Measurement of the CP-violating phase in $B_s^0$ mixing

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Abstract. Determination of the CP-violating phase $\phi_s$ in $B_s^0 \to J/\psi K^+K^-$ decays is one of the key goals of the LHCb experiment. Its value is predicted to be very small in the Standard Model but can be significantly enhanced in many other models. We present the most precise measurement of $\phi_s$ to date and the first observation of a non-zero $\Delta \Gamma_s$ based upon 1 fb$^{-1}$ of data collected at LHCb during 2011. Also the measurement of $\phi_s$ with the decay mode $B_s^0 \to J/\psi\pi\pi$ and a combination of the $J/\psi K^+K^-$ and $J/\psi\pi\pi$ results are reported. Additionally we present first results from the measurement of the decay $B_s^0 \to J/\psi K^*0$, which is potentially interesting for controlling currently neglected higher order corrections in $B_s^0 \to J/\psi K^+K^-$.  

1. Introduction
Mixing of $B_s^0$ and anti-$B_s^0$ ($\bar{B}_s^0$) mesons is governed by the processes shown in figure 1 in the Standard Model of particle physics. Violation of symmetry under a combined charge conjugation and parity reversal (CP) transformation induced by these processes is expected to be small. However, significant violation of CP symmetry may be introduced by corrections from presently unknown contributions.

![Feynman diagrams](image)

Figure 1. Feynman diagrams for $B_s^0$-$\bar{B}_s^0$ mixing in the Standard Model.

CP violation in $B_s^0$-$\bar{B}_s^0$ mixing may appear in two ways [1]. Firstly, it can cause a difference between the probabilities for $\bar{B}_s^0 \to B_s^0$ and $B_s^0 \to \bar{B}_s^0$ transitions (CP violation in mixing). Secondly, it can contribute to the phase difference between the interfering $B_s^0$ ($\bar{B}_s^0$) decay processes with and without a transition to $\bar{B}_s^0$ ($B_s^0$). In general, this phase is also affected by CP violation in the decay amplitudes.

This work focuses on measurement of the CP-violating phase between mixed and unmixed decays, which is denoted by $\phi_s$. Decays of the type $B_s^0 \to J/\psi(\to \mu^+\mu^-) h^+h^-$ are studied,
where $h^+h^-$ can be $K^+K^-$ or $\pi^+\pi^-$ (see figure 2). The resonant components of these processes are CP eigenstates, which are particularly suitable for a measurement of $\phi_s$. While it is assumed that the $J/\psi$ is the only component of the $\mu^+\mu^-$ system, the $h^+h^-$ system is a sum of multiple resonant and non-resonant states.

$B^0_s \rightarrow J/\psi h^+h^-$ decays are $b \rightarrow c\bar{c}s$ transitions and hence the measured CP-violating phase is labelled $\phi_s^{c\bar{c}s}$. The decay process is dominated by the diagram shown in figure 2a. In the approximation that this tree-level amplitude is the only contribution, there is no CP violation directly in the decay and $\phi_s^{c\bar{c}s}$ is a clean measurement of CP violation induced by $B^0_s \rightarrow \bar{B}^0_s$ mixing [2].

In the Standard Model, assuming the tree-level approximation, $\phi_s^{c\bar{c}s}$ is approximately equal to $-2\beta_s \equiv -2 \arg(-V_{ts}^* V_{cb}^*/V_{cs}^* V_{cb}^*)$, where the $V_{ij}$ are elements of the CKM matrix [3]. An indirect determination with a global fit to present experimental data yields $-2\beta_s = (-0.0363^{+0.0015}_{-0.0016})$ rad [4]. Physics beyond the Standard Model may significantly affect the value of $\phi_s^{c\bar{c}s}$ determined in a direct measurement [5, 6].

Beyond the tree-level approximation, contributions from Standard Model penguin diagrams need to be considered (see for example the diagram in figure 2b). These amplitudes are doubly Cabibbo suppressed relative to the tree-level amplitude. Resulting corrections to $\phi_s^{c\bar{c}s}$ depend on the considered decay mode and may be controlled with measurements of decays in which similar penguin contributions are not Cabibbo suppressed, like $B^0_s \rightarrow J/\psi K^-\pi^+$ [7].

