

CP-violating phases in neutral meson oscillations

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Abstract

LHCb is one of the four large experiments at the Large Hadron Collider (LHC) at CERN, Geneva and is dedicated to heavy flavour physics. LHCb searches for New Physics (NP) by performing precision measurements of CP-violating parameters.

One of the key measurements of LHCb is the extraction of the CP-violating weak phase ϕ_s . The Standard Model (SM) prediction for this parameter is small: $\phi_s^{\text{SM}} = -0.0364 \pm 0.0016$ [1]. Possible deviations from this SM prediction may be attributed to NP. The parameter ϕ_s is measured by performing a time-dependent angular analysis of $B_s^0 \rightarrow J/\psi \phi$ decays and independently by a time-dependent analysis of $B_s^0 \rightarrow J/\psi \pi \pi$ decays. A simultaneous fit to both decays yields $\phi_s = -0.002 \pm 0.083$ (stat.) ± 0.027 (syst.). The fitted values of ϕ_s and the lifetime difference $\Delta\Gamma_s$ exhibit a phase ambiguity, which is resolved by performing fits in bins of the K^+K^- invariant mass and looking at the difference in fitted strong phases of P-wave and S-wave contributions. Finally, as a first step towards controlling penguin contributions to $b \rightarrow c(\bar{c}s)$ transitions such as $B_s^0 \rightarrow J/\psi \phi$ decays, a branching ratio measurement of $B_s^0 \rightarrow J/\psi \bar{K}^{*0}$ decays is presented.

In addition to the ϕ_s measurement, two other analyses are presented here. Firstly, preliminary results of the LHCb a_{sl}^s measurement are presented. The second analysis is the measurement of triple product asymmetries in $B_s^0 \rightarrow \phi\phi$ decays.

The branching ratio measurement of $B_s^0 \rightarrow J/\psi \bar{K}^{*0}$ decays is extracted from a dataset with an integrated luminosity of 0.37 fb^{-1} . The results from all other aforementioned analyses are extracted from the full 2011 LHCb data set which has an integrated luminosity of 1.0 fb^{-1} .

1. Introduction

Transitions between the meson flavour eigenstates B_s^0 and \bar{B}_s^0 is a process known as mixing. In the neutral B meson system the time dependence of mixing is governed by a 2×2 complex Hamiltonian matrix [2]

$$\mathbf{H} = \begin{pmatrix} M - \frac{i}{2}\Gamma & M_{12} - \frac{i}{2}\Gamma_{12} \\ M_{12}^* - \frac{i}{2}\Gamma_{12}^* & M - \frac{i}{2}\Gamma \end{pmatrix}, \quad (1)$$

where $M = (M_H + M_L)/2$, with M_H and M_L the eigenvalues of the mass eigenstates. Their mass difference determines the B_s^0 mixing frequency $\Delta m_s = M_H - M_L$. The mass eigenstates have different total decay widths

Γ_L and Γ_H and the total decay width $\Gamma_s = (\Gamma_L + \Gamma_H)/2$ is defined. In the Standard Model (SM) the width difference $\Delta\Gamma_s = \Gamma_L - \Gamma_H$ is expected to be sizeable: $\Delta\Gamma_s = 0.087 \pm 0.021 \text{ ps}^{-1}$ [3]. The leading order diagram for B_s^0 mixing is shown in Fig. 1(a).

The quantities Δm_s and $\Delta\Gamma_s$ are related to the off-diagonal matrix elements of Eq. 1 and the phase $\phi_{M/\Gamma} = \arg(-M_{12}/\Gamma_{12})$ as

