Evidence for the decay $B^+_c \rightarrow J/\psi \ 3\pi^+ 2\pi^-$

The LHCb collaboration

E-mail: Ivan.Belyaev@cern.ch

ABSTRACT: Evidence is presented for the decay $B^+_c \rightarrow J/\psi \ 3\pi^+ 2\pi^-$ using proton-proton collision data, corresponding to an integrated luminosity of 3 fb$^{-1}$, collected with the LHCb detector. A signal yield of $32 \pm 8$ decays is found with a significance of 4.5 standard deviations. The ratio of the branching fraction of the $B^+_c \rightarrow J/\psi \ 3\pi^+ 2\pi^-$ decay to that of the $B^+_c \rightarrow J/\psi \pi^+$ decay is measured to be

$$\frac{B(B^+_c \rightarrow J/\psi \ 3\pi^+ 2\pi^-)}{B(B^+_c \rightarrow J/\psi \pi^+)} = 1.74 \pm 0.44 \pm 0.24,$$

where the first uncertainty is statistical and the second is systematic.

KEYWORDS: Hadron-Hadron Scattering, QCD, Branching fraction, B physics, Flavor physics

ArXiv ePrint: 1404.0287
Contents

1 Introduction 1
2 Detector 2
3 Candidate selection 2
4 Signal and normalization yields 3
5 Efficiency and systematic uncertainties 5
6 Results and summary 8
The LHCb collaboration 12

1 Introduction

The $B_c^+$ meson is the only meson consisting of two heavy quarks of different flavours. It was discovered by the CDF collaboration through the semileptonic decay $B_c^+ \rightarrow J/\psi \ell^+ \nu \ell^+ X \ [1]$, where X denotes possible unobserved particles. The CDF collaboration also observed the hadronic decay mode $B_c^+ \rightarrow J/\psi \pi^+ [2]$. Recently, the LHCb experiment has observed several new channels including $B_c^+ \rightarrow J/\psi \pi^+ \pi^+ \pi^- [3]$, $B_c^+ \rightarrow \psi(2S)\pi^+ [4]$, $B_c^+ \rightarrow J/\psi D_s^+ [5]$, $B_c^+ \rightarrow J/\psi K^+ [6]$, $B_c^+ \rightarrow J/\psi K^+ K^- \pi^+ [7]$ and $B_c^+ \rightarrow B^0 \pi^+ [8]$. The lifetime of the $B_c^+$ meson [9, 10] is about three times shorter than that of the $B^0$ and $B^+$ mesons, confirming the important role played by the $c$ quark in $B_c^+$ decays. The decays of $B_c^+$ mesons into charmonia and light hadrons are expected to be well described by the factorization approximation [11, 12]. In this scheme, the $B_c^+ \rightarrow J/\psi 3\pi^+ 2\pi^-$ decay is characterized by the form factors of the $B_c^+ \rightarrow J/\psi W^+$ transition and the spectral functions for the virtual $W^+$ boson into light hadrons [13]. The predictions for the ratio of branching fractions

$$R_{5\pi} \equiv \frac{B(B_c^+ \rightarrow J/\psi 3\pi^+ 2\pi^-)}{B(B_c^+ \rightarrow J/\psi \pi^+)}$$  

are 0.95 and 1.1 [14], using form factor calculations from refs. [15] and [16], respectively.

In this article, the first evidence for the decay $B_c^+ \rightarrow J/\psi 3\pi^+ 2\pi^-$ and a measurement of $R_{5\pi}$ are reported. The analysis is based on a data sample of proton-proton (pp) collisions, corresponding to an integrated luminosity of 1 fb$^{-1}$ at a centre-of-mass energy of 7 TeV and 2 fb$^{-1}$ at 8 TeV, collected with the LHCb detector.

---

1The inclusion of charge conjugate modes is implicit throughout this paper.
2 Detector

The LHCb detector [17] 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 [18] placed downstream. The combined tracking system provides a momentum measurement with relative uncertainty that varies from 0.4% at 5 GeV/c to 0.6% at 100 GeV/c, and impact parameter resolution of 20 $\mu$m for tracks with large transverse momentum. Different types of charged hadrons are distinguished using information from two ring-imaging Cherenkov detectors [19]. 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 identified by a system composed of alternating layers of iron and multiwire proportional chambers [20]. The trigger [21] consists of a hardware stage, based on information from the calorimeter and muon systems, followed by a software stage, which applies a full event reconstruction.

This analysis uses events collected by triggers that select the $\mu^+\mu^-$ pair from the $J/\psi$ decay with high efficiency. At the hardware stage either one or two muon candidates are required to trigger the event. In the case of single muon triggers, the transverse momentum, $p_T$, of the muon candidate is required to be greater than 1.5 GeV/c. For dimuon candidates, the product of the $p_T$ of muon candidates is required to satisfy $\sqrt{p_{T1}p_{T2}} > 1.3$ GeV/c. At the subsequent software trigger stage, two muons are selected with an invariant mass in the range $2.97 < m_{\mu^+\mu^-} < 3.21$ GeV/c$^2$ and consistent with originating from a common vertex. The common vertex is required to be significantly displaced from the pp collision vertices.

