Measurement of the Branching Fraction ratio $B(B_{c} (2S))/B(B_{c} J/)$

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<table>
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<tr>
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</table>
Measurement of the branching fraction ratio

\[ \frac{\mathcal{B}(B_{c}^{+} \to \psi(2S)\pi^{+})}{\mathcal{B}(B_{c}^{+} \to J/\psi\pi^{+})} \]

R. Aaij et al.\(^*\)

(LHCb collaboration)

(Received 14 July 2015; published 20 October 2015)

Using pp collision data collected by LHCb at center-of-mass energies \(\sqrt{s} = 7\) TeV and 8 TeV, corresponding to an integrated luminosity of 3 fb\(^{-1}\), the ratio of the branching fraction of the \(B_{c}^{+} \to \psi(2S)\pi^{+}\) decay relative to that of the \(B_{c}^{+} \to J/\psi\pi^{+}\) decay is measured to be \(0.268 \pm 0.032\) (stat) \(\pm 0.007\) (syst) \(\pm 0.006\) (BF). The first uncertainty is statistical, the second is systematic, and the third is due to the uncertainties on the branching fractions of the \(J/\psi \to \mu^{+}\mu^{-}\) and \(\psi(2S) \to \mu^{+}\mu^{-}\) decays. This measurement is consistent with the previous LHCb result, and the statistical uncertainty is halved. DOI: 10.1103/PhysRevD.92.072007

PACS numbers: 13.25.Hw, 14.40.Nd, 12.38.Qk

In the Standard Model of particle physics the \(B_{c}\) meson family is unique because it contains two different heavy flavor quarks, charm and beauty. The ground state of the \(B_{c}\) meson family has a rich set of decay modes since either constituent quark can decay with the other as a spectator, or they can annihilate to a virtual W boson. The search for new \(B_{c}^{+}\) decay channels\(^1\) and precise measurements of their branching fractions can improve the understanding of quantum chromodynamics (QCD) and can test various effective models. Many properties of the \(B_{c}^{+}\) meson have been investigated by the LHCb experiment: the \(B_{c}^{+}\) mass, lifetime and production rate have been measured [1–6], while several new decay channels have been observed [2,3,7–13]. The observation of the \(B_{c}^{+} \to \psi(2S)\pi^{+}\) decay was made with pp collision data at a center-of-mass energy of \(\sqrt{s} = 7\) TeV, corresponding to an integrated luminosity of 1.0 fb\(^{-1}\) [8]. The ratio of the branching fraction of the \(B_{c}^{+} \to \psi(2S)\pi^{+}\) decay with respect to that of the \(B_{c}^{+} \to J/\psi\pi^{+}\) decay, defined as

\[ R_{B} \equiv \frac{\mathcal{B}(B_{c}^{+} \to \psi(2S)\pi^{+})}{\mathcal{B}(B_{c}^{+} \to J/\psi\pi^{+})}, \]

was measured to be \(0.250 \pm 0.068\) (stat) \(\pm 0.014\) (syst) \(\pm 0.006\) (BF). The first uncertainty is statistical, the second is systematic, and the third is due to the uncertainties on the branching fractions of the \(J/\psi \to \mu^{+}\mu^{-}\) and \(\psi(2S) \to \mu^{+}\mu^{-}\) decays. The statistical uncertainty is dominant. Several theoretical predictions for \(R_{B}\) based on different effective models [14–19] exist, and vary between 0.07 and 0.29.

\(^*\)Full author list given at end of the article.

\(^1\)Charge conjugation is implied throughout the paper.

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Further offline selections require a good quality muon track with $p_T > 1.7$ GeV/$c$, or $p_T > 1$ GeV/$c$ if identified as a muon; alternatively a dimuon trigger requires two oppositely charged muons with $p_T > 500$ MeV/$c$, and the invariant mass of the muon pair greater than 2.95 GeV/$c^2$.

