Measurement of $B_c(2S)^+$ and $B_c^*(2S)^+$ cross section ratios in proton-proton collisions at $\sqrt{s} = 13$ TeV

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The ratios of the $B_c(2S)^+$ to B_c^+, $B_c^*(2S)^+$ to B_c^+, and $B_c^*(2S)^+$ to $B_c(2S)^+$ production cross sections are measured in proton-proton collisions at $\sqrt{s} = 13$ TeV, using a data sample collected by the CMS experiment at the LHC, corresponding to an integrated luminosity of 143 fb^{-1}. The three measurements are made in the B_c^+ meson phase space region defined by the transverse momentum $p_T > 15$ GeV and absolute rapidity $|y| < 2.4$, with the excited $B_c^{(*)}(2S)^+$ states reconstructed through the $B_c^{(*)+}\pi^+\pi^-$, followed by the $B_c^+ \to J/\psi\pi^+$ and $J/\psi \to \mu^+\mu^-$ decays. The $B_c(2S)^+$ to B_c^+, $B_c^*(2S)^+$ to B_c^+, and $B_c^*(2S)^+$ to $B_c(2S)^+$ cross section ratios, including the unknown $B_c^{(*)}(2S)^+ \to B_c^{(*)+}\pi^+\pi^-$ branching fractions, are $(3.47 \pm 0.63(\text{stat}) \pm 0.33(\text{syst}))\%$, $(4.69 \pm 0.71(\text{stat}) \pm 0.56(\text{syst}))\%$, and $1.35 \pm 0.32(\text{stat}) \pm 0.09(\text{syst})$, respectively. None of these ratios shows a significant dependence on the p_T or $|y|$ of the B_c^+ meson. The normalized dipion invariant mass distributions from the decays $B_c^{(*)}(2S)^+ \to B_c^{(*)+}\pi^+\pi^-$ are also reported.

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I. INTRODUCTION

The production cross sections of the B_c^+ family of mesons, quark-antiquark bound states of two different flavors, charm and beauty, are significantly smaller than those of the charmonium and bottomonium states. The unprecedented collision energies and integrated luminosities of the proton-proton (pp) data samples collected at the CERN LHC allow, for the first time, detailed studies regarding the production and properties of B_c^+ quarkonia. The observation of the $B_c(2S)^+$ and $B_c^*(2S)^+$ states was recently reported by the CMS experiment [1], using a pp data sample collected at $\sqrt{s} = 13$ TeV between 2015 and 2018, on the basis of well-resolved peaks in the $B_c^+\pi^+\pi^-$ invariant mass distribution, with the B_c^+ meson reconstructed in the $B_c^+ \to J/\psi\pi^+$ decay channel, and $J/\psi \to \mu^+\mu^-$. The LHCb Collaboration also reported the observation of the $B_c^*(2S)^+$ state, using a pp data sample collected at 7, 8, and 13 TeV [2]. Masses of the $B_c(2S)^+$ and $B_c^*(2S)^+$ states are found to be consistent with theoretical predictions [3–5]. These results stimulated new theoretical studies aimed at reaching a better understanding of the B_c^+ quarkonium family, such as those reported in Refs. [6,7].

The present paper reports an analysis that complements the previous observation of the $B_c(2S)^+$ and $B_c^*(2S)^+$ states [1] with the measurement of the $B_c(2S)^+$ to B_c^+, $B_c^*(2S)^+$ to B_c^+, and $B_c^*(2S)^+$ to $B_c(2S)^+$ cross section ratios, an important step in making further progress on understanding these two excited B_c^+ states. The invariant mass distributions of the pair of pions emitted in the $B_c^{(*)}(2S)^+ \to B_c^{(*)+}\pi^+\pi^-$ decays are also presented, to probe the existence of possible intermediate structure analogous to the ones observed in decays between the 2S and 1S states of charmonium and bottomonium [6,7]. Throughout this paper, $B_c^{(*)+}$ denotes B_c^+ or B_c^{*+}, and $B_c^{(*)}(2S)^+$ denotes $B_c(2S)^+$ or $B_c^*(2S)^+$. Charge-conjugate states are also implied, unless stated otherwise. The data sample of 13 TeV pp collisions used in this analysis corresponds to an integrated luminosity of 143 fb^{-1} and was collected by CMS between 2015 and 2018. The measurements are performed in a phase space region defined by the B_c^+ meson transverse momentum $p_T > 15$ GeV and rapidity $|y| < 2.4$.

II. EXPERIMENTAL APPARATUS, DATA SAMPLE, AND EVENT SELECTION

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the solenoid volume are a silicon pixel and strip tracker, a lead tungstate crystal

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electromagnetic calorimeter, and a brass and scintillator hadron calorimeter, each composed of a barrel and two end cap sections. Muons are measured in the pseudorapidity range $|\eta| < 2.4$, with detection planes made using three technologies: drift tubes, cathode strip chambers, and resistive plate chambers. Matching muons to tracks measured in the silicon tracker results in a relative transverse momentum resolution, for muons with p_T up to 100 GeV, of 1% in the barrel and 3% in the end caps [8]. The single-muon trigger efficiency exceeds 90% over the full η range, and the efficiency to reconstruct and identify muons is greater than 96%. A more detailed description of the CMS detector, together with a definition of the coordinate system used and relevant kinematic variables, can be found in Ref. [9].

