Letter

Measurement of the ratio of the $B_c^+ \to J/\psi\tau^+\nu_\tau$ and $B_c^+ \to J/\psi\mu^+\nu_\mu$ branching fractions using three-prong τ lepton decays

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The ratio between the $B_c^+ \to J/\psi\tau^+\nu_\tau$ and $B_c^+ \to J/\psi\mu^+\nu_\mu$ branching fractions is measured using a data sample of proton-proton collisions collected by CMS at a center-of-mass energy of 13 TeV in the years 2016–2018 and corresponding to an integrated luminosity of 138 fb^{-1}. The J/ψ meson is identified through its $J/\psi \to \mu^+\mu^-$ decay and the tau lepton is reconstructed in the hadronic three-prong final state. The measured ratio of branching fractions in this tau decay mode, $\mathcal{R}_{J/\psi}^{\mathrm{had}} = 1.04^{+0.50}_{-0.44}$, is combined with the previous analysis based on the $\tau^+ \to \mu^+\nu_\mu\bar{\nu}_\tau$ leptonic decay channel, leading to $\mathcal{R}_{J/\psi} = 0.49 \pm 0.26$. As this result is consistent with the standard model prediction of 0.258 ± 0.004, no evidence of lepton flavor universality violation is found.

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The standard model (SM) provides an excellent description of physical processes up to the electroweak scale and was completed by the discovery of the Higgs boson [1–3] by the ATLAS and CMS Collaborations at the CERN LHC. The Yukawa couplings of the Higgs boson to fermions are proportional to the fermion masses and can contain complex phases that contribute to charge-conjugation and parity violation, particularly through the CKM matrix [4,5] in the quark sector. The Yukawa couplings are also the only source of lepton flavor universality (LFU) violation in the SM, and current measurements of the couplings are consistent with SM predictions for the second and third lepton generations [6,7]. As LFU is not explained by any underlying structure of the SM, it is natural to consider more elaborate mechanisms for LFU. Observing LFU violation in B meson decays would indicate physics beyond the SM.

To test LFU, the LHCb Collaboration measured $\mathcal{R}_{J/\psi} = \mathcal{B}(B_c^+ \to J/\psi\tau^+\nu_\tau)/\mathcal{B}(B_c^+ \to J/\psi\mu^+\nu_\mu)$, using $J/\psi \to \mu^+\mu^-$ and $\tau^+ \to \mu^+\nu_\mu\bar{\nu}_\tau$ decays, which ensures both decay modes have the same visible final state (three muons). The result, $0.71 \pm 0.17(\mathrm{stat}) \pm 0.18(\mathrm{syst})$ [8], exceeds the value predicted by the SM, 0.258 ± 0.004 [9–13], by about two standard deviations. The CMS Collaboration subsequently measured $\mathcal{R}_{J/\psi} = 0.17^{+0.18}_{-0.17}(\mathrm{stat})^{+0.21}_{-0.22}(\mathrm{syst})^{+0.19}_{-0.18}(\mathrm{theo})$ [14] in the same final states, using data collected in 2018 corresponding to an integrated luminosity of 59.7 fb^{-1} [15] (described as the "leptonic τ analysis" in this paper).

The measurement presented in this paper, also provided in a HEPData record [16], is based on a sample of proton-proton (pp) collisions at $\sqrt{s} = 13$ TeV collected by CMS in 2016–2018 corresponding to an integrated luminosity of 138 fb^{-1} [15,17,18]. We reconstruct the decay $B_c^+ \to J/\psi\tau^+\nu_\tau$ with subsequent decays of the J/ψ meson to a pair of muons and the τ lepton to its hadronic three-prong final state, reconstructed from three charged pions, referred to as τ_{had}^+. Besides the neutrino, additional (unreconstructed) pions may also be present in the decay. The data used in Ref. [14] to evaluate the $B_c^+ \to J/\psi\mu^+\nu_\mu$ yield are also used in the denominator of $\mathcal{R}_{J/\psi}$ for this measurement. The result is combined with that of the leptonic τ analysis. In this paper, the charge conjugate of a particle or its decay mode is also implied.

The CMS apparatus [19,20] is a multipurpose, nearly hermetic detector, designed to trigger on [21–23] and identify electrons, muons, photons, and (charged and neutral) hadrons [24–26]. A global "particle-flow" (PF) algorithm [27] aims to reconstruct all individual particles in an event, combining information provided by the silicon tracker and by the lead-tungstate crystal electromagnetic, and brass and scintillator hadron calorimeters, operating inside a 3.8 T superconducting solenoid, with data from the gas-ionization muon detectors embedded in the flux-return yoke outside the solenoid. Objects such as hadronically decaying τ leptons [28] are built from the reconstructed particles.