Simulated pp collisions are generated using Pythia 6.4 [22] with the configuration described in ref. [23]. Final-state QED radiative corrections are included using the Photos package [24]. The $B_c^+$ mesons are produced by a dedicated generator, Bcvegpy [25]. The decays of all hadrons are performed by EvtGen [26], and a specific model is implemented to generate the decays $B_c^+ \rightarrow J/\psi 3\pi^+ 2\pi^-$, assuming factorization [14]. The model allows the implementation of different form factors for this decay, calculated using QCD sum rules [15] or a relativistic quark model [16]. These predictions lead to very similar values and those based on the relativistic quark model are used in the simulation. The coupling of the five pion ($3\pi^+ 2\pi^-$) system to the virtual $W^+$ is taken from $\tau^+$ lepton decays [27]. The interaction of the generated particles with the detector and its response are implemented using the Geant4 toolkit [28, 29] as described in ref. [30].

3 Candidate selection

The decays $B_c^+ \rightarrow J/\psi 3\pi^+ 2\pi^-$ and $B_c^+ \rightarrow J/\psi \pi^+$ are reconstructed using the $J/\psi \rightarrow \mu^+\mu^-$ decay mode. The selection criteria chosen are similar for both channels.
All tracks are required to be in the pseudorapidity range $2 < \eta < 4.9$. Good track quality of charged particles is ensured by requiring the \( \chi^2 \) per number of degrees of freedom, \( \chi^2/\text{ndf} \), provided by the track fit, to be less than 3. Suppression of fake tracks created by the reconstruction is achieved by a neural network trained with simulated samples to discriminate between fake tracks and tracks associated with real particles [31], ensuring the rate of fake tracks below 0.3%.

Two dedicated neural networks are used for muon and pion identification. These networks use the information from the Cherenkov detectors [19], muon chambers [32] and the calorimeter system [33], together with the tracking information. The momentum of the pion candidates is required to be between 3.2 GeV/c and 150 GeV/c in order to ensure good quality particle identification in Cherenkov detectors. The requirements on the neural network output are chosen to ensure good agreement between data and simulation and significant reduction of the background due to misidentification.

Pairs of oppositely charged muons, originating from a common vertex, are combined to form \( J/\psi \rightarrow \mu^+\mu^- \) candidates. The \( p_T \) of each muon is required to be greater than 550 MeV/c. Good vertex reconstruction is ensured by requiring the \( \chi^2 \) of the vertex fit, \( \chi^2_{\text{vtx}} \), to be less than 20. To select dimuon vertices that are well-separated from the reconstructed pp interaction vertices, the decay length is required to be at least three times its uncertainty. The invariant mass of the dimuon combination is required to be between 3.020 and 3.135 GeV/c^2. The asymmetric mass range with respect to the known \( J/\psi \) meson mass [9] is chosen to include the QED radiative tail.

The selected \( J/\psi \) candidates are combined with pions to form \( B^+_c \rightarrow J/\psi 3\pi^+ \pi^- \) and \( B^+_c \rightarrow J/\psi \pi^+ \) candidates. The transverse momentum of each pion is required to be greater than 400 MeV/c. To ensure that the pions are inconsistent with being directly produced in a pp interaction, the impact parameter \( \chi^2 \), defined as the difference between the \( \chi^2 \) values of the fits of the pp collision vertex formed with and without the considered pion track, is required to satisfy \( \chi^2_{\text{IP}} > 4 \). When more than one primary vertex is reconstructed, the vertex with the smallest value of \( \chi^2_{\text{IP}} \) is chosen. Good vertex reconstruction for the \( B^+_c \) candidate vertex is ensured by requiring the \( \chi^2_{\text{vtx}}/\text{ndf} \) to be less than 12. To suppress the large combinatorial background in the \( B^+_c \rightarrow J/\psi 3\pi^+2\pi^- \) sample, the \( \chi^2 \) of the vertex fit for all \( J/\psi \pi^\pm \) combinations, as well as for all dipion combinations, is required to be less than 20. To improve the invariant mass resolution, a kinematic fit [34] is performed that constrains the \( \mu^+\mu^- \) pair to the known mass of the \( J/\psi \) meson. It is also required that the \( B^+_c \) candidate’s momentum vector points back to from the associated pp interaction vertex. The \( \chi^2 \) per number of degrees of freedom of the fit, \( \chi^2_{\text{fit}}/\text{ndf} \), is required to be less than 5. The measured decay time of the \( B^+_c \) candidate, calculated with respect to the associated primary vertex, is required to be between 150 \( \mu \text{m/c} \) and 1 mm/c.

### 4 Signal and normalization yields

The mass distribution for the selected \( J/\psi 3\pi^+2\pi^- \) candidates is shown in figure 1. To estimate the signal yield, an extended maximum likelihood fit to the unbinned mass distribution is made. The \( B^+_c \rightarrow J/\psi 3\pi^+2\pi^- \) signal is modelled by a Gaussian distribution
and the background by a constant function. The fit results for the fitted mass and mass resolution of $B^+_c$ signal, $m_{B^+_c}$ and $\sigma_{B^+_c}$, and signal yield $N_{B^+_c \rightarrow J/\psi 3\pi^+ 2\pi^-}$, are listed in table 1.

The statistical significance for the observed signal is determined as $S_\sigma = \sqrt{-2 \log \frac{L_B}{L_{S+B}}}$ where $L_{S+B}$ and $L_B$ denote the likelihood associated with the signal-plus-background and background-only hypothesis, respectively. The likelihoods are calculated with the peak position fixed to the known mass of $B^+_c$ meson [5, 9] and the mass resolution fixed to 10.1 MeV/$c^2$ as expected from simulation. The statistical significance of the $B^+_c \rightarrow J/\psi 3\pi^+ 2\pi^-$ signal is 4.5 standard deviations.