The event sample was collected with a two-level trigger system [10]. At level 1, custom hardware processors select events with two muons. The high-level trigger requires an opposite-sign muon pair of invariant mass in the range 2.9–3.3 GeV, a dimuon vertex fit χ^2 probability larger than 10%, a distance of closest approach between the two muons smaller than 0.5 cm, and a distance between the dimuon vertex and the beam axis, L_{xy}, larger than 3 times its uncertainty. Both muons must have $p_T > 4$ GeV and $|\eta| < 2.5$. In addition $\vec{p}_T$ must be aligned with the dimuon transverse decay displacement vector $\vec{L}_{xy}$ by requiring $\cos\theta > 0.9$, where $\cos\theta = \vec{L}_{xy} \cdot \vec{p}_T/(L_{xy} p_T)$. The trigger also requires a third track in the event, compatible with being produced at the dimuon vertex (normalized $\chi^2 < 10$), and having $p_T > 1.2$ GeV, $|\eta| < 2.5$, and a significance on the track impact parameter of at least 2. The off-line reconstruction requires two opposite-sign muons matching those that triggered the detector readout, with some requirements being stricter than at the trigger level, such as $|\eta| < 2.4$ and $\cos\theta > 0.98$. The muon candidates must pass high-purity track quality requirements [11], and fulfill the soft-muon identification requirements [8], which imply, in particular, that there are more than five hits in the silicon tracker, with at least one in the pixel layers. The two muons must also be close to each other in angular space: $\sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} < 1.2$, where $\Delta\eta$ and $\Delta\phi$ are the differences in pseudorapidity and azimuthal angle, respectively, between their momenta.

III. MEASUREMENT OF THE CROSS SECTION RATIOS

A. Introduction

The ratios of the $B_c^{(*)}(2S)^+$ to B_c^+ and $B_c^*(2S)^+$ to $B_c(2S)^+$ cross sections, R^{*+}, R^+, and R^{*+}/R^+, respectively, reported in this paper are derived from the ratios of the measured yields, corrected by the detection efficiencies, ϵ:

$$\begin{aligned}
R^+ &\equiv \frac{\sigma(B_c(2S)^+)}{\sigma(B_c^+)} \mathcal{B}(B_c(2S)^+ \to B_c^+\pi^+\pi^-) \\
&= \frac{N(B_c(2S)^+)}{N(B_c^+)} \frac{\epsilon(B_c^+)}{\epsilon(B_c(2S)^+)}, \\
R^{*+} &\equiv \frac{\sigma(B_c^*(2S)^+)}{\sigma(B_c^+)} \mathcal{B}(B_c^*(2S)^+ \to B_c^{*+}\pi^+\pi^-) \\
&= \frac{N(B_c^*(2S)^+)}{N(B_c^+)} \frac{\epsilon(B_c^+)}{\epsilon(B_c^*(2S)^+)}, \\
R^{*+}/R^+ &= \frac{\sigma(B_c^*(2S)^+)}{\sigma(B_c(2S)^+)} \frac{\mathcal{B}(B_c^*(2S)^+ \to B_c^{*+}\pi^+\pi^-)}{\mathcal{B}(B_c(2S)^+ \to B_c^+\pi^+\pi^-)} \\
&= \frac{N(B_c^*(2S)^+)}{N(B_c(2S)^+)} \frac{\epsilon(B_c(2S)^+)}{\epsilon(B_c^*(2S)^+)}. \qquad (1)
\end{aligned}$$

The $\mathcal{B}$ parameters are the unknown branching fractions of the $B_c^{(*)}(2S)^+ \to B_c^{(*)+}\pi^+\pi^-$ decays. The B_c^{*+} meson is assumed to decay to the B_c^+ ground state and a low-energy photon with a branching fraction of 100%, where the photon is not reconstructed.

B. Measurement of the B_c^+ yield

The $B_c^+ \to J/\psi\pi^+$ candidates are reconstructed through a kinematic vertex fit, combining the dimuon with another track. The dimuon invariant mass is constrained to the world-average J/ψ mass [12] and the other track assumed to be a pion must fulfill $|\eta| < 2.4$ and $p_T > 3.5$ GeV. The primary vertex (PV) associated with the B_c^+ candidate is selected among all the reconstructed vertices [13] as the one with the smallest angle between the reconstructed B_c^+ momentum and the vector joining the PV with the B_c^+ decay vertex. To avoid biases, this PV is then refitted without the tracks associated with the muons and the pion. The B_c^+ candidates are required to have $p_T > 15$ GeV, $|y| < 2.4$, a kinematic vertex fit χ^2 probability larger than 10%, and a decay length (distance between the $J/\psi\pi^+$ vertex and the PV) larger than 100 μm. If several B_c^+ candidates are found in the same event, which happens in 1.6% of the events, only the one with the highest p_T is kept. Simulation studies show that this choice identifies the correct candidate with 99% probability. These selection criteria were defined through studies of simulated signal samples and measured sideband events [1].

