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Measurement of b hadron lifetimes and effective lifetimes at LHCb

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This paper presents two recent measurements of b-hadron lifetimes, using 1 fb^{-1} of data collected by LHCb. The effective lifetime of the $B_s^0 \to J/\psi K_S^0$ decay is measured and found to be $\tau^{\mathrm{eff}}_{B_s^0 \to J/\psi K_S^0} = 1.75 \pm 0.12$ (stat) 0.07 (syst) ps. The result is compatible with the Standard Model prediction and is the first measurement of this quantity. The Λ_b^0 lifetime is measured in the $\Lambda_b^0 \to J/\psi pK$ decay using the same data set. The measured quantity is the difference in reciprocial lifetimes of the B^0 and Λ_b^0 hadrons and found to be $1/\tau_{\Lambda_b^0} - 1/\tau_{B^0} = 16.4 \pm 8.2 \pm 4.4\ \mathrm{ns}^{-1}$. Using the world average of the B^0 lifetime, this translates into a lifetime ratio of $\tau_{\Lambda_b^0}/\tau_{B^0} = 0.976 \pm 0.012 \pm 0.006$, which is the precise measurement of this quantity to date.

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PoS(EPS-HEP 2013)344

1. Introduction

This paper reports on two recent measurements of b-hadron lifetimes by LHCb [1]. The results presented are a measurement of the effective lifetime in the $B^0_s \to J/\psi K^0_S$ decay [2] and a precision measurement of the Λ^0_b lifetime [3] using the $\Lambda^0_b \to J/\psi pK$ decay. The first measurement can be used to constrain *CP* violation in this decay and is presented in Section 2. The second result is the most precise measurement of the Λ^0_b lifetime to date and is presented in Section 3.

The lifetimes of singly heavy b hadrons are domnated by the weak decay of the b quark with only small contributions from the light spectator quarks. Hence the lifetimes of the B^0, B^0_s, B^+ and Λ^0_b are expected to be the same to first order. More precise predictions can be made using a theory know as *Heavy Quark Expansion* (HQE) [4], exploiting of the fact that the mass of the b quark (m_b) is much larger than Λ_{QCD}. The decay rate can be expressed as

$$\Gamma = \Gamma_0 + \frac{\Lambda}{m_b}\Gamma_1 + \frac{\Lambda^2}{m_b^2}\Gamma_2 + \frac{\Lambda^3}{m_b^3}\Gamma_3 + \ldots \tag{1.1}$$

where the coefficients Γ_i are determined using both perturbative and non-perturbative methods. The predictions of ratios of b-hadron lifeimes are even more precise since the first two terms in Equation 1.1 cancel. In the ratios of the B^0, B^+ and B^0_s lifetimes also the second order term cancels, resulting in ratios close to unity. For instance, recent predictions give $\tau_{B^+}/\tau_{B^0} = 1.06 \pm 0.02$ and $\tau_{B^0_s}/\tau_{B^0} = 1.00 \pm 0.01$ [5, 6].

The second order term does not cancel for the ratio $\tau_{\Lambda^0_b}/\tau_{B^0}$, hence a larger deviation from unity is possible and the uncertainties in the predictions are slightly larger. Predictions vary and values from ~ 0.98 [7, 8] to $\sim 0.86 - 0.88$ [5, 6] are found in the literature. Experimentally, early measurements indicated a value of this ratio smaller than one [9, 10, 11, 12, 13], however with relatively large uncertainties. More recent measurements have brought the avereage closer to unity [14, 15, 16, 17]. The world average of $\tau_{\Lambda^0_b}/\tau_{B^0}$ prior to this measurement was 0.975 ± 0.034 [18].

Lifetime measurements of B^0_s meson decays have an additional interest due to the finite decay width difference of the two mass eigenstates. Hence the decay time distribution is described by the sum of two exponential functions. The untagged decay time distribution is described by

$$\Gamma(t) \propto \left[(1 - A_{\Delta\Gamma_s})\, e^{-\Gamma_s - \frac{\Delta\Gamma_s}{2} t} + (1 + A_{\Delta\Gamma_s})\, e^{-\Gamma_s + \frac{\Delta\Gamma_s}{2} t} \right], \tag{1.2}$$

