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Observation of the $\Upsilon(3S)$ Meson and Suppression of Υ States in Pb-Pb Collisions at $\sqrt{s_{NN}} = 5.02$ TeV

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

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The production of $\Upsilon(2S)$ and $\Upsilon(3S)$ mesons in lead-lead (Pb-Pb) and proton-proton (pp) collisions is studied in their dimuon decay channel using the CMS detector at the LHC. The $\Upsilon(3S)$ meson is observed for the first time in Pb-Pb collisions, with a significance above 5 standard deviations. The ratios of yields measured in Pb-Pb and pp collisions are reported for both the $\Upsilon(2S)$ and $\Upsilon(3S)$ mesons, as functions of transverse momentum and Pb-Pb collision centrality. These ratios, when appropriately scaled, are significantly less than unity, indicating a suppression of Υ yields in Pb-Pb collisions. This suppression increases from peripheral to central Pb-Pb collisions. Furthermore, the suppression is stronger for $\Upsilon(3S)$ mesons compared to $\Upsilon(2S)$ mesons, extending the pattern of sequential suppression of quarkonium states in nuclear collisions previously seen for the J/ψ , $\psi(2S)$, $\Upsilon(1S)$, and $\Upsilon(2S)$ mesons.

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High-energy heavy ion collisions are useful to study the properties of the quark-gluon plasma (QGP), a strongly coupled medium of deconfined quarks and gluons. It has long been proposed that the yields of quarkonium states are suppressed because of interactions in the QGP [1–7]. These in-medium effects have been theoretically studied with calculations based on lattice quantum chromodynamics and effective field theories [8–11]. One of the fundamental aspects of these interactions with the medium is that the amount of suppression for different quarkonium states is expected to be stronger for those with smaller binding energies. On the other hand, quarkonia can also be produced by recombination processes [7–10,12–15]. Studies of Υ production are particularly interesting, because the number of quark-antiquark pairs in a single lead-lead (Pb-Pb) collision is much smaller for bottom than for charm quarks, so that the recombination of independently produced quarks and antiquarks can be neglected [16].

Experimentally, the dynamics of quarkonium production in heavy ion collisions are commonly studied using the nuclear modification factor (R_{AA}), which is defined as the ratio of particle yields in nucleus-nucleus (AA) collisions to those in proton-proton (pp) collisions scaled by the average number of binary nucleon-nucleon (NN) interactions in the AA events.

Measurements of R_{AA} have been performed at the SPS, RHIC, and LHC accelerators, in both the charmonium and bottomonium families [17–32]. For Υ states, R_{AA} results have been reported by CMS [27], ALICE [28], and ATLAS [29] at the LHC and by STAR [30,31] and PHENIX [32] at RHIC. These results show a significant suppression of $\Upsilon(1S)$ mesons in heavy ion collisions, and $\Upsilon(2S)$ mesons are even more suppressed. For the $\Upsilon(3S)$ meson, only upper limits have been reported in AA collisions, by CMS [27].

In this Letter, the first observation of the $\Upsilon(3S)$ meson in Pb-Pb collisions is reported. Nuclear modification factors for $\Upsilon(2S)$ and $\Upsilon(3S)$ mesons are found using Pb-Pb and pp data collected with the CMS detector at a nucleon-nucleon center-of-mass energy of $\sqrt{s_{NN}} = 5.02$ TeV in 2018 and 2017, respectively. The double ratios, obtained by dividing the $\Upsilon(3S)$ over $\Upsilon(2S)$ yield ratios in Pb-Pb by those for pp collisions, are also reported. The Υ states are identified using their decay into two oppositely charged muons. The results are presented as functions of Pb-Pb collision centrality, as well as Υ meson transverse momentum (p_T) in the rapidity range of $|y| < 2.4$. Centrality is related to the overlap of the two lead nuclei and is quantified as the percentage of the total inelastic nucleus-nucleus hadronic cross section, with 0% representing the largest overlap [33]. Tabulated results are provided in the HEPData record for this analysis [34].

The CMS apparatus [35] is a multipurpose, nearly hermetic detector, designed to trigger on [36,37] and identify electrons, muons, photons, and hadrons [38–41]. A superconducting solenoid of 6 m internal diameter provides a magnetic field of 3.8 T. Within the solenoid volume are the silicon pixel and strip tracker, a crystal

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

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electromagnetic calorimeter, and a brass-scintillator hadron calorimeter. The pseudorapidity (η) coverage of these calorimeters is extended by the forward hadron (HF) calorimeters, located at $3 < |\eta| < 5$. Muons are measured in the range $|\eta| < 2.4$ using gas-ionization detectors embedded in the steel flux-return yoke outside the solenoid. Events are filtered using a two-tiered trigger system [37]. The first level (L1), composed of custom hardware processors, uses information from the calorimeters and muon detectors [36]. The second level, known as the high-level trigger (HLT), consists of a farm of processors running a version of the full event reconstruction software. Centrality is determined using the sum of the total transverse energy deposited in both of the HF calorimeters [42].

The events are selected online using an L1 trigger requiring two muons in a single bunch crossing without explicit requirements on the muon momentum. Additional criteria on the single-muon quality and dimuon mass selection are applied at the HLT in Pb-Pb collisions [43]. The collected pp (Pb-Pb) sample corresponds to an integrated luminosity of 300 pb^{-1} (1.61 nb^{-1}) [44–46].

In order to reject beam-gas interactions and nonhadronic collisions, an offline event selection is applied for pp and Pb-Pb collisions [47]. For both systems, events are required to have at least one reconstructed primary vertex (PV), which is the vertex corresponding to the hardest scattering in the event, evaluated using tracking information alone [48]. In addition, more than 25% of the tracks have to pass a tight track-quality selection in pp collisions [41,47]. For Pb-Pb collisions, selections are applied on the silicon pixel detector cluster widths [47,49] and on the HF information [43]. The reconstructed muons are selected using criteria that optimize the muon identification [43]. In addition, to ensure high reconstruction efficiency for Υ mesons, the individual muons are required to have $p_T > 3.5 \text{ GeV}/c$ and $|\eta| < 2.4$.

Monte Carlo (MC) samples for each Υ meson are simulated using the “CP5” tune [50] of PYTHIA8.212 [51], with the assumption that they are produced unpolarized [52–55]. To reproduce the background environment in Pb-Pb collisions, each PYTHIA Υ event is embedded into a Pb-Pb event simulated using HYDJET1.9 [56]. The MC events are then weighted to match the measured Υ p_T spectra for either pp or Pb-Pb collisions [43]. A full simulation of the CMS detector using GEANT4 [57] is performed to determine the acceptance and reconstruction efficiency. The feed-down contributions, i.e., decays from heavier quarkonium states, are not considered in this analysis. The effect of such contributions on the kinematic distributions of the simulated Υ states is, to a large extent, accounted for by the weighting procedure.

The dimuon invariant mass distribution is studied in the $8\text{--}14 \text{ GeV}/c^2$ region. To reduce the large amount of background in Pb-Pb collisions, signal-enriched dimuon candidates are selected using boosted decision trees

(BDTs), using the TMVA package [58]. For the BDT training, MC samples and dimuons from the invariant mass spectra in data except where the Υ signals are present (i.e., $8.8\text{--}10.8 \text{ GeV}/c^2$) are used for the signal and background, respectively. In both cases, the dimuons must satisfy the selection criteria previously mentioned. The training variables for the BDT include the χ^2 probability of the dimuon vertex fit; the distance of closest approach of the Υ meson momentum vector relative to the PV; the distance between the PV and the dimuon vertex, both in three dimensions and projected onto the transverse plane; and the pointing angle, defined as the angle between the line segment connecting the PV and decay vertex and the momentum vector of the reconstructed particle candidates, again in three dimensions and projected onto the transverse plane. To avoid potential biases, the algorithms and selections are optimized using a quarter of the Pb-Pb data for dimuon $p_T < 30 \text{ GeV}/c$, $|y| < 2.4$, and centrality 0%–90%. A threshold is set on the resulting BDT variable to maximize the signal significance, $S/\sqrt{S+B}$, where S and B represent the yields for signal and background, respectively.

The yields of the Υ states are extracted by an extended unbinned maximum likelihood fit to the dimuon invariant mass distributions. The line shape of each Υ state is modeled by a sum of three Crystal Ball (CB) functions [59], with common means and tail parameters but independent widths. The means and widths for the $\Upsilon(2S)$ and $\Upsilon(3S)$ are found by multiplying the fitted values of those for the $\Upsilon(1S)$ by the ratio of their world-average masses [60] over that for the $\Upsilon(1S)$. All other fit parameters, except the yields for the excited states, are fixed to those found for the ground state. The shape parameters of the signal fit model, with the exception of the $\Upsilon(1S)$ mean, are constrained by Gaussian probability density functions (PDFs), of means and widths determined, for each p_T bin, from the central values and uncertainties obtained from fits to the MC samples. The background of the mass distribution is modeled using three different functional forms: an error function multiplied by an exponential, a simple exponential, and a Chebyshev polynomial. An Akaike information criterion (AIC) test [61], which estimates the relative quality of each function, is performed to determine, for each kinematic region, the nominal function for the background PDF. The order of the Chebyshev polynomial is chosen based on a log likelihood ratio test [62].

Figure 1 shows the dimuon invariant mass distribution in Pb-Pb collisions, integrated over the full kinematic range, $p_T < 30 \text{ GeV}/c$ and $|y| < 2.4$, and centrality 0%–90%.

Acceptance and efficiency correction factors are applied to the extracted number of Υ mesons to compute the R_{AA} values. The acceptance is computed with simulated samples, as the fraction of generated Υ mesons that decay to muons of $p_T^\mu > 3.5 \text{ GeV}/c$ and $|\eta^\mu| < 2.4$. The efficiency is also evaluated with simulated events, as the fraction of

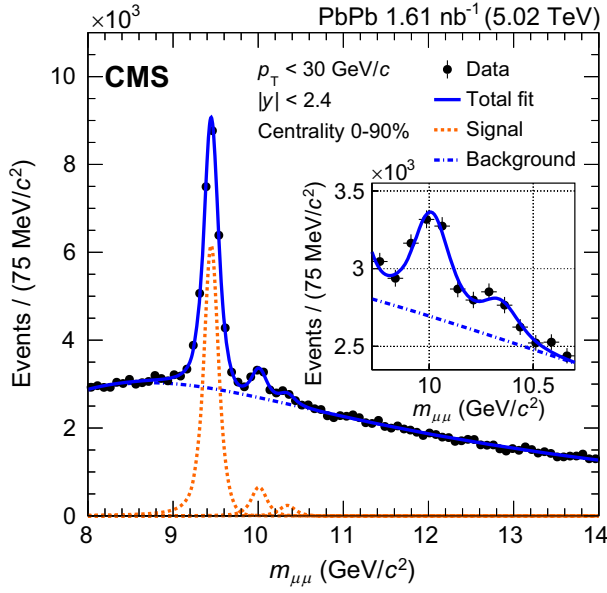


FIG. 1. Dimuon invariant mass distribution in Pb-Pb collisions, integrated over the full kinematic range $p_T < 30$ GeV/c and $|y| < 2.4$. The solid curves show the result of the fit, whereas the orange dashed and blue dash-dotted curves represent the three Υ states and the background, respectively. The inset shows the region around the mass of the $\Upsilon(3S)$ meson.

accepted dimuons that are reconstructed and pass the trigger and analysis selection criteria. To take into account possible differences between data and MC simulations, the individual components of the dimuon efficiency (reconstruction, identification, and triggering) are measured using single muons from J/ψ meson decays in both data and simulation, with the *tag-and-probe* (T&P) method [63]. The data over simulation ratios, for each of the three components, are applied as event-by-event weights to each dimuon. The acceptance and efficiency values for the full kinematic region are 40% (43%) and 37% (38%) for $\Upsilon(2S)$ [$\Upsilon(3S)$] in Pb-Pb collisions.

The systematic uncertainties are analyzed for various sources and summarized in Table I. For each source, the

difference of the signal yields in the variation compared to the nominal is taken as the systematic uncertainty. Three sources are considered for the uncertainty in the signal extraction: choice of signal PDF parameters, choice of signal PDF, and choice of background PDF. For the parametrization of the signal PDF, the fit results using either the $\Upsilon(2S)$ or $\Upsilon(3S)$ MC samples are used to determine different values for the mean and width of the Gaussian function for each signal parameter. The signal PDF is modified from a sum of three CB functions to a sum of two CB functions and a Gaussian function. For the background PDF systematic study, functions rejected by the AIC test in the nominal background PDF determination, for each kinematic region, are used as alternatives.

The acceptance and efficiency uncertainties are evaluated by varying the p_T weights (used to match the simulated and measured Υ p_T spectra) by their fit uncertainties. The uncertainty on the T&P correction of the single muon efficiencies is propagated to the dimuon efficiencies.

For the Pb-Pb analysis, additional uncertainties arise from the BDT training and centrality calibration. To evaluate the uncertainty reflecting the BDT training, the event samples used as signal or background are split in two. Each trained algorithm is applied to the other half of the samples, and the average of the two BDT variable values is used as the nominal. Alternatively, the two individual values of each BDT variable are used, and the largest difference of the corrected signal yields compared to the nominal is taken as the systematic uncertainty. The centrality calibration is varied by changing the boundaries of the centrality intervals [43] considering the inefficiency in the event selection.

The total uncertainty, dominated by the uncertainties from the BDT training and background PDF, is the quadratic sum of the uncertainties from all the different sources. In addition, global uncertainties reflect the integrated luminosity of the pp dataset (1.9%) [44] and the number of minimum bias Pb-Pb collision events (N_{MB}) sampled by the trigger (1.3%) [64]. The overlap function

TABLE I. Systematic uncertainties from various sources in pp and Pb-Pb collisions listed in percentage. The global uncertainties described in the text are not included in the total uncertainties.

