Measurement of the $CP$-violating phase $\phi_s$ in the decay $B_s^0 \to J/\psi \phi$

The LHCb Collaboration

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We present a measurement of the time-dependent CP-violating asymmetry in \(B^0_s \rightarrow J/\psi \phi\) decays, using data collected with the LHCb detector at the LHC. The decay time distribution of \(B^0_s \rightarrow J/\psi \phi\) is characterized by the decay widths \(\Gamma_L\) and \(\Gamma_H\) of the heavy and light mass eigenstates of the \(B^0_s \rightarrow \phi\) system and by a CP-violating phase \(\phi_s\). In a sample of about 8500 \(B^0_s \rightarrow J/\psi \phi\) events isolated from 0.37 fb\(^{-1}\) of pp collisions at \(\sqrt{s} = 7\) TeV we measure \(\phi_s = 0.15 \pm 0.18\) (stat) \(\pm 0.06\) (syst) rad. We also find an average \(B^0_s\) decay width \(\Gamma_s \equiv (\Gamma_L + \Gamma_H)/2 = 0.657 \pm 0.009\) (stat) \(\pm 0.008\) (syst) ps\(^{-1}\) and a decay width difference \(\Delta \Gamma_s \equiv \Gamma_L - \Gamma_H = 0.123 \pm 0.029\) (stat) \(\pm 0.011\) (syst) ps\(^{-1}\). Our measurement is insensitive to the transformation \(\langle \phi_s, \Delta \Gamma_s \rangle \rightarrow (\pi - \phi_s, -\Delta \Gamma_s)\).

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In the Standard Model (SM) CP violation arises through a single phase in the CKM quark mixing matrix \([1]\). In neutral \(B\) meson decays to a final state which is accessible to both \(B\) and \(\bar{B}\) mesons, the interference between the amplitude for the direct decay and the amplitude for decay after oscillation, leads to a time-dependent \(CP\)-violating asymmetry between the decay time distributions of \(B\) and \(\bar{B}\) mesons. The decay \(B^0_s \rightarrow J/\psi \phi\) allows the measurement of such an asymmetry, which can be expressed in terms of the decay width difference of the heavy (H) and light (L) \(B^0_s\) mass eigenstates \(\Delta \Gamma_s \equiv \Gamma_L - \Gamma_H\) and a single phase \(\phi_s\) \([2]\). In the SM, the decay width difference is \(\Delta \Gamma_s^{SM} = 0.087 \pm 0.021\) ps\(^{-1}\) \([3]\), while the phase is predicted to be small, \(\phi_s^{SM} = -2 \text{arg} \left(-V_{ts}^* V_{tb} / V_{ts} V_{tb}^* \right) = -0.036 \pm 0.002\) rad \([4]\). This value ignores a possible contribution from subleading decay amplitudes \([5]\). Contributions from physics beyond the SM could lead to much larger values of \(\phi_s\) \([6]\).

In this Letter we present measurements of \(\phi_s\), \(\Delta \Gamma_s\) and the average decay width \(\Gamma_s \equiv (\Gamma_L + \Gamma_H)/2\). Previous measurements of these quantities have been reported by the CDF and DØ collaborations \([7]\). We use an integrated luminosity of 0.37 fb\(^{-1}\) of pp collision data recorded at a centre-of-mass energy \(\sqrt{s} = 7\) TeV by the LHCb experiment during the first half of 2011. The LHCb detector is a forward spectrometer at the Large Hadron Collider and is described in detail in Ref. \([8]\).

We look for \(B^0_s \rightarrow J/\psi \phi\) candidates in decays to \(J/\psi \rightarrow \mu^+ \mu^-\) and \(\phi \rightarrow K^+ K^-\). Events are selected by a trigger system consisting of a hardware trigger, which selects muon or hadron candidates with high transverse momentum with respect to the beam direction (\(p_T\)), followed by a two stage software trigger. In the first stage a simplified event reconstruction is applied. Events are required to either have two well-identified muons with invariant mass above 2.7 GeV, or at least one muon or one high-\(p_T\) track with a large impact parameter to any primary vertex. In the second stage a full event reconstruction is performed and only events with a muon candidate pair with invariant mass within 120 MeV of the nominal \(J/\psi\) mass \([9]\) are retained. We adopt units such that \(c = 1\) and \(\hbar = 1\).

