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Measurement of b hadron lifetimes in pp collisions at CMS

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Abstract

Precise measurements of the lifetimes of the B^0, B_s^0, Λ_b^0, and B_c^+ hadrons using the decay channels $B^0 \to J/\psi K^*(892)^0$, $B^0 \to J/\psi K_s^0$, $B_s^0 \to J/\psi \pi^+\pi^-$, $B_s^0 \to J/\psi \phi(1020)$, $\Lambda_b^0 \to J/\psi \Lambda^0$, and $B_c^+ \to J/\psi \pi^+$ were performed. The data sample, corresponding to an integrated luminosity of 19.7 fb^{-1}, was collected by the CMS detector at the LHC in proton-proton collisions at $\sqrt{s} = 8$ TeV. The B^0 lifetime is measured to be 453.0 ± 1.6(stat) $\pm$ 1.5(syst) μm in $J/\psi K^*(892)^0$ and 457.8 ± 2.7(stat) $\pm$ 2.7(syst) μm in $J/\psi K_s^0$. The effective lifetime of the B_s^0 meson is measured in two decay modes, with contributions from different amounts of the heavy and light eigenstates. This results in two different measured lifetimes: $c\tau_{B_s^0 \to J/\psi \pi^+\pi^-} = 502.7 \pm 10.2$(stat) $\pm$ 3.2(syst) μm and $c\tau_{B_s^0 \to J/\psi \phi(1020)} = 443.9 \pm 2.0$(stat) $\pm$ 1.2(syst) μm. The Λ_b^0 lifetime is found to be 442.9 ± 8.2(stat) $\pm$ 2.7(syst) μm. The precision from each of these channels is as good as or better than previous measurements. The B_c^+ lifetime, measured with respect to the B^+ to reduce the systematic uncertainty, is 162.3 ± 8.2(stat) $\pm$ 4.7(syst) $\pm$ 0.1 (τ_{B^+}) μm. All results are in agreement with current world-average values.

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Measurement of b hadron lifetimes in pp collisions at CMS

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Precise measurements of the lifetimes of the B^0, B^0_s, Λ^0_b, and B^+_c hadrons using the decay channels $B^0 \to J/\psi K^*(892)^0$, $B^0 \to J/\psi K^0_s$, $B^0_s \to J/\psi\pi^+\pi^-$, $B^0_s \to J/\psi\phi(1020)$, $\Lambda^0_b \to J/\psi\Lambda^0$, and $B^+_c \to J/\psi\pi^+$were performed. The data sample, corresponding to an integrated luminosity of 19.7 fb^{-1}, was collected by the CMS detector at the LHC in proton-proton collisions at $\sqrt{s} = 8$ TeV. The B^0 lifetime is measured to be $453.0 \pm 1.6(\text{stat}) \pm 1.5(\text{syst})$ μm in $J/\psi K^*(892)^0$ and $457.8 \pm 2.7(\text{stat}) \pm 2.7(\text{syst})$ μm in $J/\psi K^0_s$. The effective lifetime of the B^0_s meson is measured in two decay modes, with contributions from different amounts of the heavy and light eigenstates. This results in two different measured lifetimes: $c\tau_{B^0_s \to J/\psi\pi^+\pi^-} = 502.7 \pm 10.2(\text{stat}) \pm 3.2(\text{syst})$ μm and $c\tau_{B^0_s \to J/\psi\phi(1020)} = 443.9 \pm 2.0(\text{stat}) \pm 1.2(\text{syst})$ μm. The Λ^0_b lifetime is found to be $442.9 \pm 8.2(\text{stat}) \pm 2.7(\text{syst})$ μm. The precision from each of these channels is as good as or better than previous measurements. The B^+_c lifetime, measured with respect to the B^+ to reduce the systematic uncertainty, is $162.3 \pm 8.2(\text{stat}) \pm 4.7(\text{syst}) \pm 0.1\,(\tau_{B^+})$ μm. All results are in agreement with current world-average values.

