Production of $B_c^+$ mesons in proton-proton collisions at a center-of-mass energy of 8 TeV is studied with data corresponding to an integrated luminosity of 2.0 fb$^{-1}$ recorded by the LHCb experiment. The ratio of production cross sections times branching fractions between the $B_c^+ \rightarrow J/\psi \pi^+$ and $B^+ \rightarrow J/\psi K^+$ decays is measured as a function of transverse momentum and rapidity in the regions $0 < p_T < 20$ GeV/c and $2.0 < y < 4.5$. The ratio in this kinematic range is measured to be $(0.683 \pm 0.018 \pm 0.009)$%, where the first uncertainty is statistical and the second systematic.

In this Letter, we report on the first measurement of the ratio of double-differential inclusive production cross sections multiplied by branching fractions,

$$R(p_T, y) = \frac{d\sigma_{B_c^+}(p_T, y)\mathcal{B}(B_c^+ \rightarrow J/\psi \pi^+)}{d\sigma_{B^+}(p_T, y)\mathcal{B}(B^+ \rightarrow J/\psi K^+)},$$

where transverse momentum $p_T$ and rapidity $y$ refer to the $b$ meson. The cross section includes contributions from excited states. We use a sample of $pp$ collision data at 8 TeV corresponding to an integrated luminosity of 2.0 fb$^{-1}$ recorded by the LHCb experiment. The $B_c^+$ and $B^+$ mesons are reconstructed in the exclusive decays $B_c^+ \rightarrow J/\psi \pi^+$ and $B^+ \rightarrow J/\psi K^+$, respectively, with $J/\psi \rightarrow \mu^+\mu^-$. The inclusion of charge conjugate modes is implied throughout this Letter.

The LHCb detector [32] is a single-arm forward spectrometer covering the pseudorapidity range $2 < \eta < 5$ designed for the study of particles containing $b$ or $c$ quarks. The detector includes a high-precision tracking system consisting of a silicon-strip vertex detector surrounding the $pp$ interaction region, a large-area silicon-strip detector located upstream of a dipole magnet with a bending power of about 4 Tm, and three stations of silicon-strip detectors and straw drift tubes placed downstream of the magnet. The combined tracking system provides a momentum measurement with a relative uncertainty that varies from 0.4% at low momentum $p$ to 0.6% at 100 GeV/c. The minimum distance of a track to a primary vertex, the impact parameter (IP), is measured with a resolution of $(15 + 29/p_T)$ μm, where $p_T$ is in GeV/c. Different types of charged hadrons are distinguished using information from two ring-imaging Cherenkov detectors, a scintillating-pad and preshower detectors, an electromagnetic calorimeter, and a hadronic calorimeter. Muons are

* Full author list given at the end of the article.

Published by the American Physical Society under the terms of the Creative Commons Attribution 3.0 License. Further distribution of this work must maintain attribution to the author(s) and the published articles title, journal citation, and DOI.
The trigger consists of a hardware stage based on information from the calorimeter and muon systems, followed by a software stage, in which all charged particles with $p_T > 300 \text{ MeV}/c$ are reconstructed [33]. Events are first required to pass the hardware trigger, which requires one or two muons with high $p_T$. In the subsequent software trigger, the event is required to have one muon with high $p_T$ and large IP with respect to all primary $pp$ interaction vertices (PVs) or a pair of oppositely charged muons with an invariant mass consistent with the known $J/\psi$ meson mass [34]. Finally, the tracks of two or more of the final state particles are required to form a vertex that is significantly displaced from the PVs. A multivariate algorithm [35] is also used to identify secondary vertices consistent with the decay of a $b$ meson.

The $b$-meson candidate selection is performed in two steps: a preselection and a final selection on the output of a multivariate classifier based on a boosted decision tree algorithm (BDT) [36,37]. Simulated $B_c^+$ and $B^+$ decays are used to optimize the $b$-meson candidate selection. Production of $B^+$ mesons is simulated using PYTHIA 6.4 [38] with a LHCb specific configuration [39]. The generator BCVEGPY [40] is used to simulate $B_c^+$-meson production. Decays of $B_c^+$, $B^+$, and $J/\psi$ mesons are described by EVTGEN [41], and photon radiation is simulated using the PHOTOS package [42]. The decay products are traced through the detector by the GEANT4 package [43,44]. Following Ref. [45], the $B_c^+$-meson lifetime is set to $\tau_{B_c^+} = 0.590$ ps. The selection requirements are the same for the $B_c^+ \rightarrow J/\psi \pi^+$ and $B^+ \rightarrow J/\psi K^+$ candidates.

