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

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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 $B_c^+ \to (J/\psi \to \mu^+\mu^-)\mu^+\nu_\mu$ 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 trimuon 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 Υ(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 $B_c^+ \to J/\psi \ell^+ \nu_\ell$ decay mode [21]. Its ground and excited states were then studied

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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 $B_c^+ \to (J/\psi \to \mu^+\mu^-)\mu^+\nu_\mu$ 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 $B_c^+ \to (J/\psi \to \mu^+\mu^-)\mu^+\nu_\mu$ 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 ($J/\psi + random\,X$) 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 $J/\psi + \text{random}\,X$ sample in Pb-Pb collisions, are provided by the data. In Pb-Pb collisions, the $J/\psi + \text{random}\,X$ and fake J/ψ backgrounds are dominant. In pp collisions, the region above the B_c^+ mass strongly constrains the $J/\psi + \text{random}\,X$ 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 $J/\psi + \text{random}\,X$ 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

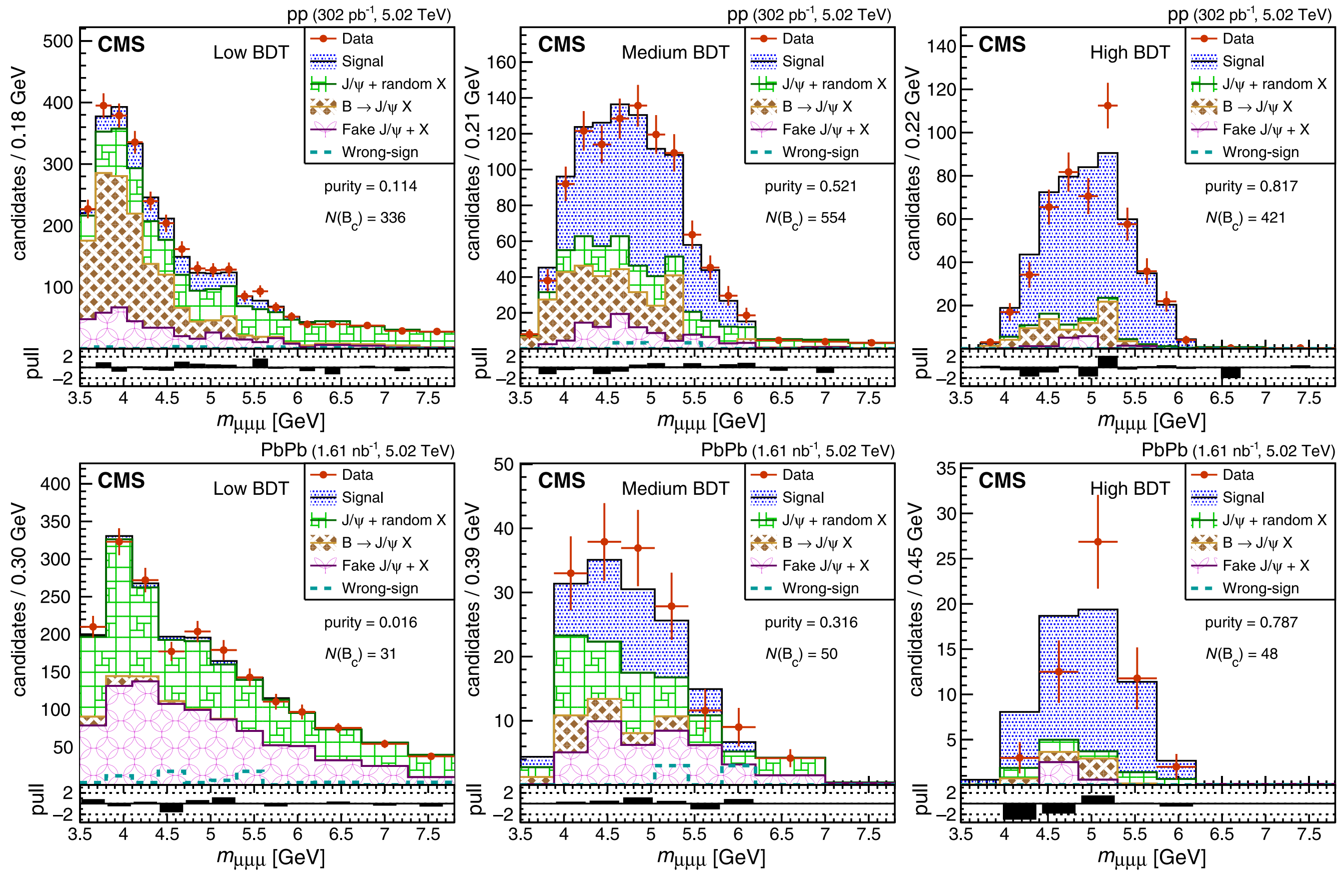

FIG. 1. Template fit of the trimuon mass distributions in the three BDT bins, for the pp (top row) and Pb-Pb (bottom row) data samples integrated over the two studied kinematic regions. The lower panels show the pull between the data and the fitted distributions.