For the selected $B^+_c$ candidates, the existence of resonant structures is searched for in the $\pi^+ \pi^-, \pi^+ \pi^+ \pi^-, \pi^+ \pi^- \pi^-, 2\pi^+ 2\pi^-, 3\pi^+ 2\pi^-$ and $J/\psi \pi^+ \pi^-$ combinations of final state particles using the sPlot technique [35], with the reconstructed $J/\psi 3\pi^+ 2\pi^-$ mass as discriminating variable, to subtract the background. No significant narrow structures are observed; in particular, no indication of a contribution from $B^+_c \rightarrow \psi(2S) \pi^+ \pi^+ \pi^-$, followed by the $\psi(2S) \rightarrow J/\psi \pi^+ \pi^-$ decay, is seen. The background-subtracted five-pion mass distribution is shown in figure 2, along with the theoretical prediction in ref. [14], which describes the data well. The consistency between data and the model prediction is estimated using a $\chi^2$-test and gives a p-value of 14 %. The corresponding p-value for the phase space decay model is 4 %.
Table 1. Signal parameters of the unbinned extended maximum likelihood fit to the \( J/\psi 3\pi^+2\pi^- \) mass distribution. Uncertainties are statistical only.

| Parameter | Value |
|-----------|-------|
| \( m_{B_c^+} \) [MeV/\( c^2 \)] | 6273 ± 3 |
| \( \sigma_{B_c^+} \) [MeV/\( c^2 \)] | 11.4 ± 3.4 |
| \( N_{B_c^+ \to J/\psi 3\pi^+2\pi^-} \) | 32 ± 8 |

Figure 2. Background-subtracted distribution of five-pion mass from \( B_c^+ \to J/\psi 3\pi^+2\pi^- \) events (points with error bars). The model prediction from ref. [14] is shown by a red solid line, and the expectation from the phase space model is shown by a blue dashed line.

The mass distribution of the selected \( B_c^+ \to J/\psi \pi^+ \) candidates is shown in figure 3, together with the result of an extended unbinned maximum likelihood fit. The \( B_c^+ \) signal is modelled by a Gaussian distribution and the background by an exponential function. The fit gives a yield of 2271 ± 63 events.

5 Efficiency and systematic uncertainties

The overall efficiency for each decay is the product of the geometrical acceptance of the detector, reconstruction, selection and trigger efficiencies. These are estimated using simula-
Figure 3. Mass distribution for selected $B_{c}^{+} \rightarrow J/\psi \pi^{+}$ candidates. The result of a fit using the model described in the text (red solid line) is shown together with the background component (blue dashed line).

The ratio of the efficiencies is found to be

$$\frac{\varepsilon(B_{c}^{+} \rightarrow J/\psi \pi^{+})}{\varepsilon(B_{c}^{+} \rightarrow J/\psi 3\pi^{+} 2\pi^{-})} = 123.8 \pm 5.6 \pm 15.1,$$

where the first uncertainty is statistical, due to the finite size of the simulated sample, and the second one is systematic, as discussed below. The large difference in efficiencies is due to the reconstruction of four additional low-$p_T$ pions in the $B_{c}^{+} \rightarrow J/\psi 3\pi^{+} 2\pi^{-}$ mode. The efficiencies for the data samples collected at a centre-of-mass energy of 7 TeV and 8 TeV are found to be similar and a luminosity-weighted average is used, with the corresponding systematic uncertainty discussed below.

Many sources of systematic uncertainty cancel in the ratio, in particular those related to the muon and $J/\psi$ reconstruction and identification. Those that do not cancel are discussed below and summarized in table 2.

A systematic uncertainty arises from the imperfect knowledge of the shape of the signal and background in the $J/\psi 3\pi^{+} 2\pi^{-}$ and $J/\psi \pi^{+}$ mass distributions. The dependence of the signal yields on the fit model is studied by varying the signal and background parameterizations. This is assessed by using Crystal Ball [36] and double-sided Crystal Ball [37] functions for the parameterization of the $B_{c}^{+}$ signals. The background parametrization
Table 2. Relative systematic uncertainties for the ratio \( R_{5\pi} \). The total uncertainty is the quadratic sum of the individual components.

| Source                                | Uncertainty [%] |
|---------------------------------------|-----------------|
| Fit model                             | 6.6             |
| Decay model                           |                 |
| \( m_{3\pi^+2\pi^-} \) reweighting    | 7.7             |
| \( \psi(2S) \) mass veto              | 3.1             |
| Data-simulation agreement             |                 |
| Hadron interactions                   | 4 \times 2.0    |
| Track quality selection               | 4 \times 0.6    |
| Trigger                               | 1.1             |
| Pion identification                   | 0.7             |
| Selection variables                   | 1.0             |
| \( B_c^+ \) lifetime                  | 0.9             |
| Stability for various data taking conditions | 2.5         |
| Acceptance                            | 0.8             |
| Total                                 | 13.9            |

is performed using both exponential and polynomial functions. The maximum observed change of 6.6 % in the ratio of \( B_c^+ \to J/\psi 3\pi^+2\pi^- \) and \( B_c^+ \to J/\psi \pi^+ \) yields is assigned as a systematic uncertainty.

To assess the systematic uncertainty related to the \( B_c^+ \to J/\psi 3\pi^+2\pi^- \) decay model used in the simulation [14], the reconstructed mass distribution of the five-pion system in simulated events is reweighted to reproduce the distribution observed in data. As a cross-check the efficiency is also recalculated using a phase space model for the \( B_c^+ \to J/\psi 3\pi^+2\pi^- \) decays. There is a maximal change in efficiency of 7.7 %, which is taken as the systematic uncertainty for the decay model. In addition, the analysis is repeated with the removal of all \( B_c^+ \) candidates where the \( J/\psi \pi^+\pi^- \) mass is compatible with originating from \( \psi(2S) \to J/\psi \pi^+\pi^- \) decays. The observed difference of 3.1 % is assigned as an additional systematic uncertainty.