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1. Introduction

Precise lifetime measurements involving the weak interaction play an important role in the study of nonperturbative aspects of quantum chromodynamics (QCD). The phenomenology is commonly described by the QCD-inspired heavy-quark expansion model, which provides estimates of the ratio of lifetimes for hadrons containing a common heavy quark [1]. CMS [2] has recently reported measurements of the lifetimes of the B^0, B_s^0, Λ_b^0, and B_c^+ hadrons.

The measurements are based on the reconstruction of the transverse decay length L_{xy}, where $\vec{L}_{xy}$ is defined as the flight distance vector from the primary vertex to the decay vertex of the b hadron, projected onto the transverse component $\vec{p}_T$ (perpendicular to the beam axis) of the b hadron momentum. The proper decay time of the b hadron times the speed of light is measured using

$$ct = cL_{xy}\frac{M}{p_T}, \tag{1.1}$$

where M is the world average value of the mass of the b hadron [3].

In this analysis, the b hadrons are reconstructed from decays containing a J/ψ meson. The data were recorded by the CMS detector [5] at the CERN LHC using dedicated triggers that require two oppositely charged muons consistent with originating from a common vertex and with an invariant mass compatible with that of the J/ψ meson. Specifically, we reconstruct the decay modes $B^0 \to J/\psi K^*(892)^0$, $B^0 \to J/\psi K_s^0$, $B_s^0 \to J/\psi\pi^+\pi^-$, $B_s^0 \to J/\psi\phi(1020)$, $\Lambda_b^0 \to J/\psi\Lambda^0$, and $B_c^+ \to J/\psi\pi^+$ where $J/\psi \to \mu^+\mu^-$, $K^*(892)^0 \to K^+\pi^-$, $K_s^0 \to \pi^+\pi^-$, $\phi(1020) \to K^+K^-$, and $\Lambda^0 \to p^+\pi^-$. The $B^+ \to J/\psi K^+$ decay is used as a reference mode and in evaluating some of the systematic uncertainties. Charge conjugation is implied throughout, unless otherwise indicated.

Since the B^0 system has a small lifetime difference with respect to the average lifetime, $\Delta\Gamma_\mathrm{d}/\Gamma_\mathrm{d} = (-0.2 \pm 1.0)\%$ [3], the ct distribution is close to an exponential, and it is treated as such for the lifetime measurement. In the B_s^0 system, $\Delta\Gamma_\mathrm{s}/\Gamma_\mathrm{s} = (13.0 \pm 0.9)\%$ [4] and the deviation from an exponential ct distribution is sizeable.
In this analysis, the two lifetimes associated with the B_s^0 meson are measured in the $J/\psi\pi^+\pi^-$ and $J/\psi\phi(1020)$ decay channels. The $B_s^0 \to J/\psi\pi^+\pi^-$ decays are reconstructed in the invariant mass range $0.9240 < M(\pi^+\pi^-) < 1.0204$ GeV, which is dominated by the $f_0(980)$ resonance [6, 7], ma-king it a CP-odd final state. Therefore, the lifetime measured in this channel is related to the inverse of the decay width of the heavy B_s^0 mass eigenstate, $\tau_{B_s}^{\text{CP-odd}} \approx 1/\Gamma_\mathrm{H}$, as CP violation in mixing is measured to be negligible [3]. The $J/\psi\phi(1020)$ decay channel is an admixture of CP-even and CP-odd states, corresponding to the light and heavy mass eigenstates, respectively, neglecting CP violation in mixing.

The weak decay of the B_c^+ meson can occur through either the b or c quark decaying, with the other quark as a spectator, or through an annihilation process. The latter is predicted to contribute 10% of the decay width [8], and lifetime measurements can be used to test the B_c^+ decay model. As fewer and less precise measurements of the B_c^+ lifetime exist [9, 10, 11, 12, 13, 14] compared to other b hadrons, the B_c^+ lifetime measurement presented in this report is particularly valuable.

2. Measurement and reconstruction of b hadrons

Details of the reconstruction of b hadrons and their signal extraction can be found at Ref [2]. For the B^+, B^0_s, B^0, and Λ^0_b hadrons, a three-dimensional unbinned maximum-likelihood fit to the data is performed. In all cases the input variables are the b hadron mass, ct, and ct uncertainty (σ_{ct}). The measurement of the B^+_c lifetime will be discussed later.