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 $B_c^+ \to J/\psi(\tau^+ \to \mu^+ X)\nu_\tau$ or $B_c^+ \to (c\bar{c} \to J/\psi X)\mu^+\nu_\mu$, 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

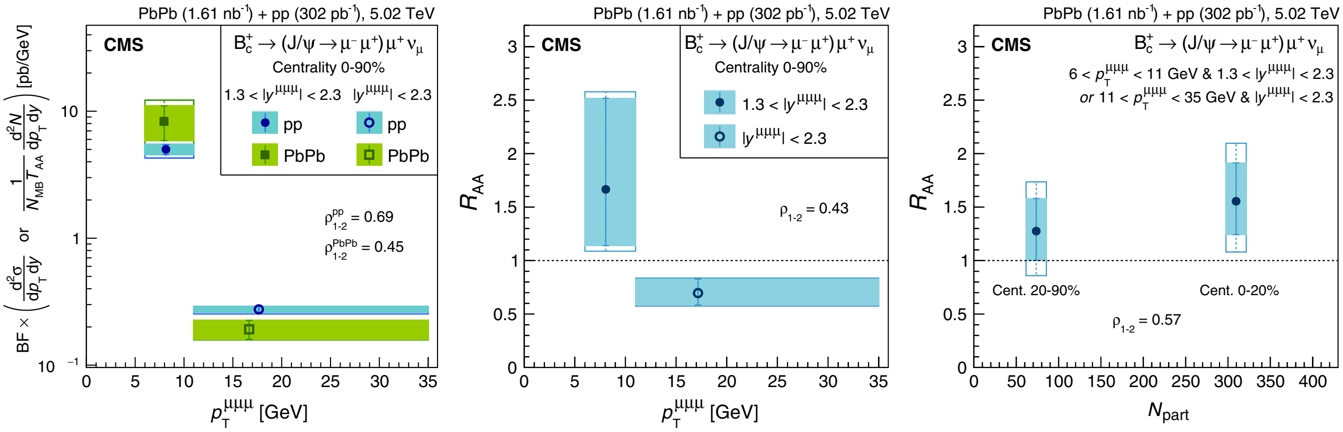

FIG. 2. B_c^+ meson production in pp and Pb-Pb collisions. Left: the pp-equivalent cross-section times branching fraction of the studied decay in pp and Pb-Pb collisions. Middle and right: the nuclear modification factor in $p_T^{\mu\mu\mu}$ bins (middle), and in centrality bins integrated over the studied 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-$p_T^{\mu\mu\mu}$ region, the B_c^+ shows a moderate suppression, while the low-$p_T^{\mu\mu\mu}$ modification factor stands above unity and above the high-$p_T^{\mu\mu\mu}$ 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 $R_{\mathrm{AA}}(B_c^+)$ 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 $B_c^+ \to (J/\psi \to \mu^+\mu^-)\mu^+\nu_\mu$ 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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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,jj] 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] S. Thakur,[60,kk] P. K. Behera,[61] S. C. Behera,[61] P. Kalbhor,[61] A. Muhammad,[61] R. Pradhan,[61] P. R. Pujahari,[61] A. Sharma,[61] 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] A. Colaleo,[69a] D. Creanza,[69a,69c] N. De Filippis,[69a,69c] M. De Palma,[69a,69b] A. Di Florio,[69a,69b] A. Di Pilato,[69a,69b] W. Elmetenawee,[69a,69b] L. Fiore,[69a] A. Gelmi,[69a,69b] M. Gul,[69a] G. Iaselli,[69a,69c] M. Ince,[69a,69b] S. Lezki,[69a,69b] G. Maggi,[69a,69c] M. Maggi,[69a] I. Margjeka,[69a,69b] V. Mastrapasqua,[69a,69b] J. A. Merlin,[69a] S. My,[69a,69b] S. Nuzzo,[69a,69b] A. Pellecchia,[69a,69b] A. Pompili,[69a,69b] G. Pugliese,[69a,69c] D. Ramos,[69a] A. Ranieri,[69a] G. Selvaggi,[69a,69b] L. Silvestris,[69a] F. M. Simone,[69a,69b] R. Venditti,[69a] P. Verwilligen,[69a] G. Abbiendi,[70a] C. Battilana,[70a,70b] D. Bonacorsi,[70a,70b] L. Borgonovi,[70a] L. Brigliadori,[70a] R. Campanini,[70a,70b] P. Capiluppi,[70a,70b] A. Castro,[70a,70b] F. R. Cavallo,[70a] M. Cuffiani,[70a,70b] G. M. Dallavalle,[70a] T. Diotalevi,[70a,70b] F. Fabbri,[70a] A. Fanfani,[70a,70b] P. Giacomelli,[70a] L. Giommi,[70a,70b] C. Grandi,[70a] L. Guiducci,[70a,70b] S. Lo Meo,[70a,ss] L. Lunerti,[70a,70b] S. Marcellini,[70a] G. Masetti,[70a] F. L. Navarria,[70a,70b] A. Perrotta,[70a] F. Primavera,[70a,70b] A. M. Rossi,[70a,70b] T. Rovelli,[70a,70b] G. P. Siroli,[70a,70b] S. Albergo,[71a,71b,tt] S. Costa,[71a,71b,tt] A. Di Mattia,[71a] R. Potenza,[71a,71b] A. Tricomi,[71a,71b,tt] C. Tuve,[71a,71b] G. Barbagli,[72a] A. Cassese,[72a] R. Ceccarelli,[72a,72b] V. Ciulli,[72a,72b] C. Civinini,[72a] R. D'Alessandro,[72a,72b] E. Focardi,[72a,72b] G. Latino,[72a,72b] P. Lenzi,[72a,72b] M. Lizzo,[72a,72b] M. Meschini,[72a] S. Paoletti,[72a] R. Seidita,[72a,72b] G. Sguazzoni,[72a] L. Viliani,[72a] L. Benussi,[73] S. Bianco,[73] D. Piccolo,[73] M. Bozzo,[74a,74b] F. Ferro,[74a] R. Mulargia,[74a,74b] E. Robutti,[74a] S. Tosi,[74a,74b] A. Benaglia,[75a] G. Boldrini,[75a] F. Brivio,[75a,75b] F. Cetorelli,[75a,75b] F. De