![Feynman diagrams contributing to the decay $B^0_s \rightarrow J/\psi h^+h^-$ in the Standard Model ($h^+h^- \in \{K^+K^-, \pi^+\pi^-\}$). (a): tree-level diagram; (b): penguin diagram.](image)

In addition to $\phi_s^{c\bar{c}s}$, also other mixing and decay parameters of the $B^0_s, \bar{B}^0_s$ system can be measured, such as the mean decay width ($\Gamma_s$), the differences between the masses and decay widths of the mass eigenstates ($\Delta m_s$ and $\Delta \Gamma_s$, respectively) and the relative amplitudes of different contributions to the decay. While $\Delta m_s$ is constrained to the estimate from a dedicated LHCb measurement ($17.63 \pm 0.11$ ps$^{-1}$ [8]), values for the other parameters are determined with the measurements described here.

The quantities $\phi_s^{c\bar{c}s}$, $\Gamma_s$ and $\Delta \Gamma_s$ are measured as parameters in the distribution of the time between production and decay of $B^0_s$ or $\bar{B}^0_s$ mesons [1, 2]. A model of this decay time distribution is fitted to the experimental data. The main sensitivity to $\phi_s^{c\bar{c}s}$ comes from an oscillation that modulates an (approximately) exponential shape. The frequency of this oscillation is the mass difference $\Delta m_s$ and its amplitude is proportional to $\sin \phi_s^{c\bar{c}s}$.

The preliminary results in the $B^0_s \rightarrow J/\psi K^+K^-$ decay channel presented here are an update of previous LHCb results [9]. The parameters $\phi_s^{c\bar{c}s}$ and $\Delta \Gamma_s$ were also measured by the D0 [10], CDF [11] and ATLAS [12] collaborations and $\Delta \Gamma_s$ by the CMS collaboration [13]. All measurements are compatible with the Standard Model expectations $\phi_s^{c\bar{c}s} \approx -2\beta_s$ and $\Delta \Gamma_s = (0.087 \pm 0.021)$ ps$^{-1}$ [14].
2. Experimental aspects
The LHCb detector is described in reference [15]. It is designed for studies of particles containing b or c quarks produced in the proton–proton collisions of the Large Hadron Collider (LHC [16]). Excellent charged particle tracking and decay vertex finding enable a precise determination of the decay time, which is measured as the distance between the B meson production and decay vertices. Different decay modes are distinguished by the use of particle identification techniques.

Selection of decay events is based on finding $J/\psi \rightarrow \mu^+\mu^-$ decays, which are subsequently combined with oppositely charged hadron pairs. Kinematic restrictions are applied to candidate events in order to reject background from four particles that do not originate from a $B^0 \rightarrow J/\psi h^+h^-$ decay. Background that is remaining after selection is separated from the signal $B^0 \rightarrow J/\psi h^+h^-$ decay on a statistical basis, by exploiting the difference in invariant $J/\psi h^+h^-$ mass distributions.

The decay time measurement has a finite resolution, which effectively gives a dilution of the oscillation amplitude in its distribution and hence reduces the sensitivity to $\delta \phi^{cs}$. This effect is modelled by smearing the theoretical distribution [17, 18]. The resolution is estimated for each decay event individually.

The resolution estimate is calibrated with a measurement of the decay time distribution of background events in which a real $J/\psi$ is combined with two unrelated hadrons. All particles in these events are assumed to come directly from the proton–proton interaction point (prompt background), which makes their “true decay time” equal to zero. The resolution is determined from the width of the peak in the measured decay time distribution around zero. The effective measured resolution is 45 fs. This is precise enough to resolve the oscillation, which has a period of $2\pi/\Delta m_s \approx 350$ fs.