For each data-taking year, a sample of simulated events containing B_c^+ mesons is produced with the BCVEGPY

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[29,30] Monte Carlo (MC) event generator, interfaced with EVTGEN1.6.0 [31,32] for decays of weakly decaying hadrons, and with PYTHIA8.240 [33] for parton showering, hadronization, and underlying event modeling using the CP5 tune [34]. The events include the signal modes, $B_c^+ \to J/\psi\tau^+\nu_\tau$ and $B_c^+ \to J/\psi\mu^+\nu_\mu$, and other $B_c^+ \to J/\psi H_c X$ decays, where H_c indicates a (possibly excited) charm meson and X indicates additional products. The TAUOLA1.1.5 program is used to simulate τ decays [35,36]. Contributions from $\psi(2S)$, $\chi_{c1}(1P)$, and $\chi_{c2}(1P)$ feed-down decays to J/ψ mesons are also included. The branching fractions of the decays are obtained from their measured values or theoretical predictions [37–41]. Most of the contributions that satisfy our selection criteria come from $B_c^+ \to J/\psi D_s^{(*)+}$ decays. Contributions from other B_c^+ decays ($B_c^+ \to$ others) are primarily from $B_c^+ \to J/\psi D^{(*)+}$, $B_c^+ \to J/\psi D^+ K^{(*)0}$, and $B_c^+ \to J/\psi D^{(*)0} K^+$ decays. To account for decays not included in the simulation, the $B_c^+ \to$ others yields are scaled up with a factor calculated from an investigation of the effect in simulation of other expected but unobserved B_c^+ decay modes: $B_c^+ \to J/\psi H_c X$, where H_c includes charm meson excited states above the $D^{(*)}$ and X includes up to two pions or kaons, either neutral or charged. The $B_c^+ \to J/\psi \ell \nu$ ($\ell = \mu$, τ) decay was generated with an hadronic model using the Kiselev form factor parametrization [42], updated to the parametrization in Ref. [43] by reweighting the generated events using the HAMMER [44] framework. The events are also reweighted to match the world-average B_c^+ mean lifetime value of 0.510 ps [45]. We initially normalize the B_c^+ MC samples to the data in a two step process. The normalization of the 2018 MC sample is taken from the leptonic τ analysis [14] by comparing the $B_c^+ \to J/\psi\mu^+\nu_\mu$ yields in the measured and simulated event samples. To normalize the 2016 and 2017 MC samples, we reconstruct and select $B_c^+ \to J/\psi\pi^+\pi^-\pi^+$ candidates, fit the invariant mass distributions of data and MC to obtain the yields for each year, calculate the data/MC ratio of yields, calculate the ratio of the 2016 and 2017 results to the 2018 result, and multiply by the 2018 normalization value.

A second (background) simulated sample of $H_b \to J/\psi X$ decay events, where H_b indicates a ground state b hadron other than B_c^+, and the J/ψ decays to a pair of muons, is generated by PYTHIA with the "SoftQCD:nonDiffractive" process. One H_b hadron in each event is forced to decay in a mode with a J/ψ meson. The $H_b \to J/\psi X$ decays are simulated with EVTGEN, including feed-down decays of heavier charmonium states. This sample is used to derive corrections in the estimation of the inclusive $H_b \to J/\psi X$ background.

The simulated samples include effects from additional pp interactions in the same or nearby bunch crossings (pileup), generated with PYTHIA, with a multiplicity distribution tuned to match the data. Final-state photon radiation is modeled by PHOTOS3.61 [46]. The interactions between particles and the CMS detector are simulated using GEANT4 [47] and the output is processed through the standard CMS reconstruction software.

Events are collected with a trigger that requires a pair of oppositely-charged muons, each with transverse momentum $p_\mathrm{T} > 4$ GeV. The two muons are used to form a J/ψ candidate, which must have vertex fit probability above 10%, $p_\mathrm{T} > 6.9$ GeV, and invariant mass of 2.9–3.3 GeV. The displacement in the transverse plane between the beam axis and the dimuon vertex is required to be at least three times the uncertainty in the displacement, i.e., a significance above 3. An additional track with $p_\mathrm{T} > 1.2$ GeV is required to be present, form a vertex with the J/ψ candidate muons, and be displaced with respect to the beam axis with a significance above 2.

