



# Measurement of the lifetime of the $B_c^+$ meson using the $B_c^+ \rightarrow J/\psi\pi^+$ decay mode



LHCb Collaboration

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## ABSTRACT

The difference in total widths between the  $B_c^+$  and  $B^+$  mesons is measured using a data sample corresponding to an integrated luminosity of  $3.0 \text{ fb}^{-1}$  collected by the LHCb experiment in 7 and 8 TeV centre-of-mass energy proton–proton collisions at the LHC. Through the study of the time evolution of  $B_c^+ \rightarrow J/\psi\pi^+$  and  $B^+ \rightarrow J/\psi K^+$  decays, the width difference is measured to be

$$\Delta\Gamma \equiv \Gamma_{B_c^+} - \Gamma_{B^+} = 4.46 \pm 0.14 \pm 0.07 \text{ mm}^{-1} c,$$

where the first uncertainty is statistical and the second systematic. The known lifetime of the  $B^+$  meson is used to convert this to a precise measurement of the  $B_c^+$  lifetime,

$$\tau_{B_c^+} = 513.4 \pm 11.0 \pm 5.7 \text{ fs},$$

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

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## 1. Introduction

For weakly decaying beauty hadrons the heavy quark expansion [1–4] predicts lifetime differences of the order  $(\Lambda_{\text{QCD}}/m_b)$ , where  $\Lambda_{\text{QCD}}$  is the scale parameter of the strong interaction and  $m_b$  is the b-quark mass. In agreement with the expectations, differences between  $B^+$ ,  $B^0$ ,  $B_s^0$ ,  $\Lambda_b^0$ ,  $\Xi_b^0$  and  $\Xi_b^-$  lifetimes not exceeding a few per cent are found experimentally [5–11]. The  $B_c^+$  meson is a bound state of an anti-b quark and a charm quark, and Cabibbo-favoured decays of the charm quark are expected to account for 70% of its total width, resulting in a significantly shorter lifetime than for other B mesons. In addition, non-spectator topologies, in particular annihilation amplitudes, are not Cabibbo-suppressed. These could give sizeable contributions to the total width [12–18]. Understanding the relative contributions of beauty and charm quarks to the total width of the  $B_c^+$  meson is important for predicting the properties of unobserved baryons with two heavy quarks [19,20].

The lifetime of the  $B_c^+$  meson was first measured by the CDF [21–23] and D0 [24] Collaborations using semileptonic  $B_c^+ \rightarrow J/\psi\mu^+\nu_\mu X$  and hadronic  $B_c^+ \rightarrow J/\psi\pi^+$  decays.<sup>1</sup> The average value of these measurements is  $\tau_{B_c^+} = 452 \pm 32 \text{ fs}$  [25]. Recently, the LHCb Collaboration made the most precise measurement to date

of the  $B_c^+$  meson lifetime using semileptonic  $B_c^+ \rightarrow J/\psi\mu^+\nu_\mu X$  decays,  $\tau_{B_c^+} = 509 \pm 14 \text{ fs}$  [26].

In this Letter we report a measurement of the  $B_c^+$  meson lifetime obtained via the difference between the total width of the  $B_c^+$  and  $B^+$  mesons in the hadronic modes  $B_c^+ \rightarrow J/\psi\pi^+$  and  $B^+ \rightarrow J/\psi K^+$ , using the technique developed in Refs. [7–11,27]. The measurement uses a data sample corresponding to an integrated luminosity of  $3.0 \text{ fb}^{-1}$  collected by the LHCb experiment in proton–proton (pp) collisions at centre-of-mass energies of 7 and 8 TeV. This study is complementary to the measurement of the  $B_c^+$  lifetime using the semileptonic  $B_c^+ \rightarrow J/\psi\mu^+\nu_\mu X$  decays described in Ref. [26].