Figure 1 shows the invariant mass distribution of the reconstructed and selected $B_c^+ \to J/\psi\pi^+$ candidates, where the B_c^+ signal is clearly seen as a prominent peak [1]. The result of an unbinned maximum-likelihood fit is also shown, together with the signal and background contributions. The underlying background is modeled as the sum of three terms: (a) uncorrelated J/ψ-track combinations (combinatorial background) parametrized by a first-order polynomial, (b) partially reconstructed $B_c^+ \to J/\psi\pi^+X$ decays, only relevant for invariant mass values below 6.2 GeV and parametrized by a generalized ARGUS function [14] convolved with a Gaussian resolution, and (c) a small contribution from $B_c^+ \to J/\psi K^+$ decays, with a shape fixed from simulation studies (described later) and a normalization fixed by the $B_c^+ \to J/\psi\pi^+$ yield, scaled by the ratio of the corresponding branching fractions [15] and reconstruction efficiencies. The B_c^+ signal peak is modeled by a double-Gaussian function,

$$wG(\mu,\sigma_1) + (1-w)G(\mu,\sigma_2), \qquad (2)$$

where $G(\mu,\sigma)$ represents a Gaussian function with mean μ and standard deviation σ, and w is the relative fraction of the narrower Gaussian in the fit. The single mean μ corresponds to the average reconstructed B_c^+ mass. The fit gives $w = 47\%$, $\sigma_1 = 21$ MeV, and $\sigma_2 = 42$ MeV, the very different Gaussian widths reflecting the fact that the B_c^+ mass resolution depends on rapidity degrading from the barrel to the end cap regions. The B_c^+ mass resolution [1] agrees with expectations from simulation studies, of approximately 34 MeV.

The fitted B_c^+ mass is $M(B_c^+) = 6271.1 \pm 0.5$ MeV and the B_c^+ signal yield is 7629 ± 225 events, where the uncertainties are statistical only. The measured invariant mass distribution is well reproduced by the sum of the fitted contributions reflected in the χ^2 between the binned distribution and the fit function of 35 for 30 degrees of freedom.

C. Measurement of the $B_c(2S)^+$ and $B_c^*(2S)^+$ yields

The $B_c(2S)^+$ and $B_c^*(2S)^+$ candidates are also reconstructed through vertex kinematic fits, combining a B_c^+ candidate with two opposite-sign, high-purity tracks assumed to be pions. The selected B_c^+ candidates must have invariant mass in the 6.2–6.355 GeV range, where the low-mass edge is selected so as to avoid the background caused by partially reconstructed decays (represented by the gray area below 6.2 GeV in Fig. 1). The lifetimes of the $B_c(2S)^+$ and $B_c^*(2S)^+$ are assumed to be negligible with respect to the measurement resolution, so that the production and decay vertices essentially coincide. Therefore, the daughter pions are among the tracks used in the refitted PV. Furthermore, one of the pions must have $p_T > 0.8$ GeV and the other $p_T > 0.6$ GeV. The $B_c^+\pi^+\pi^-$ candidates must have $|y| < 2.4$ and a vertex kinematic fit χ^2 probability larger than 10%. As before, if several $B_c^+\pi^+\pi^-$ candidates are found in the same event, only the one with the highest p_T is kept.

Figure 2 shows the $M(B_c^+\pi^+\pi^-) - M(B_c^+) + m_{B_c^+}$ distribution, where $M(B_c^+\pi^+\pi^-)$ and $M(B_c^+)$ are the reconstructed invariant masses of the $B_c^+\pi^+\pi^-$ and B_c^+ candidates, respectively, and $m_{B_c^+}$ is the world-average B_c^+ mass [12]. This variable is used in the analysis because it is measured with a better resolution than $M(B_c^+\pi^+\pi^-)$, given that some of the measurement uncertainties cancel in the difference. The measured distribution is fitted to a superposition of two signal peaks using the same parametrization as in Eq. (2), plus a third-order Chebyshev polynomial modeling the nonpeaking, combinatorial background. Two background contributions arising from $B_c^+ \to J/\psi K^+$ decays are also considered, with shapes identical to those of the signal peaks, ignoring a negligible shift (less than 1 MeV) to lower mass values, and normalizations fixed by the ratio of the $B_c^+ \to J/\psi K^+$ to $B_c^+ \to J/\psi\pi^+$ signal yields.

Given the small number of events in the two signal peaks, the w and σ_2 double-Gaussian parameters are fixed to values determined in simulation studies: $w = 92\%$ and

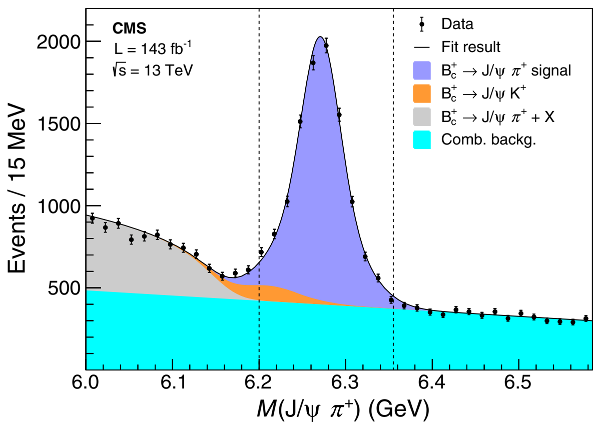

FIG. 1. Invariant mass distribution of the $B_c^+ \to J/\psi\pi^+$ candidates, after applying all event selection criteria [1]. The fitted contributions are shown by the stacked distributions, the solid line representing their sum. The vertical dashed lines indicate the mass window used to select the B_c^+ candidates for the $B_c^{(*)}(2S)^+$ reconstruction.