$$\begin{aligned} \Delta m_s &= 2|M_{12}| \left(1 - \frac{1}{8} \frac{|\Gamma_{12}|^2}{|M_{12}|^2} \sin^2 \phi_{M/\Gamma} + \dots \right) \\ \Delta\Gamma_s &= 2|\Gamma_{12}| \cos \phi_{M/\Gamma} \left(1 + \frac{1}{8} \frac{|\Gamma_{12}|^2}{|M_{12}|^2} \sin^2 \phi_{M/\Gamma} + \dots \right) \\ a_{\text{sl}}^s &= \frac{\Gamma(\bar{B}_s^0(t) \rightarrow f) - \Gamma(B_s^0(t) \rightarrow \bar{f})}{\Gamma(\bar{B}_s^0(t) \rightarrow f) + \Gamma(B_s^0(t) \rightarrow \bar{f})} = \frac{\Delta\Gamma_s}{\Delta m_s} \tan \phi_{M/\Gamma}, \end{aligned}$$

where f indicates a flavour-specific final state unreach-

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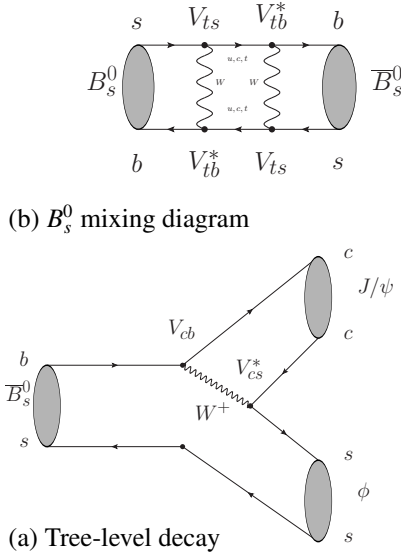


Figure 1: The $\bar{B}_s^0 \rightarrow J/\psi \phi$ decay can occur via a direct decay (a) or via mixing (b) followed by a direct decay.

able by the instantaneous decay of the \bar{B}_s^0 meson and $B_s^0(t)$ is the state into which a produced B_s^0 meson has evolved after a proper time t .

The phase $\phi_{M/\Gamma}$ is tiny in the SM, $\phi_{M/\Gamma} \approx 0.2^\circ$ [4], but can be affected by New Physics (NP) [5, 6]. The D0 collaboration has published evidence for a decay asymmetry in a mixture of \bar{B}^0 and \bar{B}_s^0 semileptonic decays of -0.787 ± 0.172 (stat.) ± 0.093 (syst.) [7]. This asymmetry is much larger in magnitude than the SM predictions of 2×10^{-5} for \bar{B}_s^0 decays and -4×10^{-4} for \bar{B}^0 decays [6]. Preliminary results of the LHCb a_{sl}^s measurement will be presented here.

The CP-violating phase ϕ_s is related to the interference between direct decay amplitudes and amplitudes of decay after mixing (see Fig. 1). When neglecting penguin contributions, which are expected to be small [8], the SM prediction for this phase is $\phi_s^{\text{SM}} = -2\beta_s$, where $\beta_s = \arg(-V_{ts}V_{tb}^*/V_{cs}V_{cb}^*)$ is one of the angles in the $b-s$ unitarity triangle. NP contributions in the box diagram could enhance this phase: $\phi_s = \phi_s^{\text{SM}} \rightarrow \phi_s = \phi_s^{\text{SM}} + \Delta\phi_s^{\text{NP}}$. This means that measuring ϕ_s to high precision is a good probe for NP.

The first LHCb measurement of ϕ_s was presented using a dataset of 0.37 fb^{-1} [9]. That measurement has been updated using the full 2011 dataset of 1.0 fb^{-1} and is presented here.

2. Measurement of ϕ_s using $B_s^0 \rightarrow J/\psi \phi$ Decays

The offline event selection in this updated analysis is the same as the one discussed in [9]. The trigger conditions changed however to a configuration where the first trigger stage does not bias the decay-time distribution whereas the second trigger stage does. In order to remove the majority of the prompt background, only events with decay time $t > 0.3 \text{ ps}$ are used. The remaining background in the sample is of the order of a few percent. A total of 21 200 $B_s^0 \rightarrow J/\psi \phi$ candidates are selected for the final analysis.

