# Measurement of the lifetime of the B+c meson using the B+c→J/$\psi\pi$+ decay mode

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

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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 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 $B_c^+ \to J/\psi\pi^+$ and $B^+ \to J/\psi K^+$ 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.



## 1. Introduction

For weakly decaying beauty hadrons the heavy quark expansion [1–4] predicts lifetime differences of the order $(\Lambda_{QCD}/m_b)$, where $\Lambda_{QCD}$ 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 $B_c^+ \to J/\psi\mu^+\nu_\mu X$ and hadronic $B_c^+ \to J/\psi\pi^+$ decays.[1] The average value of these measurements is $\tau_{B_c^+} = 452 \pm 32$ fs [25]. Recently, the LHCb Collaboration made the most precise measurement to date of the $B_c^+$ meson lifetime using semileptonic $B_c^+ \to J/\psi\mu^+\nu_\mu X$ decays, $\tau_{B_c^+} = 509 \pm 14$ 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 $B_c^+ \to J/\psi\pi^+$ and $B^+ \to J/\psi K^+$, using the technique developed in Refs. [7–11,27]. The measurement uses a data sample corresponding to an integrated luminosity of 3.0 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 $B_c^+ \to J/\psi\mu^+\nu_\mu X$ 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

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

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

[1] The inclusion of charge-conjugate process is implied through this Letter.

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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 $(15 + 29/p_T)$ μm, 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) 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 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 $B_c^+ \to J/\psi\pi^+$ and $B^+ \to J/\psi K^+$ 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 MeV/$c$. Pairs of muon candidates are required to form a common vertex and to have an invariant mass within $\pm 60$ 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, $\chi^2_{\rm fit}$, is imposed and the decay time of the reconstructed $B_c^+$ ($B^+$) candidate is required to be in the range $50 < t < 1000$ μm/$c$.

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 $\chi^2_{\rm fit}$. 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 $B_c^+ \to J/\psi\pi^+$ 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 $\sigma(\mathcal{S})/\mathcal{S}$, where $\mathcal{S}$ is the $B_c^+$ signal yield and $\sigma(\mathcal{S})$ is the yield uncertainty, as determined by the mass fit described in the next section. The same MLP classifier is used for the $B^+ \to J/\psi K^+$ 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 $586\,065 \pm 798$ 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 μm/$c$ at low $t$ increasing to 200 μm/$c$ 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, $50 < t < 1000$ μm/$c$.

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 μm/$c$ and 11.5 μm/$c$ 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-

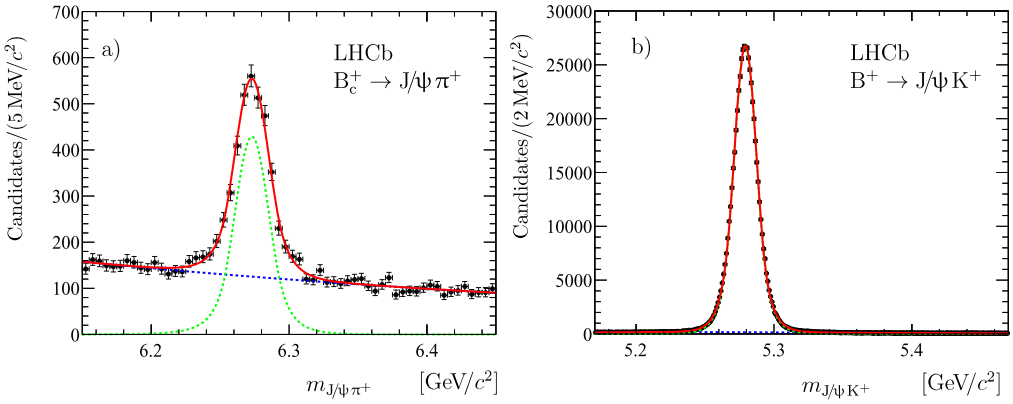


**Fig. 1.** Invariant mass distributions for (a) selected $B_c^+ \to J/\psi\pi^+$ and (b) $B^+ \to J/\psi K^+$ candidates. The fit result with the function described in the text is shown by the red solid line; the signal (background) components are shown with green (blue) dotted lines. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

