⁴³, A. Cardini⁴³, C. Cheng⁴³, F. Colombina⁴³,
 S. Consuegra Rodríguez⁴³, G. Correia Silva⁴³, M. De Silva⁴³, L. Didukh⁴³, G. Eckerlin⁴³, D. Eckstein⁴³,
 L. I. Estevez Banos⁴³, O. Filatov⁴³, E. Gallo^{43,w}, A. Geiser⁴³, A. Giraldi⁴³, G. Greau⁴³, A. Grohsjean⁴³,
 V. Guglielmi⁴³, M. Guthoff⁴³, A. Jafari^{43,y}, N. Z. Jomhari⁴³, B. Kaeck⁴³, A. Kasem^{43,x}, M. Kasemann⁴³,
 H. Kaveh⁴³, C. Kleinwort⁴³, R. Kogler⁴³, M. Komm⁴³, D. Krücker⁴³, W. Lange⁴³, D. Leyva Pernia⁴³,
 K. Lipka⁴³, W. Lohmann^{43,z}, R. Mankel⁴³, I.-A. Melzer-Pellmann⁴³, M. Mendizabal Morentin⁴³, J. Metwally⁴³,
 A. B. Meyer⁴³, G. Milella⁴³, M. Mormile⁴³, A. Mussgiller⁴³, A. Nürnberg⁴³, Y. Otari⁴³, D. Pérez Adán⁴³,
 A. Raspereza⁴³, B. Ribeiro Lopes⁴³, J. Rübenach⁴³, A. Saggio⁴³, A. Saibel⁴³, M. Savitskyi⁴³, M. Scham^{43,aa,x},
 V. Scheurer⁴³, S. Schnake^{43,x}, P. Schütze⁴³, C. Schwanenberger^{43,w}, M. Shchedrolosiev⁴³, R. E. Sosa Ricardo⁴³,
 D. Stafford⁴³, N. Tonon^{43,a}, M. Van De Klundert⁴³, F. Vazzoler⁴³, A. Ventura Barroso⁴³, R. Walsh⁴³, D. Walter⁴³,
 Q. Wang⁴³, Y. Wen⁴³, K. Wichmann⁴³, L. Wiens^{43,x}, C. Wissing⁴³, S. Wuchterl⁴³, Y. Yang⁴³,
 A. Zimmermann Castro Santos⁴³, A. Albrecht⁴⁴, S. Albrecht⁴⁴, M. Antonello⁴⁴, S. Bein⁴⁴, L. Benato⁴⁴,
 M. Bonanomi⁴⁴, P. Connor⁴⁴, K. De Leo⁴⁴, M. Eich⁴⁴, K. El Morabit⁴⁴, F. Feindt⁴⁴, A. Fröhlich⁴⁴, C. Garbers⁴⁴

- E. Garutti⁴⁴, M. Hajheidari⁴⁴, J. Haller⁴⁴, A. Hinzmann⁴⁴, H. R. Jabusch⁴⁴, G. Kasieczka⁴⁴, R. Klanner⁴⁴, W. Korcari⁴⁴, T. Kramer⁴⁴, V. Kutzner⁴⁴, J. Lange⁴⁴, A. Lobanov⁴⁴, C. Matthies⁴⁴, A. Mehta⁴⁴, L. Moureaux⁴⁴, M. Mrowietz⁴⁴, A. Nigamova⁴⁴, Y. Nissan⁴⁴, A. Paasch⁴⁴, K. J. Pena Rodriguez⁴⁴, M. Rieger⁴⁴, O. Rieger⁴⁴, P. Schleper⁴⁴, M. Schröder⁴⁴, J. Schwandt⁴⁴, H. Stadie⁴⁴, G. Steinbrück⁴⁴, A. Tews⁴⁴, M. Wolf⁴⁴, J. Bechtel⁴⁵, S. Brommer⁴⁵, M. Burkart⁴⁵, E. Butz⁴⁵, R. Caspart⁴⁵, T. Chwalek⁴⁵, A. Dierlamm⁴⁵, A. Droll⁴⁵, N. Faltermann⁴⁵, M. Giffels⁴⁵, J. O. Gosewisch⁴⁵, A. Gottmann⁴⁵, F. Hartmann^{45,v}, M. Horzela⁴⁵, U. Husemann⁴⁵, P. Keicher⁴⁵, M. Klute⁴⁵, R. Koppenhöfer⁴⁵, S. Maier⁴⁵, S. Mitra⁴⁵, Th. Müller⁴⁵, M. Neukum⁴⁵, G. Quast⁴⁵, K. Rabbertz⁴⁵, J. Rauser⁴⁵, D. Savoio⁴⁵, M. Schnepf⁴⁵, D. Seith⁴⁵, I. Shvetsov⁴⁵, H. J. Simonis⁴⁵, N. Trevisani⁴⁵, R. Ulrich⁴⁵, J. van der Linden⁴⁵, R. F. Von Cube⁴⁵, M. Wassmer⁴⁵, S. Wieland⁴⁵, R. Wolf⁴⁵, S. Wozniowski⁴⁵, S. Wunsch⁴⁵, G. Anagnostou⁴⁶, P. Assiouras⁴⁶, G. Daskalakis⁴⁶, A. Kyriakis⁴⁶, A. Stakia⁴⁶, M. Diamantopoulou⁴⁷, D. Karasavvas⁴⁷, P. Kontaxakis⁴⁷, A. Manousakis-Katsikakis⁴⁷, A. Panagiotou⁴⁷, I. Papavergou⁴⁷, N. Saoulidou⁴⁷, K. Theofilatos⁴⁷, E. Tziaferi⁴⁷, K. Vellidis⁴⁷, E. Vourliotis⁴⁷, I. Zisopoulos⁴⁷, G. Bakas⁴⁸, T. Chatzistavrou⁴⁸, K. Kousouris⁴⁸, I. Papakrivopoulos⁴⁸, G. Tsipolitis⁴⁸, A. Zacharopoulou⁴⁸, K. Adamidis⁴⁹, I. Bestintzanos⁴⁹, I. Evangelou⁴⁹, C. Foudas⁴⁹, P. Gianneios⁴⁹, C. Kamtsikis⁴⁹, P. Katsoulis⁴⁹, P. Kokkas⁴⁹, P. G. Kosmoglou Kioseoglou⁴⁹, N. Manthos⁴⁹, I. Papadopoulos⁴⁹, J. Strolgas⁴⁹, M. Csanád⁵⁰, K. Farkas⁵⁰, M. M. A. Gadallah^{50,bb}, S. Lökös^{50,cc}, P. Major⁵⁰, K. Mandal⁵⁰, G. Pásztor⁵⁰, A. J. Rádl^{50,dd}, O. Surányi⁵⁰, G. I. Veres⁵⁰, M. Bartók^{51,ee}, G. Bencze⁵¹, C. Hajdu⁵¹, D. Horvath^{51,ff,gg}, F. Sikler⁵¹, V. Veszpremi⁵¹, N. Beni⁵², S. Czellar⁵², J. Karancsi^{52,ee}, J. Molnar⁵², Z. Szillasi⁵², D. Teyssier⁵², P. Raics⁵³, B. Ujvari^{53,hh}, T. Csorgo^{54,dd}, F. Nemes^{54,dd}, T. Novak⁵⁴, J. Babbar⁵⁵, S. Bansal⁵⁵, S. B. Beri⁵⁵, V. Bhatnagar⁵⁵, G. Chaudhary⁵⁵, S. Chauhan⁵⁵, N. Dhingra^{55,ii}, R. Gupta⁵⁵, A. Kaur⁵⁵, A. Kaur⁵⁵, H. Kaur⁵⁵, M. Kaur⁵⁵, S. Kumar⁵⁵, P. Kumari⁵⁵, M. Meena⁵⁵, K. Sandeep⁵⁵, T. Sheokand⁵⁵, J. B. Singh^{55,jj}, A. Singla⁵⁵, A. K. Viridi⁵⁵, A. Ahmed⁵⁶, A. Bhardwaj⁵⁶, B. C. Choudhary⁵⁶, M. Gola⁵⁶, A. Kumar⁵⁶, M. Naimuddin⁵⁶, P. Priyanka⁵⁶, K. Ranjan⁵⁶, S. Saumya⁵⁶, A. Shah⁵⁶, S. Baradia⁵⁷, S. Barman^{57,kk}, S. Bhattacharya⁵⁷, D. Bhowmik⁵⁷, S. Dutta⁵⁷, S. Dutta⁵⁷, B. Gomber^{57,ll}, M. Maity^{57,kk}, P. Palit⁵⁷, P. K. Rout⁵⁷, G. Saha⁵⁷, B. Sahu⁵⁷, S. Sarkar⁵⁷, P. K. Behera⁵⁸, S. C. Behera⁵⁸, P. Kalbhor⁵⁸, J. R. Komaragiri^{58,mm}, D. Kumar^{58,mm}, A. Muhammad⁵⁸, L. Panwar^{58,nmm}, R. Pradhan⁵⁸, P. R. Pujahari⁵⁸, A. Sharma⁵⁸, A. K. Sikdar⁵⁸, P. C. Tiwari^{58,mm}, S. Verma⁵⁸, K. Naskar^{59,nn}, T. Aziz⁶⁰, I. Das⁶⁰, S. Dugad⁶⁰, M. Kumar⁶⁰, G. B. Mohanty⁶⁰, P. Suryadevara⁶⁰, S. Banerjee⁶¹, R. Chudasama⁶¹, M. Guchait⁶¹, S. Karmakar⁶¹, S. Kumar⁶¹, G. Majumder⁶¹, K. Mazumdar⁶¹, S. Mukherjee⁶¹, A. Thachayath⁶¹, S. Bahinipati^{62,oo}, A. K. Das⁶², C. Kar⁶², P. Mal⁶², T. Mishra⁶², V. K. Muraleedharan Nair Bindhu^{62,pp}, A. Nayak^{62,pp}, P. Saha⁶², S. K. Swain⁶², D. Vats^{62,pp}, A. Alpna⁶³, S. Dube⁶³, B. Kansal⁶³, A. Laha⁶³, S. Pandey⁶³, A. Rastogi⁶³, S. Sharma⁶³, H. Bakhshiansohi^{64,qq}, E. Khazaie⁶⁴, M. Zeinali^{64,rr}, S. Chenarani^{65,ss}, S. M. Etesami⁶⁵, M. Khakzad⁶⁵, M. Mohammadi Najafabadi⁶⁵, M. Grunewald⁶⁶, M. Abbrescia^{67a,67b}, R. Aly^{67a,67c,tt}, C. Aruta^{67a,67b}, A. Colaleo^{67a}, D. Creanza^{67a,67c}, N. De Filippis^{67a,67c}, M. De Palma^{67a,67b}, A. Di Florio^{67a,67b}, W. Elmetenawee^{67a,67b}, F. Errico^{67a,67b}, L. Fiore^{67a}, G. Iaselli^{67a,67c}, M. Ince^{67a,67b}, G. Maggi^{67a,67c}, M. Maggi^{67a}, I. Margjeka^{67a,67b}, V. Mastrapasqua^{67a,67b}, S. My^{67a,67b}, S. Nuzzo^{67a,67b}, A. Pellicchia^{67a,67b}, A. Pompili^{67a,67b}, G. Pugliese^{67a,67c}, R. Radogna^{67a}, D. Ramos^{67a}, A. Ranieri^{67a}, G. Selvaggi^{67a,67b}, L. Silvestris^{67a}, F. M. Simone^{67a,67b}, Ü. Sözbilir^{67a}, A. Stamerra^{67a}, R. Venditti^{67a}, P. Verwilligen^{67a}, G. Abbiendi^{68a}, C. Battilana^{68a,68b}, D. Bonacorsi^{68a,68b}, L. Borgonovi^{68a}, L. Brigliadori^{68a}, R. Campanini^{68a,68b}, P. Capiluppi^{68a,68b}, A. Castro^{68a,68b}, F. R. Cavallo^{68a}, M. Cuffiani^{68a,68b}, G. M. Dallavalle^{68a}, T. Diotallevi^{68a,68b}, F. Fabbri^{68a}, A. Fanfani^{68a,68b}, P. Giacomelli^{68a}, L. Giommi^{68a,68b}, C. Grandi^{68a}, L. Guiducci^{68a,68b}, S. Lo Meo^{68a,uu}, L. Lunerti^{68a,68b}, S. Marcellini^{68a}, G. Masetti^{68a}, F. L. Navarria^{68a,68b}, A. Perrotta^{68a}, F. Primavera^{68a,68b}, A. M. Rossi^{68a,68b}, T. Rovelli^{68a,68b}, G. P. Siroli^{68a,68b}, S. Costa^{69a,69b,vv}, A. Di Mattia^{69a}, R. Potenza^{69a,69b}, A. Tricomi^{69a,69b,vv}, C. Tuve^{69a,69b}, G. Barbagli^{70a}, B. Camaiani^{70a,70b}, A. Cassese^{70a}, R. Ceccarelli^{70a,70b}, V. Ciulli^{70a,70b}, C. Civinini^{70a}, R. D'Alessandro^{70a,70b}, E. Focardi^{70a,70b}, G. Latino^{70a,70b}, P. Lenzi^{70a,70b}, M. Lizzo^{70a,70b}, M. Meschini^{70a}, S. Paoletti^{70a}, R. Seidita^{70a,70b}, G. Sguazzoni^{70a}, L. Viliani^{70a}, L. Benussi⁷¹, S. Bianco⁷¹, S. Meola^{71,v}, D. Piccolo⁷¹, M. Bozzo^{72a,72b}, F. Ferro^{72a}, R. Mulargia^{72a}, E. Robutti^{72a,72b}, S. Tosi^{72a,72b}, A. Benaglia^{73a}, G. Boldrini^{73a}, F. Brivio^{73a,73b}, F. Cetorelli^{73a,73b}, F. De Guio^{73a,73b}, M. E. Dinardo^{73a,73b}, P. Dini^{73a}, S. Gennai^{73a}, A. Ghezzi^{73a,73b}, P. Govoni^{73a,73b}, L. Guzzi^{73a,73b}, M. T. Lucchini^{73a,73b}, M. Malberti^{73a}, S. Malvezzi^{73a}

