

MIT Open Access Articles

Measurement of $B[+ \text{ over } c]$ Production in Proton-Proton Collisions at $\sqrt{s} = 8 \text{ TeV}$

The MIT Faculty has made this article openly available. **Please share**
how this access benefits you. Your story matters.

Citation: Aaij, R. et al. "Measurement of $B[+ \text{ over } c]$ Production in Proton-Proton Collisions at $\sqrt{s} = 8 \text{ TeV}$." Phys. Rev. Lett. 114, 132001 (April 2015). © 2015 CERN, for the LHCb Collaboration

As Published: <http://dx.doi.org/10.1103/PhysRevLett.114.132001>

Publisher: American Physical Society

Persistent URL: <http://hdl.handle.net/1721.1/96371>

Version: Final published version: final published article, as it appeared in a journal, conference proceedings, or other formally published context

Terms of use: Creative Commons Attribution



Measurement of B_c^+ Production in Proton-Proton Collisions at $\sqrt{s} = 8$ TeV

R. Aaij *et al.**

(LHCb Collaboration)

(Received 12 November 2014; published 2 April 2015)

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 $0 < p_T < 20 \text{ GeV}/c$ 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.

DOI: 10.1103/PhysRevLett.114.132001

PACS numbers: 14.40.Nd, 13.85.Ni, 14.40.Lb

In the standard model, the B_c mesons are the only states formed by two heavy quarks of different flavor, the \bar{b} and the c quarks. The production of B_c mesons in hadron collisions implies the simultaneous production of $b\bar{b}$ and $c\bar{c}$ pairs; therefore, it is rarer than that of other b mesons. The production of $b\bar{b}$ and $c\bar{c}$ quarkonium states in hadron collisions has been studied for two decades; however, significant puzzles remain [1]. The relative role of competing production mechanisms [2–5] is poorly understood and theory is unable to predict all experimentally observed features [6–11]. The study of B_c production offers a promising way of shedding light over these discrepancies and gaining insight on the underlying physics. In proton-proton (pp) collisions at the Large Hadron Collider (LHC), B_c mesons are expected to be mainly produced through the gluon-gluon fusion process $gg \rightarrow B_c + b + \bar{c}$. The production cross sections of the B_c mesons have been calculated in the fragmentation approach [12,13] and in the complete order- α_s^4 approach [14–21], where α_s is the strong-interaction coupling. In the latter approach, the total production cross section of the B_c ground state B_c^+ at a center-of-mass energy of 8 TeV integrated over the whole phase space and including contributions from intermediate excited states is predicted to be about 0.2% [22,23] of the inclusive $b\bar{b}$ cross section [24].

Previously, only the average ratios of B_c^+ to B^+ or B_s^0 cross sections in specific kinematic regions had been measured [25–27], and double-differential cross sections have not yet been measured. The production cross sections of b hadrons show different transverse momentum dependencies [28–31]. A precise measurement of B_c^+ production as a function of transverse momentum and rapidity will provide useful information on the largely unknown

production mechanism of the B_c^+ meson and other bound states of heavy quarks and is also important to guide B_c^+ studies at the LHC.

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

$$R(p_T, y) \equiv \frac{d\sigma_{B_c^+}(p_T, y)\mathcal{B}(B_c^+ \rightarrow J/\psi\pi^+)}{d\sigma_{B^+}(p_T, y)\mathcal{B}(B^+ \rightarrow J/\psi K^+)}, \quad (1)$$

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 $100 \text{ GeV}/c$. The minimum distance of a track to a primary vertex, the impact parameter (IP), is measured with a resolution of $(15 + 29/p_T) \mu\text{m}$, where p_T is in GeV/c . Different types of charged hadrons are distinguished using information from two ring-imaging Cherenkov detectors. Photon, electron, and hadron candidates are identified by a calorimeter system consisting of 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.

identified by a system composed of alternating layers of iron and multiwire proportional chambers.

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 $p_T > 300$ 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/ψ 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/ψ 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 $\tau_{B_c^+} = 0.509$ 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/ψ 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/ψ 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/ψ candidate and the hadron (π 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/ψ -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: χ_{IP}^2 of all particles, p_T of muons, p_T of J/ψ and π^+ , and the b -meson decay length, decay time, and the vertex fit χ^2 of a fit to the decay tree [46]. The quantity χ_{IP}^2 is defined as the difference in χ^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

$$R(p_T, y) = \frac{N_{B_c^+}(p_T, y) \epsilon_{B_c^+}(p_T, y)}{N_{B^+}(p_T, y) \epsilon_{B^+}(p_T, y)}, \quad (2)$$

where $N_B(p_T, y)$ is the number of reconstructed signal decays, and $\epsilon_B(p_T, y)$ 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

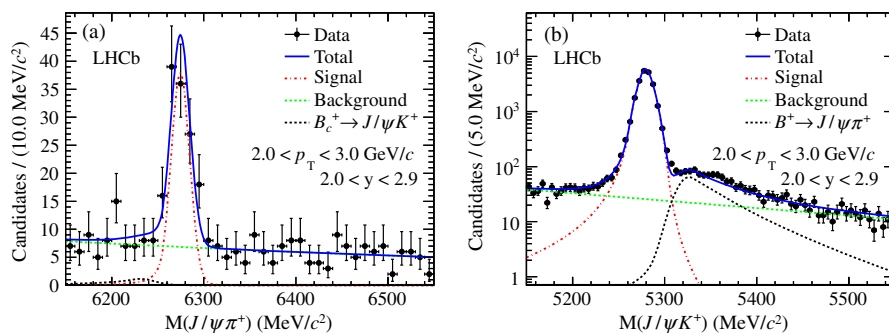


FIG. 1 (color online). Invariant mass distribution of (left) $B_c^+ \rightarrow J/\psi\pi^+$ and (right) $B^+ \rightarrow J/\psi K^+$ candidates with $2.0 < p_T < 3.0$ GeV/ c and $2.0 < y < 2.9$. The results of the fit described in the text are superimposed.

