

Observation of the B_c^+ Meson in Pb-Pb and pp Collisions at $\sqrt{s_{NN}}=5.02$ TeV and Measurement of its Nuclear Modification Factor

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

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The B_c^+ meson is observed for the first time in heavy ion collisions. Data from the CMS detector are used to study the production of the B_c^+ meson in lead-lead (Pb-Pb) and proton-proton (pp) collisions at a center-of-mass energy per nucleon pair of $\sqrt{s_{NN}} = 5.02$ TeV, via the $B_c^+ \rightarrow (J/\psi \rightarrow \mu^+\mu^-)\mu^+\nu_\mu$ decay. The B_c^+ nuclear modification factor, derived from the Pb-Pb-to- pp ratio of production cross sections, is measured in two bins of the triuon transverse momentum and of the Pb-Pb collision centrality. The B_c^+ meson is shown to be less suppressed than quarkonia and most of the open heavy-flavor mesons, suggesting that effects of the hot and dense nuclear matter created in heavy ion collisions contribute to its production. This measurement sets forth a promising new probe of the interplay of suppression and enhancement mechanisms in the production of heavy-flavor mesons in the quark-gluon plasma.

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The very high temperatures and densities reached in high-energy heavy ion collisions allow quarks and gluons to form a deconfined state of matter, often referred to as the quark-gluon plasma (QGP). Among the various signatures of the QGP formation, the suppression of heavy quarkonia (e.g., J/ψ or Υ mesons) due to the screening of the heavy-quark potential has been intensely studied since its proposal by Matsui and Satz [1]. The strong J/ψ suppression observed in heavy ion collisions at the Super Proton Synchrotron [2] and Relativistic Heavy Ion Collider [3] was indeed qualitatively consistent with color screening effects. However, lead-lead (Pb-Pb) collisions at the Large Hadron Collider (LHC) reach higher temperatures, but show less J/ψ suppression [4]. This observation is interpreted as arising from the formation of bound states of charm quarks originating from different hard scatterings, a mechanism referred to as recombination [5,6]. By contrast, the bottomonium LHC data show no evidence for recombination, consistent with the relatively small b -quark production cross section. In addition, the suppression of $\Upsilon(nS)$ states is sequential (more suppression for smaller binding energies) [7], as expected from color screening.

While understanding the effects of the QGP on heavy-quark bound states is progressing [8], quantifying them still remains a key challenge. The B_c^+ meson is composed of a charm quark and a bottom antiquark, and is

intermediate in size and binding energy between the J/ψ and $\Upsilon(1S)$ mesons [9]. Since it bridges the gap between charmonia and bottomonia, the modification of B_c^+ yields contributes to probing heavy quark interactions at extreme temperatures.

The recombination of heavy quarks can also affect the B_c^+ yield. The production rates of J/ψ and B_c^+ mesons from this process should scale quadratically and linearly, respectively, with the large number of charm quarks in the QGP, up to hundreds in central Pb-Pb collisions. However, as the B_c^+ production cross section in proton-proton (pp) scatterings is small, owing to the dominant production mechanism requiring both $b\bar{b}$ and $c\bar{c}$ pairs, the enhancement of B_c^+ production in heavy ion collisions may greatly exceed that of the J/ψ meson [9,10]. These recombination effects would manifest more strongly at low transverse momentum (p_T) [9].

For $p_T \gg m(B_c^+)$, B_c^+ mesons are produced predominantly via heavy-quark fragmentation [11,12], and are therefore sensitive to the energy loss of a massive color triplet charge in the QGP—possibly causing the suppression observed for other B mesons [13,14], J/ψ mesons from B decays [15], and D mesons [16,17]. Conversely, the modification of prompt J/ψ meson production for $p_T \gg m(J/\psi)$ [15,18] probes the energy loss of a massive color octet state [19]. Therefore, comparing the B_c^+ yield with that of other heavy flavor mesons at large p_T can probe both the mass dependence of energy loss (from a possible dead-cone effect [20]) and its color charge dependence.

The B_c^+ meson was first observed in proton-antiproton collisions at the Tevatron in the $B_c^+ \rightarrow J/\psi \ell^+ \nu_\ell$ decay mode [21]. Its ground and excited states were then studied

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

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in pp collisions at the LHC [22–26]. In this Letter, the first observation of B_c^+ mesons produced in heavy ion collisions is reported, and their cross sections are measured and compared in Pb-Pb and pp collisions. The data were collected with the CMS detector in 2017 for pp and in 2018 for Pb-Pb collisions at the same center-of-mass energy per nucleon pair, $\sqrt{s_{NN}} = 5.02$ TeV, corresponding to integrated luminosities of 302 pb^{-1} and 1.61 nb^{-1} , respectively. The signal is reconstructed from the three muons in the $B_c^+ \rightarrow (J/\psi \rightarrow \mu^+\mu^-)\mu^+\nu_\mu$ decay mode. While this mode features a neutrino that prevents a full reconstruction of the decay, it has a much larger branching fraction than neutrinoless decay channels [24]. In this Letter, charge-conjugate states are implied, and the quoted cross sections correspond to the sum of B_c^+ and B_c^- mesons.

The results are presented in two kinematic regions that are defined in terms of the vector sum of the three muon momenta, and whose limits are chosen based on the single-muon acceptance of the CMS apparatus: a low- $p_T^{\mu\mu\mu}$ bin, $6 < p_T^{\mu\mu\mu} < 11$ GeV with rapidity $1.3 < |y^{\mu\mu\mu}| < 2.3$, and a high- $p_T^{\mu\mu\mu}$ bin, $11 < p_T^{\mu\mu\mu} < 35$ GeV with $|y^{\mu\mu\mu}| < 2.3$. In simulations, the trimuon p_T is, on average, about 15% smaller than the B_c^+ p_T . In Pb-Pb collisions, the analysis is performed in the 0%–90% centrality range, where centrality refers to the fraction of the inelastic nucleus-nucleus cross section, with lower values denoting a larger overlap of the nuclei [27]. The results integrated over the two kinematic regions are also presented, separated in the centrality ranges 0%–20% and 20%–90%. To reduce potential biases, the analysis was performed in a “blind” way: the algorithms and selection procedures were finalized and formally approved using a quarter of the Pb-Pb data, before examining the entire sample. Tabulated results are provided in a HEPData record [28].

The central feature of the CMS apparatus [29] is a superconducting solenoid providing a magnetic field of 3.8 T. Within the solenoid volume are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter, and a brass and scintillator hadron calorimeter, each composed of a barrel and two end cap sections. Hadron forward calorimeters extend the pseudorapidity coverage to $3 < |\eta| < 5$, and the sum of the transverse energy deposited in them is used to estimate the collision centrality. Muons are detected in gas-ionization detectors embedded in the steel flux-return yoke outside the solenoid and covering $|\eta| < 2.4$. Muons with $p_T > 1.2$ and 3.3 GeV are reconstructed in the end cap and barrel regions, respectively [30]. For $p_T = 1.2$ GeV muons in the end caps, the transverse and longitudinal impact parameter resolutions are 150 and 400 μm , respectively, which improve to 20 and 40 μm for $p_T = 10$ GeV muons in the barrel [31].

Events of interest are selected using a two-tiered trigger system [32]. The first level, composed of custom hardware processors, uses information from the calorimeters and muon detectors [33]. The high-level trigger consists of a

farm of processors running a fast version of the full event reconstruction software. The events used in this analysis were selected by triggers designed to collect all events containing a J/ψ meson, hence requiring two muons, without p_T requirements. Loose criteria on the single-muon quality and the dimuon mass and opening angle are also applied in the Pb-Pb high-level trigger, as in Refs. [34,35].

Monte Carlo (MC) simulations are used for various signal and background studies, and for estimating the acceptance and efficiency of the reconstruction, triggering, and selection. The B_c^+ mesons are generated with BCVEGPy2.2 [12], while their decays are handled with EVTGEN1.3 [36]. The underlying event is generated with PYTHIA8.212 [37], tune CP5 [38]. PYTHIA8 is also used to generate prompt and nonprompt (from B meson decays) J/ψ background samples. To simulate Pb-Pb collisions, the generated events are embedded into simulated Pb-Pb collisions created using HYDJET1.8 [39]. All samples are passed to GEANT4 [40] to simulate the detector response, and then reconstructed with the same software as the collision data.

The $B_c^+ \rightarrow (J/\psi \rightarrow \mu^+\mu^-)\mu^+\nu_\mu$ decay features three muons originating from the same displaced vertex, an opposite-sign muon pair consistent with the J/ψ mass, and a trimuon invariant mass $m_{\mu\mu\mu}$ between $m_{J/\psi} + m_\mu \simeq 3.2$ GeV and $m_{B_c^+} \simeq 6.3$ GeV. Three main background sources can mimic this topology. *Fake J/ψ* events arise when neither of the opposite-sign muon pairs originate from a J/ψ decay. It is estimated by summing the trimuon mass distributions obtained in the lower and higher dimuon mass sidebands of J/ψ candidates. The second category (*B decays*) comes from b hadrons (excluding B_c^+) decaying to a true J/ψ meson associated with a muon (usually a misidentified hadron) from the same b -hadron decay. It is estimated via simulation, where the p_T spectrum is corrected using nonprompt J/ψ production measurements [15]. Its normalization is unconstrained to cover a possible mismodeling of the muon misidentification rate. The third contribution (*$J/\psi + \text{random } X$*) combines a true J/ψ meson with a muon candidate (usually an uncorrelated misidentified hadron) from another decay. It is estimated in data by rotating the momentum and decay vertex of J/ψ candidates around the collision vertex before associating them with third muon candidates. Several azimuthal rotation angles (excluding the vicinity of the original J/ψ meson) are used, with or without inverting rapidity. In Pb-Pb collisions, the associated muons are mostly uncorrelated with the J/ψ meson, so the distributions from various rotation angles are identical (within statistical uncertainties) and averaged, with a data-derived normalization (fixed in the fit). In pp collisions, significant residual J/ψ - μ correlations lead to different distributions for different rotation angles, which is accounted for by considering various mixes of these distributions.

The off-line selection includes the same event-level and single-muon identification criteria as in Refs. [34,35].