Guio,[75a,75b] M. E. Dinardo,[75a,75b] P. Dini,[75a] S. Gennai,[75a] A. Ghezzi,[75a,75b] P. Govoni,[75a,75b] L. Guzzi,[75a,75b] M. T. Lucchini,[75a,75b] M. Malberti,[75a] S. Malvezzi,[75a] A. Massironi,[75a] D. Menasce,[75a] L. Moroni,[75a] M. Paganoni,[75a,75b] D. Pedrini,[75a] B. S. Pinolini,[75a] S. Ragazzi,[75a,75b] N. Redaelli,[75a] T. Tabarelli de Fatis,[75a,75b] D. Valsecchi,[75a,75b,v] D. Zuolo,[75a,75b] S. Buontempo,[76a] F. Carnevali,[76a,76b] N. Cavallo,[76a,76c] A. De Iorio,[76a,76b] F. Fabozzi,[76a,76c] A. O. M. Iorio,[76a,76b] L. Lista,[76a,76b] S. Meola,[76a,76d,v] P. Paolucci,[76a,v] B. Rossi,[76a] C. Sciacca,[76a,76b] P. Azzi,[77a] N. Bacchetta,[77a] D. Bisello,[77a,77b] P. Bortignon,[77a] A. Bragagnolo,[77a,77b] R. Carlin,[77a,77b] P. Checchia,[77a] T. Dorigo,[77a] U. Dosselli,[77a] F. Gasparini,[77a,77b] U. Gasparini,[77a,77b] G. Grosso,[77a] S. Y. Hoh,[77a,77b] L. Layer,[77a,uu] E. Lusiani,[77a] M. Margoni,[77a,77b] A. T. Meneguzzo,[77a,77b] J. Pazzini,[77a,77b] M. Presilla,[77a,77b] P. Ronchese,[77a,77b] R. Rossin,[77a,77b] F. Simonetto,[77a,77b] G. Strong,[77a] M. Tosi,[77a,77b] H. Yarar,[77a,77b] M. Zanetti,[77a,77b] P. Zotto,[77a,77b] A. Zucchetta,[77a,77b] G. Zumerle,[77a,77b] C. Aime`,[78a,78b] A. Braghieri,[78a] S. Calzaferri,[78a,78b] D. Fiorina,[78a,78b] P. Montagna,[78a,78b] S. P. Ratti,[78a,78b]

V. Re,[78a] C. Riccardi,[78a,78b] P. Salvini,[78a] I. Vai,[78a] P. Vitulo,[78a,78b] P. Asenov,[79a,vv] G. M. Bilei,[79a] D. Ciangottini,[79a,79b] L. Fanò,[79a,79b] P. Lariccia,[79a,79b] M. Magherini,[79a,79b] G. Mantovani,[79a,79b] V. Mariani,[79a,79b] M. Menichelli,[79a] F. Moscatelli,[79a,vv] A. Piccinelli,[79a,79b] A. Rossi,[79a,79b] A. Santocchia,[79a,79b] D. Spiga,[79a] T. Tedeschi,[79a,79b] P. Azzurri,[80a] G. Bagliesi,[80a] V. Bertacchi,[80a,80c] L. Bianchini,[80a] T. Boccali,[80a] E. Bossini,[80a,80b] R. Castaldi,[80a] M. A. Ciocci,[80a,80b] V. D'Amante,[80a,80d] R. Dell'Orso,[80a] M. R. Di Domenico,[80a,80d] S. Donato,[80a] A. Giassi,[80a] F. Ligabue,[80a,80c] E. Manca,[80a,80c] G. Mandorli,[80a,80c] A. Messineo,[80a,80b] F. Palla,[80a] S. Parolia,[80a,80b] G. Ramirez-Sanchez,[80a,80c] A. Rizzi,[80a,80b] G. Rolandi,[80a,80c] S. Roy Chowdhury,[80a,80c] A. Scribano,[80a] N. Shafiei,[80a,80b] P. Spagnolo,[80a] R. Tenchini,[80a] G. Tonelli,[80a,80b] N. Turini,[80a,80d] A. Venturi,[80a] P. G. Verdini,[80a] P. Barria,[81a] M. Campana,[81a,81b] F. Cavallari,[81a] D. Del Re,[81a,81b] E. Di Marco,[81a] M. Diemoz,[81a] E. Longo,[81a,81b] P. Meridiani,[81a] G. Organtini,[81a,81b] F. Pandolfi,[81a] R. Paramatti,[81a,81b] C. Quaranta,[81a,81b] S. Rahatlou,[81a,81b] C. Rovelli,[81a] F. Santanastasio,[81a,81b] L. Soffi,[81a] R. Tramontano,[81a,81b] N. Amapane,[82a,82b] R. Arcidiacono,[82a,82c] S. Argiro,[82a,82b] M. Arneodo,[82a,82c] N. Bartosik,[82a] R. Bellan,[82a,82b] A. Bellora,[82a,82b] J. Berenguer