where Γ_s and $\Delta\Gamma_s$ are the average decay rate and the decay rate difference and $A_{\Delta\Gamma_s}$is the decay rate asymmetry. Decays that are only accessible from either B^0_s or $\bar{B}^0_s$ have $A_{\Delta\Gamma_s} = 0$, hence have an equal contribution of the two exponentials. For decays into *CP* eigenstates the decay rate asymmetry depends on the mixing and decay parameters amplitudes, in particular the mixing phase ϕ_s and the *CP* violation in the decay. The decay time distribution in Equation 1.2 is normally fitted with a single exponential distribution, resulting in an *effective* lifetime measurement. If the distribution is fitted with an unbinned maximum likelihood fit, it will yield the result [19]

$$\tau^{\text{eff}} = \frac{\int t \cdot \Gamma(t)}{\int \Gamma(t)} = \frac{\tau_{B^0_s}}{1 - y_s^2} \frac{1 + 2A_{\Delta\Gamma_s} y_s + y_s^2}{1 + A_{\Delta\Gamma_s} y_s}, \tag{1.3}$$

where $y_s \equiv \frac{\Delta\Gamma_s}{2\Gamma_s}$ and $\tau_{B^0_s}$ is the average B^0_s lifetime.

PoS(EPS-HEP 2013)344

2. Effecitve Lifetime Measurement of $B^0_s \to J/\psi K^0_S$

The decay $B^0_s \to J/\psi K^0_S$ is of particular interest since it is related to the decay $B^0 \to J/\psi K^0_S$ through the U-spin symmetry of the strong interaction. This decay is considered to be the golden mode to measure the CKM angle $\sin(2\beta)$. Two of the dominant Feynman diagrams for the two decays are shown in Figure 1. The similarity of the decays can be exploited to determine the CKM angle γ from a measurement of the time dependent *CP* violation in the $B^0_s \to J/\psi K^0_S$ decay with the overall normalisation taken from the $B^0 \to J/\psi K^0_S$ decay [20].

In order to reach the precision on $\sin(2\beta)$ that is achievable from the statistics that will be available at LHCb, the penguin contributions to the $B^0 \to J/\psi K^0_S$ decay have to be determined. This can also be done by exploiting the similarity between the $B^0_{(s)} \to J/\psi K^0_S$ decays. The penguin contributions shown in Figure 1 (right) are Cabbibo suppressed in the $B^0 \to J/\psi K^0_S$ decay but give a sizable contribution in the $B^0_s \to J/\psi K^0_S$ decay. Hence they can be measured from an analysis of the time dependent *CP* violation in the $B^0_s \to J/\psi K^0_S$ decay and by assuming U-spin symmetry translated back to the $B^0 \to J/\psi K^0_S$ analysis.

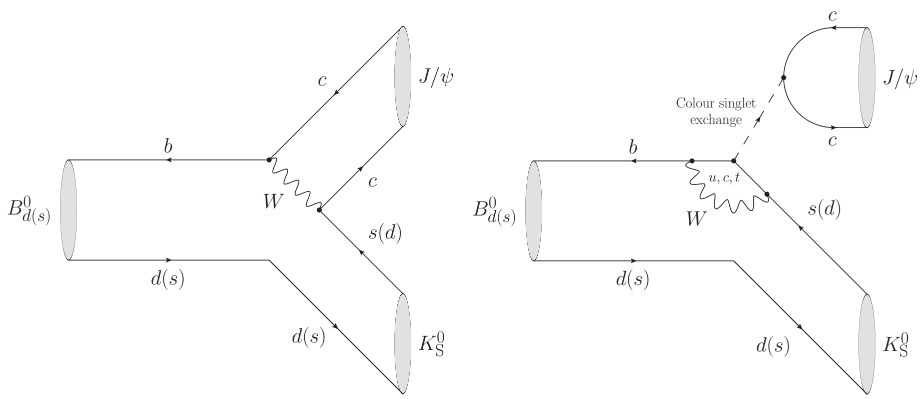

Figure 1: Feyman diagrams for the $B^0_{(s)} \to J/\psi K^0_S$ decays, showing the (left) tree and (right) penguin diagrams.

The first step in the process of achieving those two goals is to measure the branching ratio and the effective lifetime of the decay. The signal candidates are reconstructed in the $B^0_{(s)} \to J/\psi(\to \mu^+\mu^-)K^0_S(\to \pi^+\pi^-)$final state and selected with a multivariate selection. The candidates are divided into two different categories depending on if the K^0_S decayed within or outside of the vertex detector (VELO), and are called *long* or *downstream* candidates respectively. The two invariant mass spectra are shown in Figure 2. The event yields are used to determine the relative branching ratios of the B^0_s and B^0 decays, resulting in

$$\frac{\mathcal{B}(B^0_s \to J/\psi K^0_S)}{\mathcal{B}(B^0 \to J/\psi K^0_S)} = 0.0439 \pm 0.0032\ (\text{stat}) \pm 0.0015\ (\text{syst}) \pm 0.0034\ (f_s/f_d) \qquad (2.1)$$

where the last uncertainty originates from the ratio of hadronisation probability into B^0_s and B^0 mesons, as measured by LHCb [21].