In the preselection, $J/\psi$ candidates are formed from pairs of oppositely charged particles with $p_T$ larger than 0.55 GeV/$c$, with a good quality of the track fit and identified as muons. The two muons are required to originate from a common vertex. The $J/\psi$ candidates with invariant mass between 3.04 and 3.14 GeV$/c^2$ are combined with a charged particle that has $p_T > 1.0$ GeV/$c$, a good quality of the track fit and is separated from any PV. The pion mass hypothesis is assigned to the track for the selection of the $B_c^+$ candidate and the kaon hypothesis for that of the $B^+$ candidate. The $J/\psi$ candidate and the hadron ($\pi$ or $K$) are required to originate from a common vertex. To improve the $b$-meson mass resolution, the mass of the muon pair is constrained to the known $J/\psi$-meson mass [34] in this vertex fit. The $b$-meson candidates are required to have a decay time larger than 0.2 ps and to point toward the primary vertex.

In the final selection, the BDT is trained using a simulated $B_c^+$ signal sample and background events populating the data mass sideband $6376 < M_{J/\psi\pi^+} < 6600$ MeV/$c^2$. The following variables are used as input to the BDT: $\chi^2_{IP}$ of all particles, $p_T$ of muons, $p_T$ of $J/\psi$ and $\pi^+$, and the $b$-meson decay length, decay time, and the vertex fit $\chi^2$ of a fit to the decay tree [46]. The quantity $\chi^2_{IP}$ is defined as the difference in $\chi^2$ of a given primary vertex reconstructed with and without the considered particle. The selection value on the BDT output is chosen to maximize the signal significance $N_S/\sqrt{N_S + N_B}$, where $N_S$ and $N_B$ are the expected numbers of signal and background events, respectively. The same BDT requirements are used for the $B^+$ meson.

The $B_c^+$ and $B^+$ candidates are subdivided into ten bins of $p_T$ and three bins of $y$. Bin sizes are chosen to contain approximately the same number of signal candidates, except for the highest $p_T$ bin. The differential production ratio $R$ is measured as

$$R(p_T, y) = \frac{N_{B_c^+}(p_T, y) \epsilon_{B_c^+}(p_T, y)}{N_{B^+}(p_T, y) \epsilon_{B^+}(p_T, y)},$$

where $N_{B_c^+}(p_T, y)$ is the number of reconstructed signal decays, and $\epsilon_{B_c^+}(p_T, y)$ is the total efficiency in a given $(p_T, y)$ bin, including geometrical acceptance, reconstruction, selection, and trigger effects.

In each $p_T$ and $y$ bin, the number of signal decays is determined by performing an extended maximum likelihood fit to the unbinned invariant mass distribution.
of $B^+_c$ candidates reconstructed in $6150 < M_{J/\psi K^+} < 6550$ MeV/$c^2$ and $B^+$ candidates in $5150 < M_{J/\psi K^+} < 5550$ MeV/$c^2$. For both $B^+_c \to J/\psi \pi^+$ and $B^+ \to J/\psi K^+$ decays, the fit includes components for signal, combinatorial background, and Cabibbo-suppressed backgrounds $B^+_c \to J/\psi K^+$ and $B^+ \to J/\psi \pi^+$. Other sources of backgrounds, such as $B^+_c \to J/\psi \mu^+\nu_\mu$, are negligible. The $B^+_c \to J/\psi \pi^+$ signal is described by a double-sided Crystal Ball (DSCB) function, which is an empirical function with a Gaussian core and power-law tails on both sides. The $B^+ \to J/\psi K^+$ signal is described by the sum of two DSCB functions, to account for different mass resolutions in different kinematic regions. The tail parameters are determined from simulation. The combinatorial background is described by an exponential function. The shapes of the Cabibbo-suppressed backgrounds are determined from simulation. The ratios of the yield of the Cabibbo-suppressed background to that of the signal are fixed to the central value of $B(B^+_c \to J/\psi K^+)/B(B^+_c \to J/\psi \pi^+) = (6.9 \pm 2.0)\%$ for $B^+_c$ candidates [47] and $B(B^+ \to J/\psi \pi^+)/B(B^+ \to J/\psi K^+) = (3.83 \pm 0.13)\%$ for $B^+$ candidates [48], respectively.