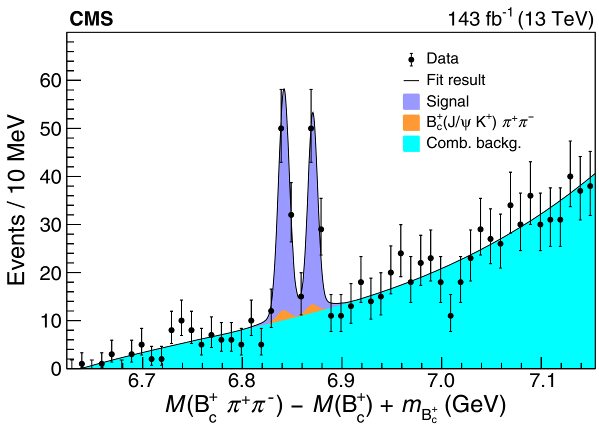

FIG. 2. Invariant mass distribution of the $B_c^{(*)}(2S)^+ \to B_c^{(*)+}\pi^+\pi^-$ candidates [1]. The $B_c^*(2S)^+$ corresponds to the lower-mass peak, the $B_c(2S)^+$ to the higher. The fitted contributions are shown by the stacked distributions, the solid line representing their sum.

$\sigma_2 = 3.1\sigma_1$ for the lower-mass peak, and $w = 86\%$ and $\sigma_2 = 2.8\sigma_1$ for the higher-mass peak. The two resonances are well resolved, with a mass difference of 28.9 ± 1.5 MeV, where the uncertainty is statistical only. The widths of the peaks are consistent with the measurement resolution evaluated through simulation studies, which is approximately $\sigma = 6$ MeV [1]. The unbinned extended maximum-likelihood fit gives 67 ± 10 and 52 ± 9 events for the lower- and higher-mass peaks, respectively. The quality of the fit can be quantified through the χ^2 per degrees of freedom ratio, 41/35.

As explained in Ref. [1], the $B_c^*(2S)^+$ peak is seen in the $B_c^+\pi^+\pi^-$ invariant mass distribution at a mass value lower than that of the $B_c(2S)^+$ peak. The reason is that, contrary to what happens to the $B_c(2S)^+$, which decays directly to $B_c^+\pi^+\pi^-$, the $B_c^*(2S)^+$ meson decays to $B_c^{*+}\pi^+\pi^-$ where the photon emitted in the subsequent $B_c^{*+} \to B_c^+\gamma$ decay has too low energy to be reconstructed. Therefore, the $B_c^*(2S)^+$ peak is seen in the $B_c^+\pi^+\pi^-$ mass spectrum at the mass $M(B_c(2S)^+) - \Delta M$, where $\Delta M \equiv [M(B_c^{*+}) - M(B_c^+)] - [M(B_c^*(2S)^+) - M(B_c(2S)^+)]$. Since $M(B_c^{*+}) - M(B_c^+)$ is expected to be larger than $M(B_c^*(2S)^+) - M(B_c(2S)^+)$, the $B_c^*(2S)^+$ state corresponds to the lower-mass peak [3–5].

D. Reconstruction efficiencies

With respect to the observation analysis reported in Ref. [1], the main challenge in the determination of the $B_c^{(*)}(2S)^+$ to B_c^+ cross section ratios is the evaluation of the corresponding (relative) detection efficiencies. Since the trigger requires $J/\psi \to \mu^+\mu^-$ from the $B_c^+ \to J/\psi\pi^+$ decay, the trigger efficiencies for the B_c^+ and $B_c^+\pi^+\pi^-$ candidates are essentially the same and cancel in the cross section ratios. So only the reconstruction efficiencies need to be evaluated, which is done using simulated event samples. All three mesons [B_c^+, $B_c(2S)^+$, and $B_c^*(2S)^+$] are generated using the BCVEGPY 2.2 [16] Monte Carlo event generator. The events are then passed to PYTHIA 8.230 [17] to simulate the hadronization process. The decays are performed by the EvtGen 1.6.0 package [18] and the quantum electrodynamic final-state radiation is modeled with PHOTOS 3.61 [19]. The simulated events are then processed through a detailed simulation of the CMS detector, based on the GEANT4 package [20], using the same trigger and reconstruction algorithms used to collect and process the data. The simulated events include multiple pp interactions in the same or nearby beam crossings (pileup), with a distribution matching the one observed in the data. Monte Carlo samples were extensively validated using control regions in the data.

