CP Violation in the B_s^0 system in LHCb

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Latest LHCb measurements of *CP* violation in the interference between mixing and decay are presented based on *pp* collision data collected in 2011 at centre-of-mass energy $\sqrt{s} = 7\,\mathrm{TeV}$, corresponding to an integrated luminosity of $1.0\,fb^{-1}$. A combination of about $27.6k$ $B_s^0 \to J/\psi\, K^+K^-$ and $7.4k$ $B_s^0 \to J/\psi\,\pi\pi$ signal events yield the most accurate measurement of the *CP*-violating phase, $\phi_s^{c\bar{c}s}$. This is found to be $\phi_s^{c\bar{c}s} = 0.01 \pm 0.07\,(\mathrm{stat.}) \pm 0.01\,(\mathrm{syst.})\,\mathrm{rad}$. The combination also yields the most accurate measurements of the average B_s^0 decay width and decay width difference. These are found to be $\Gamma_s = 0.661 \pm 0.004\,(\mathrm{stat.}) \pm 0.006\,(\mathrm{syst.})\,\mathrm{ps}^{-1}$ and $\Delta\Gamma_s = 0.106 \pm 0.011\,(\mathrm{stat.}) \pm 0.007\,(\mathrm{syst.})\,\mathrm{ps}^{-1}$, respectively. The first measurement of the *CP*-violating phase in the $B_s^0 \to \phi\phi$ decay, $\phi_s^{s\bar{s}s}$, is found to be in the interval $[-2.46, -0.76]$ rad at 68% confidence level.

1 Introduction

Efforts to measure mixing induced *CP* violation in the B_s^0 system have mainly focused on the $B_s^0 \to J/\psi\,\phi$ decay, utilising angular observables to disentangle the different *CP* eigenstates. This then allows for the *CP*-violating phase $\phi_s^{c\bar{c}s}$ to be measured. In the Standard Model, this is given by $\phi_s^{c\bar{c}s} \approx -2\beta_s = 2arg(-V_{ts}V_{tb}^*/V_{cs}V_{cb}^*)$ [1,2,3]. The Standard Model prediction for $\phi_s^{c\bar{c}s}$ has been obtained from global fits to experimental data yielding a value of -0.036 ± 0.002 rad [4,5,6]. There are however many BSM theories that provide additional contributions to B_s^0 mixing diagrams that alter this value [7,8]. The addition of the $B_s^0 \to J/\psi\,\pi^+\pi^-$ decay allows for a separate determination of $\phi_s^{c\bar{c}s}$. As this decay mode is almost entirely *CP*-odd, an angular analysis is not required. The *CP*-violating phase measured in the $B_s^0 \to \phi\phi$ decay results from $b \to s\bar{s}s$ transitions (unlike $B_s^0 \to J/\psi\, K^+K^-$ and $B_s^0 \to J/\psi\,\pi^+\pi^-$ decays, which result from $b \to c\bar{c}s$ transitions) and is therefore expected to be zero in the Standard Model due to the cancellation of the *CP*-violating weak phase between the B_s^0 mixing diagrams and the penguin decay diagrams [9]. Calculations using QCD factorisation provide an upper limit of 0.02 rad for $|\phi_s^{s\bar{s}s}|$ [10,11,12].

The following sections summarise updated measurements of the *CP*-violating weak phase, $\phi_s^{c\bar{c}s}$, in $B_s^0 \to J/\psi\, K^+K^-$ and $B_s^0 \to J/\psi\,\pi^+\pi^-$ decays [13], and the first measurement of the *CP* violating phase, $\phi_s^{s\bar{s}s}$, in the $B_s^0 \to (\phi \to KK)\;(\phi \to KK)$ decay [14]. All analyses discussed are based on the full 2011 dataset of 1.0 fb^{-1} collected with the LHCb detector at centre-of-mass (COM) energy $\sqrt{s} = 7$ TeV.