Since the oscillation in the decay time distribution is exactly opposite for $B^0$ decays and $\bar{B}^0$ decays, determination of the initial meson flavour is required. This flavour tag has a probability to be wrong, which leads to a partial cancellation of the oscillations in the measured distributions and gives another dilution. Also the wrong-tag probability is estimated on an event-by-event basis.

The estimated wrong-tag probability is calibrated with the decay mode $B^\mp \rightarrow J/\psi K^\mp$, for which the initial meson flavour is known from the final state [19]. The effective tagging efficiency is determined to be $\epsilon_{\text{tag}}(D^2) \approx 2.3\%$ [17, 18]. This number can be interpreted as the effective fraction of events with a perfect flavour tag.

3. Analysis of $B^0 \rightarrow J/\psi K^+K^-$ decays
The most promising decay mode for the measurement of $\delta \phi^{cs}$ is $B^0 \rightarrow J/\psi K^+K^-$ [2, 5, 6]. The preliminary LHCb measurement with the 2011 data set of 1 fb$^{-1}$ of integrated luminosity is described in reference [17]. Approximately 21,200 signal events are extracted.

Several intermediate angular momentum states of the $J/\psi K^+K^-$ system contribute to the decay, each with a different distribution of final state particles decay angles [2, 20]. If expressed in terms of CP eigenstates, these contributions are either even or odd under a CP transformation. CP-even states, CP-odd states and their interferences have different decay time distributions, which are separated by an angular analysis to enhance the sensitivity of the measurement.

Analysis of the data is restricted to events with invariant $K^+K^-$ masses in the range 1008–1032 MeV/$c^2$, for which the system is dominated by the $\phi(1020)$ resonance. While the $K^+K^-$ system is in a $L = 1$ orbital angular momentum state (P-wave) for the $\phi(1020)$, there is also a small $L = 0$ (S-wave) contribution of approximately 1% [21].

The sums of the measured $B^0$ and $\bar{B}^0$ time and angular distributions are shown in figure 3. Only events with a measured decay time greater than 0.3 ps are selected to reject the large number of prompt background events that were used earlier to determine the decay time resolution.
Figure 3. Measured distributions and the fitted model for the decay time (a) and angles (b, c, d) in $B_s^0 \to J/\psi K^+ K^-$. See reference [2] for definition of the decay angles. The data are shown as black points with error bars. The sum of the signal contributions is shown as the blue, solid line, background as the red, solid line and the total sum as the black, solid line. The dotted and dashed blue contributions are the CP-even and CP-odd $B_s^0 \to J/\psi \phi$ angular momentum components, respectively. The $K^+ K^-$ S-wave component is shown as the magenta, solid line.

Preliminary results for the principal physics parameters in the 1 fb$^{-1}$ $B_s^0 \to J/\psi K^+ K^-$ measurement are

$$\phi_s^{CS} = (-0.001 \pm 0.101 \pm 0.027) \text{ rad}$$
$$\Delta \Gamma_s = (+0.116 \pm 0.018 \pm 0.006) \text{ ps}^{-1}$$
$$\Gamma_s = (0.6580 \pm 0.0054 \pm 0.0066) \text{ ps}^{-1},$$

where the first uncertainty is statistical and the second systematic. This is the most sensitive measurement of $\phi_s$ to date and the first direct observation of a non-zero decay width difference in the $B_s^0$–$\overline{B_s^0}$ system. The results are compatible with Standard Model expectations.

A parameter transformation exists that takes the values $(\phi_s^{CS}, \Delta \Gamma_s)$ to $(\pi - \phi_s^{CS}, -\Delta \Gamma_s)$, but leaves the model for the decay time and angular distributions invariant. This gives an alternative set of parameter values, which describes the measured data equally well as the set quoted above. The transformation also affects the phases of the decay amplitudes for the $B_s^0 \to J/\psi \phi$ and $K^+ K^-$ S-wave contributions, which can be used to resolve this ambiguity in the results [20].
The phase of the $J/\psi\phi$ contribution is expected to increase rapidly with increasing $K^+K^-$ mass across the $\phi(1020)$ resonance, while the phase of the $K^+K^-$ $S$-wave is expected to vary slowly. This leads to a decreasing trend in the phase difference between the $S$-wave and $J/\psi\phi$, which can be observed. One of the sets of parameter values gives this expected decreasing trend, while the alternative set instead gives an increasing trend. An LHCb study in a wider $K^+K^-$ mass interval of 988–1050 MeV/c$^2$ has demonstrated that the set with $\phi_s \approx 0$ and $\Delta\Gamma_s > 0$ gives the expected behaviour \cite{22} (see figure 4).