The effective lifetime of the $B^0_s \to J/\psi K^0_S$ decay is determined from a 2-dimensional unbinned maximum likelihood fit in mass and decay time. The decay time distributions of the B^0_s and B^0 sig-

PoS(EPS-HEP 2013)344

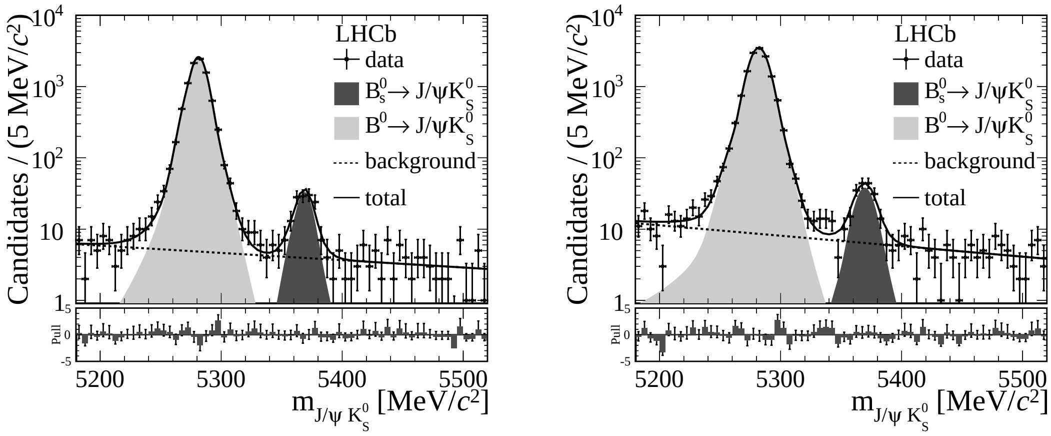

Figure 2: Mass spectra of the $B^0_{(s)} \to J/\psi K^0_S$ candidates from 1 fb^{-1} of data collected at $\sqrt{s} = 7$ TeV by LHCb. The candidates are divided into two samples, those where the K^0_S decays (left) within and (right) outside the vertex detector.

nals are described by single exponential distributions convolved with a Gaussian resolution function. The decay time distribution of the combinatorial background is determined from data using *sWeights* [22] and is modelled with one (two) exponentials for the long (downstream) candidates.

The decay time acceptance function is assumed to be the same for both decays and is modelled with the function

$$f_{\rm Acc}(t) = \frac{1+\beta t}{1+(\lambda t)^{-\kappa}}. \quad (2.2)$$

The parameters are determined from a fit to the B^0 decay time distribution using the well-known B^0 lifetime as input [18]. This is done separately for the long and downstream candidates. The measured effective lifetime is

$$\tau^{\rm eff}_{B^0_s \to J/\psi K^0_S} = 1.75 \pm 0.12 \text{ (stat) } 0.07 \text{ (syst)} \quad (2.3)$$

which can be compared to the Standard Model (SM) prediction [23] calculated from Equation 1.3, using [24] as input

$$\tau^{\rm eff}_{B^0_s \to J/\psi K^0_S}\Big|_{\rm SM} = 1.639 \pm 0.022. \quad (2.4)$$

The values are consistent within the relatively large uncertainties.

3. Λ^0_b Lifetime Measurement

As described in Section 1, there has been a long-standing discrepancy between the theoretical predictions and the experimental measurements of the ratio between the Λ^0_b and B^0 lifetime. The decay $\Lambda^0_b \to J/\psi pK$ is used by LHCb to measure the Λ^0_b lifetime. The candidates are selected in the final state $\Lambda^0_b \to J/\psi(\to \mu^+\mu^-)pK^-$ using a multivariate selection and the mass spectrum is shown in Figure 3 (left). This is the first observation of this decay and a measurement of the branching ratio relative to the $B^0 \to J/\psi K^{*0}$ decay is in preparation.

