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Study of b-hadron to $J/\psi h^+h^-$ decays

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Abstract

Using data collected by the LHCb detector corresponding to an integrated luminosity of $3\,\text{fb}^{-1}$, several types of b-hadron to $J/\psi h^+h^-$ decays are studied. Reported are the most recent results including amplitude analyses of $\overline{B}{}^0_s$ and $\overline{B}{}^0 \to J/\psi\pi^+\pi^-$ decays, precision measurement of lifetime ratio of Λ^0_b to $\overline{B}{}^0$ using $\Lambda^0_b \to J/\psi pK^-$, and first observation of a Cabibbo-suppressed decay $\Lambda^0_b \to J/\psi p\pi^-$. Studies of $f_0(980)$ and $f_0(500)$ substructure are also discussed in $\pi^+\pi^-$ final states.

Keywords: Standard Model, Amplitude analysis, HEQ, B Lifetime, Cabibbo-suppressed decay, LHCb, Scalar mesons

1. Introduction

Decays $\overline{B}{}^0_s$ and $\overline{B}{}^0 \to J/\psi h^+h^-$, where h is either a pion or kaon, are useful for CP violation measurements [1, 2] and $\overline{B}{}^0_s$, in particular, is used for New Physics searches [3]. (Charged conjugated modes are also used when appropriate.) In order to best exploit these decays, a better understanding of the final state composition is necessary. The study of b-baryon charmonium decays is of considerable interest both to probe the dynamics of heavy flavour decay processes and to search for the effects of physics beyond the Standard Model.

Here, we report the recent studies performed using the run I data collected by the LHCb detector [4], corresponding to an integrated luminosity of $3\,\text{fb}^{-1}$. There are also other decays I didn't cover, especially $\overline{B}{}^0_s$ [5] and $\overline{B}{}^0 \to J/\psi K^+K^-$ [6] that have been studied with the $1\,\text{fb}^{-1}$ LHCb data. Thanks to the $J/\psi \to \mu^+\mu^-$ decays, for same number of final particles charmonium modes generally have higher reconstruction and trigger efficiencies than hadronic modes at LHCb.

2. Amplitude analyses of $\overline{B}{}^0_{(s)} \to J/\psi\pi^+\pi^-$ decays

The decay also provides an excellent environment for study of the light scalar states which decay to a $\pi^+\pi^-$ pair, e.g. $f_0(980)$ and $f_0(500)$ also called σ. Figure 1 shows the leading order diagrams for the two decays, where only $s\bar{s}$ content is involved in the $\overline{B}{}^0_s$ decays and $d\bar{d}$ in the $\overline{B}{}^0$ decays. We have used time-integrated amplitude analysis on both channels to understand the resonant structure and CP components of the decays using data of an integrated luminosity of $3\,\text{fb}^{-1}$.

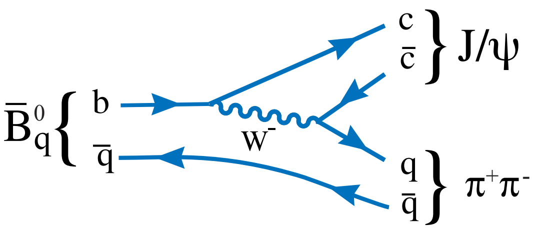

Figure 1: Leading order diagram for $\overline{B}{}^0_q$ decays into $J/\psi\pi^+\pi^-$, where $q = s$ or d.

The decay $\overline{B}{}^0_s$ or $\overline{B}{}^0 \to J/\psi\pi^+\pi^-$ with $J/\psi \to \mu^+\mu^-$ is described by 4 variables, chosen to be the $\pi^+\pi^-$ mass and three helicity angles. Zhang and Stone developed a new theoretical approach which includes all four variables and enables the measurement of the fractions of *CP*-even and -odd transversity states [7][1]. Since one of the particles in the final state, the J/ψ, has spin 1, its three decay amplitudes must be considered, while the $\pi^+\pi^-$ system is described as the coherent sum of resonant and possibly nonresonant amplitudes.