2.1 Reconstruction and selection efficiency

The reconstruction and selection efficiency for each decay mode is determined as a function of ct by using fully simulated MC samples. This efficiency is defined as the generated ct distribution of the selected events after reconstruction and selection divided by the ct distribution obtained from an exponential decay with the lifetime set to the value used to generate the events. The efficiency for the $B^0_s \to J/\psi\phi(1020)$ channel is defined as the ct distribution of the selected events after reconstruction divided by the sum of the two exponentials generated with the theoretical $B^0_s \to J/\psi\phi(1020)$ decay rate model. In the theoretical model, the values of the physics parameters are set to those used in the simulated sample.

Figure 1 shows the efficiency as a function of ct for the $B^+ \to J/\psi K^+$ and $B^0_s \to J/\psi\pi^+\pi^-$ decay modes as examples, with an arbitrary normalization since only the shape of the efficiency is relevant. The efficiencies display a sharp rise as ct increases from 0 to 0.01 cm, followed by a slow decrease as ct increases further. For all channels the ct efficiency is modelled with an inverse power function.

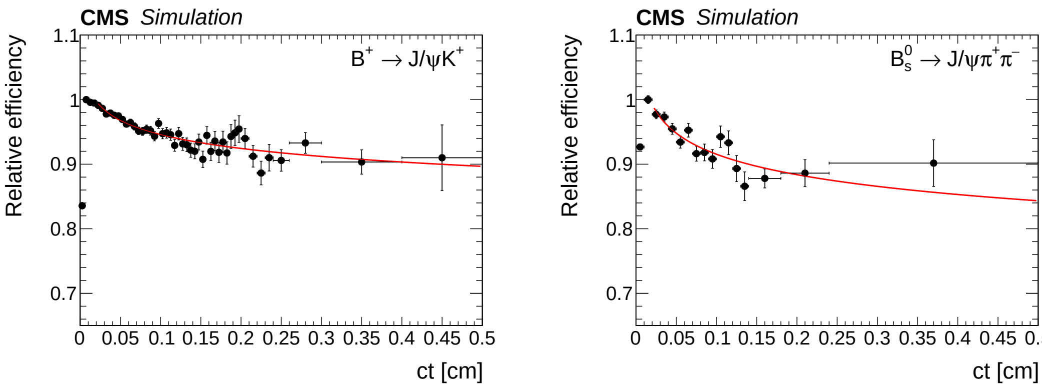


Figure 1: From Ref [2]. The combined reconstruction and selection efficiency from simulation versus ct with a superimposed fit to an inverse power function for $B^+ \to J/\psi K^+$ (left) and $B^0_s \to J/\psi\pi^+\pi^-$ (right). The efficiency scale is arbitrary.

2.2 Data modelling

Depending on the decay channel, the invariant mass distribution for the signal is modelled with one or two Gaussian functions, and a linear polynomial or an exponential function is used to model the combinatorial background.

The signal ct distribution is modelled by an exponential function convolved with the detector resolution and then multiplied by a function describing the reconstruction and selection efficiency.

The resolution is described by a Gaussian function with the per-event width taken from the ct uncertainty distribution. The backgrounds are described by a superposition of exponential functions convolved with the resolution. The number of exponentials needed to describe the background is determined from data events in the mass sideband regions for each decay mode.
The signal and background σ_{ct} distributions are modelled with either a sum of two gamma functions or two exponential functions convolved with a Gaussian function. The background parameters are obtained from a fit to the mass sideband distributions. The signal parameters are obtained from a fit to the signal region after subtracting the background contribution using the mass sideband region to estimate the background. The parameters of the efficiency function and the functions modelling the ct resolution are kept constant in the fit. The remaining fit parameters are allowed to vary freely.

2.3 Fit results

The invariant mass and *ct* distributions obtained from data are shown with the fit results superimposed in Figs. 2–4.