2.1. Angular Analysis

Since the B_s^0 meson is a spin-0 particle and the final state $J/\psi \phi$ consists of two vector meson (spin-1) particles, the final state is an admixture of CP-even and CP-odd states. Therefore the analysis can be performed in terms of three transversity amplitudes A_0 , A_{\parallel} (both CP-even) and A_{\perp} (CP-odd) and their associated phases δ_0 , δ_{\parallel} and δ_{\perp} . The final state can also be produced with K^+K^- pairs with zero relative orbital angular momentum. This so-called S-wave component is CP-odd and is parameterized in the analysis by the S-wave fraction f_S and its corresponding phase δ_S . An angular analysis is used to statistically disentangle the CP-even and CP-odd components, as these have an opposite contribution to the value of ϕ_s . The angular acceptance is obtained from fully simulated data. Differences between simulated and observed kaon momentum spectra are used to derive a systematic uncertainty on the angular acceptance.

2.2. Flavour Tagging

The main sensitivity to ϕ_s comes from information on the flavour of the produced B_s^0 meson. This flavour tag is indicated by the tag decision $q = \pm 1$, with a per-event mistag probability w . The analysis presented here makes use of the opposite-side (OS) taggers only. These are calibrated [10] using a $B^+ \rightarrow J/\psi K^+$ sample (of which the true flavour is known) as

$$w = p_0 + p_1(\eta_c - \langle \eta_c \rangle) \quad . \quad (2)$$

Here, p_0 and p_1 are calibration parameters, η_c is the estimated mistag probability and $\langle \eta_c \rangle$ is the average estimated mistag probability. In the final fit, p_0 and p_1 are constrained to float within their uncertainty.

The effective tagging power of the $B_s^0 \rightarrow J/\psi \phi$ sample is defined as

$$Q = \epsilon_{\text{tag}} D^2 = \epsilon_{\text{tag}} (1 - 2w)^2 \quad . \quad (3)$$

For the OS taggers, $Q = (2.29 \pm 0.27)\%$.

2.3. Decay-Time Resolution

To account for the finite decay-time resolution, all time-dependent functions are convolved with a Gaussian distribution. The width of this Gaussian is $S_{\sigma_t} \cdot \sigma_t$, where σ_t is the per-event decay-time resolution, measured from the decay vertex and decay-length uncertainty. The scale factor S_{σ_t} is obtained from a double-Gaussian fit on the decay-time distribution of prompt J/ψ candidates. This result is then translated to a single Gaussian with the same effective dilution, resulting in $S_{\sigma_t} = 1.45 \pm 0.06$ and this scale factor is constrained to float within its uncertainty in the final fit. The effective decay-time resolution is approximately 45 fs.

2.4. Decay-Time Acceptance

The decay-time acceptance introduced by the trigger to enrich the fraction of B events in the sample is obtained from events from a prescaled trigger line, in which no lifetime-biasing cuts are used. In simulation studies a shallow fall in acceptance at high decay time is observed as well, which is attributed to a reduction in track finding efficiency for tracks originating from displaced vertices far from the beam line. A correction of $0.0112 \pm 0.0013 \text{ ps}^{-1}$ on Γ_s is obtained from these studies and is accounted for in the final results.

2.5. Results

The probability density function (PDF) used in the fit consists of signal and background components which include the aforementioned detector resolution and acceptance effects. The distribution of the signal decay time and angles is described in [9]. The background decay time distribution is modeled by a sum of two exponential functions. The lifetime parameters and the relative fractions are determined by the fit. The decay angle distribution is modeled by using a histogram obtained from the data in the m_B sidebands. The values obtained from the fit for all physics parameters are given in Table 1. The parameter Δm_s has been constrained in the fit to float within the uncertainties of an independent LHCb measurement: $\Delta m_s = 17.63 \pm 0.11 \text{ ps}^{-1}$ [11].