As an example, Fig. 1 shows the $B^+_c$ and $B^+$ mass distributions together with the fit results for the bin $2.0 < p_T < 3.0$ GeV/$c$ and $2.0 < y < 2.9$. The mass resolution is approximately 11 MeV/$c^2$ for $B^+_c$ signals and 8.7 MeV/$c^2$ for $B^+$ signals. Summing over all bins, a total signal yield of $3.1 \times 10^3 B^+_c$ candidates and $7.1 \times 10^3$ $B^+$ candidates is obtained. In each $(p_T, y)$ bin, the total efficiency is determined from simulation and ranges from 2.4% to 23.2% for $B^+_c$ candidates and from 3.6% to 33.5% for $B^+$ candidates.

The systematic uncertainties associated with the signal shape in each bin (0.1%–2.6%) are estimated by comparing the ratios between input signal yields and fit results in simulation. The uncertainties from the combinatorial background shape (0.1%–4.4%) are determined by varying the fit function. The input value for the ratio of branching fractions $B(B^+_c \to J/\psi K^+)/B(B^+_c \to J/\psi \pi^+)$ is varied within its uncertainty, and the resulting difference (0.1%–0.9%) is taken as systematic uncertainty. The effect of $B(B^+ \to J/\psi \pi^+)/B(B^+ \to J/\psi K^+)$ is found to be negligible. The systematic uncertainty associated with the relative trigger efficiency is estimated to be 1%. Other effects, such as the $(p_T, y)$ binning scheme, the shapes of the Cabibbo-suppressed backgrounds, the $B^+_c$ lifetime uncertainty, and the uncertainty of tracking efficiency, are negligible.

Figure 2 shows that simulation provides a good description of $p_T$ and $y$ distributions of $B^+_c$ mesons in the data. The values of $R(p_T, y)$ in the range $0 < p_T < 20$ GeV/$c$ and $2.0 < y < 4.5$ are shown in Fig. 3 and Ref. [49]. Figure 4 shows the ratio $R(p_T)$ integrated over $y$ in the region $2.0 < y < 4.5$ and $R(y)$ integrated over $p_T$ in the region $0 < p_T < 20$ GeV/$c$. The ratios are found to vary as a function of $p_T$ and $y$. The results are compared with the theoretical predictions in Ref. [49].
The resulting integrated value of \( R \) in the region 
\[ 0 < p_T < 20 \text{ GeV}/c \] and 
\[ 2.0 < y < 4.5 \] is measured to be

\[ R = (0.683 \pm 0.018 \pm 0.009)\% \]

where the first uncertainty is statistical and the second systematic. To enable comparison with the previous LHCb measurement [26], \( R \) and its total uncertainty are also reported in the range \( 4 < p_T < 20 \text{ GeV}/c \) and \( 2.5 < \eta < 4.5 \) as \( (0.698 \pm 0.023)\% \). The previous LHCb measurement of \( R \) at 7 TeV of Ref. [26] is updated using the recent measurement of the \( B^+_c \) lifetime [45] to be \((0.61 \pm 0.12)\%\).

In summary, we present the first measurement of the \( B^+_c \) double-differential production cross-section ratio with respect to that of the \( B^+ \) meson. The measurement is performed in three bins of rapidity and ten bins of \( p_T \) in \( pp \) collisions at \( \sqrt{s} = 8 \text{ TeV} \) on a data sample collected with the LHCb detector. The relative production rates of \( B^+_c \) and \( B^+ \) mesons are found to depend on their transverse momentum and rapidity. The measured transverse momentum and rapidity distributions of the \( B^+_c \) meson are well described by the complete \( \alpha_s^4 \) calculation. However, the theoretical predictions on the \( B^+_c \) and \( B^+ \) production cross sections suffer from big uncertainties [22,54], and the prediction of the branching fraction of the \( B^+_c \rightarrow J/\psi \pi^+ \) decay has a big spread (see, for example, Ref. [55]); more work on the theoretical side is required to have concluding remarks on the \( B^+_c \) absolute production rate. These results will provide useful information on the \( B^+_c \) production mechanism and help us understand the quarkonium production and, therefore, deepen our understanding of QCD.