The Λ^0_b lifetime is measured relative to the B^0 lifetime, comparing the decay time distributions of the decays $\Lambda^0_b \to J/\psi pK$ and $B^0 \to J/\psi K^{*0}$. The two decays are topologically indentical and differ in the selection only by the particle identification requirements applied. Moreover, the uncertainty of the B^0 lifetime is small. The yields of the two decays is determined in 16 decay time bins and the ratio of yields is fitted with the function

$$R(t) = \frac{N_{\Lambda_b^0}(0)}{N_{\bar{B}^0}(0)} \frac{e^{-t/\tau_{\Lambda_b^0}}}{e^{-t/\tau_{\bar{B}^0}}} = R(0)e^{-t\Delta_{\Lambda B}}, \tag{3.1}$$

where $\Delta_{\Lambda B} = 1/\tau_{\Lambda_b^0} - 1/\tau_{B^0}$. The decay time acceptance is expected to be close to identical for the two decays, but a linear difference in acceptance is allowed in the fit described by

$$R(t) = R(0)[1 + a \cdot t]e^{-t\Delta_{\Lambda B}}. \tag{3.2}$$

The free parameter is determined from full simulations and is found to be $a = 3.3 \pm 2.4\ \mathrm{ns}^{-1}$, hence compatible with zero. The directly measured quantity is

$$\Delta_{\Lambda B} = 16.4 \pm 8.2 \pm 4.4\ \mathrm{ns}^{-1} \tag{3.3}$$

which using the world average of the B^0 lifetime [18] can be expressed as a ratio of lifetimes

$$\frac{\tau_{\Lambda_b^0}}{\tau_{B^0}} = \frac{1}{1 + \tau_{B^0}\Delta_{\Lambda B}} = 0.976 \pm 0.012 \pm 0.006. \tag{3.4}$$

This is the most precise measurement of this quantity to date and translates into a lifetime of $\tau_{\Lambda_b^0} = 1.482 \pm 0.018 \pm 0.012$ ps.

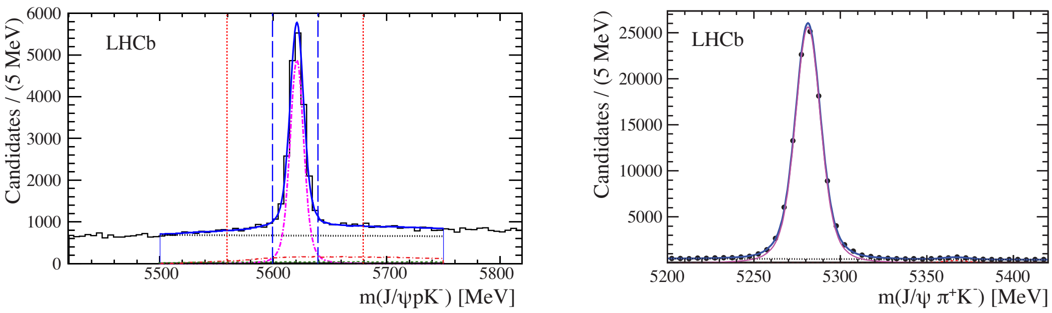

Figure 3: Left: Mass spectra of the $\Lambda_b^0 \to J/\psi pK$ candidates from 1 fb^{-1} of data collected at $\sqrt{s} = 7$ TeV by LHCb. The signal is shown in magenta, the combinatorial background in black and the reflections $B_s^0 \to J/\psi K^+K^-$ and $B^0 \to J/\psi \pi^+K^-$ in red and green respectively. The fit is shown in blue. Right: The mass spectrum of the normalisation channel $B^0 \to J/\psi K^{*0}$.

4. Conclusions

The decay of singly heavy b-hadrons is dominated by the weak decay of the b-quark and hence the lifetimes are expected to be the same to first order. More precise predictions can be done using heavy quark expansion. In the particular case of the B_s^0 meson decaying in to *CP* eigenstates, effective lifetime measurements can be used to constrain *CP* violation in the decay and in interference between mixing and decay.

An effective lifetime measurement of the $B_s^0 \to J/\psi K_S^0$ decay is presented together with branching ratio measurement relative to the $B^0 \to J/\psi K_S^0$ decay. This is the first measurement of these two quantities. The measured lifetime is compatible with the predictions by the Standard Model.

The Λ_b^0 lifetime is measured in the decay $\Lambda_b^0 \to J/\psi pK$, yielding the most precise measurement of the Λ_b^0 lifetime to date. The ratio of the Λ_b^0 to B^0 lifetime is also determined yielding a result close to unity, as predicted by theory.

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PoS(EPS-HEP 2013)344