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Search for CP violation in $B^0 \to J/\psi K^0_S$ decays with first LHCb data

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Abstract. We report a measurement of the CP violation in $B^0 \to J/\psi K^0_S$ decays. We perform a time-dependent analysis of the decays reconstructed in $35pb^{-1}$ of LHCb data that was taken in 2010. We measure the CP asymmetry parameter $S_{J/\psi K^0_S} = 0.53^{+0.28}_{-0.29}$ (stat) ±0.05 (syst), which is connected to the CKM angle β.

1 Introduction

The decay $B^0 \to J/\psi K^0_S$ is well known as the gold-plated mode for the study of CP violation in the B^0 meson decays to a CP eigenstate common to both B^0 and $\bar{B}^0$, allowing for interference through oscillation. Therefore, measurements of the decay B^0 and $\bar{B}^0$ have a good sensitivity to the CKM angle $sin(2\beta)$, which is connected to the parameters $S_{J/\psi K^0_S}$ and $C_{J/\psi K^0_S}$:

$$\mathcal{A}_{J/\psi K^0_S}(t) \equiv \frac{\Gamma(\bar{B}^0(t) \to J/\psi K^0_S) - \Gamma(B^0(t) \to J/\psi K^0_S)}{\Gamma(\bar{B}^0(t) \to J/\psi K^0_S) + \Gamma(B^0(t) \to J/\psi K^0_S)} = S_{J/\psi K^0_S} \sin(\Delta m_d t) - C_{J/\psi K^0_S} \cos(\Delta m_d t)\ , \quad (1)$$

where $\Delta m_d = m_{B^0_H} - m_{B^0_L}$ is the mass difference between the mass eigenstates. We have neglected the decay width difference between the mass eigenstates of the B^0 system. The connection of the $S_{J/\psi K^0_S}$ and $C_{J/\psi K^0_S}$ parameters to the CKM angle is

$$S_{J/\psi K^0_S} \simeq \sqrt{1 - {C_{J/\psi K^0_S}}^2} \sin 2\beta\ . \quad (2)$$

In the Standard Model, both *CP* violation in mixing and direct *CP* violation are negligible in $b \to c\bar{c}s$ decays. As a consequence the cosine term vanishes, implying

$$S_{J/\psi K^0_S} \simeq \sin 2\beta\ . \quad (3)$$

During the last decade the B-factories BABAR and Belle reached outstanding precision in the measurement of $S_{J/\psi K^0_S}$. The most recent BABAR measurement reports $S_{J/\psi K^0_S} = 0.663 \pm 0.039$ (stat) $\pm$ 0.012 (syst) [1]. The most recent Belle result is $S_{J/\psi K^0_S} = 0.642 \pm 0.031$ (stat) ±0.017 (syst) [2]. Currently, the world average [3] is $sin2\beta = 0.673 \pm 0.023$.

The measurement presented in this note [4] with the first LHCb data is an important step to demonstrate the potential of the LHCb experiment in this topic and it demonstrates that the flavour tagging algorithms are under control. We measure $S_{J/\psi K^0_S}$ under the assumption that $C_{J/\psi K^0_S} = 0$, and we quote the resulting value of $C_{J/\psi K^0_S}$ if the Standard Model constraint is relaxed.

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2 Analysis Strategy

The results presented are based on data collected with the LHCb detector at the LHC collider at a center-of-mass energy of $\sqrt{s} = 7\,\text{TeV}$. Details on the LHCb experiment can be found in elsewhere [5]. The data set analyzed has an integrated luminosity of $\approx 35\,\text{pb}^{-1}$. We use Monte Carlo (MC) simulated samples that are based on the Pythia 6.4 generator [6]. The EvtGen package [7] was used to generate hadron decays and the Geant4 package [8] for detector simulation.

We reconstruct J/ψ candidates in the decay mode $J/\psi \to \mu^+\mu^-$, from pairs of opposite sign tracks that have a transverse momentum of $p_T > 500\,\text{MeV}/c$ each and particle identification signatures consistent with those of muons. The invariant mass of the pair must be compatible with the known J/ψ mass. K^0_S candidates are reconstructed through their decay into $\pi^+\pi^-$ with take pairs of oppositely charged tracks. An additional requirement of $L/\sigma_L > 5$ is made on the K^0_S candidate, where L is the distance between the K^0_S decay vertex and the B decay vertex and σ_L is the uncertainty of L. We constrain the invariant masses of the reconstructed J/ψ and K^0_S candidates to their known masses.