Source	$\Upsilon(2S)$ (%)		$\Upsilon(3S)$ (%)		$\Upsilon(3S)/\Upsilon(2S)$ (%)	
	pp	Pb-Pb	pp	Pb-Pb	pp	Pb-Pb
BDT selection	...	0.3–9.0	...	1.5–18.6	...	1.2–22.8
Background PDF	0.1–1.4	0.3–11.7	0.2–1.6	1.4–21.4	<0.5	0.6–17.6
Signal PDF	0.1–1.1	0.5–2.6	0.4–1.1	0.1–2.5	0.3–0.6	0.1–3.0
Signal parameter	0.1–1.2	0.0–3.8	0.1–1.6	0.3–3.7	0.05–1.4	0.1–0.9
Event selection	...	0.0–0.5	...	0.2–13.1	...	0.1–13.6
Correction factors	<0.1	<0.5	<0.1	<0.4	<2.0	...
T&P	0.9–1.0	3.8–4.5	0.9–1.1	3.8–4.4	...	...
Total uncertainty	1.0–1.8	3.9–13.5	1.1–2.2	6.0–22.2	0.4–1.5	4.1–23.8

T_{AA} for each centrality interval is the average number of binary NN collisions per Pb-Pb interaction divided by the inelastic NN cross section. Its uncertainty is estimated by varying the Glauber model parameters within their uncertainties [65] and is found to be in the range of 1.8%–5.4%.

The significance of the $\Upsilon(3S)$ in Pb-Pb collisions corresponds to 5.6 standard deviations, calculated using the fit likelihood ratio [66–68]. The nuclear modification factors are computed as

$$R_{AA}(p_T) = \frac{N_{AA}(p_T)}{\langle T_{AA} \rangle \sigma^{pp}(p_T)}, \quad (1)$$

where N_{AA} and σ^{pp} are the efficiency- and acceptance-corrected normalized yields in Pb-Pb collisions and the pp cross sections, respectively, for Υ mesons in a given kinematic range. The average value of T_{AA} computed in each centrality bin is denoted by $\langle T_{AA} \rangle$.

Figure 2 presents the R_{AA} values for $\Upsilon(2S)$ and $\Upsilon(3S)$, together with the previous measurements for the $\Upsilon(1S)$ [27], as functions of Υ meson p_T and Pb-Pb collision centrality, with the latter represented using $\langle N_{part} \rangle$, the average number of participating nucleons in each of the centrality intervals [65]. The measurements as a function of p_T are reported in five intervals for the $\Upsilon(2S)$, 0–3, 3–6, 6–9, 9–15, and 15–30 GeV/ c , and four for the $\Upsilon(3S)$, 0–4, 4–9, 9–15, and 15–30 GeV/ c . The centrality intervals and the corresponding $\langle N_{part} \rangle$ values used for this analysis are listed in the HEPData record [34]. The results for the $\Upsilon(1S)$ are taken from Ref. [27], because the new data do not improve the statistical significance. Furthermore, the systematic uncertainties, which are dominant for the $\Upsilon(1S)$ results, are found to not improve when including the BDT training.

A gradual decrease of R_{AA} is observed toward more central collisions (i.e., higher N_{part}) for both $\Upsilon(2S)$ and $\Upsilon(3S)$. On the other hand, no significant dependence on p_T is found for either of them. Both states are strongly suppressed in central Pb-Pb collisions, as well as over the entire p_T region when averaged over centrality. Furthermore, the R_{AA} of the $\Upsilon(3S)$ is smaller than that of the $\Upsilon(2S)$, with values integrated over p_T and centrality 0%–90% of $0.115 \pm 0.008(\text{stat}) \pm 0.007(\text{syst})$ and $0.080 \pm 0.014(\text{stat}) \pm 0.012(\text{syst})$ for the $\Upsilon(2S)$ and $\Upsilon(3S)$, respectively. These results indicate, much more clearly than the previous measurements [27–29], that the sequential suppression pattern of the bottomonium states follows the ordering of their binding energies [69].

Figure 3 shows, as functions of $\langle N_{part} \rangle$ and p_T , the $\Upsilon(3S)$ to $\Upsilon(2S)$ double ratios, obtained by dividing the $\Upsilon(3S)$ over $\Upsilon(2S)$ yield ratios in Pb-Pb collisions by the corresponding ratios in pp collisions. The bins are identical to those used in the $\Upsilon(3S)$ measurement. The uncertainties in the $\Upsilon(3S)/\Upsilon(2S)$ ratios are computed by propagating the $\Upsilon(2S)$ and $\Upsilon(3S)$ uncertainties, taking into account their

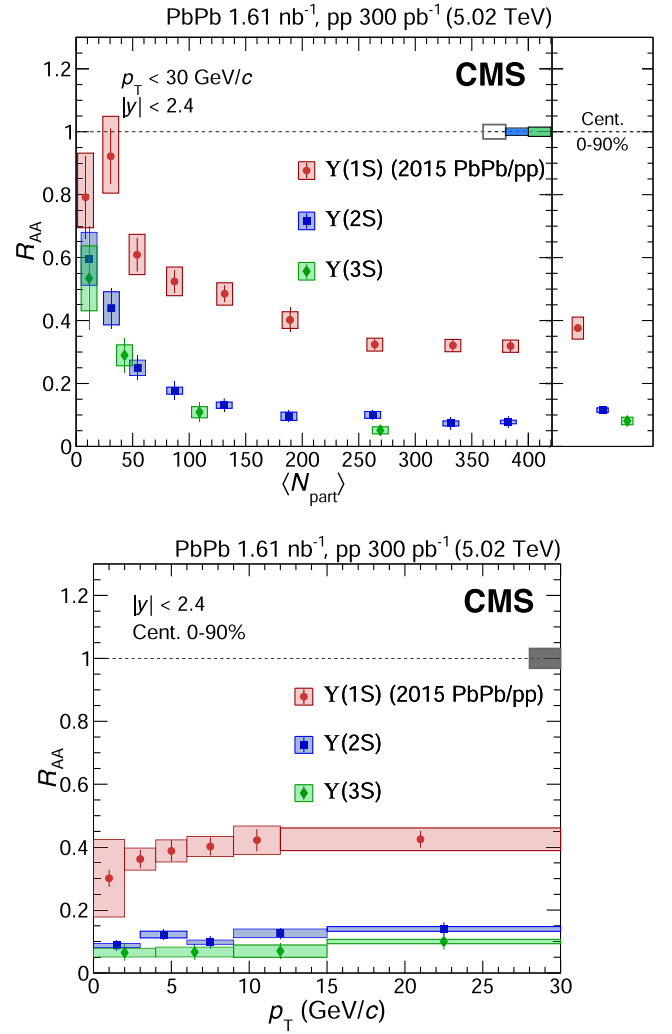


FIG. 2. Measured R_{AA} for the Υ states as functions of $\langle N_{part} \rangle$ (upper), showing also the 0%–90% centrality interval, and of p_T (lower). The vertical lines and boxes correspond to statistical and systematic uncertainties, respectively. In the left plot, the leftmost box at unity represents the pp luminosity and Pb-Pb N_{MB} combined uncertainties, whereas the second (third) box corresponds to the uncertainty on the $\Upsilon(2S)$ [$\Upsilon(3S)$] pp yields. The box at unity in the right plot combines the uncertainties of T_{AA} , pp luminosity, and Pb-Pb N_{MB} . The results for the $\Upsilon(1S)$ are taken from Ref. [27] and are not affected by the boxes at unity.

correlation, whereas the global uncertainties on T_{AA} , pp luminosity, and Pb-Pb N_{MB} cancel out. The decreasing trend of the double ratios toward more central Pb-Pb collisions indicates a stronger suppression for the $\Upsilon(3S)$ than for the $\Upsilon(2S)$, whereas no significant dependence on p_T is seen. Comparisons to various theoretical calculations [9,10,70–73] and previous experimental results [24,74–77] can be found in Supplemental Material [78].

In summary, data from Pb-Pb and pp collisions at a nucleon-nucleon center-of-mass energy of $\sqrt{s_{NN}} = 5.02$ TeV, collected with the CMS detector, were analyzed to measure the yields and nuclear modification factors, R_{AA} , of the $\Upsilon(2S)$

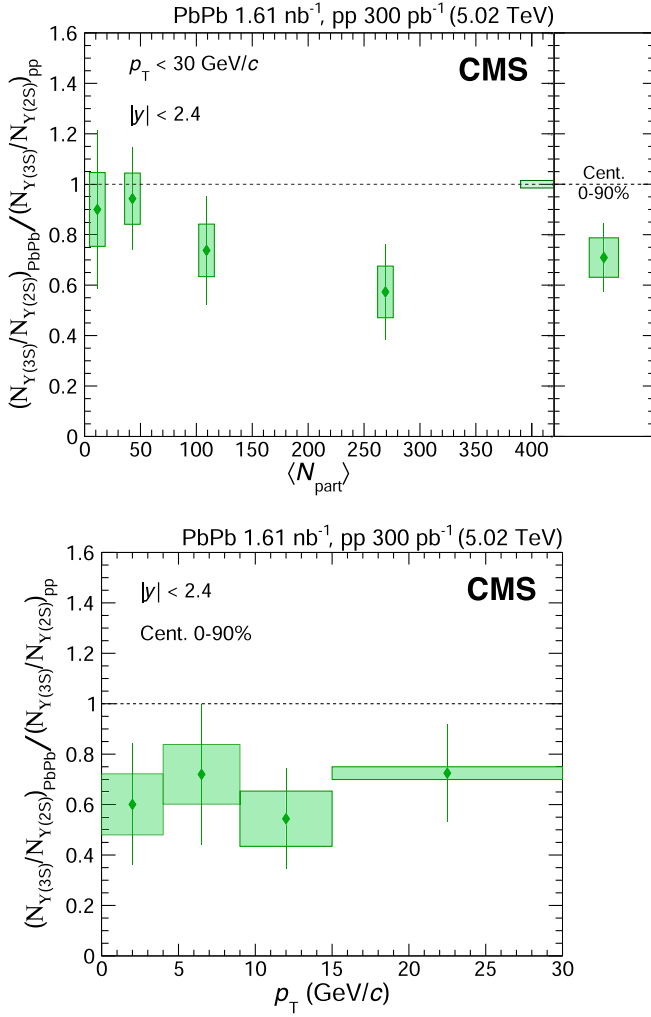


FIG. 3. The double ratios of $\Upsilon(3S)/\Upsilon(2S)$ as functions of $\langle N_{\text{part}} \rangle$ (upper), showing also the 0%–90% centrality interval, and of p_T (lower). The vertical lines and boxes correspond to statistical and systematic uncertainties, respectively. The box at unity in the left plot shows the combined systematic and statistical uncertainties from pp data, which is common to all the points.

and $\Upsilon(3S)$ mesons. The $\Upsilon(3S)$ meson is observed for the first time in Pb-Pb collisions, with a significance above 5 standard deviations. Dividing the $\Upsilon(3S)$ over $\Upsilon(2S)$ yield ratios in Pb-Pb by those in pp collisions gives the double ratios that quantify the relative modification of the two mesons. Results are shown as functions of Υ transverse momentum and Pb-Pb collision centrality. Both the $\Upsilon(2S)$ and $\Upsilon(3S)$ mesons are suppressed ($R_{AA} < 1$), with a stronger effect for the $\Upsilon(3S)$. The suppression increases for more central Pb-Pb collisions, whereas no significant dependence on p_T is seen. The $\Upsilon(3S)$ over $\Upsilon(2S)$ double ratios show a gradual decrease toward more central Pb-Pb collisions, indicating that the degree to which the suppression is stronger for the $\Upsilon(3S)$ meson increases for more central Pb-Pb collisions. Combined with previous measurements, these results indicate that the

strength of the suppression increases in the sequence $\Upsilon(1S)$, $\Upsilon(2S)$, and $\Upsilon(3S)$. These results provide new constraints on the understanding of the dynamics of quarkonium states in the QGP created in heavy ion collisions.