The systematic uncertainties quoted in Table 1 account for uncertainties that are not directly treated in the maximum likelihood fit. The uncertainty on ϕ_s is dominated by imperfect knowledge of the angular acceptances and neglecting potential contributions of direct CP violation.

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

Table 1: Fit results for physics parameters in the $B_s^0 \rightarrow J/\psi \phi$ analysis.

3. Resolving the Phase Ambiguity

The PDF is invariant under the transformation $(\phi_s, \Delta\Gamma_s, \delta_\parallel, \delta_\perp, \delta_S) \rightarrow (\pi - \phi_s, -\Delta\Gamma_s, -\delta_\parallel, \pi - \delta_\perp, -\delta_S)$ which gives rise to a twofold ambiguity in the results. This is the reason why for the strong phase δ_\parallel in Table 1 only a symmetric 68% confidence level interval is given, as its fitted value is close to its degenerate value, resulting in a non-parabolic likelihood curve.

The phase ambiguity can be solved by performing the fit of the $B_s^0 \rightarrow J/\psi \phi$ analysis in bins of the $K^+ K^-$ invariant mass. It is expected that, since the S-wave amplitude will remain roughly constant, δ_s will increase slowly as the $K^+ K^-$ invariant mass passes through the $\phi(1020)$ meson, whereas the P-wave strong phase δ_\perp is expected to rise quickly. Therefore the physical solution is the one with a falling trend in $\delta_{S\perp} \equiv \delta_S - \delta_\perp$ as a function of $K^+ K^-$ invariant mass. Fig. 2 shows that the physical solution is the one with $\Delta\Gamma_s > 0$ [12].

4. Measurement of ϕ_s using $\bar{B}_s^0 \rightarrow J/\psi \pi \pi$ Decays

Similar to $B_s^0 \rightarrow J/\psi \phi$ events, decays of the type $\bar{B}_s^0 \rightarrow J/\psi \pi \pi$ are $b \rightarrow c(\bar{c}s)$ transitions and therefore are sensitive to ϕ_s . Although the $\bar{B}_s^0 \rightarrow J/\psi \pi \pi$ branching ratio is smaller than that for $B_s^0 \rightarrow J/\psi \phi$, the advantage of measuring ϕ_s in $\bar{B}_s^0 \rightarrow J/\psi \pi \pi$ decays is the fact the final state is predominantly CP-odd and therefore an angular analysis is not needed. In this analysis, 7421 ± 105 signal candidates are selected. The decay-time resolution is a double-Gaussian with per-event decay-time resolution and the effective decay-time resolution is 40 fs. The effective tagging power Q is found to be $Q = (2.43 \pm 0.08 \pm 0.26)\%$. A time-dependent fit to the data yields a value of $\phi_s = -0.019^{+0.173+0.004}_{-0.174-0.003}$ [13], where the values of Γ_s and $\Delta\Gamma_s$ are constrained to the values from the LHCb $B_s^0 \rightarrow J/\psi \phi$ analysis.

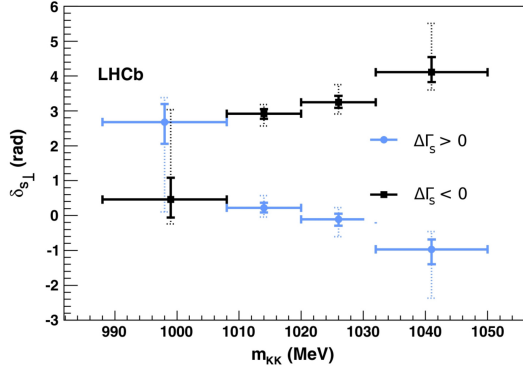


Figure 2: Measured phase differences $\delta_{S\perp}$ between the S -wave strong phase and the perpendicular P -wave strong phase in four bins of m_{KK} for the solution with $\Delta\Gamma_s > 0$ (circles) and the solution with $\Delta\Gamma_s < 0$ (squares). The dotted and solid asymmetric error bars correspond to different confidence levels of the fitted difference, $\delta_{S\perp}$. Figure taken from [12].