Loose kinematic acceptance criteria are applied to the muon candidates, matching the efficient region for the two triggering muons, and even looser for the third one. At least one of the two opposite-sign dimuon combinations must have an invariant mass in the J/ψ peak region, or in the sidebands used for background estimation. The sideband and peak regions are both asymmetric to account for radiative tails, and are separated by small gaps. The total sideband width equals that of the peak region, from 180 to 260 MeV depending on the muon pseudorapidity (which affects the mass resolution). For the trimuons having two opposite-sign dimuons in the studied mass regions (5%–6% of the overall sample), the two corresponding trimuon candidates are kept, weighted by the probability of the chosen dimuon to be a true J/ψ meson. This probability is extracted from the dimuon mass distribution from events with only one J/ψ candidate in the signal or sideband regions.

Requirements are also set on the probability of the trimuon vertex fit, the significance of its displacement from the collision vertex, the angle between the trimuon momentum and the segment joining the collision and trimuon vertices, the invariant mass corrected for the momentum of the neutrino transverse to the B_c^+ momentum direction, and the sum of the angular separations $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$ between the three muon pairs.

After the selection, the simulated signal and the three background samples are used to train a boosted decision tree (BDT) using the TMVA package [41]. This combines and optimizes the discriminating power of eight variables: the five discussed in the previous paragraph, the imbalance between the p_T of the J/ψ and of the third muon, the ratio of the ΔR of the J/ψ muons to the sum of the ΔR values from the other two dimuon combinations, and the significance of the displacement from the collision vertex for the non- J/ψ muon.

Candidates with very low values of the resulting discriminant BDT variable (hence very high background probability) are rejected, losing only 0.1% in signal efficiency. For each analysis bin, low, medium, and high BDT intervals are set to contain about 25%, 40%, and 35%, respectively, of the expected signal. The first and last intervals are dominated by background and signal, respectively. A binned likelihood fit of the pp or Pb-Pb trimuon mass distributions provides the signal yields. Using ROOFIT [42], templates from the signal and the three backgrounds are simultaneously fitted in the three BDT intervals, and in either two kinematic bins, two centrality bins, or the whole kinematic range. The BDT distribution of the sum of the fitted templates is checked against that of data, and, in pp collisions, corrected before rerunning the template fit.

The results of the fits in the three BDT intervals and integrated over the two kinematic regions are shown for pp and Pb-Pb collisions in Fig. 1. In each BDT bin, the signal purity and the measured yield, $N(B_c)$, are given. The wrong-sign distributions, containing three same-sign

muons in data, are superimposed to illustrate that the purely combinatorial background is easily rejected. The normalizations of the fake J/ψ sample, and of the J/ψ + random X sample in Pb-Pb collisions, are provided by the data. In Pb-Pb collisions, the J/ψ + random X and fake J/ψ backgrounds are dominant. In pp collisions, the region above the B_c^+ mass strongly constrains the J/ψ + random X contribution, and the remaining background comes from B decays and fake J/ψ events.

The signal yields extracted from the fit are corrected for the acceptance and efficiency of the reconstruction, triggering, and selection. These are calculated in each analysis bin using the simulated signal trimuons. The simulated efficiencies of single muon reconstruction, identification, and triggering are corrected by a tag-and-probe method using the J/ψ resonance, similarly to Refs. [15,34]. The acceptance and efficiency are evaluated iteratively by first performing the $p_T^{\mu\mu\mu}$ -differential analysis using the original simulation. The resulting corrected yields are fitted to correct the $p_T^{\mu\mu\mu}$ spectrum of the simulation before a second run of the analysis. This $p_T^{\mu\mu\mu}$ spectrum is then corrected again based on the second-step results, notably improving upon the initial acceptance and efficiency estimation.

The corrected yields are divided by the pp integrated luminosity [43] or by its Pb-Pb equivalent, the number of minimum bias Pb-Pb hadronic collisions N_{MB} times the nuclear overlap function $T_{\text{Pb-Pb}}$ from Ref. [27]. The Pb-Pb-to- pp ratio of these pp -equivalent normalized yields then provides the nuclear modification factor, R_{AA} . In case of no modification by the medium, R_{AA} is expected to be equal to unity.

Uncertainties arise from different sources: *statistical*, *background* (shapes and normalizations), choice of the *fit method*, *muon efficiency*, B_c^+ *kinematics* (acceptance and efficiency), *contamination* from other B_c^+ decays, and overall *normalization*. The fit uncertainties, ranging from 5% to 9% in pp and 17% to 31% in Pb-Pb collisions, include the purely *statistical* and the *background* uncertainties. The latter are implemented via nuisance parameters allowing variations of the trimuon mass templates, such as controlling their statistical uncertainties with the Barlow-Beeston procedure [44], varying the fake J/ψ background between the lower and higher dimuon sideband, or varying the rotation angles in the J/ψ + random X background. Variations of the *fit method* are also considered, such as changing the $m_{\mu\mu\mu}$ or BDT bin size, neglecting the low-BDT bin, using a BDT variable whose $m_{\mu\mu\mu}$ dependence is subtracted, or regularizing the low-statistics templates instead of using the Barlow-Beeston procedure. The resulting uncertainty remains below 7% (12%) in pp (Pb-Pb) collisions. The uncertainty from the tag-and-probe derived *muon efficiency* corrections is 2%–5%.

Since the B_c^+ *kinematic* distributions are not precisely known, acceptance and efficiency corrections are recalculated 1500 times with $p_T^{\mu\mu\mu}$ spectra fitted on variations of the

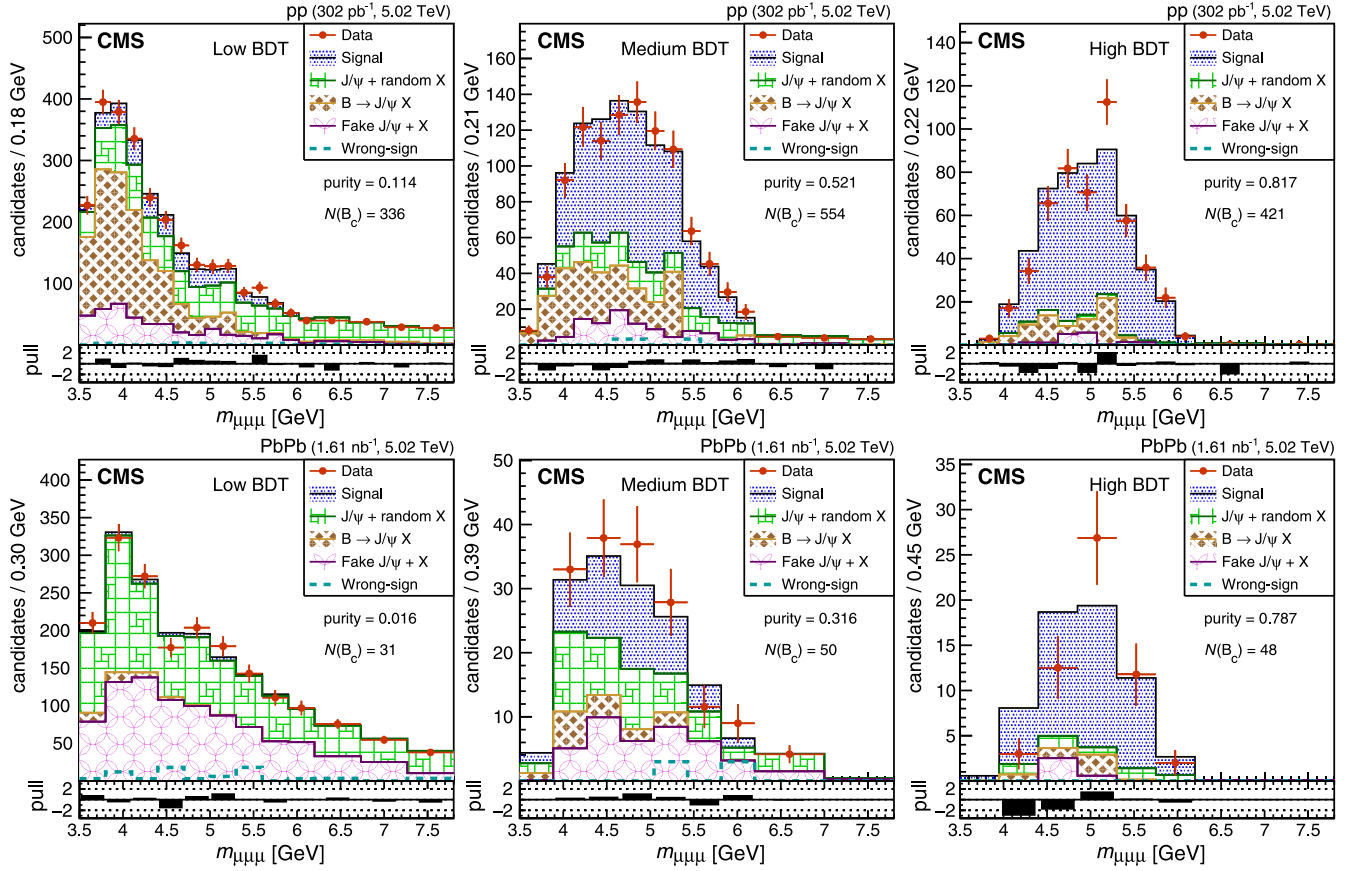


FIG. 1. Template fit of the trimuon mass distributions in the three BDT bins, for the pp (top row) and Pb-Pb (bottom row) data samples integrated over the two studied kinematic regions. The lower panels show the pull between the data and the fitted distributions.

measured $p_T^{\mu\mu\mu}$ -differential yields within the above-mentioned uncertainties. For the $p_T^{\mu\mu\mu}$ -integrated results, the root mean square (RMS) of the varied acceptance and efficiency corrections, of order 7% and 24% for pp and Pb-Pb collisions, respectively, is used as the systematic uncertainty related to the B_c^+ kinematics. For the $p_T^{\mu\mu\mu}$ dependence, these variations are correlated with the other uncertainty sources, so the combined uncertainty is assessed as the RMS of the varied corrected yields. The correlation between the variations of the spectrum and of the acceptance and efficiency is small or negative for the Pb-Pb high- $p_T^{\mu\mu\mu}$ bin and for both pp p_T bins, so that the uncertainties with or without this systematic effect are similar. This correlation is large and positive for the Pb-Pb low- $p_T^{\mu\mu\mu}$ bin, inducing an additional 12%–31% uncertainty. The uncertainty in the Pb-Pb-to- pp ratio is the RMS of the ratios of the relevant varied quantities.