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 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, L. Thomas⁵, M. Vanden Bemden⁵, C. Vander Velde⁵, P. Vanlaere⁵, 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,
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 F. Torres Da Silva De Araujo^{9,i}, A. Vilela Pereira⁹, C. A. Bernardes^{10,g}, L. Calligaris¹⁰,
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 A. Aleksandrov¹¹, G. Antchev¹¹, R. Hadjiiska¹¹, P. Iaydjiev¹¹, M. Misheva¹¹, M. Rodozov¹¹, M. Shopova¹¹,
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 H. Liao¹⁶, Z.-A. Liu^{16,m}, V. Milosevic¹⁶, F. Monti¹⁶, R. Sharma¹⁶, J. Tao¹⁶, J. Thomas-Wilsker¹⁶, J. Wang¹⁶,
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 B. K. Chitroda²⁵, D. Ferencek²⁵, S. Mishra²⁵, M. Roguljic²⁵, A. Starodumov^{25,n}, T. Susa²⁵, A. Attikis²⁶,
 K. Christoforou²⁶, M. Kolosova²⁶, S. Konstantinou²⁶, J. Mousa²⁶, C. Nicolaou²⁶, F. Ptochos²⁶, P. A. Razis²⁶,
 H. Rykaczewski²⁶, H. Saka²⁶, A. Stepenov²⁶, M. Finger²⁷, M. Finger Jr.²⁷, A. Kveton²⁷, E. Ayala²⁸,
 E. Carrera Jarrin²⁹, A. A. Abdelalim^{30,o,p}, E. Salama^{30,q,r}, M. A. Mahmoud³¹, Y. Mohammed³¹, S. Bhowmik³²,
 R. K. Dewanjee³², K. Ehataht³², M. Kadastik³², T. Lange³², S. Nandan³², C. Nielsen³², J. Pata³², M. Raidal³²,
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 A. Savoy-Navarro^{36,s}, P. Simkina³⁶, M. Titov³⁶, C. Baldenegro Barrera³⁷, F. Beaudette³⁷, A. Buchot Perraguin³⁷,
 P. Busson³⁷, A. Cappati³⁷, C. Charlot³⁷, F. Damas³⁷, O. Davignon³⁷, B. Diab³⁷, G. Falmagne³⁷,
 B. A. Fontana Santos Alves³⁷, S. Ghosh³⁷, R. Granier de Cassagnac³⁷, A. Hakimi³⁷, B. Harikrishnan³⁷, G. Liu³⁷,
 J. Motta³⁷, M. Nguyen³⁷, C. Ochando³⁷, L. Portales³⁷, R. Salerno³⁷, U. Sarkar³⁷, J. B. Sauvan³⁷, Y. Sirois³⁷,
 A. Tarabini³⁷, E. Vernazza³⁷, A. Zabi³⁷, A. Zghiche³⁷, J.-L. Agram^{38,t}, J. Andrea³⁸, D. Apparu³⁸, D. Bloch³⁸,
 G. Bourgatte³⁸, J.-M. Brom³⁸, E. C. Chabert³⁸, C. Collard³⁸, D. Darej³⁸, U. Goerlach³⁸, C. Grimault³⁸,
 A.-C. Le Bihan³⁸, P. Van Hove³⁸, S. Beauceron³⁹, B. Blancon³⁹, G. Boudoul³⁹, A. Carle³⁹, N. Chanon³⁹,
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 M. Vander Donckt³⁹, P. Verdier³⁹, S. Viret³⁹, I. Lomidze⁴⁰, T. Toriashvili^{40,v}, Z. Tsamalaidze^{40,n}, V. Botta⁴¹

- L. Feld⁴¹, K. Klein⁴¹, M. Lipinski⁴¹, D. Meuser⁴¹, A. Pauls⁴¹, N. Röwert⁴¹, M. Teroerde⁴¹, S. Diekmann⁴², A. Dodonova⁴², N. Eich⁴², D. Eliseev⁴², M. Erdmann⁴², P. Fackeldey⁴², D. Fasanella⁴², B. Fischer⁴², T. Hebbeker⁴², K. Hoepfner⁴², F. Ivone⁴², M. y. Lee⁴², L. Mastrolorenzo⁴², M. Merschmeyer⁴², A. Meyer⁴², S. Mondal⁴², S. Mukherjee⁴², D. Noll⁴², A. Novak⁴², F. Nowotny⁴², A. Pozdnyakov⁴², Y. Rath⁴², W. Redjeb⁴², H. Reithler⁴², A. Schmidt⁴², S. C. Schuler⁴², A. Sharma⁴², L. Vigilante⁴², S. Wiedenbeck⁴², S. Zaleski⁴², C. Dziwok⁴³, G. Flüge⁴³, W. Haj Ahmad^{43,w}, O. Hlushchenko⁴³, T. Kress⁴³, A. Nowack⁴³, O. Pooth⁴³, A. Stahl⁴³, T. Ziemons⁴³, A. Zotz⁴³, H. Aarup Petersen⁴⁴, M. Aldaya Martin⁴⁴, P. Asmuss⁴⁴, S. Baxter⁴⁴, M. Bayatmakou⁴⁴, O. Behnke⁴⁴, A. Bermúdez Martínez⁴⁴, S. Bhattacharya⁴⁴, A. A. Bin Anuar⁴⁴, F. Blekman^{44,x}, K. Borrás^{44,y}, D. Brunner⁴⁴, A. Campbell⁴⁴, A. Cardini⁴⁴, C. Cheng⁴⁴, F. Colombina⁴⁴, S. Consuegra Rodríguez⁴⁴, G. Correia Silva⁴⁴, M. De Silva⁴⁴, L. Didukh⁴⁴, G. Eckerlin⁴⁴, D. Eckstein⁴⁴, L. I. Estevez Banos⁴⁴, O. Filatov⁴⁴, E. Gallo^{44,x}, A. Geiser⁴⁴, A. Giraldi⁴⁴, G. Greau⁴⁴, A. Grohsjean⁴⁴, V. Guglielmi⁴⁴, M. Guthoff⁴⁴, A. Jafari^{44,z}, N. Z. Jomhari⁴⁴, B. Kaeck⁴⁴, A. Kasem^{44,y}, M. Kasemann⁴⁴, H. Kaveh⁴⁴, C. Kleinwort⁴⁴, R. Kogler⁴⁴, M. Komm⁴⁴, D. Krücker⁴⁴, W. Lange⁴⁴, D. Leyva Pernia⁴⁴, K. Lipka^{44,aa}, W. Lohmann^{44,bb}, R. Mankel⁴⁴, I.-A. Melzer-Pellmann⁴⁴, M. Mendizabal Morentin⁴⁴, J. Metwally⁴⁴, A. B. Meyer⁴⁴, G. Milella⁴⁴, M. Mormile⁴⁴, A. Mussgiller⁴⁴, A. Nürnberg⁴⁴, Y. Otari⁴⁴, D. Pérez Adán⁴⁴, A. Raspereza⁴⁴, B. Ribeiro Lopes⁴⁴, J. Rübenach⁴⁴, A. Saggio⁴⁴, A. Saibel⁴⁴, M. Savitskyi⁴⁴, M. Scham^{44,y,cc}, V. Scheurer⁴⁴, S. Schnake^{44,y}, P. Schütze⁴⁴, C. Schwanenberger^{44,x}, M. Shchedrolosiev⁴⁴, R. E. Sosa Ricardo⁴⁴, D. Stafford⁴⁴, N. Tonon^{44,a}, M. Van De Klundert⁴⁴, F. Vazzoler⁴⁴, A. Ventura Barroso⁴⁴, R. Walsh⁴⁴, D. Walter⁴⁴, Q. Wang⁴⁴, Y. Wen⁴⁴, K. Wichmann⁴⁴, L. Wiens^{44,y}, C. Wissing⁴⁴, S. Wuchterl⁴⁴, Y. Yang⁴⁴, A. Zimmermann Castro Santos⁴⁴, A. Albrecht⁴⁵, S. Albrecht⁴⁵, M. Antonello⁴⁵, S. Bein⁴⁵, L. Benato⁴⁵, M. Bonanomi⁴⁵, P. Connor⁴⁵, K. De Leo⁴⁵, M. Eich⁴⁵, K. El Morabit⁴⁵, F. Feindt⁴⁵, A. Fröhlich⁴⁵, C. Garbers⁴⁵, E. Garutti⁴⁵, M. Hajheidari⁴⁵, J. Haller⁴⁵, A. Hinzmann⁴⁵, H. R. Jabusch⁴⁵, G. Kasięczka⁴⁵, P. Keicher⁴⁵, R. Klanner⁴⁵, W. Korcarı⁴⁵, T. Kramer⁴⁵, V. Kutzner⁴⁵, F. Labe⁴⁵, J. Lange⁴⁵, A. Lobanov⁴⁵, C. Matthies⁴⁵, A. Mehta⁴⁵, L. Moureaux⁴⁵, M. Mrowietz⁴⁵, A. Nigamova⁴⁵, Y. Nissan⁴⁵, A. Paasch⁴⁵, K. J. Pena Rodriguez⁴⁵, T. Quadfasel⁴⁵, M. Rieger⁴⁵, O. Rieger⁴⁵, D. Savoıu⁴⁵, P. Schleper⁴⁵, M. Schröder⁴⁵, J. Schwandt⁴⁵, M. Sommerhalder⁴⁵, H. Stadie⁴⁵, G. Steinbrück⁴⁵, A. Tews⁴⁵, M. Wolf⁴⁵, S. Brommer⁴⁶, M. Burkart⁴⁶, E. Butz⁴⁶, R. Caspart⁴⁶, T. Chwalek⁴⁶, A. Dierlamm⁴⁶, A. Droll⁴⁶, N. Faltermann⁴⁶, M. Giffels⁴⁶, J. O. Gosewisch⁴⁶, A. Gottmann⁴⁶, F. Hartmann^{46,dd}, M. Horzela⁴⁶, U. Husemann⁴⁶, M. Klute⁴⁶, R. Koppenhöfer⁴⁶, S. Maier⁴⁶, S. Mitra⁴⁶, Th. Müller⁴⁶, M. Neukum⁴⁶, M. Oh⁴⁶, G. Quast⁴⁶, K. Rabbertz⁴⁶, J. Rauser⁴⁶, M. Schnepf⁴⁶, D. Seith⁴⁶, I. Shvetsov⁴⁶, H. J. Simonis⁴⁶, N. Trevisani⁴⁶, R. Ulrich⁴⁶, J. van der Linden⁴⁶, R. F. Von Cube⁴⁶, M. Wassmer⁴⁶, S. Wieland⁴⁶, R. Wolf⁴⁶, S. Woznięski⁴⁶, S. Wunsch⁴⁶, X. Zuo⁴⁶, G. Anagnostou⁴⁷, P. Assiouras⁴⁷, G. Daskalakis⁴⁷, A. Kyriakis⁴⁷, A. Stakia⁴⁷, M. Diamantopoulou⁴⁸, D. Karasavvas⁴⁸, P. Kontaxakis⁴⁸, A. Manousakis-Katsikakis⁴⁸, A. Panagiotou⁴⁸, I. Papavergou⁴⁸, N. Saoulidou⁴⁸, K. Theofilatos⁴⁸, E. Tziaferi⁴⁸, K. Vellidis⁴⁸, I. Zisopoulos⁴⁸, G. Bakas⁴⁹, T. Chatzistavrou⁴⁹, K. Kousouris⁴⁹, I. Papakrivopoulos⁴⁹, G. Tsiolitis⁴⁹, A. Zacharopoulou⁴⁹, K. Adamidis⁵⁰, I. Bestintzanos⁵⁰, I. Evangelou⁵⁰, C. Foudas⁵⁰, P. Gianneios⁵⁰, C. Kamtsikis⁵⁰, P. Katsoulis⁵⁰, P. Kokkas⁵⁰, P. G. Kosmoglou Kioseoglou⁵⁰, N. Manthos⁵⁰, I. Papadopoulos⁵⁰, J. Strogas⁵⁰, M. Csanád⁵¹, K. Farkas⁵¹, M. M. A. Gadallah^{51,ee}, S. Lökös^{51,ff}, P. Major⁵¹, K. Mandal⁵¹, G. Pásztor⁵¹, A. J. Rádl^{51,gg}, O. Surányi⁵¹, G. I. Veres⁵¹, M. Bartók^{52,hh}, G. Bencze⁵², C. Hajdu⁵², D. Horvath^{52,ii,jj}, F. Sikler⁵², V. Veszpremi⁵², N. Beni⁵³, S. Czellar⁵³, J. Karancsi^{53,hh}, J. Molnar⁵³, Z. Szillasi⁵³, D. Teyssier⁵³, P. Raics⁵⁴, B. Ujvari^{54,kk}, T. Csorgo^{55,gg}, F. Nemes^{55,gg}, T. Novak⁵⁵, J. Babbar⁵⁶, S. Bansal⁵⁶, S. B. Beri⁵⁶, V. Bhatnagar⁵⁶, G. Chaudhary⁵⁶, S. Chauhan⁵⁶, N. Dhingra^{56,ll}, R. Gupta⁵⁶, A. Kaur⁵⁶, A. Kaur⁵⁶, H. Kaur⁵⁶, M. Kaur⁵⁶, S. Kumar⁵⁶, P. Kumari⁵⁶, M. Meena⁵⁶, K. Sandeep⁵⁶, T. Sheokand⁵⁶, J. B. Singh^{56,mm}, A. Singla⁵⁶, A. K. Viridi⁵⁶, A. Ahmed⁵⁷, A. Bhardwaj⁵⁷, B. C. Choudhary⁵⁷, A. Kumar⁵⁷, M. Naimuddin⁵⁷, K. Ranjan⁵⁷, S. Saumya⁵⁷, S. Baradia⁵⁸, S. Barman^{58,nn}, S. Bhattacharya⁵⁸, D. Bhowmik⁵⁸, S. Dutta⁵⁸, S. Dutta⁵⁸, B. Gomber^{58,oo}, M. Maity^{58,nn}, P. Palit⁵⁸, G. Saha⁵⁸, B. Sahu⁵⁸, S. Sarkar⁵⁸, P. K. Behera⁵⁹, S. C. Behera⁵⁹, P. Kalbhor⁵⁹, J. R. Komaragiri^{59,pp}, D. Kumar^{59,pp}, A. Muhammad⁵⁹, L. Panwar^{59,pp}, R. Pradhan⁵⁹, P. R. Pujahari⁵⁹, A. Sharma⁵⁹, A. K. Sikdar⁵⁹, P. C. Tiwari^{59,pp}, S. Verma⁵⁹, K. Naskar^{60,qq}, T. Aziz⁶¹, I. Das⁶¹

