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Charmless $B \to VV$ decays at LHCb

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B_s^0 meson decays into non–charmonium vector pairs are of particular interest to search for indirect CP violation. The analyses of two specific decays are presented here, $B_s^0 \to \phi\phi$ and $B_s^0 \to K^{*0}\bar{K}^{*0}$. These studies have been performed using, respectively, $1\,fb^{-1}$ and $35\,pb^{-1}$ of data collected by LHCb in pp collisions at a centre–of–mass energy of 7 TeV. In $B_s^0 \to \phi\phi$ decay, the CP–violating phase arising in the interference between B_s^0 –$\bar{B}_s^0$ mixing and the $b \to s\bar{s}s$ penguin decay has been determined to be in the interval $[-2.46, -0.76]$ rad at 68% confidence level. The first observation of $B_s^0 \to K^{*0}\bar{K}^{*0}$ decay is also reported. The branching fraction and the CP–averaged K^{*0} longitudinal polarization fraction are measured to be $\mathscr{B}(B_s^0 \to K^{*0}\bar{K}^{*0}$) = (2.81 $\pm$ 0.46(stat.) $\pm$ 0.45(syst.) $\pm$ 0.34(f_s/f_d))$\times 10^{-5}$ and f_L = 0.31 $\pm$ 0.12(stat.) $\pm$ 0.04(syst.).

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1. Introduction

Both $B_s^0 \to \phi\phi$ and $B_s^0 \to K^{*0}\bar{K}^{*0}$ decays are forbidden at tree level in the Standard Model (SM) and proceed via $b \to s\bar{s}s$ and $b \to s\bar{d}d$ penguin transitions, respectively. These decays constitute therefore an excellent probe of new heavy particles entering the penguin diagrams that could lead to observable deviations from the SM [1, 2]. In particular, it is possible to look for *CP* violation beyond the SM by studing the interference between the mixing and decay of B_s^0 mesons to *CP*–eigenstates, which is characterised by a *CP*–violating phase, ϕ_s. In the SM, the value of ϕ_s for these two processes is expected to be close to zero [3, 4].

In the decay of a pseudo–scalar (P) B_s^0 meson to a pair of vector mesons (V), with $V \to P_1P_2$, three different amplitudes arise - A_0, $A_\parallel$ and $A_\perp$ - corresponding to each possible relative orbital angular momentum among the vector mesons. However, the same final state can be reached through decays involving scalar resonances (S). The total decay amplitude is then a coherent sum of VV, VS (*S*–wave) and SS (double *S*–wave) contributions. A time dependent angular analysis is then needed to disentangle the different amplitudes and measure the weak phase ϕ_s. Since the oscillation in the decay time distribution, which gives sensitivity to the measurement of ϕ_s, is exactly opposite for B_s^0 and $\bar{B}_s^0$ decays, determination of the initial meson flavour is also required.

Using *pp* collisions data, corresponding to an integrated luminosity of $1 fb^{-1}$, collected by LHCb in 2011 at $\sqrt{s} = 7$ TeV, the *CP*–violating phase ϕ_s was measured by means of the $B_s^0 \to \phi\phi$ decay. The $B_s^0 \to K^{*0}\bar{K}^{*0}$ decay was observed for the first time within a data sample corresponding to $35 pb^{-1}$ of integrated luminosity of data from *pp* collisions at $\sqrt{s} = 7$ TeV. Its branching ratio and longitudinal polarization fraction were also measured.

2. The $B_s^0 \to \phi\phi$ analysis

A multivariate selection was designed to optimize the sensitivity to ϕ_s [5]. This resulted in a total of 880 signal candidates.

An unbinned maximum log-likelihood fit was then performed to the decay time and the three helicity angles, $\Omega = \{\theta_1, \theta_2, \Phi\}$ [6]. Angular and lifetime acceptances are determined from simulated events, as well as the lifetime resolution. The decay width difference between the light and heavy B_s^0 mass eigenstates ($\Delta\Gamma_s$), the average decay width (Γ_s) and the B_s^0 oscillation frequency (Δm_s), are gaussian–constrained to the values measured by LHCb [7, 8], taking into account the correlations. Opposite–side and Same–side Kaon flavour tagging algorithms were used [9, 10]. The total tagging power is determined from data to be $(3.29 \pm 0.48)\%$ [11].

The total *S*–wave fraction, which originates from a pair of kaons either in a non-resonant state or from a spin-0 resonance, was determined to be $(1.6^{+2.4}_{-1.2})$, where double *S*–wave amplitude, A_{ss}, was set to zero. As a cross-check, a sideband subtracted fit to the two-dimensional mass, m_{KK}, for both kaon pairs was performed, yielding a consistent *S*–wave fraction of $(2.1 \pm 1.2)\%$.