Offline, the two muons are required to match the muons used in the trigger, satisfy the trigger requirements, pass a set of loose identification (ID) criteria [25], and have an invariant mass of 2.95–3.25 GeV. If multiple J/ψ candidates are found in an event (around 1% of the events), the highest p_T one is selected. We define the primary vertex (PV) as the pp collision vertex with the shortest distance along the beam axis to the line defined by the J/ψ candidate momentum direction that intersects the dimuon vertex. Scale factors are derived for each data-taking year and applied to the simulated events to match the data efficiencies. The trigger efficiency comes from events that pass a different trigger than used for the signal and the offline muon reconstruction and identification efficiency uses the tag-and-probe method with J/ψ events [25]. Three trigger scale factors are applied, one for the J/ψ selection binned in muon p_T and pseudorapidity ($|\eta|$), one for the J/ψ displacement binned in the significance of the displacement in the transverse plane between the beam axis and the dimuon vertex, and one for the hadron track binned in track p_T, $|\eta|$, and impact parameter significance. The muon scale factor is applied to both muons and is binned in muon p_T and $|\eta|$.

Triplets of PF charged hadrons are used to create τ_had^+ candidates, with each charged hadron required to have $p_\mathrm{T} > 0.5$ GeV, $|\eta| < 2.5$, pass within 1.2 mm of the PV in the longitudinal direction, have $\sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} < 1$, where $\Delta\eta$ and $\Delta\phi$ are measured with respect to the J/ψ candidate momentum, and a distance of closest approach with respect to the J/ψ vertex between -0.4 and 0.6 mm, where the sign depends on the angle between the track and the J/ψ momentum direction. The triplet must have a charge of ± 1, vertex fit probability above 10%, $p_\mathrm{T} > 3$ GeV, displacement significance with respect to the PV above 3, and invariant mass below 1.7 GeV. At least one pion candidate must match the track object found by the trigger. When multiple triplets are found, we select the highest-p_T one. This occurs in 20% of simulated signal events and the selection is correct in 70% of the events.

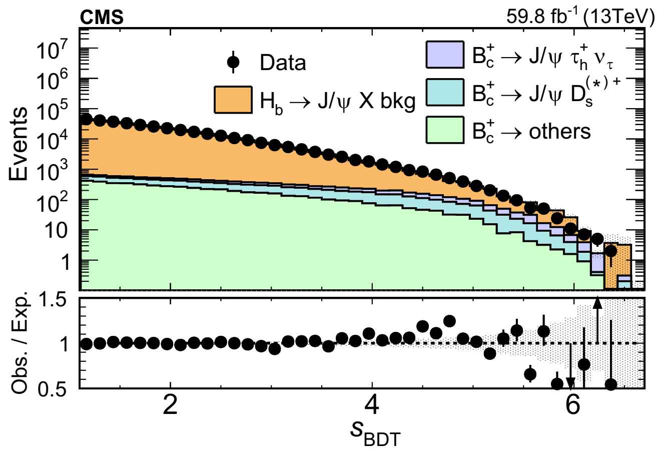

FIG. 1. The s_{BDT} distribution. The bars on the data points represent the statistical uncertainties. The simulated $H_b \to J/\psi X$ contribution is normalized to match the yield in data after applying all event selection criteria except the BDT. The $B_c^+ \to J/\psi X$ processes are normalized before the $\mathcal{R}_{J/\psi}$ fit. The lower panel displays the ratio between the data and the sum of expected signal and background contributions, with the statistical uncertainty in the sum of the simulated contributions shown by a gray band.

After these requirements, over 99.98% of the events are inclusive B^0 and B^+ background events with a J/ψ candidate in the final state. We use a discriminator based on a boosted decision tree (BDT) trained with the XGBOOST algorithm [48] to suppress the background. The $B_c^+ \to J/\psi\tau^+\nu_\tau$ simulated sample is used as signal for the training with the selected τ lepton candidate matched to the generator-level τ_{had}^+. The simulated $H_b \to J/\psi X$ sample is used as the background process. The BDT hyperparameters were optimized using a Bayesian technique and comparisons between data and simulation on control regions not used in the analysis were used to check the agreement. A training with background events from data was found to yield similar results. The BDT uses 18 input variables related to the kinematic and topological properties of the B meson and τ lepton candidates, as well as global event-level observables. The s_{BDT} distribution is depicted in Fig. 1, where expected simulated events are compared to 2018 data considering just the statistical uncertainties before the fit for $\mathcal{R}_{J/\psi}$.

