Mixing and CP Violation in the B System

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The following sections summarize analyses of the measurement of the CP-violating weak phase ϕ_s in the $B^0_s \to J/\psi\phi$ [1] and $B^0_s \to J/\psi\pi^+\pi^-$ decays [2] (including the resolution of the ambiguity of ϕ_s associated with the sign of the decay width difference in the B^0_s system [3]). Also presented is the time-integrated analysis of the $B^0_s \to (\phi \to KK)\ (\phi \to KK)$ decay including the T-violating triple product asymmetries [4]. 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.

1 Direct ϕ_s Measurements

1.1 The $B^0_s \to J/\psi\phi$ Analysis Method

The $B^0_s \to J/\psi\phi$ decay is selected using a cut based method described in Aaij *et al.* (2011) [5]. This results in ~ 21200 signal events with low background. The decay time resolution of the $B^0_s \to J/\psi\phi$ 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 event-by-event decay time resolution of the i^{th} event (determined from vertex and decay length uncertainty); S_{σ_t} is determined from prompt $J/\psi \to \mu^+\mu^-$ events to be 1.45 ± 0.06, where errors are both systematic (derived from simulation) and statistical.

Decay time acceptance effects due to time-biasing cuts used to select $J/\psi \to \mu^+\mu^-$ events are determined with the assistance of a prescaled, unbiased trigger. A small drop in acceptance is also seen at longer lifetimes due to the lower track finding efficiencies associated with tracks from vertices far from the beam line. A correction on Γ_s is found from simulation to be 0.0112 ± 0.0013 ps^{-1}. Half of this value is applied as a systematic uncertainty.

The efficiency of reconstructing a $B^0_s \to J/\psi\phi$ event also depends on the decay angles in the transversity basis (described in detail in Reference [5]). The correction applied in the fit is found using Monte Carlo $B^0_s \to J/\psi\phi$ 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 are used to determine associated systematic uncertainties.

The sensitivity of the fit to the weak phase ϕ_s is greatly enhanced through the ability to determine the flavour of the B_s^0 meson when it is produced. The methods of determination of the flavour and associated uncertainties are described in detail in Reference [5].

1.2 The $B_s^0 \to J/\psi\,\pi\pi$ Analysis Method

The anaysis of the $B_s^0 \to J/\psi\pi^+\pi^-$ decay [2] updates a previous study on the $B_s^0 \to J/\psi\, f_0(980)$ decay [6] using the fact that the $775 < m(\pi^+\pi^-) < 1500$ MeV/c^2 invariant mass range is 97.5% CP-odd at 95% C.L. [7]. This then allows for ϕ_s to be measured without the need to disentangle CP eigenstates. As such, a fit to the decay time is sufficient to measure ϕ_s. The tagging method and time resolution methods are the same as those used for the $B_s^0 \to J/\psi\phi$ decay.

1.3 Results

Both the $B_s^0 \to J/\psi\phi$ and $B_s^0 \to J/\psi\pi^+\pi^-$ analyses utilize unbinned maximum log-likelihood fitting methods in the measurement of the weak phase ϕ_s. A number of physics parameters are measured at the same time as ϕ_s in the analysis of the $B_s^0 \to J/\psi\phi$ decay. These are the decay width (Γ_s), the decay width difference between the two B_s^0 mass eigenstates ($\Delta\Gamma_s$) and the polarization 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[1] (δ_0, $\delta_\parallel$, $\delta_\perp$, δ_S) defined at $t = 0$. Normalization is chosen such that $|A_0|^2 + |A_\parallel|^2 + |A_\perp|^2 = 1$. In fits the B_s^0 oscillation frequency Δm_s is constrained within errors of the LHCb measured value [8].

The results of the fit in the $B_s^0 \to J/\psi\phi$ decay are given in Table 1. The 68% C.L. is quoted for $\delta_\parallel$ as the likelihood is not parabolic about the minimum for this parameter. This is due to the central value lying close to the ambiguous solution found through the transformation $\delta_\parallel \to -\delta_\parallel + 2\pi$.

In addition to the uncertainties discussed in Section 1.1, the only other dominant contribution is that of direct CP violation (DCPV), which is understood from simplified simulations. The uncertainties for tagging calibration, time resolution and B_s^0 oscillation frequency are included in the fit using Gaussian constraints within their uncertainties. Studies have shown that these inflate the statistical uncertainty on ϕ_s by no more than 5%.

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 $\phi_s = -0.02 \pm 0.17 \pm 0.02$ rad [2]. The systematic uncertainties arising from time resolution, time acceptance and tagging are treated in the same way as in the analysis of the $B_s^0 \to J/\psi\phi$ decay.

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

Parameter	Value	Stat.	Syst.
Γ_s [ps^{-1}]	0.6580	0.0054	0.0066
$\Delta\Gamma_s$ [ps^{-1}]	0.116	0.018	0.006
$\vert A_\perp(0)\vert^2$	0.246	0.010	0.013
$\vert A_0(0)\vert^2$	0.523	0.007	0.024
$F_{\rm S}$	0.022	0.012	0.007
$\delta_\perp$ [rad]	2.90	0.36	0.07
$\delta_\parallel$ [rad]	[2.81, 3.47]		0.13
δ_s [rad]	2.90	0.36	0.08
ϕ_s [rad]	-0.001	0.101	0.027

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.

