Measurement of the CP violation phase \( \phi_s \) in the \( B_s \) system at LHCb

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1 Introduction

The interference between \( B_s^0 \) decay amplitudes to CP eigenstates \( J/\psi X \) directly or including \( B_s^0 - \bar{B}_s^0 \) oscillation gives rise to a measurable CP violating phase \( \phi_s \). In the Standard Model (SM), these decays are dominated by the tree level \( b \to c (\bar{s}s) \) transition, and hence \( \phi_s \) is predicted to be \( \phi_s^{SM} \approx -2\beta_s \), where \( \beta_s = \text{arg} (\frac{-V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}) \) \cite{1}. The indirect determination, via global fits to experimental data, predicts \( 2\beta_s = 0.036 \pm 0.002 \text{ rad} \) \cite{2}. However, non-SM contributions to \( B_s^0 - \bar{B}_s^0 \) mixing may alter this prediction \cite{3}.

Here, a preliminary measurement of \( \phi_s \) with \( B_s^0 \to J/\psi K^+K^- \) decays \cite{4}, and the measurement using \( B_s^0 \to J/\psi \pi^+\pi^- \) decays \cite{5}, both obtained from a sample of 1 fb\(^{-1}\) of \( pp \) collisions, collected by the LHCb experiment at a centre-of-mass energy \( \sqrt{s} = 7\text{ TeV} \) during 2011, are presented. In addition, the determination of the branching fraction and polarization fractions of \( B_s^0 \to J/\psi K^*0 \) \cite{6}, which can be used to constrain the contribution of sub-leading penguin contributions to the decay \( B_s^0 \to J/\psi \phi \), is shown.

2 \( B_s^0 \to J/\psi K^+K^- \)

The phenomenological aspects of \( B_s^0 \to J/\psi K^+K^- \) decays, where the \( K^+K^- \) pair arises through the \( \phi \) resonance, are described in many articles, e.g. in Refs \cite{7}. The effects induced by the sub-leading penguins contribution are discussed, for example, in \cite{8}.

As the \( B_s^0 \to J/\psi \phi \) decay proceeds via two intermediate spin-1 particles (i.e. with the \( K^+K^- \) pair in a P-wave), the final state is a superposition of CP-even and CP-odd states depending upon the relative orbital angular momentum between the \( J/\psi \) and the \( \phi \). In addition, the same final state can be produced with \( K^+K^- \) pairs with zero relative orbital angular momentum (S-wave) \cite{9}, which produces a CP-odd contribution. In order to measure \( \phi_s \), it is necessary to disentangle these CP-even and CP-odd components. This is achieved by analysing the distribution of the reconstructed decay angles.
Figure 1: Left: Invariant mass distribution of selected $B_s^0 \rightarrow J/\psi K^+ K^-$ candidates. The background is shown as the horizontal (red) line. Right: Invariant mass distribution of selected $B_s^0 \rightarrow J/\psi \pi^+ \pi^-$ candidates. The signal is shown as the red solid line. Backgrounds are combintorial (brown dotted), $B_s^0 \rightarrow J/\psi \phi$ (black long-dot) and $B^+ \rightarrow J/\psi K^+, J/\psi \pi^+$ (dashed green). Additional backgrounds are shown, but are irrelevant as the analysis only uses the data above a mass of 5346 MeV/c^2.

The event selection is the same as the one described in [10]. However, due to the increased instantaneous luminosity, the trigger conditions were changed in the second half of the 2011 data taking period, and decay time biasing cuts were added. A non-parametric description of this acceptance is determined using events triggered by a prescaled trigger line without these extra cuts, and accounted for in the fit. An additional correction, based on simulation, is made to correct for the small reduction of tracking efficiency for tracks originating from vertices far from the beamline. The decay angle acceptance is obtained from simulation, and the difference between the observed and simulated kaon momentum spectra is used to derive the corresponding systematic uncertainty.

To account for the decay time resolution of the detector, the Probability Density Functions (PDFs) used in the fit are convolved with a Gaussian whose width is proportional to the per-event computed decay time resolution. The scale factor is determined from the $J/\psi \rightarrow \mu^+ \mu^-$ component of the prompt background and is found to be $1.45 \pm 0.06$, where the error includes both statistical and systematic uncertainties, the latter derived from simulation. The scale factor is allowed to vary within its uncertainty in the fit. The effective average decay time resolution is $45 \pm 2\,\text{fs}$.