The contamination from other B_c^+ decays, such as $B_c^+ \rightarrow J/\psi(\tau^+ \rightarrow \mu^+ X)\nu_\tau$ or $B_c^+ \rightarrow (c\bar{c} \rightarrow J/\psi X)\mu^+\nu_\mu$, where X denotes any decay product(s), is estimated to be below 4.5%, and to have largely canceling pp and Pb-Pb contributions. The overall normalization uncertainty arising from the luminosity and centrality determination is 1.9%–3.8%. The leading uncertainties

in the $p_T^{\mu\mu\mu}$ -differential and $p_T^{\mu\mu\mu}$ -integrated measurements are from the fit and the B_c^+ kinematics, respectively.

The significance of the B_c^+ signal in Pb-Pb collisions, calculated from the fit likelihood ratio and including the fit method uncertainty, is well above 5 standard deviations. The left panel of Fig. 2 shows the measured B_c^+ meson $p_T^{\mu\mu\mu}$ -differential cross sections in pp and (pp -equivalent) Pb-Pb collisions. The two bins of the trimuon p_T correspond to different rapidity ranges. The markers of the $p_T^{\mu\mu\mu}$ bins are placed according to the Lafferty-Wyatt prescription [45]. The bin-to-bin correlation factor ρ_{1-2} is also displayed. The filled and empty rectangles show the fit and total uncertainties, respectively. The ratio between the low- $p_T^{\mu\mu\mu}$ and high- $p_T^{\mu\mu\mu}$ regions is $18.2^{+1.3}_{-2.1}$ in pp data and 24.1 in the BCVEGPy2.2 simulation, suggesting that the latter overestimates the spectrum steepness.

The other panels of Fig. 2 show the B_c^+ nuclear modification factor, i.e., the ratio of the (pp -equivalent) Pb-Pb to pp cross sections, as a function of $p_T^{\mu\mu\mu}$ (middle) and of centrality (right). The markers of the $p_T^{\mu\mu\mu}$ bins are placed at the average of their values for pp and Pb-Pb collisions, while the centrality bin markers are placed at the minimum bias average number of participants N_{part} . The filled and empty rectangles, respectively, show

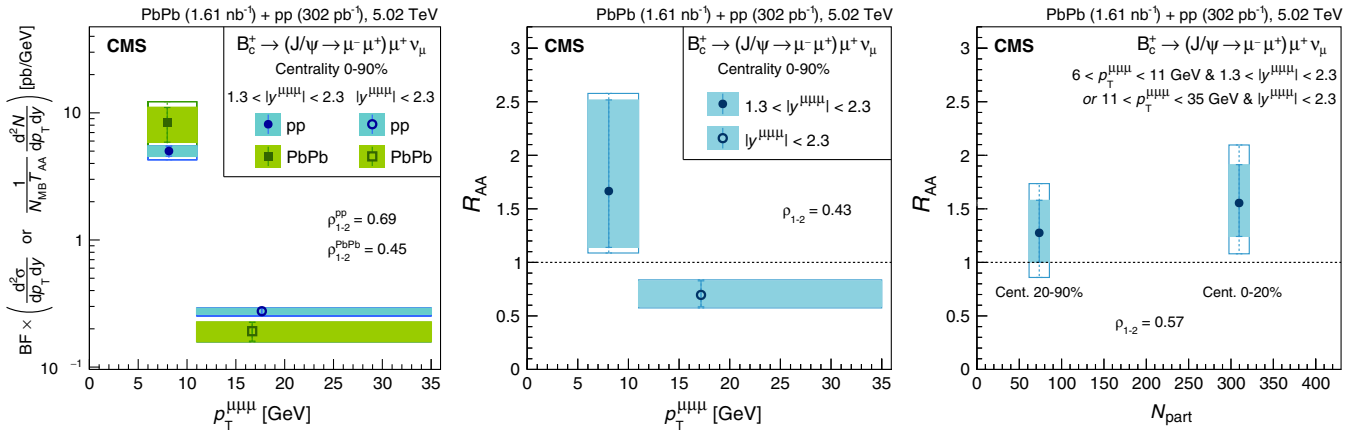


FIG. 2. B_c^+ meson production in pp and Pb-Pb collisions. Left: the pp -equivalent cross-section times branching fraction of the studied decay in pp and Pb-Pb collisions. Middle and right: the nuclear modification factor in $p_T^{\mu\mu}$ bins (middle), and in centrality bins integrated over the studied kinematic range (right). See the text for details.

the bin-to-bin-uncorrelated and total uncertainties, such that the uncertainty in the difference of the two bins is the quadratic sum of uncorrelated uncertainties.

In the high- $p_T^{\mu\mu}$ region, the B_c^+ shows a moderate suppression, while the low- $p_T^{\mu\mu}$ modification factor stands above unity and above the high- $p_T^{\mu\mu}$ region, respectively, by 1.2 and 1.8 standard deviations, consistent with an enhancement of the integrated production and a softening of the p_T spectrum in the QGP. No significant variation is observed as a function of centrality. As shown in the Supplemental Material [46], except for the B_s^0 meson [14], other heavy mesons in these p_T ranges typically show more suppression than our measurement [4,7,13,15–17], which may indicate that heavy-quark recombination is a significant B_c^+ production mechanism in the QGP. A study based on Ref. [47], ignoring the recombination of B_c^+ excited states and possibly underestimating initial correlations, predicts an $R_{AA}(B_c^+)$ about an order of magnitude smaller than our measurement.

In summary, the first observation of the B_c^+ meson in heavy ion collisions is presented, using the $B_c^+ \rightarrow (J/\psi \rightarrow \mu^+\mu^-)\mu^+\nu_\mu$ decay. The production cross sections in lead-lead and proton-proton collisions and the nuclear modification factor derived from their ratio are measured in two bins of the trimuon transverse momentum, and in two ranges of the heavy-ion centrality. This unique bottom-charm state can help disentangle the enhancement (possibly dominant in central events at low p_T) and suppression (dominant at high p_T) mechanisms at play in the evolution of heavy quarks through the quark-gluon plasma.