The initial B flavour is determined by the combination of various tagging algorithms. These either determine the flavour of the non-signal b hadron produced in the event (*opposite side*, OS), or they search for an additional pion accompanying the signal B^0 or $\bar{B}^0$ (*same side*, SSπ). There are four tagging algorithms that use the charge of the lepton (μ, e) from semileptonic B decays, or that of the kaon from the $b \to c \to s$ decay chain, or the charge of the inclusive secondary vertex reconstructed from b decay products. All of these algorithms have an intrinsic mistag rate, due to picking up tracks from the underlying event, or due to flavour oscillations of neutral tag B mesons. For each signal B^0 candidate the tagging algorithms also predict the mistag probability ω. For this various kinematic variables such as momenta and angles of the tagging particles are combined into neural networks. The neural networks are trained on MC simulated events.

The flavour asymmetry that is accessible in $B^0 \to J/\psi K^0_S$ decays directly depends on the dilution D due to the mistag probability for each signal candidate, $\langle D^2 \rangle = \frac{1}{N}\sum_i (1 - 2\omega_i)^2$. Its statistical precision is proportional to the inverse square root of the effective tagging efficiency $\varepsilon_{\rm eff}$,

$$\varepsilon_{\rm eff} = \varepsilon_{\rm tag} \left\langle D^2 \right\rangle \ , \tag{4}$$

where $\varepsilon_{\rm tag}$ is the probability that a tagging decision is found. The tagging algorithms are optimized for highest $\varepsilon_{\rm eff}$ on data, using the self-tagging decays $B^+ \to J/\psi K^+$ and $B^0 \to D^{*-}\mu^+\nu$. The estimated mistag probability is calibrated on these same channels. The effective tagging efficiency is measured to be $\varepsilon_{\rm eff} = (2.82 \pm 0.87)\%$.

To extract the $S_{J/\psi K^0_S}$ parameter, we perform a simultaneous, extended unbinned maximum likelihood fit to the proper time and the invariant mass distributions:

$$\mathcal{L}(\lambda) = \frac{e^{-N} N^n}{n!} \prod_s \prod_{i=1}^{N^s} \mathcal{P}^s(\mathbf{x}_i; \lambda_s) \ . \tag{5}$$

We minimize $-\ln \mathcal{L}$ to find optimal values for the fit parameters λ.

The fit is simultaneous in four subsamples s. These subsamples are defined by whether the candidates were triggered by a lifetime unbiased ("U") or a lifetime biased ("B") decision; and by whether or not a tagging decision is available ("u" for untagged, "t" for tagged). Each subsample contains N^s events, and $n = \sum_s N^s$.

We consider four observables: the reconstructed mass m of the B^0 candidate ($5.15\,{\rm GeV}/c^2 < m < 5.4\,{\rm GeV}/c^2$), its proper time t ($-1\,{\rm ps} < t < 4\,{\rm ps}$), the flavour tag decision d, and the combined per-event mistag prediction ω. The flavour tag d can take the discrete values $d = 1$ if tagged as initial B^0 and $d = -1$ if tagged as initial $\overline{B}^0$.

The probability density functions (p.d.f.s) $\mathcal{P}^s$ consist of three components, signal (S), prompt background (P), and long lived background (L). The mass p.d.f. of the signal component consists of a single Gaussian. We assume both background components have similar mass distributions, and we use the same parameterization for both. It is modeled as an exponential with a single shape parameter. The proper time p.d.f. of the signal component can be written as $\mathcal{P}_S(t, d, \omega) = \mathcal{P}_S(t, d|\omega) \cdot \mathcal{P}_S(\omega)$. The first term is a conditional p.d.f. as it depends on the value of ω, the second term describes the distribution of ω. The background parameterization of the proper time factorizes, $\mathcal{P}_B(t, d, \omega) = \mathcal{P}_B(t, d) \cdot \mathcal{P}_B(\omega)$, where $B = P, L$.