A. Massironi^{73a} D. Menasce^{73a} L. Moroni^{73a} M. Paganoni^{73a,73b} D. Pedrini^{73a} B. S. Pinolini^{73a}
 S. Ragazzi^{73a,73b} N. Redaelli^{73a} T. Tabarelli de Fatis^{73a,73b} D. Zuolo^{73a,73b} S. Buontempo^{74a} F. Carnevali^{74a,74b}
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 E. Lusiani^{75a} M. Margoni^{75a,75b} A. T. Meneguzzo^{75a,75b} J. Pazzini^{75a,75b} P. Ronchese^{75a,75b} R. Rossin^{75a,75b}
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 M. Konecki¹⁰⁴ J. Krolikowski¹⁰⁴ M. Araujo¹⁰⁵ P. Bargassa¹⁰⁵ D. Bastos¹⁰⁵ A. Boletti¹⁰⁵ P. Faccioli¹⁰⁵
 M. Gallinaro¹⁰⁵ J. Hollar¹⁰⁵ N. Leonardo¹⁰⁵ T. Niknejad¹⁰⁵ M. Pisano¹⁰⁵ J. Seixas¹⁰⁵ J. Varela¹⁰⁵
 P. Adzic^{106,eee} M. Dordevic¹⁰⁶ P. Milenovic¹⁰⁶ J. Milosevic¹⁰⁶ M. Aguilar-Benitez¹⁰⁷ J. Alcaraz Maestre¹⁰⁷
 A. Álvarez Fernández¹⁰⁷ M. Barrio Luna¹⁰⁷ Cristina F. Bedoya¹⁰⁷ C. A. Carrillo Montoya¹⁰⁷ M. Cepeda¹⁰⁷