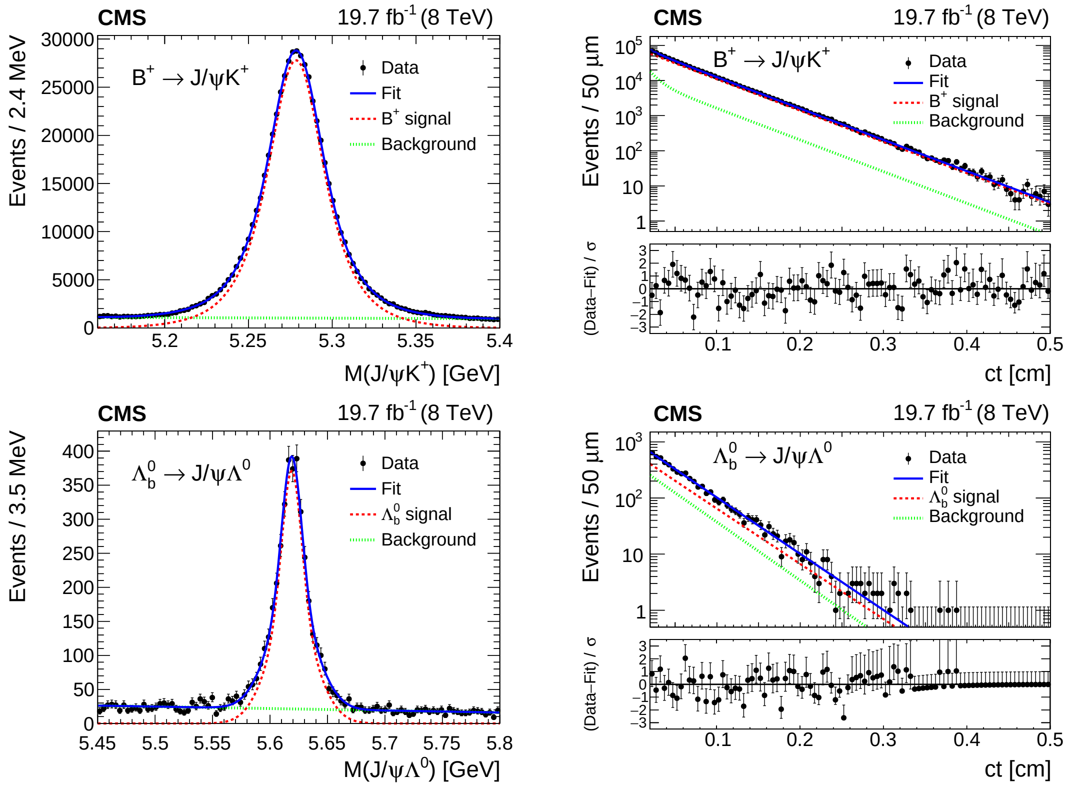


Figure 2: From Ref [2]. Invariant mass (left) and *ct* (right) distributions for B^+ (upper) and for Λ_b^0 (lower) candidates. The curves are projections of the fit to the data, with the contributions from signal (dashed), background (dotted), and the sum of signal and background (solid) shown. The bottom panels of the figures on the right show the difference between the observed data and the fit divided by the data uncertainty. The vertical bars on the data points represent the statistical uncertainties.

2.4 Measurement of the B_c^+ lifetime

The decay time distribution for the signal $N_{\mathrm{B}}(ct)$ can be expressed as the product of an effi-