4. Analysis of $B_s^0 \rightarrow J/\psi\pi^+\pi^-$ decays
For invariant $\pi^+\pi^-$ masses in the range 775–1550 MeV/c$^2$, the $B_s^0 \rightarrow J/\psi\pi^+\pi^-$ decay almost exclusively proceeds via intermediate states that are odd under a CP transformation. The fraction of these contributions is found to be greater than 0.977 at 95\% confidence level by an LHCb analysis of the resonant components of the decay \cite{23}. Since CP-odd states and their interferences have identical decay time distributions, the measurement of $\phi_s^{\cos}$ in this decay mode does not require an analysis of the decay angles to separate the different contributions.

Because of the CP-odd nature of $B_s^0 \rightarrow J/\psi\pi^+\pi^-$ and small CP violation, the decay is dominated by the heavy mass eigenstate of the $B_s^0$–$ar{B}_s^0$ system. As a consequence, the average and the difference of the decay widths of the light and heavy eigenstates are almost fully anti-correlated and cannot be determined both in this measurement. Therefore, the values of $\Gamma_s$ and...
The $\Delta \Gamma_s$ are constrained to the $J/\psi K^+ K^-$ estimates from the measurement described in reference [9].

The $B_s^0 \rightarrow J/\psi \pi^+ \pi^-$ measurement is described in reference [18]. It uses the 1 fb$^{-1}$ data set collected in 2011, from which $7421 \pm 105$ signal events are extracted in a region of $\pm 20$ MeV/c$^2$ around the nominal $B_s^0$ mass. The resulting estimate for the value of $\phi_s^{\text{CS}}$ is

$$\phi_s^{\text{CS}} = (-0.019^{+0.173+0.004}_{-0.174-0.003}) \text{ rad},$$

where the first uncertainty is statistical and the second systematic.

Figure 5 shows the measured asymmetry between the decay time distributions of decay events tagged as $B_s^0$ and decay events tagged as $B_s^0$. The amplitude of the oscillation in the time development of this asymmetry provides a measurement of $\sin \phi_s^{\text{CS}}$. The absence of a significant oscillation is consistent with the estimated value of $\phi_s^{\text{CS}}$, which is compatible with zero.

5. Combination of results for $\phi_s^{\text{CS}}$ and $\Delta \Gamma_s$

Results from the $B_s^0 \rightarrow J/\psi K^+ K^-$ and $B_s^0 \rightarrow J/\psi \pi^+ \pi^-$ measurements can be combined by extracting an estimate for $\phi_s^{\text{CS}}$ from a simultaneous fit of the decay models to both data samples. The preliminary combined result for the 1 fb$^{-1}$ data set is [17]

$$\phi_s^{\text{CS}} = (-0.002 \pm 0.083 \pm 0.027) \text{ rad},$$

where the first uncertainty is statistical and the second systematic.

A combination of the Atlas, CDF, D0 and LHCb measurements of $\phi_s^{\text{CS}}$ and $\Delta \Gamma_s$ by the Heavy Flavor Averaging Group yields [24]

$$\phi_s^{\text{CS}} = (-0.013^{+0.083}_{-0.009}) \text{ rad} \quad \Delta \Gamma_s = (+0.089^{+0.041}_{-0.013}) \text{ ps}^{-1}.$$ 

6. Measurement of the $B_s^0 \rightarrow J/\psi K^{*0}$ branching and polarization fractions

Contributions from higher order diagrams to $B_s^0 \rightarrow J/\psi h^+ h^-$ decays are neglected in the decay models used for the presented $\phi_s^{\text{CS}}$ measurements. This is assumed to be a good approximation with the current experimental precision, but for future measurements the effect of penguin contributions (figure 2b) will need to be considered.