For the final event selection muon candidates are required to have \(p_T > 0.5\) GeV. \(J/\psi\) candidates are created from pairs of oppositely charged muons that have a common vertex and an invariant mass in the range 3030 – 3150 MeV. The latter corresponds to about eight times the \(\mu^+ \mu^-\) invariant mass resolution and covers part of the \(J/\psi\) radiative tail. The \(\phi\) selection requires two oppositely charged particles that are identified as kaons, form a common vertex and have an invariant mass within \(\pm 12\) MeV of the nominal \(\phi\) mass \([9]\). The \(p_T\) of the \(\phi\) candidate is required to exceed 1 GeV. The mass window covers approximately 90% of the \(\phi \rightarrow K^+ K^-\) lineshape.

We select \(B^0_s\) candidates from combinations of a \(J/\psi\) and a \(\phi\) with invariant mass \(m_B\) in the range 5200 – 5550 MeV. The latter is computed with the invariant mass of the \(\mu^+ \mu^-\) pair constrained to the nominal \(J/\psi\) mass. The decay time \(t\) of the \(B^0_s\) is obtained from a vertex fit that constrains the \(B^0_s \rightarrow \mu^+ \mu^- K^+ K^-\) candidate to originate from the primary vertex \([10]\). The \(\chi^2\) of the fit, which has 7 degrees of freedom, is required to be less than 35. In the small fraction of events with more than one candidate, only the candidate with the smallest \(\chi^2\) is kept. \(B^0_s\) candidates are required to have a decay time within the range \(0.3 < t < 14.0\) ps. Applying a lower bound on the decay time suppresses a large fraction of the prompt combinatorial background whilst having a small effect on the sensitivity to \(\phi_s\). From a fit to the \(m_B\) distribution, shown in Fig. \([1]\) we extract a signal of 8492 \(\pm 97\) events.

The \(B^0_s \rightarrow J/\psi \phi \rightarrow \mu^+ \mu^- K^+ K^-\) decay proceeds via two intermediate spin-1 particles (i.e. with the \(K^+ K^-\) pair in a P-wave). The final state can be \(CP\)-even or \(CP\)-odd depending upon the relative orbital angular momentum between the \(J/\psi\) and the \(\phi\). The same final state can also be produced with \(K^+ K^-\) pairs with zero relative orbital angular momentum (S-wave) \([11]\). This S-wave final state is \(CP\)-odd. In order to measure \(\phi_s\) it is necessary to disentangle the \(CP\)-even and \(CP\)-odd components. This is achieved by analysing the distribution of the reconstructed decay angle \(\Omega = (\theta, \psi, \phi)\) in the transversity basis \([12, 13]\). In the \(J/\psi\) rest frame we define a right-handed coordinate system such that the \(x\) axis is parallel to the direction of the \(\phi\) momentum and the \(z\) axis is parallel to the cross-product of the \(K^-\) and \(K^+\) momenta. In this frame \(\theta\) and \(\phi\) are the azimuthal and polar angles of the \(\mu^+\). The angle \(\psi\) is the angle
The PDFs are factorised into separate components for the mass and for the remaining observables.

The signal $m_B$ distribution is described by two Gaussian functions with a common mean. The mean and width of the narrow Gaussian are fit parameters. The fraction of the second Gaussian and its width relative to the narrow Gaussian are fixed to values obtained from simulated events. The $m_B$ distribution for the combinatorial background is described by an exponential function with a slope determined by the fit. Possible peaking background from decays with similar final states such as $B^0 \rightarrow J/\psi K^{*0}$ is found to be negligible from studies using simulated events.