The  $B_c^+$  lifetime is determined as follows. The decay time distribution for signal,  $N_B(t)$ , can be described as the product of an acceptance function  $\varepsilon_B(t)$  and an exponential decay  $E_B(t) = \exp(-t/\tau_B)$  convolved with the decay time resolution of the detector. The effect of the decay time resolution on the ratio  $\mathcal{R}(t) \equiv N_{B_c^+}(t)/N_{B^+}(t)$  is found to be small and is absorbed into the ratio of acceptance functions. This leads to the simplified expression

$$\mathcal{R}(t) \propto \frac{\varepsilon_{B_c^+}(t) E_{B_c^+}(t)}{\varepsilon_{B^+}(t) E_{B^+}(t)} \equiv \mathcal{R}_\varepsilon(t) e^{-\Delta\Gamma t}$$

$$\text{with } \Delta\Gamma \equiv \Gamma_{B_c^+} - \Gamma_{B^+} = \frac{1}{\tau_{B_c^+}} - \frac{1}{\tau_B}, \quad (1)$$

<sup>1</sup> The inclusion of charge-conjugate process is implied through this Letter.

where the factor  $\mathcal{R}_\varepsilon(t)$  denotes the ratio of the acceptance functions. This allows a precise measurement of  $\Delta\Gamma$  and hence of the lifetime of the  $B_c^+$  meson.

## 2. Detector and event simulation

The LHCb detector [28] 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 [29], 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 [30] placed downstream of the magnet. The tracking system provides a measurement of momentum,  $p$ , with a relative uncertainty that varies from 0.4% at low momentum to 0.6% at 100 GeV/c. The minimum distance of a track to a primary vertex, the impact parameter, is measured with a resolution of  $(15 + 29/p_T) \mu\text{m}$ , where  $p_T$  is the component of momentum transverse to the beam, in GeV/c. Different types of charged hadrons are distinguished using information from two ring-imaging Cherenkov detectors (RICH) [31]. 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 [32].

The trigger [33] comprises two stages. Events are first required to pass the hardware trigger, which selects muon candidates with  $p_T > 1.5$  GeV/c or pairs of opposite-sign muon candidates with a requirement that the product of the muon transverse momenta is larger than  $1.7$  ( $2.6$ )  $\text{GeV}^2/c^2$  for data collected at  $\sqrt{s} = 7$  ( $8$ ) TeV. The subsequent software trigger is composed of two stages, the first of which performs a partial event reconstruction, while full event reconstruction is done at the second stage. At the first stage of the software trigger the invariant mass of well-reconstructed pairs of oppositely charged muons forming a good two-prong vertex is required to exceed  $2.7 \text{ GeV}/c^2$ , and the two-prong vertex is required to be significantly displaced with respect to the reconstructed pp collision vertex.

In the simulation, pp collisions are generated using PYTHIA [34] with a specific LHCb configuration [35]. A dedicated generator, BCVEGPY [36], which implements explicit leading-order matrix element calculations [37–39], is used for production of  $B_c^+$  mesons. The kinematic distributions of  $B_c^+$  mesons are reproduced by the BCVEGPY generator with percent-level precision [26,40–47], while the simulated  $B^+$  samples, produced with PYTHIA, are corrected to reproduce the observed kinematic distributions. Decays of hadronic particles are described by EVTGEN [48], in which final-state radiation is generated using PHOTOS [49]. The interaction of the generated particles with the detector and the detector response are implemented using the GEANT4 toolkit [50] as described in Ref. [51].

## 3. Event selection

The offline selection of  $B_c^+ \rightarrow J/\psi\pi^+$  and  $B^+ \rightarrow J/\psi K^+$  candidates is divided into two parts. An initial selection is applied to reduce the combinatorial background. Subsequently, a multivariate estimator based on an artificial neural network algorithm [52,53], configured with a cross-entropy cost estimator [54], in the following referred as MLP classifier, is applied. The same criteria are used for both the  $B_c^+$  and  $B^+$  candidates.