The results of the fit for the main observables are shown in Table 2. Figure 1 shows the distributions for the decay time and the helicity angles with the projections for the best fit model overlaid. The negative $\Delta\ln$ likelihood scan for ϕ_s, shown in Figure 2, is highly non–parabolic. A 68% confidence level is calculated through a Feldman Cousins analysis that includes both systematic and statistical uncertainties. The result is $\phi_s \in [-2.46, -0.76]$ rad at 68%

confidence level. The main sources of systematic uncertainty are the decay time acceptance and the parametrization of the S–wave component. For more details on how the systematic uncertainties have been evaluated, the reader can refer to [5].

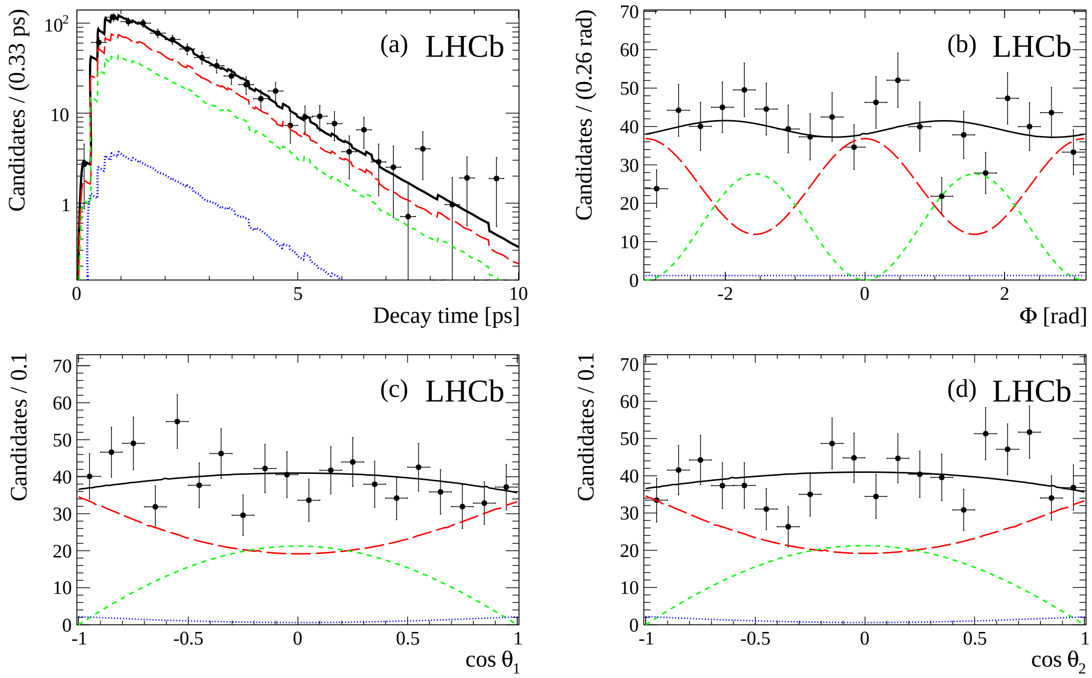

Figure 1: One-dimensional projections of the $B_s^0 \to \phi\phi$ fit for (a) decay time, (b) helicity angle Φ and the cosine of the helicity angles (c) θ_1 and (d) θ_2. The data are marked as points, while the solid lines represent the projections of the best fit. The CP-even P-wave, the CP-odd P-wave and S-wave components are shown by the long dashed, short dashed and dotted lines, respectively.

3. The $B_s^0 \to K^{*0}\bar{K}^{*0}$ analysis

The $B_s^0 \to K^{*0}\bar{K}^{*0}$ decay had not been observed before the LHCb analysis. Predictions in the framework of QCD factorization report $\mathscr{B}(B_s^0 \to K^{*0}\bar{K}^{*0}) = (9.1^{+11.3}_{-6.8}) \times 10^{-6}$ for the branching

Table 1: Fit results with statistical and systematic uncertainties. A 68% statistical confidence interval is quoted for ϕ_s . Amplitudes magnitudes, $|A_i|$, and phases, δ_i, are defined at $t = 0$.