Antequera,[82a,82b] C. Biino,[82a] N. Cartiglia,[82a] S. Cometti,[82a] M. Costa,[82a,82b] R. Covarelli,[82a,82b] N. Demaria,[82a] B. Kiani,[82a,82b] F. Legger,[82a] C. Mariotti,[82a] S. Maselli,[82a] E. Migliore,[82a,82b] E. Monteil,[82a,82b] M. Monteno,[82a] M. M. Obertino,[82a,82b] G. Ortona,[82a] L. Pacher,[82a,82b] N. Pastrone,[82a] M. Pelliccioni,[82a] G. L. Pinna Angioni,[82a,82b] M. Ruspa,[82a,82c] K. Shchelina,[82a] F. Siviero,[82a,82b] V. Sola,[82a] A. Solano,[82a,82b] D. Soldi,[82a,82b] A. Staiano,[82a] M. Tornago,[82a,82b] D. Trocino,[82a] A. Vagnerini,[82a,82b] S. Belforte,[83a] V. Candelise,[83a,83b] M. Casarsa,[83a] F. Cossutti,[83a] A. Da Rold,[83a,83b] G. Della Ricca,[83a,83b] G. Sorrentino,[83a,83b] F. Vazzoler,[83a,83b] S. Dogra,[84] C. Huh,[84] B. Kim,[84] D. H. Kim,[84] G. N. Kim,[84] J. Kim,[84] J. Lee,[84] S. W. Lee,[84] C. S. Moon,[84] Y. D. Oh,[84] S. I. Pak,[84] B. C. Radburn-Smith,[84] S. Sekmen,[84] Y. C. Yang,[84] H. Kim,[85] D. H. Moon,[85] B. Francois,[86] T. J. Kim,[86] J. Park,[86] S. Cho,[87] S. Choi,[87] Y. Go,[87] B. Hong,[87] K. Lee,[87] K. S. Lee,[87] J. Lim,[87] J. Park,[87] S. K. Park,[87] J. Yoo,[87] J. Goh,[88] A. Gurtu,[88] H. S. Kim,[89] Y. Kim,[89] J. Almond,[90] J. H. Bhyun,[90] J. Choi,[90] S. Jeon,[90] J. Kim,[90] J. S. Kim,[90] S. Ko,[90] H. Kwon,[90] H. Lee,[90] S. Lee,[90] B. H. Oh,[90] M. Oh,[90] S. B. Oh,[90] H. Seo,[90] U. K. Yang,[90] I. Yoon,[90] W. Jang,[91] D. Y. Kang,[91] Y. Kang,[91] S. Kim,[91] B. Ko,[91] J. S. H. Lee,[91] Y. Lee,[91] I. C. Park,[91] Y. Roh,[91] M. S. Ryu,[91] D. Song,[91] I. J. Watson,[91] S. Yang,[91] S. Ha,[92] H. D. Yoo,[92] M. Choi,[93] H. Lee,[93] Y. Lee,[93] I. Yu,[93] T. Beyrouthy,[94] Y. Maghrbi,[94] T. Torims,[95] V. Veckalns,[95,ww] M. Ambrozas,[96] A. Carvalho Antunes De Oliveira,[96] A. Juodagalvis,[96] A. Rinkevicius,[96] G. Tamulaitis,[96] N. Bin Norjoharuddeen,[97] W. A. T. Wan Abdullah,[97] M. N. Yusli,[97] Z. Zolkapli,[97] J. F. Benitez,[98] A. Castaneda Hernandez,[98] M. León Coello,[98] J. A. Murillo Quijada,[98] A. Sehrawat,[98] L. Valencia Palomo,[98] G. Ayala,[99] H. Castilla-Valdez,[99] E. De La Cruz-Burelo,[99] I. Heredia-De La Cruz,[99,xx] R. Lopez-Fernandez,[99] C. A. Mondragon Herrera,[99] D. A. Perez Navarro,[99] A. Sánchez Hernández,[99] S. Carrillo Moreno,[100] C. Oropeza Barrera,[100] F. Vazquez Valencia,[100] I. Pedraza,[101] H. A. Salazar Ibarguen,[101] C. Uribe Estrada,[101] J. Mijuskovic,[102,yy] N. Raicevic,[102] D. Krofcheck,[103] P. H. Butler,[104] A. Ahmad,[105] M. I. Asghar,[105] A. Awais,[105] M. I. M. Awan,[105] H. R. Hoorani,[105] W. A. Khan,[105] M. A. Shah,[105] M. Shoaib,[105] M. Waqas,[105] V. Avati,[106] L. Grzanka,[106] M. Malawski,[106] H. Bialkowska,[107] M. Bluj,[107] B. Boimska,[107] M. Górski,[107] M. Kazana,[107] M. Szleper,[107] P. Zalewski,[107] K. Bunkowski,[108] K. Doroba,[108] A. Kalinowski,[108] M. Konecki,[108] J. Krolikowski,[108] M. Araujo,[109] P. Bargassa,[109] D. Bastos,[109] A. Boletti,[109] P. Faccioli,[109] M. Gallinaro,[109] J. Hollar,[109] N. Leonardo,[109] T. Niknejad,[109] M. Pisano,[109] J. Seixas,[109] O. Toldaiev,[109] J. Varela,[109] S. Afanasiev,[110] D. Budkouski,[110] I. Golutvin,[110] I. Gorbunov,[110] V. Karjavine,[110] V. Korenkov,[110] A. Lanev,[110] A. Malakhov,[110] V. Matveev,[110,zz,aaa] V. Palichik,[110] V. Perelygin,[110] M. Savina,[110] 