PROCEEDINGS OF SCIENCE

Measurements of b-hadron lifetimes and effective lifetimes at LHCb

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Precision measurements of b-hadron lifetimes are a key goal of the LHCb experiment. In the B_s^0 sector, the measurement of the effective lifetimes for B_s^0 mesons decaying to CP-odd, CP-even and flavour specific final states are essential for constraining the B_s^0 mixing parameters: the width difference $\Delta\Gamma_s$, the average width Γ_s and the CP-violating phase ϕ_s. Measurements of the effective lifetimes in the decay modes $B_s^0 \to J/\psi f_0(980)$ and $B_s^0 \to K^+K^-$ are presented, as well as a determination of $\Delta\Gamma_s$ and Γ_s using the $B_s^0 \to J/\psi\phi$ decay mode.

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1. Introduction

In the Standard Model, the mass and flavour eigenstates of the B_s^0 meson are not the same. This gives rise to particle-antiparticle oscillations, which proceed through second order weak interactions. The time evolution of the $B_s^0-\overline{B}_s^0$ system is described by the Schrödinger equation:

$$i\frac{d}{dt}\begin{pmatrix}|B_s^0(t)\rangle\\ |\overline{B}_s^0(t)\rangle\end{pmatrix}=\left(M-\frac{i}{2}\Gamma\right)\begin{pmatrix}|B_s^0(t)\rangle\\ |\overline{B}_s^0(t)\rangle\end{pmatrix} \tag{1.1}$$

where the mass, M, and decay rate, Γ, matrices are Hermitian, and CPT invariance implies $M_{11}=M_{22}$ and $\Gamma_{11}=\Gamma_{22}$. The off-diagonal elements $M_{12}=M_{21}^*$ and $\Gamma_{12}=\Gamma_{21}^*$ describe $B_s^0-\overline{B}_s^0$ mixing. Diagonalising $M-\frac{i}{2}\Gamma$ leads to the mass eigenstates:

$$|B_\mathrm{H}\rangle=p\,|B_s^0(t)\rangle-q\,|\overline{B}_s^0(t)\rangle \text{ and } |B_\mathrm{L}\rangle=p\,|B_s^0(t)\rangle+q\,|\overline{B}_s^0(t)\rangle\text{, where } |p|^2+|q|^2=1, \tag{1.2}$$

with distinct masses, M_H and M_L, lifetimes and decay rates, $\tau_\mathrm{H}=1/\Gamma_\mathrm{H}$ and $\tau_\mathrm{L}=1/\Gamma_\mathrm{L}$.

The decay time evolution for the sum of B_s^0 and $\overline{B}_s^0$ decays to a common final state, f, can be written as [1]:

$$\Gamma(B_s^0(t)\to f)+\Gamma(\overline{B}_s^0(t)\to f)\propto(1-A_{\Delta\Gamma_s,f})e^{-\Gamma_{s\mathrm{L}}t}+(1+A_{\Delta\Gamma_s,f})e^{-\Gamma_{s\mathrm{H}}t}, \tag{1.3}$$

where $\Delta\Gamma_s=\Gamma_\mathrm{L}-\Gamma_\mathrm{H}$ and $\Gamma_s=(\Gamma_\mathrm{H}+\Gamma_\mathrm{L})/2$. The parameter $A_{f,\Delta\Gamma_s}$ is defined as $A_{\Delta\Gamma_s,f}=-2\mathrm{Re}(\lambda_f)/(1+|\lambda_f|^2)$ where $\lambda_f=(q/p)(\bar{A}_f/A_f)$ and A_f ($\bar{A}_f$) is the amplitude for a B_s^0 ($\overline{B}_s^0$) meson to decay to the final state f. If this equation is fitted with a single exponential function, the *effective lifetime* is given by [1]:

$$\tau_f=\frac{\tau_s}{1+y_s^2}\left[\frac{1+2A_{\Delta\Gamma_s,f}y_s+y_s^2}{1+A_{\Delta\Gamma_s,f}y_s}\right]=\tau_s(1+A_{\Delta\Gamma_s,f}+\mathscr{O}(y_s^2)) \tag{1.4}$$

where $\tau_s=1/\Gamma_s$ and $y_s=\Delta\Gamma_s/2\Gamma_s$.