Both the analysis of the $B_s^0 \to J/\psi\phi$ decay and the $B_s^0 \to J/\psi\pi^+\pi^-$ decay contain an ambiguity in the results associated with the transformations ($\phi_s \leftrightarrow \pi - \phi_s$; $\Delta\Gamma_s \leftrightarrow -\Delta\Gamma_s$) and associated strong phase changes [3]. This ambiguity has been resolved through measuring the difference in P-wave and S-wave strong phases in different KK invariant mass bins. Through the separation in to four bins chosen to have roughly equal numbers of events, a negative trend of strong phase difference is observed with increasing KK invariant mass with significance of 4.7σ. This therefore implies that $\Delta\Gamma_s > 0$, hence only this result has been quoted throughout these Proceedings.

2 Time-integrated Analysis of the $B_s^0 \to \phi\phi$ Decay

The $B_s^0 \to \phi\phi$ 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 801 ± 29 signal candidates are observed through a cut based selection optimized with the use of the ${}_s\mathcal{P}lot$ method [9] to distinguish signal from background.

The measurement of the polarization amplitudes ($|A_0|^2$, $|A_\parallel|^2$, $|A_\perp|^2$) and strong phase difference ($\cos\delta_\parallel$) is performed using a time-integrated, untagged PDF under the assumption that the time acceptance is uniform and that the CP-violating weak phase is zero. A maximum log-likelihood fit is then performed to the three helicity angles (see Reference [4] for more information). The lifetimes of the heavy and light B_s^0 mass eigenstates are constrained to be within the errors of the LHCb measured values [2] taking in to account correlations. S-wave contributions are ignored in the fit. Data-driven methods indicate the S-wave contribution to be $(1 \pm 1)\%$, therefore systematic uncertainties are based on a 2% S-wave contribution. The angular acceptance is determined from simulated events. The limited number of simulated events determines the systematic uncertainty due to the angular acceptance. The time acceptance is understood from Monte Carlo events and simplified simulations are used to assign a systematic uncertainty from the assumption that it is uniform. The other major source of systematic uncertainty arises from the background model, where a background histogram from mass sidebands (defined to be between 60-150 MeV/c^2 away from the measured B_s^0 mass) is used instead of the nominal flat angular background. The polarization amplitudes and strong phase difference are measured to be

$$\begin{aligned} |A_0|^2 &= 0.365 \pm 0.022\,(\text{stat}) \pm 0.012\,(\text{syst})\,, \\ |A_\perp|^2 &= 0.291 \pm 0.024\,(\text{stat}) \pm 0.010\,(\text{syst})\,, \\ |A_\parallel|^2 &= 0.344 \pm 0.024\,(\text{stat}) \pm 0.014\,(\text{syst})\,, \\ \cos(\delta_\parallel) &= -0.844 \pm 0.068\,(\text{stat}) \pm 0.029\,(\text{syst})\,. \end{aligned}$$

Triple product asymmetries are based on T-odd observables U and V (defined in Reference [4]). Events are separated in to datasets according to whether $U(V) > 0$ and a simultaneous fit is then performed to the obtain the asymmetries (A_U,A_V) using the $KKKK$ invariant mass as the discriminating observable.

The main systematic uncertainties arise from the choice of signal and background model; the effect of ignoring the time acceptance and the angular acceptance of the $B_s^0 \to \phi\phi$ decay. The systematic uncertainties on the triple product asymmetries due to acceptance effects are estimated using simplified simulation studies (where both the time and angular acceptances are understood from simulated events).

Simultaneous fits to the U(V) datasets yield triple product asymmetries of

$$\begin{aligned} A_U &= -0.055 \pm 0.036\,(\text{stat}) \pm 0.018\,(\text{syst})\,, \\ A_V &= 0.010 \pm 0.036\,(\text{stat}) \pm 0.018\,(\text{syst})\,. \end{aligned}$$

3 Summary

Direct measurements of the CP-violating weak phase have been measured using the full 2011 dataset collected with the LHCb dectector at $\sqrt{s} = 7$ TeV. The combination of $\sim$ 21200 $B_s^0 \to J/\psi\phi$ decays and $\sim$ 7420 $B_s^0 \to J/\psi\pi^+\pi^-$ decays yields a measurement of $\phi_s = -0.002 \pm 0.083(stat) \pm 0.027(syst)$ rad. This therefore provides the world's most precise measurement of ϕ_s. Also, it is worth mentioning that we observe the first measurement of $\Delta\Gamma_s$ different from zero and have resolved the ambiguity in the $\phi_s - \Delta\Gamma_s$ plane, i.e. that the heavy B_s^0 mass eigenstate lives longer.

We provide the most accurate measurements of the physics parameters in the $B_s^0 \to \phi\phi$ penguin decay. The most precise measurements of CP violation in the $B_s^0 \to \phi\phi$ decay through triple product asymmetries is also reported.

References

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