- M. Cerrada¹⁰⁷, N. Colino¹⁰⁷, B. De La Cruz¹⁰⁷, A. Delgado Peris¹⁰⁷, D. Fernández Del Val¹⁰⁷,
 J. P. Fernández Ramos¹⁰⁷, J. Flix¹⁰⁷, M. C. Fouz¹⁰⁷, O. Gonzalez Lopez¹⁰⁷, S. Goy Lopez¹⁰⁷, J. M. Hernandez¹⁰⁷,
 M. I. Josa¹⁰⁷, J. León Holgado¹⁰⁷, D. Moran¹⁰⁷, C. Perez Dengra¹⁰⁷, A. Pérez-Calero Yzquierdo¹⁰⁷,
 J. Puerta Pelayo¹⁰⁷, I. Redondo¹⁰⁷, D. D. Redondo Ferrero¹⁰⁷, L. Romero¹⁰⁷, S. Sánchez Navas¹⁰⁷, J. Sastre¹⁰⁷,
 L. Urda Gómez¹⁰⁷, J. Vazquez Escobar¹⁰⁷, C. Willmott¹⁰⁷, J. F. de Trocóniz¹⁰⁸, B. Alvarez Gonzalez¹⁰⁹,
 J. Cuevas¹⁰⁹, J. Fernandez Menendez¹⁰⁹, S. Folgueras¹⁰⁹, I. Gonzalez Caballero¹⁰⁹, J. R. González Fernández¹⁰⁹,
 E. Palencia Cortezon¹⁰⁹, C. Ramón Álvarez¹⁰⁹, V. Rodríguez Bouza¹⁰⁹, A. Soto Rodríguez¹⁰⁹, A. Trapote¹⁰⁹,
 C. Vico Villalba¹⁰⁹, J. A. Brochero Cifuentes¹¹⁰, I. J. Cabrillo¹¹⁰, A. Calderon¹¹⁰, J. Duarte Campderros¹¹⁰,
 M. Fernandez¹¹⁰, C. Fernandez Madrazo¹¹⁰, A. García Alonso¹¹⁰, G. Gomez¹¹⁰, C. Lasiosa García¹¹⁰,
 C. Martinez Rivero¹¹⁰, P. Martinez Ruiz del Arbol¹¹⁰, F. Matorras¹¹⁰, P. Matorras Cuevas¹¹⁰, J. Piedra Gomez¹¹⁰,
 C. Prieels¹¹⁰, A. Ruiz-Jimeno¹¹⁰, L. Scodellaro¹¹⁰, I. Vila¹¹⁰, J. M. Vizan Garcia¹¹⁰, M. K. Jayananda¹¹¹,
 B. Kailasapathy^{111,fff}, D. U. J. Sonnadara¹¹¹, D. D. C. Wickramaratna¹¹¹, W. G. D. Dharmaratna¹¹²,
 K. Liyanage¹¹², N. Perera¹¹², N. Wickramage¹¹², D. Abbaneo¹¹³, J. Alimena¹¹³, E. Auffray¹¹³, G. Auzinger¹¹³,
 J. Baechler¹¹³, P. Baillon^{113,a}, D. Barney¹¹³, J. Bendavid¹¹³, M. Bianco¹¹³, B. Bilin¹¹³, A. Bocci¹¹³,
 E. Brondolin¹¹³, C. Caillol¹¹³, T. Camporesi¹¹³, G. Cerminara¹¹³, N. Chernyavskaya¹¹³, S. S. Chhibra¹¹³,
 S. Choudhury¹¹³, M. Cipriani¹¹³, L. Cristella¹¹³, D. d'Enterria¹¹³, A. Dabrowski¹¹³, A. David¹¹³, A. De Roeck¹¹³,
 M. M. Defranchis¹¹³, M. Deile¹¹³, M. Dobson¹¹³, M. Dünser¹¹³, N. Dupont¹¹³, A. Elliott-Peisert¹¹³,
 F. Fallavollita^{113,ggg}, A. Florent¹¹³, L. Forthomme¹¹³, G. Franzoni¹¹³, W. Funk¹¹³, S. Ghosh¹¹³, S. Giani¹¹³,
 D. Gigi¹¹³, K. Gill¹¹³, F. Glege¹¹³, L. Gouskos¹¹³, E. Govorkova¹¹³, M. Haranko¹¹³, J. Hegeman¹¹³,
 V. Innocente¹¹³, T. James¹¹³, P. Janot¹¹³, J. Kaspar¹¹³, J. Kieseler¹¹³, N. Kratochwil¹¹³, S. Laurila¹¹³,
 P. Lecoq¹¹³, E. Leutgeb¹¹³, A. Lintuluoto¹¹³, C. Lourenço¹¹³, B. Maier¹¹³, L. Malgeri¹¹³, M. Mannelli¹¹³,
 A. C. Marini¹¹³, F. Meijers¹¹³, S. Mersi¹¹³, E. Meschi¹¹³, F. Moortgat¹¹³, M. Mulders¹¹³, S. Orfanelli¹¹³,
 L. Orsini¹¹³, F. Pantaleo¹¹³, E. Perez¹¹³, M. Peruzzi¹¹³, A. Petrilli¹¹³, G. Petrucciani¹¹³, A. Pfeiffer¹¹³,
 M. Pierini¹¹³, D. Piparo¹¹³, M. Pitt¹¹³, H. Qu¹¹³, T. Quast¹¹³, D. Rabady¹¹³, A. Racz¹¹³, G. Reales Gutiérrez¹¹³,
 M. Rovere¹¹³, H. Sakulin¹¹³, J. Salfeld-Nebgen¹¹³, S. Scarfi¹¹³, M. Selvaggi¹¹³, A. Sharma¹¹³, P. Silva¹¹³,
 P. Sphicas^{113,hhh}, A. G. Stahl Leiton¹¹³, S. Summers¹¹³, K. Tatar¹¹³, V. R. Tavolaro¹¹³, D. Treille¹¹³, P. Tropea¹¹³,
 A. Tsiros¹¹³, J. Wanczyk^{113,iii}, K. A. Wozniak¹¹³, W. D. Zeuner¹¹³, L. Caminada^{114,jjj}, A. Ebrahimi¹¹⁴,
 W. Erdmann¹¹⁴, R. Horisberger¹¹⁴, Q. Ingram¹¹⁴, H. C. Kaestli¹¹⁴, D. Kotlinski¹¹⁴, C. Lange¹¹⁴,
 M. Missiroli^{114,jjj}, L. Noehte^{114,jjj}, T. Rohe¹¹⁴, T. K. Aarrestad¹¹⁵, K. Androsov^{115,iii}, M. Backhaus¹¹⁵, P. Berger¹¹⁵,
 A. Calandri¹¹⁵, K. Datta¹¹⁵, A. De Cosa¹¹⁵, G. Dissertori¹¹⁵, M. Dittmar¹¹⁵, M. Donegà¹¹⁵, F. Eble¹¹⁵,
 M. Galli¹¹⁵, K. Gedia¹¹⁵, F. Glessgen¹¹⁵, T. A. Gómez Espinosa¹¹⁵, C. Grab¹¹⁵, D. Hits¹¹⁵, W. Lustermann¹¹⁵,
 A.-M. Lyon¹¹⁵, R. A. Manzoni¹¹⁵, L. Marchese¹¹⁵, C. Martin Perez¹¹⁵, A. Mascellani^{115,iii}, M. T. Meinhard¹¹⁵,
 F. Nessi-Tedaldi¹¹⁵, J. Niedziela¹¹⁵, F. Pauss¹¹⁵, V. Perovic¹¹⁵, S. Pigazzini¹¹⁵, M. G. Ratti¹¹⁵, M. Reichmann¹¹⁵,
 C. Reissel¹¹⁵, T. Reitenspiess¹¹⁵, B. Ristic¹¹⁵, F. Riti¹¹⁵, D. Ruini¹¹⁵, D. A. Sanz Becerra¹¹⁵, J. Steggemann^{115,iii},
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 K. Cormier¹¹⁶, A. De Wit¹¹⁶, R. Del Burgo¹¹⁶, J. K. Heikkilä¹¹⁶, M. Huwiler¹¹⁶, W. Jin¹¹⁶, A. Jofrehei¹¹⁶,
 B. Kilminster¹¹⁶, S. Leontsinis¹¹⁶, S. P. Liechi¹¹⁶, A. Macchiolo¹¹⁶, P. Meiring¹¹⁶, V. M. Mikuni¹¹⁶,
 U. Molinatti¹¹⁶, I. Neutelings¹¹⁶, A. Reimers¹¹⁶, P. Robmann¹¹⁶, S. Sanchez Cruz¹¹⁶, K. Schweiger¹¹⁶,
 M. Senger¹¹⁶, Y. Takahashi¹¹⁶, C. Adloff^{117,III}, C. M. Kuo¹¹⁷, W. Lin¹¹⁷, S. S. Yu¹¹⁷, L. Ceard¹¹⁸, Y. Chao¹¹⁸,
 K. F. Chen¹¹⁸, P. s. Chen¹¹⁸, H. Cheng¹¹⁸, W.-S. Hou¹¹⁸, R. Khurana¹¹⁸, Y. y. Li¹¹⁸, R.-S. Lu¹¹⁸, E. Paganis¹¹⁸,
 A. Psallidas¹¹⁸, A. Steen¹¹⁸, H. y. Wu¹¹⁸, E. Yazgan¹¹⁸, P. r. Yu¹¹⁸, C. Asawatangtrakuldee¹¹⁹, N. Srimanobhas¹¹⁹,
 D. Agyel¹²⁰, F. Boran¹²⁰, Z. S. Demiroglu¹²⁰, F. Dolek¹²⁰, I. Dumanoglu^{120,mmm}, E. Eskut¹²⁰, Y. Guler^{120,nnn},
 E. Gurpinar Guler^{120,nnn}, C. Isik¹²⁰, O. Kara¹²⁰, A. Kayis Topaksu¹²⁰, U. Kiminsu¹²⁰, G. Onengut¹²⁰,
 K. Ozdemir^{120,ooo}, A. Polatoz¹²⁰, A. E. Simsek¹²⁰, B. Tali^{120,ppp}, U. G. Tok¹²⁰, S. Turkcapar¹²⁰, E. Uslan¹²⁰,
 I. S. Zorbakir¹²⁰, G. Karapinar^{121,qqq}, K. Ocalan^{121,rrr}, M. Yalvac^{121,sss}, B. Akgun¹²², I. O. Atakisi¹²²,
 E. Gülmez¹²², M. Kaya^{122,ttt}, O. Kaya^{122,uuu}, Ö. Özgelik¹²², S. Tekten^{122,vvv}, A. Cakir¹²³, K. Cankocak^{123,mmm},
 Y. Komurcu¹²³, S. Sen^{123,www}, O. Aydılek¹²⁴, S. Cerci^{124,ppp}, B. Hacısalinoglu¹²⁴, I. Hos^{124,xxx}, B. Isildak^{124,yyy},
 B. Kaynak¹²⁴, S. Ozkorucuklu¹²⁴, C. Simsek¹²⁴, D. Sunar Cerci^{124,ppp}, B. Grynyov¹²⁵, L. Levchuk¹²⁶,
 D. Anthony¹²⁷, E. Bhal¹²⁷, J. J. Brooke¹²⁷, A. Bundock¹²⁷, E. Clement¹²⁷, D. Cussans¹²⁷, H. Flacher¹²⁷