The distribution of the signal decay time and angles is described by a sum of ten terms, corresponding to the four polarization amplitudes and their interference terms. Each of these is the product of a time-dependent function and an angular function [12].

$$\frac{d^4\Gamma(B^0_s \rightarrow J/\psi \phi)}{dt \, d\Omega} \propto \sum_{k=1}^{10} h_k(t) \, f_k(\Omega).$$

The time-dependent functions $h_k(t)$ can be written as

$$h_k(t) = N_k e^{-\Delta m_s t} \left[ c_k \cos(\Delta m_s t) + d_k \sin(\Delta m_s t) \right] + a_k \, \cos(\frac{1}{2} \Delta \Gamma_s t) + b_k \, \sin(\frac{1}{2} \Delta \Gamma_s t).$$

where $\Delta m_s$ is the $B_s^0$ oscillation frequency. The coefficients $N_k$ and $a_k, \ldots, d_k$ can be expressed in terms of $\phi_s$ and four complex transversity amplitudes $A_i$ at $t = 0$. The label $i$ takes the values $\{\perp, \parallel, 0\}$ for the three $P$-wave amplitudes and $S$ for the $S$-wave amplitude. In the fit we parameterize each $A_i(0)$ by its magnitude squared $|A_i(0)|^2$ and its phase $\delta_i$, and adopt the convention $\delta_0 = 0$ and $\sum |A_i(0)|^2 = 1$. For a particle produced in a $B_s^0$ flavour eigenstate the coefficients in Eq. [2] and the angular functions $f_k(\Omega)$ are then, see [13] [14], given by

| $k$ | $f_k(\theta, \psi, \phi)$ | $N_k$ | $a_k$ | $b_k$ | $c_k$ | $d_k$ |
|-----|-------------------|------|------|------|------|------|
| 1   | $2 \cos^2 \psi (1 - \sin^2 \theta \cos^2 \phi)$ | $|A_0(0)|^2$ | 1    | $-\cos \phi_s$ | 0    | $\sin \phi_s$ |
| 2   | $\sin^2 \psi (1 - \sin^2 \theta \sin^2 \phi)$ | $|A_1(0)|^2$ | 1    | $-\cos \phi_s$ | 0    | $\sin \phi_s$ |
| 3   | $\sin^2 \psi \sin^2 \phi$ | $|A_{1\perp}(0)|^2$ | 1    | $\cos \phi_s$ | 0    | $-\sin \phi_s$ |
| 4   | $-\sin^2 \psi \sin 2 \theta \sin \phi$ | $|A_{1\parallel}(0), A_{1\perp}(0)|$ | 0    | $-\cos(\delta_{\perp} - \delta_{\parallel}) \sin \phi_s$ | $\sin(\delta_{\perp} - \delta_{\parallel})$ | $-\cos(\delta_{\perp} - \delta_{\parallel}) \cos \phi_s$ |
| 5   | $\frac{1}{2} \sqrt{2} \sin 2 \psi \sin^2 \theta \sin \phi$ | $|A_{1\parallel}(0), A_{1\perp}(0)|$ | $\cos(\delta_{\parallel} - \delta_{0})$ | $-\cos(\delta_{\parallel} - \delta_{0}) \cos \phi_s$ | 0    | $\cos(\delta_{\parallel} - \delta_{0}) \sin \phi_s$ |
| 6   | $\frac{1}{2} \sqrt{2} \sin 2 \psi \sin 2 \theta \cos \phi$ | $|A_{1\parallel}(0), A_{1\perp}(0)|$ | 0    | $-\cos(\delta_{\perp} - \delta_{0}) \sin \phi_s$ | $\sin(\delta_{\perp} - \delta_{0})$ | $-\cos(\delta_{\perp} - \delta_{0}) \cos \phi_s$ |
| 7   | $\frac{2}{3} (1 - \sin^2 \theta \cos^2 \phi)$ | $|A_{S}(0)|^2$ | 1    | $\cos \phi_s$ | 0    | $-\sin \phi_s$ |
| 8   | $\frac{1}{2} \sqrt{6} \sin \psi \sin^2 \theta \sin 2 \phi$ | $|A_{S}(0), A_{1\perp}(0)|$ | 0    | $-\sin(\delta_{\parallel} - \delta_{0}) \sin \phi_s$ | $\cos(\delta_{\parallel} - \delta_{0})$ | $-\sin(\delta_{\parallel} - \delta_{0}) \cos \phi_s$ |
| 9   | $\frac{1}{2} \sqrt{6} \sin \psi \sin 2 \theta \cos \phi$ | $|A_{S}(0), A_{1\parallel}(0)|$ | $\sin(\delta_{\parallel} - \delta_{0})$ | $\cos(\delta_{\parallel} - \delta_{0}) \sin \phi_s$ | 0    | $-\sin(\delta_{\parallel} - \delta_{0}) \sin \phi_s$ |
| 10  | $\frac{1}{3} \sqrt{3} \cos \psi (1 - \sin^2 \theta \cos^2 \phi)$ | $|A_{S}(0), A_{0}(0)|$ | 0    | $-\sin(\delta_{0} - \delta_{0}) \sin \phi_s$ | $\cos(\delta_{0} - \delta_{0})$ | $-\sin(\delta_{0} - \delta_{0}) \cos \phi_s$ |