The invariant mass of the selected $J/\psi\pi^+\pi^-$ combinations is shown in Fig. 2, where the dimuon is constrained to the J/ψ mass [8]. There are 27 400 $\overline{B}{}^0_s$ and 18 800 $\overline{B}{}^0$ signal events within ±20 MeV of the respective peaks. The invariant masses of $\pi^+\pi^-$ are shown in Fig. 3 and 4 for the $\overline{B}{}^0_s$ and $\overline{B}{}^0$ candidates, respectively, superimposed with fit function and each resonance contribution. The two decays show very distinct spectra.

The $\overline{B}{}^0_s$ decays can be described by 5 resonances: $f_0(980)$, $f_0(1500)$, $f_0(1790)$, $f_2(1270)$ and $f_2'(1525)$ [9]. Another solution with a significant nonresoance component along with these five resonances also describe the data equally well. Even though the two solutions have quite different fit fractions for the $f_0(980)$, the largest final state component. Similar fractions are found for the two spin-2 states in both solutions, and the total D-wave fraction is 2.3%. As only perpendicular transversity components of the two spin-2 states are *CP*-even, we set the upper limit of *CP*-even fraction < 2.3% at 95% confidence level (CL).

The $\overline{B}{}^0$ decays can be described by 6 resonances: $\rho(770)$, $f_0(500)$, $f_2(1270)$, $\omega(782)$, $\rho(1450)$ and $\rho(1700)$ [10]. The largest two contributions with fit fractions are $\rho(770)$ of $(63.1 \pm 2.2^{+3.4}_{-2.2})\%$ and $f_0(500)$ of $(22.2 \pm 1.2^{+2.6}_{-3.5})\%$. Whenever two uncertainties are quoted, the first is statistical and the second is systematic. The *CP*-even fraction is 56%.

3. Substructure of the $f_0(980)$ and $f_0(500)$ mesons

Scalar mesons, especially the $f_0(980)$, are not well understood. Their masses do not follow the expectation in the naïve quark model that the state containing two strange quarks is heavier than the state containing only one, in stark contrast to the vector mesons [8]. Stone and Zhang [11] suggested the use of $B \to J/\psi f_0$ decays to discern the $q\bar{q}$ or tetraquark [12], i.e. $[qq][\bar{q}\bar{q}]$, nature of scalar mesons. In the $q\bar{q}$ model, the $f_0(980)$, denoted as f_0, and the $f_0(500)$, denoted as σ, are considered as a mixture of light and strange quarks governed by a single mixing angle ϕ, so that their wave functions are

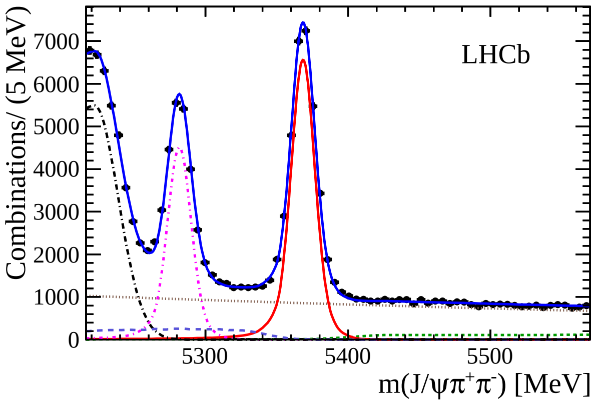

Figure 2: Invariant mass of $J/\psi\pi^+\pi^-$ combinations. The data have been fitted with double Crystal Ball signals and several background functions. The (red) solid curve shows the $\overline{B}{}^0_s$ signal, the (purple) dot-dashed curve is $\overline{B}{}^0$ signal, the (brown) dotted line shows the combinatorial background, the (green) short-dashed line shows the B^- background, the (light blue) long-dashed line is the sum of $\overline{B}{}^0_s \to J/\psi\eta'$, $\overline{B}{}^0_s \to J/\psi\phi$ with $\phi \to \pi^+\pi^-\pi^0$ backgrounds and the $\Lambda^0_b \to J/\psi K^- p$ reflection, the (black) dot-long dashed curve is the $\overline{B}{}^0 \to J/\psi K^-\pi^+$ reflection and the (blue) solid curve is the total.

$$\begin{aligned}
|f_0\rangle &= \cos\phi|s\bar{s}\rangle + \sin\phi|n\bar{n}\rangle \\
|\sigma\rangle &= -\sin\phi|s\bar{s}\rangle + \cos\phi|n\bar{n}\rangle, \\
\text{where } |n\bar{n}\rangle &\equiv \frac{1}{\sqrt{2}}\left(|u\bar{u}\rangle + |d\bar{d}\rangle\right). \qquad (1)
\end{aligned}$$