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S. M. Silva Do Amaral,¹⁰ A. Sznajder,¹⁰ M. Thiel,¹⁰ F. Torres Da Silva De Araujo,^{10,g} A. Vilela Pereira,¹⁰
 C. A. Bernardes,^{11,f} L. Calligaris,¹¹ T. R. Fernandez Perez Tomei,¹¹ E. M. Gregores,¹¹ D. S. Lemos,¹¹ P. G. Mercadante,¹¹
 S. F. Novaes,¹¹ Sandra S. Padula,¹¹ A. Aleksandrov,¹² G. Antchev,¹² R. Hadjiiska,¹² P. Iaydjiev,¹² M. Misheva,¹²
 M. Rodozov,¹² M. Shopova,¹² G. Sultanov,¹² A. Dimitrov,¹³ T. Ivanov,¹³ L. Litov,¹³ B. Pavlov,¹³ P. Petkov,¹³ A. Petrov,¹³
 T. Cheng,¹⁴ T. Javai,^{14,h} M. Mittal,¹⁴ L. Yuan,¹⁴ M. Ahmad,¹⁵ G. Bauer,¹⁵ C. Dozen,^{15,i} Z. Hu,¹⁵ J. Martins,^{15,j} Y. Wang,¹⁵
 K. Yi,^{15,k,l} E. Chapon,¹⁶ G. M. Chen,^{16,h} H. S. Chen,^{16,h} M. Chen,¹⁶ F. Iemmi,¹⁶ A. Kapoor,¹⁶ D. Leggat,¹⁶ H. Liao,¹⁶
 Z.-A. Liu,^{16,m} V. Milosevic,¹⁶ F. Monti,¹⁶ R. Sharma,¹⁶ J. Tao,¹⁶ J. Thomas-Wilsker,¹⁶ J. Wang,¹⁶ H. Zhang,¹⁶ J. Zhao,¹⁶
 A. Agapitos,¹⁷ Y. An,¹⁷ Y. Ban,¹⁷ C. Chen,¹⁷ A. Levin,¹⁷ Q. Li,¹⁷ X. Lyu,¹⁷ Y. Mao,¹⁷ S. J. Qian,¹⁷ D. Wang,¹⁷ Q. Wang,¹⁷
 J. Xiao,¹⁷ M. Lu,¹⁸ Z. You,¹⁸ X. Gao,^{19,d} H. Okawa,¹⁹ Z. Lin,²⁰ M. Xiao,²⁰ C. Avila,²¹ A. Cabrera,²¹ C. Florez,²¹ J. Fraga,²¹
 J. Mejia Guisao,²² F. Ramirez,²² J. D. Ruiz Alvarez,²² C. A. Salazar González,²² D. Giljanovic,²³ N. Godinovic,²³ D. Lelas,²³
 I. Puljak,²³ Z. Antunovic,²⁴ M. Kovac,²⁴ T. Sculac,²⁴ V. Brigljevic,²⁵ D. Ferencek,²⁵ D. Majumder,²⁵ M. Roguljic,²⁵
 A. Starodumov,^{25,n} T. Susa,²⁵ A. Attikis,²⁶ K. Christoforou,²⁶ E. Erodotou,²⁶ A. Ioannou,²⁶ G. Kole,²⁶ M. Kolosova,²⁶
 S. Konstantinou,²⁶ J. Mousa,²⁶ C. Nicolaou,²⁶ F. Ptochos,²⁶ P. A. Razis,²⁶ H. Rykaczewski,²⁶ H. Saka,²⁶ M. Finger,^{27,o}
 M. Finger Jr.,^{27,o} A. Kveton,²⁷ E. Ayala,²⁸ E. Carrera Jarrin,²⁹ S. Elgammal,^{30,p} A. Ellithi Kamel,^{30,q} M. A. Mahmoud,³¹
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 S. Bharthuar,³⁴ E. Brücken,³⁴ F. Garcia,³⁴ J. Havukainen,³⁴ M. S. Kim,³⁴ R. Kinnunen,³⁴ T. Lampén,³⁴ K. Lassila-Perini,³⁴
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 B. Lenzi,³⁶ E. Locci,³⁶ J. Malcles,³⁶ J. Rander,³⁶ A. Rosowsky,³⁶ M. Ö. Sahin,³⁶ A. Savoy-Navarro,^{36,r} M. Titov,³⁶
 G. B. Yu,³⁶ S. Ahuja,³⁷ F. Arleo,³⁷ F. Beaudette,³⁷ M. Bonanomi,³⁷ A. Buchot Perraguin,³⁷ P. Busson,³⁷ A. Cappati,³⁷
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 A. Tarabini,³⁷ A. Zabi,³⁷ A. Zghiche,³⁷ J.-L. Agram,^{38,s} J. Andrea,³⁸ D. Apparu,³⁸ D. Bloch,³⁸ G. Bourgatte,³⁸ J.-M. Brom,³⁸
 E. C. Chabert,³⁸ C. Collard,³⁸ D. Darej,³⁸ J.-C. Fontaine,^{38,s} U. Goerlach,³⁸ C. Grimault,³⁸ A.-C. Le Bihan,³⁸ E. Nibigira,³⁸
 P. Van Hove,³⁸ E. Asilar,³⁹ S. Beauceron,³⁹ C. Bernet,³⁹ G. Boudoul,³⁹ C. Camen,³⁹ A. Carle,³⁹ N. Chanon,³⁹ D. Contardo,³⁹
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 M. Vander Donckt,³⁹ S. Viret,³⁹ I. Lomidze,⁴⁰ T. Toriashvili,^{40,t} Z. Tsamalaidze,^{40,o} V. Botta,⁴¹ L. Feld,⁴¹ K. Klein,⁴¹
 M. Lipinski,⁴¹ D. Meuser,⁴¹ A. Pauls,⁴¹ N. Röwert,⁴¹ J. Schulz,⁴¹ M. Teroerde,⁴¹ A. Dodonova,⁴² D. Eliseev,⁴²
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 S. Wiedenbeck,⁴² S. Zaleski,⁴² C. Dziwok,⁴³ G. Flüge,⁴³ W. Haj Ahmad,^{43,u} O. Hlushchenko,⁴³ T. Kress,⁴³ A. Nowack,⁴³
 C. Pistone,⁴³ O. Pooth,⁴³ D. Roy,⁴³ H. Sert,⁴³ A. Stahl,^{43,v} T. Ziemons,⁴³ A. Zotz,⁴³ H. Aarup Petersen,⁴⁴ M. Aldaya Martin,⁴⁴
 P. Asmuss,⁴⁴ S. Baxter,⁴⁴ M. Bayatmakou,⁴⁴ O. Behnke,⁴⁴ A. Bermúdez Martínez,⁴⁴ S. Bhattacharya,⁴⁴ A. A. Bin Anuar,⁴⁴
 K. Borras,^{44,w} D. Brunner,⁴⁴ A. Campbell,⁴⁴ A. Cardini,⁴⁴ C. Cheng,⁴⁴ F. Colombina,⁴⁴ S. Consuegra Rodríguez,⁴⁴
 G. Correia Silva,⁴⁴ V. Danilov,⁴⁴ M. De Silva,⁴⁴ L. Didukh,⁴⁴ G. Eckerlin,⁴⁴ D. Eckstein,⁴⁴ L. I. Estevez Banos,⁴⁴
 O. Filatov,⁴⁴ E. Gallo,^{44,x} A. Geiser,⁴⁴ A. Giralddi,⁴⁴ A. Grohsjean,⁴⁴ M. Guthoff,⁴⁴ A. Jafari,^{44,y} N. Z. Jomhari,⁴⁴ H. Jung,⁴⁴
 A. Kasem,^{44,w} M. Kasemann,⁴⁴ H. Kaveh,⁴⁴ C. Kleinwort,⁴⁴ D. Krücker,⁴⁴ W. Lange,⁴⁴ J. Lidrych,⁴⁴ K. Lipka,⁴⁴
 W. Lohmann,^{44,z} R. Mankel,⁴⁴ I.-A. Melzer-Pellmann,⁴⁴ M. Mendizabal Morentin,⁴⁴ J. Metwally,⁴⁴ A. B. Meyer,⁴⁴
 M. Meyer,⁴⁴ J. Mnich,⁴⁴ A. Mussgiller,⁴⁴ Y. Otari,⁴⁴ D. Pérez Adán,⁴⁴ D. Pitzl,⁴⁴ A. Raspereza,⁴⁴ B. Ribeiro Lopes,⁴⁴
 J. Rübenach,⁴⁴ A. Saggio,⁴⁴ A. Saibel,⁴⁴ M. Savitskyi,⁴⁴ M. Scham,^{44,aa} V. Scheurer,⁴⁴ P. Schütze,⁴⁴ C. Schwanenberger,^{44,x}
 A. Singh,⁴⁴ R. E. Sosa Ricardo,⁴⁴ D. Stafford,⁴⁴ N. Tonon,⁴⁴ M. Van De Klundert,⁴⁴ R. Walsh,⁴⁴ D. Walter,⁴⁴ Y. Wen,⁴⁴
 K. Wichmann,⁴⁴ L. Wiens,⁴⁴ C. Wissing,⁴⁴ S. Wuchterl,⁴⁴ R. Aggleton,⁴⁵ S. Albrecht,⁴⁵ S. Bein,⁴⁵ L. Benato,⁴⁵ P. Connor,⁴⁵
 K. De Leo,⁴⁵ M. Eich,⁴⁵ F. Feindt,⁴⁵ A. Fröhlich,⁴⁵ C. Garbers,⁴⁵ E. Garutti,⁴⁵ P. Gunnellini,⁴⁵ M. Hajheidari,⁴⁵ J. Haller,⁴⁵
 A. Hinzmann,⁴⁵ G. Kasieczka,⁴⁵ R. Klanner,⁴⁵ R. Kogler,⁴⁵ T. Kramer,⁴⁵ V. Kutzner,⁴⁵ J. Lange,⁴⁵ T. Lange,⁴⁵ A. Lobanov,⁴⁵
 A. Malara,⁴⁵ A. Nigamova,⁴⁵ K. J. Pena Rodriguez,⁴⁵ O. Rieger,⁴⁵ P. Schleper,⁴⁵ M. Schröder,⁴⁵ J. Schwandt,⁴⁵