The B_s^0 mixing and lifetime parameters are related through the equation $\Delta\Gamma_s=2|\Gamma_{12}|\cos\phi_s$, where $\phi_s=\arg(-M_{12}/\Gamma_{12})$ describes CP-violation in B_s^0 mixing. As the measured value of ϕ_s is small [2], the mass and CP-eigenstates of the B_s^0 system coincide to good approximation. Therefore the measurement of effective lifetime in a CP-eigenstate can be interpreted as a measurement of lifetime of the corresponding mass eigenstate.

In these proceedings, I present measurements of Γ_s and $\Delta\Gamma_s$ from $B_s^0\to J/\psi\phi$ and the effective lifetimes of $B_s^0\to J/\psi f_0(980)$ and $B_s^0\to K^+K^-$ using $1.0\,\mathrm{fb}^{-1}$ of data collected by LHCb in 2011. A detailed description of these analyses can be found in dedicated papers and conference reports [2, 3, 4].

2. Analysis of the decay $B_s^0\to J/\psi\phi$

The decay $B_s^0\to J/\psi\phi$ is considered the golden mode for measuring ϕ_s . It is a pseudoscalar to vector vector decay, resulting in a final state that is an admixture of CP-even and CP-odd components, and thus the time-dependent angular analysis of the decay required to determine ϕ_s is also sensitive to $\Delta\Gamma_s$ and Γ_s. Based on $0.4\,\mathrm{pb}^{-1}$ of data, the LHCb collaboration published the most

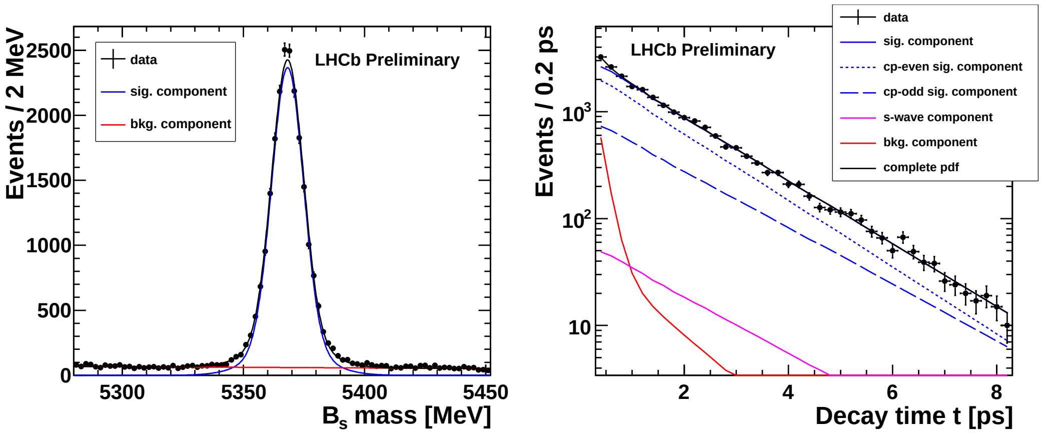

Figure 1: (a) Invariant mass spectrum for all selected $B_s^0 \to J/\psi\phi$ candidates with fits for signal and background components. (b) Decay time distribution of $B_s^0 \to J/\psi\phi$ candidates within a mass range of ±20 MeV around the reconstructed B_s^0 mass with fit projections from angular analysis.

precise measurement of ϕ_s, providing the first direct evidence for a non-zero value of $\Delta\Gamma_s$ [5]. This dataset was also used to determine the sign of $\Delta\Gamma_s$ to be positive [6], thus implying that the mass eigenstate that is almost *CP*-odd is heavier and lives longer than the state that is almost *CP*-even.