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
$\lvert A_S\rvert^2$	0.016	$^{+0.024}_{-0.012}$	0.009
$\delta_\perp - \delta_\parallel$ [rad]	2.19	0.44	0.12
$\delta_\perp - \delta_0$ [rad]	-1.47	0.48	0.10
δ_S [rad]	0.65	$^{+0.89}_{-1.65}$	0.33

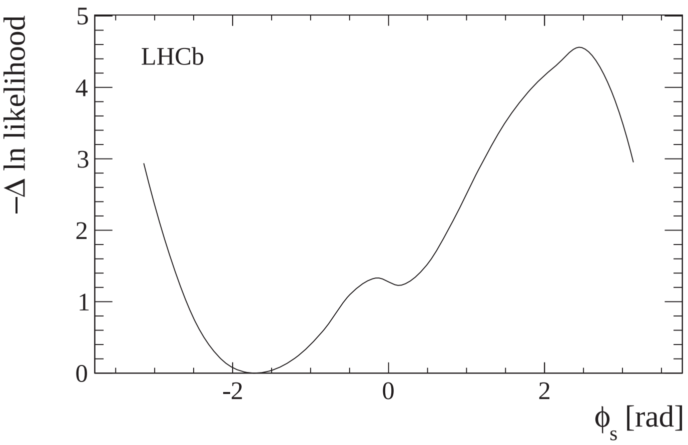

Figure 2: Negative Δln likelihood scan of ϕ_s. Only the statistical uncertainty is included.

fraction and $f_L = 0.63^{+0.42}_{-0.29}$ for the K^{*0} longitudinal polarization fraction [1] [2]. An upper limit for the $B_s^0 \to K^{*0}\bar{K}^{*0}$ branching fraction of 1.68×10^{-3} at 90% confidence level was reported by the SLD experiment [12].

After a multivariate selection, optimized to maximize the signal significance, 50.1 ± 7.5 candidates were found with a signal significance of 10.9σ. Figure 3 shows the mass spectrum for the selected $K^+\pi^-K^-\pi^+$ candidates. The details of the analysis can be found in [13].

The decay amplitudes were obtained from a fit to the helicity angles assuming no *CP* violation in either the mixing or the decay. The values $\Delta\Gamma_s = (0.062^{+0.034}_{-0.037}) \times 10^{12} s^{-1}$ and $\Gamma_s = (0.679^{+0.012}_{-0.011}) \times 10^{12} s^{-1}$ [14] were used. The S–wave contribution is not considered in the fit, but a systematic uncertainty, based on the S–wave fraction measured in $B^0 \to J/\psi K^{*0}$ by LHCb [15], is added to take into account this assumption. The angular acceptance is parametrized using simulated events.

The angular parameters for $B_s^0 \to K^{*0}\bar{K}^{*0}$ were measured to be $f_L = 0.31 \pm 0.12(\text{stat.}) \pm 0.04(\text{syst.})$ and $f_\perp = 0.38 \pm 0.11(\text{stat.}) \pm 0.04(\text{syst.})$. Remarkably different values have been measured for the U–spin rotated channel $B_d \to K^{*0}\bar{K}^{*0}$, $f_L = 0.80^{+0.10}_{-0.12}(\text{stat.}) \pm 0.06(\text{syst.})$ [16]. One dimensional projections of the fit results are shown in Figure 4.

The branching ratio of $B_s^0 \to K^{*0}\bar{K}^{*0}$ is obtained from

$$\mathscr{B}\left(B_s^0 \to K^{*0}\bar{K}^{*0}\right) = \lambda_{f_L} \times \frac{\varepsilon_{B^0 \to J/\psi K^{*0}}}{\varepsilon_{B_s^0 \to K^{*0}\bar{K}^{*0}}} \times \frac{N_{B_s^0 \to K^{*0}\bar{K}^{*0}}}{N_{B^0 \to J/\psi K^{*0}}} \times \frac{\mathscr{B}(J/\psi \to \mu\mu)}{\mathscr{B}(K^{*0} \to K^+\pi^-)} \times \mathscr{B}(B^0 \to J/\psi K^{*0}) \times \frac{f_d}{f_s} \quad (3.1)$$

using $B^0 \to J/\psi K^{*0}$ as normalization channel. $N_{B_s^0 \to K^{*0}\bar{K}^{*0}}$ and $N_{B^0 \to J/\psi K^{*0}}$ are the number of

[1] The polarization fractions are defined as

$$f_L = \frac{|A_0|^2}{|A_0|^2 + |A_\parallel|^2 + |A_\perp|^2} \quad \text{and} \quad f_i = \frac{|A_i|}{|A_0|^2 + |A_\parallel|^2 + |A_\perp|^2}, \quad i = \parallel, \perp$$