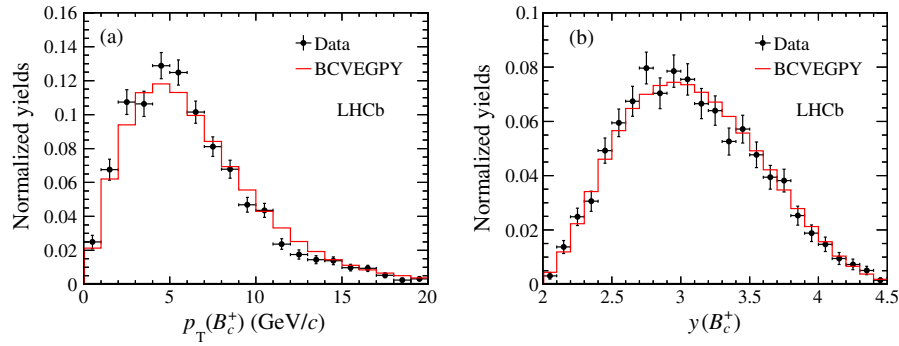


FIG. 2 (color online). Distributions of (left) p_T and (right) y of the B_c^+ signal after event selection. The points with error bars are background-subtracted data, and the solid histogram is the simulation based on the complete order- α_s^4 calculation implemented in the B_c^+ generator BCVEGPY [40]. The uncertainties are statistical.

of B_c^+ candidates reconstructed in $6150 < M_{J/\psi\pi^+} < 6550 \text{ MeV}/c^2$ and B^+ candidates in $5150 < M_{J/\psi K^+} < 5550 \text{ MeV}/c^2$. For both $B_c^+ \rightarrow J/\psi\pi^+$ and $B^+ \rightarrow J/\psi K^+$ decays, the fit includes components for signal, combinatorial background, and Cabibbo-suppressed backgrounds $B_c^+ \rightarrow J/\psi K^+$ and $B^+ \rightarrow J/\psi\pi^+$. Other sources of backgrounds, such as $B_c^+ \rightarrow J/\psi\mu^+\nu_\mu$, are negligible. The $B_c^+ \rightarrow J/\psi\pi^+$ 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 $B^+ \rightarrow J/\psi K^+$ 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 $\mathcal{B}(B_c^+ \rightarrow J/\psi K^+)/\mathcal{B}(B_c^+ \rightarrow J/\psi\pi^+) = (6.9 \pm 2.0)\%$ for B_c^+ candidates [47] and $\mathcal{B}(B^+ \rightarrow J/\psi\pi^+)/\mathcal{B}(B^+ \rightarrow J/\psi K^+) = (3.83 \pm 0.13)\%$ 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 $2.0 < p_T < 3.0 \text{ GeV}/c$ and $2.0 < y < 2.9$. The mass resolution is approximately $11 \text{ MeV}/c^2$ for B_c^+ signals and $8.7 \text{ MeV}/c^2$ for B^+ signals. Summing over all bins, a total signal yield of 3.1×10^3 B_c^+ candidates and 7.1×10^5 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 $\mathcal{B}(B_c^+ \rightarrow J/\psi K^+)/\mathcal{B}(B_c^+ \rightarrow J/\psi\pi^+)$ is varied within its uncertainty, and the resulting difference

(0.1%–0.9%) is taken as systematic uncertainty. The effect of $\mathcal{B}(B^+ \rightarrow J/\psi\pi^+)/\mathcal{B}(B^+ \rightarrow J/\psi K^+)$ 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 $0 < p_T < 20 \text{ GeV}/c$ 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 $0 < p_T < 20 \text{ GeV}/c$. 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].

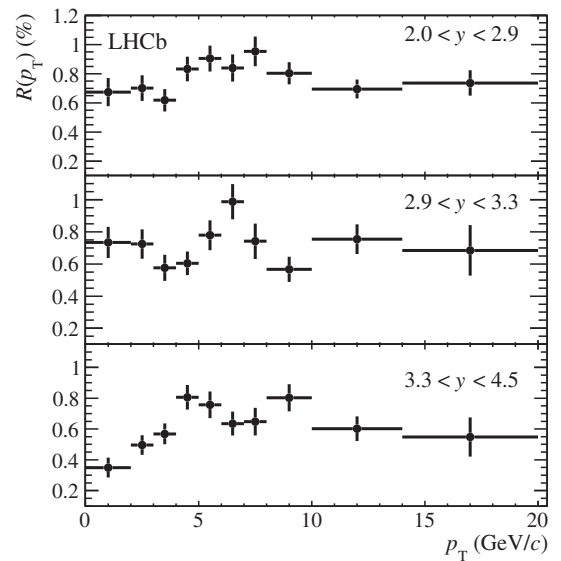


FIG. 3. Ratio $R(p_T, y)$ as a function of p_T in the regions (top) $2.0 < y < 2.9$, (middle) $2.9 < y < 3.3$, and (bottom) $3.3 < y < 4.5$. The error bars on the data show the statistical and systematic uncertainties added in quadrature.

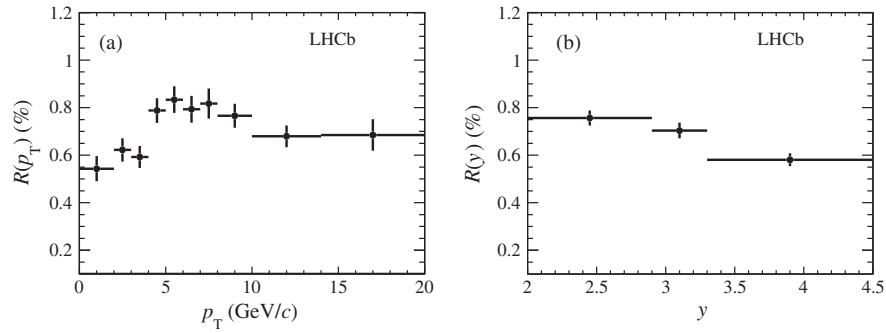


FIG. 4. Ratio (left) $R(p_T)$ as a function of p_T integrated over y in the region $2.0 < y < 4.5$ and (right) $R(y)$ as a function of y integrated over p_T in the region $0 < p_T < 20$ GeV/ c . The error bars on the data show the statistical and systematic uncertainties added in quadrature.

The resulting integrated value of R in the region $0 < p_T < 20$ 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 $4 < p_T < 20$ 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 $\sqrt{s} = 8$ 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 order- α_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, HGF, and MPG (Germany); SFI (Ireland); INFN (Italy); FOM and NWO (Netherlands); MNiSW and NCN (Poland); MEN/IFA (Romania); MinES

and FANO (Russia); MinCo (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 OCEVU, 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.