M. Glowacki,¹²⁷ J. Goldstein¹²⁷ , G. P. Heath,¹²⁷ H. F. Heath¹²⁷ , L. Kreczko¹²⁷ , B. Krikler¹²⁷ , S. Paramesvaran¹²⁷ ,
 S. Seif El Nasr-Storey,¹²⁷ V. J. Smith¹²⁷ , N. Stylianou^{127,zzz} , K. Walkingshaw Pass,¹²⁷ R. White¹²⁷ , A. H. Ball,¹²⁸
 K. W. Bell¹²⁸ , A. Belyaev^{128,aaaa} , C. Brew¹²⁸ , R. M. Brown¹²⁸ , D. J. A. Cockerill¹²⁸ , C. Cooke¹²⁸ , K. V. Ellis,¹²⁸
 K. Harder¹²⁸ , S. Harper¹²⁸ , M.-L. Holmberg^{128,bbbb} , J. Linacre¹²⁸ , K. Manolopoulos,¹²⁸ D. M. Newbold¹²⁸ ,
 E. Olaiya,¹²⁸ D. Petyt¹²⁸ , T. Reis¹²⁸ , G. Salvi¹²⁸ , T. Schuh,¹²⁸ C. H. Shepherd-Themistocleous¹²⁸ , I. R. Tomalin,¹²⁸
 T. Williams¹²⁸ , R. Bainbridge¹²⁹ , P. Bloch¹²⁹ , S. Bonomally,¹²⁹ J. Borg¹²⁹ , S. Breeze,¹²⁹ C. E. Brown¹²⁹ ,
 O. Buchmuller,¹²⁹ V. Cacchio,¹²⁹ V. Cepaitis¹²⁹ , G. S. Chahal^{129,cccc} , D. Colling¹²⁹ , J. S. Dancu,¹²⁹ P. Dauncey¹²⁹ ,
 G. Davies¹²⁹ , J. Davies,¹²⁹ M. Della Negra¹²⁹ , S. Fayer,¹²⁹ G. Fedi¹²⁹ , G. Hall¹²⁹ , M. H. Hassanshahi¹²⁹ ,
 A. Howard,¹²⁹ G. Iles¹²⁹ , J. Langford¹²⁹ , L. Lyons¹²⁹ , A.-M. Magnan¹²⁹ , S. Malik,¹²⁹ A. Martelli¹²⁹ ,
 M. Mieskolainen¹²⁹ , D. G. Monk¹²⁹ , J. Nash^{129,dddd} , M. Pesaresi,¹²⁹ B. C. Radburn-Smith¹²⁹ , D. M. Raymond,¹²⁹
 A. Richards,¹²⁹ A. Rose¹²⁹ , E. Scott¹²⁹ , C. Seez¹²⁹ , A. Shtiplieski,¹²⁹ R. Shukla¹²⁹ , A. Tapper¹²⁹ , K. Uchida¹²⁹ ,
 G. P. Uttley¹²⁹ , L. H. Vage,¹²⁹ T. Virdee^{129,v} , M. Vojinovic¹²⁹ , N. Wardle¹²⁹ , S. N. Webb¹²⁹ , D. Winterbottom,¹²⁹
 K. Coldham,¹³⁰ J. E. Cole¹³⁰ , A. Khan,¹³⁰ P. Kyberd¹³⁰ , I. D. Reid¹³⁰ , S. Abdullin¹³¹ , A. Brinkerhoff¹³¹ ,
 B. Caraway¹³¹ , J. Dittmann¹³¹ , K. Hatakeyama¹³¹ , A. R. Kanuganti¹³¹ , B. McMaster¹³¹ , M. Saunders¹³¹ ,
 S. Sawant¹³¹ , C. Sutantawibul¹³¹ , J. Wilson¹³¹ , R. Bartek¹³² , A. Dominguez¹³² , R. Uniyal¹³² ,
 A. M. Vargas Hernandez¹³² , A. Buccilli¹³³ , S. I. Cooper¹³³ , D. Di Croce¹³³ , S. V. Gleyzer¹³³ , C. Henderson¹³³ ,
 C. U. Perez¹³³ , P. Rumerio^{133,eeee} , C. West¹³³ , A. Akpinar¹³⁴ , A. Albert¹³⁴ , D. Arcaro¹³⁴ , C. Cosby¹³⁴ ,
 Z. Demiragli¹³⁴ , C. Erice¹³⁴ , E. Fontanesi¹³⁴ , D. Gastler¹³⁴ , S. May¹³⁴ , J. Rohlf¹³⁴ , K. Salyer¹³⁴ , D. Sperka¹³⁴ ,
 D. Spitzbart¹³⁴ , I. Suarez¹³⁴ , A. Tsatsos¹³⁴ , S. Yuan¹³⁴ , G. Benelli¹³⁵ , B. Burkle¹³⁵ , X. Coubez,^{135,x} D. Cutts¹³⁵ ,
 M. Hadley¹³⁵ , U. Heintz¹³⁵ , J. M. Hogan^{135,ffff} , T. Kwon¹³⁵ , G. Landsberg¹³⁵ , K. T. Lau¹³⁵ , D. Li¹³⁵ , J. Luo¹³⁵ ,
 M. Narain¹³⁵ , N. Pervan¹³⁵ , S. Sagir^{135,gggg} , F. Simpson¹³⁵ , E. Usai¹³⁵ , W. Y. Wong,¹³⁵ X. Yan¹³⁵ , D. Yu¹³⁵ ,
 W. Zhang,¹³⁵ J. Bonilla¹³⁶ , C. Brainerd¹³⁶ , R. Breedon¹³⁶ , M. Calderon De La Barca Sanchez¹³⁶ , M. Chertok¹³⁶ ,
 J. Conway¹³⁶ , P. T. Cox¹³⁶ , R. Erbacher¹³⁶ , G. Haza¹³⁶ , F. Jensen¹³⁶ , O. Kukral¹³⁶ , G. Mocellin¹³⁶ ,
 M. Mulhearn¹³⁶ , D. Pellett¹³⁶ , B. Regnery¹³⁶ , D. Taylor¹³⁶ , Y. Yao¹³⁶ , F. Zhang¹³⁶ , M. Bachtis¹³⁷ ,
 R. Cousins¹³⁷ , A. Datta¹³⁷ , D. Hamilton¹³⁷ , J. Hauser¹³⁷ , M. Ignatenko¹³⁷ , M. A. Iqbal¹³⁷ , T. Lam¹³⁷ ,
 E. Manca¹³⁷ , W. A. Nash¹³⁷ , S. Regnard¹³⁷ , D. Saltzberg¹³⁷ , B. Stone¹³⁷ , V. Valuev¹³⁷ , Y. Chen,¹³⁸ R. Clare¹³⁸ ,
 J. W. Gary¹³⁸ , M. Gordon,¹³⁸ G. Hanson¹³⁸ , G. Karapostoli¹³⁸ , O. R. Long¹³⁸ , N. Manganelli¹³⁸ , W. Si¹³⁸ ,
 S. Wimpenny¹³⁸ , J. G. Branson,¹³⁹ P. Chang¹³⁹ , S. Cittolin,¹³⁹ S. Cooperstein¹³⁹ , D. Diaz¹³⁹ , J. Duarte¹³⁹ ,
 R. Gerosa¹³⁹ , L. Giannini¹³⁹ , J. Guiang¹³⁹ , R. Kansal¹³⁹ , V. Krutelyov¹³⁹ , R. Lee¹³⁹ , J. Letts¹³⁹ ,
 M. Masciovecchio¹³⁹ , F. Mokhtar¹³⁹ , M. Pieri¹³⁹ , B. V. Sathia Narayanan¹³⁹ , V. Sharma¹³⁹ , M. Tadel¹³⁹ ,
 F. Würthwein¹³⁹ , Y. Xiang¹³⁹ , A. Yagil¹³⁹ , N. Amin,¹⁴⁰ C. Campagnari¹⁴⁰ , M. Citron¹⁴⁰ , G. Collura¹⁴⁰ ,
 A. Dorsett¹⁴⁰ , V. Dutta¹⁴⁰ , J. Incandela¹⁴⁰ , M. Kilpatrick¹⁴⁰ , J. Kim¹⁴⁰ , A. J. Li¹⁴⁰ , P. Masterson¹⁴⁰ , H. Mei¹⁴⁰ ,
 M. Oshiro¹⁴⁰ , M. Quinnan¹⁴⁰ , J. Richman¹⁴⁰ , U. Sarica¹⁴⁰ , R. Schmitz¹⁴⁰ , F. Setti¹⁴⁰ , J. Sheplock¹⁴⁰ ,
 P. Siddireddy,¹⁴⁰ D. Stuart¹⁴⁰ , S. Wang¹⁴⁰ , A. Bornheim¹⁴¹ , O. Cerri,¹⁴¹ I. Dutta¹⁴¹ , J. M. Lawhorn¹⁴¹ , N. Lu¹⁴¹ ,
 J. Mao¹⁴¹ , H. B. Newman¹⁴¹ , T. Q. Nguyen¹⁴¹ , M. Spiropulu¹⁴¹ , J. R. Vlimant¹⁴¹ , C. Wang¹⁴¹ , S. Xie¹⁴¹ ,
 R. Y. Zhu¹⁴¹ , J. Alison¹⁴² , S. An¹⁴² , M. B. Andrews¹⁴² , P. Bryant¹⁴² , T. Ferguson¹⁴² , A. Harilal¹⁴² , C. Liu¹⁴² ,
 T. Mudholkar¹⁴² , S. Murthy¹⁴² , M. Paulini¹⁴² , A. Roberts¹⁴² , A. Sanchez¹⁴² , W. Terrill¹⁴² , J. P. Cumalat¹⁴³ ,
 W. T. Ford¹⁴³ , A. Hassani¹⁴³ , G. Karathanasis¹⁴³ , E. MacDonald¹⁴³ , F. Marini¹⁴³ , R. Patel,¹⁴³ A. Perloff¹⁴³ ,
 C. Savard¹⁴³ , N. Schonbeck¹⁴³ , K. Stenson¹⁴³ , K. A. Ulmer¹⁴³ , S. R. Wagner¹⁴³ , N. Zipper¹⁴³ , J. Alexander¹⁴⁴ ,
 S. Bright-Thonney¹⁴⁴ , X. Chen¹⁴⁴ , D. J. Cranshaw¹⁴⁴ , J. Fan¹⁴⁴ , X. Fan¹⁴⁴ , D. Gadkari¹⁴⁴ , S. Hogan¹⁴⁴ ,
 J. Monroy¹⁴⁴ , J. R. Patterson¹⁴⁴ , D. Quach¹⁴⁴ , J. Reichert¹⁴⁴ , M. Reid¹⁴⁴ , A. Ryd¹⁴⁴ , J. Thom¹⁴⁴ , P. Wittich¹⁴⁴ ,
 R. Zou¹⁴⁴ , M. Albrow¹⁴⁵ , M. Alyari¹⁴⁵ , G. Apollinari¹⁴⁵ , A. Apresyan¹⁴⁵ , L. A. T. Bauerdick¹⁴⁵ , D. Berry¹⁴⁵ ,
 J. Berryhill¹⁴⁵ , P. C. Bhat¹⁴⁵ , K. Burkett¹⁴⁵ , J. N. Butler¹⁴⁵ , A. Canepa¹⁴⁵ , G. B. Cerati¹⁴⁵ , H. W. K. Cheung¹⁴⁵ ,
 F. Chlebana¹⁴⁵ , K. F. Di Petrillo¹⁴⁵ , J. Dickinson¹⁴⁵ , V. D. Elvira¹⁴⁵ , Y. Feng¹⁴⁵ , J. Freeman¹⁴⁵ ,
 A. Gandrakota¹⁴⁵ , Z. Gecse¹⁴⁵