When these states are viewed as $q\bar{q}q\bar{q}$ states the wave functions becomes

$$|f_0\rangle = \frac{1}{\sqrt{2}}\left([su][\bar{s}\bar{u}] + [sd][\bar{s}\bar{d}]\right), \quad |\sigma\rangle = [ud][\bar{u}\bar{d}]. \qquad (2)$$

Here the tetraquark states are consider to be unmixed, for which there is some justification with a mixing angle estimate of < 5° [12][2].

Two ratios of decay widths suggested by Stone and Zhang [11] as discriminates between the two and four quark models are tested by the LHCb data. Table 1 shows the predictions of the two ratios compared between the $q\bar{q}$ and the tetraquark models. LHCb measures both ratios of branching fraction are consistent with zero, as

$$\frac{\mathcal{B}\left(\overline{B}{}^0_s \to J/\psi f_0(500), f_0(500) \to \pi^+\pi^-\right)}{\mathcal{B}\left(\overline{B}{}^0_s \to J/\psi f_0(980), f_0(980) \to \pi^+\pi^-\right)} < 3.4\% \qquad (3)$$

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[1] The approach is applied here after integrating over the decay time.

[2] The LHCb result using $\overline{B}{}^0_s \to J/\psi\pi^+\pi^-$ decays shown in Table 2 gives tetraquark mixing angle < 7.7° at 90% CL.

Table 1: Ratios of decay widths and predictions of the value for $r_{\bar{B}^0_{(s)}}$ in either the $q\bar{q}$ model, or the tetraquark model. The form-factors are notated as F^i_j, and the phase space factor Φ^i_j, where i indicates either σ or f_0 and j indicates either $\bar{B}^0$ or $\bar{B}^0_s$.

Mode ratio	$q\bar{q}$	tetraquark
$\dfrac{\Gamma(\bar{B}^0_s \to J/\psi\,\sigma)}{\Gamma(\bar{B}^0_s \to J/\psi\, f_0)} = \dfrac{\lvert F^{\sigma}_{B^0_s}(m^2_{J/\psi})\rvert^2}{\lvert F^{f_0}_{B^0_s}(m^2_{J/\psi})\rvert^2} \dfrac{\Phi^{\sigma}_{B^0_s}}{\Phi^{f_0}_{B^0_s}} \times r_{\bar{B}^0_s}$	$r_{\bar{B}^0_s} = \tan^2\phi$	$r_{\bar{B}^0_s} = 0$
$\dfrac{\Gamma(\bar{B}^0 \to J/\psi\, f_0)}{\Gamma(\bar{B}^0 \to J/\psi\,\sigma)} = \dfrac{\lvert F^{f_0}_{B^0}(m^2_{J/\psi})\rvert^2}{\lvert F^{\sigma}_{B^0}(m^2_{J/\psi})\rvert^2} \dfrac{\Phi^{f_0}_{B^0}}{\Phi^{\sigma}_{B^0}} \times r_{\bar{B}^0}$	$r_{\bar{B}^0} = \tan^2\phi$	$r_{\bar{B}^0} = \frac{1}{2}$

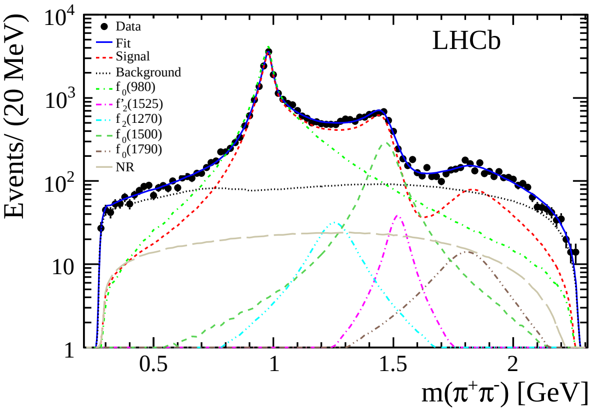

Figure 3: Invariant mass of $\pi^+\pi^-$ from $\bar{B}^0_s$ candidates.