J. Sonneveld,⁴⁵ H. Stadie,⁴⁵ G. Steinbrück,⁴⁵ A. Tews,⁴⁵ I. Zoi,⁴⁵ J. Bechtel,⁴⁶ S. Brommer,⁴⁶ E. Butz,⁴⁶ R. Caspart,⁴⁶
 T. Chwalek,⁴⁶ W. De Boer,^{46,a} A. Dierlamm,⁴⁶ A. Droll,⁴⁶ K. El Morabit,⁴⁶ N. Faltermann,⁴⁶ M. Giffels,⁴⁶ J. o. Gosewisch,⁴⁶
 A. Gottmann,⁴⁶ F. Hartmann,^{46,v} C. Heidecker,⁴⁶ U. Husemann,⁴⁶ P. Keicher,⁴⁶ R. Koppenhöfer,⁴⁶ S. Maier,⁴⁶ M. Metzler,⁴⁶
 S. Mitra,⁴⁶ Th. Müller,⁴⁶ M. Neukum,⁴⁶ A. Nürnberg,⁴⁶ G. Quast,⁴⁶ K. Rabbertz,⁴⁶ J. Rauser,⁴⁶ D. Savoie,⁴⁶ M. Schnepf,⁴⁶
 D. Seith,⁴⁶ I. Shvetsov,⁴⁶ H. J. Simonis,⁴⁶ R. Ulrich,⁴⁶ J. Van Der Linden,⁴⁶ R. F. Von Cube,⁴⁶ M. Wassmer,⁴⁶ M. Weber,⁴⁶
 S. Wieland,⁴⁶ R. Wolf,⁴⁶ S. Wozniowski,⁴⁶ S. Wunsch,⁴⁶ G. Anagnostou,⁴⁷ G. Daskalakis,⁴⁷ T. Gerasis,⁴⁷ A. Kyriakis,⁴⁷
 D. Loukas,⁴⁷ A. Stakia,⁴⁷ M. Diamantopoulou,⁴⁸ D. Karasavvas,⁴⁸ G. Karathanasis,⁴⁸ P. Kontaxakis,⁴⁸ C. K. Koraka,⁴⁸
 A. Manousakis-Katsikakis,⁴⁸ A. Panagiotou,⁴⁸ I. Papavergou,⁴⁸ N. Saoulidou,⁴⁸ K. Theofilatos,⁴⁸ E. Tziaferi,⁴⁸ K. Vellidis,⁴⁸
 E. Vourliotis,⁴⁸ G. Bakas,⁴⁹ K. Kousouris,⁴⁹ I. Papakrivopoulos,⁴⁹ G. Tsipolitis,⁴⁹ A. Zacharopoulou,⁴⁹ K. Adamidis,⁵⁰
 I. Bestintzanos,⁵⁰ I. Evangelou,⁵⁰ C. Foudas,⁵⁰ P. Gianneios,⁵⁰ P. Katsoulis,⁵⁰ P. Kokkas,⁵⁰ N. Manthos,⁵⁰ I. Papadopoulos,⁵⁰
 J. Strologas,⁵⁰ M. Csanad,⁵¹ K. Farkas,⁵¹ M. M. A. Gadallah,^{51,bb} S. Lökös,^{51,cc} P. Major,⁵¹ K. Mandal,⁵¹ A. Mehta,⁵¹
 G. Pasztor,⁵¹ A. J. Rádl,⁵¹ O. Surányi,⁵¹ G. I. Veres,⁵¹ M. Bartók,^{52,dd} G. Bencze,⁵² C. Hajdu,⁵² D. Horvath,^{52,ee} F. Sikler,⁵²
 V. Veszpremi,⁵² S. Czellar,⁵³ J. Karancsi,^{53,dd} J. Molnar,⁵³ Z. Szillasi,⁵³ D. Teyssier,⁵³ P. Raics,⁵⁴ Z. L. Trocsanyi,^{54,ff}
 B. Ujvari,⁵⁴ T. Csorgo,^{55,gg} F. Nemes,^{55,gg} T. Novak,⁵⁵ J. R. Komaragiri,⁵⁶ D. Kumar,⁵⁶ L. Panwar,⁵⁶ P. C. Tiwari,⁵⁶
 S. Bahinipati,^{57,hh} C. Kar,⁵⁷ P. Mal,⁵⁷ T. Mishra,⁵⁷ V. K. Muraleedharan Nair Bindhu,^{57,ii} A. Nayak,^{57,ii} P. Saha,⁵⁷ N. Sur,⁵⁷
 S. K. Swain,⁵⁷ D. Vats,^{57,ii} S. Bansal,⁵⁸ S. B. Beri,⁵⁸ V. Bhatnagar,⁵⁸ G. Chaudhary,⁵⁸ S. Chauhan,⁵⁸ N. Dhingra,^{58,ji}
 R. Gupta,⁵⁸ A. Kaur,⁵⁸ M. Kaur,⁵⁸ S. Kaur,⁵⁸ P. Kumari,⁵⁸ M. Meena,⁵⁸ K. Sandeep,⁵⁸ J. B. Singh,⁵⁸ A. K. Virdi,⁵⁸
 A. Ahmed,⁵⁹ A. Bhardwaj,⁵⁹ B. C. Choudhary,⁵⁹ M. Gola,⁵⁹ S. Keshri,⁵⁹ A. Kumar,⁵⁹ M. Naimuddin,⁵⁹ P. Priyanka,⁵⁹
 K. Ranjan,⁵⁹ A. Shah,⁵⁹ M. Bharti,^{60,kk} R. Bhattacharya,⁶⁰ S. Bhattacharya,⁶⁰ D. Bhowmik,⁶⁰ S. Dutta,⁶⁰ S. Dutta,⁶⁰
 B. Gomber,^{60,ll} M. Maity,^{60,mm} P. Palit,⁶⁰ P. K. Rout,⁶⁰ G. Saha,⁶⁰ B. Sahu,⁶⁰ S. Sarkar,⁶⁰ M. Sharan,⁶⁰ B. Singh,^{60,kk}
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 A. K. Sikdar,⁶¹ D. Dutta,⁶² V. Jha,⁶² V. Kumar,⁶² D. K. Mishra,⁶² K. Naskar,^{62,nn} P. K. Netrakanti,⁶² L. M. Pant,⁶² P. Shukla,⁶²
 T. Aziz,⁶³ S. Dugad,⁶³ M. Kumar,⁶³ S. Banerjee,⁶⁴ R. Chudasama,⁶⁴ M. Guchait,⁶⁴ S. Karmakar,⁶⁴ S. Kumar,⁶⁴
 G. Majumder,⁶⁴ K. Mazumdar,⁶⁴ S. Mukherjee,⁶⁴ K. Alpana,⁶⁵ S. Dube,⁶⁵ B. Kansal,⁶⁵ A. Laha,⁶⁵ S. Pandey,⁶⁵ A. Rane,⁶⁵
 A. Rastogi,⁶⁵ S. Sharma,⁶⁵ H. Bakhshiansohi,^{66,oo} E. Khazaie,⁶⁶ M. Zeinali,^{66,pp} S. Chenarani,^{67,qq} S. M. Etesami,⁶⁷
 M. Khakzad,⁶⁷ M. Mohammadi Najafabadi,⁶⁷ M. Grunewald,⁶⁸ M. Abbrescia,^{69a,69b} R. Aly,^{69a,69b,rr} C. Aruta,^{69a,69b}
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 D. Seitova,¹¹⁰ V. ShalaeV,¹¹⁰ S. Shmatov,¹¹⁰ S. Shulha,¹¹⁰ V. Smirnov,¹¹⁰ O. Teryaev,¹¹⁰ N. Voytishin,¹¹⁰
 B. S. Yuldashev,^{110,bbb} A. Zarubin,¹¹⁰ I. Zhizhin,¹¹⁰ G. GavriloV,¹¹¹ V. Golovtcov,¹¹¹ Y. Ivanov,¹¹¹ V. Kim,^{111,ccc}
 E. Kuznetsova,^{111,ddd} V. Murzin,¹¹¹ V. Oreshkin,¹¹¹ I. Smirnov,¹¹¹ D. Sosnov,¹¹¹ V. Sulimov,¹¹¹ L. Uvarov,¹¹¹ S. Volkov,¹¹¹
 A. Vorobyev,¹¹¹ Yu. Andreev,¹¹² A. Dermenev,¹¹² S. Gninenko,¹¹² N. Golubev,¹¹² A. Karneyeu,¹¹² D. Kirpichnikov,¹¹²
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 N. Lychkovskaya,¹¹³ A. Nikitenko,^{113,eee} V. Popov,¹¹³ A. Stepenov,¹¹³ M. Toms,¹¹³ E. Vlasov,¹¹³ A. Zhokin,¹¹³
 T. Aushev,¹¹⁴ O. Bychkova,¹¹⁵ M. Chadeeva,^{115,fff} A. Oskin,¹¹⁵ P. Parygin,¹¹⁵ S. Polikarpov,^{115,fff} E. Popova,¹¹⁵
 V. Andreev,¹¹⁶ M. Azarkin,¹¹⁶ I. Dremin,¹¹⁶ M. Kirakosyan,¹¹⁶ A. Terkulov,¹¹⁶ A. Belyaev,¹¹⁷ E. Boos,¹¹⁷ A. Ershov,¹¹⁷
 A. Gribushin,¹¹⁷ A. Kaminskiy,^{117,ggg} O. Kodolova,¹¹⁷ V. Korotkikh,¹¹⁷ I. Lokhtin,¹¹⁷ S. Obraztsov,¹¹⁷ S. Petrushanko,¹¹⁷
 V. Savrin,¹¹⁷ A. Snigirev,¹¹⁷ I. Vardanyan,¹¹⁷ V. Blinov,^{118,hhh} T. Dimova,^{118,hhh} L. Kardapoltsev,^{118,hhh} A. Kozyrev,^{118,hhh}
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- M. Dordevic,¹²² P. Milenovic,¹²² J. Milosevic,¹²² M. Aguilar-Benitez,¹²³ J. Alcaraz Maestre,¹²³ A. Álvarez Fernández,¹²³
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C. Cooke,¹⁴⁴ K. V. Ellis,¹⁴⁴ K. Harder,¹⁴⁴ S. Harper,¹⁴⁴ M.-L. Holmberg,^{144, hhh} J. Linacre,¹⁴⁴ K. Manolopoulos,¹⁴⁴
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 A. Tapper,¹⁴⁵ K. Uchida,¹⁴⁵ T. Virdee,^{145, v} M. Vojinovic,¹⁴⁵ N. Wardle,¹⁴⁵ S. N. Webb,¹⁴⁵ D. Winterbottom,¹⁴⁵
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 T. KWON,¹⁵¹ G. Landsberg,¹⁵¹ K. T. Lau,¹⁵¹ D. Li,¹⁵¹ M. Lukasik,¹⁵¹ J. Luo,¹⁵¹ M. Narain,¹⁵¹ N. Pervan,¹⁵¹ S. Sagir,^{151, mmmm}
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 A. Apyan,¹⁶¹ S. Banerjee,¹⁶¹ L. A. T. Bauerdick,¹⁶¹ D. Berry,¹⁶¹ J. Berryhill,¹⁶¹ P. C. Bhat,¹⁶¹ K. Burkett,¹⁶¹ J. N. Butler,¹⁶¹
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 B. Klima,¹⁶¹ K. H. M. Kwok,¹⁶¹ S. Lammel,¹⁶¹ D. Lincoln,¹⁶¹ R. Lipton,¹⁶¹ T. Liu,¹⁶¹ C. Madrid,¹⁶¹ K. Maeshima,¹⁶¹
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 V. Papadimitriou,¹⁶¹ K. Pedro,¹⁶¹ C. Pena,^{161, nnnn} O. Prokofyev,¹⁶¹ F. Ravera,¹⁶¹ A. Reinsvold Hall,¹⁶¹ L. Ristori,¹⁶¹
 E. Sexton-Kennedy,¹⁶¹ N. Smith,¹⁶¹ A. Soha,¹⁶¹ W. J. Spalding,¹⁶¹ L. Spiegel,¹⁶¹ S. Stoynev,¹⁶¹ J. Strait,¹⁶¹ L. Taylor,¹⁶¹
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 M. M. Baarmand,¹⁶⁴ S. Butalla,¹⁶⁴ T. Elkafray,^{164, oooo} M. Hohlmann,¹⁶⁴ R. Kumar Verma,¹⁶⁴ D. Noonan,¹⁶⁴
 M. Rahmani,¹⁶⁴ F. Yumiceva,¹⁶⁴ M. R. Adams,¹⁶⁵ H. Becerril Gonzalez,¹⁶⁵ R. Cavanaugh,¹⁶⁵ X. Chen,¹⁶⁵ S. Dittmer,¹⁶⁵