We neglect $CP$ violation in mixing and in the decay amplitudes. The differential decay rates for a $B_s^0$ meson produced at time $t = 0$ are obtained by changing the sign of $\phi_s$, $A_{1\parallel}(0)$ and $A_{S}(0)$, or, equivalently, the sign of $c_k$ and $d_k$ in the expressions above. The PDF is invariant under the transformation $(\phi_s, \Delta \Gamma_s, \delta_{\parallel}, \delta_{\perp}, \delta_{0}) \rightarrow (\pi - \phi_s, -\Delta \Gamma_s, -\delta_{\parallel}, \pi - \delta_{\perp}, -\delta_{0})$ which gives rise to a two-fold ambiguity in the results.
We have verified that correlations between decay time and decay angles in the background are small enough to be ignored. Using the data in the $m_{BS}$ sidebands, which we define as selected events with $m_B$ outside the range $5311 - 5411$ MeV, we determine that the background decay time distribution can be modelled by a sum of two exponential functions. The lifetime parameters and the relative fraction are determined by the fit. The decay angle distribution is modelled using a histogram obtained from the data in the $m_{BS}$ sidebands. The normalisation of the background with respect to the signal is determined by the fit.

The measurement of $\phi_s$ requires knowledge of the flavour of the $B_S^0$ meson at production. We exploit the following flavour specific features of the accompanying (non-signal) $b$-hadron decay to tag the $B_S^0$ flavour: the charge of a muon or an electron with large transverse momentum produced by semileptonic decays, the charge of a kaon from a subsequent charmed hadron decay and the momentum-weighted charge of all tracks included in the inclusively reconstructed decay vertex. These signatures are combined using a neural network to estimate a per-event mistag probability, $\omega$, which is calibrated with data from control channels. The fraction of tagged events in the signal sample is $\varepsilon_{\text{tag}} = (24.9 \pm 0.5)\%$. The dilution of the $CP$ asymmetry due to the mistag probability is $D = 1 - 2\omega$. The effective dilution in our signal sample is $D = 0.277 \pm 0.006$ (stat) $\pm 0.016$ (syst), resulting in an effective tagging efficiency of $\varepsilon_{\text{tag}} D^2 = (1.91 \pm 0.23)\%$. The uncertainty in $\omega$ is taken into account by allowing calibration parameters described in Ref. [15] to vary in the fit with Gaussian constraints given by their estimated uncertainties. Both tagged and untagged events are used in the fit. The untagged events dominate the sensitivity to the lifetimes and amplitudes.

To account for the decay time resolution, the PDF is convolved with a sum of three Gaussian functions with a common mean and different widths. Studies on simulated data have shown that selected prompt $J/\psi K^+ K^-$ combinations have nearly identical resolution to signal events. Consequently, we determine the parameters of the resolution model from a fit to the decay time distribution of such prompt combinations in the data, after subtracting non-$J/\psi$ events with the sPlot method [16] using the $\mu^+ \mu^-$ invariant mass as discriminating variable. The resulting dilution is equivalent to that of a single Gaussian with a width of 50 fs. The uncertainty on the decay time resolution is estimated to be 4% by varying the selection of events and by comparing in the simulation the resolutions obtained for prompt combinations and $B_S^0$ signal events. This uncertainty is accounted for by scaling the widths of the three Gaussians by a common factor of $1.00 \pm 0.04$, which is varied in the fit subject to a Gaussian constraint. In similar fashion the uncertainty on the mixing frequency is taken into account by varying it within the constraint imposed by the LHCb measurement $\Delta m_s = 17.63 \pm 0.11$ (stat) $\pm 0.02$ (syst) ps$^{-1}$ [17].