The $B_c(2S)^+$ and $B_c^*(2S)^+$ efficiencies are computed as $N_{\text{rec}}(B_c^{(*)}(2S)^+)/N_{\text{gen}}(B_c^{(*)}(2S)^+)$, where $N_{\text{gen}}(B_c^{(*)}(2S)^+)$ are the numbers of $B_c^{(*)}(2S)^+$ events generated in the $B_c^{(*)+}\pi^+\pi^-$ channel, in the phase space region of the analysis, $p_{\text{T}}(B_c^+) > 15$ GeV and $|y(B_c^+)| < 2.4$, and $N_{\text{rec}}(B_c^{(*)}(2S)^+)$ are the numbers of events that survive all the reconstruction steps and event selection criteria. The B_c^+ efficiency is computed in a completely analogous way, except that it uses B_c^+ events generated in the $B_c^+ \to J/\psi\pi^+$ decay channel. These evaluations are independently made for the 2016, 2017, and 2018 running periods. The events collected in 2015, corresponding to 2% of the total sample, are treated the same as the 2016 sample for the purpose of efficiency determination. It was checked that the 2016 Monte Carlo simulation describes the 2015 data well enough so that no residual systematic uncertainty is required. The final efficiencies are obtained as weighted averages, using the integrated luminosities as weights: $2.8 + 36.1$, 42.1, and 61.6 fb^{-1}, respectively, for the 2015 + 2016, 2017, and 2018 periods [21–24]. The results are $\epsilon(B_c^+) = 1.31\%$, $\epsilon(B_c(2S)^+) = 0.26\%$, and $\epsilon(B_c^*(2S)^+) = 0.24\%$. The $B_c(2S)^+$ and $B_c^*(2S)^+$ reconstruction efficiencies are very similar, the slightly smaller $B_c^*(2S)^+$ value reflecting the (missed) low-energy photon, which implies a small reduction of the $B_c^+\pi^+\pi^-$ phase space.

TABLE I. Ratios of the reconstruction efficiencies relevant for the determination of the R^+, R^{*+}, and R^{*+}/R^+ cross section ratios. The central values are followed by the several uncertainties presented in the text.

	Central	Stat.	Spread	Pions
$\epsilon(B_c(2S)^+)/\epsilon(B_c^+)$	0.196	1.1%	1.8%	4.2%
$\epsilon(B_c^*(2S)^+)/\epsilon(B_c^+)$	0.187	1.0%	1.6%	4.2%
$\epsilon(B_c^*(2S)^+)/\epsilon(B_c(2S)^+)$	0.955	1.4%	0.9%	···

Table I lists the efficiency ratios relevant for the determination of the cross section ratios. The first uncertainty ("Stat.") shown reflects the finite size of the three simulated samples. The second ("Spread") reflects the standard deviation of the computed values around their average and is used to conservatively cover potential residual mismatches between the running conditions and the settings used in simulation. For example, it could be that the simulated samples do not accurately reproduce the time evolution of the instantaneous luminosity within each data-taking period, which would create differences in the measured and simulated pileup distributions. The last column ("Pions") reflects the uncertainty in the reconstruction efficiency [25] of the two pions emitted in the $B_c^{(*)}(2S)^+ \to B_c^{(*)+}\pi^+\pi^-$ decays. This uncertainty is relevant for the R^{*+} and R^+ ratios, but cancels in the R^{*+}/R^+ ratio.

E. Determination of the cross section ratios

Correcting the yield ratios by the corresponding efficiency ratios leads to the following $B_c(2S)^+$ to B_c^+, $B_c^*(2S)^+$ to B_c^+, and $B_c^*(2S)^+$ to $B_c(2S)^+$ cross section ratios, always including the $B_c^{(*)}(2S)^+ \to B_c^{(*)+}\pi^+\pi^-$ branching fractions, and always for $p_{\text{T}}(B_c^+) > 15$ GeV and $|y(B_c^+)| < 2.4$:

$$R^+ = (3.47 \pm 0.63)\%,$$
$$R^{*+} = (4.69 \pm 0.71)\%, \quad \text{and}$$
$$R^{*+}/R^+ = 1.35 \pm 0.32. \qquad (3)$$

The quoted uncertainties are statistical only. The fact that the $B_c^{(*)}(2S)^+$ events are a subset of the B_c^+ events has a negligible effect (less than 1%) on the uncertainties. The correlation between $B_c^*(2S)^+$ and $B_c(2S)^+$ yields, used in the double cross section ratio, is taken into account using an alternative fit to the $M(B_c^+\pi^+\pi^-) - M(B_c^+) + m_{B_c^+}$ distribution, which directly provides the ratio of these yields. It is worth noting again that these ratios include branching fractions [shown in Eq. (1)] that have not yet been measured.

F. Dependence on the B_c^+ kinematics

In order to probe if these cross section ratios show a dependence on the kinematics of the B_c^+ meson, the analysis is redone after splitting the events into three B_c^+ meson p_T bins and (independently) into three $|y|$ bins. The bin edges are chosen so as to have similar uncertainties in the three bins: 15, 22.5, 30, and 60 GeV for p_T, and 0, 0.4, 0.8, and 2.4 for $|y|$. The amount of events with $p_T >$ 60 GeV corresponds to 3.4% of the total sample and they are excluded from these kinematical distributions.

As shown in Fig. 3, none of the measured ratios shows significant variations with the p_T or $|y|$ of the B_c^+ meson, within the probed kinematical regions. The markers are shown at the average B_c^+ p_T or $|y|$ values of the events contributing to each bin. The horizontal displacements between the markers seen in the top panels reflect the differences between the $B_c(2S)^+$ and $B_c^*(2S)^+$ kinematic distributions.