-
- [1] N. Brambilla *et al.*, Heavy quarkonium: Progress, puzzles, and opportunities, *Eur. Phys. J. C* **71**, 1534 (2011).
 - [2] C.-H. Chang, Hadronic production of J/ψ associated with a gluon, *Nucl. Phys.* **B172**, 425 (1980).
 - [3] R. Baier and R. Ruckl, Hadronic collisions: A quarkonium factory, *Z. Phys. C* **19**, 251 (1983).
 - [4] G. T. Bodwin, E. Braaten, and G. P. Lepage, Rigorous QCD analysis of inclusive annihilation and production of heavy quarkonium, *Phys. Rev. D* **51**, 1125 (1995); **55**, 5853(E) (1997).
 - [5] P. L. Cho and A. K. Leibovich, Color octet quarkonia production, *Phys. Rev. D* **53**, 150 (1996); P. L. Cho and A. K. Leibovich, Color octet quarkonia production. II, *Phys. Rev. D* **53**, 6203 (1996).
 - [6] F. Abe *et al.* (CDF Collaboration), J/ψ and $\psi(2S)$ Production in $p\bar{p}$ Collisions at $\sqrt{s} = 1.8$ TeV, *Phys. Rev. Lett.* **79**, 572 (1997); Production of J/ψ Mesons from χ_c Meson decays in $p\bar{p}$ Collisions at $\sqrt{s} = 1.8$ TeV, *Phys. Rev. Lett.* **79**, 578 (1997).

- [7] A. Abulencia *et al.* (CDF Collaboration), Polarization of J/ψ and $\psi(2S)$ Mesons Produced in $p\bar{p}$ Collisions at $\sqrt{s} = 1.96$ TeV, *Phys. Rev. Lett.* **99**, 132001 (2007).
- [8] B. Abelev *et al.* (ALICE Collaboration), J/ψ Polarization in pp Collisions at $\sqrt{s} = 7$ TeV, *Phys. Rev. Lett.* **108**, 082001 (2012).
- [9] S. Chatrchyan *et al.* (CMS Collaboration), Measurement of the $\Upsilon(1S)$, $\Upsilon(2S)$, and $\Upsilon(3S)$ Polarizations in pp Collisions at $\sqrt{s} = 7$ TeV, *Phys. Rev. Lett.* **110**, 081802 (2013).
- [10] R. Aaij *et al.* (LHCb Collaboration), Measurement of J/ψ polarization in pp collisions at $\sqrt{s} = 7$ TeV, *Eur. Phys. J. C* **73**, 2631 (2013).
- [11] R. Aaij *et al.* (LHCb Collaboration), Measurement of $\psi(2S)$ polarisation in pp collisions at $\sqrt{s} = 7$ TeV, *Eur. Phys. J. C* **74**, 2872 (2014).
- [12] E. Braaten, K. Cheung, and T. C. Yuan, Perturbative QCD fragmentation functions for B_c and B_c^* production, *Phys. Rev. D* **48**, R5049 (1993).
- [13] K. Cheung, B_c meson production at the Tevatron revisited, *Phys. Lett. B* **472**, 408 (2000).
- [14] C.-H. Chang and Y.-Q. Chen, Hadronic production of the B_c meson at TeV energies, *Phys. Rev. D* **48**, 4086 (1993).
- [15] C.-H. Chang, Y.-Q. Chen, G.-P. Han, and H.-T. Jiang, On hadronic production of the B_c meson, *Phys. Lett. B* **364**, 78 (1995).
- [16] C.-H. Chang, Y.-Q. Chen, and R. J. Oakes, Comparative study of the hadronic production of B_c mesons, *Phys. Rev. D* **54**, 4344 (1996).
- [17] C.-H. Chang, C.-F. Qiao, J.-X. Wang, and X.-G. Wu, Color-octet contributions to P -wave B_c meson hadroproduction, *Phys. Rev. D* **71**, 074012 (2005).
- [18] K. Kolodziej, A. Leike, and R. Ruckl, Production of B_c mesons in hadronic collisions, *Phys. Lett. B* **355**, 337 (1995).
- [19] A. V. Berezhnoy, A. K. Likhoded, and M. V. Shevlyagin, Hadronic production of B_c mesons, *Phys. At. Nucl.* **58**, 672 (1995).
- [20] A. V. Berezhnoy, V. V. Kiselev, and A. K. Likhoded, Photonic production of S - and P -wave B_c states and doubly heavy baryons, *Z. Phys. A* **356**, 89 (1996).
- [21] S. P. Baranov, Pair production of $B_c^{(*)}$ mesons in pp and $\gamma\gamma$ collisions, *Phys. Rev. D* **55**, 2756 (1997).
- [22] C.-H. Chang and X.-G. Wu, Uncertainties in estimating B_c hadronic production and comparisons of the production at TEVATRON and LHC, *Eur. Phys. J. C* **38**, 267 (2004).
- [23] Y.-N. Gao, J.-B. He, P. Robbe, M.-H. Schune, and Z.-W. Yang, Experimental prospects of the B_c studies of the LHCb experiment, *Chin. Phys. Lett.* **27**, 061302 (2010).
- [24] R. Aaij *et al.* (LHCb Collaboration), Measurement of J/ψ production in pp collisions at $\sqrt{s} = 7$ TeV, *Eur. Phys. J. C* **71**, 1645 (2011).
- [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_c mesons in $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV, *Phys. Rev. D* **58**, 112004 (1998).
- [26] R. Aaij *et al.* (LHCb Collaboration), Measurements of B_c^+ Production and Mass with the $B_c^+ \rightarrow J/\psi\pi^+$ Decay, *Phys. Rev. Lett.* **109**, 232001 (2012).
- [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 $B(\Lambda_b^0 \rightarrow \Lambda_c^+\mu^-\bar{\nu}_\mu)/B(\Lambda_b^0 \rightarrow \Lambda_c^+\pi^-)$, *Phys. Rev. D* **79**, 032001 (2009).
- [29] R. Aaij *et al.* (LHCb Collaboration), Measurement of b hadron production fractions in 7 TeV pp collisions, *Phys. Rev. D* **85**, 032008 (2012).
- [30] R. Aaij *et al.* (LHCb Collaboration), Study of the kinematic dependences of Λ_b^0 production in pp collisions and a measurement of the $\Lambda_b^0 \rightarrow \Lambda_c^+\pi^-$ branching fraction, *J. High Energy Phys.* **08** (2014) 143.
- [31] R. Aaij *et al.* (LHCb Collaboration), Study of Beauty Hadron Decays into Pairs of Charm Hadrons, *Phys. Rev. Lett.* **112**, 202001 (2014).
- [32] A. A. Alves Jr. *et al.* (LHCb Collaboration), The LHCb detector at the LHC, *JINST* **3**, S08005 (2008).
- [33] R. Aaij *et al.*, The LHCb trigger and its performance in 2011, *JINST* **8**, P04022 (2013).
- [34] K. A. Olive *et al.* (Particle Data Group), The review of particle physics, *Chin. Phys. C* **38**, 090001 (2014).
- [35] V. V. Gligorov and M. Williams, Efficient, reliable and fast high-level triggering using a bonsai boosted decision tree, *JINST* **8**, P02013 (2013).
- [36] L. Breiman, J. H. Friedman, R. A. Olshen, and C. J. Stone, *Classification and Regression Trees* (Wadsworth International Group, Belmont, CA, 1984).
- [37] R. E. Schapire and Y. Freund, A decision-theoretic generalization of on-line learning and an application to boosting, *J. Comput. Syst. Sci.* **55**, 119 (1997).
- [38] T. Sjöstrand, S. Mrenna, and P. Skands, PYTHIA 6.4 physics and manual, *J. High Energy Phys.* **05** (2006) 026.
- [39] I. Belyaev *et al.*, *Handling of the generation of primary events in Gauss, the LHCb simulation framework*, Nuclear Science Symposium Conference Record (NSS/MIC) (IEEE, 2010), p. 1155.
- [40] C.-H. Chang, J.-X. Wang, and X.-G. Wu, BCVEGPY2.0: An upgraded version of the generator BCVEGPY with the addition of hadroproduction of the P -wave B_c states, *Comput. Phys. Commun.* **174**, 241 (2006).
- [41] D. J. Lange, The EVTGEN particle decay simulation package, *Nucl. Instrum. Methods Phys. Res., Sect. A* **462**, 152 (2001).
- [42] P. Golonka and Z. Was, PHOTOS Monte Carlo: A precision tool for QED corrections in Z and W decays, *Eur. Phys. J. C* **45**, 97 (2006).
- [43] J. Allison *et al.* (GEANT4 Collaboration), GEANT4 developments and applications, *IEEE Trans. Nucl. Sci.* **53**, 270 (2006); S. Agostinelli *et al.* (GEANT4 Collaboration), GEANT4: A simulation toolkit, *Nucl. Instrum. Methods Phys. Res., Sect. A* **506**, 250 (2003).
- [44] M. Clemencic, G. Corti, S. Easo, C. R. Jones, S. Miglioranza, M. Pappagallo, and P. Robbe, The LHCb simulation application, GAUSS : Design, evolution and experience, *J. Phys. Conf. Ser.* **331**, 032023 (2011).

