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Measurement of the time-dependent *CP* asymmetry in $B^0 \to J/\psi K^0_S$ decays ☆

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ABSTRACT

This Letter reports a measurement of the *CP* violation observables $S_{J/\psi K^0_S}$ and $C_{J/\psi K^0_S}$ in the decay channel $B^0 \to J/\psi K^0_S$ performed with 1.0 fb^{-1} of *pp* collisions at $\sqrt{s} = 7$ TeV collected by the LHCb experiment. The fit to the data yields $S_{J/\psi K^0_S} = 0.73 \pm 0.07\,(\text{stat}) \pm 0.04\,(\text{syst})$ and $C_{J/\psi K^0_S} = 0.03 \pm 0.09\,(\text{stat}) \pm 0.01\,(\text{syst})$. Both values are consistent with the current world averages and within expectations from the Standard Model.

1. Introduction

The source of *CP* violation in the electroweak sector of the Standard Model (SM) is the single irreducible complex phase of the Cabibbo–Kobayashi–Maskawa (CKM) quark mixing matrix [1,2]. The decay $B^0 \to J/\psi K^0_S$ is one of the theoretically cleanest modes for the study of *CP* violation in the B^0 meson system. Here, the B^0 and $\overline{B}^0$ mesons decay to a common *CP*-odd eigenstate allowing for interference through B^0–$\overline{B}^0$ mixing.

In the B^0 system the decay width difference $\Delta\Gamma_d$ between the heavy and light mass eigenstates is negligible. Therefore, the time-dependent decay rate asymmetry can be written as [3,4]

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

Here $B^0(t)$ and $\overline{B}^0(t)$ are the states into which particles produced at $t = 0$ as B^0 and $\overline{B}^0$ respectively have evolved, when decaying at time t. The parameter Δm_d is the mass difference between the two B^0 mass eigenstates. The sine term results from the interference between direct decay and decay after B^0–$\overline{B}^0$ mixing. The cosine term arises either from the interference between decay amplitudes with different weak and strong phases (direct *CP* violation) or from *CP* violation in B^0–$\overline{B}^0$ mixing.

In the SM, *CP* violation in mixing and direct *CP* violation are both negligible in $B^0 \to J/\psi K^0_S$ decays, hence $C_{J/\psi K^0_S} \approx 0$, while $S_{J/\psi K^0_S} \approx \sin 2\beta$, where the CKM angle β can be expressed in terms of the CKM matrix elements as $\arg|-V_{cd}V^*_{cb}/V_{td}V^*_{tb}|$. It can also be measured in other B^0 decays to final states including charmonium such as $J/\psi K^0_L$, $J/\psi K^{*0}$, $\psi(2S)K^{(*)0}$, which have been used in measurements by the BaBar and Belle Collaborations [5,6]. Currently, the world averages are $S_{J/\psi K^0_S} = 0.679 \pm 0.020$ and $C_{J/\psi K^0_S} = 0.005 \pm 0.017$ [7].

The time-dependent measurement of the *CP* parameters $S_{J/\psi K^0_S}$ and $C_{J/\psi K^0_S}$ requires flavour tagging, *i.e.* the knowledge whether the decaying particle was produced as a B^0 or a $\overline{B}^0$ meson. If a fraction ω of candidates is tagged incorrectly, the accessible time-dependent asymmetry $\mathcal{A}_{J/\psi K^0_S}(t)$ is diluted by a factor $(1-2\omega)$. Hence, a measurement of the *CP* parameters requires precise knowledge of the wrong tag fraction. Additionally, the asymmetry between the production rates of B^0 and $\overline{B}^0$ has to be determined as it affects the observed asymmetries.

In this Letter, the most precise measurement of $S_{J/\psi K^0_S}$ and $C_{J/\psi K^0_S}$ to date at a hadron collider is presented using approximately 8200 flavour-tagged $B^0 \to J/\psi K^0_S$ decays.