2 The $\mathbf{B^0_s} \to \mathrm{J}/\psi\,\mathbf{K^+K^-}$ Analysis

The $B^0_s \to \mathrm{J}/\psi\,K^+K^-$ decay is selected using a cut based method described in Aaij *et al.* (2013)[13]. This results in $\sim 27,500$ signal events with low background. The decay time resolution of the $B^0_s \to \mathrm{J}/\psi\,K^+K^-$ decay is accounted for in fitting through convolution of the probably density function (PDF) with a Gaussian function of width $S_{\sigma_t} \cdot \sigma^i_t$, where σ^i_t is the decay time resolution of the i^{th} event (determined from vertex and decay length uncertainty); S_{σ_t} is determined from prompt $\mathrm{J}/\psi \to \mu^+\mu^-$ events to be 1.45 ± 0.06, where the error includes both systematic (derived from simulation) and statistical contributions.

Decay time acceptance effects due to the time-biasing variables used in the triggering of $\mathrm{J}/\psi \to \mu^+\mu^-$ events are determined with the assistance of a pre-scaled, unbiased trigger. A small drop in acceptance is also seen at longer decay times due to the lower track finding efficiencies associated with tracks from vertices far from the beam line. The slope of this acceptance at large decay times is measured to be $\beta = (8.3 \pm 4.0) \times 10^3\,\mathrm{ps}^{-1}$ leading to a $4.0 \times 10^3\,\mathrm{ps}^{-1}$ uncertainty on Γ_s.

The efficiency of reconstructing a $B^0_s \to \mathrm{J}/\psi\,K^+K^-$ event also depends on the decay angles in the helicity basis. The correction applied in the fit is found using Monte Carlo $B^0_s \to \mathrm{J}/\psi\,K^+K^-$ events. The difference in the spectra of kinematic observables of the tracks in simulated events compared to that observed in the data in addition to the limited quantity of simulated events contribute to the systematic uncertainties.

The sensitivity of the fit to the weak phase $\phi_\mathrm{s}^{c\bar{c}s}$ is greatly enhanced through the ability to determine the flavour of the B^0_s meson when it is produced. The methods of determination of the flavour and associated uncertainties are described in detail in the paper of Aaij *et al.* (2013)[13].

An un-binned maximum log-likelihood fitting method is used in the measurement of the weak phase $\phi_\mathrm{s}^{c\bar{c}s}$. A number of physics parameters are measured together with the *CP*-violating phase. These are the decay width (Γ_s), the decay width difference between the two B^0_s mass eigenstates ($\Delta\Gamma_\mathrm{s}$), the amount of direct *CP* violation, $|\lambda|$, and the polarisation amplitudes of the P-wave ($|A_0|^2$, $|A_\parallel|^2$, $|A_\perp|^2$) and S-wave ($|A_S|^2$) contributions along with corresponding phases[a] (δ_0, $\delta_\parallel$, $\delta_\perp$, δ_S) defined at $t = 0$. Normalisation is chosen such that $|A_0|^2 + |A_\parallel|^2 + |A_\perp|^2 = 1$. In fits the B^0_s oscillation frequency Δm_s is constrained within errors of the LHCb measured value[15]. The data sample is split in to six bins according to the m_{KK} mass in the range $[990, 1050]\,\mathrm{MeV}/c^2$. The sizes of the individual bins are chosen to ensure that coupling factors between the P-wave and S-wave line shapes are ~ 1. Performing the fit in this way improves the statistical precision by separating mass ranges with different S-wave fractions and also allows the analysis to be less sensitive to correction factors on the interference terms[13]. The results of the fit in the $B^0_s \to \mathrm{J}/\psi\,K^+K^-$ decay are given in Table 1. In addition to the uncertainties discussed earlier the only other dominant contribution is that of contamination from mis-reconstructed $B^0 \to \mathrm{J}/\psi\,\mathrm{K}^{*0}$ decays, in which a pion from the K^{*0} meson is reconstructed as a kaon. The number of such events present in the sample is estimated from simulation. The simulated $B^0 \to \mathrm{J}/\psi\,\mathrm{K}^{*0}$ events are then embedded in the sample to provide a quantitative estimate of the associated systematic uncertainty.