C. Pena^{145,hhhh} F. Ravera¹⁴⁵ A. Reinsvold Hall^{145,iiii} L. Ristori¹⁴⁵ E. Sexton-Kennedy¹⁴⁵ N. Smith¹⁴⁵
 A. Soha¹⁴⁵ L. Spiegel¹⁴⁵ J. Strait¹⁴⁵ L. Taylor¹⁴⁵ S. Tkaczyk¹⁴⁵ N. V. Tran¹⁴⁵ L. Uplegger¹⁴⁵
 E. W. Vaandering¹⁴⁵ H. A. Weber¹⁴⁵ I. Zoi¹⁴⁵ P. Avery¹⁴⁶ D. Bourilkov¹⁴⁶ L. Cadamuro¹⁴⁶
 V. Cherepanov¹⁴⁶ R. D. Field¹⁴⁶ D. Guerrero¹⁴⁶ M. Kim¹⁴⁶ E. Koenig¹⁴⁶ J. Konigsberg¹⁴⁶ A. Korytov¹⁴⁶
 K. H. Lo¹⁴⁶ K. Matchev¹⁴⁶ N. Menendez¹⁴⁶ G. Mitselmakher¹⁴⁶ A. Muthirakalayil Madhu¹⁴⁶ N. Rawal¹⁴⁶
 D. Rosenzweig¹⁴⁶ S. Rosenzweig¹⁴⁶ K. Shi¹⁴⁶ J. Wang¹⁴⁶ Z. Wu¹⁴⁶ T. Adams¹⁴⁷ A. Askew¹⁴⁷
 R. Habibullah¹⁴⁷ V. Hagopian¹⁴⁷ T. Kolberg¹⁴⁷ G. Martinez¹⁴⁷ H. Prosper¹⁴⁷ C. Schiber¹⁴⁷ O. Viazlo¹⁴⁷
 R. Yohay¹⁴⁷ J. Zhang¹⁴⁷ M. M. Baarmann¹⁴⁸ S. Butalla¹⁴⁸ T. Elkafrawy^{148,zz} M. Hohmann¹⁴⁸
 R. Kumar Verma¹⁴⁸ M. Rahmani¹⁴⁸ F. Yumiceva¹⁴⁸ M. R. Adams¹⁴⁹ H. Becerril Gonzalez¹⁴⁹ R. Cavanaugh¹⁴⁹
 S. Dittmer¹⁴⁹ O. Evdokimov¹⁴⁹ C. E. Gerber¹⁴⁹ D. J. Hofman¹⁴⁹ D. S. Lemos¹⁴⁹ A. H. Merrit¹⁴⁹ C. Mills¹⁴⁹
 G. Oh¹⁴⁹ T. Roy¹⁴⁹ S. Rudrabhatla¹⁴⁹ M. B. Tonjes¹⁴⁹ N. Varelas¹⁴⁹ X. Wang¹⁴⁹ Z. Ye¹⁴⁹ J. Yoo¹⁴⁹
 M. Alhusseini¹⁵⁰ K. Dilsiz^{150,iiii} L. Emediato¹⁵⁰ R. P. Gandrajula¹⁵⁰ G. Karaman¹⁵⁰ O. K. Köseyan¹⁵⁰
 J.-P. Merlo¹⁵⁰ A. Mestvirishvili^{150,kkkk} J. Nachtman¹⁵⁰ O. Neogi¹⁵⁰ H. Ogul^{150,iiii} Y. Onel¹⁵⁰ A. Penzo¹⁵⁰
 C. Snyder¹⁵⁰ E. Tiras^{150,mmmm} O. Amram¹⁵¹ B. Blumenfeld¹⁵¹ L. Corcodilos¹⁵¹ J. Davis¹⁵¹ A. V. Gritsan¹⁵¹
 L. Kang¹⁵¹ S. Kyriacou¹⁵¹ P. Maksimovic¹⁵¹ J. Roskes¹⁵¹ S. Sekhar¹⁵¹ M. Swartz¹⁵¹ T. Á. Vámi¹⁵¹
 A. Abreu¹⁵² L. F. Alcerro Alcerro¹⁵² J. Anguiano¹⁵² P. Baringer¹⁵² A. Bean¹⁵² Z. Flowers¹⁵² T. Isidori¹⁵²
 S. Khalil¹⁵² J. King¹⁵² G. Krintiras¹⁵² M. Lazarovits¹⁵² C. Le Mahieu¹⁵² C. Lindsey¹⁵² J. Marquez¹⁵²
 N. Minafra¹⁵² M. Murray¹⁵² M. Nickel¹⁵² C. Rogan¹⁵² C. Royon¹⁵² R. Salvatico¹⁵² S. Sanders¹⁵²
 C. Smith¹⁵² Q. Wang¹⁵² J. Williams¹⁵² G. Wilson¹⁵² B. Allmond¹⁵³ S. Duric¹⁵³ R. Gujju Gurunadha¹⁵³
 A. Ivanov¹⁵³ K. Kaadze¹⁵³ D. Kim¹⁵³ Y. Maravin¹⁵³ T. Mitchell¹⁵³ A. Modak¹⁵³ K. Nam¹⁵³ J. Natoli¹⁵³
 D. Roy¹⁵³ F. Rebasoo¹⁵⁴ D. Wright¹⁵⁴ E. Adams¹⁵⁵ A. Baden¹⁵⁵ O. Baron¹⁵⁵ A. Belloni¹⁵⁵ A. Bethani¹⁵⁵
 S. C. Eno¹⁵⁵ N. J. Hadley¹⁵⁵ S. Jabeen¹⁵⁵ R. G. Kellogg¹⁵⁵ T. Koeth¹⁵⁵ Y. Lai¹⁵⁵ S. Lascio¹⁵⁵
 A. C. Mignerey¹⁵⁵ S. Nabili¹⁵⁵ C. Palmer¹⁵⁵ C. Papageorgakis¹⁵⁵ L. Wang¹⁵⁵ K. Wong¹⁵⁵ D. Abercrombie¹⁵⁶
 W. Busza¹⁵⁶ I. A. Cali¹⁵⁶ Y. Chen¹⁵⁶ M. D'Alfonso¹⁵⁶ J. Eysermans¹⁵⁶ C. Freer¹⁵⁶ G. Gomez-Ceballos¹⁵⁶
 M. Goncharov¹⁵⁶ P. Harris¹⁵⁶ M. Hu¹⁵⁶ D. Kovalskiy¹⁵⁶ J. Krupa¹⁵⁶ Y.-J. Lee¹⁵⁶ K. Long¹⁵⁶ C. Mironov¹⁵⁶
 C. Paus¹⁵⁶ D. Rankin¹⁵⁶ C. Roland¹⁵⁶ G. Roland¹⁵⁶ Z. Shi¹⁵⁶ G. S. F. Stephans¹⁵⁶ J. Wang¹⁵⁶ Z. Wang¹⁵⁶
 B. Wyslouch¹⁵⁶ R. M. Chatterjee¹⁵⁷ B. Crossman¹⁵⁷ A. Evans¹⁵⁷ J. Hiltbrand¹⁵⁷ Sh. Jain¹⁵⁷ B. M. Joshi¹⁵⁷
 C. Kapsiak¹⁵⁷ M. Krohn¹⁵⁷ Y. Kubota¹⁵⁷ J. Mans¹⁵⁷ M. Revering¹⁵⁷ R. Rusack¹⁵⁷ R. Saradhy¹⁵⁷
 N. Schroeder¹⁵⁷ N. Strobbe¹⁵⁷ M. A. Wadud¹⁵⁷ L. M. Cremaldi¹⁵⁸ K. Bloom¹⁵⁹ M. Bryson¹⁵⁹ D. R. Claes¹⁵⁹
 C. Fangmeier¹⁵⁹ L. Finco¹⁵⁹ F. Golf¹⁵⁹ C. Joo¹⁵⁹ I. Kravchenko¹⁵⁹ I. Reed¹⁵⁹ J. E. Siado¹⁵⁹ G. R. Snow^{159,a}
 W. Tabb¹⁵⁹ A. Wightman¹⁵⁹ F. Yan¹⁵⁹ A. G. Zecchinelli¹⁵⁹ G. Agarwal¹⁶⁰ H. Bandyopadhyay¹⁶⁰ L. Hay¹⁶⁰
 I. Iashvili¹⁶⁰ A. Kharchilava¹⁶⁰ C. McLean¹⁶⁰ M. Morris¹⁶⁰ D. Nguyen¹⁶⁰ J. Pekkanen¹⁶⁰ S. Rappoccio¹⁶⁰
 A. Williams¹⁶⁰ G. Alverson¹⁶¹ E. Barberis¹⁶¹ Y. Haddad¹⁶¹ Y. Han¹⁶¹ A. Krishna¹⁶¹ J. Li¹⁶¹ J. Lidrych¹⁶¹
 G. Madigan¹⁶¹ B. Marzocchi¹⁶¹ D. M. Morse¹⁶¹ V. Nguyen¹⁶¹ T. Orimoto¹⁶¹ A. Parker¹⁶¹ L. Skinnari¹⁶¹
 A. Tishelman-Charny¹⁶¹ T. Wamorkar¹⁶¹ B. Wang¹⁶¹ A. Wisecarver¹⁶¹ D. Wood¹⁶¹ S. Bhattacharya¹⁶²
 J. Bueghly¹⁶² Z. Chen¹⁶² A. Gilbert¹⁶² K. A. Hahn¹⁶² Y. Liu¹⁶² N. Odell¹⁶² M. H. Schmitt¹⁶² M. Velasco¹⁶²
 R. Band¹⁶³ R. Bucci¹⁶³ S. Castells¹⁶³ M. Cremonesi¹⁶³ A. Das¹⁶³ R. Goldouzian¹⁶³ M. Hildreth¹⁶³
 K. Hurtado Anampa¹⁶³ C. Jessop¹⁶³ K. Lannon¹⁶³ J. Lawrence¹⁶³ N. Loukas¹⁶³ L. Lutton¹⁶³ J. Mariano¹⁶³
 N. Marinelli¹⁶³ I. Mcalister¹⁶³ T. McCauley¹⁶³ C. Mcgrady¹⁶³ K. Mohrman¹⁶³ C. Moore¹⁶³ Y. Musienko^{163,n}
 H. Nelson¹⁶³ R. Ruchti¹⁶³ A. Townsend¹⁶³ M. Wayne¹⁶³ H. Yockey¹⁶³ M. Zarucki¹⁶³ L. Zygala¹⁶³
 B. Bylsma¹⁶⁴ M. Carrigan¹⁶⁴ L. S. Durkin¹⁶⁴ B. Francis¹⁶⁴ C. Hill¹⁶⁴ A. Lesauvage¹⁶⁴ M. Nunez Ornelas¹⁶⁴
 K. Wei¹⁶⁴ B. L. Winer¹⁶⁴ B. R. Yates¹⁶⁴ F. M. Addesa¹⁶⁵ P. Das¹⁶⁵ G. Dezoort¹⁶⁵ P. Elmer¹⁶⁵
 A. Frankenthal¹⁶⁵ B. Greenberg¹⁶⁵ N. Haubrich¹⁶⁵ S. Higginbotham¹⁶⁵ A. Kalogeropoulos¹⁶⁵ G. Kopp¹⁶⁵
 S. Kwan¹⁶⁵ D. Lange¹⁶⁵ D. Marlow¹⁶⁵ K. Mei¹⁶⁵ I. Ojalvo¹⁶⁵ J. Olsen¹⁶⁵ D. Stickland¹⁶⁵ C. Tully¹⁶⁵
 S. Malik¹⁶⁶ S. Norberg¹⁶⁶ A. S. Bakshi¹⁶⁷ V. E. Barnes¹⁶⁷ R. Chawla¹⁶⁷ S. Das¹⁶⁷ L. Gutay¹⁶⁷ M. Jones¹⁶⁷
 A. W. Jung¹⁶⁷ D. Kondratyev¹⁶⁷ A. M. Koshy¹⁶⁷ M. Liu¹⁶⁷ G. Negro¹⁶⁷ N. Neumeister¹⁶⁷ G. Paspalaki¹⁶⁷
 S. Piperov¹⁶⁷ A. Purohit¹⁶⁷ J. F. Schulte¹⁶⁷ M. Stojanovic¹⁶⁷ J. Thieman¹⁶⁷ F. Wang¹⁶⁷ R. Xiao¹⁶⁷
 W. Xie¹⁶⁷ J. Dolen¹⁶⁸ N. Parashar¹⁶⁸ D. Acosta¹⁶⁹ A. Baty¹⁶⁹ T. Carnahan¹⁶⁹ M. Decaro¹⁶⁹ S. Dildick¹⁶⁹
 K. M. Ecklund¹⁶⁹ P. J. Fernández Manteca¹⁶⁹ S. Freed¹⁶⁹ P. Gardner¹⁶⁹ F. J. M. Geurts¹⁶⁹ A. Kumar¹⁶⁹ W. Li¹⁶⁹