2. Data samples and selection requirements

The data sample consists of 1.0 fb^{-1} of *pp* collisions recorded in 2011 at a centre-of-mass energy of $\sqrt{s} = 7$ TeV with the LHCb experiment at CERN. The detector [8] is a single-arm forward spectrometer covering the pseudorapidity range 2 to 5, designed for the study of particles containing *b* or *c* quarks. It includes a high precision tracking system consisting of a silicon-strip vertex detector surrounding the *pp* interaction region, a large-area silicon-strip detector located upstream of a dipole magnet with a bending power of about 4 T m, and three stations of silicon-strip detectors and straw drift-tubes placed downstream. The combined tracking system has a momentum resolution $\Delta p/p$ that varies from 0.4% at 5 GeV/*c* to 0.6% at 100 GeV/*c*, and an impact parameter resolution of 20 μm for tracks with high transverse momentum. Charged hadrons are identified using two ring-imaging Cherenkov detectors. Photon, electron and hadron candidates are identified by a

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calorimeter system consisting of scintillating-pad and preshower detectors, an electromagnetic and a hadronic calorimeter. Muons are identified by a system composed of alternating layers of iron and multiwire proportional chambers.

The analysis is performed on events with reconstructed $B^0 \to J/\psi K^0_S$ candidates with subsequent $J/\psi \to \mu^+\mu^-$ and $K^0_S \to \pi^+\pi^-$ decays. Events are selected by the trigger consisting of hardware and software stages. The hardware stage accepts events if muon or hadron candidates with high transverse momentum (p_T) with respect to the beam axis are detected. In the software stage, events are required to contain two oppositely-charged particles, both compatible with a muon hypothesis, that form an invariant mass greater than 2.7 GeV/c^2. The resulting J/ψ candidate has to be clearly separated (decay length significance greater than 3) from the production vertex (PV) with which it is associated on the basis of the impact parameter. The overall signal efficiency of these triggers is found to be 64%.

Further selection criteria are applied offline to decrease the number of background candidates. The J/ψ candidates are reconstructed from two oppositely-charged, well identified muons with $p_T > 500$ MeV/c that form a common vertex with a fit χ^2/ndf of less than 11, where ndf is the number of degrees of freedom, and with an invariant mass in the range 3035–3160 MeV/c^2. It is required that the J/ψ candidate fulfils the trigger requirements described above. The K^0_S candidates are formed from two oppositely-charged pions, both with (long K^0_S candidate) or without (downstream K^0_S candidate) hits in the vertex detector. Any K^0_S candidates where both pion tracks have hits in the tracking stations but only one has additional hits in the vertex detector are ignored, as they would only contribute to $< 2\%$ of the events. Each pion must have $p > 2$ GeV/c and a clear separation from any PV. Furthermore, they must form a common vertex with a fit χ^2/ndf of less than 20 and an invariant mass within the range 485.6–509.6 MeV/c^2 (long K^0_S candidates) or 476.6–518.6 MeV/c^2 (downstream K^0_S candidates). Different mass windows are chosen to account for different mass resolutions for long and downstream K^0_S candidates. The K^0_S candidate's decay vertex is required to be significantly displaced with respect to the associated PV.

The B^0 candidates are constructed from combinations of J/ψ and K^0_S candidates that form a vertex with a reconstructed mass $m_{J/\psi K^0_S}$ in the range 5230–5330 MeV/c^2. The value of $m_{J/\psi K^0_S}$ is computed constraining the invariant masses of the $\mu^+\mu^-$ and $\pi^+\pi^-$ to the known J/ψ and K^0_S masses [9], respectively. As most events involve more than one reconstructed PV, B^0 candidates are required to be associated to one PV only and are therefore omitted if their impact parameter significance with respect to other PVs in the event is too small. Additionally, the K^0_S candidate's decay vertex is required to be separated from the B^0 decay vertex by a decay time significance of the K^0_S greater than 5.

The decay time t of the B^0 candidates is determined from a vertex fit to the whole decay chain under the constraint that the B^0 candidate originates from the associated PV [10]. Only candidates with a good quality vertex fit and with $0.3 < t < 18.3$ ps are retained. In case more than one candidate is selected in an event, that with the best vertex fit quality is chosen. The fit uncertainty on t is used as an estimate of the decay time resolution σ_t, which is required to be less than 0.2 ps. Finally, candidates are only retained if the flavour tagging algorithms provide a prediction for the production flavour of the candidate, as discussed in Section 3.

Simulated samples are used for cross-checks and studies of decay time distributions. For the simulation, pp collisions are generated using Pythia 6.4 [11] with a specific LHCb configuration [12]. Decays of hadronic particles are described by EvtGen [13] in which final state radiation is generated using Photos [14]. The interaction of the generated particles with the detector is implemented using the Geant4 toolkit [15] as described in Ref. [16].