We present an update of the previous $\Delta\Gamma_s$ and Γ_s measurement using a sample of approximately 20,000 $B_s^0 \to J/\psi\phi$ signal candidates extracted from $1.0\,\mathrm{pb}^{-1}$ of data [2]. While increasing the data set by a factor of three, the rest of the analysis remained almost unchanged. Both the fit to the invariant mass spectrum and decay time distribution are shown in Fig. 1. We find $\Gamma_s = 0.6580 \pm 0.0054 \pm 0.0066\,\mathrm{ps}^{-1}$ and $\Delta\Gamma_s = 0.116 \pm 0.018 \pm 0.006\,\mathrm{ps}^{-1}$.

3. Measurement of the $B_s^0 \to J/\psi f_0(980)$ effective lifetime

Motivated by a predication [7], the LHCb collaboration made the first observation of $B_s^0 \to J/\psi f_0(980)$, $f_0(980) \to \pi^+\pi^-$ [8] and subsequently used it to determine ϕ_s [9]. Using $1.0\,\mathrm{fb}^{-1}$ of data, wemeasure the effective $B_s^0 \to J/\psi f_0(980)$ lifetime relative to that of the decay $B^0 \to J/\psi K^{*0}(892)$ [3] , utilising the similar kinematics of the two decay modes to help cancel many of the systematic uncertainties. $J/\psi f_0(980)$ is a *CP*-odd eigenstate, and since the measured *CP* violation in this final state is small [9], a measurement of the effective lifetime, $\tau_{J/\psi f_0}$, can be translated into a measurement of the decay width, Γ_H.

The analysis uses the same selection criteria used to measure ϕ_s in $B_s^0 \to J/\psi\pi^+\pi^-$ decays [10]. Events are triggered by a $J/\psi\mu^+\mu^-$ decay and a Boosted Decision Tree (BDT) [11, 12] is used to set the $J/\psi\pi^+\pi^-$ selection requirements. The same trigger and BDT is used to select $J/\psi K^+\pi^-$ events, except for the hadron identification that is applied independently of the BDT. Further selections of ±90 MeV around the nominal $f_0(980)$ mass [13] and ±100 MeV around the nominal $K^{*0}(892)$ mass [13] are applied. The time-integrated fits to the $J/\psi f_0(980)$ and the $J/\psi K^{*0}(892)$ invariant mass spectra are shown in Fig. 2.

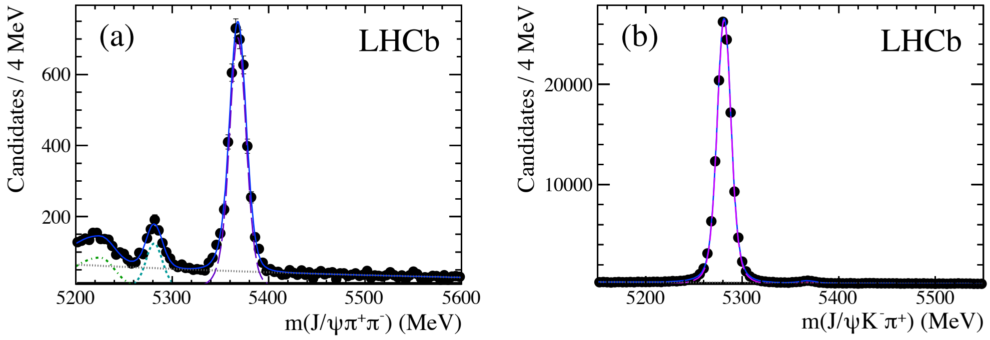

Figure 2: Invariant mass distributions of selected (a) $J/\psi\pi^+\pi^-$ and (b) $J/\psi K^+\pi^-$ candidates. The solid (blue) curves show the total fits, the long dashed (purple) curves show the respective $B^0 \to J/\psi f_0(980)$ and $B^0 \to J/\psi K^{*0}(892)$ signals and the dotted (grey) curve shows the combinatorial background. In (a) the short dashed (light blue) curve shows the $B^0 \to J/\psi\pi^+\pi^-$ background and the dash dotted (green) curve shows the $B^0 \to J/\psi K^+\pi^-$ reflection. In (b) the short dashed (pink) curve shows the $B^0_s \to J/\psi K^{*0}(892)$ background.