O. Evdokimov,¹⁶⁵ C. E. Gerber,¹⁶⁵ D. A. Hangal,¹⁶⁵ D. J. Hofman,¹⁶⁵ A. H. Merrit,¹⁶⁵ C. Mills,¹⁶⁵ G. Oh,¹⁶⁵ T. Roy,¹⁶⁵
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 A. Abreu,¹⁶⁸ J. Anguiano,¹⁶⁸ C. Baldenegro Barrera,¹⁶⁸ P. Baringer,¹⁶⁸ A. Bean,¹⁶⁸ A. Bylinkin,¹⁶⁸ Z. Flowers,¹⁶⁸
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 M. Musich,¹⁷⁴ I. Reed,¹⁷⁴ J. E. Siado,¹⁷⁴ G. R. Snow,^{174,a} W. Tabb,¹⁷⁴ F. Yan,¹⁷⁴ A. G. Zecchinelli,¹⁷⁴ G. Agarwal,¹⁷⁵
 H. Bandyopadhyay,¹⁷⁵ L. Hay,¹⁷⁵ I. Iashvili,¹⁷⁵ A. Kharchilava,¹⁷⁵ C. McLean,¹⁷⁵ D. Nguyen,¹⁷⁵ J. Pekkanen,¹⁷⁵
 S. Rappoccio,¹⁷⁵ A. Williams,¹⁷⁵ G. Alverson,¹⁷⁶ E. Barberis,¹⁷⁶ Y. Haddad,¹⁷⁶ A. Hortiangtham,¹⁷⁶ J. Li,¹⁷⁶ G. Madigan,¹⁷⁶
 B. Marzocchi,¹⁷⁶ D. M. Morse,¹⁷⁶ V. Nguyen,¹⁷⁶ T. Orimoto,¹⁷⁶ A. Parker,¹⁷⁶ L. Skinnari,¹⁷⁶ A. Tishelman-Charny,¹⁷⁶
 T. Wamorkar,¹⁷⁶ B. Wang,¹⁷⁶ A. Wisecarver,¹⁷⁶ D. Wood,¹⁷⁶ S. Bhattacharya,¹⁷⁷ J. Bueghly,¹⁷⁷ Z. Chen,¹⁷⁷ A. Gilbert,¹⁷⁷
 T. Gunter,¹⁷⁷ K. A. Hahn,¹⁷⁷ Y. Liu,¹⁷⁷ N. Odell,¹⁷⁷ M. H. Schmitt,¹⁷⁷ M. Velasco,¹⁷⁷ R. Band,¹⁷⁸ R. Bucci,¹⁷⁸ A. Das,¹⁷⁸
 N. Dev,¹⁷⁸ R. Goldouzian,¹⁷⁸ M. Hildreth,¹⁷⁸ K. Hurtado Anampa,¹⁷⁸ C. Jessop,¹⁷⁸ K. Lannon,¹⁷⁸ J. Lawrence,¹⁷⁸
 N. Loukas,¹⁷⁸ D. Lutton,¹⁷⁸ N. Marinelli,¹⁷⁸ I. Mcalister,¹⁷⁸ T. McCauley,¹⁷⁸ C. Mcgrady,¹⁷⁸ K. Mohrman,¹⁷⁸
 Y. Musienko,^{178,zz} R. Ruchti,¹⁷⁸ P. Siddireddy,¹⁷⁸ A. Townsend,¹⁷⁸ M. Wayne,¹⁷⁸ A. Wightman,¹⁷⁸ M. Zarucki,¹⁷⁸
 L. Zygala,¹⁷⁸ B. Bylsma,¹⁷⁹ B. Cardwell,¹⁷⁹ L. S. Durkin,¹⁷⁹ B. Francis,¹⁷⁹ C. Hill,¹⁷⁹ M. Nunez Ornelas,¹⁷⁹ K. Wei,¹⁷⁹
 B. L. Winer,¹⁷⁹ B. R. Yates,¹⁷⁹ F. M. Addesa,¹⁸⁰ B. Bonham,¹⁸⁰ P. Das,¹⁸⁰ G. Dezoort,¹⁸⁰ P. Elmer,¹⁸⁰ A. Frankenthal,¹⁸⁰
 B. Greenberg,¹⁸⁰ N. Haubrich,¹⁸⁰ S. Higginbotham,¹⁸⁰ A. Kalogeropoulos,¹⁸⁰ G. Kopp,¹⁸⁰ S. Kwan,¹⁸⁰ D. Lange,¹⁸⁰
 D. Marlow,¹⁸⁰ K. Mei,¹⁸⁰ I. Ojalvo,¹⁸⁰ J. Olsen,¹⁸⁰ D. Stickland,¹⁸⁰ C. Tully,¹⁸⁰ S. Malik,¹⁸¹ S. Norberg,¹⁸¹ A. S. Bakshi,¹⁸²
 V. E. Barnes,¹⁸² R. Chawla,¹⁸² S. Das,¹⁸² L. Gutay,¹⁸² M. Jones,¹⁸² A. W. Jung,¹⁸² S. Karmarkar,¹⁸² D. Kondratyev,¹⁸²
 M. Liu,¹⁸² G. Negro,¹⁸² N. Neumeister,¹⁸² G. Paspalaki,¹⁸² C. C. Peng,¹⁸² S. Piperov,¹⁸² A. Purohit,¹⁸² J. F. Schulte,¹⁸²
 M. Stojanovic,^{182,r} J. Thieman,¹⁸² F. Wang,¹⁸² R. Xiao,¹⁸² W. Xie,¹⁸² J. Dolen,¹⁸³ N. Parashar,¹⁸³ A. Baty,¹⁸⁴ M. Decaro,¹⁸⁴
 S. Dildick,¹⁸⁴ K. M. Ecklund,¹⁸⁴ S. Freed,¹⁸⁴ P. Gardner,¹⁸⁴ F. J. M. Geurts,¹⁸⁴ A. Kumar,¹⁸⁴ W. Li,¹⁸⁴ B. P. Padley,¹⁸⁴
 R. Redjimi,¹⁸⁴ W. Shi,¹⁸⁴ A. G. Stahl Leiton,¹⁸⁴ S. Yang,¹⁸⁴ L. Zhang,¹⁸⁴ Y. Zhang,¹⁸⁴ A. Bodek,¹⁸⁵ P. de Barbaro,¹⁸⁵
 R. Demina,¹⁸⁵ J. L. Dulemba,¹⁸⁵ C. Fallon,¹⁸⁵ T. Ferbel,¹⁸⁵ M. Galanti,¹⁸⁵ A. Garcia-Bellido,¹⁸⁵ O. Hindrichs,¹⁸⁵
 A. Khukhunaishvili,¹⁸⁵ E. Ranken,¹⁸⁵ R. Taus,¹⁸⁵ B. Chiarito,¹⁸⁶ J. P. Chou,¹⁸⁶ A. Gandrakota,¹⁸⁶ Y. Gershtein,¹⁸⁶
 E. Halkiadakis,¹⁸⁶ A. Hart,¹⁸⁶ M. Heindl,¹⁸⁶ O. Karacheban,^{186,z} I. Laflotte,¹⁸⁶ A. Lath,¹⁸⁶ R. Montalvo,¹⁸⁶ K. Nash,¹⁸⁶
 M. Osherson,¹⁸⁶ S. Salur,¹⁸⁶ S. Schnetzer,¹⁸⁶ S. Somalwar,¹⁸⁶ R. Stone,¹⁸⁶ S. A. Thayil,¹⁸⁶ S. Thomas,¹⁸⁶ H. Wang,¹⁸⁶
 H. Acharya,¹⁸⁷ A. G. Delannoy,¹⁸⁷ S. Fiorendi,¹⁸⁷ S. Spanier,¹⁸⁷ O. Bouhali,^{188,ttt} M. Dalchenko,¹⁸⁸ A. Delgado,¹⁸⁸
 R. Eusebi,¹⁸⁸ J. Gilmore,¹⁸⁸ T. Huang,¹⁸⁸ T. Kamon,^{188,uuuu} H. Kim,¹⁸⁸ S. Luo,¹⁸⁸ S. Malhotra,¹⁸⁸ R. Mueller,¹⁸⁸
 D. Overton,¹⁸⁸ D. Rathjens,¹⁸⁸ A. Safonov,¹⁸⁸ N. Akchurin,¹⁸⁹ J. Damgov,¹⁸⁹ V. Hegde,¹⁸⁹ S. Kunori,¹⁸⁹ K. Lamichhane,¹⁸⁹
 S. W. Lee,¹⁸⁹ T. Mengke,¹⁸⁹ S. Muthumuni,¹⁸⁹ T. Peltola,¹⁸⁹ I. Volobouev,¹⁸⁹ Z. Wang,¹⁸⁹ A. Whitbeck,¹⁸⁹ E. Appelt,¹⁹⁰
 S. Greene,¹⁹⁰ A. Gurrola,¹⁹⁰ W. Johns,¹⁹⁰ A. Melo,¹⁹⁰ H. Ni,¹⁹⁰ K. Padeken,¹⁹⁰ F. Romeo,¹⁹⁰ P. Sheldon,¹⁹⁰ S. Tuo,¹⁹⁰
 J. Velkovska,¹⁹⁰ M. W. Arenton,¹⁹¹ B. Cox,¹⁹¹ G. Cummings,¹⁹¹ J. Hakala,¹⁹¹ R. Hirosky,¹⁹¹ M. Joyce,¹⁹¹ A. Ledovskoy,¹⁹¹
 A. Li,¹⁹¹ C. Neu,¹⁹¹ C. E. Perez Lara,¹⁹¹ B. Tannenwald,¹⁹¹ S. White,¹⁹¹ E. Wolfe,¹⁹¹ N. Poudyal,¹⁹² K. Black,¹⁹³ T. Bose,¹⁹³
 C. Caillol,¹⁹³ S. Dasu,¹⁹³ I. De Bruyn,¹⁹³ P. Everaerts,¹⁹³ F. Fienga,¹⁹³ C. Galloni,¹⁹³ H. He,¹⁹³ M. Herndon,¹⁹³ A. Hervé,¹⁹³
 U. Hussain,¹⁹³ A. Lanaro,¹⁹³ A. Loeliger,¹⁹³ R. Loveless,¹⁹³ J. Madhusudan Sreekala,¹⁹³ A. Mallampalli,¹⁹³

A. Mohammadi,¹⁹³ D. Pinna,¹⁹³ A. Savin,¹⁹³ V. Shang,¹⁹³ V. Sharma,¹⁹³ W. H. Smith,¹⁹³ D. Teague,¹⁹³
S. Trembath-Reichert,¹⁹³ and W. Vetens¹⁹³

(CMS Collaboration)