Using the s_{BDT} variable, two regions are defined in each data-taking period: for the 2016 (2017–2018) data a signal-enriched region (SR) with $s_{\mathrm{BDT}} > 3.5$ ($s_{\mathrm{BDT}} > 4.2$) and a background-enriched sideband region (SB) with $2 < s_{\mathrm{BDT}} < 3$ ($2.5 < s_{\mathrm{BDT}} < 3.5$). The SR region is optimized to maximize the signal significance, while the SB region is defined to include a sufficiently large number of events with s_{BDT} values close enough to the SR to represent the background in that region, but far enough to minimize signal contamination. In the SR, the signal and background efficiencies relative to the baseline selection are 10% and 0.01%, respectively. The 2016 and 2017–2018 s_{BDT} regions differ because of a new pixel system installed after the 2016 data-taking period [49]. For simulated signal events in the SR, 90% of the τ_{had}^+ candidates are created from the three pions from the τ decay, while 10% are created from two pions from the τ decay plus an unrelated track. Both are considered signal.

We exploit the dominant three-prong hadronic τ lepton decay $\tau^+ \to a_1(1260)^+\bar{\nu}_\tau$ [50] for the signal extraction, where $a_1(1260)^+ \to \rho(770)^0(\to \pi^+\pi^-)\pi^+$. A one-dimensional distribution is built from the ρ_1 vs ρ_2 invariant masses two-dimensional distribution, where ρ_1 and ρ_2 are the two possible $\rho(770)^0 \to \pi^+\pi^-$ candidates from each τ_{had}^+ candidate ordered in p_{T}. We consider the mass range 0.2–1.5 GeV for ρ_1 and ρ_2, each split into four bins with widths of 0.225 GeV for the first three and 0.625 GeV for the last. This is referred to as the unrolled $m(\rho_1)$ vs $m(\rho_2)$ distribution. Genuine τ lepton decays will tend to peak in either the ρ_1 or ρ_2 invariant mass distribution. This is not the case for background events, which typically do not include τ lepton decays. The ρ_1 and ρ_2 invariant masses are not included in the BDT and are found to be independent of s_{BDT}.

Maximum likelihood fits are performed using the COMBINE tool [51]. The data used by the fit are the same as used in the leptonic τ analysis [14] plus six unrolled $m(\rho_1)$ vs $m(\rho_2)$ mass distributions (SB and SR for three data-taking periods). The signal strength parameter r is proportional to the parameter of interest, $\mathcal{R}_{J/\psi}$ and therefore only scales the $B_c^+ \to J/\psi\tau^+\nu_\tau$ yield. Another free parameter, $r_{B_c^+}$, multiplies the initial normalization of all B_c^+ MC events, including the B_c^+ background as well as the $B_c^+ \to J/\psi\mu^+\nu_\mu$ and $B_c^+ \to J/\psi\tau^+\nu_\tau$ contributions. The value of $r_{B_c^+}$ is primarily determined by the (large) number of $B_c^+ \to J/\psi\mu^+\nu_\mu$ events. The fit model for the leptonic τ distributions is the same as in Ref. [14]. For the hadronic τ distributions, the B_c^+ MC sample is split into $B_c^+ \to J/\psi\tau^+\nu_\tau$ signal, $B_c^+ \to J/\psi D_s^{(*)+}$ background, and other B_c^+ backgrounds, with the unrolled $m(\rho_1)$ vs $m(\rho_2)$ shapes for each contribution determined from simulation and the normalization set by r and $r_{B_c^+}$.

The expected yield of $H_b \to J/\psi X$ events in the ith bin of the unrolled $m(\rho_1)$ vs $m(\rho_2)$ distribution in the SR is derived from the SB data after subtracting the expected number of B_c^+ events:

$$N_{H_b}(\mathrm{SR}, i) = f_{\mathrm{ext}}(i)[N_{\mathrm{data}}(\mathrm{SB}, i) - r_{B_c^+}N_{B_c^+,\mathrm{bkg}}(\mathrm{SB}, i) - r_{B_c^+}rN_{B_c^+,\mathrm{sig}}(\mathrm{SB}, i)]. \quad (1)$$

The parameters $N_{B_c^+,\mathrm{bkg}}$ and $N_{B_c^+,\mathrm{sig}}$ denote the number of B_c^+ background events ($B_c^+ \to J/\psi D_s^{(*)+}$ and $B_c^+ \to$ others) and signal events, respectively. The $f_{\mathrm{ext}}(i)$ factors, around 0.06–0.11, are calculated from simulated $H_b \to J/\psi X$

events to scale the $H_b \to J/\psi X$ background from the SB to the SR. Before calculating $f_{\mathrm{ext}}(i)$, the simulated $H_b \to J/\psi X$ events are reweighted to account for differences in the data and MC s_{BDT} distributions. The reweighting is done by fitting the data to simulation s_{BDT} ratio after subtracting the expected B_c^+ contribution to the data, fitting this ratio in the region of $0 < s_{\mathrm{BDT}} < 3$ for 2016 and $0 < s_{\mathrm{BDT}} < 3.5$ for 2017–2018 samples, and using this fitted function to reweight all MC $H_b \to J/\psi X$ events in the SB and SR regions.