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] M. Kirsanov,[112] N. Krasnikov,[112] A. Pashenkov,[112] G. Pivovarov,[112] A. Toropin,[112] V. Epshteyn,[113] V. Gavrilov,[113] N. Lychkovskaya,[113] A. Nikitenko,[113,eee] V. Popov,[113] A. Stepennov,[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] I. Ovtin,[118,hhh] Y. Skovpen,[118,hhh] I. Azhgirey,[119] I. Bayshev,[119] D. Elumakhov,[119] V. Kachanov,[119] D. Konstantinov,[119] P. Mandrik,[119] V. Petrov,[119] R. Ryutin,[119] S. Slabospitskii,[119] A. Sobol,[119] S. Troshin,[119] N. Tyurin,[119] A. Uzunian,[119] A. Volkov,[119] A. Babaev,[120] V. Okhotnikov,[120] V. Borshch,[121] V. Ivanchenko,[121] E. Tcherniaev,[121] P. Adzic,[122,iii]

M. Dordevic,[122] P. Milenovic,[122] J. Milosevic,[122] M. Aguilar-Benitez,[123] J. Alcaraz Maestre,[123] A. Álvarez Fernández,[123] I. Bachiller,[123] M. Barrio Luna,[123] Cristina F. Bedoya,[123] C. A. Carrillo Montoya,[123] M. Cepeda,[123] M. Cerrada,[123] N. Colino,[123] B. De La Cruz,[123] A. Delgado Peris,[123] J. P. Fernández Ramos,[123] J. Flix,[123] M. C. Fouz,[123] O. Gonzalez Lopez,[123] S. Goy Lopez,[123] J. M. Hernandez,[123] M. I. Josa,[123] J. León Holgado,[123] D. Moran,[123] Á. Navarro Tobar,[123] C. Perez Dengra,[123] A. Pérez-Calero Yzquierdo,[123] J. Puerta Pelayo,[123] I. Redondo,[123] L. Romero,[123] S. Sánchez Navas,[123] L. Urda Gómez,[123] C. Willmott,[123] J. F. de Trocóniz,[124] R. Reyes-Almanza,[124] B. Alvarez Gonzalez,[125] J. Cuevas,[125] C. Erice,[125] J. Fernandez Menendez,[125] S. Folgueras,[125] I. Gonzalez Caballero,[125] J. R. González Fernández,[125] E. Palencia Cortezon,[125] C. Ramón Álvarez,[125] V. Rodríguez Bouza,[125] A. Soto Rodríguez,[125] A. Trapote,[125] N. Trevisani,[125] C. Vico Villalba,[125] J. A. Brochero Cifuentes,[126] I. J. Cabrillo,[126] A. Calderon,[126] J. Duarte Campderros,[126] M. Fernandez,[126] C. Fernandez Madrazo,[126] P. J. Fernández Manteca,[126] A. García Alonso,[126] G. Gomez,[126] C. Martinez Rivero,[126] P. Martinez Ruiz del Arbol,[126] F. Matorras,[126] P. Matorras Cuevas,[126] J. Piedra Gomez,[126] C. Prieels,[126] T. Rodrigo,[126] A. Ruiz-Jimeno,[126] L. Scodellaro,[126] I. Vila,[126] J. M. Vizan Garcia,[126] M. K. Jayananda,[127] B. Kailasapathy,[127,jjj] D. U. J. Sonnadara,[127] D. D. C. Wickramarathna,[127] W. G. D. Dharmaratna,[128] K. Liyanage,[128] N. Perera,[128] N. Wickramage,[128] T. K. Aarrestad,[129] D. Abbaneo,[129] J. Alimena,[129] E. Auffray,[129] G. Auzinger,[129] J. Baechler,[129] P. Baillon,[129,a] D. Barney,[129] J. Bendavid,[129] M. Bianco,[129] A. Bocci,[129] T. Camporesi,[129] M. Capeans Garrido,[129] G. Cerminara,[129] N. Chernyavskaya,[129] S. S. Chhibra,[129] M. Cipriani,[129] L. Cristella,[129] D. d'Enterria,[129] A. Dabrowski,[129] A. David,[129] A. De