3. Flavour tagging

A mandatory step for the study of *CP* violating quantities is to tag the initial, *i.e.* production, flavour of the decaying B^0 meson. Since b quarks are predominantly produced in $b\bar{b}$ pairs in LHCb, the flavour tagging algorithms used in this analysis [17] reconstruct the flavour of the non-signal b hadron. The flavour of the non-signal b hadron is determined by identifying the charge of its decay products, such as that of an electron or a muon from a semileptonic b decay, a kaon from a $b \to c \to s$ decay chain, or the charge of its inclusively reconstructed decay vertex. The algorithms use this information to provide a tag d that takes the value $+1$ (-1) in the case where the signal candidate is tagged as an initial B^0 ($\overline{B}^0$) meson.

A careful study of the fraction of candidates that are wrongly tagged (mistag fraction) is necessary as the measured asymmetry is diluted due to the imperfect tagging performance. The mistag fraction (ω) is extracted on an event-by-event basis from the combined per-event mistag probability prediction η of the tagging algorithms. On average, the mistag fraction is found to depend linearly on η and is parameterised as

$$\omega(\eta) = p_1 \cdot \big(\eta - \langle\eta\rangle\big) + p_0. \tag{2}$$

Using events from the self-tagging control channel $B^+ \to J/\psi K^+$, the parameters are determined to be $p_1 = 1.035 \pm 0.021\,(\text{stat}) \pm 0.012\,(\text{syst})$, $p_0 = 0.392 \pm 0.002\,(\text{stat}) \pm 0.009\,(\text{syst})$ and $\langle\eta\rangle = 0.391$ [18]. The systematic uncertainties on the tagging calibration parameters are estimated by comparing the tagging performance obtained in different decay channels such as $B^0 \to J/\psi K^{*0}$, in B^+ and B^- subsamples separately, and in different data taking periods.

The difference in tagging response between B^0 and $\overline{B}^0$ is parameterised by using

$$\omega = \omega(\eta) \pm \frac{\Delta p_0}{2}, \tag{3}$$

where the $+$ ($-$) is used for a B^0 ($\overline{B}^0$) meson at production and Δp_0 is the mistag fraction asymmetry parameter, which is the difference of p_0 for B^0 and $\overline{B}^0$ mesons. It is measured as $\Delta p_0 = 0.011 \pm 0.003$ using events from the control channel $B^+ \to J/\psi K^+$. By using Δp_0 in the analysis, the systematic uncertainty on the p_0 parameter is reduced to 0.008. The difference of tagging efficiency for B^0 and $\overline{B}^0$ mesons is measured in the same control channel as $\Delta\varepsilon_{\text{tag}} = 0.000 \pm 0.001$ and is therefore negligible. Thus, it is only used to estimate possible systematic uncertainties in the analysis.

The effect of imperfect tagging is the reduction of the statistical power by a factor $\varepsilon_{\text{tag}}\mathcal{D}^2$, where ε_{tag} is the tagging efficiency and $\mathcal{D} = 1 - 2\omega$ is the dilution factor. The effective ε_{tag} and $\mathcal{D}$ values are measured as $\varepsilon_{\text{tag}} = (32.65 \pm 0.31)\%$ and $\mathcal{D} = 0.270 \pm 0.015$, resulting in $\varepsilon_{\text{tag}}\mathcal{D}^2 = (2.38 \pm 0.27)\%$, where combined systematic and statistical uncertainties are quoted. The measured dilution corresponds to a mistag fraction of $\omega = 0.365 \pm 0.008$.

4. Decay time acceptance and resolution

The bias on the decay time distribution due to the trigger is estimated by comparing candidates selected using different trigger requirements. In the selection, the reconstructed decay times of the $B^0 \to J/\psi K^0_S$ candidates are required to be greater than 0.3 ps. This requirement makes the acceptance effects of the trigger nearly negligible. However, some small efficiency loss remains for small decay times. Neglecting this efficiency loss is treated as a source of systematic uncertainty.

A decrease of efficiency is also observed at large decay times, mostly affecting the candidates in the long K^0_S subsample. This can be described with a linear efficiency function with parameters determined from simulated data for the downstream and long K^0_S subsamples separately. The efficiency function is then used to correct the description of the decay time distribution.

