Measurement of relative branching fractions of $B$ decays to $\psi(2S)$ and $J/\psi$ mesons

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Abstract The relative rates of $B$-meson decays into $J/\psi$ and $\psi(2S)$ mesons are measured for the three decay modes in $pp$ collisions recorded with the LHCb detector. The ratios of branching fractions ($B$) are measured to be

$$
\frac{\mathcal{B}(B^+ \to \psi(2S)K^+)}{\mathcal{B}(B^+ \to J/\psi K^+)} = 0.594 \pm 0.006 \text{(stat)} \pm 0.016 \text{(syst)} \pm 0.015 \text{(R_\phi)},
$$

$$
\frac{\mathcal{B}(B^0 \to \psi(2S)K^{*0})}{\mathcal{B}(B^0 \to J/\psi K^{*0})} = 0.476 \pm 0.014 \text{(stat)} \pm 0.010 \text{(syst)} \pm 0.012 \text{(R_\phi)},
$$

$$
\frac{\mathcal{B}(B^0 \to \psi(2S)\phi)}{\mathcal{B}(B^0 \to J/\psi \phi)} = 0.489 \pm 0.026 \text{(stat)} \pm 0.021 \text{(syst)} \pm 0.012 \text{(R_\phi)},
$$

where the third uncertainty is from the ratio of the $\psi(2S)$ and $J/\psi$ branching fractions to $\mu^+\mu^-$.

1 Introduction

Decays of $B$ mesons to two-body final states containing a charmonium resonance such as a $J/\psi$ or $\psi(2S)$ offer a powerful way of studying electroweak transitions. Such decays probe charmonium properties and play a role in the study of $CP$ violation and mixing in the neutral $B$ system [1].

The relative branching fractions of $B^+$, $B^0$ and $B^{*0}$ mesons into $J/\psi$ and $\psi(2S)$ mesons have previously been studied by both the CDF and D0 collaborations [2–4]. Since the current experimental results for the study of $CP$ violation in $B^0$ mixing using the $B^0 \to J/\psi \phi$ decay [5–7] are statistically limited, it is important to establish other channels where this analysis can be done. One such channel is the $B^{*0} \to \psi(2S)\phi$ decay.

In this paper, measurements of the ratios of the branching fractions of $B$ mesons decaying to $\psi(2S)X$ and $J/\psi X$ are reported, where $B$ denotes a $B^+$, $B^0$ or $B^{*0}$ meson (charge conjugate decays are implicitly included) and $X$ denotes a $K^+$, $K^{*0}$ or $\phi$ meson. The data were collected by the LHCb experiment in $pp$ collisions at the centre-of-mass energy $\sqrt{s} = 7$ TeV during 2011 and correspond to an integrated luminosity of 0.37 fb$^{-1}$.

2 Detector description

The LHCb detector [8] is a single-arm forward spectrometer covering the pseudorapidity range $2 < \eta < 5$, designed for the study of $b$- and $c$-hadrons. The detector includes a high precision tracking system consisting of a silicon-strip vertex detector surrounding the $pp$ interaction region, 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 placed downstream. The combined tracking system has a momentum resolution $\Delta p/p$ that varies from 0.4 % at 5 GeV/c to 0.6 % at 100 GeV/c, and an impact parameter resolution of 20 $\mu$m for tracks with high transverse momentum. Data were taken with both magnet polarities to reduce systematic effects due to detector asymmetries. Charged hadrons are identified using two ring-imaging Cherenkov (RICH) detectors. Photon, electron and hadron candidates are identified by a calorimeter system consisting of scintillating-pad and pre-shower detectors, and electromagnetic and hadronic calorimeters. Muons are identified by a muon system composed of alternating layers of iron and multiwire proportional chambers. The trigger consists of a hardware stage based on information from the calorimeter and muon systems, followed by a software stage which applies a full event reconstruction.

Events with a $J/\psi \to \mu^+\mu^-$ final state are triggered using two hardware trigger decisions: the single-muon decision, which requires one muon candidate with a transverse momentum $p_T$ larger than 1.5 GeV/c, and the di-muon decision, which requires two muon candidates with
transverse momenta $p_{T1}$ and $p_{T2}$ satisfying the relation $\sqrt{p_{T1}^2 + p_{T2}^2} > 1.3$ GeV/c. The di-muon trigger decision in the software trigger requires muon pairs of opposite charge with $p_T > 500$ MeV/c, forming a common vertex and with an invariant mass in excess of 2.9 GeV/c$^2$.

3 Event selection

In this analysis, the decays $B^+ \to \psi K^+(B^0 \to \psi K^{*0})$, $B^0 \to \psi \phi$ are reconstructed, where $\psi$ represents $\psi(2S)$ or $J/\psi$. The nondynamical background from particles produced in the primary vertex constraint is required to be less than 5, where the DTF algorithm takes into account the number of degrees of freedom. The $B^+$ candidates, where a muon from the $\psi(2S) \to \mu^+\mu^-$ decay is reconstructed as both muon and kaon, are removed by requiring the angle between the same sign muon and kaon to be greater than 3 mrad.