Roeck,[129] M. M. Defranchis,[129] M. Deile,[129] M. Dobson,[129] M. Dünser,[129] N. Dupont,[129] A. Elliott-Peisert,[129] N. Emriskova,[129] F. Fallavollita,[129,kkk] D. Fasanella,[129] A. Florent,[129] G. Franzoni,[129] W. Funk,[129] S. Giani,[129] D. Gigi,[129] K. Gill,[129] F. Glege,[129] L. Gouskos,[129] M. Haranko,[129] J. Hegeman,[129] V. Innocente,[129] T. James,[129] P. Janot,[129] J. Kaspar,[129] J. Kieseler,[129] M. Komm,[129] N. Kratochwil,[129] C. Lange,[129] S. Laurila,[129] P. Lecoq,[129] A. Lintuluoto,[129] K. Long,[129] C. Lourenço,[129] B. Maier,[129] L. Malgeri,[129] S. Mallios,[129] M. Mannelli,[129] A. C. Marini,[129] F. Meijers,[129] S. Mersi,[129] E. Meschi,[129] F. Moortgat,[129] M. Mulders,[129] S. Orfanelli,[129] L. Orsini,[129] F. Pantaleo,[129] L. Pape,[129] E. Perez,[129] M. Peruzzi,[129] A. Petrilli,[129] G. Petrucciani,[129] A. Pfeiffer,[129] M. Pierini,[129] D. Piparo,[129] M. Pitt,[129] H. Qu,[129] T. Quast,[129] D. Rabady,[129] A. Racz,[129] G. Reales Gutiérrez,[129] M. Rieger,[129] M. Rovere,[129] H. Sakulin,[129] J. Salfeld-Nebgen,[129] S. Scarfi,[129] C. Schäfer,[129] C. Schwick,[129] M. Selvaggi,[129] A. Sharma,[129] P. Silva,[129] W. Snoeys,[129] P. Sphicas,[129,lll] S. Summers,[129] K. Tatar,[129] V. R. Tavolaro,[129] D. Treille,[129] P. Tropea,[129] A. Tsirou,[129] G. P. Van Onsem,[129] J. Wanczyk,[129,mmm] K. A. Wozniak,[129] W. D. Zeuner,[129] L. Caminada,[130,nnn] A. Ebrahimi,[130] W. Erdmann,[130] R. Horisberger,[130] Q. Ingram,[130] H. C. Kaestli,[130] D. Kotlinski,[130] U. Langenegger,[130] M. Missiroli,[130,nnn] L. Noehte,[130,nnn] T. Rohe,[130] K. Androsov,[131,mmm] M. Backhaus,[131] P. Berger,[131] A. Calandri,[131] A. De Cosa,[131] G. Dissertori,[131] M. Dittmar,[131] M. Donegà,[131] C. Dorfer,[131] F. Eble,[131] K. Gedia,[131] F. Glessgen,[131] T. A. Gómez Espinosa,[131] C. Grab,[131] D. Hits,[131] W. Lustermann,[131] A.-M. Lyon,[131] R. A. Manzoni,[131] L. Marchese,[131] C. Martin Perez,[131] M. T. Meinhard,[131] F. Nessi-Tedaldi,[131] J. Niedziela,[131] F. Pauss,[131] V. Perovic,[131] S. Pigazzini,[131] M. G. Ratti,[131] M. Reichmann,[131] C. Reissel,[131] T. Reitenspiess,[131] B. Ristic,[131] D. Ruini,[131] D. A. Sanz Becerra,[131] V. Stampf,[131] J. Steggemann,[131,mmm] R. Wallny,[131] D. H. Zhu,[131] C. Amsler,[132,ooo] P. Bärtschi,[132] C. Botta,[132] D. Brzhechko,[132] M. F. Canelli,[132] K. Cormier,[132] A. De Wit,[132] R. Del Burgo,[132] J. K. Heikkilä,[132] M. Huwiler,[132] W. Jin,[132] A. Jofrehei,[132] B. Kilminster,[132] S. Leontsinis,[132] S. P. Liechti,[132] A. Macchiolo,[132] P. Meiring,[132] V. M. Mikuni,[132] U. Molinatti,[132] I. Neutelings,[132] A. Reimers,[132] P. Robmann,[132] S. Sanchez Cruz,[132] K. Schweiger,[132] Y. Takahashi,[132] C. Adloff,[133,ppp] C. M. Kuo,[133] W. Lin,[133] A. Roy,[133] T. Sarkar,[133,mm] S. S. Yu,[133] L. Ceard,[134] Y. Chao,[134] K. F. Chen,[134] P. H. Chen,[134] W.-S. Hou,[134] Y. y. Li,[134] R.