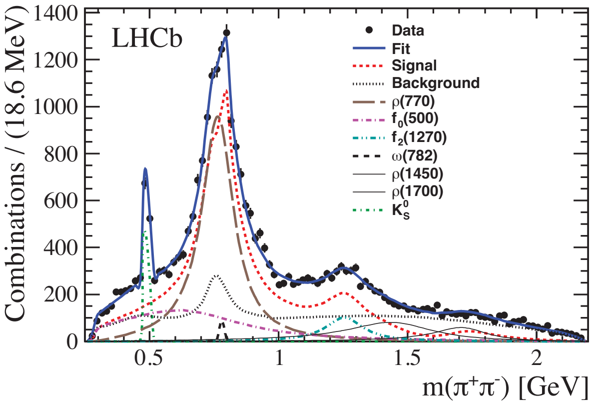

Figure 4: Invariant mass of $\pi^+\pi^-$ from $\bar{B}^0$ candidates.

at 90% CL, and

$$\frac{\mathcal{B}\left(\bar{B}^0 \to J/\psi\, f_0(980),\, f_0(980) \to \pi^+\pi^-\right)}{\mathcal{B}\left(\bar{B}^0 \to J/\psi\, f_0(500),\, f_0(500) \to \pi^+\pi^-\right)} = (0.6^{+0.7+3.3}_{-0.4-2.6})\%. \tag{4}$$

To interpret the results, we use $\mathcal{B}(f_0(980) \to \pi^+\pi^-) = (0.46 \pm 0.06)$ and $\mathcal{B}(f_0(980) \to \pi^+\pi^-) = \frac{2}{3}$, and phase space ratio $\frac{\Phi^{\sigma}}{\Phi^{f_0}} = 1.25$. The interpretation of the results is listed in Table 2. With current data, the pure $q\bar{q}$ gives a consistent picture where both channels give upper limit on the mixing phase. Using the pure tetraquark model, the measured $r_{\bar{B}^0}$ is inconsistent with the prediction of 50% at the 8 standard deviation level. Thus we have ruled out $f_0(980)$ and $f_0(500)$ being pure tetraqaurk state. The mixing of $q\bar{q}$ and tetraquark for the scalar mesons is also possible [12]. In the calculations, we use the form factor ratios equal to 1. Both two and four quark models give the same prediction for the decay width ratio of $\bar{B}^0_s \to J/\psi f_0$ to $\bar{B}^0 \to J/\psi\sigma$. Using LHCb measured values, Ref. [11] verified that $\lvert F^{f_0}_{B^0_s}(m^2_{J/\psi})/F^{\sigma}_{B^0}(m^2_{J/\psi})\rvert = 0.99^{+0.13}_{-0.04}$ consistent with 1.

Table 2: Interpretation of the results for substructure of the $f_0(980)$ and $f_0(500)$ mesons using either the $q\bar{q}$ model or the tetraquark model, where the upper limits are at 90% CL.

Model	$\bar{B}^0_s \to J/\psi\pi^+\pi^-$	$\bar{B}^0 \to J/\psi\pi^+\pi^-$
$q\bar{q}$	$\lvert\phi\rvert < 7.7°$	$\lvert\phi\rvert < 17°$
Tetraquark	$r_{\bar{B}^0_s} < 1.8\%$	$r_{\bar{B}^0} = (1.1^{+1.2+6.0}_{-0.7-0.7})\%$

4. Precision measurement of Λ^0_b to $\bar{B}^0$ lifetime ratio

The heavy quark expansion (HQE) theory, first developed in 1986 [13], is used to extract values of $|V_{ub}|$ and $|V_{cb}|$ from inclusive B^- and $\bar{B}^0$ semileptonic decays, so its verification is of prime importance. It leads to a theoretical prediction for the decay width, and hence lifetime, for each b-flavored hadron [14]. One such set of predictions was [15] that $\tau(\bar{B}^0_s)/\tau(\bar{B}^0) \approx 1.0$, $\tau(B^-)/\tau(\bar{B}^0) \approx 1.1$ and $\tau(\Lambda^0_b)/\tau(\bar{B}^0) \approx 0.96$. The theory was improved by further calculations. For example, in the case of the ratio of lifetimes of the Λ^0_b baryon, $\tau(\Lambda^0_b)$, to the $\bar{B}^0$ meson, $\tau(\bar{B}^0)$, differences of only a few percent were expected [16, 17], as the corrections of order $O(1/m_b^2)$ and $O(1/m_b^3)$ effects are both small.