4 Measurement of $N_{\psi(2S)}/N_J\phi$

The mass distributions for selected candidates are shown in Fig. 1. The number of the $B^+ \to \psi K^+$ candidates is estimated by performing an unbinned maximum likelihood fit. The same procedure is used to determine the number of the $B^0 \to \psi K^+\pi^-$ candidates in a $942 < M_{K^+\pi^-} < 942$ MeV/c$^2$ mass window and the number of the $B^0 \to \psi K^+K^-$ candidates in a $1030 < M_{K^+K^-} < 1030$ MeV/c$^2$ mass window. The number of signal candidates is determined by fitting a double-sided Crystal Ball function [12, 13] for signal together with an exponential function to model the background. The tail parameters of the Crystal Ball function are fixed to values determined from simulation.

To estimate the contribution from non-resonant $B^0 \to \psi K^+\pi^-$ and $B^0 \to \psi K^+K^-$, the $K^+\pi^-$ and $K^+K^-$ invariant mass distributions have been studied after relaxing requirements on the $K^+\pi^-$ and $K^+K^-$ invariant masses, see Fig. 2. The $K^+\pi^-$ and $K^+K^-$ invariant mass distributions are then fitted with the sum of a relativistic Breit-Wigner function convolved with a Gaussian, to describe the resonant contribution from the $K^{*0}$ or $\phi$, two-body phase space function multiplied by a second order polynomial, to describe the non-resonant $K^+\pi^-$ or $K^+K^-$ contribution. The sPlot technique [14] is used to unfold the $\psi K^+\pi^-$ or $\psi K^+K^-$ invariant mass of the non-resonant (in $K^+\pi^-$ and $K^+K^-$) candidates. This unfolded distribution contains a mixture of combinatorial background and non-resonant $B^0 \to \psi K^+\pi^-$ or $B^0 \to \psi K^+K^-$ decays. The invariant mass of the unfolded $B$ candidates is shown in Fig. 3. The same function used in Fig. 1 is then used to estimate the contribution from the non-resonant $B$ decays, which is subtracted from the total yield to estimate the contribution from resonant $B^0 \to \psi K^{*0}$ or $B^0 \to \psi \phi$ decays. The contribution of the resonant decays can also be extracted by unfolding the contribution of resonant $K^+\pi^-$ or $K^+K^-$ decays to the $\psi K^+\pi^-$ or $\psi K^+K^-$ invariant mass distribution. This yields a compatible, but a statistically less precise, result. The yields are summarized listed in Table 1.
5 Efficiencies and systematic uncertainties

The branching fraction ratio is calculated using

\[
\frac{B(B \rightarrow \psi(2S) X)}{B(B \rightarrow J/\psi X)} = \frac{N_{\text{res}}^{\psi(2S)X}}{N_{\text{res}}^{J/\psi X}} \times \frac{\varepsilon_{J/\psi X}}{\varepsilon_{\psi(2S)X}} \times \frac{B(J/\psi \rightarrow \mu^+\mu^-)}{B(\psi(2S) \rightarrow \mu^+\mu^-)},
\]

where \(N_{\text{res}}\) is the number of signal candidates and \(\varepsilon\) is the overall efficiency.
the hardware and software trigger and then reconstructed in digitized output is passed through a full simulation of both the combinatorial background (dashed) and the signal yield for resonant and non-resonant modes only and \( N_{s} / N_{X} \) is the signal yield for resonant decays (through \( K^{*0} \) or \( \phi \)). The uncertainties are statistical only.

The overall efficiency ratio is 0.901 ± 0.016, 1.011 ± 0.014 and 0.994 ± 0.014 for the \( B^{+} \), the \( B^{0} \) and the \( B^{0} \) channels respectively. Since the selection criteria for \( B \to J/\psi X \) and \( B \to \psi(2S)X \) decays are identical, the ratio of efficiencies is expected to be close to unity. The deviation of the overall efficiency ratio from unity in the case of the \( B^{+} \to \psi K^{+} \) decays is due to the difference between the \( p_{T} \) spectra of muons for the \( J/\psi \) and \( \psi(2S) \) decays. For the \( B^{0} \) and \( B^{0} \) channels this difference is small. It has been checked that the behaviour of the efficiencies of all selection criteria is consistent in the data and simulation.

Since the decay products in each of the pairs of channels considered have similar kinematics, most uncertainties cancel in the ratio. The different contributions to the systematic uncertainties affecting this analysis are discussed in the following and summarized in Table 2.

The dominant source of systematic uncertainty arises from the subtraction of the non-resonant components in the digitized output is passed through a full simulation of both the hardware and software trigger and then reconstructed in the same way as the data.