The finite decay time resolution of the detector leads to an additional dilution of the experimentally accessible asymmetry. It is modelled event-by-event with a triple Gaussian function,

$$\mathcal{R}\big(t-t'\big|\sigma_t\big)=\sum_{i=1}^{3} f_i\frac{1}{\sqrt{2\pi}\,s_i\sigma_t}\exp\left(-\frac{(t-t'-b\sigma_t)^2}{2(s_i\sigma_t)^2}\right), \qquad (4)$$

where t is the reconstructed decay time, t' is the true decay time, and σ_t is the per-event decay time resolution estimate. The parameters are: the three fractions f_i, which sum to unity, the three scale factors s_i, and a relative bias b, which is found to be small. They are determined from a fit to the t and σ_t distributions of prompt J/ψ events that pass the selection and trigger criteria for $B^0 \to J/\psi K^0_S$, except for decay time biasing requirements. The parameters are determined separately for the subsamples formed from downstream and long K^0_S candidates. This results in an average effective decay time resolution of 55.6 fs (65.6 fs) for candidates with long (downstream) K^0_S.

5. Measurement of $S_{J/\psi K^0_S}$ and $C_{J/\psi K^0_S}$

The analysis is performed using the following set of observables: the reconstructed mass $m_{J/\psi K^0_S}$, the decay time t, the estimated decay time resolution σ_t, the flavour tag d, and the per-event mistag probability η. The *CP* observables $S_{J/\psi K^0_S}$ and $C_{J/\psi K^0_S}$ are determined as parameters in an unbinned extended maximum likelihood fit to the data.

Due to different resolution and acceptance effects for the downstream and long K^0_S subsamples, a simultaneous fit to both subsamples is performed. In each subsample, the probability density function (PDF) is defined as the sum of two individual PDFs, one for each of the components of the fit: the B^0 signal and the background. The latter component contains both combinatorial background and mis-reconstructed b-hadron decays.

The reconstructed mass distribution of the signal is described by the sum of two Gaussian PDFs with common mean but different widths. Only the mean is shared between the two subsamples. The background component is parameterised as an exponential function, different for each subsample.

The signal and background distributions of the per-event mistag probability η are modelled with PDFs formed from histograms obtained with the *sPlot* technique [19] on the reconstructed mass distribution. In both subsamples the same signal and background models are used.

The distributions of the estimated decay time resolution σ_t are different in each component and each subsample. Hence, no parameters are shared between subsamples or components. All σ_t PDFs are modelled with lognormal functions

$$\mathrm{Ln}(\sigma_t; M_{\sigma_t}, k)=\frac{1}{\sqrt{2\pi}\,\sigma_t\ln k}\exp\left(-\frac{\ln^2(\sigma_t/M_{\sigma_t})}{2\ln^2(k)}\right), \qquad (5)$$

where M_{σ_t} is the median and k the tail parameter. The background components in both subsamples are parameterised by single lognormal functions. For the signal a sum of two lognormals with common (different) median parameter(s) is chosen for the long K^0_S (downstream K^0_S) subsample.

The background PDFs of the decay time are modelled in each subsample by the sum of two exponential functions. These are convolved with the corresponding resolution function $\mathcal{R}(t-t'|\sigma_t)$. The parameters are not shared between the two subsamples. The background distribution of tags d is described as a uniform distribution.

The signal PDF for the decay time simultaneously describes the distribution of tags d, and is given by

$$\mathcal{P}(t,d|\sigma_t,\eta)=\epsilon(t)\cdot\mathcal{P}_{CP}\big(t',d\big|\sigma_t,\eta\big)\otimes\mathcal{R}\big(t-t'\big|\sigma_t\big), \qquad (6)$$

with

$$\begin{aligned}&\mathcal{P}_{CP}\big(t',d\big|\sigma_t,\eta\big)\\&\quad\propto e^{-t'/\tau}\Big(1-d\Delta p_0-dA_{\mathrm{P}}\big(1-2\omega(\eta)\big)\\&\qquad-\big(d\big(1-2\omega(\eta)\big)-A_{\mathrm{P}}(1-d\Delta p_0)\big)S_{J/\psi K^0_S}\sin\Delta m_d t'\\&\qquad+\big(d\big(1-2\omega(\eta)\big)-A_{\mathrm{P}}(1-d\Delta p_0)\big)C_{J/\psi K^0_S}\cos\Delta m_d t'\Big). \qquad (7)\end{aligned}$$

This PDF description exploits time-dependent asymmetries, while its normalisation adds sensitivity by accessing time-integrated asymmetries. The lifetime τ, the mass difference Δm_d, and the *CP* parameters $S_{J/\psi K^0_S}$ and $C_{J/\psi K^0_S}$ are shared in the PDFs of the downstream and long K^0_S subsamples, as well as the asymmetry $A_{\mathrm{P}}=(R_{\overline{B}^0}-R_{B^0})/(R_{\overline{B}^0}+R_{B^0})$ of the production rates R for $\overline{B}^0$ and B^0 mesons in pp collisions at LHCb. The latter value has been measured in Refs. [20,21] to be $A_{\mathrm{P}}=-0.015\pm0.013$.