- [45] R. Aaij *et al.* (LHCb Collaboration), Measurement of the B_c^+ meson lifetime using $B_c^+ \rightarrow J/\psi \mu^+ \nu_\mu X$ decays, *Eur. Phys. J. C* **74**, 2839 (2014).
- [46] W. D. Hulsbergen, Decay chain fitting with a Kalman filter, *Nucl. Instrum. Methods Phys. Res., Sect. A* **552**, 566 (2005).
- [47] R. Aaij *et al.* (LHCb Collaboration), First observation of the decay $B_c^+ \rightarrow J/\psi K^+$, *J. High Energy Phys.* **09** (2013) 075.
- [48] R. Aaij *et al.* (LHCb Collaboration), Measurements of the branching fractions and CP asymmetries of $B^\pm \rightarrow J/\psi \pi^\pm$ and $B^\pm \rightarrow \psi(2S) \pi^\pm$ decays, *Phys. Rev. D* **85**, 091105(R) (2012).
- [49] See Supplemental Material at <http://link.aps.org/supplemental/10.1103/PhysRevLett.114.132001>, which includes Refs. [50–53].
- [50] J. Pumplin, D. R. Stump, J. Huston, H.-L. Lai, P. Nadolsky, and W.-K. Tung, New generation of parton distributions with uncertainties from global QCD analysis, *J. High Energy Phys.* **07** (2002) 012.
- [51] P. Nadolsky, H.-L. Lai, Q.-H. Cao, J. Huston, J. Pumplin, D. Stump, W.-K. Tung, and C.-P. Yuan, Implications of CTEQ global analysis for collider observables, *Phys. Rev. D* **78**, 013004 (2008).
- [52] R. Aaij *et al.* (LHCb Collaboration), Measurement of B meson production cross-sections in proton-proton collisions at $\sqrt{s} = 7$ TeV, *J. High Energy Phys.* **08** (2013) 117.
- [53] R. Aaij *et al.* (LHCb Collaboration), Production of J/ψ and Υ mesons in pp collisions at $\sqrt{s} = 8$ TeV, *J. High Energy Phys.* **06** (2013) 064.
- [54] M. Cacciari, S. Frixione, N. Houdeau, M. L. Mangano, P. Nason, and G. Ridolfi, Theoretical predictions for charm and bottom production at the LHC, *J. High Energy Phys.* **10** (2012) 137.
- [55] C.-F. Qiao, P. Sun, D. Yang, and R.-L. Zhu, B_c exclusive decays to charmonium and a light meson at next-to-leading-order accuracy, *Phys. Rev. D* **89**, 034008 (2014).