The selection starts from well-identified muon candidates that have a transverse momentum in excess of  $550 \text{ MeV}/c$ . Pairs of muon candidates are required to form a common vertex and to

have an invariant mass within  $\pm 60 \text{ MeV}/c^2$  of the known  $J/\psi$  mass [5]. To ensure that the  $J/\psi$  candidate originates in a b-hadron decay, a significant decay length with respect to the pp collision vertex is required. The charged pions and kaons must be positively identified using the combined information from the RICH, calorimeter and muon detectors. The  $B_c^+$  and  $B^+$  candidates are formed from  $J/\psi\pi^+$  and  $J/\psi K^+$  combinations, respectively. To improve the invariant mass and decay time resolutions for selected candidates, a kinematic fit [55] is applied in which a primary vertex pointing constraint and a mass constraint on the intermediate  $J/\psi$  states are applied. To reduce combinatorial background, a requirement on the  $\chi^2$  of this fit,  $\chi_{\text{fit}}^2$ , is imposed and the decay time of the reconstructed  $B_c^+$  ( $B^+$ ) candidate is required to be in the range  $50 < t < 1000 \mu\text{m}/c$ .

The final selection of candidates using the MLP classifier is based on the transverse momenta and rapidities of reconstructed  $B_c^+$  ( $B^+$ ) and  $J/\psi$ , the transverse momentum and pseudorapidity of the  $\pi^+$  ( $K^+$ ) candidate, the cosine of the decay angle  $\theta$  between the momentum of the  $\pi^+$  ( $K^+$ ) in the rest frame of the  $B_c^+$  ( $B^+$ ) candidate and the boost direction from the  $B_c^+$  ( $B^+$ ) rest frame to the laboratory frame, the  $\chi^2$  of the  $B_c^+$  ( $B^+$ ) vertex fit, and  $\chi_{\text{fit}}^2$ . These variables provide good discrimination between signal and background whilst keeping the selection efficiency independent of the  $B_c^+$  ( $B^+$ ) decay time. The MLP classifier is trained on a simulated sample of  $B_c^+ \rightarrow J/\psi\pi^+$  events and a background data sample from the mass sidebands of the  $B_c^+$  signal peak. It is tested on independent samples from the same sources. The working point of the classifier is chosen to minimize  $\sigma(S)/S$ , where  $S$  is the  $B_c^+$  signal yield and  $\sigma(S)$  is the yield uncertainty, as determined by the mass fit described in the next section. The same MLP classifier is used for the  $B^+ \rightarrow J/\psi K^+$  mode.

## 4. Measurement of $\Delta\Gamma$

The invariant mass distributions for selected  $B_c^+$  and  $B^+$  candidates are presented in Fig. 1. The signal yields are determined using an extended unbinned maximum likelihood fit in which the signal distributions are modelled by a Gaussian function with power-law tails on both sides of the peak [56], and the background is modelled by the product of an exponential and a first-order polynomial function. Simulation studies suggest that the same tail parameters apply for the  $B_c^+$  and  $B^+$  signals. The tail parameters determined from the data for the large  $B^+$  signal are in good agreement with the simulation. The fit gives  $2886 \pm 71$  signal  $B_c^+$  decays and  $586065 \pm 798$  signal  $B^+$  decays. The fitted values for the  $B_c^+$  and  $B^+$  invariant masses are consistent with the known values [5] and the fitted mass resolutions agree with the expectation from simulation.

The signal yields of  $B_c^+$  and  $B^+$  mesons in bins of decay time are shown in Fig. 2(a). A non-uniform binning scheme is chosen with a minimal bin width of  $25 \mu\text{m}/c$  at low  $t$  increasing to  $200 \mu\text{m}/c$  at the largest decay times, to keep the  $B_c^+$  signal yield above 20 for all  $t$  bins. In the mass fits of the individual decay time bins the peak positions and mass resolutions are fixed to the values obtained from the fit in the entire region,  $50 < t < 1000 \mu\text{m}/c$ .

The decay time resolution function is estimated using simulated samples and found to be well described by triple Gaussian functions with overall rms widths of  $10.9 \mu\text{m}/c$  and  $11.5 \mu\text{m}/c$  for  $B_c^+$  and  $B^+$  decays, respectively. The ratio of acceptance functions,  $\mathcal{R}_\varepsilon(t)$ , is determined using the simulation and shown in Fig. 2(b). The variation in the acceptance ratio is caused by the requirement on the  $J/\psi$  decay length imposed in the trigger and the subsequent selection. The acceptance is calculated as the ratio of decay time distributions of the reconstructed and selected simulated events to the theoretical (exponential) distributions con-

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