Both the analysis of the $B^0_s \to \mathrm{J}/\psi\,K^+K^-$ decay and the $B^0_s \to \mathrm{J}/\psi\,\pi^+\pi^-$ decay contain an ambiguity in the results associated with the transformations ($\phi_s \leftrightarrow \pi - \phi_s$; $\Delta\Gamma_\mathrm{s} \leftrightarrow -\Delta\Gamma_\mathrm{s}$) and associated strong phase changes[16]. This ambiguity is resolved through measuring the difference in P-wave and S-wave strong phases in different KK invariant mass bins. A negative trend of strong phase difference is observed with increasing KK invariant mass. This therefore implies that $\Delta\Gamma_\mathrm{s} > 0$, hence only this result has been quoted throughout these Proceedings.

[a] The convention has been chosen such that $\delta_0 \equiv 0$.

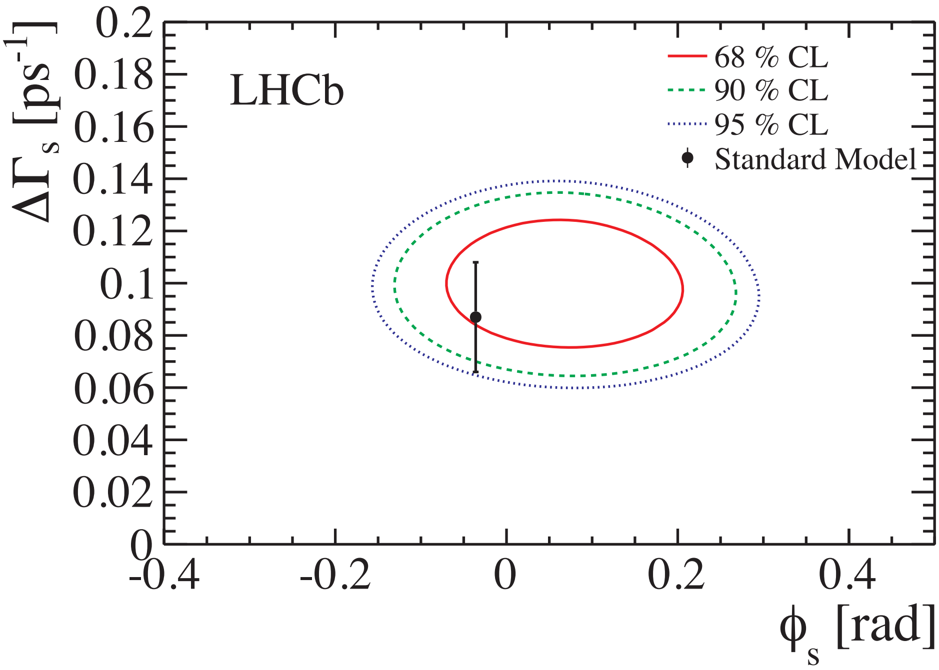

Figure 1: Confidence regions for the fitted parameters $\Delta\Gamma_s$ and $\phi_s^{c\bar{c}s}$. The Standard Model prediction is shown in black. Confidence levels contain statistical errors only.

Parameter	Value	Stat.	Syst.
Γ_s [ps^{-1}]	0.663	0.005	0.006
$\Delta\Gamma_s$ [ps^{-1}]	0.100	0.016	0.003
$\lvert A_\perp(0)\rvert^2$	0.249	0.009	0.006
$\lvert A_0(0)\rvert^2$	0.521	0.006	0.010
$\delta_\perp$ [rad]	3.07	0.22	0.07
$\delta_\parallel$ [rad]	3.30	$^{+0.13}_{-0.21}$	0.08
ϕ_s [rad]	0.07	0.09	0.01
$\lvert\lambda\rvert$	0.94	0.03	0.02

Table 1: Results for the physics parameters and their statistical and systematic uncertainties for the fit to $B_s^0 \to J/\psi K^+K^-$ events.