S. Dugad,⁶¹ M. Kumar⁶¹ G. B. Mohanty⁶¹ P. Suryadevara,⁶¹ S. Banerjee⁶² R. Chudasama⁶² M. Guchait⁶²
 S. Karmakar⁶² S. Kumar⁶² G. Majumder⁶² K. Mazumdar⁶² S. Mukherjee⁶² A. Thachayath⁶²
 S. Bahinipati^{63,ir} C. Kar⁶³ P. Mal⁶³ T. Mishra⁶³ V. K. Muraleedharan Nair Bindhu^{63,ss} A. Nayak^{63,ss}
 P. Saha⁶³ S. K. Swain,⁶³ D. Vats^{63,ss} A. Alpina⁶⁴ S. Dube⁶⁴ B. Kansal⁶⁴ A. Laha⁶⁴ S. Pandey⁶⁴
 A. Rastogi⁶⁴ S. Sharma⁶⁴ H. Bakhshiansohi^{65,tt} E. Khazaie⁶⁵ M. Zeinali^{65,uu} S. Chenarani^{66,vv}
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 S. Y. Hoh^{96,ddd} I. Yusuff^{96,ddd} Z. Zolkapli⁹⁶ J. F. Benitez⁹⁷ A. Castaneda Hernandez⁹⁷ H. A. Encinas Acosta⁹⁷
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 H. A. Salazar Ibarguen¹⁰⁰ C. Uribe Estrada¹⁰⁰ I. Bujanja¹⁰¹ J. Mijuskovic^{101,fff} N. Raicevic¹⁰¹ A. Ahmad¹⁰²
 M. I. Asghar¹⁰² A. Awais¹⁰² M. I. M. Awan¹⁰² M. Gul¹⁰² H. R. Hoorani¹⁰² W. A. Khan¹⁰² M. Shoaib¹⁰²
 M. Waqas¹⁰² V. Avati¹⁰³ L. Grzanka¹⁰³ M. Malawski¹⁰³ H. Bialkowska¹⁰⁴ M. Bluj¹⁰⁴ B. Boimska¹⁰⁴
 M. Górski¹⁰⁴ M. Kazana¹⁰⁴ M. Szleper¹⁰⁴ P. Zalewski¹⁰⁴ K. Bunkowski¹⁰⁵ K. Doroba¹⁰⁵ A. Kalinowski¹⁰⁵
 M. Konecki¹⁰⁵ J. Krolikowski¹⁰⁵ M. Araujo¹⁰⁶ P. Bargassa¹⁰⁶ D. Bastos¹⁰⁶ A. Boletti¹⁰⁶ P. Faccioli¹⁰⁶
 M. Gallinaro¹⁰⁶ J. Hollar¹⁰⁶ N. Leonardo¹⁰⁶ T. Niknejad¹⁰⁶ M. Pisano¹⁰⁶ J. Seixas¹⁰⁶ J. Varela¹⁰⁶
 P. Adzic^{107,ggg} M. Dordevic¹⁰⁷ P. Milenovic¹⁰⁷ J. Milosevic¹⁰⁷ M. Aguilar-Benitez¹⁰⁸ J. Alcaraz Maestre¹⁰⁸
 A. Álvarez Fernández¹⁰⁸ M. Barrio Luna¹⁰⁸ Cristina F. Bedoya¹⁰⁸ C. A. Carrillo Montoya¹⁰⁸ M. Cepeda¹⁰⁸
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 C. Martinez Rivero¹¹¹ P. Martinez Ruiz del Arbol¹¹¹ F. Matorras¹¹¹ P. Matorras Cuevas¹¹¹ J. Piedra Gomez¹¹¹
 C. Prieels¹¹¹ A. Ruiz-Jimeno¹¹¹ L. Scodellaro¹¹¹ I. Vila¹¹¹ J. M. Vizan Garcia¹¹¹ M. K. Jayananda¹¹²
 B. Kailasapathy^{112,hhh} D. U. J. Sonnadara¹¹² D. D. C. Wickramaratna¹¹² W. G. D. Dharmaratna¹¹³
 K. Liyanage¹¹³ N. Perera¹¹³ N. Wickramage¹¹³ D. Abbaneo¹¹⁴ J. Alimena¹¹⁴ E. Auffray¹¹⁴ G. Auzinger¹¹⁴
 J. Baechler¹¹⁴ P. Baillon^{114,a} D. Barney¹¹⁴ J. Bendavid¹¹⁴ M. Bianco¹¹⁴ B. Bilin¹¹⁴ A. Bocci¹¹⁴
 E. Brondolin¹¹⁴ C. Caillol¹¹⁴ T. Camporesi¹¹⁴ G. Cerminara¹¹⁴ N. Chernyavskaya¹¹⁴ S. S. Chhibra¹¹⁴
 S. Choudhury¹¹⁴ M. Cipriani¹¹⁴ L. Cristella¹¹⁴ D. d'Enterria¹¹⁴ A. Dabrowski¹¹⁴ A. David¹¹⁴ A. De Roeck¹¹⁴
 M. M. Defranchis¹¹⁴ M. Deile¹¹⁴ M. Dobson¹¹⁴ M. Dünser¹¹⁴ N. Dupont¹¹⁴ F. Fallavollita^{114,iii} A. Florent¹¹⁴
 L. Forthomme¹¹⁴ G. Franzoni¹¹⁴ W. Funk¹¹⁴ S. Ghosh¹¹⁴ S. Giani¹¹⁴ D. Gigi¹¹⁴ K. Gill¹¹⁴ F. Glege¹¹⁴
 L. Gouskos¹¹⁴ E. Govorkova¹¹⁴ M. Haranko¹¹⁴ J. Hegeman¹¹⁴ V. Innocente¹¹⁴ T. James¹¹⁴ P. Janot¹¹⁴
 J. Kaspar¹¹⁴ J. Kieseler¹¹⁴ N. Kratochwil¹¹⁴ S. Laurila¹¹⁴ P. Lecoq¹¹⁴ E. Leutgeb¹¹⁴ A. Lintuluoto¹¹⁴
 C. Lourenço¹¹⁴ B. Maier¹¹⁴ L. Malgeri¹¹⁴ M. Mannelli¹¹⁴ A. C. Marini¹¹⁴ F. Meijers¹¹⁴ S. Mersi¹¹⁴
 E. Meschi¹¹⁴ F. Moortgat¹¹⁴ M. Mulders¹¹⁴ S. Orfanelli¹¹⁴ L. Orsini¹¹⁴ F. Pantaleo¹¹⁴ E. Perez¹¹⁴ M. Peruzzi¹¹⁴

A. Petrilli¹¹⁴, G. Petrucciani¹¹⁴, A. Pfeiffer¹¹⁴, M. Pierini¹¹⁴, D. Piparo¹¹⁴, M. Pitt¹¹⁴, H. Qu¹¹⁴, T. Quast¹¹⁴, D. Rabad¹¹⁴, A. Racz¹¹⁴, G. Reales Gutiérrez¹¹⁴, M. Rovere¹¹⁴, H. Sakulin¹¹⁴, J. Salfeld-Nebgen¹¹⁴, S. Scarfi¹¹⁴, M. Selvaggi¹¹⁴, A. Sharma¹¹⁴, P. Silva¹¹⁴, P. Sphicas^{114,jjj}, A. G. Stahl Leiton¹¹⁴, S. Summers¹¹⁴, K. Tatar¹¹⁴, V. R. Tavoraro¹¹⁴, D. Treille¹¹⁴, P. Tropea¹¹⁴, A. Tsirou¹¹⁴, J. Wanczyk^{114,kkk}, K. A. Wozniak¹¹⁴, W. D. Zeuner¹¹⁴, L. Caminada^{115,lll}, A. Ebrahimi¹¹⁵, W. Erdmann¹¹⁵, R. Horisberger¹¹⁵, Q. Ingram¹¹⁵, H. C. Kaestli¹¹⁵, D. Kotlinski¹¹⁵, C. Lange¹¹⁵, M. Missiroli^{115,lll}, L. Nochte^{115,lll}, T. Rohe¹¹⁵, T. K. Aarrestad¹¹⁶, K. Androsov^{116,kkk}, M. Backhaus¹¹⁶, P. Berger¹¹⁶, A. Calandri¹¹⁶, K. Datta¹¹⁶, A. De Cosa¹¹⁶, G. Dissertori¹¹⁶, M. Dittmar¹¹⁶, M. Donegà¹¹⁶, F. Eble¹¹⁶, M. Galli¹¹⁶, K. Gedia¹¹⁶, F. Glessgen¹¹⁶, T. A. Gómez Espinosa¹¹⁶, C. Grab¹¹⁶, D. Hits¹¹⁶, W. Lustermann¹¹⁶, A.-M. Lyon¹¹⁶, R. A. Manzoni¹¹⁶, L. Marchese¹¹⁶, C. Martin Perez¹¹⁶, A. Mascellani^{116,kkk}, F. Nessi-Tedaldi¹¹⁶, J. Niedziela¹¹⁶, F. Pauss¹¹⁶, V. Perovic¹¹⁶, S. Pigazzini¹¹⁶, M. G. Ratti¹¹⁶, M. Reichmann¹¹⁶, C. Reissel¹¹⁶, T. Reitenspiess¹¹⁶, B. Ristic¹¹⁶, F. Riti¹¹⁶, D. Ruini¹¹⁶, D. A. Sanz Becerra¹¹⁶, J. Steggemann^{116,kkk}, D. Valsecchi^{116,dd}, R. Wallny¹¹⁶, C. Amsler^{117,mmm}, P. Bärtschi¹¹⁷, C. Botta¹¹⁷, D. Brzhechko¹¹⁷, M. F. Canelli¹¹⁷, K. Cormier¹¹⁷, A. De Wit¹¹⁷, R. Del Burgo¹¹⁷, J. K. Heikkilä¹¹⁷, M. Huwiler¹¹⁷, W. Jin¹¹⁷, A. Jofrehei¹¹⁷, B. Kilminster¹¹⁷, S. Leontsinis¹¹⁷, S. P. Liechti¹¹⁷, A. Macchiolo¹¹⁷, P. Meiring¹¹⁷, V. M. Mikuni¹¹⁷, U. Molinatti¹¹⁷, I. Neutelings¹¹⁷, A. Reimers¹¹⁷, P. Robmann¹¹⁷, S. Sanchez Cruz¹¹⁷, K. Schweiger¹¹⁷, M. Senger¹¹⁷, Y. Takahashi¹¹⁷, C. Adloff^{118,nnn}, C. M. Kuo¹¹⁸, W. Lin¹¹⁸, P. K. Rout¹¹⁸, S. S. Yu¹¹⁸, L. Ceard¹¹⁹, Y. Chao¹¹⁹, K. F. Chen¹¹⁹, P. s. Chen¹¹⁹, H. Cheng¹¹⁹, W.-S. Hou¹¹⁹, R. Khurana¹¹⁹, G. Kole¹¹⁹, Y. y. Li¹¹⁹, R.-S. Lu¹¹⁹, E. Paganis¹¹⁹, A. Psallidas¹¹⁹, A. Steen¹¹⁹, H. y. Wu¹¹⁹, E. Yazgan¹¹⁹, P. r. Yu¹¹⁹, C. Asawatangtrakuldee¹²⁰, N. Srimanobhas¹²⁰, D. Agyel¹²¹, F. Boran¹²¹, Z. S. Demiroglu¹²¹, F. Dolek¹²¹, I. Dumanoglu^{121,ooo}, E. Eskut¹²¹, Y. Guler^{121,ppp}, E. Gurpinar Guler^{121,ppp}, C. Isik¹²¹, O. Kara¹²¹, A. Kayis Topaksu¹²¹, U. Kiminsu¹²¹, G. Onengut¹²¹, K. Ozdemir^{121,qqq}, A. Polatoz¹²¹, A. E. Simsek¹²¹, B. Tali^{121,rrr}, U. G. Tok¹²¹, S. Turkcapar¹²¹, E. Uslan¹²¹, I. S. Zorbakir¹²¹, G. Karapinar^{122,sss}, K. Ocalan^{122,ttt}, M. Yalvac^{122,uuu}, B. Akgun¹²³, I. O. Atakisi¹²³, E. Gülmez¹²³, M. Kaya^{123,vvv}, O. Kaya^{123,www}, S. Tekten^{123,xxx}, A. Cakir¹²⁴, K. Cankocak^{124,ooo}, Y. Komurcu¹²⁴, S. Sen^{124,ooo}, O. Aydilek¹²⁵, S. Cerci^{125,rrr}, B. Hacıahinoglu¹²⁵, I. Hos^{125,yyy}, B. Isildak^{125,zzz}, B. Kaynak¹²⁵, S. Ozkorucuklu¹²⁵, C. Simsek¹²⁵, D. Sunar Cerci^{125,rrr}, B. Grynyov¹²⁶, L. Levchuk¹²⁷, D. Anthony¹²⁸, E. Bhal¹²⁸, J. J. Brooke¹²⁸, A. Bundock¹²⁸, E. Clement¹²⁸, D. Cussans¹²⁸, H. Flacher¹²⁸, M. Glowacki¹²⁸, J. Goldstein¹²⁸, G. P. Heath¹²⁸, H. F. Heath¹²⁸, L. Kreczko¹²⁸, B. Krikler¹²⁸, S. Paramesvaran¹²⁸, S. Seif El Nasr-Storey¹²⁸, V. J. Smith¹²⁸, N. Stylianou^{128,aaaa}, K. Walkingshaw Pass¹²⁸, R. White¹²⁸, A. H. Ball¹²⁹, K. W. Bell¹²⁹, A. Belyaev^{129,bbbb}, C. Brew¹²⁹, R. M. Brown¹²⁹, D. J. A. Cockerill¹²⁹, C. Cooke¹²⁹, K. V. Ellis¹²⁹, K. Harder¹²⁹, S. Harper¹²⁹, M.-L. Holmberg^{129,cccc}, J. Linacre¹²⁹, K. Manolopoulos¹²⁹, D. M. Newbold¹²⁹, E. Olaiya¹²⁹, D. Petyt¹²⁹, T. Reis¹²⁹, G. Salvi¹²⁹, T. Schuh¹²⁹, C. H. Shepherd-Themistocleous¹²⁹, I. R. Tomalin¹²⁹, T. Williams¹²⁹, R. Bainbridge¹³⁰, P. Bloch¹³⁰, S. Bonomally¹³⁰, J. Borg¹³⁰, S. Breeze¹³⁰, C. E. Brown¹³⁰, O. Buchmuller¹³⁰, V. Cacchio¹³⁰, V. Cepaitis¹³⁰, G. S. Chahal^{130,dddd}, D. Colling¹³⁰, J. S. Dancu¹³⁰, P. Dauncey¹³⁰, G. Davies¹³⁰, J. Davies¹³⁰, M. Della Negra¹³⁰, S. Fayer¹³⁰, G. Fedi¹³⁰, G. Hall¹³⁰, M. H. Hassanshahi¹³⁰, A. Howard¹³⁰, G. Iles¹³⁰, J. Langford¹³⁰, L. Lyons¹³⁰, A.-M. Magnan¹³⁰, S. Malik¹³⁰, A. Martelli¹³⁰, M. Mieskolainen¹³⁰, D. G. Monk¹³⁰, J. Nash^{130,eeee}, M. Pesaresi¹³⁰, B. C. Radburn-Smith¹³⁰, D. M. Raymond¹³⁰, A. Richards¹³⁰, A. Rose¹³⁰, E. Scott¹³⁰, C. Seez¹³⁰, A. Shtipliyski¹³⁰, R. Shukla¹³⁰, A. Tapper¹³⁰, K. Uchida¹³⁰, G. P. Uttley¹³⁰, L. H. Vage¹³⁰, T. Virdee^{130,dd}, M. Vojinovic¹³⁰, N. Wardle¹³⁰, S. N. Webb¹³⁰, D. Winterbottom¹³⁰, K. Coldham¹³¹, J. E. Cole¹³¹, A. Khan¹³¹, P. Kyberd¹³¹, I. D. Reid¹³¹, S. Abdullin¹³², A. Brinkerhoff¹³², B. Caraway¹³², J. Dittmann¹³², K. Hatakeyama¹³², A. R. Kanuganti¹³², B. McMaster¹³², M. Saunders¹³², S. Sawant¹³², C. Sutantawibul¹³², J. Wilson¹³², R. Bartek¹³³, A. Dominguez¹³³, R. Uniyal¹³³, A. M. Vargas Hernandez¹³³, S. I. Cooper¹³⁴, D. Di Croce¹³⁴, S. V. Gleyzer¹³⁴, C. Henderson¹³⁴, C. U. Perez¹³⁴, P. Rumerio^{134,fff}, C. West¹³⁴, A. Akpinar¹³⁵, A. Albert¹³⁵, D. Arcaro¹³⁵, C. Cosby¹³⁵, Z. Demiragli¹³⁵, C. Erice¹³⁵, E. Fontanesi¹³⁵, D. Gastler¹³⁵, S. May¹³⁵, J. Rohlf¹³⁵, K. Salyer¹³⁵, D. Sperka¹³⁵, D. Spitzbart¹³⁵, I. Suarez¹³⁵, A. Tsatsos¹³⁵, S. Yuan¹³⁵, G. Benelli¹³⁶, B. Burkle¹³⁶, X. Coubez^{136,y}, D. Cutts¹³⁶, M. Hadley¹³⁶, U. Heintz¹³⁶, J. M. Hogan^{136,gggg}, T. Kwon¹³⁶, G. Landsberg¹³⁶, K. T. Lau¹³⁶, D. Li¹³⁶, J. Luo¹³⁶, M. Narain¹³⁶, N. Pervan¹³⁶, S. Sagir^{136,hhhh}, F. Simpson¹³⁶, E. Usai¹³⁶