5. Combined Measurement of ϕ_s

Combining the LHCb ϕ_s measurements using $\bar{B}_s^0 \rightarrow J/\psi \pi \pi$ and $B_s^0 \rightarrow J/\psi \phi$ decays yields $\phi_s = -0.002 \pm 0.083$ (stat.) ± 0.027 (syst.). The measurements of the CDF, D0 and LHCb collaborations are summarized in Fig. 3. The combined contour is in agreement with the SM predictions [14].

6. BR Measurement of $B_s^0 \rightarrow J/\psi \bar{K}^{*0}$

A simultaneous analysis of the decays $B_s^0 \rightarrow J/\psi \phi$ and $B_s^0 \rightarrow J/\psi \bar{K}^{*0}$ with $\bar{K}^{*0} \rightarrow K^- \pi^+$ and $J/\psi \rightarrow \mu^+ \mu^-$, allows to control penguin effects in $B_s^0 \rightarrow J/\psi \phi$ and their impact on the extraction of the CP-violating phase ϕ_s [8]. The $B_s^0 \rightarrow J/\psi \bar{K}^{*0}$ branching ratio measurement presented here is an update of an earlier branching ratio measurement of this decay by LHCb [16] and is the average of the branching fraction for B_s^0 and \bar{B}_s^0 with \bar{K}^{*0} and K^{*0} in the final state, respectively. The $B_s^0 \rightarrow J/\psi \bar{K}^{*0}$ branching ratio is related to $\mathcal{B}(B_d^0 \rightarrow J/\psi K^{*0})$ assuming that the light quark (s, d) is the spectator quark of the b decay. Using a dataset of 0.37 fb^{-1} , 114 events are selected and the branching ratio is measured to be $\mathcal{B}(B_s^0 \rightarrow J/\psi \bar{K}^{*0}) = 4.42_{-0.44}^{+0.46}$ (stat.) ± 0.80 (syst.) $\times 10^{-5}$.

7. a_{sl}^s Measurement

The CP-violating asymmetry a_{sl}^s is studied using a sample of B_s^0 and \bar{B}_s^0 semileptonic (sl) decays. The studied final states are $D_s^\pm \mu^\mp$ with D_s^\pm reconstructed in the

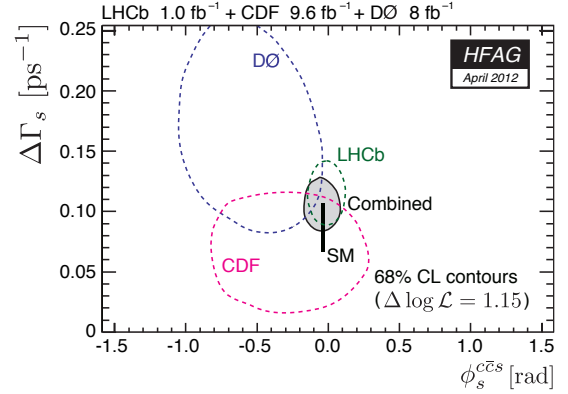


Figure 3: 68% confidence level contours in the $(\phi_s, \Delta\Gamma_s)$ plane from the D0 collaboration, the CDF collaboration, the LHCb collaboration and the combined contour (grey area). The SM prediction is also indicated. Figure taken from [15].