A large class of uncertainties arises from the differences between data and simulation, in particular those affecting the efficiency for reconstruction of charged-particle tracks. The largest of these arises from the simulation of hadronic interactions in the detector, which has an uncertainty of 2 % per track [31, 38, 39]. An additional uncertainty associated with the track quality requirements for the additional four pions in the signal decay is estimated to be 0.6 % per track [5, 7]. The trigger efficiency for events with \( J/\psi \to \mu^+\mu^- \) produced in beauty hadron decays is studied on data in high-yield modes [5, 40] and a systematic uncertainty of 1.1 % is assigned based on the comparison of the ratio of trigger efficiencies for high-yield samples of \( B^+ \to J/\psi K^+ \) and \( B^+ \to \psi(2S)K^+ \) decays on data and simulation [40].
The systematic uncertainty associated with pion identification is studied using a sample of $B^+ \to J/\psi K^+ \pi^+ \pi^-$ decays. The efficiency to identify a $\pi^+ \pi^-$ pair is compared for data and simulation. This comparison shows a 0.35% difference between the data and simulation in the efficiency to identify a pion pair. As a result of this study an uncertainty of 0.7% is assigned for the four additional pions in the analysis.

The transverse momentum and rapidity spectra for the selected $B^+_c \to J/\psi \pi^+$ candidates, as well their daughter $J/\psi$ mesons and pions, are found to be in good agreement with the predictions from the BCVEGPy generator. Good agreement in efficiencies determined from the data and simulation has been observed for all variables used in the selection of $B^+_c \to J/\psi \pi^+$ candidates. The differences do not exceed 1%, which is used as a conservative estimate for the systematic uncertainty from the selection variables. The agreement between data and simulation has also been cross-checked using the $B^+_c \to J/\psi 3\pi^+2\pi^-$ signal by varying the selection criteria to the values that correspond to a 20% change in the signal yield in simulation. No unexpectedly large deviation is found.

The different acceptance as a function of decay time for the $B^+_c \to J/\psi 3\pi^+2\pi^-$ and $B^+ \to J/\psi \pi^+$ decay modes results in an additional systematic uncertainty related to the imprecise knowledge of the $B^+_c$ lifetime. To assess the related uncertainty, the decay time distributions for simulated events are reweighted after changing the $B^+_c$ lifetime by one standard deviation around the value of $509 \pm 8 \pm 12$ fs [10] measured by LHCb and the efficiencies are recomputed. The observed 0.9% variation in the ratio of efficiencies is used as the systematic uncertainty.

The uncertainty related to the stability of the analysis results against variations of the detector and trigger configurations occurring in different data-taking periods are tested by studying the ratio of the yields of $B^+ \to J/\psi K^+ \pi^+ \pi^-$ and $B^+ \to J/\psi K^+$ decays as a function of the data-taking period. According to this study an additional systematic uncertainty of 2.5% is assigned [5].

The last systematic uncertainty originates from the dependence of the geometrical acceptance on both the beam crossing angle and the position of the luminosity region. The resulting 0.8% difference in the efficiency ratios is taken as an estimate of the systematic uncertainty.

A summary of systematic uncertainties is presented in table 2. The total systematic uncertainty on the ratio of the branching fractions $R_{5\pi}$ is 13.9%.

6 Results and summary

The first evidence for the decay $B^+_c \to J/\psi 3\pi^+2\pi^-$ is found using pp collisions, corresponding to an integrated luminosity of 3 fb$^{-1}$, collected with the LHCb detector A signal yield of $32 \pm 8$ events is found. The significance, taking into account the systematic uncertainties due to the fit function, peak position and mass resolution in the fit, is estimated to be 4.5 standard deviations.

Using the $B^+_c \to J/\psi \pi^+$ mode as a normalization channel, the ratio of branching fractions is calculated as

$$R_{5\pi} = \frac{N(B^+_c \to J/\psi 3\pi^+2\pi^-)}{N(B^+_c \to J/\psi \pi^+)} \times \frac{\varepsilon(B^+_c \to J/\psi \pi^+)}{\varepsilon(B^+_c \to J/\psi 3\pi^+2\pi^-)},$$

(6.1)
where $N$ is the number of reconstructed decays obtained from the fit described in section 4 and the efficiency ratio is taken from eq. (5.1). The ratio of branching fractions is measured to be
\[
\frac{\mathcal{B} (B^+_c \to J/\psi 3\pi^+ 2\pi^-)}{\mathcal{B} (B^+_c \to J/\psi \pi^+)} = 1.74 \pm 0.44 \pm 0.24,
\]
where the first uncertainty is statistical and the second is systematic. The result is in agreement with theoretical predictions [14] of 0.95 and 1.1 using the form factors from refs. [15] and [16], respectively. This result is also consistent with analogous measurements in $B^0$ and $B^+$ meson decays [9]
\[
\frac{\mathcal{B} (B^0 \to D^{*-}3\pi^+ 2\pi^-)}{\mathcal{B} (B^0 \to D^{*-}\pi^+)} = 1.70 \pm 0.34,
\]
\[
\frac{\mathcal{B} (B^+ \to D^{*0}3\pi^+ 2\pi^-)}{\mathcal{B} (B^+ \to D^{*0}\pi^+)} = 1.10 \pm 0.24,
\]
as expected from factorization.