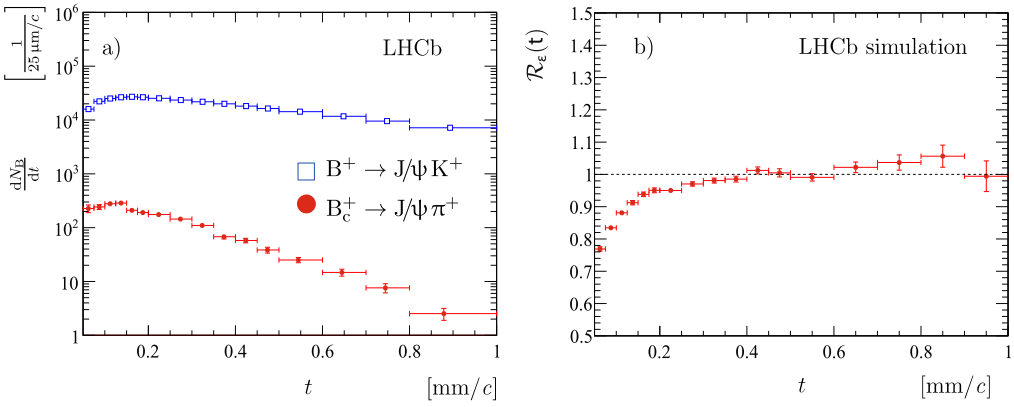


**Fig. 2.** (a) Decay time distributions for selected $B_c^+ \to J/\psi\pi^+$ (red solid circles) and $B^+ \to J/\psi K^+$ (blue open squares) decays, with the data points positioned within the $t$ bins according to Eq. (6) in Ref. [57]; (b) Ratio of acceptance functions $\mathcal{R}_\varepsilon(ct)$. The uncertainties are due to sample size only. For visualization purposes the efficiency ratio is normalized as $\mathcal{R}_\varepsilon(0.5\ \text{mm}/c) = 1$.

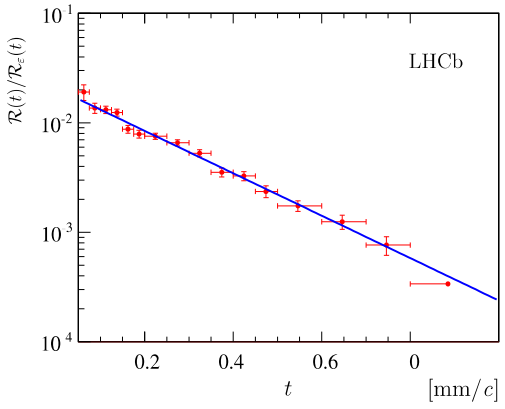


**Fig. 3.** Ratio of the efficiency-corrected decay time distributions (points with error bars). The curve shows the result of the fit with an exponential function. The data points are positioned within the $t$ bins according to Eq. (6) in Ref. [57] and the horizontal error bars denote the bin widths.

volved with the resolution function. This effectively includes the corrections due to resolution effects, neglected in Eq. (1). It is estimated that any residual bias is smaller than 0.1% in the range $50 < t < 1000$ μm/$c$.

The efficiency-corrected ratio $\mathcal{R}(t)/\mathcal{R}_\varepsilon(t)$ is shown in Fig. 3. A minimum $\chi^2$ fit with an exponential function, according to Eq. (1), gives

$$\Delta\Gamma = 4.46 \pm 0.14\ \text{mm}^{-1}\,c, \qquad (2)$$

**Table 1**
Summary of systematic uncertainties for $\Delta\Gamma$.

| Source | $\sigma_{\Delta\Gamma}$ [mm$^{-1}\,c$] |
|---|---|
| Fit model (signal and background) | 0.012 |
| $ct$ fit range | 0.040 |
| $ct$ binning | 0.016 |
| Acceptance | |
| Simulation sample size | 0.011 |
| MLP filtering | 0.025 |
| J/ψ displacement | 0.050 |
| Total | 0.072 |

where the uncertainty is statistical. The quality of the fit is good, with a $p$-value of 42%.

## 5. Systematic uncertainties and cross-checks

Several sources of systematic uncertainty are considered, as summarized in Table 1 and discussed below.

The uncertainty related to the determination of the signal yields in $t$ bins is estimated by comparing the nominal results with those obtained using different fit models. As an alternative model for the $B_c^+$ and $B^+$ signals, a modified Novosibirsk function [58] and a Gaussian function are used. Although the latter provides poor description for the large $B^+$ sample for all decay time bins and the low-background $B_c^+$ signal for bins with $t > 150$ μm/$c$, there is no effect on the determination of $\Delta\Gamma$. For the combi-

natorial background two alternative parameterizations are used: a pure exponential function and a product of an exponential function and a second-order polynomial function. As an additional check, feed-down components from the Cabibbo-suppressed decays $B_c^+ \to J/\psi K^+$ and $B^+ \to J/\psi\pi^+$ are added to the fit. The shapes for these components are determined using the simulation, while the yields are allowed to float in the fit. Based on these studies a systematic uncertainty of 0.012 $\text{mm}^{-1}\,c$ is assigned. Allowing the position and resolution for $B_c^+$ and $B^+$ signals to vary in fits to the individual $t$ bins does not affect the value of $\Delta\Gamma$, and no systematic uncertainty is assigned.