$\phi\pi^\pm$ mode. The $D_s^\pm \mu^\mp$ yields are summed over untagged \bar{B}_s^0 and B_s^0 initial states and integrated with respect to decay time. Therefore, to first order in a_{sl}^s , the measured asymmetry $A_{\text{meas.}}$ is

$$A_{\text{meas.}} = \frac{\Gamma(D_s^- \mu^+) - \Gamma(D_s^+ \mu^-)}{\Gamma(D_s^- \mu^+) + \Gamma(D_s^+ \mu^-)} = \frac{a_{\text{sl}}^s}{2} + \left(a_p - \frac{a_{\text{sl}}^s}{2} \right) \frac{\int_{t=0}^{\infty} e^{-\Gamma_s t} \cos(\Delta m_s t) \epsilon(t) dt}{\int_{t=0}^{\infty} e^{-\Gamma_s t} \cosh \frac{\Delta \Gamma_s t}{2} \epsilon(t) dt}, \quad (4)$$

where $\epsilon(t)$ is the decay-time acceptance and a_p is the production asymmetry. Due to the large value of Δm_s , the oscillations are rapid and the integral ratio in Eq. 4 for the case of $\bar{B}_s^0 \rightarrow D_s^+ X \mu^- \bar{\nu}$ is only 0.2% and is therefore neglected. Finally, the measured asymmetry will be determined by evaluating the ratio

$$A_{\text{meas.}} = \frac{N(D_s^- \mu^+) - N(D_s^+ \mu^-) \cdot \frac{\epsilon(D_s^- \mu^+)}{\epsilon(D_s^+ \mu^-)}}{N(D_s^- \mu^+) + N(D_s^+ \mu^-) \cdot \frac{\epsilon(D_s^- \mu^+)}{\epsilon(D_s^+ \mu^-)}}, \quad (5)$$

where $N(D_s^- \mu^+)$ and $N(D_s^+ \mu^-)$ are measured yields of $D_s \mu$ pairs and $\epsilon(D_s^- \mu^+)$ and $\epsilon(D_s^+ \mu^-)$ are the efficiency corrections including trigger, tracking and muon identification effects. Detector asymmetries are minimized by reversing the spectrometer polarity on a regular basis.

From the corrected yields according to Eq. 5 and using Eq. 4, it is found that $a_{\text{sl}}^s = (-0.24 \pm 0.54 \pm 0.33)\%$ [17]. This is in agreement with the SM prediction $a_{\text{sl}}^s = (1.9 \pm 0.3) \times 10^{-5}$ [6]. Fig. 4 shows the LHCb measurement in the $(a_{\text{sl}}^d, a_{\text{sl}}^s)$ plane. In addition, the D0 dimuon asymmetry measurement that indicates a deviation from the predicted SM value is shown.

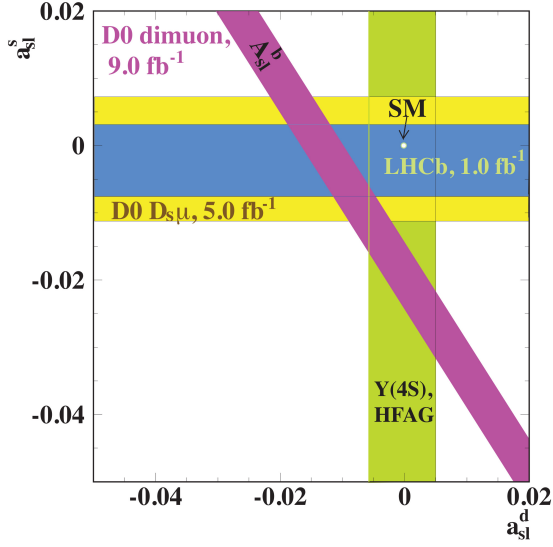


Figure 4: Measurements of semileptonic decay asymmetries. Shown are the D^0 dimuon asymmetry measurement (diagonal band) [18], the $D^0 D_s \mu$ measurement (outer horizontal band) [19], the LHCb $D_s \mu$ measurement (inner horizontal band) as presented here [17] and the average value of a_{sl}^d from $\Upsilon(4S)$ measurements (vertical band) [15]. The bands correspond to the central values ± 1 standard deviation, defined as the quadrature of the statistical and systematic errors.