-S. Lu,[134] E. Paganis,[134] A. Psallidas,[134] A. Steen,[134] H. y. Wu,[134] E. Yazgan,[134] P. r. Yu,[134] B. Asavapibhop,[135] C. Asawatangtrakuldee,[135] N. Srimanobhas,[135] F. Boran,[136] S. Damarseckin,[136,qqq] Z. S. Demiroglu,[136] F. Dolek,[136] I. Dumanoglu,[136,rrr] E. Eskut,[136] Y. Guler,[136,sss] E. Gurpinar Guler,[136,sss] I. Hos,[136,ttt] C. Isik,[136] O. Kara,[136] A. Kayis Topaksu,[136] U. Kiminsu,[136] G. Onengut,[136] K. Ozdemir,[136,uuu] A. Polatoz,[136] A. E. Simsek,[136] B. Tali,[136,vvv] U. G. Tok,[136] S. Turkcapar,[136] I. S. Zorbakir,[136] C. Zorbilmez,[136] B. Isildak,[137,www] G. Karapinar,[137,xxx] K. Ocalan,[137,yyy] M. Yalvac,[137,zzz] B. Akgun,[138] I. O. Atakisi,[138] E. Gülmez,[138] M. Kaya,[138,aaaa] O. Kaya,[138,bbbb] Ö. Özçelik,[138] S. Tekten,[138,cccc] E. A. Yetkin,[138,dddd] A. Cakir,[139] K. Cankocak,[139,rrr] Y. Komurcu,[139] S. Sen,[139,eeee] S. 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Kyberd,[146] I. D. Reid,[146] L. Teodorescu,[146] S. Zahid,[146] S. Abdullin,[147] A. Brinkerhoff,[147] B. Caraway,[147] J. Dittmann,[147] K. Hatakeyama,[147] A. R. Kanuganti,[147] B. McMaster,[147] N. Pastika,[147] M. Saunders,[147] S. Sawant,[147] C. Sutantawibul,[147] J. Wilson,[147] R. Bartek,[148] A. Dominguez,[148] R. Uniyal,[148] A. M. Vargas Hernandez,[148] A. Buccilli,[149] S. I. Cooper,[149] D. Di Croce,[149] S. V. Gleyzer,[149] C. Henderson,[149] C. U. Perez,[149] P. Rumerio,[149,kkkk] C. West,[149] A. Akpinar,[150] A. Albert,[150] D. Arcaro,[150] C. Cosby,[150] Z. Demiragli,[150] E. Fontanesi,[150] D. Gastler,[150] S. May,[150] J. Rohlf,[150] K. Salyer,[150] D. Sperka,[150] D. Spitzbart,[150] I. Suarez,[150] A. Tsatsos,[150] S. Yuan,[150] D. Zou,[150] G. Benelli,[151] B. Burkle,[151] X. Coubez,[151,w] D. Cutts,[151] M. Hadley,[151] U. Heintz,[151] J. M. Hogan,[151,llll] T. KWON,[151] G. Landsberg,[151] K. T. Lau,[151] D. Li,[151] M. Lukasik,[151] J. Luo,[151] M. 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Terrill,[158] J. P. Cumalat,[159] W. T. Ford,[159] A. Hassani,[159] E. MacDonald,[159] R. Patel,[159] A. Perloff,[159] C. Savard,[159] K. Stenson,[159] K. A. Ulmer,[159] S. R. Wagner,[159] J. Alexander,[160] S. Bright-Thonney,[160] Y. Cheng,[160] D. J. Cranshaw,[160] S. Hogan,[160] J. Monroy,[160] J. R. Patterson,[160] D. Quach,[160] J. Reichert,[160] M. Reid,[160] A. Ryd,[160] W. Sun,[160] J. Thom,[160] P. Wittich,[160] R. Zou,[160] M. Albrow,[161] M. Alyari,[161] G. Apollinari,[161] A. Apresyan,[161] 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] A. Canepa,[161] G. B. Cerati,[161] H. W. K. Cheung,[161] F. Chlebana,[161] M. Cremonesi,[161] K. F. Di Petrillo,[161] V. D. Elvira,[161] Y. Feng,[161] J. Freeman,[161] Z. Gecse,[161] L. Gray,[161] D. Green,[161] S. Grünendahl,[161] O. Gutsche,[161] R. M. Harris,[161] R. Heller,[161] T. C. Herwig,[161] J. Hirschauer,[161] B. Jayatilaka,[161] S. Jindariani,[161] M. Johnson,[161] U. Joshi,[161] T. Klijnsma,[161] 