B. P. Padley¹⁶⁹, R. Redjimi¹⁶⁹, J. Rotter¹⁶⁹, W. Shi¹⁶⁹, S. Yang¹⁶⁹, E. Yigitbasi¹⁶⁹, L. Zhang^{169,nnnn}, Y. Zhang¹⁶⁹,
 X. Zuo¹⁶⁹, A. Bodek¹⁷⁰, P. de Barbaro¹⁷⁰, R. Demina¹⁷⁰, J. L. Dulemba¹⁷⁰, C. Fallon¹⁷⁰, T. Ferbel¹⁷⁰,
 M. Galanti¹⁷⁰, A. Garcia-Bellido¹⁷⁰, O. Hindrichs¹⁷⁰, A. Khukhunaishvili¹⁷⁰, E. Ranken¹⁷⁰, R. Taus¹⁷⁰,
 G. P. Van Onsem¹⁷⁰, K. Goulianos¹⁷¹, B. Chiarito¹⁷², J. P. Chou¹⁷², Y. Gershtein¹⁷², E. Halkiadakis¹⁷², A. Hart¹⁷²,
 M. Heindl¹⁷², D. Jaroslawski¹⁷², O. Karacheban^{172,z}, I. Laflotte¹⁷², A. Lath¹⁷², R. Montalvo¹⁷², K. Nash¹⁷²,
 M. Osherson¹⁷², S. Salur¹⁷², S. Schnetzer¹⁷², S. Somalwar¹⁷², R. Stone¹⁷², S. A. Thayil¹⁷², S. Thomas¹⁷²,
 H. Wang¹⁷², H. Acharya¹⁷³, A. G. Delannoy¹⁷³, S. Fiorendi¹⁷³, T. Holmes¹⁷³, E. Nibigira¹⁷³, S. Spanier¹⁷³,
 O. Bouhali^{174,oooo}, M. Dalchenko¹⁷⁴, A. Delgado¹⁷⁴, R. Eusebi¹⁷⁴, J. Gilmore¹⁷⁴, T. Huang¹⁷⁴, T. Kamon^{174,pppp},
 H. Kim¹⁷⁴, S. Luo¹⁷⁴, S. Malhotra¹⁷⁴, R. Mueller¹⁷⁴, D. Overton¹⁷⁴, D. Rathjens¹⁷⁴, A. Safonov¹⁷⁴,
 N. Akchurin¹⁷⁵, J. Damgov¹⁷⁵, V. Hegde¹⁷⁵, K. Lamichhane¹⁷⁵, S. W. Lee¹⁷⁵, T. Mengke¹⁷⁵, S. Muthumuni¹⁷⁵,
 T. Peltola¹⁷⁵, I. Volobouev¹⁷⁵, Z. Wang¹⁷⁵, A. Whitbeck¹⁷⁵, E. Appelt¹⁷⁶, S. Greene¹⁷⁶, A. Gurrola¹⁷⁶,
 W. Johns¹⁷⁶, A. Melo¹⁷⁶, F. Romeo¹⁷⁶, P. Sheldon¹⁷⁶, S. Tuo¹⁷⁶, J. Velkovska¹⁷⁶, J. Viinikainen¹⁷⁶,
 B. Cardwell¹⁷⁷, B. Cox¹⁷⁷, G. Cummings¹⁷⁷, J. Hakala¹⁷⁷, R. Hirosky¹⁷⁷, M. Joyce¹⁷⁷, A. Ledovskoy¹⁷⁷,
 A. Li¹⁷⁷, C. Neu¹⁷⁷, C. E. Perez Lara¹⁷⁷, B. Tannenwald¹⁷⁷, P. E. Karchin¹⁷⁸, N. Poudyal¹⁷⁸, S. Banerjee¹⁷⁹,
 K. Black¹⁷⁹, T. Bose¹⁷⁹, S. Dasu¹⁷⁹, I. De Bruyn¹⁷⁹, P. Everaerts¹⁷⁹, C. Galloni¹⁷⁹, H. He¹⁷⁹, M. Herndon¹⁷⁹,
 A. Herve¹⁷⁹, C. K. Koraka¹⁷⁹, A. Lanaro¹⁷⁹, A. Loeliger¹⁷⁹, R. Loveless¹⁷⁹, J. Madhusudanan Sreekala¹⁷⁹,
 A. Mallampalli¹⁷⁹, A. Mohammadi¹⁷⁹, S. Mondal¹⁷⁹, G. Parida¹⁷⁹, D. Pinna¹⁷⁹, A. Savin¹⁷⁹, V. Shang¹⁷⁹,
 V. Sharma¹⁷⁹, W. H. Smith¹⁷⁹, D. Teague¹⁷⁹, H. F. Tsoi¹⁷⁹, W. Vetens¹⁷⁹, S. Afanasiev¹⁸⁰, V. Andreev¹⁸⁰,
 Yu. Andreev¹⁸⁰, T. Aushev¹⁸⁰, M. Azarkin¹⁸⁰, A. Babaev¹⁸⁰, A. Belyaev¹⁸⁰, V. Blinov^{180,n}, E. Boos¹⁸⁰,
 V. Borshch¹⁸⁰, D. Budkouski¹⁸⁰, V. Bunichev¹⁸⁰, O. Bychkova¹⁸⁰, M. Chadeeva^{180,n}, V. Chekhovsky¹⁸⁰,
 A. Dermenev¹⁸⁰, T. Dimova^{180,n}, I. Dremin¹⁸⁰, V. Epshteyn¹⁸⁰, A. Ershov¹⁸⁰, G. Gavrilo¹⁸⁰, V. Gavrilo¹⁸⁰,
 S. Gninenko¹⁸⁰, V. Golovtsov¹⁸⁰, N. Golubev¹⁸⁰, I. Golutvin¹⁸⁰, I. Gorbunov¹⁸⁰, A. Gribushin¹⁸⁰,
 V. Ivanchenko¹⁸⁰, Y. Ivanov¹⁸⁰, V. Kachanov¹⁸⁰, L. Kardapoltsev^{180,n}, V. Karjavine¹⁸⁰, A. Karneyeu¹⁸⁰,
 L. Khein¹⁸⁰, V. Kim^{180,n}, M. Kirakosyan¹⁸⁰, D. Kirpichnikov¹⁸⁰, M. Kirsanov¹⁸⁰, O. Kodolova^{180,qqqq},
 D. Konstantinov¹⁸⁰, V. Korenkov¹⁸⁰, V. Korotkiikh¹⁸⁰, A. Kozyrev^{180,n}, N. Krasnikov¹⁸⁰, E. Kuznetsova^{180,rrrr},
 A. Lanev¹⁸⁰, P. Levchenko¹⁸⁰, A. Litomin¹⁸⁰, N. Lychkovskaya¹⁸⁰, V. Makarenko¹⁸⁰, A. Malakhov¹⁸⁰,
 V. Matveev^{180,n}, V. Murzin¹⁸⁰, A. Nikitenko^{180,ssss}, S. Obraztsov¹⁸⁰, V. Okhotnikov¹⁸⁰, A. Oskin¹⁸⁰, I. Ovtin^{180,n},
 V. Palichik¹⁸⁰, P. Parygin¹⁸⁰, V. Perelygin¹⁸⁰, S. Petrushanko¹⁸⁰, G. Pivovarov¹⁸⁰, V. Popov¹⁸⁰, E. Popova¹⁸⁰,
 O. Radchenko^{180,n}, V. Rusinov¹⁸⁰, M. Savina¹⁸⁰, V. Savrin¹⁸⁰, V. Shalaev¹⁸⁰, S. Shmatov¹⁸⁰, S. Shulha¹⁸⁰,
 Y. Skovpen^{180,n}, S. Slabospitskii¹⁸⁰, V. Smirnov¹⁸⁰, A. Snigirev¹⁸⁰, D. Sosnov¹⁸⁰, A. Stepennov¹⁸⁰,
 V. Sulimov¹⁸⁰, E. Tcherniaev¹⁸⁰, A. Terkulov¹⁸⁰, O. Teryaev¹⁸⁰, I. Tlisova¹⁸⁰, M. Toms¹⁸⁰, A. Toropin¹⁸⁰,
 L. Uvarov¹⁸⁰, A. Uzunian¹⁸⁰, I. Vardanyan¹⁸⁰, E. Vlasov¹⁸⁰, A. Vorobyev¹⁸⁰, N. Voytishin¹⁸⁰, B. S. Yuldashev^{180,tttt},
 A. Zarubin¹⁸⁰, I. Zhizhin¹⁸⁰, and A. Zhokin¹⁸⁰

(CMS Collaboration)