Reporting the cross section ratios as a function of the B_c^+ kinematics and in a phase space domain defined by the B_c^+ is the choice that best reflects the data analysis procedure and that cancels to the largest extent the systematic uncertainties related to the B_c^+ detection. Given the relatively small mass difference between the mother $B_c^{(*)}(2S)^+$ and the daughter B_c^+ states, the ratio of laboratory momentum to mass remains practically unchanged in the decays, on average, so that the following kinematical relations hold to a very good approximation: $y^M = y^d$ and $p_T{}^M = (M/m)p_T^d$, where y^M, p_T^M, and M (respectively y^d, p_T^d, and m) are the rapidity, p_T, and mass of the mother (respectively daughter) [26].

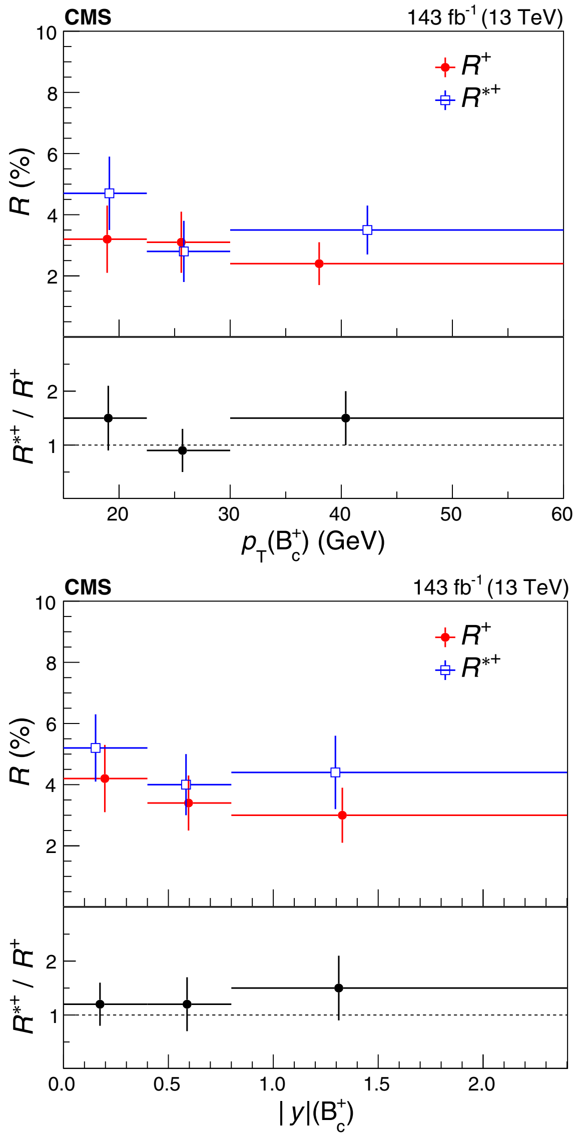

FIG. 3. The R^+ and R^{*+} (upper), and R^{*+}/R^+ (lower) cross section ratios, including the $B_c^{(*)}(2S)^+ \to B_c^{(*)+}\pi^+\pi^-$ branching fractions, as functions of the B_c^+ p_T (left) and $|y|$ (right). The horizontal bars show the bin widths. The markers are shown at the average B_c^+ p_T or $|y|$ values of the events contributing to each bin, in the background-subtracted distributions, and the vertical bars represent the statistical uncertainties only. The systematic uncertainties are essentially independent of the B_c^+ kinematics.

G. Systematic uncertainties

Several sources of systematic effects that could potentially affect the measurement of the cross section ratios have been considered. For each of those effects, the analysis has been redone using an alternative option and the resulting cross section ratios are compared to those obtained in the baseline analysis. The observed difference between the two results is taken as the systematic uncertainty associated with that specific effect.

Naturally, no uncertainties are considered in factors that affect identically the numerator and denominator values that provide the cross section ratios, such as the efficiency of the J/ψ trigger used to collect the event sample or the efficiency of the event selections that determine the total number of $B_c^+ \to J/\psi\pi^+$ candidates contributing to Fig. 1. But even if the integral of the measured $J/\psi\pi^+$ invariant mass distribution does not change, it is possible to vary the extracted B_c^+ yield by changing the functions used in the fit to describe the shapes of the signal and background contributions, given that such variations might change the assignment of some events from the B_c^+ yield to the background yield, or vice versa. The importance of this effect is evaluated by independently varying the signal and background models used in the fit.

The background model is varied by using an exponential function, instead of a first-order polynomial, to describe the uncorrelated $J/\psi\pi^+$ pairs. The varied scenario for the B_c^+ signal line shape consisted in replacing the double-Gaussian function by a Student's t function [27]. Since these two variations only change the fitted B_c^+ yield, having no effect on the number of $B_c^+ \to J/\psi\pi^+$ candidates used in the search for the $B_c^{(*)}(2S)^+$ excited states, the corresponding (relative) systematic uncertainties, 4.3% for the signal model and 3.5% for the background model, are identical for the R^+ and R^{*+} ratios, and cancel in the R^{*+}/R^+ double ratio.