Experimental tests of the HQE using lifetime mea-

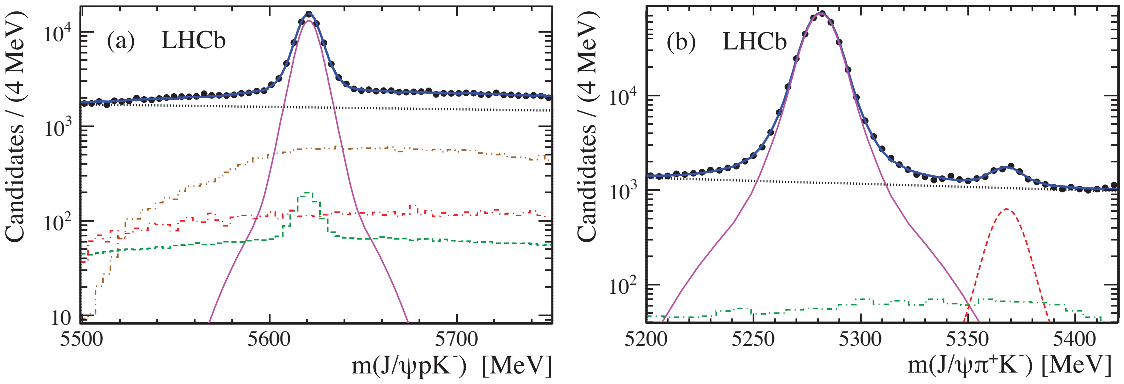

Figure 5: Fits to the invariant mass spectrum of (a) $J/\psi\, pK^-$ and (b) $J/\psi\,\pi^+K^-$ combinations. The Λ_b^0 and $\overline{B}^0$ signals are shown by the (magenta) solid curves. The (black) dotted lines are the combinatorial backgrounds, and the (blue) solid curves show the totals. In (a) the $\overline{B}_s^0 \to J/\psi\, K^+K^-$ and $\overline{B}^0 \to J/\psi\,\pi^+K^-$ reflections, caused by particle misidentification, are shown with the (brown) dot-dot-dashed and (red) dot-dashed shapes, respectively, and the (green) dashed shape represents the doubly misidentified $J/\psi\, K^+\overline{p}$ final state, where the kaon and proton masses are swapped. In (b) the $B_s^0 \to J/\psi\,\pi^+K^-$ mode is shown by the (red) dashed curve and the (green) dot-dashed shape represents the $\Lambda_b^0 \to J/\psi\, pK^-$ reflection.

surements started in the 1990's. Measurements at LEP indicated that $\tau(\Lambda_b^0)/\tau(\overline{B}^0)$ was significantly lower than the prediction: in 2003 one widely quoted average of all data gave 0.798 ± 0.052 [18], while another gave 0.786 ± 0.034 [19].

More recent measurements showed indications that a higher value is possible [20], although the uncertainties of these measurements are large. The LHCb collaboration performed measurements of the lifetime ratio utilizing the $\Lambda_b^0 \to J/\psi\, pK^-$ decay using 1 fb^{-1} of data [21] and then updated with 3 fb^{-1} sample [22]. This Λ_b^0 decay mode was first seen by LHCb. For similar decay width, this decay mode has much better reconstruction efficiency than the $J/\psi\,\Lambda$ final state [23], as it contains four charged tracks from the Λ_b^0 decay vertex. Only the 3 fb^{-1} measurement is discussed here.

In this measurement the Λ_b^0 decay time distribution is compared to that of $\overline{B}^0 \to J/\psi\, K^-\pi^+$ decays. The reconstructed invariant mass distributions for both modes are shown in Fig. 5. For $\overline{B}^0$ candidates the invariant π^+K^- mass was required to be within ±100 MeV of the $\overline{K}^{*0}(892)$ mass. There are approximately 50 000 Λ_b^0 signal events and 340 000 $\overline{B}^0$ signal events.

The decay time acceptances obtained from the simulations are shown in Fig. 6(a). The individual acceptances in both cases exhibit the same behaviour of decreasing below 1 ps. The ratio of the decay time acceptances is shown in Fig. 6(b). The yield of b hadrons for both decay modes is determined by fitting the candidate invariant mass distributions in each decay time bin. The resulting signal yields as a function of decay time are shown in Fig. 7.