¹Yerevan Physics Institute, Yerevan, Armenia

²Institut für Hochenergiephysik, Vienna, Austria

³Universiteit Antwerpen, Antwerpen, Belgium

⁴Vrije Universiteit Brussel, Brussel, Belgium

⁵Université Libre de Bruxelles, Bruxelles, Belgium

⁶Ghent University, Ghent, Belgium

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

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

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

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

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

¹²University of Sofia, Sofia, Bulgaria

¹³Beihang University, Beijing, China

¹⁴Department of Physics, Tsinghua University, Beijing, China

¹⁵Institute of High Energy Physics, Beijing, China

- ¹⁶State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China
- ¹⁷Sun Yat-Sen University, Guangzhou, China
- ¹⁸Institute of Modern Physics and Key Laboratory of Nuclear Physics and Ion-beam Application (MOE)—Fudan University, Shanghai, China
- ¹⁹Zhejiang University, Hangzhou, Zhejiang, China
- ²⁰Universidad de Los Andes, Bogota, Colombia
- ²¹Universidad de Antioquia, Medellin, Colombia
- ²²University of Split, Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, Split, Croatia
- ²³University of Split, Faculty of Science, Split, Croatia
- ²⁴Institute Rudjer Boskovic, Zagreb, Croatia
- ²⁵University of Cyprus, Nicosia, Cyprus
- ²⁶Charles University, Prague, Czech Republic
- ²⁷Escuela Politecnica Nacional, Quito, Ecuador
- ²⁸Universidad San Francisco de Quito, Quito, Ecuador
- ²⁹Academy of Scientific Research and Technology of the Arab Republic of Egypt, Egyptian Network of High Energy Physics, Cairo, Egypt
- ³⁰Center for High Energy Physics (CHEP-FU), Fayoum University, El-Fayoum, Egypt
- ³¹National Institute of Chemical Physics and Biophysics, Tallinn, Estonia
- ³²Department of Physics, University of Helsinki, Helsinki, Finland
- ³³Helsinki Institute of Physics, Helsinki, Finland
- ³⁴Lappeenranta-Lahti University of Technology, Lappeenranta, Finland
- ³⁵IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France
- ³⁶Laboratoire Leprince-Ringuet, CNRS/IN2P3, Ecole Polytechnique, Institut Polytechnique de Paris, Palaiseau, France
- ³⁷Université de Strasbourg, CNRS, IPHC UMR 7178, Strasbourg, France
- ³⁸Institut de Physique des 2 Infinis de Lyon (IP2I), Villeurbanne, France
- ³⁹Georgian Technical University, Tbilisi, Georgia
- ⁴⁰RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany
- ⁴¹RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
- ⁴²RWTH Aachen University, III. Physikalisches Institut B, Aachen, Germany
- ⁴³Deutsches Elektronen-Synchrotron, Hamburg, Germany
- ⁴⁴University of Hamburg, Hamburg, Germany
- ⁴⁵Karlsruher Institut fuer Technologie, Karlsruhe, Germany
- ⁴⁶Institute of Nuclear and Particle Physics (INPP), NCSR Demokritos, Aghia Paraskevi, Greece
- ⁴⁷National and Kapodistrian University of Athens, Athens, Greece
- ⁴⁸National Technical University of Athens, Athens, Greece
- ⁴⁹University of Ioánnina, Ioánnina, Greece
- ⁵⁰MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary
- ⁵¹Wigner Research Centre for Physics, Budapest, Hungary
- ⁵²Institute of Nuclear Research ATOMKI, Debrecen, Hungary
- ⁵³Institute of Physics, University of Debrecen, Debrecen, Hungary
- ⁵⁴Karoly Robert Campus, MATE Institute of Technology, Gyongyos, Hungary
- ⁵⁵Panjab University, Chandigarh, India
- ⁵⁶University of Delhi, Delhi, India
- ⁵⁷Saha Institute of Nuclear Physics, HBNI, Kolkata, India
- ⁵⁸Indian Institute of Technology Madras, Madras, India
- ⁵⁹Bhabha Atomic Research Centre, Mumbai, India
- ⁶⁰Tata Institute of Fundamental Research-A, Mumbai, India
- ⁶¹Tata Institute of Fundamental Research-B, Mumbai, India
- ⁶²National Institute of Science Education and Research, An OCC of Homi Bhabha National Institute, Bhubaneswar, Odisha, India
- ⁶³Indian Institute of Science Education and Research (IISER), Pune, India
- ⁶⁴Isfahan University of Technology, Isfahan, Iran
- ⁶⁵Institute for Research in Fundamental Sciences (IPM), Tehran, Iran
- ⁶⁶University College Dublin, Dublin, Ireland
- ^{67a}INFN Sezione di Bari, Bari, Italy
- ^{67b}Università di Bari, Bari, Italy
- ^{67c}Politecnico di Bari, Bari, Italy
- ^{68a}INFN Sezione di Bologna, Bologna, Italy
- ^{68b}Università di Bologna, Bologna, Italy
- ^{69a}INFN Sezione di Catania, Catania, Italy

- ^{69b} *Università di Catania, Catania, Italy*
- ^{70a} *INFN Sezione di Firenze, Firenze, Italy*
- ^{70b} *Università di Firenze, Firenze, Italy*
- ⁷¹ *INFN Laboratori Nazionali di Frascati, Frascati, Italy*
- ^{72a} *INFN Sezione di Genova, Genova, Italy*
- ^{72b} *Università di Genova, Genova, Italy*
- ^{73a} *INFN Sezione di Milano-Bicocca, Milano, Italy*
- ^{73b} *Università di Milano-Bicocca, Milano, Italy*
- ^{74a} *INFN Sezione di Napoli, Napoli, Italy*
- ^{74b} *Università di Napoli 'Federico II', Napoli, Italy*
- ^{74c} *Università della Basilicata, Potenza, Italy*
- ^{74d} *Università G. Marconi, Roma, Italy*
- ^{75a} *INFN Sezione di Padova, Padova, Italy*
- ^{75b} *Università di Padova, Padova, Italy*
- ^{75c} *Università di Trento, Trento, Italy*
- ^{76a} *INFN Sezione di Pavia, Pavia, Italy*
- ^{76b} *Università di Pavia, Pavia, Italy*
- ^{77a} *INFN Sezione di Perugia, Perugia, Italy*
- ^{77b} *Università di Perugia, Perugia, Italy*
- ^{78a} *INFN Sezione di Pisa, Pisa, Italy*
- ^{78b} *Università di Pisa, Pisa, Italy*
- ^{78c} *Scuola Normale Superiore di Pisa, Pisa, Italy*
- ^{78d} *Università di Siena, Siena, Italy*
- ^{79a} *INFN Sezione di Roma, Roma, Italy*
- ^{79b} *Sapienza Università di Roma, Roma, Italy*
- ^{80a} *INFN Sezione di Torino, Torino, Italy*
- ^{80b} *Università di Torino, Torino, Italy*
- ^{80c} *Università del Piemonte Orientale, Novara, Italy*
- ^{81a} *INFN Sezione di Trieste, Trieste, Italy*
- ^{81b} *Università di Trieste, Trieste, Italy*
- ⁸² *Kyungpook National University, Daegu, Korea*
- ⁸³ *Chonnam National University, Institute for Universe and Elementary Particles, Kwangju, Korea*
- ⁸⁴ *Hanyang University, Seoul, Korea*
- ⁸⁵ *Korea University, Seoul, Korea*
- ⁸⁶ *Kyung Hee University, Department of Physics, Seoul, Korea*
- ⁸⁷ *Sejong University, Seoul, Korea*
- ⁸⁸ *Seoul National University, Seoul, Korea*
- ⁸⁹ *University of Seoul, Seoul, Korea*
- ⁹⁰ *Yonsei University, Department of Physics, Seoul, Korea*
- ⁹¹ *Sungkyunkwan University, Suwon, Korea*
- ⁹² *College of Engineering and Technology, American University of the Middle East (AUM), Dasman, Kuwait*
- ⁹³ *Riga Technical University, Riga, Latvia*
- ⁹⁴ *Vilnius University, Vilnius, Lithuania*
- ⁹⁵ *National Centre for Particle Physics, Universiti Malaya, Kuala Lumpur, Malaysia*
- ⁹⁶ *Universidad de Sonora (UNISON), Hermosillo, Mexico*
- ⁹⁷ *Centro de Investigación y de Estudios Avanzados del IPN, Mexico City, Mexico*
- ⁹⁸ *Universidad Iberoamericana, Mexico City, Mexico*
- ⁹⁹ *Benemerita Universidad Autónoma de Puebla, Puebla, Mexico*
- ¹⁰⁰ *University of Montenegro, Podgorica, Montenegro*
- ¹⁰¹ *National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan*
- ¹⁰² *AGH University of Science and Technology Faculty of Computer Science, Electronics and Telecommunications, Krakow, Poland*
- ¹⁰³ *National Centre for Nuclear Research, Swierk, Poland*
- ¹⁰⁴ *Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland*
- ¹⁰⁵ *Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal*
- ¹⁰⁶ *VINCA Institute of Nuclear Sciences, University of Belgrade, Belgrade, Serbia*
- ¹⁰⁷ *Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain*
- ¹⁰⁸ *Universidad Autónoma de Madrid, Madrid, Spain*
- ¹⁰⁹ *Universidad de Oviedo, Instituto Universitario de Ciencias y Tecnologías Espaciales de Asturias (ICTEA), Oviedo, Spain*
- ¹¹⁰ *Instituto de Física de Cantabria (IFCA), CSIC-Universidad de Cantabria, Santander, Spain*
- ¹¹¹ *University of Colombo, Colombo, Sri Lanka*