8. Triple Product Asymmetries in $B_s^0 \rightarrow \phi \phi$ Decays

The final measurement that is presented here is a measurement of the triple product asymmetries in $B_s^0 \rightarrow \phi \phi$ decays. This decay is a $b \rightarrow s \bar{s} s$ penguin process. In the SM, the value of $\phi_s^{\prime 1}$ in this mode is expected to be very close to zero due to a cancellation between the phases arising from mixing and decay [20].

Studies of the triple product asymmetries in these decays provide powerful tests for the presence of contributions from processes beyond the SM [21]. Non-zero values of triple product asymmetries can be either due to T violation or final-state interactions. Assuming CPT conservation, the former case implies that CP is violated. Experimentally, the extraction of the triple product asymmetries is straightforward and provides a measure of CP violation that does not require flavour tagging or a time-dependent analysis. There are two observable triple products, defined as $U = \sin(2\Phi)/2$ and $V = \pm \sin(\Phi)$. Here, Φ is the angle between the two ϕ meson decay planes and the sign in V is chosen positive

¹The notation ϕ_s^{\prime} is used here to avoid confusion with the parameter ϕ_s in $B_s^0 \rightarrow J/\psi \phi$ decays. The definition is similar however as ϕ_s^{\prime} refers to the weak phase difference measured in $B_s^0 \rightarrow \phi \phi$ decays.

if the T-even quantity $\cos \theta_1 \cos \theta_2 \geq 0$ and negative otherwise, where θ_i is the angle between the positive kaon and the decay axis in the ϕ_i meson rest frame. As these quantities are products of three momentum vectors, they are CP-odd. A measurement of significant asymmetries, defined as $A_{U,V} = \frac{N_+ - N_-}{N_+ + N_-}$, where N_+ (N_-) is the number of events with $U, V > 0$ ($U, V < 0$), would therefore be an unambiguous signal for the effects of NP.

The triple product asymmetries in this mode are measured to be [22]

$$A_U = -0.055 \pm 0.036 (\text{stat.}) \pm 0.018 (\text{syst.}) \quad (6)$$

$$A_V = 0.010 \pm 0.036 (\text{stat.}) \pm 0.018 (\text{syst.}) \quad (7)$$

Both values are in agreement with those reported by the CDF collaboration [23] and with the hypothesis of CP conservation.

9. Summary

LHCb has presented the world's best measurement of the weak phase ϕ_s by combining the analyses of $B_s^0 \rightarrow J/\psi \phi$ and $\bar{B}_s^0 \rightarrow J/\psi \pi \pi$ decays. The measured value is $\phi_s = -0.002 \pm 0.083 (\text{stat.}) \pm 0.027 (\text{syst.})$. In addition, LHCb measured $\Delta\Gamma_s = 0.116 \pm 0.018 (\text{stat.}) \pm 0.006 (\text{syst.})$, which is the first observation of non-zero $\Delta\Gamma_s$. The phase ambiguity in the ϕ_s measurement has been resolved by fitting in multiple bins of the $K^+ K^-$ invariant mass and measuring the strong-phase difference between perpendicularly polarized P-wave and S-wave contributions in every bin, from which it was established that $\Delta\Gamma_s > 0$. In order to control penguin contributions to $B_s^0 \rightarrow J/\psi \phi$ decays, a simultaneous fit where $B_s^0 \rightarrow J/\psi \bar{K}^{*0}$ decays are included should be performed. The first step towards such a simultaneous fit is the measurement of the branching ratio of $B_s^0 \rightarrow J/\psi \bar{K}^{*0}$ decays: $\mathcal{B}(B_s^0 \rightarrow J/\psi \bar{K}^{*0}) = 4.42^{+0.46}_{-0.44} (\text{stat.}) \pm 0.80 (\text{syst.}) \times 10^{-5}$. LHCb also performed its first measurement of the CP-violating asymmetry a_{sl}^s and found a result in agreement with the SM: $a_{sl}^s = (-0.24 \pm 0.54 \pm 0.33)\%$. Finally, triple product asymmetries in $B_s^0 \rightarrow \phi \phi$ decays were studied and no indications of CP violation were observed.

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