Simulated samples are generated to study the behavior of signal events. The $B_c^+$ signals are generated with a dedicated generator BCVEGPY [30,31] through the dominant hard subprocess $gg \rightarrow B_c^+ + b + \bar{c}$. The fragmentation and hadronization processes are simulated with PYTHIA [32,33]. The detector simulation is based on the GEANT4 package [34,35]. The BDT classifier uses information on the candidate’s kinematic properties, decay length, vertex quality, impact parameter, and angle between the particle momentum and the vector from the primary to the secondary vertex. The distributions of the variables that are used in the BDT are similar for $B_c^+ \rightarrow J/\psi \pi^+$ and $B_c^+ \rightarrow J/\psi (2S)\pi^+$ decays. The simulated sample of $B_c^+ \rightarrow J/\psi \pi^+$ is used as the signal sample for the BDT training. The main background is combinatorial, and is represented by the upper sideband in the $B_c^+$ mass spectrum from the $B_c^+ \rightarrow J/\psi \pi^+$ data sample, requiring the reconstructed mass to be in the range [6346, 6444] MeV/$c^2$. Since the upper sideband is used for the BDT training, the BDT could overperform in this region and distort the expected combinatorial background in the signal region. To avoid possible bias, two BDT classifiers are trained, denoted as BDT1 and BDT2 in the following. The $B_c^+ \rightarrow J/\psi \pi^+$ simulation and data samples are both split into two halves. One half of the simulated data sample and of the $B_c^+$ upper

FIG. 1 (color online). Fit to the reconstructed $B_c^+$ mass distribution for $B_c^+ \rightarrow J/\psi \pi^+$ using (top) 2011 and (bottom) 2012 data samples. The plots on the left (right) correspond to the data selected with BDT1 (BDT2). Black points with error bars represent the data, and the various components are indicated in the keys.

$ p_T $ is required in the hardware trigger. The software trigger requires a charged particle with $ p_T > 1.7 $ GeV/$c$, or $ p_T > 1 $ GeV/$c$ if identified as a muon; alternatively a dimuon trigger requires two oppositely charged muons with $ p_T > 500 $ MeV/$c$, and the invariant mass of the muon pair greater than 2.95 GeV/$c^2$.

The main background is combinatorial, and is represented by the upper sideband in the $B_c^+$ mass spectrum from the $B_c^+ \rightarrow J/\psi \pi^+$ data sample, requiring the reconstructed mass to be in the range [6346, 6444] MeV/$c^2$. Since the upper sideband is used for the BDT training, the BDT could overperform in this region and distort the expected combinatorial background in the signal region. To avoid possible bias, two BDT classifiers are trained, denoted as BDT1 and BDT2 in the following. The $B_c^+ \rightarrow J/\psi \pi^+$ simulation and data samples are both split into two halves. One half of the simulated data sample and of the $B_c^+$ upper
sideband is used to train the BDT1 classifier, and the other half for BDT2. Each BDT classifier is applied to the other half of the $B_c^+ \to J/\psi \pi^+$ data sample, which is not used for its training. The $B_c^+ \to J/\psi (2S)\pi^+$ data sample is also split into two subsamples, one for each BDT classifier. The threshold value for the BDT response is chosen to maximize the signal significance. Finally, the $\mu^+\mu^-$ invariant mass window $[3030, 3170]$ MeV/$c^2$ is applied to $J/\psi$ candidates, and $[3620, 3760]$ MeV/$c^2$ to $\psi(2S)$ candidates.

After the full selection, the background in the $B_c^+ \to J/\psi \pi^+$ sample consists of three categories: combinatorial background; partially reconstructed background, mainly from $B_c^+ \to J/\psi \rho^+$ decays with $\rho^+ \to \pi^+\pi^0$, where the $\pi^0$ is not reconstructed; and contamination from the Cabibbo-suppressed decay, $B_c^+ \to J/\psi K^+$, with the kaon misidentified as a pion. The background in the $B_c^+ \to \psi(2S)\pi^+$ sample consists of a combinatorial background and a partially reconstructed background. The contribution from $B_c^+ \to \psi(2S)K^+$ is negligible.

The signal yields are extracted from unbinned extended maximum likelihood fits to the invariant mass distributions of $J/\psi \pi^+$ or $\psi(2S)\pi^+$ in the range $[6027, 6527]$ MeV/$c^2$, as shown in Figs. 1 and 2 for 2011 and 2012 data, and are summarized in Tables I and II. To improve the $B_c^+$ mass resolution, the masses of $J/\psi$ and $\psi(2S)$ candidates are constrained to their known values [27]. For the $B_c^+ \to J/\psi \pi^+$ channel, the signal probability density function is modeled by the sum of two double-sided Crystal Ball functions [36], with the same mean value and tail parameters determined from simulation; the combinatorial background is described with an exponential function; and the partially reconstructed background is modeled with the distribution of the $B_c^+$ invariant mass obtained from a simulated $B_c^+ \to J/\psi \rho^+$ sample using a kernel estimation [37]. This last shape is convolved with a Gaussian distribution to take into account a difference in mass resolution between data and simulation. For the $B_c^+ \to J/\psi K^+$ background, the shape of the $B_c^+$ mass distribution is modeled by a double-sided Crystal Ball function with parameters determined from simulation. For the $B_c^+ \to \psi(2S)\pi^+$ channel, due to the limited statistics, the signal shape is modeled by a single double-sided Crystal Ball function with the tail parameters determined from simulation; the combinatorial and partially reconstructed backgrounds are described with the same models as used for the $B_c^+ \to J/\psi \pi^+$ channel.