To validate the background extrapolation method, two studies are performed using different control regions. First, we use the SB data to predict the backgrounds in the "separation" region between the SB and the SR, i.e., $3.0 < s_{\mathrm{BDT}} < 3.5$ for 2016 and $3.5 < s_{\mathrm{BDT}} < 4.2$ for 2017–2018 samples. Second, we select events by inverting at least one requirement on the vertex probability and the displacement significance of the τ lepton in the SR and SB. The modified SB is used to predict the background in the modified SR. Agreement between the predicted and observed background is found in both cases. In addition, the background predicted from the nominal SB is seen to agree with the simulated background within the statistical uncertainty in the simulation.

Systematic uncertainties for the normalization and shapes of the model are implemented as nuisance parameters in the fit. Table I provides a summary of the systematic uncertainties, including information on the type of systematic uncertainty (affecting shape or normalization), which samples it affects, and its correlation across the different analysis channels. All systematic uncertainties are fully correlated between the SB and SR.

The B_c^+ form factor uncertainty is evaluated with the HAMMER framework [44] by considering ten variations that modify both the $B_c^+ \to J/\psi\mu^+\nu_\mu$ and $B_c^+ \to J/\psi\tau^+\nu_\tau$ decays, with each variation corresponding to an eigenvector of the ten different BGL parameters [43].

While $\tau^+ \to a_1(1260)^+\bar{\nu}_\tau$, $a_1(1260)^+ \to \rho(770)^0 (\to \pi^+\pi^-)\pi^+$ dominates $\tau^+ \to a_1(1260)^+\bar{\nu}_\tau \to \pi^+\pi^-\pi^+\nu_\tau$ decays, the nonresonant $a_1(1260)^+ \to \pi^+\pi^-\pi^+$ decay has also been observed, and the relative rates are unknown [37]. To account for this, generator-level events are simulated with an alternative TAUOLA setting (changing "TauolaCurrentOption" from 1 (*BABAR*-tuned) to 0 (CLEO-tuned)), and the resulting signal template is built by reweighting events based on the generator-level unrolled $m(\rho_1)$ vs $m(\rho_2)$ distribution.

The $H_b \to J/\psi X$ background is estimated from data in the SB region. Possible shape differences in the ρ^0 mass distributions between SB and SR are corrected via the bin-by-bin extrapolation factors $f_{\mathrm{ext}}(i)$, which are obtained from simulation. These factors are varied within their uncertainties and the resulting templates are included as a systematic uncertainty. They are treated as uncorrelated between all bins of the unrolled $m(\rho_1)$ vs $m(\rho_2)$ distribution, as they are dominated by the statistical uncertainties of the simulated events. The uncertainties are typically in the 5–20% range.

The variation of the B_c^+ lifetime within its measured uncertainty is applied to all B_c^+ decays.

TABLE I. Systematic uncertainties considered in this analysis. The first, second, and third columns give the source, the type of effect (shape or normalization), and affected processes, respectively. A given uncertainty treated as fully correlated between analysis channels is marked with "✓". Uncertainties that are irrelevant or negligible are marked with "$\cdots$".

			Channel			
Source	Type	Affected process	τ_μ 2018	τ_{h} 2018	τ_{h} 2017	τ_{h} 2016
Form factor	Shape	$B_c^+ \to J/\psi\ell\nu_\ell$	✓	✓	✓	✓
TAUOLA model	Shape	$B_c^+ \to J/\psi\tau^+\nu_\tau$	$\cdots$	✓	✓	✓
$H_b \to J/\psi X$ shape	Shape	$H_b \to J/\psi X$ (data)	$\cdots$	✓	✓	✓
Pileup weight	Shape	All MC	✓	✓	✓	✓
B_c^+ lifetime	Shape	All B_c^+ processes	✓	✓	✓	✓
$B_c^+ \to$ others	Shape	$B_c^+ \to$ others	$\cdots$	✓	✓	✓
Finite MC size	Shape	All	✓	✓	✓	✓
Triplet reconstruction efficiency	Normalization	$B_c^+ \to J/\psi\tau^+\nu_\tau$	$\cdots$	6.9% (✓)	6.9% (✓)	6.9% (✓)
$B_c^+ \to J/\psi D_s^{(*)+}$ normalization	Normalization	$B_c^+ \to J/\psi D_s^{(*)+}$	38% (✓)	38% (✓)	38% (✓)	38% (✓)
$B_c^+ \to$ others normalization	Normalization	$B_c^+ \to$ others	$\cdots$	50% (✓)	50% (✓)	50% (✓)
Trigger ($\mu^+\mu^-$)	Normalization	All MC	10% (✓)	10% (✓)$\oplus$ 5%	10%	10%
Trigger (track)	Normalization	All MC	$\cdots$	10%	10%	10%
Trigger (J/ψ)	Normalization	All MC	$\cdots$	10%	10%	10%
Muon ID	Normalization	All MC	4%	4%	4%	4%
Muon reconstruction efficiency	Normalization	All MC	4% (✓)	4% (✓)	4%	4%
$H_b \to J/\psi X$ normalization	Normalization	$H_b \to J/\psi X$ (data)	$\cdots$	30%	30%	30%
B_c^+ MC normalization	Normalization	All B_c^+	$\cdots$	5%	30%	30%