The initial flavour of the signal decay is inferred from the other $b$-hadron in the event by the opposite-side flavour tagger, described in [11]. This algorithm combines muons, electrons and kaons with large transverse momentum, and the charge of inclusively reconstructed secondary vertices and provides an estimated per-event mistag probability, which is calibrated with $B^+ \rightarrow J/\psi K^+$ decays. The effective average mistag probability $w = (36.8 \pm 0.2 \pm 0.7)\%$ yields, when combined with the efficiency $\varepsilon_{\text{tag}} = (33.0 \pm 0.3)\%$,
an effective tagging power of $Q = \varepsilon_{\text{tag}}(1 - 2w)^2 = (2.29 \pm 0.07 \pm 0.26)\%$. The effects of a possible difference in mistag probability between $B_s^0$ and $\bar{B}_s^0$, and of a potential tagging efficiency asymmetry were estimated to be negligible. The uncertainties from the flavour tag calibration are included by allowing the calibration parameters to vary in the likelihood fit within their uncertainties.

$3 \ B_s^0 \rightarrow J/\psi \pi^+ \pi^-$

The analysis of the $B_s^0 \rightarrow J/\psi \pi^+ \pi^-$ channel is published as [5]. It is also based upon the 1 fb$^{-1}$ of data taken during 2011, and utilizes a $\pi^+\pi^-$ invariant mass range of $[775 - 1550]$ MeV/$c^2$. Although this range is dominated by $f_0(980)$, it also encompasses $f_2(1270)$, $f_0(1370)$ and a non-resonant component. It has been shown [12] that this range is almost entirely $CP$-odd, with a $CP$-odd fraction > 97.7% at 95% C.L. As a result, no angular analysis is required. The analysis relies upon the same tagging information as the $B_s^0 \rightarrow J/\psi K^+K^-$ analysis. The invariant mass distribution of the selected events is shown on the right of Fig. 1.

$4 \ \text{Results}$

The $CP$ violating phase $\phi_s$ is extracted from the $B_s^0 \rightarrow J/\psi K^+K^-$ sample with an unbinned maximum likelihood fit to the candidate invariant mass, decay time, initial $B_s^0$ flavour and the decay angles. The signal and background PDFs of the likelihood are given in [10]. We determine several physics parameters, namely the decay width, $\Gamma_s$, the decay width difference between the light and heavy $B_s^0$ mass eigenstate $\Delta\Gamma$, and the polarization amplitudes of the $K^+K^-$ system. In the fit we parameterise the P-wave transversity amplitudes, $A_i$, by their absolute value at production time, $|A_i(0)|$, and their phases $\delta_i$ and adopt the convention $\delta_0 = 0$. We utilize the following normalization: $|A_0(0)|^2 + |A_\parallel(0)|^2 + |A_\perp(0)|^2 = 1$, and define the fraction of S-wave contribution $F_S = |A_S(0)|^2/(1+|A_S(0)|^2)$. This choice of the normalization insures that the P-wave amplitudes have the same value independently of the range of the $K^+K^-$ invariant mass chosen. We use the measurement of the $B_s^0$ oscillation frequency $\Delta m_s = 17.63 \pm 0.11$ ps$^{-1}$ [13] and allow it to vary within its uncertainty. The values obtained, as well as their statistical and systematic uncertainties, are given in Table 1. All parameters, except $\delta_\parallel$, have a well behaved parabolic profile likelihood. The exception for the $\delta_\parallel$ is caused by the fact that its central value lies just above $\pi$ which implies that it is almost degenerate with the ambiguous solution at $\delta_\parallel \rightarrow 2\pi - \delta_\parallel$ which lies symmetrically just below $\pi$. The quoted 68% C.L. encompasses both minima.

The results for $\phi_s$ and $\Delta\Gamma_s$ are in good agreement with the Standard Model predictions [14]. Figure 2 shows the projection of the fitted PDF on the decay time and the transversity angle distributions for candidates with an invariant mass within 20 MeV/$c^2$ around the nominal $B_s^0$ mass. The systematic uncertainties quoted in Table 1 are those which are not directly treated in the maximum likelihood fit. The systematic uncertainty
Table 1: Results for the physics parameters and their statistical and systematic uncertainties. We quote a 68% C.L. interval for $\delta_\parallel$ as described in the text.

on $\phi_s$ is dominated by imperfect knowledge of the angular acceptances and neglecting potential contributions of direct CP-violation.