R. Aaij,⁴¹ B. Adeva,³⁷ M. Adinolfi,⁴⁶ A. Affolder,⁵² Z. Ajaltouni,⁵ S. Akar,⁶ J. Albrecht,⁹ F. Alessio,³⁸ M. Alexander,⁵¹ S. Ali,⁴¹ G. Alkhazov,³⁰ P. Alvarez Cartelle,³⁷ A. A. Alves Jr.,^{25,38} S. Amato,² S. Amerio,²² Y. Amhis,⁷ L. An,³ L. Anderlini,^{17,a} J. Anderson,⁴⁰ R. Andreassen,⁵⁷ M. Andreotti,^{16,b} J. E. Andrews,⁵⁸ R. B. Appleby,⁵⁴ O. Aquines Gutierrez,¹⁰ F. Archilli,³⁸ A. Artamonov,³⁵ M. Artuso,⁵⁹ E. Aslanides,⁶ G. Auriemma,^{25,c} M. Baalouch,⁵ S. Bachmann,¹¹ J. J. Back,⁴⁸ A. Badalov,³⁶ C. Baesso,⁶⁰ W. Baldini,¹⁶ R. J. Barlow,⁵⁴ C. Barschel,³⁸ S. Barsuk,⁷ W. Barter,⁴⁷ V. Batozskaya,²⁸ V. Battista,³⁹ A. Bay,³⁹ L. Beaucourt,⁴ J. Beddow,⁵¹ F. Bedeschi,²³ I. Bediaga,¹ S. Belogurov,³¹ K. Belous,³⁵ I. Belyaev,³¹ E. Ben-Haim,⁸ G. Bencivenni,¹⁸ S. Benson,³⁸ J. Benton,⁴⁶ A. Bereznoi,³² R. Bernet,⁴⁰ M.-O. Bettler,⁴⁷ M. van Beuzekom,⁴¹ A. Bien,¹¹ S. Bifani,⁴⁵ T. Bird,⁵⁴ A. Bizzeti,^{17,d} P. M. Bjørnstad,⁵⁴ T. Blake,⁴⁸ F. Blanc,³⁹ J. Blouw,¹⁰ S. Blusk,⁵⁹ V. Bocci,²⁵ A. Bondar,³⁴ N. Bondar,^{30,38} W. Bonivento,^{15,38} S. Borghi,⁵⁴ A. Borgia,⁵⁹ M. Borsato,⁷ T. J. V. Bowcock,⁵² E. Bowen,⁴⁰ C. Bozzi,¹⁶ T. Brambach,⁹ D. Brett,⁵⁴ M. Britsch,¹⁰ T. Britton,⁵⁹ J. Brodzicka,⁵⁴ N. H. Brook,⁴⁶ H. Brown,⁵² A. Bursche,⁴⁰ J. Buytaert,³⁸ S. Cadeddu,¹⁵ R. Calabrese,^{16,b} M. Calvi,^{20,e} M. Calvo Gomez,^{36,f} P. Campana,¹⁸ D. Campora Perez,³⁸ L. Capriotti,⁵⁴ A. Carbone,^{14,g} G. Carboni,^{24,h} R. Cardinale,^{19,38,i} A. Cardini,¹⁵ L. Carson,⁵⁰ K. Carvalho Akiba,² G. Casse,⁵² L. Cassina,^{20,e} L. Castillo Garcia,³⁸ M. Cattaneo,³⁸ Ch. Cauet,⁹ R. Cenci,^{23,j} M. Charles,⁸ Ph. Charpentier,³⁸ M. Chefdeville,⁴ S. Chen,⁵⁴ S.-F. Cheung,⁵⁵ N. Chiapolini,⁴⁰ M. Chrzaszcz,^{40,26} X. Cid Vidal,³⁸ G. Ciezarek,⁵³ P. E. L. Clarke,⁵⁰ M. Clemencic,³⁸ H. V. Cliff,⁴⁷ J. Closier,³⁸ V. Coco,³⁸ J. Cogan,⁶ E. Cogneras,⁵ V. Cogoni,¹⁵ L. Cojocariu,²⁹ G. Collazuol,²² P. Collins,³⁸ A. Comerma-Montells,¹¹ A. Contu,^{15,38} A. Cook,⁴⁶ M. Coombes,⁴⁶ S. Coquereau,⁸ G. Corti,³⁸ M. Corvo,^{16,b} I. Counts,⁵⁶ B. Couturier,³⁸ G. A. Cowan,⁵⁰ D. C. Craik,⁴⁸ A. C. Crocombe,⁴⁸ M. Cruz Torres,⁶⁰ S. Cunliffe,⁵³ R. Currie,⁵³ C. D'Ambrosio,³⁸ J. Dalseno,⁴⁶ P. David,⁸ P. N. Y. David,⁴¹ A. Davis,⁵⁷ K. De Bruyn,⁴¹ S. De Capua,⁵⁴ M. De Cian,¹¹ J. M. De Miranda,¹ L. De Paula,² W. De Silva,⁵⁷ P. De Simone,¹⁸ C.-T. Dean,⁵¹ D. Decamp,⁴ M. Deckenhoff,⁹ L. Del Buono,⁸ N. Déléage,⁴ D. Derkach,⁵⁵ O. Deschamps,⁵ F. Dettori,³⁸ A. Di Canto,³⁸ H. Dijkstra,³⁸ S. Donleavy,⁵² F. Dordei,¹¹ M. Dorigo,³⁹ A. Dosil Suárez,³⁷ D. Dossett,⁴⁸ A. Dovbnya,⁴³ K. Dreimanis,⁵² G. Dujany,⁵⁴ F. Dupertuis,³⁹ P. Durante,³⁸ R. Dzhelyadin,³⁵ A. Dziurda,²⁶ A. Dzyuba,³⁰ S. Easo,^{49,38} U. Egede,⁵³ V. Egorychev,³¹ S. Eidelman,³⁴ S. Eisenhardt,⁵⁰ U. Eitschberger,⁹ R. Ekelhof,⁹ L. Eklund,⁵¹ I. El Rifai,⁵ Ch. Elsasser,⁴⁰ S. Ely,⁵⁹ S. Esen,¹¹ H.-M. Evans,⁴⁷ T. Evans,⁵⁵ A. Falabella,¹⁴ C. Färber,¹¹ C. Farinelli,⁴¹ N. Farley,⁴⁵ S. Farry,⁵² R. Fay,⁵² D. Ferguson,⁵⁰ V. Fernandez Albor,³⁷ F. Ferreira Rodrigues,¹ M. Ferro-Luzzi,³⁸ S. Filippov,³³ M. Fiore,^{16,b} M. Fiorini,^{16,b} M. Firlej,²⁷ C. Fitzpatrick,³⁹ T. Fiutowski,²⁷ P. Fol,⁵³ M. Fontana,¹⁰ F. Fontanelli,^{19,i} R. Forty,³⁸ O. Francisco,² M. Frank,³⁸ C. Frei,³⁸ M. Frosini,^{17,a} J. Fu,^{21,38} E. Furfaro,^{24,h} A. Gallas Torreira,³⁷ D. Galli,^{14,g} S. Gallorini,^{22,38} S. Gambetta,^{19,i} M. Gandelman,² P. Gandini,⁵⁹ Y. Gao,³ J. García Pardiñas,³⁷ J. Garofoli,⁵⁹ J. Garra Tico,⁴⁷ L. Garrido,³⁶ D. Gascon,³⁶ C. Gaspar,³⁸ R. Gauld,⁵⁵ L. Gavardi,⁹ G. Gazzoni,⁵ A. Geraci,^{21,k} E. Gersabeck,¹¹ M. Gersabeck,⁵⁴ T. Gershon,⁴⁸ Ph. Ghez,⁴ A. Gianelle,²² S. Giani,³⁹ V. Gibson,⁴⁷ L. Giubega,²⁹ V. V. Gligorov,³⁸ C. Göbel,⁶⁰