The pileup modeling uncertainty is assessed for all simulated processes by varying the total inelastic cross section used to generate the pileup distributions [52].

As previously described, the unknown contributions to $B_c^+ \to$ others are accounted for by scaling up the generated MC events. Uncertainties on the normalization (amounting to half of the scaling) and shape are assessed.

The statistical uncertainties of the simulated events are included independently in each bin. This uncertainty is also propagated to the $H_b \to J/\psi X$ background estimate from the subtraction in Eq. (1).

The hadronic τ decay contains three pions compared to the normalization channel of one muon. Therefore, discrepancies in the track reconstruction efficiency between data and simulation will affect the result. A 2.3% uncertainty [53] is assumed per track, yielding a total normalization uncertainty of 6.9% affecting the $B_c^+ \to J/\psi\tau^+\nu_\tau$ process. A check is performed by measuring the yields of the $B^+ \to J/\psi K^+$ and $B^+ \to \psi(2S)(\to J/\psi\pi^+\pi^-)K^+$ processes, as the only difference between the two processes is the track multiplicity. The ratios of the yields in data and simulation differ by 4.4%, corresponding to an uncertainty of 2.2% per track, compatible with the assumed 2.3% uncertainty per track.

The normalization uncertainty for the $B_c^+ \to J/\psi D_s^{(*)+}$ background originates from experimentally measured branching fractions as in the leptonic τ analysis [14].

Uncertainties in the efficiencies of the muon reconstruction (4%), ID (4%), and trigger selection (10%) are considered. These uncertainties are considered uncorrelated across data-taking years. For 2018, the muon trigger uncertainties are partly correlated between this analysis and the leptonic τ analysis because the event selection is similar, with an additional uncorrelated 5% uncertainty owing to differences in online muon selection. The muon reconstruction uncertainty is also correlated, whereas the muon ID uncertainty is uncorrelated as different criteria are used. Trigger efficiency uncertainties related to the track reconstruction (10%) and the J/ψ candidate vertex displacement requirement (10%) are also considered.

Given the uncertainty in the check of the backgrounds predicted from the SBs in the "separation" regions and those with the inverted τ lepton selection, a 30% uncertainty is assigned to the $H_b \to J/\psi X$ background normalization, uncorrelated across years.

The normalization of the B_c^+ MC samples for 2016 and 2017 relative to 2018 is obtained from the ratio of the yields of $B_c^+ \to J/\psi\pi^+\pi^-\pi^+$ events in data and MC in each year. These relative correction factors for 2016 and 2017 are also calculated using the $B_c^+ \to J/\psi\pi^+$ invariant mass peak, and the difference with respect to the ones from $B_c^+ \to J/\psi\pi^+\pi^-\pi^+$ is used to determine a B_c^+ MC normalization systematic uncertainty of 30% for each of 2016 and 2017 periods, uncorrelated by year.

The leading systematic uncertainties for the hadronic τ analysis are from the $H_b \to J/\psi X$ background estimation, obtained from data, and its extrapolation from the SB to the SR, which is based on simulation.

Several fits have been performed using different subsets of the data. As the hadronic τ analysis relies on the leptonic