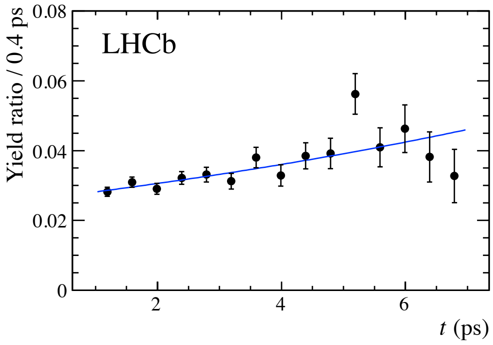

Figure 3: Decay time ratio between $B^0_s \to J/\psi f_0(980)$ and $B^0 \to J/\psi K^{*0}(892)$, and the fit for $\Delta_{J/\psi f_0}$.

The $B^0_s \to J/\psi f_0(980)$ lifetime is measured relative to the $B^0 \to J/\psi K^{*0}(892)$ lifetime, using the variation of the ratio of B meson yields in bins of decay time: $R(t) = R(0)e^{-t(1/\tau_{J/\psi f_0} - 1/\tau_{J/\psi K^{*0}})} = R(0)e^{-t\Delta_{J/\psi f_0}}$, where the width difference is $\Delta_{J/\psi f_0} = 1/\tau_{J/\psi f_0} - 1/\tau_{J/\psi K^{*0}}$. The decay time ratio distribution is shown in Fig. 3, and the fitted width difference is $\Delta_{J/\psi f_0} = -0.070 \pm 0.014 \pm 0.001\,\mathrm{ps}^{-1}$. Taking $\tau_{J/\psi K^{*0}}$ to be the mean B^0 lifetime 1.519 ± 0.007 ps [13], the effective $B^0_s \to J/\psi f_0(980)$ lifetime is found to be $\tau_{J/\psi f_0} = 1.700 \pm 0.040 \pm 0.026\,\mathrm{ps}$. Interpreting this as the lifetime of the heavy B^0_s eigenstate, with an additional source of systematic uncertainty due to a possible non-zero value of ϕ_s, we obtain $\Gamma_H = 0.588 \pm 0.014 \pm 0.009\,\mathrm{ps}^{-1}$.

4. Measurement of the $B^0_s \to K^+K^-$ effective lifetime

The $B^0_s \to K^+K^-$ decay was first observed by the CDF collaboration [14], and the most precise measurement of the effective lifetime, τ_{KK}, to date was made by the LHCb collaboration using data taken during 2010 [15]. K^+K^- is a CP-even eigenstate and $B^0_s \to K^+K^-$ decays are dominated by

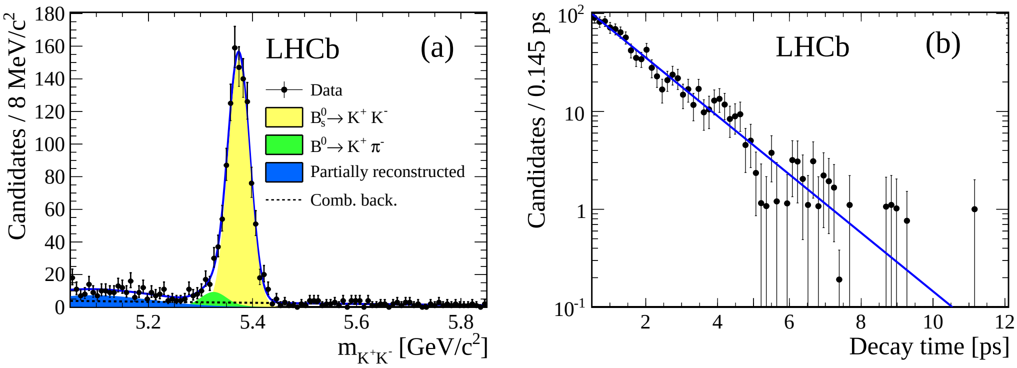

Figure 4: (a) Invariant mass spectrum for all selected $B_s^0 \to K^+K^-$ candidates. (b) Decay time distribution of $B_s^0 \to K^+K^-$ signal extracted using sWeights and the fitted exponential function.

loop diagrams carrying, in the Standard Model, the same phase as the $B_s^0 - \overline{B}{}_s^0$ mixing amplitude, and hence the measured effective lifetime is expected to be close to τ_L. The unmeasured double Cabibbo suppressed tree contribution, however, introduces *CP* violation effects and hence τ_{KK} can only be interpreted as τ_L with the assumption $|A_{\Delta\Gamma_s,K^+K^-}| = 1$.