W. Y. Wong,¹³⁶ X. Yan¹³⁶, D. Yu¹³⁶, W. Zhang,¹³⁶ J. Bonilla¹³⁷, C. Brainerd¹³⁷, R. Breedon¹³⁷,
M. Calderon De La Barca Sanchez¹³⁷, M. Chertok¹³⁷, J. Conway¹³⁷, P. T. Cox¹³⁷, R. Erbacher¹³⁷, G. Haza¹³⁷,
F. Jensen¹³⁷, O. Kukral¹³⁷, G. Mocellin¹³⁷, M. Mulhearn¹³⁷, D. Pellett¹³⁷, B. Regnery¹³⁷, Y. Yao¹³⁷,
F. Zhang¹³⁷, M. Bachtis¹³⁸, R. Cousins¹³⁸, A. Datta¹³⁸, D. Hamilton¹³⁸, J. Hauser¹³⁸, M. Ignatenko¹³⁸,
M. A. Iqbal¹³⁸, T. Lam¹³⁸, E. Manca¹³⁸, W. A. Nash¹³⁸, S. Regnard¹³⁸, D. Saltzberg¹³⁸, B. Stone¹³⁸,
V. Valuev¹³⁸, R. Clare¹³⁹, J. W. Gary¹³⁹, M. Gordon¹³⁹, G. Hanson¹³⁹, G. Karapostoli¹³⁹, O. R. Long¹³⁹,
N. Manganello¹³⁹, W. Si¹³⁹, S. Wimpenny¹³⁹, J. G. Branson¹⁴⁰, P. Chang¹⁴⁰, S. Cittolin¹⁴⁰, S. Cooperstein¹⁴⁰,
D. Diaz¹⁴⁰, J. Duarte¹⁴⁰, R. Gerosa¹⁴⁰, L. Giannini¹⁴⁰, J. Guiang¹⁴⁰, R. Kansal¹⁴⁰, V. Krutelyov¹⁴⁰, R. Lee¹⁴⁰,
J. Letts¹⁴⁰, M. Masciovecchio¹⁴⁰, F. Mokhtar¹⁴⁰, M. Pieri¹⁴⁰, B. V. Sathia Narayanan¹⁴⁰, V. Sharma¹⁴⁰,
M. Tadel¹⁴⁰, E. Vourliotis¹⁴⁰, F. Würthwein¹⁴⁰, Y. Xiang¹⁴⁰, A. Yagil¹⁴⁰, N. Amin¹⁴¹, C. Campagnari¹⁴¹,
M. Citron¹⁴¹, G. Collura¹⁴¹, A. Dorsett¹⁴¹, V. Dutta¹⁴¹, J. Incandela¹⁴¹, M. Kilpatrick¹⁴¹, J. Kim¹⁴¹, A. J. Li¹⁴¹,
P. Masterson¹⁴¹, H. Mei¹⁴¹, M. Oshiro¹⁴¹, M. Quinlan¹⁴¹, J. Richman¹⁴¹, U. Sarica¹⁴¹, R. Schmitz¹⁴¹,
F. Setti¹⁴¹, J. Shephlock¹⁴¹, P. Siddireddy¹⁴¹, D. Stuart¹⁴¹, S. Wang¹⁴¹, A. Bornheim¹⁴², O. Cerri¹⁴², I. Dutta¹⁴²,
A. Latorre¹⁴², J. M. Lawhorn¹⁴², N. Lu¹⁴², J. Mao¹⁴², H. B. Newman¹⁴², T. Q. Nguyen¹⁴², M. Spiropulu¹⁴²,
J. R. Vlimant¹⁴², C. Wang¹⁴², S. Xie¹⁴², R. Y. Zhu¹⁴², J. Alison¹⁴³, S. An¹⁴³, M. B. Andrews¹⁴³, P. Bryant¹⁴³,
T. Ferguson¹⁴³, A. Harilal¹⁴³, C. Liu¹⁴³, T. Mudholkar¹⁴³, S. Murthy¹⁴³, M. Paulini¹⁴³, A. Roberts¹⁴³,
A. Sanchez¹⁴³, W. Terrill¹⁴³, J. P. Cumalat¹⁴⁴, W. T. Ford¹⁴⁴, A. Hassani¹⁴⁴, G. Karathanasis¹⁴⁴, E. MacDonald¹⁴⁴,
F. Marini¹⁴⁴, R. Patel¹⁴⁴, A. Perloff¹⁴⁴, C. Savard¹⁴⁴, N. Schonbeck¹⁴⁴, K. Stenson¹⁴⁴, K. A. Ulmer¹⁴⁴,
S. R. Wagner¹⁴⁴, N. Zipper¹⁴⁴, J. Alexander¹⁴⁵, S. Bright-Thonney¹⁴⁵, X. Chen¹⁴⁵, D. J. Cranshaw¹⁴⁵, J. Fan¹⁴⁵,
X. Fan¹⁴⁵, D. Gadkari¹⁴⁵, S. Hogan¹⁴⁵, J. Monroy¹⁴⁵, J. R. Patterson¹⁴⁵, D. Quach¹⁴⁵, J. Reichert¹⁴⁵,
M. Reid¹⁴⁵, A. Ryd¹⁴⁵, J. Thom¹⁴⁵, P. Wittich¹⁴⁵, R. Zou¹⁴⁵, M. Albrow¹⁴⁶, M. Alyari¹⁴⁶, G. Apollinari¹⁴⁶,
A. Apresyan¹⁴⁶, L. A. T. Bauerdick¹⁴⁶, D. Berry¹⁴⁶, J. Berryhill¹⁴⁶, P. C. Bhat¹⁴⁶, K. Burkett¹⁴⁶, J. N. Butler¹⁴⁶,
A. Canepa¹⁴⁶, G. B. Cerati¹⁴⁶, H. W. K. Cheung¹⁴⁶, F. Chlebana¹⁴⁶, K. F. Di Petrillo¹⁴⁶, J. Dickinson¹⁴⁶,
V. D. Elvira¹⁴⁶, Y. Feng¹⁴⁶, J. Freeman¹⁴⁶, A. Gandrakota¹⁴⁶, Z. Gecse¹⁴⁶, L. Gray¹⁴⁶, D. Green¹⁴⁶,
S. Grünendahl¹⁴⁶, O. Gutsche¹⁴⁶, R. M. Harris¹⁴⁶, R. Heller¹⁴⁶, T. C. Herwig¹⁴⁶, J. Hirschauer¹⁴⁶, L. Horyn¹⁴⁶,
B. Jayatilaka¹⁴⁶, S. Jindariani¹⁴⁶, M. Johnson¹⁴⁶, U. Joshi¹⁴⁶, T. Klijsma¹⁴⁶, B. Klima¹⁴⁶, K. H. M. Kwok¹⁴⁶,
S. Lammel¹⁴⁶, D. Lincoln¹⁴⁶, R. Lipton¹⁴⁶, T. Liu¹⁴⁶, C. Madrid¹⁴⁶, K. Maeshima¹⁴⁶, C. Mantilla¹⁴⁶,
D. Mason¹⁴⁶, P. McBride¹⁴⁶, P. Merkel¹⁴⁶, S. Mrenna¹⁴⁶, S. Nahn¹⁴⁶, J. Ngadiuba¹⁴⁶, D. Noonan¹⁴⁶,
V. Papadimitriou¹⁴⁶, N. Pastika¹⁴⁶, K. Pedro¹⁴⁶, C. Pena^{146,iiii}, F. Ravera¹⁴⁶, A. Reinsvold Hall^{146,ijii},
L. Ristori¹⁴⁶, E. Sexton-Kennedy¹⁴⁶, N. Smith¹⁴⁶, A. Soha¹⁴⁶, L. Spiegel¹⁴⁶, J. Strait¹⁴⁶, L. Taylor¹⁴⁶,
S. Tkaczyk¹⁴⁶, N. V. Tran¹⁴⁶, L. Uplegger¹⁴⁶, E. W. Vaandering¹⁴⁶, H. A. Weber¹⁴⁶, I. Zoi¹⁴⁶, P. Avery¹⁴⁷,
D. Bourilkov¹⁴⁷, L. Cadamuro¹⁴⁷, V. Cherepanov¹⁴⁷, R. D. Field¹⁴⁷, D. Guerrero¹⁴⁷, M. Kim¹⁴⁷, E. Koenig¹⁴⁷,
J. Konigsberg¹⁴⁷, A. Korytov¹⁴⁷, K. H. Lo¹⁴⁷, K. Matchev¹⁴⁷, N. Menendez¹⁴⁷, G. Mitselmakher¹⁴⁷,
A. Muthirakalayil Madhu¹⁴⁷, N. Rawal¹⁴⁷, D. Rosenzweig¹⁴⁷, S. Rosenzweig¹⁴⁷, K. Shi¹⁴⁷, J. Wang¹⁴⁷,
Z. Wu¹⁴⁷, T. Adams¹⁴⁸, A. Askew¹⁴⁸, R. Habibullah¹⁴⁸, V. Hagopian¹⁴⁸, T. Kolberg¹⁴⁸, G. Martinez¹⁴⁸,
H. Prosper¹⁴⁸, C. Schiber¹⁴⁸, O. Viazlo¹⁴⁸, R. Yohay¹⁴⁸, J. Zhang¹⁴⁸, M. M. Baarmand¹⁴⁹, S. Butalla¹⁴⁹,
T. Elkafrawy^{149,q}, M. Hohlmann¹⁴⁹, R. Kumar Verma¹⁴⁹, M. Rahmani¹⁴⁹, F. Yumiceva¹⁴⁹, M. R. Adams¹⁵⁰,
H. Becerril Gonzalez¹⁵⁰, R. Cavanaugh¹⁵⁰, S. Dittmer¹⁵⁰, O. Evdokimov¹⁵⁰, C. E. Gerber¹⁵⁰, D. J. Hofman¹⁵⁰,
D. S. Lemos¹⁵⁰, A. H. Merrit¹⁵⁰, C. Mills¹⁵⁰, G. Oh¹⁵⁰, T. Roy¹⁵⁰, S. Rudrabhatla¹⁵⁰, M. B. Tonjes¹⁵⁰,
N. Varelas¹⁵⁰, X. Wang¹⁵⁰, Z. Ye¹⁵⁰, J. Yoo¹⁵⁰, M. Alhusseini¹⁵¹, K. Dilsiz^{151,kkkk}, L. Emediato¹⁵¹,
R. P. Gandrajula¹⁵¹, G. Karaman¹⁵¹, O. K. Köseyan¹⁵¹, J.-P. Merlo¹⁵¹, A. Mestvirishvili^{151,llll}, J. Nachtman¹⁵¹,
O. Neogi¹⁵¹, H. Ogul^{151,mmmm}, Y. Onel¹⁵¹, A. Penzo¹⁵¹, C. Snyder¹⁵¹, E. Tiras^{151,nnnn}, O. Amram¹⁵²,
B. Blumenfeld¹⁵², L. Corcodilos¹⁵², J. Davis¹⁵², A. V. Gritsan¹⁵², S. Kyriacou¹⁵², P. Maksimovic¹⁵²,
J. Roskes¹⁵², S. Sekhar¹⁵², M. Swartz¹⁵², T. Á. Vami¹⁵², A. Abreu¹⁵³, L. F. Alcerro Alcerro¹⁵³, J. Anguiano¹⁵³,
P. Baringer¹⁵³, A. Bean¹⁵³, Z. Flowers¹⁵³, T. Isidori¹⁵³, J. King¹⁵³, G. Krintiras¹⁵³, M. Lazarovits¹⁵³,
C. Le Mahieu¹⁵³, C. Lindsey¹⁵³, J. Marquez¹⁵³, N. Minafra¹⁵³, M. Murray¹⁵³, M. Nickel¹⁵³, C. Rogan¹⁵³,
C. Royon¹⁵³, R. Salvatico¹⁵³, S. Sanders¹⁵³, C. Smith¹⁵³, Q. Wang¹⁵³, J. Williams¹⁵³, G. Wilson¹⁵³