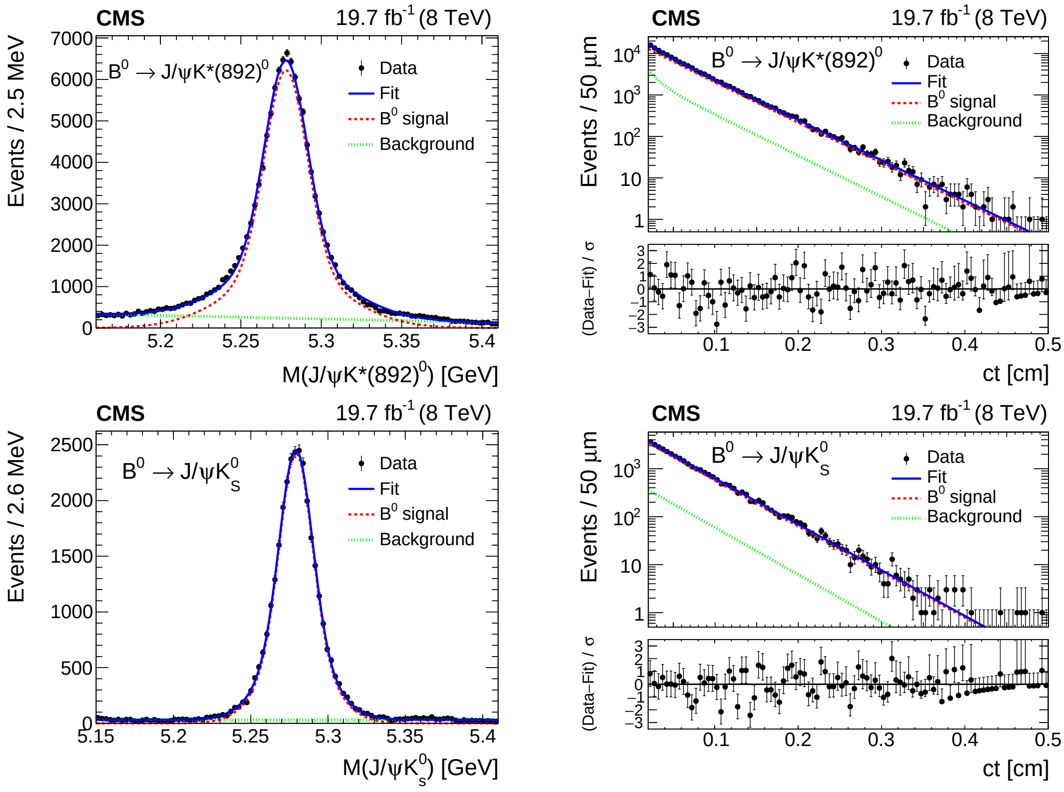


Figure 3: From Ref [2]. Invariant mass (left) and ct (right) distributions for B^0 candidates reconstructed from $J/\psi K^*(892)^0$ (upper) and $J/\psi K^0_S$ (lower) decays. The curves are projections of the fit to the data, with the contributions from signal (dashed), background (dotted), and the sum of signal and background (solid) shown. The bottom panels of the figures on the right show the difference between the observed data and the fit divided by the data uncertainty. The vertical bars on the data points represent the statistical uncertainties.

ciency function $\varepsilon_{\mathrm{B}}(ct)$ and an exponential decay function $E_{\mathrm{B}}(ct) = \exp(-ct/c\tau_{\mathrm{B}})$, convolved with the time resolution function of the detector $r(ct)$. The ratio of B_c^+ to B^+ events, at a given proper time, can be expressed as

$$\frac{N_{B_c^+}(ct)}{N_{B^+}(ct)} \equiv R(ct) = \frac{\varepsilon_{B_c^+}(ct)[r(ct) \otimes E_{B_c^+}(ct)]}{\varepsilon_{B^+}(ct)[r(ct) \otimes E_{B^+}(ct)]} \approx R_\varepsilon(ct)\exp(-\Delta\Gamma t). \tag{2.1}$$

where the approximation holds after having verified that the ratio is negligibly affected by the time resolution. The quantity $\Delta\Gamma$ is defined as

$$\Delta\Gamma \equiv \Gamma_{B_c^+} - \Gamma_{B^+} = \frac{1}{\tau_{B_c^+}} - \frac{1}{\tau_{B^+}}. \tag{2.2}$$

The $J/\psi\pi^+$invariant mass distribution is fitted with a Gaussian function and an exponential function for the background. An additional background contribution from $B_c^+ \to J/\psi K^+$ decays is modelled from a simulated sample of $B_c^+ \to J/\psi K^+$ events, and its contribution is constrained using the value of the branching fraction relative to $J/\psi\pi^+$.