Acknowledgments

We thank A.K. Likhoded and A.V. Luchinsky for fruitful discussions about the dynamics of $B^+_c$ decays. 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 and Region Auvergne (France); BMBF, DFG, HGF and MPG (Germany); SFI (Ireland); INFN (Italy); FOM and NWO (The Netherlands); SCSR (Poland); MEN/IFA (Romania); MinES, Rosatom, RFBR and NRC “Kurchatov Institute” (Russia); MinECo, XuntaGal and GENCAT (Spain); SNSF and SER (Switzerland); NASU (Ukraine); STFC and the Royal Society (United Kingdom); NSF (U.S.A.). We also acknowledge the support received from EPLANET, Marie Curie Actions and the ERC under FP7. The Tier1 computing centres are supported by IN2P3 (France), KIT and BMBF (Germany), INFN (Italy), NWO and SURF (The Netherlands), PIC (Spain), 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).

Open Access. This article is distributed under the terms of the Creative Commons Attribution License (CC-BY 4.0), which permits any use, distribution and reproduction in any medium, provided the original author(s) and source are credited.

References

[1] CDF collaboration, F. Abe et al., Observation of the $B_c$ meson in $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV, Phys. Rev. Lett. 81 (1998) 2432 [hep-ex/9805034] [inSPIRE].
[2] CDF collaboration, T. Aaltonen et al., Observation of the Decay $B_c^+ \to J/\psi \pi^\pm$ and Measurement of the $B_c^+$ Mass, *Phys. Rev. Lett.* **100** (2008) 182002 [arXiv:0712.1506] [inSPIRE].

[3] LHCb collaboration, First observation of the decay $B_c^+ \to J/\psi \pi^+ \pi^- \pi^+$, *Phys. Rev. Lett.* **108** (2012) 251802 [arXiv:1204.0079] [inSPIRE].

[4] LHCb collaboration, Observation of the decay $B_c^+ \to \psi(2S) \pi^+$, *Phys. Rev. D* **87** (2013) 071103 [arXiv:1303.1737] [inSPIRE].

[5] LHCb collaboration, Observation of $B_c^+ \to J/\psi D_s^+$ and $B_c^+ \to J/\psi D_s^*+$ decays, *Phys. Rev. D* **87** (2013) 112012 [arXiv:1304.4530] [inSPIRE].

[6] LHCb collaboration, First observation of the decay $B_c^+ \to J/\psi K^+$, *Phys. Rev. D* **87** (2013) 181801 [arXiv:1308.4544] [inSPIRE].

[7] Particle Data Group collaboration, J. Beringer et al., Review of particle physics, *Phys. Rev. D* **86** (2012) 010001 [inSPIRE].

[8] LHCb collaboration, Measurement of the $B_c^+$ meson lifetime using $B_c^+ \to J/\psi \mu^+ \nu \mu X$ decays, arXiv:1401.6932 [inSPIRE].

[9] M. Bauer, B. Stech and M. Wirbel, Exclusive nonleptonic decays of $D_-, D_s-$ and $B-$mesons, *Z. Phys. C* **34** (1987) 103 [inSPIRE].

[10] M. Wirbel, Description of weak decays of $D$ and $B$ Mesons, *Prog. Part. Nucl. Phys.* **21** (1988) 33 [inSPIRE].

[11] A. Likhoded and A. Luchinsky, Light hadron production in $B_c \to J/\psi + X$ decays, *Phys. Rev. D* **81** (2010) 014015 [arXiv:0910.3089] [inSPIRE].

[12] V. Kiselev, A. Kovalsky and A. Likhoded, $B_c$ decays and lifetime in QCD sum rules, *Nucl. Phys. B* **585** (2000) 353 [hep-ph/0002127] [inSPIRE].

[13] LHCb collaboration, The LHCb Detector at the LHC, 2008 *JINST* **3** S08005 [inSPIRE].

[14] R. Arink et al., Performance of the LHCb Outer Tracker, 2014 *JINST* **9** 01002 [arXiv:1311.3893] [inSPIRE].

[15] M. Adinolfi et al., Performance of the LHCb RICH detector at the LHC, *Eur. Phys. J. C* **73** (2013) 2431 [arXiv:1211.6759] [inSPIRE].

[16] J. Alves et al., Performance of the LHCb muon system, 2013 *JINST* **8** P04022 [arXiv:1211.1346] [inSPIRE].

[17] R. Aaij et al., The LHCb trigger and its performance in 2011, 2013 *JINST* **8** P04022 [arXiv:1211.3055] [inSPIRE].
[22] T. Sjöstrand, S. Mrenna and P.Z. Skands, PYTHIA 6.4 physics and manual, JHEP 05 (2006) 026 [hep-ph/0603175] [inSPIRE].

[23] I. Belyaev et al., Handling of the generation of primary events in GAUSS, the LHCb simulation framework, IEEE Nucl. Sci. Symp. Conf. Rec. IEEE (2010) 1155.

[24] P. Golonka and Z. Was, PHOTOS Monte Carlo: a precision tool for QED corrections in Z and W decays, Eur. Phys. J. C 45 (2006) 97 [hep-ph/0506026] [inSPIRE].

[25] C.-H. Chang, C. Driouichi, P. Eerola and X.G. Wu, BCVEGPY: an event generator for hadronic production of the Bc meson, Comput. Phys. Commun. 159 (2004) 192 [hep-ph/0309120] [inSPIRE].

[26] D. Lange, The EvtGen particle decay simulation package, Nucl. Instrum. Meth. A 462 (2001) 152 [inSPIRE].

[27] BABAR collaboration, J. Lees et al., Study of high-multiplicity 3-prong and 5-prong τ decays at BABAR, Phys. Rev. D 86 (2012) 092010 [arXiv:1209.2734] [inSPIRE].