The measurement of the $B_c(2S)^+$ and $B_c^*(2S)^+$ yields is also affected by the choices made to model the shapes of the signal peaks and the underlying combinatorial background seen in Fig. 2. The effect of the signal modeling is evaluated with two independent approaches. First, the default double-Gaussian function having a common mean and fixing the relative widths and amplitudes from fits to the simulated distributions is replaced by a single-Gaussian function. The number of free parameters for each signal peak remains at three, but this simpler model is unable to describe the non-Gaussian tails of the peaks. Second, the signal yields are evaluated with a simple procedure that avoids fitting the mass region of the two signal peaks, thereby being insensitive to specific signal shape models. It starts by fitting the signal-free mass sidebands with the background function and then integrating that function within the two signal regions to evaluate the background yields under the peaks, which are then subtracted from the total number of events in those two regions. To evaluate the impact of the background model, these alternative fits have been made with the third-order Chebyshev polynomial used in the baseline analysis and also with the function $\delta^\lambda \exp(\nu\delta)$, where $\delta \equiv M(B_c^+\pi^+\pi^-) - q_0$, and λ, ν, and q_0 are free parameters. Comparing the cross section ratios obtained using the alternative fits with those of the baseline fit leads to fit modeling systematic uncertainties of 5.9%, 2.9%, and 2.9%, respectively for the R^+, R^{*+}, and R^{*+}/R^+ ratios.

The fit of the $B_c^+\pi^+\pi^-$ invariant mass distribution also includes two small contributions representing the cases where the B_c^+ meson decays through the $B_c^+ \to J/\psi K^+$ channel rather than through the $B_c^+ \to J/\psi\pi^+$ channel assumed in the reconstruction. In the baseline analysis, these terms are modeled using the same shapes as the $B_c^{(*)}(2S)^+$ signal shapes and yields fixed to the yields of those resonances, scaled by the ratio of the two branching fractions, 0.079 ± 0.008 [15], and by the ratio of the two reconstruction efficiencies, 1.06 ± 0.01, in the signal region defined above. To evaluate the influence of these terms on the measured cross section ratios, the analysis is redone varying those two scale factors by their uncertainties. The results are insensitive to those variations, so no systematic uncertainty is assigned to this source.

When searching for $B_c^{(*)}(2S)^+$ candidates, the baseline analysis starts from an event sample composed of $B_c^+ \to J/\psi\pi^+$ events with invariant mass in the 6.2–6.355 GeV range. In order to probe if a potential residual contribution of the partially reconstructed B_c^+ decays could have a significant effect on the determination of the cross section ratios, the analysis is repeated with the lowest allowed invariant mass value changed from 6.2 to 6.1 GeV. The results remain essentially identical, the variations being smaller than their statistical uncertainties evaluated taking into account that one event sample is a subset of the other, so that the results are fully correlated. Therefore, no systematic uncertainty is assigned to this potential effect.

The uncertainties affecting the ratios of reconstruction efficiencies already presented in Table I translate directly into corresponding systematic uncertainties in the cross section ratios. In the evaluation of the $B_c^{(*)}(2S)^+$ reconstruction efficiencies, it is assumed that the two pions emitted in the $B_c^+\pi^+\pi^-$ decay have no kinematical correlations between them, besides the constraint of being decay products of the same mother particle. To evaluate the sensitivity of the measured cross section ratios to this assumption, the reconstruction efficiencies are recomputed under two other scenarios. These assume that the $\pi^+\pi^-$ kinematic distributions (a) reflect the existence of an intermediate resonance, or (b) are dependent on the (different) spins of the $B_c(2S)^+$ and $B_c^*(2S)^+$ states. The first scenario is simulated by independently reweighting the generated $B_c^{(*)}(2S)^+$ event samples, which previously reflected a simple phase space model, so that their $\pi^+\pi^-$ invariant mass distributions ("decay kinematics") match that in the data (presented in Sec. IV). The second scenario follows an analogous procedure using the helicity angle distribution ("helicity angle"), where the helicity angle is the angle between the directions of the π^+ and B_c^+ in the dipion rest frame. The differences between the resulting ratios of reconstruction efficiencies and those obtained in the baseline scenario are considered as systematic uncertainties: 1.5%, 6.9%, and 4.2% for the decay kinematics, and 1.0%, 6.0%, and 3.5% for the helicity angle, respectively, for the R^+, R^{*+}, and R^{*+}/R^+ ratios.

Several studies have been performed to verify the stability of the results with respect to the selection criteria, including the threshold values used to select the daughter particles. The variations in the reported ratios were smaller

TABLE II. Relative systematic uncertainties (in %) in the cross section ratios, including the $B_c^{(*)}(2S)^+ \to B_c^{(*)+}\pi^+\pi^-$ branching fractions, corresponding to the sources described in the text. The total uncertainty is the sum in quadrature of the individual terms.

	R^+	R^{*+}	R^{*+}/R^+
$J/\psi\pi^+$ fit model	5.5	5.5	…
$B_c^+\pi^+\pi^-$ fit model	5.9	2.9	2.9
Efficiencies: statistical uncertainty	1.1	1.0	1.4
Efficiencies: spread among years	1.8	1.6	0.9
Efficiencies: pion tracking	4.2	4.2	…
Decay kinematics	1.5	6.9	4.2
Helicity angle	1.0	6.0	3.5
Total	9.5	12.0	6.4

than the respective uncertainties computed accounting for the correlation induced by the overlap of the baseline and varied event samples, so that no corresponding systematic uncertainty has been considered.

All the values mentioned above are listed in Table II, which also shows the total systematic uncertainties computed as the sum in quadrature of the individual terms.