The B_c^+ lifetime is extracted through a binned χ^2 fit to the ratio of the efficiency-corrected ct

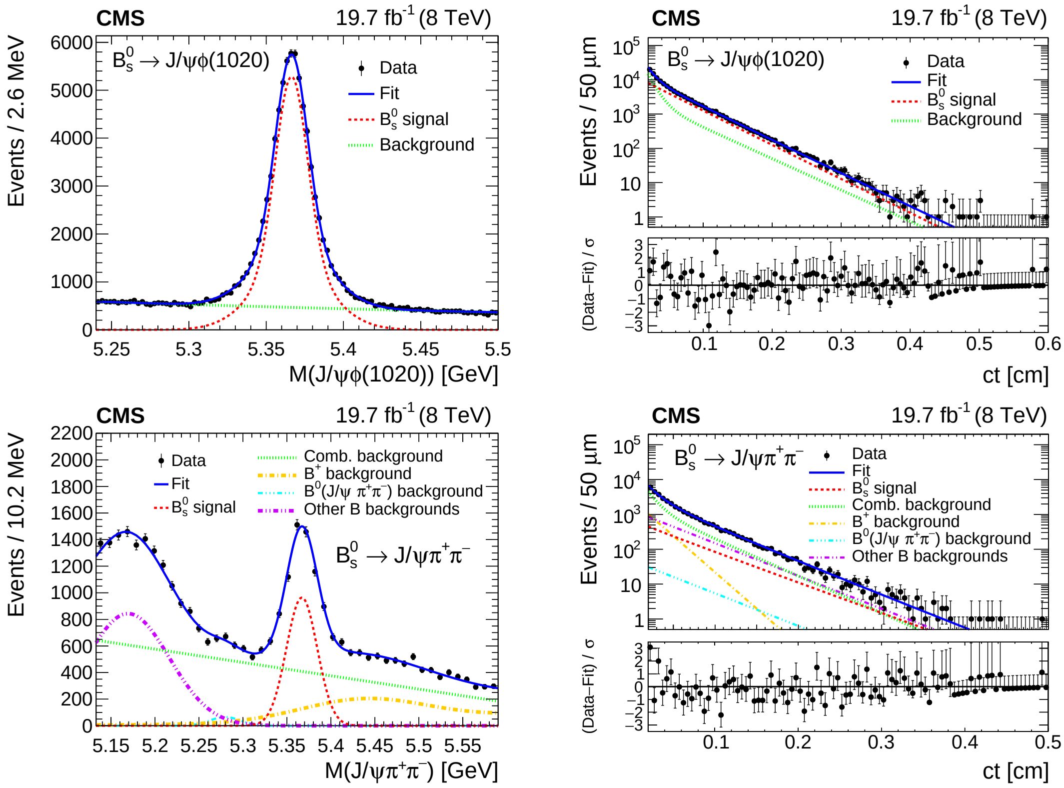


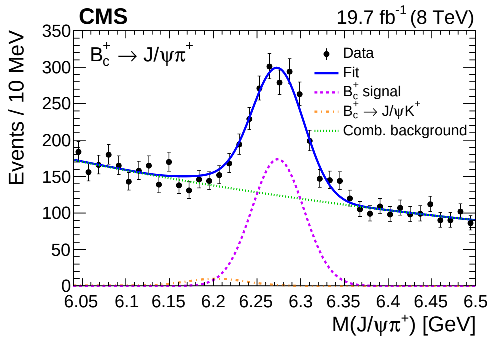
Figure 4: From Ref [2]. Invariant mass (left) and ct (right) distributions for B_s^0 candidates reconstructed from $J/\psi\phi(1020)$ (upper) and $J/\psi\pi^+\pi^-$ (lower) decays. The curves are projections of the fit to the data, with the full fit function (solid) and signal (dashed) shown for both decays, the total background (dotted) shown for the upper plots, and the combinatorial background (dotted), misidentified $B^+ \to J/\psi K^+$ background (dashed-dotted), $B_s^0 \to J/\psi\pi^+\pi^-$ contribution (dashed-dotted-dotted-dotted), and partially reconstructed and other misidentified B backgrounds (dashed-dotted-dotted) shown for the lower plots. The bottom panels of the figures on the right show the difference between the observed data and the fit divided by the data uncertainty. The vertical bars on the data points represent the statistical uncertainties.

distributions of the $B_c^+ \to J/\psi\pi^+$ and $B^+ \to J/\psi K^+$ channels. The B_c^+ and B^+ ct signal distribution from data are obtained by dividing the data sample into ct bins and performing an unbinned maximum-likelihood fit to the $J/\psi\pi^+$ and $J/\psi K^+$ invariant mass distribution in each bin, with the peak position and resolution fixed to the values obtained by the fits to the full samples. Varied ct bin widths are used to ensure a similar statistical uncertainty in the B_c^+ signal yield among the bins. The B_c^+invariant mass and the ratio of the B_c^+ to B^+ efficiency-corrected ct distributions, R/R_ε, is shown in Fig. 5.