In the fit all parameters related to decay time resolution and acceptance are fixed. The tagging parameters and the production asymmetry parameter are constrained within their statistical uncertainties by Gaussian constraints in the likelihood. The fit yields

$$S_{J/\psi K^0_S}=0.73\pm0.07, \qquad C_{J/\psi K^0_S}=0.03\pm0.09,$$

with a correlation coefficient $\rho(S_{J/\psi K^0_S}, C_{J/\psi K^0_S})=0.42$. Both of the uncertainties and the correlation are statistical only. The lifetime is fitted as $\tau=1.496\pm0.018$ ps and the oscillation frequency as $\Delta m_d=0.53\pm0.05\ \mathrm{ps}^{-1}$, both in good agreement with the world averages [7,22]. The mass and decay time distributions are shown in Fig. 1. The measured signal asymmetry and the projection of the signal PDF are shown in Fig. 2.

6. Systematic uncertainties

Most systematic uncertainties are estimated by generating a large number of pseudo-experiments from a modified PDF and fitting each sample with the nominal PDF. The PDF used in the generation is chosen according to the source of systematic uncertainty that is being investigated. The variation of the fitted values of the *CP* parameters is used to estimate systematic effects on the measurement.

The largest systematic uncertainty arises from the limited knowledge of the accuracy of the tagging calibration. It is estimated by varying the calibration parameters within their systematic uncertainties in the pseudo-experiments. Another minor systematic uncertainty related to tagging emerges from ignoring a possible difference of tagging efficiencies of B^0 and $\overline{B}^0$.

The effect of an incorrect description of the decay time resolution model is derived from pseudo-experiments in which the scale factors of the resolution model are multiplied by a factor of either 0.5 or 2 in the generation. As the mean decay time resolution of LHCb is much smaller than the oscillation period of the B^0 system this variation leads only to a small systematic uncertainty. The omission of acceptance effects for low decay times is estimated

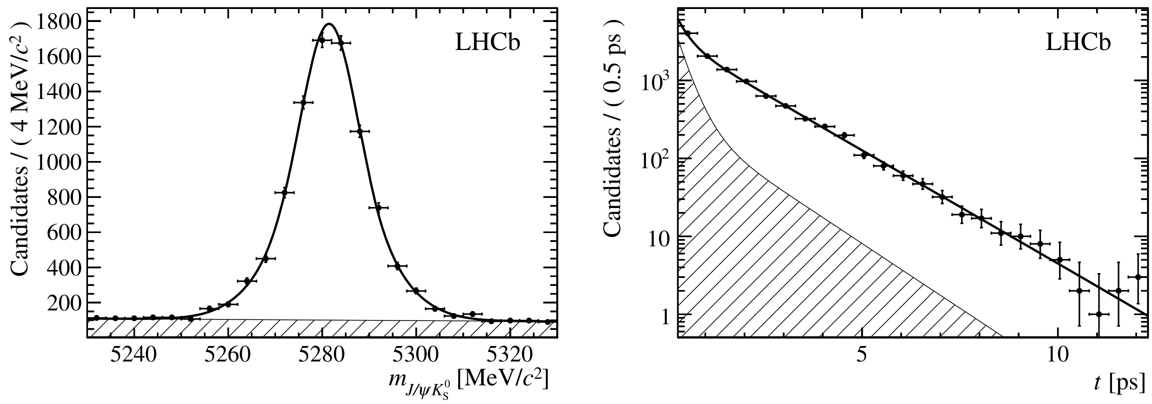

Fig. 1. Invariant mass (left) and decay time (right) distributions of the $B^0 \to J/\psi K^0_S$ candidates. The solid line shows the projection of the full PDF and the shaded area the projection of the background component.