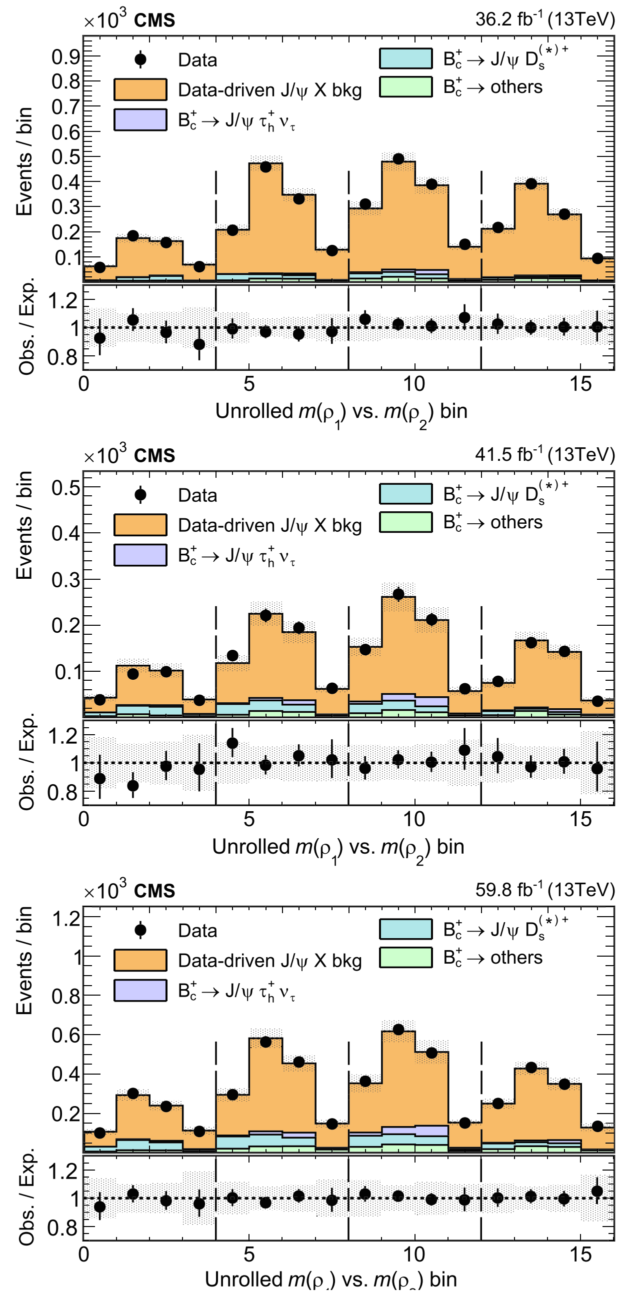

FIG. 2. The SR unrolled $m(\rho_1)$ vs $m(\rho_2)$ distributions for the 2016 (upper), 2017 (middle), and 2018 (lower) data-taking periods. The dashed vertical lines indicate bins in $m(\rho_1)$. Histograms show the postfit expected yields of the $H_b \to J/\psi X$ background estimated from data and simulated $B_c^+ \to J/\psi\tau^+\nu_\tau$, $B_c^+ \to J/\psi D_s^{(*)+}$, and $B_c^+ \to$ others processes. The ratio between the data and the sum of postfit signal and background is shown in the lower panel, with a gray band showing the total expected event yield uncertainty.

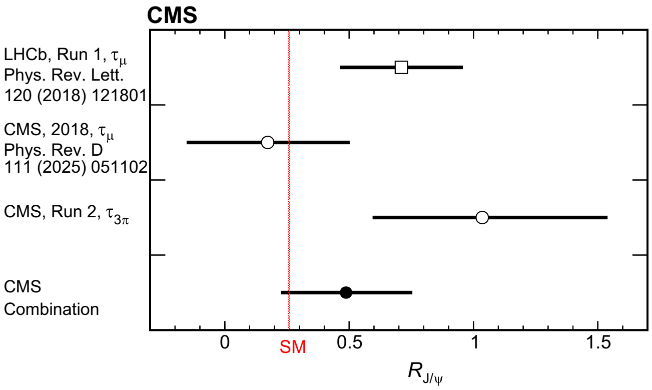

FIG. 3. Summary of $\mathcal{R}_{J/\psi}$ measurements from LHCb leptonic τ decays [8], CMS leptonic τ decays [14], CMS hadronic τ decays, and the CMS combination. The total uncertainties in the measured values are indicated by the horizontal lines. The vertical red line is the SM prediction.

τ data to determine the $B_c^+ \to J/\psi\mu^+\nu_\mu$ yield, we cannot obtain a completely independent hadronic τ value for $\mathcal{R}_{J/\psi}$. However, we can fit the hadronic τ and leptonic τ data with separate $\mathcal{R}_{J/\psi}$ parameters for each. In this case, the two results share a common denominator ($B_c^+ \to J/\psi\mu^+\nu_\mu$ yield), but the $B_c^+ \to J/\psi\tau^+\nu_\tau$ yields are independent. Incorporating just the 2018 data to match the leptonic τ analysis, this fit returns $\mathcal{R}_{J/\psi}^{\mathrm{had},2018} = 0.74^{+0.57}_{-0.53}$. Including the hadronic τ decay data recorded in 2016 and 2017, a value of $\mathcal{R}_{J/\psi}^{\mathrm{had}} = 1.04^{+0.50}_{-0.44}$ is obtained. We verified that this result is stable against inflating the prefit uncertainty in the $B_c^+ \to J/\psi X$ normalization. Given the uncertainties, this result is compatible with that of the leptonic τ analysis, 0.17 ± 0.33. We compared the likelihoods of the fits to the data of this analysis and to the data of the leptonic τ analysis when assuming one common parameter r or two independent parameters r_{lep} and r_{had}. The likelihood ratio, expressed as $-2\ln\mathcal{L}(\mathrm{data}|r)/\mathcal{L}(\mathrm{data}|r_{\mathrm{lep}}, r_{\mathrm{had}})$, is 2.06, corresponding to a p-value [54] of 0.15, indicating that the two measurements are compatible.