We express our gratitude to our colleagues in the CERN accelerator departments for the excellent performance of the LHC. We thank the technical and administrative staff at the LHCb institutes. We acknowledge support from CERN and from the national agencies CAPES, CNPq, FAPERJ, and FINEP (Brazil); NSFC (China); CNRS/IN2P3 (France); BMBF, DFG, and MPG (Germany); SFI (Ireland); INFN (Italy); NWO and SURF (Netherlands); MNiSW and NCN (Poland); MEN/IFA (Romania); MinES and FANO (Russia); MinECo (Spain); SNSF and SER (Switzerland); NASU (Ukraine); STFC (United Kingdom); NSF (USA). The Tier1 computing centers are supported by IN2P3 (France), KIT and BMBF (Germany), INFN (Italy), NWO and SURF (Netherlands), PIC (Spain), and GridPP (United Kingdom). We are indebted to the communities behind the multiple open source software packages on which we depend. We are also thankful for the computing resources and the access to software R&D tools provided by Yandex LLC (Russia). Individual groups or members have received support from EPLANET, Marie Skłodowska-Curie Actions and ERC (European Union), Conseil général de Haute-Savoie, Labex ENIGMASS and OCEUV, Région Auvergne (France), RFBR (Russia), XuntaGal and GENCAT (Spain), and Royal Society and Royal Commission for the Exhibition of 1851 (United Kingdom). We would like to thank Matteo Cacciari, Chao-Hsi Chang, Xing-Gang Wu, and Rui-Lin Zhu for useful discussions.

[6] F. Abe et al. (CDF Collaboration), \( J/\psi \) and \( \psi(2S) \) Production in \( pp \) Collisions at \( \sqrt{s} = 1.8 \text{ TeV} \), Phys. Rev. Lett. 79, 572 (1997); Production of \( J/\psi \) Mesons from \( \chi_c \) Meson decays in \( pp \) Collisions at \( \sqrt{s} = 1.8 \text{ TeV} \), Phys. Rev. Lett. 79, 578 (1997).


[25] F. Abe et al. (CDF Collaboration), Observation of the $B_c$ Meson in $p\bar{p}$ Collisions at $\sqrt{s} = 1.8$ TeV, Phys. Rev. Lett. 81, 2432 (1998); Observation of $B_s$ mesons in $pp$ collisions at $\sqrt{s} = 1.8$ TeV, Phys. Rev. D 58, 112004 (1998).


[27] R. Aaij et al. (LHCb Collaboration), Observation of the Decay $B_{c}^{+} \rightarrow B_{s}^{0} \pi^{+}$, Phys. Rev. Lett. 111, 181801 (2013).

[28] T. Aaltonen et al. (CDF Collaboration), First measurement of the ratio of branching fractions $B(B_{c}^{+} \rightarrow B_{s}^{0} \mu^{+}\nu_{\mu})/B(B_{c}^{0} \rightarrow \Lambda_{c}^{+}\pi^{-})$, Phys. Rev. D 79, 032001 (2009).


[30] R. Aaij et al. (LHCb Collaboration), Study of the kinematic dependences of $\Lambda_{c}^{0}$ production in $pp$ collisions and a measurement of the $\Lambda_{c}^{0} \rightarrow \Lambda_{c}^{+}\pi^{-}$ branching fraction, J. High Energy Phys. 08 (2014) 143.


[59] R. Aaij et al. (LHCb Collaboration), Measurements of the branching fractions and $CP$ asymmetries of $B^\pm \rightarrow J/\psi \pi^\pm$ and $B^0 \rightarrow \psi(2S)\pi^\pm$ decays, *Phys. Rev. D* 85, 091105(R) (2012).


(LHCb Collaboration)