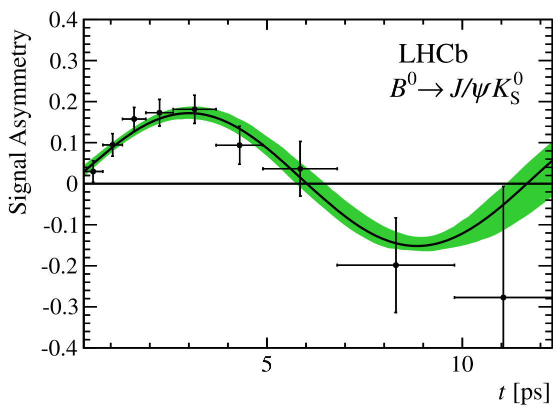

Fig. 2. (Colour online.) Time-dependent asymmetry $(N_{\overline{B}^0} - N_{B^0})/(N_{\overline{B}^0} + N_{B^0})$. Here, N_{B^0} ($N_{\overline{B}^0}$) is the number of $B^0 \to J/\psi K^0_S$ decays with a B^0 ($\overline{B}^0$) flavour tag. The data points are obtained with the *sPlot* technique, assigning signal weights to the events based on a fit to the reconstructed mass distributions. The solid curve is the signal projection of the PDF. The green shaded band corresponds to the one standard deviation statistical error.

from pseudo-experiments where the time-dependent efficiencies measured from data are used in the generation but omitted in the fits. Additionally, a possible inaccuracy in the description of the efficiency decrease at large decay times is checked by varying the parameters within their errors, but is found to be negligible.

The uncertainty induced by the limited knowledge of the background distributions is evaluated from a fit method based on the *sPlot* technique. A fit with the PDFs for the reconstructed mass is performed to extract signal weights for the distributions in the other observable dimensions. These weights are then used to perform a fit with the PDF of the signal component only. The difference in fit results is treated as an estimate of the systematic uncertainty.

To estimate the influence of possible biases in the *CP* parameters emerging from the fit method itself, the method is probed with a large set of pseudo-experiments. Systematic uncertainties of 0.004 for $S_{J/\psi K^0_S}$ and 0.005 for $C_{J/\psi K^0_S}$ are assigned based on the biases observed in different fit settings.

The uncertainty on the scale of the longitudinal axis and on the scale of the momentum [23] sum to a total uncertainty of $< 0.1\%$ on the decay time. This has a negligible effect on the *CP* parameters. Likewise, potential biases from a non-random choice of the B^0 candidate in events with multiple candidates are found to be negligible.

The sources of systematic effects and the resulting systematic uncertainties on the *CP* parameters are quoted in Table 1 where

Table 1
Summary of systematic uncertainties on the *CP* parameters.

Origin	$\sigma(S_{J/\psi K^0_S})$	$\sigma(C_{J/\psi K^0_S})$
Tagging calibration	0.034	0.001
Tagging efficiency difference	0.002	0.002
Decay time resolution	0.001	0.002
Decay time acceptance	0.002	0.006
Background model	0.012	0.009
Fit bias	0.004	0.005
Total	0.036	0.012

the total systematic uncertainty is calculated by summing the individual uncertainties in quadrature.

The analysis strategy makes use of the time-integrated and time-dependent decay rates of $B^0 \to J/\psi K^0_S$ decays that are tagged as $B^0/\overline{B}^0$ meson. Cross-check analyses exploiting only the time-integrated or only the time-dependent information show that both give results that are in good agreement and contribute to the full analysis with comparable statistical power.

7. Conclusion

In a dataset of 1.0 fb^{-1} collected with the LHCb detector, approximately 8200 flavour tagged decays of $B^0 \to J/\psi K^0_S$ are selected to measure the *CP* observables $S_{J/\psi K^0_S}$ and $C_{J/\psi K^0_S}$, which are related to the CKM angle β. A fit to the time-dependent decay rates of B^0 and $\overline{B}^0$ decays yields

$$S_{J/\psi K^0_S} = 0.73 \pm 0.07\,(\text{stat}) \pm 0.04\,(\text{syst}),$$
$$C_{J/\psi K^0_S} = 0.03 \pm 0.09\,(\text{stat}) \pm 0.01\,(\text{syst}),$$

with a statistical correlation coefficient of $\rho(S_{J/\psi K^0_S}, C_{J/\psi K^0_S}) = 0.42$. This is the first significant measurement of *CP* violation in $B^0 \to J/\psi K^0_S$ decays at a hadron collider [24]. The measured values are in agreement with previous measurements performed at the *B* factories [5,6] and with the world averages [7].