D. Golubkov,³¹ A. Golutvin,^{53,31,38} A. Gomes,^{1,1} C. Gotti,^{20,e} M. Grabalosa Gándara,⁵ R. Graciani Diaz,³⁶ L. A. Granado Cardoso,³⁸ E. Graugés,³⁶ E. Graverini,⁴⁰ G. Graziani,¹⁷ A. Grecu,²⁹ E. Greening,⁵⁵ S. Gregson,⁴⁷ P. Griffith,⁴⁵ L. Grillo,¹¹ O. Grünberg,⁶³ B. Gui,⁵⁹ E. Gushchin,³³ Yu. Guz,^{35,38} T. Gys,³⁸ C. Hadjivasilou,⁵⁹ G. Haefeli,³⁹ C. Haen,³⁸ S. C. Haines,⁴⁷ S. Hall,⁵³ B. Hamilton,⁵⁸ T. Hampson,⁴⁶ X. Han,¹¹ S. Hansmann-Menzemer,¹¹ N. Harnew,⁵⁵ S. T. Harnew,⁴⁶ J. Harrison,⁵⁴ J. He,³⁸ T. Head,³⁸ V. Heijne,⁴¹ K. Hennessy,⁵² P. Henrard,⁵ L. Henry,⁸ J. A. Hernando Morata,³⁷ E. van Herwijnen,³⁸ M. Heß,⁶³ A. Hicheur,² D. Hill,⁵⁵ M. Hoballah,⁵ C. Hombach,⁵⁴ W. Hulsbergen,⁴¹ P. Hunt,⁵⁵ N. Hussain,⁵⁵ D. Hutchcroft,⁵² D. Hynds,⁵¹ M. Idzik,²⁷ P. Ilten,⁵⁶ R. Jacobsson,³⁸ A. Jaeger,¹¹ J. Jalocha,⁵⁵ E. Jans,⁴¹ P. Jaton,³⁹ A. Jawahery,⁵⁸ F. Jing,³ M. John,⁵⁵ D. Johnson,³⁸ C. R. Jones,⁴⁷ C. Joram,³⁸ B. Jost,³⁸ N. Jurik,⁵⁹ S. Kandybei,⁴³ W. Kanso,⁶ M. Karacson,³⁸ T. M. Karbach,³⁸ S. Karodia,⁵¹ M. Kelsey,⁵⁹ I. R. Kenyon,⁴⁵ T. Ketel,⁴² B. Khanji,^{20,38,e} C. Khurewathanakul,³⁹ S. Klaver,⁵⁴ K. Klimaszewski,²⁸ O. Kochebina,⁷ M. Kolpin,¹¹ I. Komarov,³⁹ R. F. Koopman,⁴² P. Koppenburg,^{41,38} M. Korolev,³² A. Kozlinskiy,⁴¹ L. Kravchuk,³³ K. Kreplin,¹¹ M. Kreps,⁴⁸ G. Krocker,¹¹ P. Krokovny,³⁴ F. Kruse,⁹ W. Kucewicz,^{26,m} M. Kucharczyk,^{20,26,e} V. Kudryavtsev,³⁴ K. Kurek,²⁸ T. Kvaratskheliya,³¹ V. N. La Thi,³⁹ D. Lacarrere,³⁸ G. Lafferty,⁵⁴ A. Lai,¹⁵ D. Lambert,⁵⁰ R. W. Lambert,⁴² G. Lanfranchi,¹⁸ C. Langenbruch,⁴⁸ B. Langhans,³⁸ T. Latham,⁴⁸ C. Lazzeroni,⁴⁵ R. Le Gac,⁶ J. van Leerdam,⁴¹ J.-P. Lees,⁴ R. Lefèvre,⁵ A. Leflat,³² J. Lefrançois,⁷ S. Leo,²³ O. Leroy,⁶ T. Lesiak,²⁶ B. Leverington,¹¹ Y. Li,⁷ T. Likhomanenko,⁶⁴ M. Liles,⁵² R. Lindner,³⁸ C. Linn,³⁸ F. Lionetto,⁴⁰ B. Liu,¹⁵ S. Lohn,³⁸ I. Longstaff,⁵¹ J. H. Lopes,² N. Lopez-March,³⁹ P. Lowdon,⁴⁰ D. Lucchesi,^{22,n} H. Luo,⁵⁰ A. Lupato,²² E. Luppi,^{16,b} O. Lupton,⁵⁵ F. Machefert,⁷ I. V. Machikhiliyan,³¹ F. Maciuc,²⁹ O. Maev,³⁰ S. Malde,⁵⁵ A. Malinin,⁶⁴ G. Manca,^{15,o} G. Mancinelli,⁶ A. Mapelli,³⁸ J. Maratas,⁵ J. F. Marchand,⁴ U. Marconi,¹⁴ C. Marin Benito,³⁶ P. Marino,^{23,j} R. Märki,³⁹ J. Marks,¹¹ G. Martellotti,²⁵ A. Martín Sánchez,⁷ M. Martinelli,³⁹ D. Martinez Santos,^{42,38} F. Martinez Vidal,⁶⁵ D. Martins Tostes,² A. Massafferri,¹ R. Matev,³⁸ Z. Mathe,³⁸ C. Matteuzzi,²⁰ A. Mazurov,⁴⁵ M. McCann,⁵³ J. McCarthy,⁴⁵ A. McNab,⁵⁴ R. McNulty,¹² B. McSkelly,⁵² B. Meadows,⁵⁷ F. Meier,⁹ M. Meissner,¹¹ M. Merk,⁴¹ D. A. Milanes,⁶² M.-N. Minard,⁴ N. Moggi,¹⁴ J. Molina Rodriguez,⁶⁰ S. Monteil,⁵ M. Morandin,²² P. Morawski,²⁷ A. Mordà,⁶ M. J. Morello,^{23,j} J. Moron,²⁷ A.-B. Morris,⁵⁰ R. Mountain,⁵⁹ F. Muheim,⁵⁰ K. Müller,⁴⁰ M. Mussini,¹⁴ B. Muster,³⁹ P. Naik,⁴⁶ T. Nakada,³⁹ R. Nandakumar,⁴⁹ I. Nasteva,² M. Needham,⁵⁰ N. Neri,²¹ S. Neubert,³⁸ N. Neufeld,³⁸ M. Neuner,¹¹ A. D. Nguyen,³⁹ T. D. Nguyen,³⁹ C. Nguyen-Mau,^{39,p} M. Nicol,⁷ V. Niess,⁵ R. Niet,⁹ N. Nikitin,³² T. Nikodem,¹¹ A. Novoselov,³⁵ D. P. O'Hanlon,⁴⁸ A. Oblakowska-Mucha,^{27,38} V. Obraztsov,³⁵ S. Oggero,⁴¹ S. Ogilvy,⁵¹ O. Okhrimenko,⁴⁴ R. Oldeman,^{15,o} C. J. G. Onderwater,⁶⁶ M. Orlandea,²⁹ J. M. Otalora Goicochea,² A. Otto,³⁸ P. Owen,⁵³ A. Oyanguren,⁶⁵ B. K. Pal,⁵⁹ A. Palano,^{13,q} F. Palombo,^{21,r} M. Palutan,¹⁸ J. Panman,³⁸ A. Papanestis,^{49,38} M. Pappagallo,⁵¹ L. L. Pappalardo,^{16,b} C. Parkes,⁵⁴ C. J. Parkinson,^{9,45} G. Passaleva,¹⁷ G. D. Patel,⁵² M. Patel,⁵³ C. Patrignani,^{19,i} A. Pearce,⁵⁴ A. Pellegrino,⁴¹ G. Penso,^{25,s} M. Pepe Altarelli,³⁸ S. Perazzini,^{14,g} P. Perret,⁵ M. Perrin-Terrin,⁶ L. Pescatore,⁴⁵ E. Pesen,⁶⁷ K. Petridis,⁵³ A. Petrolini,^{19,i} E. Picatoste Olloqui,³⁶ B. Pietrzyk,⁴ T. Pilař,⁴⁸ D. Pinci,²⁵ A. Pistone,¹⁹ S. Playfer,⁵⁰ M. Plo Casasus,³⁷ F. Polci,⁸ A. Poluektov,^{48,34} I. Polyakov,³¹ E. Polcarpo,² A. Popov,³⁵ D. Popov,¹⁰ B. Popovici,²⁹ C. Potterat,² E. Price,⁴⁶ J. D. Price,⁵² J. Prisciandaro,³⁹ A. Pritchard,⁵² C. Prouve,⁴⁶ V. Pugatch,⁴⁴ A. Puig Navarro,³⁹ G. Punzi,^{23,t} W. Qian,⁴ B. Rachwal,²⁶ J. H. Rademacker,⁴⁶ B. Rakotomiamanana,³⁹ M. Rama,¹⁸ M. S. Rangel,² I. Raniuk,⁴³ N. Rauschmayr,³⁸ G. Raven,⁴² F. Redi,⁵³ S. Reichert,⁵⁴ M. M. Reid,⁴⁸ A. C. dos Reis,¹ S. Ricciardi,⁴⁹ S. Richards,⁴⁶ M. Rihl,³⁸ K. Rinnert,⁵² V. Rives Molina,³⁶ P. Robbe,⁷ A. B. Rodrigues,¹ E. Rodrigues,⁵⁴ P. Rodriguez Perez,⁵⁴ S. Roiser,³⁸ V. Romanovsky,³⁵ A. Romero Vidal,³⁷ M. Rotondo,²² J. Rouvinet,³⁹ T. Ruf,³⁸ H. Ruiz,³⁶ P. Ruiz Valls,⁶⁵ J. J. Saborido Silva,³⁷ N. Sagidova,³⁰ P. Sail,⁵¹ B. Saitta,^{15,o} V. Salustino Guimaraes,² C. Sanchez Mayordomo,⁶⁵ B. Sanmartin Sedes,³⁷ R. Santacesaria,²⁵ C. Santamarina Rios,³⁷ E. Santovetti,^{24,h} A. Sarti,^{18,s} C. Satriano,^{25,c} A. Satta,²⁴ D. M. Saunders,⁴⁶ D. Savrina,^{31,32} M. Schiller,⁴² H. Schindler,³⁸ M. Schlupp,⁹ M. Schmelling,¹⁰ B. Schmidt,³⁸ O. Schneider,³⁹ A. Schopper,³⁸ M.-H. Schune,⁷ R. Schwemmer,³⁸ B. Sciascia,¹⁸ A. Sciubba,^{25,s} A. Semennikov,³¹ I. Sepp,⁵³ N. Serra,⁴⁰ J. Serrano,⁶ L. Sestini,²² P. Seyfert,¹¹ M. Shapkin,³⁵ I. Shapoval,^{16,43,b} Y. Shcheglov,³⁰ T. Shears,⁵² L. Shekhtman,³⁴ V. Shevchenko,⁶⁴ A. Shires,⁹ R. Silva Coutinho,⁴⁸ G. Simi,²² M. Sirendi,⁴⁷ N. Skidmore,⁴⁶ I. Skillicorn,⁵¹ T. Skwarnicki,⁵⁹ N. A. Smith,⁵² E. Smith,^{55,49} E. Smith,⁵³ J. Smith,⁴⁷ M. Smith,⁵⁴ H. Snoek,⁴¹ M. D. Sokoloff,⁵⁷ F. J. P. Soler,⁵¹ F. Soomro,³⁹ D. Souza,⁴⁶ B. Souza De Paula,² B. Spaan,⁹ P. Spradlin,⁵¹ S. Sridharan,³⁸ F. Stagni,³⁸ M. Stahl,¹¹ S. Stahl,¹¹ O. Steinkamp,⁴⁰ O. Stenyakin,³⁵ S. Stevenson,⁵⁵ S. Stoica,²⁹ S. Stone,⁵⁹ B. Storaci,⁴⁰ S. Stracka,^{23,j} M. Straticiu,²⁹ U. Straumann,⁴⁰ R. Stroili,²² V. K. Subbiah,³⁸ L. Sun,⁵⁷ W. Sutcliffe,⁵³ K. Swientek,²⁷ S. Swientek,⁹ V. Syropoulos,⁴² M. Szczekowski,²⁸ P. Szczypka,^{39,38} T. Szumlak,²⁷ S. T'Jampens,⁴ M. Teklishyn,⁷ G. Tellarini,^{16,b} F. Teubert,³⁸ C. Thomas,⁵⁵ E. Thomas,³⁸ J. van Tilburg,⁴¹ V. Tisserand,⁴ M. Tobin,³⁹ J. Todd,⁵⁷ S. Tolck,⁴² L. Tomassetti,^{16,b}