The CP violating phase $\phi_s$ is extracted from the $B_s^0 \to J/\psi \pi^+\pi^-$ sample with an unbinned maximum likelihood fit to mass, decay time and flavour tag. The result is $\phi_s = -0.02 \pm 0.17 \pm 0.004$ rad. The systematic uncertainties from tagging and resolution are included in a similar way as for the $B_s^0 \to J/\psi K^+K^-$ analysis. Full details can be found in Ref. [5]. The results from the $B_s^0 \to J/\psi K^+K^-$ and $B_s^0 \to J/\psi \pi^+\pi^-$ samples are compatible, and, when combined in a simultaneous fit, give $\phi_s = -0.002 \pm 0.083 \pm 0.027$ rad.

This analysis results in a twofold ambiguity $(\phi_s, \Delta \Gamma_s) \leftrightarrow (\pi - \phi_s, -\Delta \Gamma_s)$. The ambiguity has been resolved [15] using the measurement of the evolution of the relative phase between the $K^+K^-$ P-wave and S-wave amplitudes as a function of the $K^+K^-$ mass. The solution with $\Delta \Gamma_s > 0$ is favoured and only this solution is quoted here.

5 $B_s^0 \to J/\psi K^-\pi^+$

Although the decay $B_s^0 \to J/\psi K^+K^-$ is dominated by the tree level $b \to c(\overline{c}s)$ transition, there are contributions from higher order (penguin) $b \to s(\overline{c}\tau)$ processes. These cannot be calculated reliably and could affect the measured asymmetries. It has been suggested that these effects can be controlled by means of an analysis of the decay $B_s^0 \to J/\psi \overline{K}^{*0}$, where the penguin diagrams are not suppressed relative to the tree level, and $SU(3)$ flavour symmetry can be used to determine the relevant hadronic parameters [8].

LHCb has searched [6] for the decay $B_s^0 \to J/\psi \overline{K}^{*0}$ with $\overline{K}^{*0} \to K^-\pi^+$ with 0.37 fb$^{-1}$ of $pp$ collisions at $\sqrt{s} = 7$ TeV, and observes $114 \pm 11$ $B_s^0 \to J/\psi K^-\pi^+$ signal candidates. The $K^-\pi^+$ mass spectrum of the candidates in the $B_s^0$ peak is dominated by the $\overline{K}^{*0}(892)$ contribution. Subtracting the non-resonant $K^-\pi^+$ component, the branching fraction of $B_s^0 \to J/\psi \overline{K}^{*0}(892)$ is $(4.4^{+0.5}_{-0.4} \pm 0.8) \times 10^{-5}$. A fit to the angular distribution yields the
Figure 2: Data points overlaid with fit projections for the decay time and transversity angle distributions in a mass range of ±20 MeV/$c^2$ around the reconstructed $B^0_s$ mass. The total fit result is represented by the black line. The signal component is represented by the solid blue line; the dashed and dotted blue lines show the CP-odd and CP-even signal components respectively. The S-wave component is represented by the solid pink line. The background component is given by the red line.

polarization fractions $f_L = 0.50 \pm 0.08 \pm 0.02$ and $f_\parallel = 0.19^{+0.10}_{-0.08} \pm 0.02$.

6 Conclusion

We have performed a time-dependent angular analysis of approximately 21,200 $B^0_s \to J/\psi K^+ K^-$ decays obtained from 1 fb$^{-1}$ of $pp$ collisions at $\sqrt{s} = 7$ TeV collected during
2011. From these events we extract:

\[
\phi_s = -0.001 \pm 0.101 \text{(stat)} \pm 0.027 \text{(syst)} \text{ rad},
\]

\[
\Gamma_s = 0.658 \pm 0.005 \text{(stat)} \pm 0.007 \text{(syst)} \text{ ps}^{-1},
\]

\[
\Delta \Gamma_s = 0.116 \pm 0.018 \text{(stat)} \pm 0.006 \text{(syst)} \text{ ps}^{-1}.
\]

When combined with the result from an independent analysis of approximately 7421
\(B_s^0 \to J/\psi \pi^+ \pi^-\) decays, we find

\[
\phi_s = -0.002 \pm 0.083 \text{(stat)} \pm 0.027 \text{(syst)} \text{ rad}. \quad (1)
\]

This is the world’s most precise measurement of \(\phi_s\) and the first direct observation for
a non-zero value for \(\Delta \Gamma_s\). These results are in good agreement with Standard Model
predictions \[14\].

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