The uncertainties due to the choice of $t$ range and the binning scheme are assessed by varying these and comparing all variants that give a statistical uncertainty for $\Delta\Gamma$ below 0.200 $\text{mm}^{-1}\,c$. Uncertainties of 0.040 $\text{mm}^{-1}\,c$ and 0.016 $\text{mm}^{-1}\,c$ are assigned due to the choice of $t$ range and binning scheme.

The efficiency ratio $\mathcal{R}_\varepsilon(t)$ is determined using simulation, following techniques established in Refs. [7–11,27]. The uncertainty for $\mathcal{R}_\varepsilon(t)$ due to the limited size of the simulated sample is estimated to be 0.011 $\text{mm}^{-1}\,c$ using a simplified simulation.

The result is stable with respect to large variations of the selection criteria, in particular the working points of the MLP classifier and the displacement criterion for the $J/\psi$ vertex. The latter is the only criterion explicitly affecting the lifetime acceptance. The selection criteria are varied, allowing up to a 20% increase in the statistical uncertainty for $\Delta\Gamma$. Variation of the working point of the MLP classifier results in changes of 0.025 $\text{mm}^{-1}\,c$ in $\Delta\Gamma$. Tightening the $J/\psi$ meson vertex displacement criterion leads to a 0.050 $\text{mm}^{-1}\,c$ change in $\Delta\Gamma$. These changes are assigned as systematic uncertainties. The result is also stable with respect to the choice of the input variables used in the MLP classifier. An alternative selection using a boosted decision tree [59] is used for comparison with the MLP classifier. The variation of $\Delta\Gamma$ does not exceed a small fraction of its statistical uncertainty, and no additional systematic uncertainty is assigned. The uncertainties due to the momentum scale and the knowledge of the longitudinal coordinate of the LHCb vertex detector are studied in Ref. [6] and found to be negligible. The total systematic uncertainty for $\Delta\Gamma$ is obtained from the sum in quadrature of the individual contributions listed in Table 1.

As a final cross-check, the whole analysis is repeated using a lifetime-unbiased selection, designed to reduce the lifetime dependence of the acceptance. In this selection, instead of the displacement requirements for the $J/\psi$ meson vertex, both at trigger and subsequent selection, a different approach is adopted requiring the transverse momentum of the $J/\psi$ meson to be above 3 GeV/$c$. All other selection criteria are the same, including the MLP classifier. This selection has almost uniform acceptance as a function of decay time, but a smaller overall efficiency. The value of $\Delta\Gamma$ obtained using this selection is $4.23 \pm 0.20$ $\text{mm}^{-1}\,c$, where the uncertainty is statistical only. The larger statistical uncertainty for this selection is due to the smaller signal yield and significantly larger background level for small $ct$. The result agrees with the baseline selection.

The results are supported using a pseudoexperiment technique that combines simulation and data. Each pseudoexperiment is constructed from the sample of $B^+$ candidates (signal and background) from the data, *i.e.* it is the same for all pseudoexperiments; the sample of signal $B_c^+$ mesons is obtained using the simulation, and the background sample for $B_c^+$ candidates is generated using a simplified simulation according to the measured background distributions. The sizes of sub-samples are chosen to reproduce the sample sizes and background-to-signal ratios for data. For each pseudoexperiment the mean lifetime of the $B_c^+$ meson is chosen randomly in the range between 0.6 times and 1.5 times the known $B_c^+$ meson lifetime [5]. The whole analysis is performed for each pseudoexperiment and the value of $\Delta\Gamma$ is determined using the same $\mathcal{R}_\varepsilon(t)$ function as for the baseline analysis. In total 1400 pseudoexperiments are used. The value of $\Delta\Gamma$ is found to be unbiased for the entire test interval of $B_c^+$ meson lifetimes, and the error estimate is reliable.

## 6. Results and summary

Using a data sample corresponding to an integrated luminosity of 3.0 $\text{fb}^{-1}$ collected by the LHCb experiment in pp collisions at 7 and 8 TeV centre-of-mass energies, the difference in total widths between $B_c^+$ and $B^+$ mesons 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 is systematic. Using the known lifetime of the $B^+$ meson, $\tau_{B^+} = 1.638 \pm 0.004$ ps [5], this is converted into a precise measurement of the $B_c^+$ meson lifetime,

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

where in each case the first uncertainty is statistical, and the second is systematic and includes the uncertainty related to the knowledge of the $B^+$ meson lifetime. This result is in good agreement with the previous LHCb measurement, $\tau_{B_c^+} = 509 \pm 8 \pm 12$ fs, obtained using semileptonic $B_c^+ \to J/\psi\mu^+\nu_\mu X$ decays [26], and has comparable precision. The uncertainties for these two LHCb measurements are uncorrelated, leading to a combined measurement,

$$\tau_{B_c^+} = 511.4 \pm 9.3\ \text{fs},$$

where the statistical and systematic uncertainties are added in quadrature.

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