D. Tonelli,³⁸ S. Topp-Joergensen,⁵⁵ N. Torr,⁵⁵ E. Tournefier,⁴ S. Tourneur,³⁹ M. T. Tran,³⁹ M. Tresch,⁴⁰ A. Trisovic,³⁸ A. Tsaregorodtsev,⁶ P. Tsopelas,⁴¹ N. Tuning,⁴¹ M. Ubeda Garcia,³⁸ A. Ukleja,²⁸ A. Ustyuzhanin,⁶⁴ U. Uwer,¹¹ C. Vacca,¹⁵ V. Vagnoni,¹⁴ G. Valenti,¹⁴ A. Vallier,⁷ R. Vazquez Gomez,¹⁸ P. Vazquez Regueiro,³⁷ C. Vázquez Sierra,³⁷ S. Vecchi,¹⁶ J. J. Velthuis,⁴⁶ M. Veltri,^{17,u} G. Veneziano,³⁹ M. Vesterinen,¹¹ B. Viaud,⁷ D. Vieira,² M. Vieites Diaz,³⁷ X. Vilasis-Cardona,^{36,f} A. Vollhardt,⁴⁰ D. Volyanskyy,¹⁰ D. Voong,⁴⁶ A. Vorobyev,³⁰ V. Vorobyev,³⁴ C. Voß,⁶³ J. A. de Vries,⁴¹ R. Waldi,⁶³ C. Wallace,⁴⁸ R. Wallace,¹² J. Walsh,²³ S. Wandernoth,¹¹ J. Wang,⁵⁹ D. R. Ward,⁴⁷ N. K. Watson,⁴⁵ D. Websdale,⁵³ M. Whitehead,⁴⁸ J. Wicht,³⁸ D. Wiedner,¹¹ G. Wilkinson,^{55,38} M. P. Williams,⁴⁵ M. Williams,⁵⁶ H. W. Wilschut,⁶⁶ F. F. Wilson,⁴⁹ J. Wimberley,⁵⁸ J. Wishahi,⁹ W. Wislicki,²⁸ M. Witek,²⁶ G. Wormser,⁷ S. A. Wotton,⁴⁷ S. Wright,⁴⁷ K. Wyllie,³⁸ Y. Xie,⁶¹ Z. Xing,⁵⁹ Z. Xu,³⁹ Z. Yang,³ X. Yuan,³ O. Yushchenko,³⁵ M. Zangoli,¹⁴ M. Zavertyaev,^{10,v} L. Zhang,⁵⁹ W. C. Zhang,¹² Y. Zhang,³ A. Zhelezov,¹¹ A. Zhokhov,³¹ and L. Zhong³