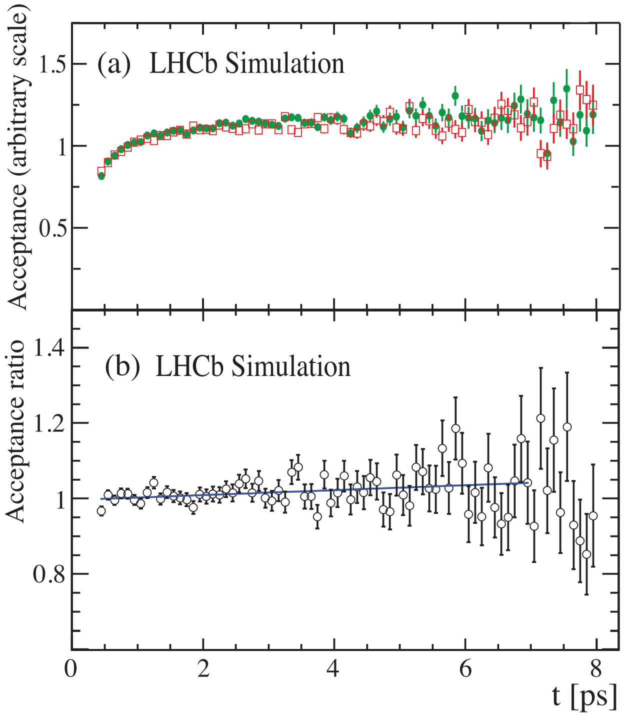

Figure 6: (a) Decay time acceptances (arbitrary scale) from simulation for (green) circles $\Lambda_b^0 \to J/\psi\, pK^-$, and (red) open-boxes $\overline{B}^0 \to J/\psi\,\overline{K}^{*0}(892)$ decays. (b) Ratio of the decay time acceptances between $\Lambda_b^0 \to J/\psi\, pK^-$ and $\overline{B}^0 \to J/\psi\,\overline{K}^{*0}(892)$ decays obtained from simulation. The (blue) line shows the result of the linear fit.

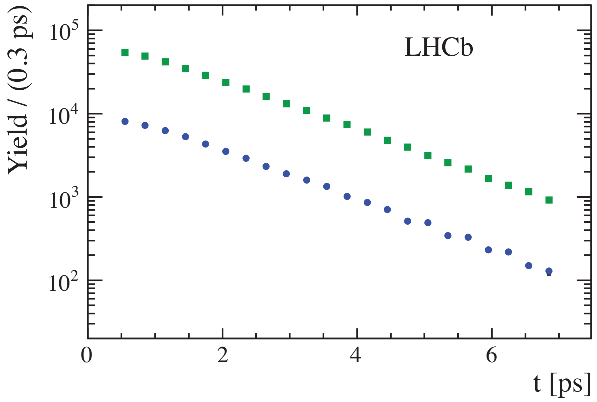

Figure 7: Decay time distributions for $\Lambda_b^0 \to J/\psi\, pK^-$ shown as (blue) circles, and $\bar{B}^0 \to J/\psi\, \bar{K}^{*0}(892)$ shown as (green) squares. For most entries the error bars are smaller than the points.

The ratio of lifetimes is determined as $\frac{\tau(\Lambda_b^0)}{\tau(\bar{B}^0)} = 0.974 \pm 0.006 \pm 0.004$. Multiplying the lifetime ratio by $\tau(\bar{B}^0) = 1.519 \pm 0.007$ ps, the Λ_b^0 baryon lifetime is $\tau(\Lambda_b^0) = 1.479 \pm 0.009 \pm 0.010$ ps. A summary of Λ_b^0 lifetime measurements done since 1990 is shown in Fig. 8.