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References

[1] M. Kobayashi, T. Maskawa, Prog. Theor. Phys. 49 (1973) 652.
[2] N. Cabibbo, Phys. Rev. Lett. 10 (1963) 531.
[3] A.B. Carter, A.I. Sanda, Phys. Rev. D 23 (1981) 1567.
[4] I.I. Bigi, A. Sanda, Nucl. Phys. B 281 (1987) 41.
[5] BaBar Collaboration, B. Aubert, et al., Phys. Rev. D 79 (2009) 072009, arXiv:0902.1708.
[6] Belle Collaboration, I. Adachi, et al., Phys. Rev. Lett. 108 (2012) 171802, arXiv:1201.4643.
[7] Heavy Flavour Averaging Group, Y. Amhis, et al., Averages of b-hadron, c-hadron, and tau-lepton properties as of early 2012, arXiv:1207.1158.
[8] LHCb Collaboration, A.A. Alves Jr., et al., JINST 3 (2008) S08005.
[9] Particle Data Group, J. Beringer, et al., Phys. Rev. D 86 (2012) 010001.
[10] W.D. Hulsbergen, Nucl. Instrum. Meth. A 552 (2005) 566, arXiv:physics/0503191.
[11] T. Sjöstrand, S. Mrenna, P. Skands, JHEP 0605 (2006) 026, arXiv:hep-ph/0603175.
[12] I. Belyaev, et al., in: Nuclear Science Symposium Conference Record (NSS/MIC), IEEE, 2010, p. 1155.
[13] D.J. Lange, Nucl. Instrum. Meth. A 462 (2001) 152.
[14] P. Golonka, Z. Was, Eur. Phys. J. C 45 (2006) 97, arXiv:hep-ph/0506026.
[15] GEANT4 Collaboration, J. Allison, et al., IEEE Trans. Nucl. Sci. 53 (2006) 270.
[16] M. Clemencic, et al., J. Phys.: Conf. Ser. 331 (2011) 032023.
[17] LHCb Collaboration, R. Aaij, et al., Eur. Phys. J. C 72 (2012) 2022, arXiv:1202.4979.
[18] LHCb Collaboration, R. Aaij, et al., Performance of flavour tagging algorithms optimised for the analysis of $B_s^0 \to J/\psi\phi$, LHCb-CONF-2012-026.
[19] M. Pivk, F.R. Le Diberder, Nucl. Instrum. Meth. A 555 (2005) 356, arXiv:physics/0402083.
[20] LHCb Collaboration, R. Aaij, et al., Phys. Rev. Lett. 108 (2012) 201601, arXiv:1202.6251.
[21] LHCb Collaboration, R. Aaij, et al., Measurement of time-dependent *CP* violation in charmless two-body *B* decays, LHCb-CONF-2012-007.
[22] LHCb Collaboration, R. Aaij, et al., Measurement of the B^0–$\bar{B}^0$ oscillation frequency Δm_d with the decays $B^0 \to D^-\pi^+$ and $B^0 \to J/\psi K^{*0}$, arXiv:1210.6750.
[23] LHCb Collaboration, R. Aaij, et al., Phys. Lett. B 708 (2012) 241, arXiv:1112.4896.
[24] CDF Collaboration, T. Affolder, et al., Phys. Rev. D 61 (2000) 072005, arXiv:hep-ex/9909003.