- ¹*Yerevan Physics Institute, Yerevan, Armenia*
- ²*Institut für Hochenergiephysik, Vienna, Austria*
- ³*Institute for Nuclear Problems, Minsk, Belarus*
- ⁴*Universiteit Antwerpen, Antwerpen, Belgium*
- ⁵*Vrije Universiteit Brussel, Brussel, Belgium*
- ⁶*Université Libre de Bruxelles, Bruxelles, Belgium*
- ⁷*Ghent University, Ghent, Belgium*
- ⁸*Université Catholique de Louvain, Louvain-la-Neuve, Belgium*
- ⁹*Centro Brasileiro de Pesquisas Físicas, Rio de Janeiro, Brazil*
- ¹⁰*Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil*
- ¹¹*Universidade Estadual Paulista, Universidade Federal do ABC, São Paulo, Brazil*
- ¹²*Institute for Nuclear Research and Nuclear Energy, Bulgarian Academy of Sciences, Sofia, Bulgaria*
- ¹³*University of Sofia, Sofia, Bulgaria*
- ¹⁴*Beihang University, Beijing, China*
- ¹⁵*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, China, 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 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*

- ⁵²Wigner Research Centre for Physics, Budapest, Hungary
- ⁵³Institute of Nuclear Research ATOMKI, Debrecen, Hungary
- ⁵⁴Institute of Physics, University of Debrecen, Debrecen, Hungary
- ⁵⁵Karoly Robert Campus, MATE Institute of Technology, Gyongyos, Hungary
- ⁵⁶Indian Institute of Science (IISc), Bangalore, India
- ⁵⁷National Institute of Science Education and Research, HBNI, Bhubaneswar, India
- ⁵⁸Panjab University, Chandigarh, India
- ⁵⁹University of Delhi, Delhi, India
- ⁶⁰Saha Institute of Nuclear Physics, HBNI, Kolkata, India
- ⁶¹Indian Institute of Technology Madras, Madras, India
- ⁶²Bhabha Atomic Research Centre, Mumbai, India
- ⁶³Tata Institute of Fundamental Research-A, Mumbai, India
- ⁶⁴Tata Institute of Fundamental Research-B, Mumbai, India
- ⁶⁵Indian Institute of Science Education and Research (IISER), Pune, India
- ⁶⁶Isfahan University of Technology, Isfahan, Iran
- ⁶⁷Institute for Research in Fundamental Sciences (IPM), Tehran, Iran
- ⁶⁸University College Dublin, Dublin, Ireland
- ^{69a}INFN Sezione di Bari, Bari, Italy
- ^{69b}Università di Bari, Bari, Italy
- ^{69c}Politecnico di Bari, Bari, Italy
- ⁷⁰INFN Sezione di Bologna, Università di Bologna, Bologna, Italy
- ^{70a}INFN Sezione di Bologna, Bologna, Italy
- ^{70b}Università di Bologna, Bologna, Italy
- ⁷¹INFN Sezione di Catania, Università di Catania, Catania, Italy
- ^{71a}INFN Sezione di Catania, Catania, Italy
- ^{71b}Università di Catania, Catania, Italy
- ⁷²INFN Sezione di Firenze, Università di Firenze, Firenze, Italy
- ^{72a}INFN Sezione di Firenze, Firenze, Italy
- ^{72b}Università di Firenze, Firenze, Italy
- ⁷³INFN Laboratori Nazionali di Frascati, Frascati, Italy
- ⁷⁴INFN Sezione di Genova, Università di Genova, Genova, Italy
- ^{74a}INFN Sezione di Genova, Genova, Italy
- ^{74b}Università di Genova, Genova, Italy
- ⁷⁵INFN Sezione di Milano-Bicocca, Università di Milano-Bicocca, Milano, Italy
- ^{75a}INFN Sezione di Milano-Bicocca, Milano, Italy
- ^{75b}Università di Milano-Bicocca, Milano, Italy
- ⁷⁶INFN Sezione di Napoli, Università di Napoli 'Federico II', Napoli, Italy,
Università della Basilicata, Potenza, Italy,
Università G. Marconi, Roma, Italy, Napoli, Italy
- ^{76a}INFN Sezione di Napoli, Napoli, Italy
- ^{76b}Università di Napoli 'Federico II', Napoli, Italy
- ^{76c}Università della Basilicata, Potenza, Italy
- ^{76d}Università G. Marconi, Roma, Italy
- ^{77a}INFN Sezione di Padova, Padova, Italy
- ^{77b}Università di Padova, Padova, Italy
- ^{77c}Università di Trento, Trento, Italy
- ^{78a}INFN Sezione di Pavia, Pavia, Italy
- ^{78b}Università di Pavia, Pavia, Italy
- ⁷⁹INFN Sezione di Perugia, Università di Perugia, Perugia, Italy
- ^{79a}INFN Sezione di Perugia, Perugia, Italy
- ^{79b}Università di Perugia, Perugia, Italy
- ⁸⁰INFN Sezione di Pisa, Università di Pisa, Scuola Normale Superiore di Pisa, Pisa Italy,
Università di Siena, Siena, Italy, Pisa, Italy
- ^{80a}INFN Sezione di Pisa, Pisa, Italy
- ^{80b}Università di Pisa, Pisa, Italy
- ^{80c}Scuola Normale Superiore di Pisa, Pisa, Italy
- ^{80d}Università di Siena, Siena, Italy
- ⁸¹INFN Sezione di Roma, Sapienza Università di Roma, Rome, Italy, Rome, Italy
- ^{81a}INFN Sezione di Roma, Rome, Italy
- ^{81b}Sapienza Università di Roma, Rome, Italy

- ⁸²*INFN Sezione di Torino, Università di Torino, Torino, Italy, Università del Piemonte Orientale, Novara, Italy, Torino, Italy*
- ^{82a}*INFN Sezione di Torino, Torino, Italy*
- ^{82b}*Università di Torino, Torino, Italy*
- ^{82c}*Università del Piemonte Orientale, Novara, Italy*
- ⁸³*INFN Sezione di Trieste, Università di Trieste, Trieste, Italy*
- ^{83a}*INFN Sezione di Trieste, Trieste, Italy*
- ^{83b}*Università di Trieste, Trieste, Italy*
- ⁸⁴*Kyungpook National University, Daegu, Korea*
- ⁸⁵*Chonnam National University, Institute for Universe and Elementary Particles, Kwangju, Korea*
- ⁸⁶*Hanyang University, Seoul, Korea*
- ⁸⁷*Korea University, Seoul, Korea*
- ⁸⁸*Kyung Hee University, Department of Physics, Seoul, Republic of Korea, Seoul, Korea*
- ⁸⁹*Sejong University, Seoul, Korea*
- ⁹⁰*Seoul National University, Seoul, Korea*
- ⁹¹*University of Seoul, Seoul, Korea*
- ⁹²*Yonsei University, Department of Physics, Seoul, Korea*
- ⁹³*Sungkyunkwan University, Suwon, Korea*
- ⁹⁴*College of Engineering and Technology, American University of the Middle East (AUM), Egaila, Kuwait, Dasman, Kuwait*
- ⁹⁵*Riga Technical University, Riga, Latvia*
- ⁹⁶*Vilnius University, Vilnius, Lithuania*
- ⁹⁷*National Centre for Particle Physics, Universiti Malaya, Kuala Lumpur, Malaysia*
- ⁹⁸*Universidad de Sonora (UNISON), Hermosillo, Mexico*
- ⁹⁹*Centro de Investigación y de Estudios Avanzados del IPN, Mexico City, Mexico*
- ¹⁰⁰*Universidad Iberoamericana, Mexico City, Mexico*
- ¹⁰¹*Benemerita Universidad Autonoma de Puebla, Puebla, Mexico*
- ¹⁰²*University of Montenegro, Podgorica, Montenegro*
- ¹⁰³*University of Auckland, Auckland, New Zealand*
- ¹⁰⁴*University of Canterbury, Christchurch, New Zealand*
- ¹⁰⁵*National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan*
- ¹⁰⁶*AGH University of Science and Technology Faculty of Computer Science, Electronics and Telecommunications, Krakow, Poland*
- ¹⁰⁷*National Centre for Nuclear Research, Swierk, Poland*
- ¹⁰⁸*Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland*
- ¹⁰⁹*Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal*
- ¹¹⁰*Joint Institute for Nuclear Research, Dubna, Russia*
- ¹¹¹*Petersburg Nuclear Physics Institute, Gatchina (St. Petersburg), Russia*
- ¹¹²*Institute for Nuclear Research, Moscow, Russia*
- ¹¹³*Institute for Theoretical and Experimental Physics named by A.I. Alikhanov of NRC 'Kurchatov Institute', Moscow, Russia*
- ¹¹⁴*Moscow Institute of Physics and Technology, Moscow, Russia*
- ¹¹⁵*National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia*
- ¹¹⁶*P.N. Lebedev Physical Institute, Moscow, Russia*
- ¹¹⁷*Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia*
- ¹¹⁸*Novosibirsk State University (NSU), Novosibirsk, Russia*
- ¹¹⁹*Institute for High Energy Physics of National Research Centre 'Kurchatov Institute', Protvino, Russia*
- ¹²⁰*National Research Tomsk Polytechnic University, Tomsk, Russia*
- ¹²¹*Tomsk State University, Tomsk, Russia*
- ¹²²*University of Belgrade: Faculty of Physics and VINCA Institute of Nuclear Sciences, Belgrade, Serbia*
- ¹²³*Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain*
- ¹²⁴*Universidad Autónoma de Madrid, Madrid, Spain*
- ¹²⁵*Universidad de Oviedo, Instituto Universitario de Ciencias y Tecnologías Espaciales de Asturias (ICTEA), Oviedo, Spain*
- ¹²⁶*Instituto de Física de Cantabria (IFCA), CSIC-Universidad de Cantabria, Santander, Spain*
- ¹²⁷*University of Colombo, Colombo, Sri Lanka*
- ¹²⁸*University of Ruhuna, Department of Physics, Matara, Sri Lanka*
- ¹²⁹*CERN, European Organization for Nuclear Research, Geneva, Switzerland*
- ¹³⁰*Paul Scherrer Institut, Villigen, Switzerland*
- ¹³¹*ETH Zurich-Institute for Particle Physics and Astrophysics (IPA), Zurich, Switzerland*
- ¹³²*Universität Zürich, Zurich, Switzerland*
- ¹³³*National Central University, Chung-Li, Taiwan*
- ¹³⁴*National Taiwan University (NTU), Taipei, Taiwan*
- ¹³⁵*Chulalongkorn University, Faculty of Science, Department of Physics, Bangkok, Thailand*