In the fit to the $B^0 \to J/\psi K^0_S$ channel we fix the mixing frequency Δm_d to its nominal value of $\Delta m_d = (0.507 \pm 0.005) \cdot 10^{12}\,\hbar s^{-1}$ [9], and $C_{J/\psi K^0_S} = 0$. In total, there are 27 floating parameters: the *CP* parameter $S_{J/\psi K^0_S}$, the B^0 lifetime τ, the B^0 mass m_0^S, twelve event yields, four parameters of the long-lived proper time background, five parameters of the time resolution, the mass signal resolution σ_m^S, and two parameters of the mass background shape. We have checked the fit implementation on a large sample of MC generated signal events, where we find good agreement with the generated values.

The measurement was performed using a "blind" analysis technique to minimize unconscious experimenter bias, the parameter of interest was encrypted in the likelihood fit. Only after the full analysis strategy was developed and proved to be stable, the encryption was removed, unblinding the true result.

Table 1. Fit result of the nominal fit to the full $B^0 \to J/\psi K^0_S$ data sample.

Parameter	Unit	Fitted Value
$S_{J/\psi K^0_S}$		$0.53^{+0.28}_{-0.29}$
$m_{\rm S}$	MeV/c^2	5278.13 ± 0.29
$\sigma_{{\rm S},m}$	MeV/c^2	8.82 ± 0.24
τ	ps	1.517 ± 0.046
$\alpha_m^{\rm B}$	(MeV/c^2)$^{-1}$	$-8.71 \pm 3.8 \cdot 10^{-4}$
$\alpha_m^{\rm U}$	(MeV/c^2)$^{-1}$	$-5.86 \pm 0.87 \cdot 10^{-4}$
$f_{{\rm L},t}^{\rm U}$		0.836 ± 0.054
$\tau_{\rm L,1}^{\rm U}$	ps	0.221 ± 0.036
$\tau_{\rm L,2}^{\rm U}$	ps	1.04 ± 0.24
$\tau_{\rm L}^{\rm B}$	ps	0.482 ± 0.029
$f_{\mathcal{R},1}$		0.500 ± 0.019
$f_{\mathcal{R},2}$		0.477 ± 0.017
$\sigma_{\mathcal{R},1}$	ps	0.02522 ± 0.00066
$\sigma_{\mathcal{R},2}$	ps	0.0685 ± 0.0016
$\sigma_{\mathcal{R},3}$	ps	0.293 ± 0.019

2.1 Results

The result of the maximum likelihood fit to the full data sample is summarized in Tables 1 and 2. The mass and proper time distributions and the fit projections are shown in Figure 1. Figure 2 shows the resulting time dependent raw asymmetry, which contains all fit components. The asymmetry in the lowest proper time bins is therefore dominated by the backgrounds, whereas the measured asymmetry in the high proper time bins is dominated by signal events. The measured value of $S_{J/\psi K^0_S}$ is

$$S_{J/\psi K^0_S} = 0.53^{+0.28}_{-0.29} \ , \tag{6}$$

where the error is statistical only. We find the global correlation coefficient of $S_{J/\psi K^0_S}$ to be $\rho(S_{J/\psi K^0_S}) = 0.016$. We also perform the nominal fit without the Standard Model constraint $C_{J/\psi K^0_S} = 0$. In this case, we find

$$C_{J/\psi K^0_S} = 0.28 \pm 0.32 \ , S_{J/\psi K^0_S} = 0.38 \pm 0.35 \ , \tag{7}$$

again quoting statistical errors only. The correlation coefficient between the parameters is $\rho(S_{J/\psi K^0_S}, C_{J/\psi K^0_S}) = 0.53$. Their correlations to other parameters are negligible.

Table 2. Fitted event yields in the full $B^0 \to J/\psi K^0_S$ data sample.

Sample	Parameter	Fitted Value
U,t	$N_{\rm S}^{\rm U,t}$	221 ± 17
	$N_{\rm P}^{\rm U,t}$	3218 ± 62
	$N_{\rm L}^{\rm U,t}$	309 ± 33
B,t	$N_{\rm S}^{\rm B,t}$	59.8 ± 8.7
	$N_{\rm P}^{\rm B,t}$	164 ± 14
	$N_{\rm L}^{\rm B,t}$	102 ± 12
U,u	$N_{\rm S}^{\rm U,u}$	767 ± 32
	$N_{\rm P}^{\rm U,u}$	21134 ± 161
	$N_{\rm L}^{\rm U,u}$	807 ± 79
B,u	$N_{\rm S}^{\rm B,u}$	279 ± 18
	$N_{\rm P}^{\rm B,u}$	747 ± 30
	$N_{\rm L}^{\rm B,u}$	339 ± 23