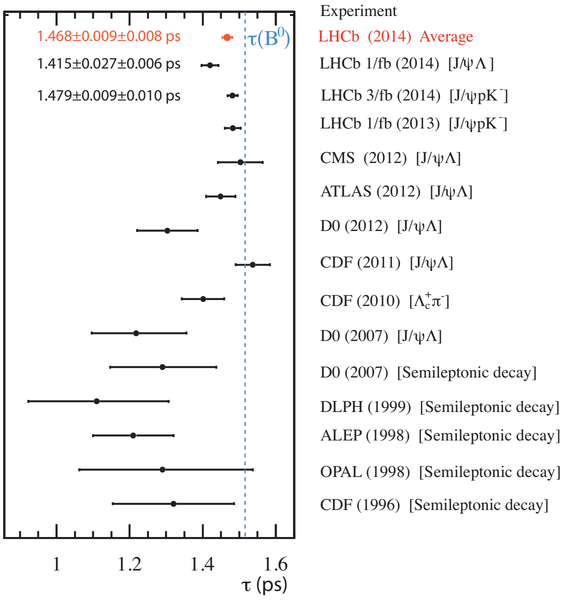

Figure 8: Summary of measured Λ_b^0 lifetimes. The vertical dashed line shows the world average $\bar{B}^0$ lifetime.

5. First observation of Cabibbo-suppressed decay $\Lambda_b^0 \to J/\psi\, p\pi^-$

LHCb has first observed the Cabibbo-suppressed decay $\Lambda_b^0 \to J/\psi p\pi^-$ using a data sample corresponding to an integrated luminosity of 3 fb^{-1} [24]. A prominent signal is observed and the branching fraction relative to the decay mode $\Lambda_b^0 \to J/\psi pK^-$ is determined to be

$$\frac{\mathcal{B}(\Lambda_b^0 \to J/\psi p\pi^-)}{\mathcal{B}(\Lambda_b^0 \to J/\psi pK^-)} = 0.0824\pm0.0025(\text{stat})\pm0.0042(\text{syst}).$$

The measured ratio is consistent with the expectation computed using relative CKM matrix elements and phase space factors. Figure 9 shows the distribution of $\Lambda_b^0 \to J/\psi p\pi^-$ and $\Lambda_b^0 \to J/\psi pK^-$ masses.

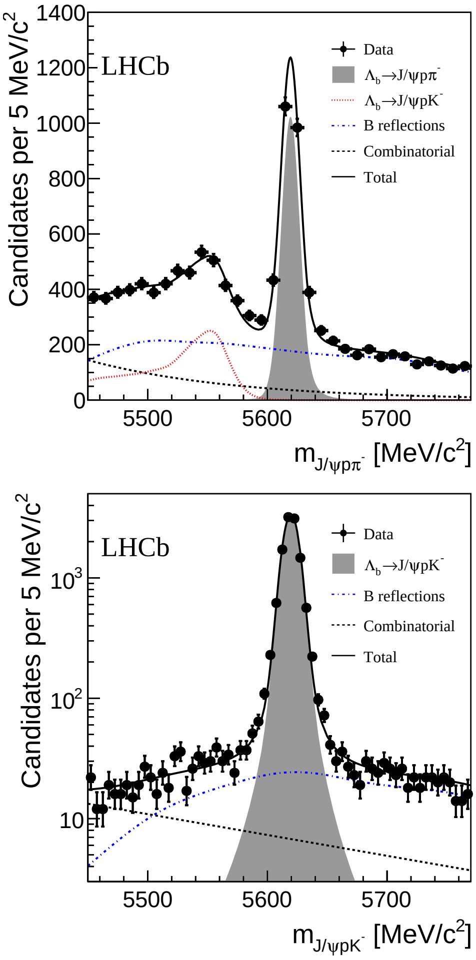

Figure 9: Distribution of (top) $\Lambda_b^0 \to J/\psi p\pi^-$ and (bottom) $\Lambda_b^0 \to J/\psi pK^-$ masses with fit projections overlaid.

A search for direct *CP* violation is performed. The difference in the CP asymmetries between these two decays is found to be

$$\begin{aligned}&\mathcal{A}_{CP}(\Lambda_b^0 \to J/\psi p\pi^-) - \mathcal{A}_{CP}(\Lambda_b^0 \to J/\psi pK^-)\\ &\quad= (+5.7 \pm 2.4\,(\text{stat}) \pm 1.2\,(\text{syst}))\%,\end{aligned}$$

which is compatible with CP symmetry at the 2.2σ level.

6. Conclusion

Using the 3 fb^{-1} data sample, LHCb has used various b-hardon to $J/\psi h^+h^-$ decays to test the Standard Model and search for New Physics, as well as understand the scalar mesons.

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