[28] GEANT4 collaboration, J. Allison et al., GEANT4 developments and applications, IEEE Trans. Nucl. Sci. 53 (2006) 270.

[29] GEANT4 collaboration, S. Agostinelli et al., GEANT4 — a simulation toolkit, Nucl. Instrum. Meth. A 506 (2003) 250 [inSPIRE].

[30] M. Clemencic et al., The LHCb simulation application, Gauss: design, evolution and experience, J. Phys. Conf. Ser. 331 (2011) 032023 [inSPIRE].

[31] R. Aaij et al., Measurement of the track reconstruction efficiency at LHCb, LHCb-DP-2013-002, in preparation.

[32] F. Archilli et al., Performance of the muon identification at LHCb, 2013 JINST 8 P10020 [arXiv:1306.0249] [inSPIRE].

[33] R. Aaij et al., Performance of the LHCb calorimeters, LHCb-DP-2013-004, in preparation.

[34] W.D. Hulsbergen, Decay chain fitting with a Kalman filter, Nucl. Instrum. Meth. A 552 (2005) 566 [physics/0503191] [inSPIRE].

[35] M. Pivk and F.R. Le Diberder, SPlot: a statistical tool to unfold data distributions, Nucl. Instrum. Meth. A 555 (2005) 356 [physics/0402083] [inSPIRE].

[36] T. Skwarnicki, A study of the radiative cascade transitions between the Υ′ and Υ resonances, Ph.D. thesis, Institute of Nuclear Physics, Krakow, Poland (1986), DESY-F31-86-02 [inSPIRE].

[37] LHCb collaboration, Observation of J/ψ pair production in pp collisions at √s = 7 TeV, Phys. Lett. B 707 (2012) 52 [arXiv:1109.0963] [inSPIRE].

[38] A. Jaeger et al., Measurement of the track finding efficiency, LHCb-PUB-2011-025 (2011).

[39] LHCb collaboration, Prompt K^0_s production in pp collisions at √s = 0.9 TeV, Phys. Lett. B 693 (2010) 69 [arXiv:1008.3105] [inSPIRE].

[40] LHCb collaboration, Measurement of relative branching fractions of B decays to ψ(2S) and J/ψ mesons, Eur. Phys. J. C 72 (2012) 2118 [arXiv:1205.0918] [inSPIRE].
The LHCb collaboration