Finally, we perform a simultaneous fit in all analysis regions of this and of the leptonic τ analysis to obtain $\mathcal{R}_{J/\psi} = 0.49 \pm 0.11(\mathrm{stat}) \pm 0.23(\mathrm{syst}) \pm 0.07(\mathrm{theo})$, where the last uncertainty corresponds to the B_c^+ form factors and the systematic uncertainty includes the other systematic uncertainties. Figure 2 shows the SR unrolled $m(\rho_1)$ vs $m(\rho_2)$ distributions of the data and of the final fit for each of the three data-taking years. The results agrees with the SM prediction of 0.258 ± 0.004, as shown in Fig. 3, where a summary of the CMS measurements in each τ decay channel, their combination, the SM prediction, and the LHCb result [8] are presented.

In summary, the branching fraction ratio $\mathcal{R}_{J/\psi} = \mathcal{B}(B_c^+ \to J/\psi\tau^+\nu_\tau)/\mathcal{B}(B_c^+ \to J/\psi\mu^+\nu_\mu)$ has been measured using $J/\psi \to \mu^+\mu^-$ decays for both the numerator and denominator, and the three-prong hadronic τ decay for the numerator. Proton-proton collision data at $\sqrt{s} = 13$ TeV collected by the CMS experiment are used, corresponding to an integrated luminosity of 138 fb^{-1} for the numerator and 59.7 fb^{-1} for the denominator. This is the first contribution to lepton flavor universality tests in B_c^+ meson decays with hadronic τ decays. The ratio is measured to be $\mathcal{R}_{J/\psi}^{\mathrm{had}} = 1.04^{+0.50}_{-0.44}$. Combined with our previous measurement using leptonic τ decays [14], the result is $\mathcal{R}_{J/\psi} = 0.49 \pm 0.26$, consistent with the standard model prediction of 0.258 ± 0.004.

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Data availability. Release and preservation of data used by the CMS Collaboration as the basis for publications is guided by the CMS data preservation, re-use and open access policy [55].

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[l]Also at China Spallation Neutron Source, Guangdong, China.
[m]Also at Henan Normal University, Xinxiang, China.
[n]Also at University of Shanghai for Science and Technology, Shanghai, China.
[o]Also at The University of Iowa, Iowa City, Iowa, USA.
[p]Also at Center for High Energy Physics, Peking University, Beijing, China.
[q]Also at Helwan University, Cairo, Egypt.
[r]Also at Zewail City of Science and Technology, Zewail, Egypt.
[s]Also at British University in Egypt, Cairo, Egypt.
[t]Also at Cairo University, Cairo, Egypt.
[u]Also at Purdue University, West Lafayette, Indiana, USA.
[v]Also at Université de Haute Alsace, Mulhouse, France.
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[kk]Also at Punjab Agricultural University, Ludhiana, India.
[ll]Also at University of Visva-Bharati, Santiniketan, India.
[mm]Also at Indian Institute of Science (IISc), Bangalore, India.
[nn]Also at Amity University Uttar Pradesh, Noida, India.
[oo]Also at UPES—University of Petroleum and Energy Studies, Dehradun, India.
[pp]Also at IIT Bhubaneswar, Bhubaneswar, India.
[qq]Also at Institute of Physics, Bhubaneswar, India.
[rr]Also at University of Hyderabad, Hyderabad, India.
[ss]Also at Deutsches Elektronen-Synchrotron, Hamburg, Germany.
[tt]Also at Isfahan University of Technology, Isfahan, Iran.
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[yy]Also at Centro Siciliano di Fisica Nucleare e di Struttura Della Materia, Catania, Italy.
[zz]Also at James Madison University, Harrisonburg, N/A, USA.

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[bbb]Also at Scuola Superiore Meridionale, Università di Napoli 'Federico II', Napoli, Italy.
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[sss]Also at Konya Technical University, Konya, Turkey.
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