Combination of the tree-level and penguin amplitudes causes CP violation in the $B_s^0 \rightarrow J/\psi h^+ h^-$ decay, which gives a small contribution to the phase $\phi_s^{\text{CS}}$. To determine the contribution of CP violation induced by $B_s^0 \rightarrow B_s^0$ mixing, both measurements of $\phi_s^{\text{CS}}$ and estimates of the size of penguin amplitudes relative to the tree-level amplitude are required. For the $B_s^0 \rightarrow J/\psi \phi$ component of $B_s^0 \rightarrow J/\psi K^+ K^-$, the size of penguin contributions can be estimated with the decay $B_s^0 \rightarrow J/\psi (\rightarrow \mu^+ \mu^-) K^{*0} (\rightarrow K^- \pi^+)$, where $K^{*0}$ is the $K^*(892)^0$ meson [7].

$B_s^0 \rightarrow J/\psi \phi$ and $B_s^0 \rightarrow J/\psi K^{*0}$ are both decays into a $J/\psi$ and a second vector meson and they are related by SU(3) flavour symmetry. However, penguin contributions in $B_s^0 \rightarrow J/\psi K^{*0}$ are not Cabibbo suppressed relative to the tree-level contribution, which enables a measurement of their size for each of the three intermediate angular momentum states of the decays. SU(3)-breaking effects need to be taken into account when the resulting estimates are used to interpret a measurement in $B_s^0 \rightarrow J/\psi \phi$.

The experimental precision with only the LHCb data collected in 2011 is not sufficient to obtain a meaningful estimate of penguin contributions. As a first step, the $B_s^0$ branching fraction into $J/\psi K^{*0}$ and the fractions of the three angular momentum states of the decay ($f_L$, $f_0$ and $f_\perp$) are measured. The first part of the 2011 data set is used, which corresponds to 0.37 fb$^{-1}$ of integrated luminosity. The results are $B(B_s^0 \rightarrow J/\psi K^{*0}) = (4.4^{+0.5}_{-0.4} \pm 0.8) \times 10^{-5}$,

$$f_L = 0.50 \pm 0.08 \pm 0.02$$

and $f_\parallel = 0.19^{+0.10}_{-0.08} \pm 0.02$ [25]. The third polarization fraction is given by $f_\perp = 1 - f_L - f_\parallel$. 
7. Summary and outlook

The LHCb collaboration have measured $\mathbf{B}_s^0 - \overline{\mathbf{B}}_s^0$ mixing and decay parameters in the decay channels $\mathbf{B}_s^0 \to J/\psi K^+ K^-$ and $\mathbf{B}_s^0 \to J/\psi \pi^+ \pi^-$ with the 2011 data set of 1 fb$^{-1}$ of integrated luminosity. A preliminary combination of the two measurements yields $\phi_{s\overline{s}s} = (-0.002 \pm 0.083 \pm 0.027)$ rad for the CP-violating phase in the interference between mixed and unmixed decays. The preliminary estimate $\Delta \Gamma_s^0 = (0.116 \pm 0.018 \pm 0.006)$ ps$^{-1}$ is the first direct observation of a non-zero decay width in the $\mathbf{B}_s^0 - \overline{\mathbf{B}}_s^0$ system. A first step towards controlling penguin contributions is made by measuring the branching and polarization fractions of the decay $\mathbf{B}_s^0 \to J/\psi K^{*0}$.

There is room for improvement of the preliminary 1 fb$^{-1}$ results for the $\mathbf{B}_s^0 \to J/\psi K^+ K^-$ decay and updates of both this measurement and the combination with $\mathbf{B}_s^0 \to J/\psi \pi^+ \pi^-$ are planned. The next step will be a combination of the 1 fb$^{-1}$ 2011 data set with the 2 fb$^{-1}$ of integrated luminosity collected in 2012 to further improve the precision of the CP violation measurement.

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