The decay time distribution is affected by two acceptance effects. First, the efficiency decreases approximately linearly with decay time due to inefficiencies in the reconstruction of tracks far from the central axis of the detector. This effect is parameterized as $\epsilon(t) \propto (1 - \beta t)$ where the factor $\beta = 0.016$ ps$^{-1}$ is determined from simulated events. Second, a fraction of approximately 14% of the events has been selected exclusively by a trigger path that exploits large impact parameters of the decay products, leading to a drop in efficiency at small decay times. This effect is described by the empirical acceptance function $\epsilon(t) \propto (at)^c / [1 + (at)^c]$, applied only to these events. The parameters $a$ and $c$ are determined in the fit. As a result, the events selected with impact parameter cuts do effectively not contribute to the measurement of $\Gamma_s$.

The uncertainty on the reconstructed decay angles is small and is neglected in the fit. The decay angle acceptance is determined using simulated events. The deviation from a flat acceptance is due to the LHCb forward geometry and selection requirements on the momenta of final state particles. The acceptance varies by less than 5% over the full range for all three angles.

The results of the fit for the main observables are shown in Table I. The likelihood profile for $\delta_\parallel$ is not parabolic and we therefore quote the 68% confidence level (CL) range $3.0 < \delta_\parallel < 3.5$. The correlation coefficients for the statistical uncertainties are $\rho(\Gamma_s, \Delta \Gamma_s) = -0.30$, $\rho(\Gamma_s, \delta_s) = 0.12$ and $\rho(\Delta \Gamma_s, \phi_s) = -0.08$. Figure 2 shows the data distribution for decay time and angles with the projections of the best fit PDF overlaid. To assess the overall agreement of the PDF with the data we calculate the goodness of fit based on the point-to-point dissimilarity test [15]. The p-value obtained is 0.68. Figure 3 shows the 68%, 90% and 95% CL contours in the $\Delta \Gamma_s - \phi_s$ plane. These contours are obtained from the likelihood profile after including systematic uncertainties, and correspond to decreases in the natural logarithm of the likelihood, with respect to its maximum, of 1.15, 2.30 and 3.00 respectively.

| parameter      | value  | $\sigma_{\text{stat.}}$ | $\sigma_{\text{syst.}}$ |
|----------------|--------|-------------------------|------------------------|
| $\Gamma_s$ [ps$^{-1}$] | 0.657  | 0.009                   | 0.008                  |
| $\Delta \Gamma_s$ [ps$^{-1}$] | 0.123  | 0.029                   | 0.011                  |
| $|A_\perp(0)|^2$ | 0.237  | 0.015                   | 0.012                  |
| $|A_\parallel(0)|^2$ | 0.497  | 0.013                   | 0.030                  |
| $|A_3(0)|^2$ | 0.042  | 0.015                   | 0.018                  |
| $\delta_\perp$ [rad] | 2.95   | 0.37                    | 0.12                   |
| $\delta_\parallel$ [rad] | 2.98   | 0.36                    | 0.12                   |
| $\phi_s$ [rad] | 0.15   | 0.18                    | 0.06                   |

TABLE I. Fit results for the solution with $\Delta \Gamma_s > 0$ with statistical and systematic uncertainties.
The sensitivity to $\phi_s$ stems mainly from its appearance as the amplitude of the $\sin(\Delta m_s t)$ term in Eq. [1] which is diluted by the decay time resolution and mistag probability. Systematic uncertainties from these sources and from the mixing frequency are absorbed in the statistical uncertainties as explained above. Other systematic uncertainties are determined as follows, and added in quadrature to give the values shown in Table [4].

To test our understanding of the decay angle acceptance we compare the rapidity and momentum distributions of the kaons and muons of selected $B^0_s$ candidates in data and simulated events. Only in the kaon momentum distribution do we observe a significant discrepancy. We reweight the simulated events to match the data, rederive the acceptance corrections and assign the resulting difference in the fit result as a systematic uncertainty. This is the dominant contribution to the systematic uncertainty on all parameters except $\Gamma_s$. The limited size of the simulated event sample leads to a small additional uncertainty. The systematic uncertainty due to the background decay angle modelling was found to be negligible by comparing with a fit where the background was removed statistically using the sPlot method [10].