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Hicks [49], D. Hill [52], M. Hoballah [5], P. Hopchev [4], W. Hulsbergen [38], P. Hunt [52], T. Huse [49], N. Hussain [52], D. Hutchcroft [49], D. Hynds [48], V. Iakovenko [41], P. Ilten [12], J. Imong [43], R. Jacobsson [35], A. Jaeger [11], M. Jahjah Hussein [5], E. Jans [38], F. Jansen [38], P. Jaton [36], B. Jean-Marie [7], F. Jing [3], M. John [52], D. Johnson [52], C.R. Jones [44], B. Jost [35], M. Kaballo [9], S. Kandybei [40], M. Karacson [35], T.M. Karbach [35], I.R. Kenyon [42], U. Kerzel [35], T. Ketel [39], A. Keune [36], B. Khanji [20], Y.M. Kim [47], O. Kochebina [7], V. Komarov [36,29], R.F. Koopman [39], P. Koppenburg [38], M. Korolev [29], A. Kozlinskiy [38], L. Kravchuk [30], K. Kreplin [11], M. Kreps [45], G. Krocker [11], P. Krokovny [31], F. Kruse [9], M. Kucharczyk [20,23,j], V. Kudryavtsev [31], T. Kvaratskheliya [28,35], V.N. La Thi [36], D. Lacarrere [35], G. Lafferty [51], A. Lai [15], D. Lambert [47], R.W. Lambert [39], E. Lanciotti [35], G. 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McNulty [12], M. Meissner [11], M. Merk [38], J. Merkel [9], D.A. Milanes [13], M.-N. Minard [4], J. Molina Rodriguez [54], S. Monteil [5], D. Moran [51], P. Morawski [23], R. Mountain [53], I. Mous [38], F. Muheim [47], K. Müller [37], R. Muresan [26], B. Muryn [24], B. Muster [36], J. Mylroie-Smith [49], P. Naik [43], T. Nakada [36], R. Nandakumar [46], I. Nasteva [1], M. Needham [47], N. Neufeld [35], A.D. Nguyen [36], T.D. Nguyen [36], C. Nguyen-Mau [36,o], M. Nicol [7], V. Niess [5], N. Nikitin [29], T. Nikodem [11], A. Nomerotski [52,35], A. Novoselov [32], A. Oblakowska-Mucha [24], V. Obraztsov [32], S. Oggero [38], S. Ogilvy [48], O. Okhrimenko [41], R. Oldeman [15,35,d], M. Orlandea [26], J.M. Otalora Goicochea [2], P. Owen [50], B.K. Pal [53], A. Palano [13,b], M. Palutan [18], J. Panman [35], A. Papanestis [46], M. Pappagallo [48], C. Parkes [51], C.J. Parkinson [50], G. Passaleva [17], G.D. Patel [49], M. Patel [50], G.N. Patrick [46], C. Patrignani [19,i], C. Pavel-Nicorescu [26], A. Pazos Alvarez [34], A. Pellegrino [38], G. Penso [22,l], M. Pepe Altarelli [35], S. Perazzini [14,c], D.L. Perego [20,j], E. Perez Trigo [34], A. Pérez-Calero Yzquierdo [33], P. Perret [5], M. Perrin-Terrin [6], G. Pessina [20], K. Petridis [50], A. Petrolini [19,i], A. Phan [53], E. Picatoste Olloqui [33], B. Pie Valls [33], B. Pietrzyk [4], T. Pilař [45], D. Pinci [22], S. Playfer [47], M. Plo Casasus [34], F. Polci [8], G. Polok [23], A. Poluektov [45,31], E. Polycarpo [2], D. Popov [10], B. Popovici [26], C. Potterat [33], A. Powell [52], J. Prisciandaro [36], V. Pugatch [41], A. Puig Navarro [36], W. Qian [4], J.H. Rademacker [43], B. Rakotomiaramanana [36], M.S. Rangel [2], I. Raniuk [40], N. Rauschmayr [35], G. Raven [39], S. Redford [52], M.M. Reid [45], A.C. dos Reis [1], S. Ricciardi [46], A. Richards [50], K. Rinnert [49], V. Rives Molina [33], D.A. Roa Romero [5], P. Robbe [7], E. Rodrigues [48,51], P. Rodriguez Perez [34], G.J. Rogers [44], S. Roiser [35], V. Romanovsky [32], A. Romero Vidal [34], J. Rouvinet [36], T. Ruf [35], H. Ruiz [33], G. Sabatino [22,k], J.J. Saborido Silva [34], N. Sagidova [27], P. Sail [48], B. Saitta [15,d], C. Salzmann [37], B. Sanmartin Sedes [34], M. Sannino [19,i], R. Santacesaria [22], C. Santamarina Rios [34], R. Santinelli [35], E. Santovetti [21,k], M. Sapunov [6], A. Sarti [18,l], C. Satriano [22,m], A. Satta [21], M. Savrie [16,e], P. Schaack [50], M. Schiller [39], H. Schindler [35], S. Schleich [9], M. Schlupp [9], M. Schmelling [10], B. Schmidt [35], O. Schneider [36], A. Schopper [35], M.-H. Schune [7], R. Schwemmer [35], B. Sciascia [18], A. Sciubba [18,l], M. Seco [34], A. Semennikov [28], K. Senderowska [24], I. Sepp [50], N. Serra [37], J. Serrano [6], P. Seyfert [11], M. Shapkin [32], I. Shapoval [40,35], P. Shatalov [28], Y. Shcheglov [27], T. Shears [49,35], L. Shekhtman [31], O. Shevchenko [40], V. Shevchenko [28], A. Shires [50], R. Silva Coutinho [45], T. 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