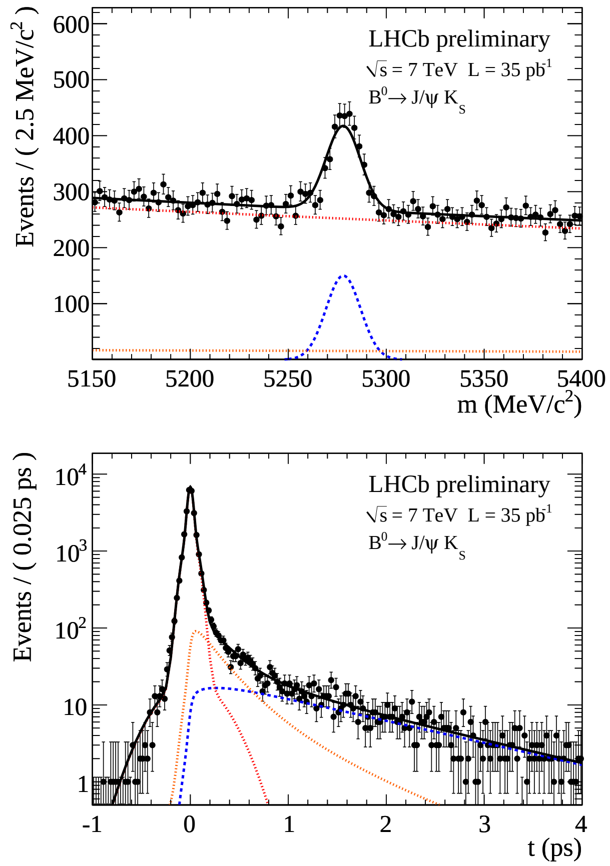

Fig. 1. Reconstructed mass (left) and proper time (right) distributions of $B^0 \to J/\psi\, K^0_S$ candidates. Overlayed are projections of the component p.d.f.s used in the fit: full p.d.f. (solid black), signal (dashed blue), prompt background (dash-dotted red), long lived background (dotted orange).

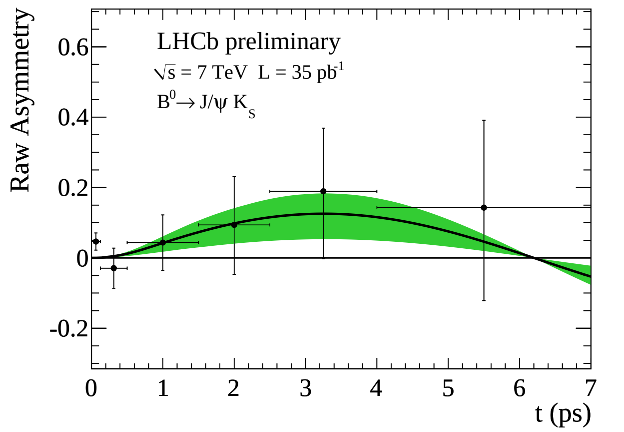

Fig. 2. Time dependent raw CP asymmetry in $B^0 \to J/\psi\, K^0_S$. The solid curve is the full p.d.f. (signal and background) overlayed onto the data points. The green band corresponds to the one standard deviation statistical error.

3 Conclusion

The final result on the CP violation parameter $S_{J/\psi K^0_S}$ is

$$S_{J/\psi K^0_S} = 0.53^{+0.28}_{-0.29}(\mathrm{stat}) \pm 0.05(\mathrm{syst})\ . \tag{8}$$

This result is compatible with the World Average, and dominated by the statistical uncertainty. We calculate the statistical significance of a non-zero CP violation from the likelihood ratio of a test fit, in which we fix $S_{J/\psi K^0_S} = 0$, to be

$$S = \sqrt{2\ \ln(\mathcal{L}_{\mathrm{nom}}/\mathcal{L}_{\mathrm{null}})} = 1.8\ . \tag{9}$$

This is the first CP violation result in the golden channel $B^0 \to J/\psi\, K^0_S$ in LHCb.

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