(LHCb Collaboration)

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

- ⁴⁶*H.H. Wills Physics Laboratory, University of Bristol, Bristol, United Kingdom*
- ⁴⁷*Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom*
- ⁴⁸*Department of Physics, University of Warwick, Coventry, United Kingdom*
- ⁴⁹*STFC Rutherford Appleton Laboratory, Didcot, United Kingdom*
- ⁵⁰*School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom*
- ⁵¹*School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom*
- ⁵²*Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom*
- ⁵³*Imperial College London, London, United Kingdom*
- ⁵⁴*School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom*
- ⁵⁵*Department of Physics, University of Oxford, Oxford, United Kingdom*
- ⁵⁶*Massachusetts Institute of Technology, Cambridge, Massachusetts, USA*
- ⁵⁷*University of Cincinnati, Cincinnati, Ohio, USA*
- ⁵⁸*University of Maryland, College Park, Maryland, USA*
- ⁵⁹*Syracuse University, Syracuse, New York, USA*
- ⁶⁰*Pontifícia Universidade Católica do Rio de Janeiro (PUC-Rio), Rio de Janeiro, Brazil*
(associated with Institution *Universidade Federal do Rio de Janeiro (UFRJ), Rio de Janeiro, Brazil*)
- ⁶¹*Institute of Particle Physics, Central China Normal University, Wuhan, Hubei, China*
(associated with Institution *Center for High Energy Physics, Tsinghua University, Beijing, China*)
- ⁶²*Departamento de Física, Universidad Nacional de Colombia, Bogota, Colombia*
(associated with Institution *LPNHE, Université Pierre et Marie Curie, Université Paris Diderot, CNRS/IN2P3, Paris, France*)
- ⁶³*Institut für Physik, Universität Rostock, Rostock, Germany*
(associated with Institution *Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany*)
- ⁶⁴*National Research Centre Kurchatov Institute, Moscow, Russia*
(associated with Institution *Institute of Theoretical and Experimental Physics (ITEP), Moscow, Russia*)
- ⁶⁵*Instituto de Física Corpuscular (IFIC), Universitat de Valencia-CSIC, Valencia, Spain*
(associated with Institution *Universitat de Barcelona, Barcelona, Spain*)
- ⁶⁶*Van Swinderen Institute, University of Groningen, Groningen, The Netherlands*
(associated with Institution *Nikhef National Institute for Subatomic Physics, Amsterdam, The Netherlands*)
- ⁶⁷*Celal Bayar University, Manisa, Turkey*
(associated with Institution *European Organization for Nuclear Research (CERN), Geneva, Switzerland*)

^aAlso at Università di Firenze, Firenze, Italy.

^bAlso at Università di Ferrara, Ferrara, Italy.

^cAlso at Università della Basilicata, Potenza, Italy.

^dAlso at Università di Modena e Reggio Emilia, Modena, Italy.

^eAlso at Università di Milano Bicocca, Milano, Italy.

^fAlso at LIFAELS, La Salle, Universitat Ramon Llull, Barcelona, Spain.

^gAlso at Università di Bologna, Bologna, Italy.

^hAlso at Università di Roma Tor Vergata, Roma, Italy.

ⁱAlso at Università di Genova, Genova, Italy.

^jAlso at Scuola Normale Superiore, Pisa, Italy.

^kAlso at Politecnico di Milano, Milano, Italy.

^lAlso at Universidade Federal do Triângulo Mineiro (UFTM), Uberaba, Minas Gerais, Brazil.

^mAlso at AGH - University of Science and Technology, Faculty of Computer Science, Electronics and Telecommunications, Kraków, Poland.

ⁿAlso at Università di Padova, Padova, Italy.

^oAlso at Università di Cagliari, Cagliari, Italy.

^pAlso at Hanoi University of Science, Hanoi, Viet Nam.

^qAlso at Università di Bari, Bari, Italy.

^rAlso at Università degli Studi di Milano, Milano, Italy.

^sAlso at Università di Roma La Sapienza, Roma, Italy.

^tAlso at Università di Pisa, Pisa, Italy.

^uAlso at Università di Urbino, Urbino, Italy.

^vAlso at P.N. Lebedev Physical Institute, Russian Academy of Science (LPI RAS), Moscow, Russia.