R. Aaij 41, B. Adeva 37, M. Adinolfi 46, A. Affolder 52, Z. Ajaltouni 37, J. Albrecht 9, F. Alessio 38, M. Alexander 31, S. Ali 41, G. Alkhazov 31, P. Alvarez Cartello 37, A. A. Alves Jr 35, S. Amato 7, S. Amerio 22, Y. Amhis 7, L. An 3, L. Anderlini 17, g, J. Anderson 40, R. Andreassen 37, M. Andreotti 16, 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. Auriumma 25, m, M. Baalouch 5, S. Bachmann 11, J.J. Back 48, A. Badalov 36, V. Balagura 31, W. Baldini 16, R.J. Barlow 54, C. Barneschel 38, S. Barsuk 7, W. Barter 47, V. Batozskaya 28, Th. Bauer 41, A. Bay 39, J. Beddow 51, F. Bedeschi 23, I. Bediaga 1, S. Belogurov 31, K. Belous 35, I. Belyaev 31, E. Ben-Haim 5, G. Bencivenni 18, S. Benson 50, J. Benton 46, A. Berezhnoy 32, R. Bernet 40, M.-O. Bettler 47, M. van Beuzekom 41, A. Bien 11, S. Bifani 59, V. Bird 54, A. Bizzeti 17, j, P.M. Bjornstad 54, T. Blake 48, F. Blanc 39, J. Blouw 10, S. Blusk 59, V. Bocci 25, A. Bonda 34, N. Bonda 30, 38, W. Bonivento 15, 38, S. Borghi 54, A. Borgia 59, M. Borsato 5, T.J.V. Bowcock 52, E. Bowen 40, C. Bozzi 16, T. Brambach 9, J. van den Brand 42, J. Bressieux 39, D. Brett 54, M. Britsch 10, T. Britton 59, N.H. Brook 46, H. Brown 52, A. Bursche 40, G. Busetto 39, J. Buylaert 54, S. Cadeddu 15, R. Calabrese 16, f, O. Callot 7, M. Calvi 20, M. Calvo Gomez 36, a, A. Camboni 36, P. Campana 18, 38, D. Campora Perez 28, F. Caponio 21, f, A. Carbone 41, G. Carboni 24, R. Cardinale 19, 38, 3, A. Cardini 15, H. Carranza-Mejia 56, L. Carson 50, K. Carvalho Akiba 2, G. Cassie 52, L. Cassina 20, L. Castillo Garcia 38, M. Cattaneo 38, Ch. Cateau 9, R. Cenci 59, M. Charles 16, Ph. Charpentier 38, S.-F. Cheung 55, N. Chiapolini 40, M. Chrzaszcz 40, K. Cihy 38, X. Cid Vidal 38, G. Ciezarek 53, P.E.L. Clarke 50, M. Clemencic 38, H.V. Cliff 47, J. Closier 38, C. Coca 29, V. Cocco 38, J. Cogan 6, E. Coigreas 5, P. Collins 38, A. Comerma-Montells 1, A. Contu 15, 38, A. Cook 36, M. Coombes 46, S. Coquereau 8, G. Corti 38, I. Counts 56, B. Couturier 38, G.A. Cowan 60, D.C. Craik 48, M. Cruz Torres 60, S. Cumilie 53, R. Currie 50, C. D’Ambrosio 38, J. Dalseno 46, P. David 5, 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, D. Decamp 59, L. Del Buono 8, N. Déléage 4, D. Derkach 55, O. Deschamps 5, F. Dettori 42, A. Di Canto 38, H. Dijkstra 38, S. Donlevy 52, F. Dorel 41, M. Dorigo 39, A. Dosil Suárez 37, D. Dossert 48, A. Dovbnya 43, F. Dupupertuis 39, P. Durante 38, R. Dzhelyadin 35, A. Dziurzak 26, A. Dzyuba 30, S. Easo 49, U. Egede 53, V. Egorychev 31, S. Eidelman 34, S. Eisenhardt 50, U. Eitschberger 4, R. Elkoff 9, L. Eklund 51, 38, I. El Rifaï 5, Ch. Elsasser 40, S. Esser 39, J. Falabella 16, f, C. Färber 11, C. Farinelli 41, N. Farley 45, S. Farrow 52, D. Ferguson 50, V. Fernandez Albor 37, F. Ferreira Rodrigues 1, M. Ferro-Luzzi 38, S. Filipov 33, M. Fiore 16, f, M. Fiorini 16, f, M. Firlej 27, C. Fitzpatrick 38, T. Fiutowski 27, M. Fontana 10, F. Fontanelli 19, j, R. Forty 38, O. Francesco 2, M. Frank 38, C. Frei 38, M. Frosoni 17, 38, g, J. Fr 21, E. Furfaro 24, j, A. Gallas Torre 37, D. Galli 14, s, S. Gallorini 22, S. Gambetta 19, j, M. Gandelman 2, P. Gandini 50, Y. Gao 3, J. Garofoli 59, J. Garra Tico 47, L. Garrido 36, C. Gaspar 38, R. Gauld 55, L. Gavardi 9, E. Gersabeck 11, M. Gersabeck 54, T. Gershon 48, Ph. Ghez 4, A. Gianelle 22, S. Gian 39, V. Gibson 47, L. Giubega 29, V.V. Gligorov 38, C. Göbel 80, D. Golubkov 31, A. Golutvin 53, 31, 38, A. Gomes 1, a, H. Gordon 38, C. Gotti 20, M. Grabalosa Gándara 5, R. Graciani Diaz 36, L.A. Granado Cardoso 38, E. Graugärtner 36, G. Grazianni 17, A. Greco 29, E. Greening 35, S. Gregson 47, P. Griffith 45, L. Grillo 11, O. Grünberg 62, B. Gu 39, E. Gushchin 33, Yu. Guz 35, 38, T. Gyas 38, C. Hadjivasiliou 59, G. Haefeli 39, C. Haen 38, T.W. Hafkenschiel 55, S.C. Haines 47, S. Hall 59, B. Hamilton 56, T. Hampson 46, X. Han 11, S. Hansmann-Menzemer 11, N. Harney 55, S.T. Harnew 46, J. Harrison 54, T. Hartmann 62, J. He 38, T. Head 38, V. Heijne 41, K. Hennessy 52, P. Hendrie 5, L. Henry 4, J.A. Hernandez Morata 37, E. van Herwijnen 38, M. Heß 62, A. Hicheur 1, D. Hill 55, M. Hoballah 5, C. Hombach 54, W. Hulsbergen 41, P. Hunt 55, N. Hussain 55, D. Hutchcroft 59, D. Hynds 51, M. Idzik 57, P. Ilten 56, R. Jacobsson 18, A. Jaeger 31, E. Jans 41,
H. Snoek, M.D. Sokoloff, F.J.P. Soler, F. Soomro, D. Souza De Paula, B. Spaan, A. Sparkes, F. Spinella, P. Spradlin, F. Stagni, S. Stahl, O. Steinkamp, S. Stevenson, S. Stoica, S. Stone, B. Storaci, S. Stracka, M. Straticiu, U. Straumann, R. Stroili, V.K. Subbiah, L. Sun, W. Sutcliffe, K. Swientek, S. Swientek, V. Syropoulos, M. Szczekowski, P. Szczypka, D. Szilard, T. Szumlak, S. T’Jampens, M. Teklishyn, G. Tellarini, F. Teubert, C. Thomas, J. van Tilburg, V. Tisserand, M. Tobin, S. Tolk, L. Tomassetti, D. Tonelli, S. Topp-Joergensen, N. Torr, E. Tournefier, S. Tourneur, M.T. Tran, M. Tresch, A. Tsaregorodtsev, S. Topp-Joergensen, X. Yuan, M. Witek, M.P. Williams, N.K. Watson, D. Websdale, M. Whitehead, J. Wicht, D. Wedner, G. Wilkinson, M.P. Williams, M. Williams, F.F. Wilson, J. Wimberley, J. Wishal, W.Wislicki, M. Witek, G. Wormser, S.A. Wotton, Z. Yang, X. Yuan, O. Yushchenko, M. Zangoli, O. Yushchenko, Y. Zhang, A. Zhel, H. Zhong, A. Zhokhov, A. Zhlevezov, S. Zhong, A. Zyvagin, W.C. Zhang, Y. Zhang, A. Zehelev, A. Zhokhov, L. Zhong, A. Zvyagin, W.C. Zhang, Y. Zhang, A. Zehelev, A. Zhokhov, L. Zhong, A. Zyvagin, W.C. Zhang, Y. Zhang, A. Zehelev, A. Zhokhov, L. Zhong, A. Zyvagin, W.C. Zhang, Y. Zhang, A. Zehelev, A. Zhokhov, L. Zhong, A. Zyvagin.
Petersburg Nuclear Physics Institute (PNPI), Gatchina, Russia
Institute of Theoretical and Experimental Physics (ITEP), Moscow, Russia
Institute of Nuclear Physics, Moscow State University (SINP MSU), Moscow, Russia
Institute for Nuclear Research of the Russian Academy of Sciences (INR RAN), Moscow, Russia
Budker Institute of Nuclear Physics (SB RAS) and Novosibirsk State University, Novosibirsk, Russia
Institute for High Energy Physics (IHEP), Protvino, Russia
Universitat de Barcelona, Barcelona, Spain
Institute for Theoretical and Experimental Physics (ITEP), Moscow, Russia
European Organization for Nuclear Research (CERN), Geneva, Switzerland
Ecole Polytechnique Fédérale de Lausanne (EPFL), Lausanne, Switzerland
Physik-Institut, Universität Zürich, Zürich, Switzerland
Nikhef National Institute for Subatomic Physics, Amsterdam, The Netherlands
Institute for Theoretical and Experimental Physics (ITEP), Moscow, Russia
Institute of Nuclear Physics, Moscow State University (SINP MSU), Moscow, Russia
Institute for Nuclear Research of the Russian Academy of Sciences (INR RAN), Moscow, Russia
Budker Institute of Nuclear Physics (SB RAS) and Novosibirsk State University, Novosibirsk, Russia
Institute for High Energy Physics (IHEP), Protvino, Russia
Universitat de Barcelona, Barcelona, Spain
Institute for Theoretical and Experimental Physics (ITEP), Moscow, Russia
European Organization for Nuclear Research (CERN), Geneva, Switzerland
Ecole Polytechnique Fédérale de Lausanne (EPFL), Lausanne, Switzerland
Physik-Institut, Universität Zürich, Zürich, Switzerland
Nikhef National Institute for Subatomic Physics, Amsterdam, The Netherlands
NSC Kharkiv Institute of Physics and Technology (NSC KIPT), Kharkiv, Ukraine
Institute for Nuclear Research of the National Academy of Sciences (KINR), Kyiv, Ukraine
University of Birmingham, Birmingham, United Kingdom
H.H. Wills Physics Laboratory, University of Bristol, Bristol, United Kingdom
Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom
Department of Physics, University of Warwick, Coventry, United Kingdom
STFC Rutherford Appleton Laboratory, Didcot, United Kingdom
School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom
School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom
Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom
Imperial College London, London, United Kingdom
School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom
Department of Physics, University of Oxford, Oxford, United Kingdom
Massachusetts Institute of Technology, Cambridge, MA, United States
University of Cincinnati, Cincinnati, OH, United States
University of Connecticut, Storrs, CT, United States
Syracuse University, Syracuse, NY, United States
Pontificia Universidade Católica do Rio de Janeiro (PUC-Rio), Rio de Janeiro, Brazil, associated to 2
Institute of Particle Physics, Central China Normal University, Wuhan, Hubei, China, associated to 3
Université Paris-Saclay, Orsay, France
Institut für Physik, Universität Rostock, Rostock, Germany, associated to 4
National Research Centre Kurchatov Institute, Moscow, Russia, associated to 5
Instituto de Fisica Corpuscular (IFIC), Universitat de Valencia-CSIC, Valencia, Spain, associated to 6
KVI - University of Groningen, Groningen, The Netherlands, associated to 7
Celal Bayar University, Manisa, Turkey, associated to 8
Universidade Federal do Triângulo Mineiro (UFTM), Uberaba-MG, Brazil
P.N. Lebedev Physical Institute, Russian Academy of Science (LPI RAS), Moscow, Russia
Università di Bari, Bari, Italy
Università di Bologna, Bologna, Italy
Università di Cagliari, Cagliari, Italy
Università di Ferrara, Ferrara, Italy
Università di Firenze, Firenze, Italy
Università di Urbino, Urbino, Italy
Università di Modena e Reggio Emilia, Modena, Italy