Conventional approaches select B meson decay products that are significantly displaced from the B meson production vertex. As a consequence, B mesons with low decay times are suppressed, introducing a bias to the decay time spectrum which must be corrected for. Using $1.0\,\text{fb}^{-1}$ of data recorded in 2011, we measure the effective $B_s^0 \to K^+K^-$ lifetime using a technique that explicitly avoids such a lifetime bias [4]. Only properties independent of the decay time are used to discriminate between signal and background. To exploit all the available information, including the correlation between variables, several neural networks based on the NeuroBayes package [16] are used in a dedicated trigger and event selection.

The effective $B_s^0 \to K^+K^-$ lifetime is evaluated using an unbinned log-likelihood fit. A fit to the invariant mass spectrum is performed to determine the sWeights [17] that are used to isolate the $B_s^0 \to K^+K^-$ decay time distribution from the residual background. Since there is no acceptance bias to correct for, the lifetime is determined using an unbinned fit of an exponential function convolved with a Gaussian function to account for the resolution of the detector. The resolution is taken from simulation. Both the fit to the invariant mass spectrum and decay time distribution are shown in Fig. 4. The effective $B_s^0 \to K^+K^-$ lifetime is found to be $\tau_{KK} = 1.455 \pm 0.046 \pm 0.006$ ps.

5. Summary

The LHCb collaboration, from $1.0\,\text{fb}^{-1}$ of data, has measured $\Gamma_s = 0.6580 \pm 0.0054 \pm 0.0066\,\text{ps}^{-1}$ and $\Delta\Gamma_s = 0.116 \pm 0.018 \pm 0.006\,\text{ps}^{-1}$ by analysing the decay $B_s^0 \to J/\psi\phi$; the effective lifetime of $B_s^0 \to J/\psi f_0(980)$ to be $\tau_{J/\psi f_0} = 1.700 \pm 0.040 \pm 0.026$ps and thus $\Gamma_H = 0.588 \pm 0.014 \pm 0.009\,\text{ps}^{-1}$; and the effective lifetime of $B_s^0 \to K^+K^-$ to be $\tau_{KK} = 1.455 \pm 0.046 \pm 0.006$ ps.

Assuming $|A_{\Delta\Gamma_s,K^+K^-}| = 1$, these measurements can be combined in a maximum log-likelihood function, as shown in Fig. 5, to obtain $\Gamma_s = 0.652 \pm 0.007\,\text{ps}^{-1}$ and $\Delta\Gamma_s = 0.111 \pm 0.016\,\text{ps}^{-1}$, in agreement with the Standard Model prediction, $\Delta\Gamma_s = 0.087 \pm 0.021\,\text{ps}^{-1}$ [18].

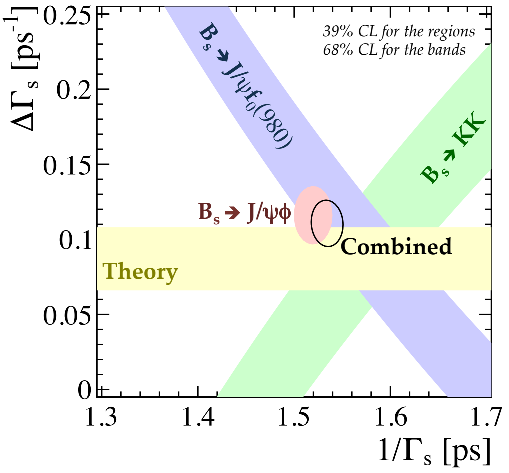

Figure 5: My personal combination of the presented LHCb B_s^0 lifetime results in terms of Γ_s and $\Delta\Gamma_s$, compared to the Standard Model prediction for $\Delta\Gamma_s$ [18]. The results are combined in a simple maximum log-likelihood scan using the central value and combined statistical and systematic errors of the presented results, assuming no correlations.

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