The total selection efficiency is the product of the detector geometrical acceptance, the trigger efficiency, the reconstruction and selection efficiency, the PID efficiency, and the BDT classifier efficiency. All efficiencies are determined using simulated samples. To account for any

![Figure 2](image-url) (color online). Fit to the reconstructed $B_c^+$ mass distribution for $B_c^+ \to \psi(2S)\pi^+$ using (top) 2011 and (bottom) 2012 data samples. The plots on the left (right) correspond to the data selected with BDT1 (BDT2). Black points with error bars represent the data, and the various components are indicated in the keys.
discrepancy between data and simulation, the PID efficiencies are calibrated using a \( \pi^+ \) sample from \( D^0 \rightarrow K^- \pi^+ \) decays. The BDT classifier efficiencies of BDT1 and BDT2 are slightly different. After correcting for the BDT classifier efficiencies the signal yields of the subsamples are consistent within the statistical uncertainties. The BDT classifier efficiency, \( \varepsilon_{\text{BDT}} \), and the product of all other efficiencies, \( \varepsilon' \), are listed in Tables I and II.

Several sources of systematic uncertainty on the \( R_B \) measurement are studied and are summarized in Table III. To account for the uncertainty due to the signal shape modeling, the data are refitted with an alternative shape. The \( B^+_c \) invariant mass distributions are modeled by a kernel estimation convolved with a Gaussian function, as determined from simulation. A difference of 0.6\% from the nominal result is observed and is taken as a systematic uncertainty.

The modeling of the partially reconstructed background can also introduce a systematic uncertainty. This is estimated by reducing the fit range to [6164, 6527] MeV/c\(^2\) to exclude its contribution. A change of 2.4\% in the result is observed. In the nominal fits, the parameters for \( B^+_c \rightarrow J/\psi K^+ \) and the partially reconstructed background are fixed; the results change by less than 1\% when these parameters are allowed to vary. The systematic uncertainty due to background modeling is estimated to be 2.4\%.

Systematic uncertainties on the \( R_B \) measurement can be introduced by the BDT classifier efficiency if the simulation fails to describe the data. The distributions of all training variables from simulation and background-subtracted data are compared, where the background subtraction is performed using the \textit{sPlot} technique, taking the \( B^+_c \) invariant mass as the discriminating variable [38]. They are generally in agreement within statistical fluctuations. Only one variable, which describes the consistency between the pion track and the PV, indicates small differences between simulation and data. Therefore, the simulated sample is reweighed to match the data, and the BDT efficiencies are recalculated with the reweighed simulated sample. The result obtained with these BDT efficiencies is different from the nominal value by 0.2\%, which is taken as the uncertainty from the BDT classifier.

The efficiencies determined from simulated samples have uncertainties due to the limited statistics. This leads to an uncertainty of 0.3\%. An uncertainty of 1.1\% is assigned due to imperfect simulation of the trigger, which is determined using data driven methods [39,40]. The \( B^+_c \) lifetime of simulated samples is set according to the latest LHCb measurement [4]. To estimate the systematic uncertainty due to this, the \( B^+_c \) lifetime is varied within the uncertainty of this measurement, and the change in the result, 0.1\%, is taken as a systematic uncertainty. The total systematic uncertainty is 2.7\%.

The ratio of the branching fractions with \( J/\psi \) and \( \psi(2S) \) mesons decaying to dimuons, denoted as

\[
R = \frac{B(B^+_c \rightarrow \psi(2S)\pi^+ \rightarrow \mu^+\mu^-)}{B(B^+_c \rightarrow J/\psi \pi^+ \rightarrow \mu^+\mu^-)}, \tag{2}
\]

is calculated as

\[
R = \frac{N_{\text{cor}}^{2011}(B^+_c \rightarrow \psi(2S)\pi^+) + N_{\text{cor}}^{2012}(B^+_c \rightarrow \rho(2S)\pi^+)}{N_{\text{cor}}^{2011}(B^+_c \rightarrow J/\psi \pi^+) + N_{\text{cor}}^{2012}(B^+_c \rightarrow J/\psi \pi^+)}, \tag{3}
\]

where \( N_{\text{cor}}^{2011(2012)} \) are the signal yields from 2011 (2012) after efficiency correction. The ratio is measured to be

\[
R = 0.0354 \pm 0.0042(\text{stat}) \pm 0.0010(\text{syst}).
\]