3 The $B_s^0 \to J/\psi\pi\pi$ Analysis and Combination with $B_s^0 \to J/\psi K^+K^-$

The anaysis of the $B_s^0 \to J/\psi\pi^+\pi^-$ decay [13] is performed using the same selected candidates used in the previous study [17]. An angular analysis is not required in this decay channel due to the fact that the $775 < m(\pi^+\pi^-) < 1500$ MeV/c^2 invariant mass range is 97.5% *CP*-odd at 95% CL [18]. This then removes the need to disentangle *CP* eigenstates and a fit to the B_s^0 decay time is sufficient to measure $\phi_s^{c\bar{c}s}$. The tagging method and time resolution methods are the same as those used for the $B_s^0 \to J/\psi K^+K^-$ decay. While the dataset is the same as in Reference 17, the analysis features improved constraints from the $B_s^0 \to J/\psi K^+K^-$ fit and an improved upper decay time acceptance model. For this, the $B^0 \to J/\psi K^{*0}$ decay (with a well known lifetime) is used to calibrate the decay time acceptance, with simulation used to account for the small differences between the $B^0 \to J/\psi K^{*0}$ and $B_s^0 \to J/\psi\pi^+\pi^-$ decay channels.

The result of the measurement of the weak phase ϕ_s in the $B_s^0 \to J/\psi\pi^+\pi^-$ decay is found to be $\phi_s = -0.14^{+0.17}_{-0.16} \pm 0.01$ rad [13]. The systematic uncertainties arising from time resolution, time acceptance and tagging are treated in the same way as in the analysis of the $B_s^0 \to J/\psi K^+K^-$ decay. A combined fit of both decay channels is performed with the common parameters being