\* Universidade Federal do Triângulo Mineiro (UFTM), Uberaba-MG, Brazil
\* P.N. Lebedev Physical Institute, Russian Academy of Science (LPI RAS), Moscow, Russia
\* Università di Bari, Bari, Italy
\* Università di Bologna, Bologna, Italy
\* Università di Cagliari, Cagliari, Italy
\* Università di Ferrara, Ferrara, Italy
\* Università di Firenze, Firenze, Italy
\* Università di Urbino, Urbino, Italy
\* Università di Modena e Reggio Emilia, Modena, Italy

\* Universidade Federal do Triângulo Mineiro (UFTM), Uberaba-MG, Brazil
\* P.N. Lebedev Physical Institute, Russian Academy of Science (LPI RAS), Moscow, Russia
\* Università di Bari, Bari, Italy
\* Università di Bologna, Bologna, Italy
\* Università di Cagliari, Cagliari, Italy
\* Università di Ferrara, Ferrara, Italy
\* Università di Firenze, Firenze, Italy
\* Università di Urbino, Urbino, Italy
\* Università di Modena e Reggio Emilia, Modena, Italy

\* Universidade Federal do Triângulo Mineiro (UFTM), Uberaba-MG, Brazil
\* P.N. Lebedev Physical Institute, Russian Academy of Science (LPI RAS), Moscow, Russia
\* Università di Bari, Bari, Italy
\* Università di Bologna, Bologna, Italy
\* Università di Cagliari, Cagliari, Italy
\* Università di Ferrara, Ferrara, Italy
\* Università di Firenze, Firenze, Italy
\* Università di Urbino, Urbino, Italy
\* Università di Modena e Reggio Emilia, Modena, Italy