IV. INVARIANT MASS DISTRIBUTION OF THE DIPION SYSTEM

As a complement to the measurement of the cross section ratios, it is also interesting to measure the invariant mass distributions of the dipions emitted in the $B_c^+\pi^+\pi^-$ decays of the two $B_c^{(*)}(2S)^+$ states. In particular, comparing these distributions to those seen in the analogous $\psi(2S) \to J/\psi\pi^+\pi^-$ and $\Upsilon(2S) \to \Upsilon(1S)\pi^+\pi^-$ decays should provide relevant information to characterize the excited B_c^+ states and their production processes [6,7].

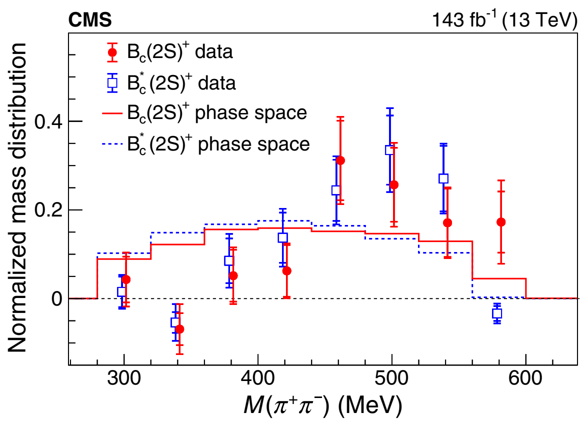

FIG. 4. The dipion invariant mass distributions from $B_c^{(*)}(2S)^+ \to B_c^{(*)+}\pi^+\pi^-$ decays in data, normalized to unity. The inner and outer tick marks designate the statistical and total uncertainties, respectively. The lines show the corresponding predictions from phase space simulations.

Figure 4 compares the invariant mass distributions normalized to unity, of the dipions emitted in the $B_c(2S)^+$ (closed red circles) and $B_c^*(2S)^+$ (open blue squares) decays between themselves and with the two corresponding simulated phase space distributions (lines). The $B_c^{(*)}(2S)^+$ data distributions are derived from the $B_c^+\pi^+\pi^-$ invariant mass distribution shown in Fig. 2. The contribution of the background events under the peaks is subtracted using the shape of the measured same-sign dipion invariant mass spectrum and normalizing the sum of the $B_c^+\pi^+\pi^+$ and $B_c^+\pi^-\pi^-$ events to the $B_c^+\pi^+\pi^-$ spectrum in the invariant mass sideband regions. The dipion invariant mass distributions have also been obtained using the sPlot technique [28] to subtract the background, which resulted in distributions consistent with those reported in Fig. 4.

Simulation studies show no dependence of the reconstruction efficiencies on the $\pi^+\pi^-$ invariant mass, so no correction is applied to these normalized distributions, where only the shapes are informative. For the same reason, systematic uncertainties that affect the distributions globally are not relevant, as they have no impact on the shapes and are canceled by the normalizations.

The dipion mass-dependent systematic uncertainties have been evaluated by comparing, bin by bin, the baseline distributions with those obtained in alternative analyses, where variations are made, as mentioned above, on the models used to fit the signal and background components of the $B_c^+\pi^+\pi^-$ mass distribution and on the small contributions from the $B_c^+ \to J/\psi K^+$ and partially reconstructed B_c^+ decays.

As seen in Fig. 4, the $B_c^{(*)}(2S)^+$ dipion invariant mass distributions are compatible with each other within the uncertainties, and have shapes different from the rather flat distributions predicted from the phase space simulations.

V. SUMMARY

The ratios of the $B_c(2S)^+$ to B_c^+, $B_c^*(2S)^+$ to B_c^+, and $B_c^*(2S)^+$ to $B_c(2S)^+$ production cross sections, R^+, R^{*+}, and R^{*+}/R^+, respectively, have been measured in proton-proton collisions at $\sqrt{s} = 13$ TeV. The dataset used in the analysis corresponds to an integrated luminosity of 143 fb^{-1} collected by the CMS experiment at the LHC between 2015 and 2018.

The $B_c^{(*)}(2S)^+$ mesons have been reconstructed through the decays $B_c^{(*)}(2S)^+ \to B_c^{(*)+}\pi^+\pi^-$, followed by the $B_c^+ \to J/\psi\pi^+$ and $J/\psi \to \mu^+\mu^-$. The measured cross section ratios, including the (unknown) $B_c^{(*)}(2S)^+ \to B_c^{(*)+}\pi^+\pi^-$ branching fractions, are

$$R^+ = (3.47 \pm 0.63(\text{stat}) \pm 0.33(\text{syst}))\%,$$
$$R^{*+} = (4.69 \pm 0.71(\text{stat}) \pm 0.56(\text{syst}))\%, \quad \text{and}$$
$$R^{*+}/R^+ = 1.35 \pm 0.32(\text{stat}) \pm 0.09(\text{syst}). \quad (4)$$

No significant dependences on the transverse momentum p_T or rapidity $|y|$ of the B_c^+ mesons have been observed for any of these three ratios. The normalized dipion invariant mass distributions for the $B_c^{(*)}(2S)^+ \to B_c^{(*)+}\pi^+\pi^-$ decays have also been reported. These results obtained in the phase space region defined by B_c^+ meson $p_T > 15$ GeV and $|y| < 2.4$ may provide new important input to improve the theoretical understanding of the nature of the $\bar{b}c$ heavy-quarkonium states and their production processes.

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