B. Allmond¹⁵⁴, S. Duric¹⁵⁴, A. Ivanov¹⁵⁴, K. Kaadze¹⁵⁴, D. Kim¹⁵⁴, Y. Maravin¹⁵⁴, T. Mitchell¹⁵⁴, A. Modak¹⁵⁴,
 K. Nam¹⁵⁴, D. Roy¹⁵⁴, F. Rebassoo¹⁵⁵, D. Wright¹⁵⁵, E. Adams¹⁵⁶, A. Baden¹⁵⁶, O. Baron¹⁵⁶, A. Belloni¹⁵⁶,
 A. Bethani¹⁵⁶, S. C. Eno¹⁵⁶, N. J. Hadley¹⁵⁶, S. Jabeen¹⁵⁶, R. G. Kellogg¹⁵⁶, T. Koeth¹⁵⁶, Y. Lai¹⁵⁶,
 S. Lascio¹⁵⁶, A. C. Mignerey¹⁵⁶, S. Nabili¹⁵⁶, C. Palmer¹⁵⁶, C. Papageorgakis¹⁵⁶, L. Wang¹⁵⁶, K. Wong¹⁵⁶,
 D. Abercrombie¹⁵⁷, W. Busza¹⁵⁷, I. A. Cali¹⁵⁷, Y. Chen¹⁵⁷, M. D'Alfonso¹⁵⁷, J. Eysermans¹⁵⁷, C. Freer¹⁵⁷,
 G. Gomez-Ceballos¹⁵⁷, M. Goncharov¹⁵⁷, P. Harris¹⁵⁷, M. Hu¹⁵⁷, D. Kovalskyi¹⁵⁷, J. Krupa¹⁵⁷, Y.-J. Lee¹⁵⁷,
 K. Long¹⁵⁷, C. Mironov¹⁵⁷, C. Paus¹⁵⁷, D. Rankin¹⁵⁷, C. Roland¹⁵⁷, G. Roland¹⁵⁷, Z. Shi¹⁵⁷,
 G. S. F. Stephans¹⁵⁷, J. Wang¹⁵⁷, Z. Wang¹⁵⁷, B. Wyslouch¹⁵⁷, T. J. Yang¹⁵⁷, R. M. Chatterjee¹⁵⁸, B. Crossman¹⁵⁸,
 A. Evans¹⁵⁸, J. Hiltbrand¹⁵⁸, Sh. Jain¹⁵⁸, B. M. Joshi¹⁵⁸, C. Kapsiak¹⁵⁸, M. Krohn¹⁵⁸, Y. Kubota¹⁵⁸, J. Mans¹⁵⁸,
 M. Revering¹⁵⁸, R. Rusack¹⁵⁸, R. Saradhy¹⁵⁸, N. Schroeder¹⁵⁸, N. Strobbe¹⁵⁸, M. A. Wadud¹⁵⁸,
 L. M. Cremaldi¹⁵⁹, K. Bloom¹⁶⁰, M. Bryson¹⁶⁰, D. R. Claes¹⁶⁰, C. Fangmeier¹⁶⁰, L. Finco¹⁶⁰, F. Golf¹⁶⁰,
 C. Joo¹⁶⁰, R. Kamalieddin¹⁶⁰, I. Kravchenko¹⁶⁰, I. Reed¹⁶⁰, J. E. Siado¹⁶⁰, G. R. Snow^{160,a}, W. Tabb¹⁶⁰,
 A. Wightman¹⁶⁰, F. Yan¹⁶⁰, A. G. Zecchinelli¹⁶⁰, G. Agarwal¹⁶¹, H. Bandyopadhyay¹⁶¹, L. Hay¹⁶¹, I. Iashvili¹⁶¹,
 A. Kharchilava¹⁶¹, C. McLean¹⁶¹, M. Morris¹⁶¹, D. Nguyen¹⁶¹, J. Pekkanen¹⁶¹, S. Rappoccio¹⁶¹,
 A. Williams¹⁶¹, G. Alverson¹⁶², E. Barberis¹⁶², Y. Haddad¹⁶², Y. Han¹⁶², A. Krishna¹⁶², J. Li¹⁶², J. Lidrych¹⁶²,
 G. Madigan¹⁶², B. Marzocchi¹⁶², D. M. Morse¹⁶², V. Nguyen¹⁶², T. Orimoto¹⁶², A. Parker¹⁶², L. Skinnari¹⁶²,
 A. Tishelman-Charny¹⁶², T. Wamorkar¹⁶², B. Wang¹⁶², A. Wisecarver¹⁶², D. Wood¹⁶², S. Bhattacharya¹⁶³,
 J. Bueghly¹⁶³, Z. Chen¹⁶³, A. Gilbert¹⁶³, K. A. Hahn¹⁶³, Y. Liu¹⁶³, N. Odell¹⁶³, M. H. Schmitt¹⁶³, M. Velasco¹⁶³,
 R. Band¹⁶⁴, R. Bucci¹⁶⁴, M. Cremonesi¹⁶⁴, A. Das¹⁶⁴, R. Goldouzian¹⁶⁴, M. Hildreth¹⁶⁴, K. Hurtado Anampa¹⁶⁴,
 C. Jessop¹⁶⁴, K. Lannon¹⁶⁴, J. Lawrence¹⁶⁴, N. Loukas¹⁶⁴, L. Lutton¹⁶⁴, J. Mariano¹⁶⁴, N. Marinelli¹⁶⁴,
 I. Mcalister¹⁶⁴, T. McCauley¹⁶⁴, C. Mcgrady¹⁶⁴, K. Mohrman¹⁶⁴, C. Moore¹⁶⁴, Y. Musienko^{164,n}, R. Ruchti¹⁶⁴,
 A. Townsend¹⁶⁴, M. Wayne¹⁶⁴, H. Yockey¹⁶⁴, M. Zarucki¹⁶⁴, L. Zygala¹⁶⁴, B. Bylsma¹⁶⁵, M. Carrigan¹⁶⁵,
 L. S. Durkin¹⁶⁵, B. Francis¹⁶⁵, C. Hill¹⁶⁵, M. Joyce¹⁶⁵, A. Lesauvage¹⁶⁵, M. Nunez Ornelas¹⁶⁵, K. Wei¹⁶⁵,
 B. L. Winer¹⁶⁵, B. R. Yates¹⁶⁵, F. M. Addesa¹⁶⁶, P. Das¹⁶⁶, G. Dezoort¹⁶⁶, P. Elmer¹⁶⁶, A. Frankenthal¹⁶⁶,
 B. Greenberg¹⁶⁶, N. Haubrich¹⁶⁶, S. Higginbotham¹⁶⁶, A. Kalogeropoulos¹⁶⁶, G. Kopp¹⁶⁶, S. Kwan¹⁶⁶,
 D. Lange¹⁶⁶, D. Marlow¹⁶⁶, K. Mei¹⁶⁶, I. Ojalvo¹⁶⁶, J. Olsen¹⁶⁶, D. Stickland¹⁶⁶, C. Tully¹⁶⁶, S. Malik¹⁶⁷,
 S. Norberg¹⁶⁷, A. S. Bakshi¹⁶⁸, V. E. Barnes¹⁶⁸, R. Chawla¹⁶⁸, S. Das¹⁶⁸, L. Gutay¹⁶⁸, M. Jones¹⁶⁸, A. W. Jung¹⁶⁸,
 D. Kondratyev¹⁶⁸, A. M. Koshy¹⁶⁸, M. Liu¹⁶⁸, G. Negro¹⁶⁸, N. Neumeister¹⁶⁸, G. Paspalaki¹⁶⁸, S. Piperov¹⁶⁸,
 A. Purohit¹⁶⁸, J. F. Schulte¹⁶⁸, M. Stojanovic¹⁶⁸, J. Thieman¹⁶⁸, F. Wang¹⁶⁸, R. Xiao¹⁶⁸, W. Xie¹⁶⁸, J. Dolen¹⁶⁹,
 N. Parashar¹⁶⁹, D. Acosta¹⁷⁰, A. Baty¹⁷⁰, T. Carnahan¹⁷⁰, M. Decaro¹⁷⁰, S. Dildick¹⁷⁰, K. M. Ecklund¹⁷⁰,
 P. J. Fernández Manteca¹⁷⁰, S. Freed¹⁷⁰, P. Gardner¹⁷⁰, F. J. M. Geurts¹⁷⁰, A. Kumar¹⁷⁰, W. Li¹⁷⁰, B. P. Padley¹⁷⁰,
 R. Redjimi¹⁷⁰, J. Rotter¹⁷⁰, W. Shi¹⁷⁰, S. Yang¹⁷⁰, E. Yigitbasi¹⁷⁰, L. Zhang^{170,oooo}, Y. Zhang¹⁷⁰, A. Bodek¹⁷¹,
 P. de Barbaro¹⁷¹, R. Demina¹⁷¹, J. L. Dulemba¹⁷¹, C. Fallon¹⁷¹, T. Ferbel¹⁷¹, M. Galanti¹⁷¹, A. Garcia-Bellido¹⁷¹,
 O. Hindrichs¹⁷¹, A. Khukhunaishvili¹⁷¹, E. Ranken¹⁷¹, R. Taus¹⁷¹, G. P. Van Onsem¹⁷¹, K. Goulianos¹⁷²,
 B. Chiarito¹⁷³, J. P. Chou¹⁷³, Y. Gershtein¹⁷³, E. Halkiadakis¹⁷³, A. Hart¹⁷³, M. Heindl¹⁷³, D. Jaroslawski¹⁷³,
 O. Karacheban^{173,bb}, I. Laflotte¹⁷³, A. Lath¹⁷³, R. Montalvo¹⁷³, K. Nash¹⁷³, M. Osherson¹⁷³, H. Routray¹⁷³,
 S. Salur¹⁷³, S. Schnetzer¹⁷³, S. Somalwar¹⁷³, R. Stone¹⁷³, S. A. Thayil¹⁷³, S. Thomas¹⁷³, H. Wang¹⁷³, H. Acharya¹⁷⁴,
 A. G. Delannoy¹⁷⁴, S. Fiorendi¹⁷⁴, T. Holmes¹⁷⁴, E. Nibigira¹⁷⁴, S. Spanier¹⁷⁴, O. Bouhali^{175,pppp},
 M. Dalchenko¹⁷⁵, A. Delgado¹⁷⁵, R. Eusebi¹⁷⁵, J. Gilmore¹⁷⁵, T. Huang¹⁷⁵, T. Kamon^{175,qqqq}, H. Kim¹⁷⁵,
 S. Luo¹⁷⁵, S. Malhotra¹⁷⁵, R. Mueller¹⁷⁵, D. Overton¹⁷⁵, D. Rathjens¹⁷⁵, A. Safonov¹⁷⁵, N. Akchurin¹⁷⁶,
 J. Damgov¹⁷⁶, V. Hegde¹⁷⁶, K. Lamichhane¹⁷⁶, S. W. Lee¹⁷⁶, T. Mengke¹⁷⁶, S. Muthumuni¹⁷⁶, T. Peltola¹⁷⁶,
 I. Volobouev¹⁷⁶, A. Whitbeck¹⁷⁶, E. Appelt¹⁷⁷, S. Greene¹⁷⁷, A. Gurrola¹⁷⁷, W. Johns¹⁷⁷, A. Melo¹⁷⁷,
 F. Romeo¹⁷⁷, P. Sheldon¹⁷⁷, S. Tuo¹⁷⁷, J. Velkovska¹⁷⁷, J. Viinikainen¹⁷⁷, B. Cardwell¹⁷⁸, B. Cox¹⁷⁸,
 G. Cummings¹⁷⁸, J. Hakala¹⁷⁸, R. Hirosky¹⁷⁸, A. Ledovskoy¹⁷⁸, A. Li¹⁷⁸, C. Neu¹⁷⁸, C. E. Perez Lara¹⁷⁸,
 B. Tannenwald¹⁷⁸, P. E. Karchin¹⁷⁹, N. Poudyal¹⁷⁹, S. Banerjee¹⁸⁰, K. Black¹⁸⁰, T. Bose¹⁸⁰, S. Dasu¹⁸⁰,
 I. De Bruyn¹⁸⁰, P. Everaerts¹⁸⁰, C. Galloni¹⁸⁰, H. He¹⁸⁰, M. Herndon¹⁸⁰, A. Herve¹⁸⁰, C. K. Koraka¹⁸⁰,
 A. Lanaro¹⁸⁰, A. Loeliger¹⁸⁰, R. Loveless¹⁸⁰, J. Madhusudan Sreekala¹⁸⁰, A. Mallampalli¹⁸⁰, A. Mohammadi¹⁸⁰