The ratio of the branching fractions of \( B^+_c \rightarrow \psi(2S)\pi^+ \) and \( B^+_c \rightarrow J/\psi \pi^+ \) is calculated as

\[
\frac{B(B^+_c \rightarrow \psi(2S)\pi^+ \rightarrow \mu^+\mu^-)}{B(B^+_c \rightarrow J/\psi \pi^+ \rightarrow \mu^+\mu^-)}.
\]

### Table I. Summary of the signal yields and efficiencies for the \( B^+_c \rightarrow J/\psi \pi^+ \) decay.

<table>
<thead>
<tr>
<th></th>
<th>BDT1</th>
<th>BDT2</th>
<th>BDT1</th>
<th>BDT2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yield</td>
<td>437 ± 24</td>
<td>475 ± 26</td>
<td>883 ± 34</td>
<td>950 ± 36</td>
</tr>
<tr>
<td>( \varepsilon_{\text{BDT}} )</td>
<td>(62.99 ± 0.07)%</td>
<td>(69.29 ± 0.06)%</td>
<td>(62.33 ± 0.06)%</td>
<td>(68.50 ± 0.06)%</td>
</tr>
<tr>
<td>( \varepsilon' )</td>
<td>(1.392 ± 0.003)%</td>
<td></td>
<td>(1.339 ± 0.003)%</td>
<td></td>
</tr>
</tbody>
</table>

### Table II. Summary of the signal yields and efficiencies for the \( B^+_c \rightarrow \psi(2S)\pi^+ \) decay.

<table>
<thead>
<tr>
<th></th>
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<th>BDT2</th>
<th>BDT1</th>
<th>BDT2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yield</td>
<td>14.4 ± 4.5</td>
<td>19.6 ± 5.3</td>
<td>40.1 ± 7.1</td>
<td>30.8 ± 7.0</td>
</tr>
<tr>
<td>( \varepsilon_{\text{BDT}} )</td>
<td>(58.79 ± 0.11)%</td>
<td>(65.84 ± 0.11)%</td>
<td>(58.32 ± 0.08)%</td>
<td>(65.08 ± 0.08)%</td>
</tr>
<tr>
<td>( \varepsilon' )</td>
<td>(1.631 ± 0.006)%</td>
<td></td>
<td>(1.529 ± 0.005)%</td>
<td></td>
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TABLE III. Summary of systematic uncertainties on the $R_B$ measurement.

<table>
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<th>Component</th>
<th>Uncertainty</th>
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<td>Signal shape</td>
<td>0.6%</td>
</tr>
<tr>
<td>Background shape</td>
<td>2.4%</td>
</tr>
<tr>
<td>BDT classifier</td>
<td>0.2%</td>
</tr>
<tr>
<td>Monte-Carlo statistics</td>
<td>0.3%</td>
</tr>
<tr>
<td>Trigger efficiency</td>
<td>1.1%</td>
</tr>
<tr>
<td>$B^+_c$ lifetime</td>
<td>0.1%</td>
</tr>
<tr>
<td>Total</td>
<td>2.7%</td>
</tr>
</tbody>
</table>

$$R_B = R \times \frac{\mathcal{B}(J/\psi \to \mu^+\mu^-)}{\mathcal{B}(\psi(2S) \to \mu^+\mu^-)}.$$  \hspace{1cm} (4)

Assuming electroweak universality, the $J/\psi \to \mu^+\mu^-$ and $\psi(2S) \to \mu^+\mu^-$ branching fractions can be substituted with the more precisely measured ones in the $e^+e^-$ channel \cite{27}. Using these values, the ratio $R_B$ is measured to be

$$R_B = 0.268 \pm 0.032(\text{stat}) \pm 0.007(\text{syst}) \pm 0.006(\text{BF}),$$

where the first uncertainty is statistical, the second is systematic, and the last term is due to the uncertainty on $\mathcal{B}(J/\psi \to e^+e^-)/\mathcal{B}(\psi(2S) \to e^+e^-)$. This result is in agreement with the previous LHCb result \cite{8}. Our measurement is consistent with the predictions of nonrelativistic QCD at next-to-leading order (0.267±0.005) \cite{18} and perturbative QCD based on $k_T$ factorization (0.29±0.17) \cite{19}. The result disfavors the theoretical calculations based on the relativistic quark model \cite{14}, the quark potential model \cite{15}, the relativistic constituent quark model \cite{16}, and the QCD relativistic potential model \cite{17}.

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