1 Centro Brasileiro de Pesquisas Físicas (CBPF), Rio de Janeiro, Brazil
2 Universidade Federal do Rio de Janeiro (UFRJ), Rio de Janeiro, Brazil
3 Center for High Energy Physics, Tsinghua University, Beijing, China
4 LAPP, Université de Savoie, CNRS/IN2P3, Annecy-Le-Vieux, France
5 Clermont Université, Université Blaise Pascal, CNRS/IN2P3, LPC, Clermont-Ferrand, France
6 CPPM, Aix-Marseille Université, CNRS/IN2P3, Marseille, France
7 LAL, Université Paris-Sud, CNRS/IN2P3, Orsay, France
8 LPNHE, Université Pierre et Marie Curie, Université Paris Diderot, CNRS/IN2P3, Paris, France
9 Fakultät Physik, Technische Universität Dortmund, Dortmund, Germany
10 Max-Planck-Institut für Kernphysik (MPIK), Heidelberg, Germany
11 Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany
12 School of Physics, University College Dublin, Dublin, Ireland
13 Sezione INFN di Bari, Bari, Italy
14 Sezione INFN di Bologna, Bologna, Italy
15 Sezione INFN di Cagliari, Cagliari, Italy
16 Sezione INFN di Ferrara, Ferrara, Italy
17 Sezione INFN di Firenze, Firenze, Italy
18 Laboratori Nazionali dell’INFN di Frascati, Frascati, Italy
19 Sezione INFN di Genova, Genova, Italy
20 Sezione INFN di Milano Bicocca, Milano, Italy
21 Sezione INFN di Milano, Milano, Italy
22 Sezione INFN di Padova, Padova, Italy
23 Sezione INFN di Pisa, Pisa, Italy
24 Sezione INFN di Roma Tor Vergata, Roma, Italy
25 Sezione INFN di Roma La Sapienza, Roma, Italy
26 Henryk Niewodniczanski Institute of Nuclear Physics Polish Academy of Sciences, Kraków, Poland
27 AGH - University of Science and Technology, Faculty of Physics and Applied Computer Science, Kraków, Poland
28 National Center for Nuclear Research (NCBJ), Warsaw, Poland
29 Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest-Magurele, Romania
30 Petersburg Nuclear Physics Institute (PNPI), Gatchina, Russia
31 Institute of Theoretical and Experimental Physics (ITEP), Moscow, Russia
32 Institute of Nuclear Physics, Moscow State University (SINP MSU), Moscow, Russia
33 Institute for Nuclear Research of the Russian Academy of Sciences (INR RAN), Moscow, Russia
34 Budker Institute of Nuclear Physics (SB RAS) and Novosibirsk State University, Novosibirsk, Russia
35 Institute for High Energy Physics (IHEP), Protvino, Russia
36 Universitat de Barcelona, Barcelona, Spain
37 Universidad de Santiago de Compostela, Santiago de Compostela, Spain
38 European Organization for Nuclear Research (CERN), Geneva, Switzerland
39 Ecole Polytechnique Fédérale de Lausanne (EPFL), Lausanne, Switzerland
40 Physik-Institut, Universität Zürich, Zürich, Switzerland
41 Nikhef National Institute for Subatomic Physics, Amsterdam, The Netherlands
42 Nikhef National Institute for Subatomic Physics and VU University Amsterdam, Amsterdam, The Netherlands
43 NSC Kharkiv Institute of Physics and Technology (NSC KIPT), Kharkiv, Ukraine
44 Institute for Nuclear Research of the National Academy of Sciences (KINR), Kyiv, Ukraine
45 University of Birmingham, Birmingham, United Kingdom
PRL 114, 132001 (2015)

Also at Università di Firenze, Firenze, Italy.
Also at Università di Ferrara, Ferrara, Italy.
Also at Università della Basilicata, Potenza, Italy.
Also at Università di Modena e Reggio Emilia, Modena, Italy.
Also at Università di Milano Bicocca, Milano, Italy.
Also at LIFAELS, La Salle, Universitat Ramon Llull, Barcelona, Spain.
Also at Università di Bologna, Bologna, Italy.
Also at Università di Roma Tor Vergata, Roma, Italy.
Also at Università di Genova, Genova, Italy.
Also at Scuola Normale Superiore, Pisa, Italy.
Also at Politecnico di Milano, Milano, Italy.
Also at Universidade Federal do Triângulo Mineiro (UFTM), Uberaba, Minas Gerais, Brazil.
Also at AGH - University of Science and Technology, Faculty of Computer Science, Electronics and Telecommunications, Kraków, Poland.
Also at Università di Padova, Padova, Italy.
Also at Università di Cagliari, Cagliari, Italy.
Also at Hanoi University of Science, Hanoi, Viet Nam.
Also at Università di Bari, Bari, Italy.
Also at Università degli Studi di Milano, Milano, Italy.
Also at Università di Roma La Sapienza, Roma, Italy.
Also at Università di Pisa, Pisa, Italy.
Also at Università di Urbino, Urbino, Italy.
Also at P.N. Lebedev Physical Institute, Russian Academy of Science (LPI RAS), Moscow, Russia.