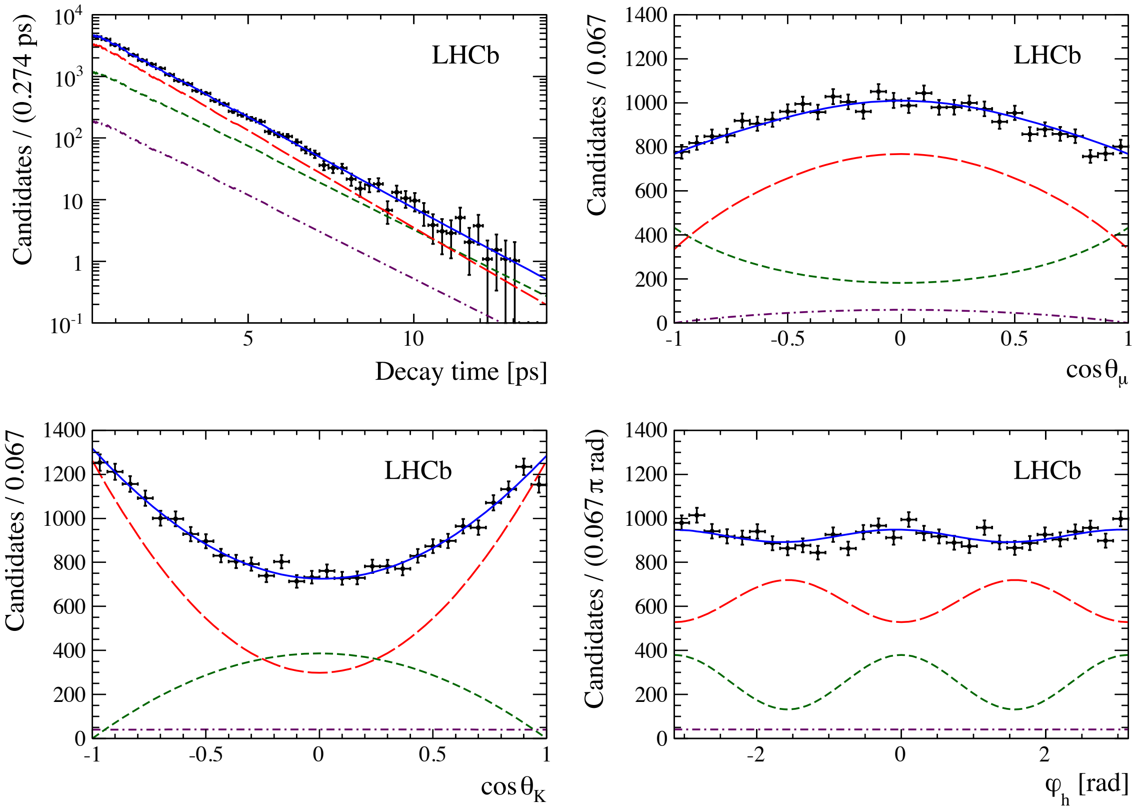

Figure 2: Decay time and helicity angle distributions for $B^0_s \to J/\psi K^+K^-$ decays (data points) with the one-dimensional projections of the PDF at the maximal likelihood point. The solid blue line shows the total signal contribution, which is composed of *CP*-even (long-dashed red), *CP*-odd (short-dashed green) and *S*-wave (dotted-dashed purple) contributions.

Γ_s, $\Delta\Gamma_s$, $\phi_s^{c\bar{c}s}$, Δm_s, and $|\lambda|$. Extra systematic uncertainties of $0.001\,\mathrm{ps}^{-1}$ and $0.006\,\mathrm{ps}^{-1}$ are included on Γ_s and $\Delta\Gamma_s$, respectively due to variations in the background model and decay time acceptance in the analysis of $B^0_s \to J/\psi\,\pi^+\pi^-$. This leads to the combined results shown in Table 2.

4 The $\mathbf{B^0_s \to \phi\phi}$ Analysis

The $B^0_s \to \phi\phi$ decay is an example of a flavour changing neutral current (FCNC) interaction and as such, may only proceed via penguin diagrams in the Standard Model. A total of 880 signal candidates are observed through a multivariate selection optimised with the use of the ${}_s\mathcal{P}lot$ method [19] to distinguish signal from background.

As in the case of the $B^0_s \to J/\psi\,K^+K^-$ analysis, a maximum log-likelihood fit is then performed to the three helicity angles and decay time (see Reference 14 for more information). The lifetimes of the heavy and light B^0_s mass eigenstates are constrained to be within the errors of the LHCb measured values [13] taking in to account correlations. *S*-wave contributions, which originate from a single pair of kaons either in a non-resonant state or from a spin-0 resonance are fitted for according to the decay time and angular dependencies. The contribution of *S*-wave from two pairs of such kaons is treated as a systematic uncertainty. The angular acceptance is determined from simulated events. The limited number of simulated events and kinematic differences between the simulation and data are used to determine the systematic uncertainties due to the angular acceptance. The time acceptance is understood from Monte Carlo events and the difference between the application as a histogram or as a fitted function forms the basis of the systematic uncertainty.

Parameter	Value	Stat.	Syst.
Γ_s [ps^{-1}]	0.661	0.004	0.006
$\Delta\Gamma_s$ [ps^{-1}]	0.106	0.011	0.007
$\|A_\perp(0)\|^2$	0.246	0.007	0.006
$\|A_0(0)\|^2$	0.523	0.005	0.010
$\delta_\perp$ [rad]	3.04	0.20	0.07
$\delta_\parallel$ [rad]	3.32	$^{+0.13}_{-0.21}$	0.08
ϕ_s [rad]	0.01	0.07	0.01
$\|\lambda\|$	0.93	0.03	0.02

Table 2: Results for the physics parameters and their statistical and systematic uncertainties for the fit to $B_s^0 \to J/\psi K^+K^-$ and $B_s^0 \to J/\psi \pi^+\pi^-$ events.