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] C. Mantilla,[161] D. Mason,[161] P. McBride,[161] P. Merkel,[161] S. Mrenna,[161] S. Nahn,[161] J. Ngadiuba,[161] V. O'Dell,[161] 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] S. Tkaczyk,[161] N. V. Tran,[161] L. Uplegger,[161] E. W. Vaandering,[161] H. A. Weber,[161] D. Acosta,[162] P. Avery,[162] D. Bourilkov,[162] L. Cadamuro,[162] V. Cherepanov,[162] F. Errico,[162] R. D. Field,[162] D. Guerrero,[162] B. M. Joshi,[162] M. Kim,[162] E. Koenig,[162] J. Konigsberg,[162] A. Korytov,[162] K. H. Lo,[162] K. Matchev,[162] N. Menendez,[162] G. Mitselmakher,[162] A. Muthirakalayil Madhu,[162] N. Rawal,[162] D. Rosenzweig,[162] S. Rosenzweig,[162] J. Rotter,[162] K. Shi,[162] J. Sturdy,[162] J. Wang,[162] E. Yigitbasi,[162] X. Zuo,[162] T. Adams,[163] A. Askew,[163] R. Habibullah,[163] V. Hagopian,[163] K. F. Johnson,[163] R. Khurana,[163] T. Kolberg,[163] G. Martinez,[163] H. Prosper,[163] C. Schiber,[163] O. Viazlo,[163] R. Yohay,[163] J. Zhang,[163] M. M. Baarmand,[164] S. Butalla,[164] T. Elkafrawy,[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] S. Rudrabhatla,[165] M. B. Tonjes,[165] N. Varelas,[165] J. Viinikainen,[165] X. Wang,[165] Z. Wu,[165] Z. Ye,[165] M. Alhusseini,[166] K. Dilsiz,[166,pppp] R. P. Gandrajula,[166] O. K. Köseyan,[166] J.-P. Merlo,[166] A. Mestvirishvili,[166,qqqq] J. Nachtman,[166] H. Ogul,[166,rrrr] Y. Onel,[166] A. Penzo,[166] C. Snyder,[166] E. Tiras,[166,ssss] O. Amram,[167] B. Blumenfeld,[167] L. Corcodilos,[167] J. Davis,[167] M. Eminizer,[167] A. V. Gritsan,[167] S. Kyriacou,[167] P. Maksimovic,[167] J. Roskes,[167] M. Swartz,[167] T. Á. Vámi,[167] A. Abreu,[168] J. Anguiano,[168] C. Baldenegro Barrera,[168] P. Baringer,[168] A. Bean,[168] A. Bylinkin,[168] Z. Flowers,[168] T. Isidori,[168] S. Khalil,[168] J. King,[168] G. Krintiras,[168] A. Kropivnitskaya,[168] M. Lazarovits,[168] C. Lindsey,[168] J. Marquez,[168] N. Minafra,[168] M. Murray,[168] M. Nickel,[168] C. Rogan,[168] C. Royon,[168] R. Salvatico,[168] S. Sanders,[168] E. Schmitz,[168] C. Smith,[168] J. D. Tapia Takaki,[168] Q. Wang,[168] Z. Warner,[168] J. Williams,[168] G. Wilson,[168] S. Duric,[169] A. Ivanov,[169] K. Kaadze,[169] D. Kim,[169] Y. Maravin,[169] T. Mitchell,[169] A. Modak,[169] K. Nam,[169] F. Rebassoo,[170] D. Wright,[170] E. Adams,[171] A. Baden,[171] O. Baron,[171] A. Belloni,[171] S. C. Eno,[171] N. J. Hadley,[171] S. Jabeen,[171] R. G. Kellogg,[171] T. Koeth,[171] A. C. Mignerey,[171] S. Nabili,[171] C. Palmer,[171] M. Seidel,[171] A. Skuja,[171] L. Wang,[171] K. Wong,[171] D. Abercrombie,[172] G. Andreassi,[172] R. Bi,[172] S. Brandt,[172] W. Busza,[172] I. A. Cali,[172] Y. Chen,[172] M. D'Alfonso,[172] J. Eysermans,[172] C. Freer,[172] G. Gomez Ceballos,[172] M. Goncharov,[172] P. Harris,[172] M. Hu,[172] M. Klute,[172] D. Kovalskyi,[172] J. Krupa,[172] Y.-J. Lee,[172] C. Mironov,[172] C. Paus,[172] D. Rankin,[172] C. Roland,[172] G. 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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. 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