In the fit each $|A_i(0)|^2$ is constrained to be greater than zero, while their sum is constrained to unity. This can result in a bias if one or more of the amplitudes is small. This is the case for the S-wave amplitude, which is compatible with zero within 3.2 standard deviations. The resulting biases on the $|A_i(0)|^2$ have been determined using simulations to be less than 0.010 and are included as systematic uncertainties.

Finally, a systematic uncertainty of 0.008 ps$^{-1}$ was assigned to the measurement of $\Gamma_s$ due to the uncertainty in the decay time acceptance parameter $\beta$. Other systematic uncertainties, such as those from the momentum scale and length scale of the detector, were found to be negligible.

In summary, in a sample of 0.37 fb$^{-1}$ of $pp$ collisions at $\sqrt{s} = 7$ TeV collected with the LHCb detector we observe $8492 \pm 97 B^0_s \rightarrow J/\psi K^+K^-$ events with $K^+K^-$ invariant mass within $\pm 12$ MeV of the $\phi$ mass. With these data we perform the most precise measurements of $\phi_s$, $\Delta \Gamma_s$ and $\Gamma_s$ in $B^0_s \rightarrow J/\psi \phi$ decays, substantially improving upon previous measurements [7] and providing the first direct evidence for a non-zero value of $\Delta \Gamma_s$. Two solutions with equal likelihood are obtained, related by the transformation $(\phi_s, \Delta \Gamma_s) \rightarrow (\pi - \phi_s, -\Delta \Gamma_s)$. The solution with positive $\Delta \Gamma_s$ is

$$\phi_s = 0.15 \pm 0.18 \text{ (stat) } \pm 0.06 \text{ (syst) rad},$$

$$\Gamma_s = 0.657 \pm 0.009 \text{ (stat) } \pm 0.008 \text{ (syst) ps}^{-1},$$

$$\Delta \Gamma_s = 0.123 \pm 0.029 \text{ (stat) } \pm 0.011 \text{ (syst) ps}^{-1},$$

and is in agreement with the Standard Model prediction [3, 4]. Values of $\phi_s$ in the range $0.52 < \phi_s < 2.62$ and $-2.93 < \phi_s < -0.21$ are excluded at 95% confidence level. In a future publication we shall differentiate between the two solutions by exploiting the dependence of the phase difference between the P-wave and S-wave contributions on the $K^+K^-$ invariant mass [14].

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[1] M. Kobayashi and T. Maskawa, CP Violation in the renormalizable theory of weak interaction, Prog. Theor. Phys. 49 (1973) 652; N. Cabibbo, Unitary symmetry and lepton decays, Phys. Rev. Lett. 10 (1963) 531

[2] A. B. Carter and A. Sanda, CP Violation in cascade decays of B mesons, Phys. Rev. Lett. 45 (1980) 952. A. B. Carter and A. Sanda, CP Violation in B meson decays, Phys. Rev. D23 (1981) 1567. I. I. Bigi and A. Sanda, Notes on the observability of CP violations in B decays, Nucl. Phys. B193 (1981) 85. I. I. Bigi and A. Sanda, CP Violation in heavy flavor decays: predictions and search strategies, Nucl. Phys. B281 (1987) 41

[3] A. Lenz and U. Nierste, Theoretical update of $B^0_s$-antiboson mixing, JHEP 06 (2007) 072. arXiv:hep-ph/0612167. A. Badin, F. Gabbiani, and A. A. Petrov, Lifetime difference in $B_s$ mixing: Standard model and beyond, Phys. Lett. B653 (2007) 230. arXiv:0707.0294. A. Lenz and U. Nierste, Numerical updates of lifetimes and mixing parameters of B mesons, arXiv:1102.4274

[4] J. Charles et al., Predictions of selected flavour observables within the Standard Model, Phys. Rev. D84 (2011) 033005. arXiv:1106.4041

[5] S. Faller, R. Fleischer, and T. Mannel, Precision physics with $B^0_s → J/ψ K^0$ at the LHC: the quest for new physics, Phys. Rev. D79 (2009) 014005. arXiv:0810.4248

For recent overviews see A. J. Buras, PoS EPS-HEP2009 (2009) 024 arXiv:0910.1032 and C.-W. Chiang et al., JHEP 1004 (2010) 031 arXiv:0910.2929 and references therein.