- ¹¹²*University of Ruhuna, Department of Physics, Matara, Sri Lanka*
- ¹¹³*CERN, European Organization for Nuclear Research, Geneva, Switzerland*
- ¹¹⁴*Paul Scherrer Institut, Villigen, Switzerland*
- ¹¹⁵*ETH Zurich—Institute for Particle Physics and Astrophysics (IPA), Zurich, Switzerland*
- ¹¹⁶*Universität Zürich, Zurich, Switzerland*
- ¹¹⁷*National Central University, Chung-Li, Taiwan*
- ¹¹⁸*National Taiwan University (NTU), Taipei, Taiwan*
- ¹¹⁹*Chulalongkorn University, Faculty of Science, Department of Physics, Bangkok, Thailand*
- ¹²⁰*Çukurova University, Physics Department, Science and Art Faculty, Adana, Turkey*
- ¹²¹*Middle East Technical University, Physics Department, Ankara, Turkey*
- ¹²²*Bogazici University, Istanbul, Turkey*
- ¹²³*Istanbul Technical University, Istanbul, Turkey*
- ¹²⁴*Istanbul University, Istanbul, Turkey*
- ¹²⁵*Institute for Scintillation Materials of National Academy of Science of Ukraine, Kharkiv, Ukraine*
- ¹²⁶*National Science Centre, Kharkiv Institute of Physics and Technology, Kharkiv, Ukraine*
- ¹²⁷*University of Bristol, Bristol, United Kingdom*
- ¹²⁸*Rutherford Appleton Laboratory, Didcot, United Kingdom*
- ¹²⁹*Imperial College, London, United Kingdom*
- ¹³⁰*Brunel University, Uxbridge, United Kingdom*
- ¹³¹*Baylor University, Waco, Texas, USA*
- ¹³²*Catholic University of America, Washington, DC, USA*
- ¹³³*The University of Alabama, Tuscaloosa, Alabama, USA*
- ¹³⁴*Boston University, Boston, Massachusetts, USA*
- ¹³⁵*Brown University, Providence, Rhode Island, USA*
- ¹³⁶*University of California, Davis, Davis, California, USA*
- ¹³⁷*University of California, Los Angeles, California, USA*
- ¹³⁸*University of California, Riverside, Riverside, California, USA*
- ¹³⁹*University of California, San Diego, La Jolla, California, USA*
- ¹⁴⁰*University of California, Santa Barbara—Department of Physics, Santa Barbara, California, USA*
- ¹⁴¹*California Institute of Technology, Pasadena, California, USA*
- ¹⁴²*Carnegie Mellon University, Pittsburgh, Pennsylvania, USA*
- ¹⁴³*University of Colorado Boulder, Boulder, Colorado, USA*
- ¹⁴⁴*Cornell University, Ithaca, New York, USA*
- ¹⁴⁵*Fermi National Accelerator Laboratory, Batavia, Illinois, USA*
- ¹⁴⁶*University of Florida, Gainesville, Florida, USA*
- ¹⁴⁷*Florida State University, Tallahassee, Florida, USA*
- ¹⁴⁸*Florida Institute of Technology, Melbourne, Florida, USA*
- ¹⁴⁹*University of Illinois at Chicago (UIC), Chicago, Illinois, USA*
- ¹⁵⁰*The University of Iowa, Iowa City, Iowa, USA*
- ¹⁵¹*Johns Hopkins University, Baltimore, Maryland, USA*
- ¹⁵²*The University of Kansas, Lawrence, Kansas, USA*
- ¹⁵³*Kansas State University, Manhattan, Kansas, USA*
- ¹⁵⁴*Lawrence Livermore National Laboratory, Livermore, California, USA*
- ¹⁵⁵*University of Maryland, College Park, Maryland, USA*
- ¹⁵⁶*Massachusetts Institute of Technology, Cambridge, Massachusetts, USA*
- ¹⁵⁷*University of Minnesota, Minneapolis, Minnesota, USA*
- ¹⁵⁸*University of Mississippi, Oxford, Mississippi, USA*
- ¹⁵⁹*University of Nebraska-Lincoln, Lincoln, Nebraska, USA*
- ¹⁶⁰*State University of New York at Buffalo, Buffalo, New York, USA*
- ¹⁶¹*Northeastern University, Boston, Massachusetts, USA*
- ¹⁶²*Northwestern University, Evanston, Illinois, USA*
- ¹⁶³*University of Notre Dame, Notre Dame, Indiana, USA*
- ¹⁶⁴*The Ohio State University, Columbus, Ohio, USA*
- ¹⁶⁵*Princeton University, Princeton, New Jersey, USA*
- ¹⁶⁶*University of Puerto Rico, Mayaguez, Puerto Rico, USA*
- ¹⁶⁷*Purdue University, West Lafayette, Indiana, USA*
- ¹⁶⁸*Purdue University Northwest, Hammond, Indiana, USA*
- ¹⁶⁹*Rice University, Houston, Texas, USA*
- ¹⁷⁰*University of Rochester, Rochester, New York, USA*
- ¹⁷¹*The Rockefeller University, New York, New York, USA*

¹⁷²*Rutgers, The State University of New Jersey, Piscataway, New Jersey, USA*

¹⁷³*University of Tennessee, Knoxville, Tennessee, USA*

¹⁷⁴*Texas A&M University, College Station, Texas, USA*

¹⁷⁵*Texas Tech University, Lubbock, Texas, USA*

¹⁷⁶*Vanderbilt University, Nashville, Tennessee, USA*

¹⁷⁷*University of Virginia, Charlottesville, Virginia, USA*

¹⁷⁸*Wayne State University, Detroit, Michigan, USA*

¹⁷⁹*University of Wisconsin—Madison, Madison, Wisconsin, USA*

¹⁸⁰*An institute or international laboratory covered by a cooperation agreement with CERN*

^aDeceased.

^bAlso at Yerevan State University, Yerevan, Armenia.

^cAlso at TU Wien, Vienna, Austria.

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

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

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

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

^hAlso at UFMS, Nova Andradina, Brazil.

ⁱAlso at The University of the State of Amazonas, Manaus, Brazil.

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

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

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

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

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

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

^pAlso at Suez University, Suez, Egypt.

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

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

^sAlso at Department of Physics, Tsinghua University, Beijing, China.

^tAlso at Ilia State University, Tbilisi, Georgia.

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

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

^wAlso at University of Hamburg, Hamburg, Germany.

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

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

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

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

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

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

^{dd}Also at Wigner Research Centre for Physics, Budapest, Hungary.

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

^{ff}Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary.

^{gg}Also at Universitatea Babes-Bolyai—Facultatea de Fizica, Cluj-Napoca, Romania.

^{hh}Also at Faculty of Informatics, University of Debrecen, Debrecen, Hungary.

ⁱⁱAlso at Punjab Agricultural University, Ludhiana, India.

^{jj}Also at UPES—University of Petroleum and Energy Studies, Dehradun, India.

^{kk}Also at University of Visva-Bharati, Santiniketan, India.

^{ll}Also at University of Hyderabad, Hyderabad, India.

^{mm}Also at Indian Institute of Science (IISc), Bangalore, India.

ⁿⁿAlso at Indian Institute of Technology (IIT), Mumbai, India.

^{oo}Also at IIT Bhubaneswar, Bhubaneswar, India.

^{pp}Also at Institute of Physics, Bhubaneswar, India.

^{qq}Also at Deutsches Elektronen-Synchrotron, Hamburg, Germany.

^{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 Helwan University, Cairo, Egypt.

^{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 Scuola Superiore Meridionale, Università di Napoli ‘Federico II’, Napoli, Italy.

- ^{xx} Also at Fermi National Accelerator Laboratory, Batavia, Illinois, USA.
- ^{yy} Also at Università di Napoli ‘Federico II’, Napoli, Italy.
- ^{zz} Also at Ain Shams University, Cairo, Egypt.
- ^{aaa} Also at Consiglio Nazionale delle Ricerche—Istituto Officina dei Materiali, Perugia, Italy.
- ^{bbb} Also at Department of Applied Physics, Faculty of Science and Technology, Universiti Kebangsaan Malaysia, Bangi, Malaysia.
- ^{ccc} Also at Consejo Nacional de Ciencia y Tecnología, Mexico City, Mexico.
- ^{ddd} Also at IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France.
- ^{eee} Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia.
- ^{fff} Also at Trincomalee Campus, Eastern University, Sri Lanka, Nilaveli, Sri Lanka.
- ^{ggg} Also at INFN Sezione di Pavia, Università di Pavia, Pavia, Italy.
- ^{hhh} Also at National and Kapodistrian University of Athens, Athens, Greece.
- ⁱⁱⁱ Also at Ecole Polytechnique Fédérale Lausanne, Lausanne, Switzerland.
- ^{jjj} Also at Universität Zürich, Zurich, Switzerland.
- ^{kkk} Also at Stefan Meyer Institute for Subatomic Physics, Vienna, Austria.
- ^{lll} Also at Laboratoire d’Annecy-le-Vieux de Physique des Particules, IN2P3-CNRS, Annecy-le-Vieux, France.
- ^{mmm} Also at Near East University, Research Center of Experimental Health Science, Mersin, Turkey.
- ⁿⁿⁿ Also at Konya Technical University, Konya, Turkey.
- ^{ooo} Also at Izmir Bakircay University, Izmir, Turkey.
- ^{ppp} Also at Adiyaman University, Adiyaman, Turkey.
- ^{qqq} Also at Istanbul Gedik University, Istanbul, Turkey.
- ^{rrr} Also at Necmettin Erbakan University, Konya, Turkey.
- ^{sss} Also at Bozok Universitetesi Rektörlüğü, Yozgat, Turkey.
- ^{ttt} Also at Marmara University, Istanbul, Turkey.
- ^{uuu} Also at Milli Savunma University, Istanbul, Turkey.
- ^{vvv} Also at Kafkas University, Kars, Turkey.
- ^{www} Also at Hacettepe University, Ankara, Turkey.
- ^{xxx} Also at Istanbul University—Cerrahpasa, Faculty of Engineering, Istanbul, Turkey.
- ^{yyy} Also at Yildiz Technical University, Istanbul, Turkey.
- ^{zzz} Also at Vrije Universiteit Brussel, Brussel, Belgium.
- ^{aaaa} Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom.
- ^{bbbb} Also at University of Bristol, Bristol, United Kingdom.
- ^{cccc} Also at IPPP Durham University, Durham, United Kingdom.
- ^{dddd} Also at Monash University, Faculty of Science, Clayton, Australia.
- ^{eeee} Also at Università di Torino, Torino, Italy.
- ^{fff} Also at Bethel University, St. Paul, Minnesota, USA.
- ^{ggg} Also at Karamanoğlu Mehmetbey University, Karaman, Turkey.
- ^{hhh} Also at California Institute of Technology, Pasadena, California, USA.
- ⁱⁱⁱ Also at United States Naval Academy, Annapolis, Maryland, USA.
- ^{jjj} Also at Bingol University, Bingol, Turkey.
- ^{kkk} Also at Georgian Technical University, Tbilisi, Georgia.
- ^{lll} Also at Sinop University, Sinop, Turkey.
- ^{mmm} Also at Erciyes University, Kayseri, Turkey.
- ⁿⁿⁿ Also at Institute of Modern Physics and Key Laboratory of Nuclear Physics and Ion-beam Application (MOE)—Fudan University, Shanghai, China.
- ^{ooo} Also at Texas A&M University at Qatar, Doha, Qatar.
- ^{ppp} Also at Kyungpook National University, Daegu, Korea.
- ^{qqq} Also at Yerevan Physics Institute, Yerevan, Armenia.
- ^{rrr} Also at University of Florida, Gainesville, Florida, USA.
- ^{sss} Also at Imperial College, London, United Kingdom.
- ^{ttt} Also at Institute of Nuclear Physics of the Uzbekistan Academy of Sciences, Tashkent, Uzbekistan.