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of candidates containing genuine $K^*(0)(\phi)$ resonances. Second, using the $B^0_s$ mass distribution as the discriminating variable to unfold the $K^+\pi^-(K^+K^-)$ mass distribution of genuine $B^0_s$ candidates and fitting this distribution to determine the number of non-resonant decays. The corresponding uncertainties are found to be 1.5 % in the $B^0$ channel and 3.4 % in the $B^0_s$ channel.

The other important source of uncertainty arises from the estimation of the efficiencies due to the potential disagreement between data and simulation. This is studied by varying independently selection criteria in data and simulation. The corresponding uncertainties are found to be 1.7 % in the $B^+$ channel, 0.5 % in the $B^0$ channel and 2.0 % in the $B^0_s$ channel. The observed difference in the efficiency ratios for the two magnet polarities is conservatively taken as an estimate of the systematic uncertainty. This is 1.4 % in the $B^+$ channel, 0.6 % in the $B^0$ channel and 0.7 % in the $B^0_s$ channel.

The trigger is highly efficient in selecting $B$ meson decays with two muons in the final state. For this analysis the di-muon pair is required to trigger the event. Differences in the trigger efficiency between data and simulation are studied in the data using events which were triggered independently on the di-muon pair [20]. Based on these studies, an uncertainty of 1.1 % is assigned.

A further uncertainty arises from the imperfect knowledge of the shape of the signal and background in the $B$ meson mass distribution. To estimate this effect, a linear and a quadratic function are considered as alternative models for the background mass distribution. In addition, a double Gaussian shape and a sum of double-sided Crystal Ball and Gaussian shapes are used as alternative models for the signal shape. The maximum observed change in the ratio of yields in the $\psi(2S)$ and $J/\psi$ modes is taken as systematic uncertainty.

The central value of the relative efficiency is determined by assuming that the angular distribution of the $B \rightarrow \psi(2S)X$ decay is the same as that of the $B \rightarrow J/\psi X$. The systematic uncertainty due to the unknown polarization of the $\psi(2S)$ in the $B$ meson decays is estimated as follows. The simulation samples were re-weighted to match the angular distributions found from the data and the relative efficiency was recalculated. The difference between the baseline analysis and the re-weighted simulation is taken as the systematic uncertainty, as shown in Table 2.

Finally, the uncertainty due to potential contribution from the Cabibbo-suppressed mode with a $\pi$ misidentified as $K$ is found to be 0.4 % in the $B^+$ channel and negligible in the $B^0$ and $B^0_s$ channels. The uncertainty due to the cross-feed between $B^0$ and $B^0_s$ channels with a $\pi$ misidentified as $K$ (or a $K$ misidentified as $\pi$) is negligible.

6 Results

Since the di-electron fraction is measured more precisely than those of the di-muon decay modes, we assume lepton universality and take $R_\psi = B(\psi \rightarrow \mu^+\mu^-)/B(\psi(2S) \rightarrow \mu^+\mu^-) = B(\psi \rightarrow e^+e^-)/B(\psi(2S) \rightarrow e^+e^-) = 7.69 \pm 0.19$ [10]. The results are combined using Eq. (1) to give

$$B(B^+ \rightarrow \psi(2S)K^+) / B(B^+ \rightarrow J/\psi K^+) = 0.594 \pm 0.006(\text{stat}) \pm 0.016(\text{syst}) \pm 0.015(R_\psi),$$

$$B(B^0 \rightarrow \psi(2S)K^{*0}) / B(B^0 \rightarrow J/\psi K^{*0}) = 0.476 \pm 0.014(\text{stat}) \pm 0.010(\text{syst}) \pm 0.012(R_\psi),$$

$$B(B^0_s \rightarrow \psi(2S)\phi) / B(B^0_s \rightarrow J/\psi \phi) = 0.489 \pm 0.026(\text{stat}) \pm 0.021(\text{syst}) \pm 0.012(R_\psi),$$

where the first uncertainty is statistical, the second is systematic and the third is the uncertainty on the $R_\psi$ value [10].

The resulting branching fraction ratios are compatible with, but significantly more precise than, the current world averages of $B(B^+ \rightarrow \psi(2S)K^+)/B(B^+ \rightarrow J/\psi K^+) = 0.60 \pm 0.07$ and $B(B^0 \rightarrow \psi(2S)\phi)/B(B^0 \rightarrow J/\psi \phi) = 0.53 \pm 0.10$ [10] and the CDF result of $B(B^0 \rightarrow \psi(2S)K^{*0})/B(B^0 \rightarrow J/\psi K^{*0}) = 0.515 \pm 0.113 \pm 0.052$ [2]. The $B^0_s \rightarrow \psi(2S)\phi$ decay is particularly interesting since, with more data, it can be used for the measurement of $CP$ violation in $B^0_s$ mixing.

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