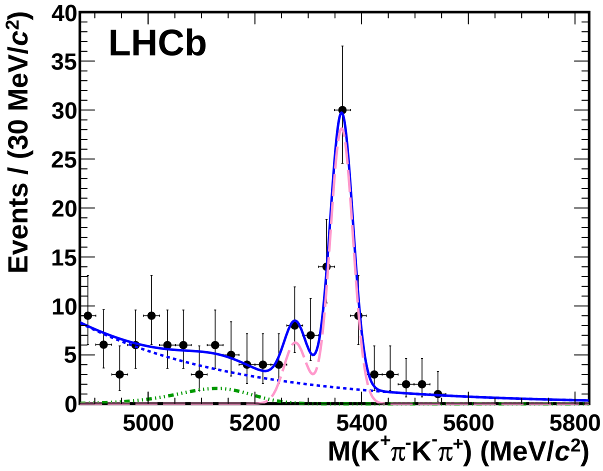

Figure 3: Fit to the $K^+\pi^-K^-\pi^+$ mass distribution of selected candidates. The fit model (blue solid line) includes a signal component for both B_s^0 and B_d decays (dashed pink curve). The dotted blue line corresponds to the combinatoric background and the dash-dotted green line represents partially reconstructed events.

candidate events in the signal and control channel data samples. The value of $\mathscr{B}(B^0 \to J/\psi K^{*0}) = (1.33 \pm 0.06) \times 10^{-3}$ is taken from the world average [14], $\mathscr{B}(J/\psi \to \mu\mu) = 0.0593 \pm 0.0006$ and $\mathscr{B}(K^{*0} \to K^+\pi^-) = 2/3$ [14]. The ratio of b-quark hadronization factors that accounts for the different production rate of B^0 and B_s^0 mesons is $f_s/f_d = 0.253 \pm 0.031$ [17]. The efficiencies in reconstructing, selecting and triggering events of signal or control channel, ε, are determined using simulation. The factor λ_{f_L} is a correction motivated by the fact that the overall efficiency of the LHCb detector is a function of the K^{*0} longitudinal polarization. The result is $\mathscr{B}\left(B_s^0 \to K^{*0}\bar{K}^{*0}\right) = (2.81 \pm 0.46(\mathrm{stat.}) \pm 0.45(\mathrm{syst.}) \pm 0.34(f_s/f_d)) \times 10^{-5}$. Dominant systematic uncertainties come from the trigger efficiency determination and the longitudinal polarization measurement.

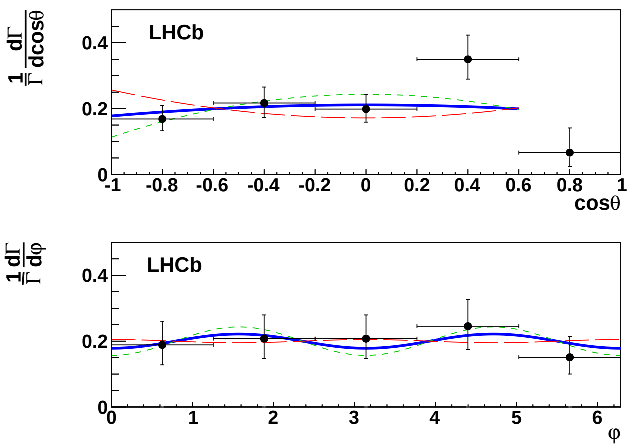

Figure 4: $\cos\theta$ (top) and Φ (bottom) acceptance corrected distributions for events in a window of 50 MeV/c^2 around the B_s^0 mass. The blue line is the projection of the fit model for the measured values of the parameters. The dotted lines indicate $\pm 1\sigma$ variation of the f_L central value.

4. Summary

The first measurement of the mixing–induced *CP*–violating phase in $B_s^0 \to \phi\phi$ penguin decays has been presented. This is found to lie in the interval $[-2.46, -0.76]$ rad at 68% confidence level.

The $B_s^0 \to K^{*0}\bar{K}^{*0}$ decay has been observed for the first time. The branching fraction $\mathscr{B}(B_s^0 \to K^{*0}\bar{K}^{*0}) = (2.81 \pm 0.46(\text{stat.}) \pm 0.45(\text{syst.}) \pm 0.34(f_s/f_d)) \times 10^{-5}$ has been determined. A measurement of polarization fractions in this decay has also been performed obtaining $f_L = 0.31 \pm 0.12(\text{stat.}) \pm 0.04(\text{syst.})$ and $f_\perp = 0.38 \pm 0.11(\text{stat.}) \pm 0.04(\text{syst.})$.

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