S. Mondal,¹⁸⁰ G. Parida¹⁸⁰ D. Pinna,¹⁸⁰ A. Savin,¹⁸⁰ V. Shang¹⁸⁰ V. Sharma¹⁸⁰ W. H. Smith¹⁸⁰ D. Teague,¹⁸⁰
 H. F. Tsoi¹⁸⁰ W. Vetens¹⁸⁰ S. Afanasiev¹⁸¹ V. Andreev¹⁸¹ Yu. Andreev¹⁸¹ T. Aushev¹⁸¹ M. Azarkin¹⁸¹
 A. Babaev¹⁸¹ A. Belyaev¹⁸¹ V. Blinov,^{181,n} E. Boos¹⁸¹ V. Borshch¹⁸¹ D. Budkouski¹⁸¹ V. Chekhovsky,¹⁸¹
 R. Chistov^{181,n} A. Demiyanov¹⁸¹ A. Dermenev¹⁸¹ T. Dimova^{181,n} I. Dremin¹⁸¹ V. Epshteyn¹⁸¹ A. Ershov¹⁸¹
 G. Gavrillov¹⁸¹ V. Gavrillov¹⁸¹ S. Gninenko¹⁸¹ V. Golovtcov¹⁸¹ N. Golubev¹⁸¹ I. Golutvin¹⁸¹ I. Gorbunov¹⁸¹
 A. Gribushin¹⁸¹ V. Ivanchenko¹⁸¹ Y. Ivanov¹⁸¹ V. Kachanov¹⁸¹ L. Kardapoltsev^{181,n} V. Karjavine¹⁸¹
 A. Karneyeu¹⁸¹ L. Khein,¹⁸¹ V. Kim^{181,n} M. Kirakosyan,¹⁸¹ D. Kirpichnikov¹⁸¹ M. Kirsanov¹⁸¹
 O. Kodolova^{181,mrr} D. Konstantinov¹⁸¹ V. Korenkov¹⁸¹ V. Korotkikh,¹⁸¹ A. Kozyrev^{181,n} N. Krasnikov¹⁸¹
 E. Kuznetsova^{181,ssss} A. Lanev¹⁸¹ P. Levchenko¹⁸¹ A. Litomin,¹⁸¹ N. Lychkovskaya¹⁸¹ V. Makarenko¹⁸¹
 A. Malakhov¹⁸¹ V. Matveev^{181,n} V. Murzin¹⁸¹ A. Nikitenko^{181,tttt} S. Obraztsov¹⁸¹ A. Oskin,¹⁸¹ I. Ovtin^{181,n}
 V. Palichik¹⁸¹ P. Parygin¹⁸¹ V. Perelygin¹⁸¹ S. Petrushanko¹⁸¹ S. Polikarpov^{181,n} V. Popov,¹⁸¹ E. Popova¹⁸¹
 O. Radchenko^{181,n} M. Savina¹⁸¹ V. Savrin¹⁸¹ D. Selivanova¹⁸¹ V. Shalaev¹⁸¹ S. Shmatov¹⁸¹ S. Shulha¹⁸¹
 Y. Skovpen^{181,n} S. Slabospitskii¹⁸¹ V. Smirnov¹⁸¹ A. Snigirev¹⁸¹ D. Sosnov¹⁸¹ V. Sulimov¹⁸¹
 E. Tcherniaev¹⁸¹ A. Terkulov¹⁸¹ O. Teryaev¹⁸¹ I. Tlisova¹⁸¹ M. Toms¹⁸¹ A. Toropin¹⁸¹ L. Uvarov¹⁸¹
 A. Uzunian¹⁸¹ I. Vardanyan¹⁸¹ E. Vlasov¹⁸¹ A. Vorobyev,¹⁸¹ N. Voytishin¹⁸¹ B. S. Yuldashev,^{181,uuuu}
 A. Zarubin¹⁸¹ I. Zhizhin¹⁸¹ and A. Zhokin¹⁸¹

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

¹⁹*Institute of Modern Physics and Key Laboratory of Nuclear Physics and Ion-beam Application (MOE) - Fudan University, Shanghai, China*

²⁰*Zhejiang University, Hangzhou, Zhejiang, China*

²¹*Universidad de Los Andes, Bogota, Colombia*

²²*Universidad de Antioquia, Medellin, Colombia*

²³*University of Split, Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, Split, Croatia*

²⁴*University of Split, Faculty of Science, Split, Croatia*

²⁵*Institute Rudjer Boskovic, Zagreb, Croatia*

²⁶*University of Cyprus, Nicosia, Cyprus*

²⁷*Charles University, Prague, Czech Republic*

²⁸*Escuela Politécnica Nacional, Quito, Ecuador*

²⁹*Universidad San Francisco de Quito, Quito, Ecuador*

³⁰*Academy of Scientific Research and Technology of the Arab Republic of Egypt, Egyptian Network of High Energy Physics, Cairo, Egypt*

³¹*Center for High Energy Physics (CHEP-FU), Fayoum University, El-Fayoum, Egypt*

³²*National Institute of Chemical Physics and Biophysics, Tallinn, Estonia*

³³*Department of Physics, University of Helsinki, Helsinki, Finland*

³⁴*Helsinki Institute of Physics, Helsinki, Finland*

- ³⁵*Lappeenranta-Lahti University of Technology, Lappeenranta, Finland*
- ³⁶*IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France*
- ³⁷*Laboratoire Leprince-Ringuet, CNRS/IN2P3, Ecole Polytechnique, Institut Polytechnique de Paris, Palaiseau, France*
- ³⁸*Université de Strasbourg, CNRS, IPHC UMR 7178, Strasbourg, France*
- ³⁹*Institut de Physique des 2 Infinis de Lyon (IP2I), Villeurbanne, France*
- ⁴⁰*Georgian Technical University, Tbilisi, Georgia*
- ⁴¹*RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany*
- ⁴²*RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany*
- ⁴³*RWTH Aachen University, III. Physikalisches Institut B, Aachen, Germany*
- ⁴⁴*Deutsches Elektronen-Synchrotron, Hamburg, Germany*
- ⁴⁵*University of Hamburg, Hamburg, Germany*
- ⁴⁶*Karlsruher Institut fuer Technologie, Karlsruhe, Germany*
- ⁴⁷*Institute of Nuclear and Particle Physics (INPP), NCSR Demokritos, Aghia Paraskevi, Greece*
- ⁴⁸*National and Kapodistrian University of Athens, Athens, Greece*
- ⁴⁹*National Technical University of Athens, Athens, Greece*
- ⁵⁰*University of Ioánnina, Ioánnina, Greece*
- ⁵¹*MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary*
- ⁵²*Wigner Research Centre for Physics, Budapest, Hungary*
- ⁵³*Institute of Nuclear Research ATOMKI, Debrecen, Hungary*
- ⁵⁴*Institute of Physics, University of Debrecen, Debrecen, Hungary*
- ⁵⁵*Karoly Robert Campus, MATE Institute of Technology, Gyongyos, Hungary*
- ⁵⁶*Panjab University, Chandigarh, India*
- ⁵⁷*University of Delhi, Delhi, India*
- ⁵⁸*Saha Institute of Nuclear Physics, HBNI, Kolkata, India*
- ⁵⁹*Indian Institute of Technology Madras, Madras, India*
- ⁶⁰*Bhabha Atomic Research Centre, Mumbai, India*
- ⁶¹*Tata Institute of Fundamental Research-A, Mumbai, India*
- ⁶²*Tata Institute of Fundamental Research-B, Mumbai, India*
- ⁶³*National Institute of Science Education and Research, An OCC of Homi Bhabha National Institute, Bhubaneswar, Odisha, India*
- ⁶⁴*Indian Institute of Science Education and Research (IISER), Pune, India*
- ⁶⁵*Isfahan University of Technology, Isfahan, Iran*
- ⁶⁶*Institute for Research in Fundamental Sciences (IPM), Tehran, Iran*
- ⁶⁷*University College Dublin, Dublin, Ireland*
- ^{68a}*INFN Sezione di Bari, Bari, Italy*
- ^{68b}*Università di Bari, Bari, Italy*
- ^{68c}*Politecnico di Bari, Bari, Italy*
- ^{69a}*INFN Sezione di Bologna, Bologna, Italy*
- ^{69b}*Università di Bologna, Bologna, Italy*
- ^{70a}*INFN Sezione di Catania, Catania, Italy*
- ^{70b}*Università di Catania, Catania, Italy*
- ^{71a}*INFN Sezione di Firenze, Firenze, Italy*
- ^{71b}*Università di Firenze, Firenze, Italy*
- ⁷²*INFN Laboratori Nazionali di Frascati, Frascati, Italy*
- ^{73a}*INFN Sezione di Genova, Genova, Italy*
- ^{73b}*Università di Genova, Genova, Italy*
- ^{74a}*INFN Sezione di Milano-Bicocca, Milano, Italy*
- ^{74b}*Università di Milano-Bicocca, Milano, Italy*
- ^{75a}*INFN Sezione di Napoli, Napoli, Italy*
- ^{75b}*Università di Napoli 'Federico II', Napoli, Italy*
- ^{75c}*Università della Basilicata, Potenza, Italy*
- ^{75d}*Università G. Marconi, Roma, Italy*
- ^{76a}*INFN Sezione di Padova, Padova, Italy*
- ^{76b}*Università di Padova, Padova, Italy*
- ^{76c}*Università di Trento, Trento, Italy*
- ^{77a}*INFN Sezione di Pavia, Pavia, Italy*
- ^{77b}*Università di Pavia, Pavia, Italy*
- ^{78a}*INFN Sezione di Perugia, Perugia, Italy*
- ^{78b}*Università di Perugia, Perugia, Italy*
- ^{79a}*INFN Sezione di Pisa, Pisa, Italy*

- ^{79b}*Università di Pisa, Pisa, Italy*
- ^{79c}*Scuola Normale Superiore di Pisa, Pisa, Italy*
- ^{79d}*Università di Siena, Siena, Italy*
- ^{80a}*INFN Sezione di Roma, Roma, Italy*
- ^{80b}*Sapienza Università di Roma, Roma, Italy*
- ^{81a}*INFN Sezione di Torino, Torino, Italy*
- ^{81b}*Università di Torino, Torino, Italy*
- ^{81c}*Università del Piemonte Orientale, Novara, Italy*
- ^{82a}*INFN Sezione di Trieste, Trieste, Italy*
- ^{82b}*Università di Trieste, Trieste, Italy*
- ⁸³*Kyungpook National University, Daegu, Korea*
- ⁸⁴*Chonnam National University, Institute for Universe and Elementary Particles, Kwangju, Korea*
- ⁸⁵*Hanyang University, Seoul, Korea*
- ⁸⁶*Korea University, Seoul, Korea*
- ⁸⁷*Kyung Hee University, Department of Physics, Seoul, Korea*
- ⁸⁸*Sejong University, Seoul, Korea*
- ⁸⁹*Seoul National University, Seoul, Korea*
- ⁹⁰*University of Seoul, Seoul, Korea*
- ⁹¹*Yonsei University, Department of Physics, Seoul, Korea*
- ⁹²*Sungkyunkwan University, Suwon, Korea*
- ⁹³*College of Engineering and Technology, American University of the Middle East (AUM), Dasman, Kuwait*
- ⁹⁴*Riga Technical University, Riga, Latvia*
- ⁹⁵*Vilnius University, Vilnius, Lithuania*
- ⁹⁶*National Centre for Particle Physics, Universiti Malaya, Kuala Lumpur, Malaysia*
- ⁹⁷*Universidad de Sonora (UNISON), Hermosillo, Mexico*
- ⁹⁸*Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico*
- ⁹⁹*Universidad Iberoamericana, Mexico City, Mexico*
- ¹⁰⁰*Benemerita Universidad Autonoma de Puebla, Puebla, Mexico*
- ¹⁰¹*University of Montenegro, Podgorica, Montenegro*
- ¹⁰²*National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan*
- ¹⁰³*AGH University of Science and Technology Faculty of Computer Science, Electronics and Telecommunications, Krakow, Poland*
- ¹⁰⁴*National Centre for Nuclear Research, Swierk, Poland*
- ¹⁰⁵*Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland*
- ¹⁰⁶*Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal*
- ¹⁰⁷*VINCA Institute of Nuclear Sciences, University of Belgrade, Belgrade, Serbia*
- ¹⁰⁸*Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain*
- ¹⁰⁹*Universidad Autónoma de Madrid, Madrid, Spain*
- ¹¹⁰*Universidad de Oviedo, Instituto Universitario de Ciencias y Tecnologías Espaciales de Asturias (ICTEA), Oviedo, Spain*
- ¹¹¹*Instituto de Física de Cantabria (IFCA), CSIC-Universidad de Cantabria, Santander, Spain*
- ¹¹²*University of Colombo, Colombo, Sri Lanka*
- ¹¹³*University of Ruhuna, Department of Physics, Matara, Sri Lanka*
- ¹¹⁴*CERN, European Organization for Nuclear Research, Geneva, Switzerland*
- ¹¹⁵*Paul Scherrer Institut, Villigen, Switzerland*
- ¹¹⁶*ETH Zurich - Institute for Particle Physics and Astrophysics (IPA), Zurich, Switzerland*
- ¹¹⁷*Universität Zürich, Zurich, Switzerland*
- ¹¹⁸*National Central University, Chung-Li, Taiwan*
- ¹¹⁹*National Taiwan University (NTU), Taipei, Taiwan*
- ¹²⁰*Chulalongkorn University, Faculty of Science, Department of Physics, Bangkok, Thailand*
- ¹²¹*Çukurova University, Physics Department, Science and Art Faculty, Adana, Turkey*
- ¹²²*Middle East Technical University, Physics Department, Ankara, Turkey*
- ¹²³*Bogazici University, Istanbul, Turkey*
- ¹²⁴*Istanbul Technical University, Istanbul, Turkey*
- ¹²⁵*Istanbul University, Istanbul, Turkey*
- ¹²⁶*Institute for Scintillation Materials of National Academy of Science of Ukraine, Kharkiv, Ukraine*
- ¹²⁷*National Science Centre, Kharkiv Institute of Physics and Technology, Kharkiv, Ukraine*
- ¹²⁸*University of Bristol, Bristol, United Kingdom*
- ¹²⁹*Rutherford Appleton Laboratory, Didcot, United Kingdom*
- ¹³⁰*Imperial College, London, United Kingdom*
- ¹³¹*Brunel University, Uxbridge, United Kingdom*