[6] For recent overviews see A. J. Buras, PoS EPS-HEP2009 (2009) 024 arXiv:0910.1032 and C.-W. Chiang et al., JHEP 1004 (2010) 031 arXiv:0910.2929 and references therein.

[7] CDF collaboration, T. Aaltonen et al., First flavor-tagged determination of bounds on mixing-induced CP violation in $B^0_s → J/ψ K^0$ decays, Phys. Rev. Lett. 100 (2008) 161802. arXiv:0712.2397. DØ collaboration, V. Abazov et al., Measurement of $B^0_s$ mixing parameters from the flavor-tagged decay $B^0_s → J/ψ K_s$, Phys. Rev. Lett. 101 (2008) 241801. arXiv:0802.2255. DØ Collaboration, V. M. Abazov et al., Measurement of the CP-violating phase $\phi_{J/ψ K^0}$ using the flavor-tagged decay $B^0_s → J/ψ K^0$ in 8 fb$^{-1}$ of $pp$ collisions. arXiv:1109.3166. CDF Collaboration, T. Aaltonen et al., Measurement of the CP-violating phase $\beta$, in $B^0_s → J/ψ K^0$ decays with the CDF II detector, arXiv:1112.1726

[8] LHCb collaboration, A. A. Alves et al., The LHCb detector at the LHC, JINST 3 (2008) S08005

[9] Particle Data Group, K. Nakamura et al., Review of particle physics, J. Phys. G37 (2010) 075021

[10] W. D. Hulsbergen, Decay chain fitting with a Kalman filter, Nucl. Instrum. Meth. A552 (2005) 566. arXiv:physics/0503191

[11] S. Stone and L. Zhang, S-waves and the measurement of CP-violating phases in $B_s$ decays, Phys. Rev. D79 (2009) 074024. arXiv:0812.2832

[12] A. S. Dighe, I. Dunietz, H. J. Lipkin, and J. L. Rosner, Angular distributions and lifetime differences in $B^0_s → J/ψ K^0$ decays, Phys. Lett. B369 (1996) 144. arXiv:hep-ph/9511363. A. S. Dighe, I. Dunietz, and R. Fleischer, Extracting CKM phases and $B^0_s$-$\bar{B}^0_s$ mixing parameters from angular distributions of nonleptonic $B$ decays, Eur. Phys. J. C6 (1999) 647. arXiv:hep-ph/9804253

[13] I. Dunietz, R. Fleischer, and U. Nierste, In pursuit of new physics with $B_s$ decays, Phys. Rev. D63 (2001) 114015. arXiv:hep-ph/0012219

[14] Y. Xie, P. Clarke, G. Cowan, and F. Muheim, Determination of $2\beta$, in $B_s → J/ψ K^+ K^-$ decays in the presence of a $K^- K^+$ S-Wave contribution, JHEP 09 (2009) 074. arXiv:0908.3627

[15] LHCb collaboration, R. Aaij et al., Flavour tagging of $B$ mesons at LHCb, LHCb-PAPER-2011-027. In preparation. To be submitted to Eur. Phys. J. C.

[16] M. Pivk and F. R. Le Diberder, sPlot: a statistical tool to unfold data distributions, Nucl. Instrum. Meth. A555 (2005) 356. arXiv:physics/0402083

[17] LHCb collaboration, R. Aaij et al., Measurement of the $B^0_s$ - $\bar{B}^0_s$ oscillation frequency $\Delta m_s$ in $B^0_s → D_s^- (3)\pi$ decays, Phys. Lett. B709 (2012) 177. arXiv:1112.4311

[18] M. Williams, How good are your fits? Unbinned multivariate goodness-of- fit tests in high energy physics, JINST 5 (2010) P09004. arXiv:1006.3019