3. Lifetime measurement results

Table 1 shows all the the lifetime measurements performed. Further details and discusion about systematic uncertainties can be found in Ref [2].

For the B_c^+ case the systematic uncertainty from the B^+ lifetime uncertainty [3] is quoted separately in the result.



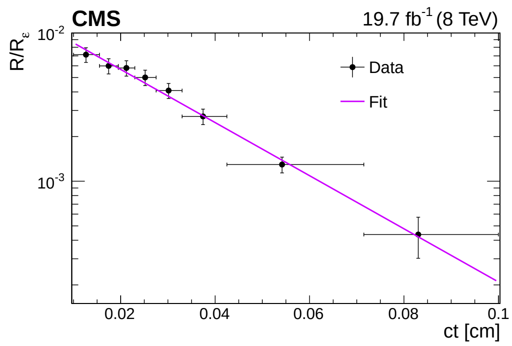


Figure 5: From Ref [2]. The $J/\psi\pi^+$invariant mass distribution (left) with the solid line representing the total fit, the dashed line the signal component, the dotted line the combinatorial background, and the dashed-dotted line the contribution from $B_c^+ \to J/\psi K^+$ decays. Ratio of the B_c^+ to B^+ efficiency-corrected ct distributions (right), R/R_ε, with a line showing the result of the fit to an exponential function. The vertical bars give the statistical uncertainty in the data, and the horizontal bars show the bin widths.

Decay channel	$c\tau$ (μm)
$B^0 \to J/\psi K^*(892)^0$	$453.0 \pm 1.6(\text{stat}) \pm 1.5(\text{syst})$
$B^0 \to J/\psi K_s^0$	$457.8 \pm 2.7(\text{stat}) \pm 2.7(\text{syst})$
$B_s^0 \to J/\psi\pi^+\pi^-$	$502.7 \pm 10.2(\text{stat}) \pm 3.2(\text{syst})$
$B_s^0 \to J/\psi\phi(1020)$	$443.9 \pm 2.0(\text{stat}) \pm 1.2(\text{syst})$
$\Lambda_b^0 \to J/\psi\Lambda^0$	$442.9 \pm 8.2(\text{stat}) \pm 2.7(\text{syst})$
$B_c^+ \to J/\psi\pi^+$	$162.3 \pm 8.2(\text{stat}) \pm 4.7(\text{syst}) \pm 0.1(\tau_{B^+})$

Table 1: Lifetime measurements reported in Ref [2].

Neglecting CP violation in mixing, the measured $B_s^0 \to J/\psi\pi^+\pi^-$ lifetime can be translated into the width of the heavy B_s^0 mass eigenstate:

$$\Gamma_\text{H} = 1/\tau_{B_s} = 0.596 \pm 0.012(\text{stat}) \pm 0.004(\text{syst})\ \text{ps}^{-1}. \tag{3.1}$$

4. Summary

The lifetimes of the B^0, B_s^0, Λ_b^0, and B_c^+ hadrons have been measured using fully reconstructed decays with a J/ψ meson. The data were collected by the CMS detector in proton-proton collision events at a centre-of-mass energy of 8 TeV, and correspond to an integrated luminosity of 19.7 fb^{-1}. The B^0 and B_s^0 meson lifetimes have each been measured in two channels: $J/\psi K^*(892)^0$, $J/\psi K_s^0$ for B^0 and $J/\psi\pi^+\pi^-$, $J/\psi\phi(1020)$ for B_s^0. The precision from each channel is as good as or better than previous measurements in the respective channel. The precision of the Λ_b^0 lifetime measurement is also as good as any previous measurement in the $J/\psi\Lambda^0$ channel. The measurement of the B_c^+ meson lifetime is in agreement with the results from LHCb and significantly more precise than the CDF and D0 measurements. All measured lifetimes are compatible with the current world-average values.

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