- ¹³²*Baylor University, Waco, Texas, USA*
- ¹³³*Catholic University of America, Washington, DC, USA*
- ¹³⁴*The University of Alabama, Tuscaloosa, Alabama, USA*
- ¹³⁵*Boston University, Boston, Massachusetts, USA*
- ¹³⁶*Brown University, Providence, Rhode Island, USA*
- ¹³⁷*University of California, Davis, Davis, California, USA*
- ¹³⁸*University of California, Los Angeles, California, USA*
- ¹³⁹*University of California, Riverside, Riverside, California, USA*
- ¹⁴⁰*University of California, San Diego, La Jolla, California, USA*
- ¹⁴¹*University of California, Santa Barbara - Department of Physics, Santa Barbara, California, USA*
- ¹⁴²*California Institute of Technology, Pasadena, California, USA*
- ¹⁴³*Carnegie Mellon University, Pittsburgh, Pennsylvania, USA*
- ¹⁴⁴*University of Colorado Boulder, Boulder, Colorado, USA*
- ¹⁴⁵*Cornell University, Ithaca, New York, USA*
- ¹⁴⁶*Fermi National Accelerator Laboratory, Batavia, Illinois, USA*
- ¹⁴⁷*University of Florida, Gainesville, Florida, USA*
- ¹⁴⁸*Florida State University, Tallahassee, Florida, USA*
- ¹⁴⁹*Florida Institute of Technology, Melbourne, Florida, USA*
- ¹⁵⁰*University of Illinois at Chicago (UIC), Chicago, Illinois, USA*
- ¹⁵¹*The University of Iowa, Iowa City, Iowa, USA*
- ¹⁵²*Johns Hopkins University, Baltimore, Maryland, USA*
- ¹⁵³*The University of Kansas, Lawrence, Kansas, USA*
- ¹⁵⁴*Kansas State University, Manhattan, Kansas, USA*
- ¹⁵⁵*Lawrence Livermore National Laboratory, Livermore, California, USA*
- ¹⁵⁶*University of Maryland, College Park, Maryland, USA*
- ¹⁵⁷*Massachusetts Institute of Technology, Cambridge, Massachusetts, USA*
- ¹⁵⁸*University of Minnesota, Minneapolis, Minnesota, USA*
- ¹⁵⁹*University of Mississippi, Oxford, Mississippi, USA*
- ¹⁶⁰*University of Nebraska-Lincoln, Lincoln, Nebraska, USA*
- ¹⁶¹*State University of New York at Buffalo, Buffalo, New York, USA*
- ¹⁶²*Northeastern University, Boston, Massachusetts, USA*
- ¹⁶³*Northwestern University, Evanston, Illinois, USA*
- ¹⁶⁴*University of Notre Dame, Notre Dame, Indiana, USA*
- ¹⁶⁵*The Ohio State University, Columbus, Ohio, USA*
- ¹⁶⁶*Princeton University, Princeton, New Jersey, USA*
- ¹⁶⁷*University of Puerto Rico, Mayaguez, Puerto Rico, USA*
- ¹⁶⁸*Purdue University, West Lafayette, Indiana, USA*
- ¹⁶⁹*Purdue University Northwest, Hammond, Indiana, USA*
- ¹⁷⁰*Rice University, Houston, Texas, USA*
- ¹⁷¹*University of Rochester, Rochester, New York, USA*
- ¹⁷²*The Rockefeller University, New York, New York, USA*
- ¹⁷³*Rutgers, The State University of New Jersey, Piscataway, New Jersey, USA*
- ¹⁷⁴*University of Tennessee, Knoxville, Tennessee, USA*
- ¹⁷⁵*Texas A&M University, College Station, Texas, USA*
- ¹⁷⁶*Texas Tech University, Lubbock, Texas, USA*
- ¹⁷⁷*Vanderbilt University, Nashville, Tennessee, USA*
- ¹⁷⁸*University of Virginia, Charlottesville, Virginia, USA*
- ¹⁷⁹*Wayne State University, Detroit, Michigan, USA*
- ¹⁸⁰*University of Wisconsin - Madison, Madison, Wisconsin, USA*
- ¹⁸¹*An institute or international laboratory covered by a cooperation agreement with CERN*

^aDeceased.

^bAlso at Yerevan State University, Yerevan, Armenia.

^cAlso at TU Wien, Vienna, Austria.

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

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

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

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

^hAlso at UFMS, Nova Andradina, Brazil.

- ⁱ Also at The University of the State of Amazonas, Manaus, Brazil.
- ^j Also at University of Chinese Academy of Sciences, Beijing, China.
- ^k Also at Nanjing Normal University Department of Physics, Nanjing, China.
- ^l Also at The University of Iowa, Iowa City, Iowa, USA.
- ^m Also at University of Chinese Academy of Sciences, Beijing, China.
- ⁿ Also at Another institute or international laboratory covered by a cooperation agreement with CERN.
- ^o Also at Helwan University, Cairo, Egypt.
- ^p Also at Zewail City of Science and Technology, Zewail, Egypt.
- ^q Also at Ain Shams University, Cairo, Egypt.
- ^r Also at British University in Egypt, Cairo, Egypt.
- ^s Also at Purdue University, West Lafayette, Indiana, USA.
- ^t Also at Université de Haute Alsace, Mulhouse, France.
- ^u Also at Department of Physics, Tsinghua University, Beijing, China.
- ^v Also at Tbilisi State University, Tbilisi, Georgia.
- ^w Also at Erzincan Binali Yildirim University, Erzincan, Turkey.
- ^x Also at University of Hamburg, Hamburg, Germany.
- ^y Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany.
- ^z Also at Isfahan University of Technology, Isfahan, Iran.
- ^{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 Physics Department, Faculty of Science, Assiut University, Assiut, Egypt.
- ^{ff} Also at Karoly Robert Campus, MATE Institute of Technology, Gyongyos, Hungary.
- ^{gg} Also at Wigner Research Centre for Physics, Budapest, Hungary.
- ^{hh} Also at Institute of Physics, University of Debrecen, Debrecen, Hungary.
- ⁱⁱ Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary.
- ^{jj} Also at Universitatea Babes-Bolyai—Facultatea de Fizica, Cluj-Napoca, Romania.
- ^{kk} Also at Faculty of Informatics, University of Debrecen, Debrecen, Hungary.
- ^{ll} Also at Punjab Agricultural University, Ludhiana, India.
- ^{mm} Also at UPES—University of Petroleum and Energy Studies, Dehradun, India.
- ⁿⁿ Also at University of Visva-Bharati, Santiniketan, India.
- ^{oo} Also at University of Hyderabad, Hyderabad, India.
- ^{pp} Also at Indian Institute of Science (IISc), Bangalore, India.
- ^{qq} Also at Indian Institute of Technology (IIT), Mumbai, India.
- ^{rr} Also at IIT Bhubaneswar, Bhubaneswar, India.
- ^{ss} Also at Institute of Physics, Bhubaneswar, India.
- ^{tt} Also at Deutsches Elektronen-Synchrotron, Hamburg, Germany.
- ^{uu} Also at Sharif University of Technology, Tehran, Iran.
- ^{vv} Also at Department of Physics, University of Science and Technology of Mazandaran, Behshahr, Iran.
- ^{ww} Also at Italian National Agency for New Technologies, Energy and Sustainable Economic Development, Bologna, Italy.
- ^{xx} Also at Centro Siciliano di Fisica Nucleare e di Struttura Della Materia, Catania, Italy.
- ^{yy} Also at Scuola Superiore Meridionale, Università di Napoli 'Federico II', Napoli, Italy.
- ^{zz} Also at Fermi National Accelerator Laboratory, Batavia, Illinois, USA.
- ^{aaa} Also at Laboratori Nazionali di Legnaro dell'INFN, Legnaro, Italy.
- ^{bbb} Also at Università di Napoli 'Federico II', Napoli, Italy.
- ^{ccc} Also at Consiglio Nazionale delle Ricerche—Istituto Officina dei Materiali, Perugia, Italy.
- ^{ddd} Also at Department of Applied Physics, Faculty of Science and Technology, Universiti Kebangsaan Malaysia, Bangi, Malaysia.
- ^{eee} Also at Consejo Nacional de Ciencia y Tecnología, Mexico City, Mexico.
- ^{fff} Also at IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France.
- ^{ggg} Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia.
- ^{hhh} Also at Trincomalee Campus, Eastern University, Sri Lanka, Nilaveli, Sri Lanka.
- ⁱⁱⁱ Also at INFN Sezione di Pavia, Università di Pavia, Pavia, Italy.
- ^{jjj} Also at National and Kapodistrian University of Athens, Athens, Greece.
- ^{kkk} Also at Ecole Polytechnique Fédérale Lausanne, Lausanne, Switzerland.
- ^{lll} Also at Universität Zürich, Zurich, Switzerland.
- ^{mmm} Also at Stefan Meyer Institute for Subatomic Physics, Vienna, Austria.
- ⁿⁿⁿ Also at Laboratoire d'Annecy-le-Vieux de Physique des Particules, IN2P3-CNRS, Annecy-le-Vieux, France.
- ^{ooo} Also at Near East University, Research Center of Experimental Health Science, Mersin, Turkey.
- ^{ppp} Also at Konya Technical University, Konya, Turkey.

- ^{qqq} Also at Izmir Bakircay University, Izmir, Turkey.
- ^{rrr} Also at Adiyaman University, Adiyaman, Turkey.
- ^{sss} Also at Istanbul Gedik University, Istanbul, Turkey.
- ^{ttt} Also at Necmettin Erbakan University, Konya, Turkey.
- ^{uuu} Also at Bozok Universitetesi Rektörlüğü, Yozgat, Turkey.
- ^{vvv} Also at Marmara University, Istanbul, Turkey.
- ^{www} Also at Milli Savunma University, Istanbul, Turkey.
- ^{xxx} Also at Kafkas University, Kars, Turkey.
- ^{yyy} Also at Istanbul University—Cerrahpasa, Faculty of Engineering, Istanbul, Turkey.
- ^{zzz} Also at Yildiz Technical University, Istanbul, Turkey.
- ^{aaa} Also at Vrije Universiteit Brussel, Brussel, Belgium.
- ^{bbb} Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom.
- ^{ccc} Also at University of Bristol, Bristol, United Kingdom.
- ^{ddd} Also at IPPP Durham University, Durham, United Kingdom.
- ^{eee} Also at Monash University, Faculty of Science, Clayton, Australia.
- ^{fff} Also at Università di Torino, Torino, Italy.
- ^{ggg} Also at Bethel University, St. Paul, Minnesota, USA.
- ^{hhh} Also at Karamanoğlu Mehmetbey University, Karaman, Turkey.
- ⁱⁱⁱ Also at California Institute of Technology, Pasadena, California, USA.
- ^{jjj} Also at United States Naval Academy, Annapolis, Maryland, USA.
- ^{kkk} Also at Bingol University, Bingol, Turkey.
- ^{lll} Also at Georgian Technical University, Tbilisi, Georgia.
- ^{mmm} Also at Sinop University, Sinop, Turkey.
- ⁿⁿⁿ Also at Erciyes University, Kayseri, Turkey.
- ^{ooo} Also at Institute of Modern Physics and Key Laboratory of Nuclear Physics and Ion-beam Application (MOE)—Fudan University, Shanghai, China.
- ^{ppp} Also at Texas A&M University at Qatar, Doha, Qatar.
- ^{qqq} Also at Kyungpook National University, Daegu, Korea.
- ^{rrr} Also at Yerevan Physics Institute, Yerevan, Armenia.
- ^{sss} Also at University of Florida, Gainesville, Florida, USA.
- ^{ttt} Also at Imperial College, London, United Kingdom.
- ^{uuu} Also at Institute of Nuclear Physics of the Uzbekistan Academy of Sciences, Tashkent, Uzbekistan.