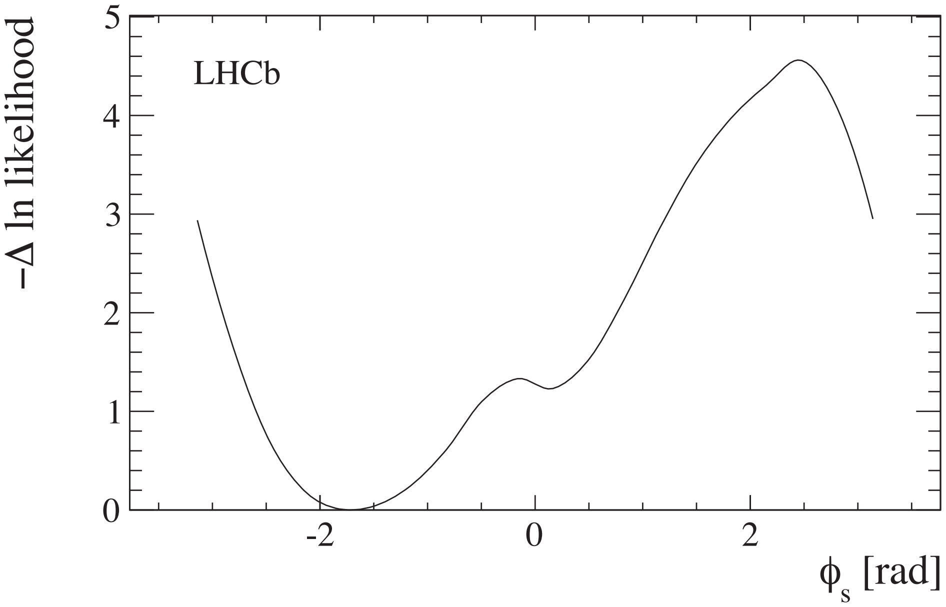

Figure 3: Negative Δln likelihood scan of $\phi_s^{s\bar{s}s}$. Only the statistical uncertainty is included.

The results of the fit to the helicity angles and B_s^0 decay time are shown in Table 3. The statistical likelihood scan is shown in Figure 3. Due to the negative Δln likelihood being highly non-parabolic, a 68% confidence level is quoted. The small data sample used to make the measurement means that it is necessary to perform a Feldman Cousins analysis in order to give a 68% confidence level that both includes systematic uncertainties and provides a coverage correction. The Feldman Cousins method yields a 68% confidence level of $[-2.46, -0.76]$ rad.

In addition to the systematic uncertainties mentioned earlier, minor sources of systematic uncertainty arise from the signal model and uncertainty on the time resolution (found from simulation).

5 Summary

The most accurate measurements of *CP* violation in B_s^0 mixing have been presented using the full 2011 dataset collected with the LHCb dectector at $\sqrt{s} = 7$ TeV. The combination of $\sim 27,500$ $B_s^0 \to J/\psi K^+K^-$ decays and $\sim 7,420$ $B_s^0 \to J/\psi \pi^+\pi^-$ decays yields a measurement of $\phi_s^{c\bar{c}s} = 0.01 \pm 0.07\,(\text{stat.}) \pm 0.01\,(\text{syst.})$ rad. The combination also provides the most accurate measurements of the B_s^0 decay width and decay width differences, measured to be $\Gamma_s = 0.661 \pm 0.004\,(\text{stat.}) \pm 0.006\,(\text{syst.})$ ps^{-1} and $\Delta\Gamma_s = 0.106 \pm 0.011\,(\text{stat.}) \pm 0.007\,(\text{syst.})$ ps^{-1}, respectively.

Parameter	Value	$\sigma_{\text{stat.}}$	$\sigma_{\text{syst.}}$
ϕ_s[rad] (68 % CL)		$[-2.37, -0.92]$	0.22
$\lvert A_0\rvert^2$	0.329	0.033	0.017
$\lvert A_\perp\rvert^2$	0.358	0.046	0.018
$\lvert A_{\mathrm{S}}\rvert^2$	0.016	$^{+0.024}_{-0.012}$	0.009
δ_1 [rad]	2.19	0.44	0.12
δ_2 [rad]	-1.47	0.48	0.10
δ_{S} [rad]	0.65	$^{+0.89}_{-1.65}$	0.33

Table 3: Fit results with statistical and systematic uncertainties. A 68% statistical confidence interval is quoted for ϕ_s. Amplitudes are defined at $t = 0$.

The ambiguity in the $\phi_{\mathrm{s}}^{c\bar{c}s} - \Delta\Gamma_{\mathrm{s}}$ plane is resolved, i.e. that the heavy B_{s}^0 mass eigenstate lives longer. We provide the first measurement of the *CP*-violating phase in the $B_{\mathrm{s}}^0 \to \phi\phi$ penguin decay, which is found to be in the interval $[-2.46, -0.76]$ rad at 68% confidence level.

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