- ¹³⁶*Çukurova University, Physics Department, Science and Art Faculty, Adana, Turkey*
- ¹³⁷*Middle East Technical University, Physics Department, Ankara, Turkey*
- ¹³⁸*Bogazici University, Istanbul, Turkey*
- ¹³⁹*Istanbul Technical University, Istanbul, Turkey*
- ¹⁴⁰*Istanbul University, Istanbul, Turkey*
- ¹⁴¹*Institute for Scintillation Materials of National Academy of Science of Ukraine, Kharkov, Ukraine*
- ¹⁴²*National Scientific Center, Kharkov Institute of Physics and Technology, Kharkov, Ukraine*
- ¹⁴³*University of Bristol, Bristol, United Kingdom*
- ¹⁴⁴*Rutherford Appleton Laboratory, Didcot, United Kingdom*
- ¹⁴⁵*Imperial College, London, United Kingdom*
- ¹⁴⁶*Brunel University, Uxbridge, United Kingdom*
- ¹⁴⁷*Baylor University, Waco, Texas, USA*
- ¹⁴⁸*Catholic University of America, Washington, DC, USA*
- ¹⁴⁹*The University of Alabama, Tuscaloosa, Alabama, USA*
- ¹⁵⁰*Boston University, Boston, Massachusetts, USA*
- ¹⁵¹*Brown University, Providence, Rhode Island, USA*
- ¹⁵²*University of California, Davis, Davis, California, USA*
- ¹⁵³*University of California, Los Angeles, California, USA*
- ¹⁵⁴*University of California, Riverside, Riverside, California, USA*
- ¹⁵⁵*University of California, San Diego, La Jolla, California, USA*
- ¹⁵⁶*University of California, Santa Barbara-Department of Physics, Santa Barbara, California, USA*
- ¹⁵⁷*California Institute of Technology, Pasadena, California, USA*
- ¹⁵⁸*Carnegie Mellon University, Pittsburgh, Pennsylvania, USA*
- ¹⁵⁹*University of Colorado Boulder, Boulder, Colorado, USA*
- ¹⁶⁰*Cornell University, Ithaca, New York, USA*
- ¹⁶¹*Fermi National Accelerator Laboratory, Batavia, Illinois, USA*
- ¹⁶²*University of Florida, Gainesville, Florida, USA*
- ¹⁶³*Florida State University, Tallahassee, Florida, USA*
- ¹⁶⁴*Florida Institute of Technology, Melbourne, Florida, USA*
- ¹⁶⁵*University of Illinois at Chicago (UIC), Chicago, Illinois, USA*
- ¹⁶⁶*The University of Iowa, Iowa City, Iowa, USA*
- ¹⁶⁷*Johns Hopkins University, Baltimore, Maryland, USA*
- ¹⁶⁸*The University of Kansas, Lawrence, Kansas, USA*
- ¹⁶⁹*Kansas State University, Manhattan, Kansas, USA*
- ¹⁷⁰*Lawrence Livermore National Laboratory, Livermore, California, USA*
- ¹⁷¹*University of Maryland, College Park, Maryland, USA*
- ¹⁷²*Massachusetts Institute of Technology, Cambridge, Massachusetts, USA*
- ¹⁷³*University of Minnesota, Minneapolis, Minnesota, USA*
- ¹⁷⁴*University of Nebraska-Lincoln, Lincoln, Nebraska, USA*
- ¹⁷⁵*State University of New York at Buffalo, Buffalo, New York, USA*
- ¹⁷⁶*Northeastern University, Boston, Massachusetts, USA*
- ¹⁷⁷*Northwestern University, Evanston, Illinois, USA*
- ¹⁷⁸*University of Notre Dame, Notre Dame, Indiana, USA*
- ¹⁷⁹*The Ohio State University, Columbus, Ohio, USA*
- ¹⁸⁰*Princeton University, Princeton, New Jersey, USA*
- ¹⁸¹*University of Puerto Rico, Mayaguez, Puerto Rico, USA*
- ¹⁸²*Purdue University, West Lafayette, Indiana, USA*
- ¹⁸³*Purdue University Northwest, Hammond, Indiana, USA*
- ¹⁸⁴*Rice University, Houston, Texas, USA*
- ¹⁸⁵*University of Rochester, Rochester, New York, USA*
- ¹⁸⁶*Rutgers, The State University of New Jersey, Piscataway, New Jersey, USA*
- ¹⁸⁷*University of Tennessee, Knoxville, Tennessee, USA*
- ¹⁸⁸*Texas A&M University, College Station, Texas, USA*
- ¹⁸⁹*Texas Tech University, Lubbock, Texas, USA*
- ¹⁹⁰*Vanderbilt University, Nashville, Tennessee, USA*
- ¹⁹¹*University of Virginia, Charlottesville, Virginia, USA*
- ¹⁹²*Wayne State University, Detroit, Michigan, USA*
- ¹⁹³*University of Wisconsin-Madison, Madison, Wisconsin, USA*

^aDeceased.

^bAlso at TU Wien, Wien, Austria.

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

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

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

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

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

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

ⁱAlso at Department of Physics, Tsinghua University, Beijing, China.

^jAlso at UFMS, Nova Andradina, Brazil.

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

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

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

ⁿAlso at Institute for Theoretical and Experimental Physics named by A.I. Alikhanov of NRC 'Kurchatov Institute', Moscow, Russia.

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

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

^qAlso at Cairo University, Cairo, Egypt.

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

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

^tAlso at Tbilisi State University, Tbilisi, Georgia.

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

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

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

^xAlso at University of Hamburg, Hamburg, Germany.

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

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

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

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

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

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

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

^{ff}Also at MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary.

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

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

ⁱⁱAlso at Institute of Physics, Bhubaneswar, India.

^{jj}Also at G. H. G. Khalsa College, Punjab, India.

^{kk}Also at Shoolini University, Solan, India.

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

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

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

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

^{pp}Also at Sharif University of Technology, Tehran, Iran.

^{qq}Also at Department of Physics, University of Science and Technology of Mazandaran, Behshahr, Iran.

^{rr}Also at INFN Sezione di Bari, Università di Bari, Politecnico di Bari, Bari, Italy.

^{ss}Also at Italian National Agency for New Technologies, Energy and Sustainable Economic Development, Bologna, Italy.

^{tt}Also at Centro Siciliano di Fisica Nucleare e di Struttura Della Materia, Catania, Italy.

^{uu}Also at Università di Napoli 'Federico II', Napoli, Italy.

^{vv}Also at Consiglio Nazionale delle Ricerche-Istituto Officina dei Materiali, Perugia, Italy.

^{ww}Also at Riga Technical University, Riga, Latvia.

^{xx}Also at Consejo Nacional de Ciencia y Tecnología, Mexico City, Mexico.

^{yy}Also at IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France.

^{zz}Also at Institute for Nuclear Research, Moscow, Russia.

^{aaa}Also at National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia.

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

^{ccc}Also at St. Petersburg Polytechnic University, St. Petersburg, Russia.

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

^{eee}Also at Imperial College, London, United Kingdom.

- fff Also at P.N. Lebedev Physical Institute, Moscow, Russia.
- ggg Also at INFN Sezione di Padova, Università di Padova, Padova, Italy, Università di Trento, Trento, Italy, Padova, Italy.
- hhh Also at Budker Institute of Nuclear Physics, Novosibirsk, Russia.
- iii Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia.
- jjj Also at Trincomalee Campus, Eastern University, Sri Lanka, Nilaveli, Sri Lanka.
- kkk Also at INFN Sezione di Pavia, Università di Pavia, Pavia, Italy.
- lll Also at National and Kapodistrian University of Athens, Athens, Greece.
- mmm Also at Ecole Polytechnique Fédérale Lausanne, Lausanne, Switzerland.
- nnn Also at Universität Zürich, Zurich, Switzerland.
- ooo Also at Stefan Meyer Institute for Subatomic Physics, Vienna, Austria.
- ppp Also at Laboratoire d'Annecy-le-Vieux de Physique des Particules, IN2P3-CNRS, Annecy-le-Vieux, France.
- qqq Also at Şirnak University, Şirnak, Turkey.
- rrr Also at Near East University, Research Center of Experimental Health Science, Nicosia, Turkey.
- sss Also at Konya Technical University, Konya, Turkey.
- ttt Also at Istanbul University-Cerrahpasa, Faculty of Engineering, Istanbul, Turkey.
- uuu Also at Piri Reis University, Istanbul, Turkey.
- vvv Also at Adiyaman University, Adiyaman, Turkey.
- www Also at Ozyegin University, Istanbul, Turkey.
- xxx Also at Izmir Institute of Technology, Izmir, Turkey.
- yyy Also at Necmettin Erbakan University, Konya, Turkey.
- zzz Also at Bozok Universitetesi Rektörlüğü, Yozgat, Turkey.
- aaaa Also at Marmara University, Istanbul, Turkey.
- bbbb Also at Milli Savunma University, Istanbul, Turkey.
- cccc Also at Kafkas University, Kars, Turkey.
- dddd Also at Istanbul Bilgi University, Istanbul, Turkey.
- eeee Also at Hacettepe University, Ankara, Turkey.
- ffff Also at Vrije Universiteit Brussel, Brussel, Belgium.
- gggg Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom.
- hhhh Also at Rutherford Appleton Laboratory, Didcot, United Kingdom.
- iiii Also at IPPP Durham University, Durham, United Kingdom.
- jjjj Also at Monash University, Faculty of Science, Clayton, Australia.
- kkkk Also at Università di Torino, Torino, Italy.
- llll Also at Bethel University, St. Paul, Minneapolis, USA.
- mmmm Also at Karamanoğlu Mehmetbey University, Karaman, Turkey.
- nnnn Also at California Institute of Technology, Pasadena, California, USA.
- oooo Also at Ain Shams University, Cairo, Egypt.
- pppp Also at Bingol University, Bingol, Turkey.
- qqqq Also at Georgian Technical University, Tbilisi, Georgia.
- rrrr Also at Sinop University, Sinop, Turkey.
- ssss Also at Erciyes University, Kayseri, Turkey.
- tttt Also at Texas A&M University at Qatar, Doha, Qatar.
- uuuu Also at Kyungpook National University, Daegu, Korea.