CP violation in two- and quasi-two-body charmless B decays at LHCb

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Abstract. Recent results of CP violation measurements in two- and quasi-two-body charmless B meson decays at LHCb are highlighted. The measurement of the CP-violating weak phase \( \phi \) from the decay \( B^0_s \to (K^+\pi^-)(K^-\pi^+) \) is discussed, as well as the CP-violating phase \( \phi_s^\tau \) from the \( B^0 \to \phi \phi \) decay. In addition, the \( B^0_s \to \phi \phi \) analysis includes the measurement of triple product asymmetries, probing for T violation. The final analysis presented measures CP violation in a time-integrated, untagged method using \( B^0(s) \to hh' \) decays.

1. Introduction

The LHCb collaboration excels in studies of CP violation. The LHCb detector is a forward single-arm spectrometer with a pseudorapidity acceptance, \( \eta \), between 2 and 5, optimised to the \( B \) meson production angle. The excellent particle identification and track reconstruction, typical flavour tagging power between 4 – 8\% and decay time resolution of roughly 45 fs are properties that are related to measurements of CP violation. These measurements can display effects of physics beyond the Standard Model (SM) by uncovering inconsistencies with respect to either the theoretical predictions based on the SM or other independent measurements of the same SM quantities.

2. \( \phi_s^{\tau} \) weak phase in \( B^0_s \to (K^+\pi^-)(K^-\pi^+) \) decays

Both the \( B^0_s \to (K^+\pi^-)(K^-\pi^+) \) and \( B^0 \to \phi \phi \) decays are flavour changing neutral currents (FCNCs) dominated by gluonic penguin decays. They are sensitive to direct CP violation as well as CP violation in interference between decay and mixing. The latter gives rise to the CP-violating weak phase, \( \phi_s^{\tau} \), which is defined as \( \phi_s^{\tau} = -2\beta_s = \Phi_M - 2\Phi_D \). Here, \( \Phi_M \) is the phase induced by mixing and \( \Phi_D \) is the phase from direct decay. The SM predictions for the weak phase are small [1], but larger values are possible in certain beyond the SM theories [2].

The \( B^0 \to (K^+\pi^-)(K^-\pi^+) \) analysis [3] considers nine different quasi-two-body decays, as outlined in Table 1, using pp collision data corresponding to an integrated luminosity of 3 fb\(^{-1}\), collected at centre-of-mass energies of 7 and 8 TeV. A time-dependent angular analysis is required to disentangle these contributions and their polarisation amplitudes. The \( K\pi \) mass window from 750 to 1600 MeV/c\(^2\) is considered.

The parameters used in the time-dependent angular fit are the CP-averaged fractions of amplitudes, \( f_i \), the CP-conserving strong phases, \( \delta_i \), the CP-violating weak phase, \( \phi_s^{\tau} \), and the direct CP violation is given by \( |\lambda| \). The number of amplitudes in the fit depends on the final state...
Table 1. Quasi-two-body decay channels and corresponding polarisation amplitudes contributing to the $B_s^0 \rightarrow (K^+\pi^-)(K^-\pi^+)$ final state in the $K\pi$ mass window from 750 to 1600 MeV/$c^2$. The table lists the modes, the spin of the final particles ($j_1, j_2$), the allowed helicity values ($h$) and the number of amplitudes per contribution.

| Decay            | Mode         | $j_1$ | $j_2$ | Allowed values of $h$ | Number of amplitudes |
|------------------|--------------|-------|-------|-----------------------|-----------------------|
| $B_s^0 \rightarrow (K^+\pi^-)\overline{B}_s^0(\pi^-\pi^+)$ | scalar-scalar | 0     | 0     | 0, 0                 | 1                     |
| $B_s^0 \rightarrow (K^+\pi^-)K^+(892)^0$ | scalar-vector | 0     | 1     | 0                     | 1                     |
| $B_s^0 \rightarrow K^*(892)^0(\pi^-\pi^+)$ | vector-scalar | 1     | 0     | 0                     | 1                     |
| $B_s^0 \rightarrow (K^+\pi^-)K^*_2(1430)^0$ | scalar-tensor | 0     | 2     | 0                     | 1                     |
| $B_s^0 \rightarrow K^*_2(1430)^0K^*(892)^0$ | tensor-scalar | 2     | 0     | 0                     | 1                     |
| $B_s^0 \rightarrow K^*_2(1430)^0K^*_2(1430)^0$ | tensor-tensor | 2     | 2     | 0                    | 5                     |

particles, where only one amplitude arises if at least one of the final particles is a scalar, three amplitudes occur in the case of vector-vector or vector-tensor final states, and the tensor-tensor contribution has five amplitudes.

Figure 1. One-dimensional projections of the $B_s^0 \rightarrow (K^+\pi^-)(K^-\pi^+)$ fit to (a), (b) the two ($K\pi$) invariant masses, (c), (d) the two ($K\pi$) decay angles $\cos(\theta_1)$ and $\cos(\theta_2)$, (e) the angle between the two ($K\pi$) decay planes, $\phi$, and (f) the decay-time. The top solid line represents the total fit along with the $CP$-averaged components for each contributing decay as outlined in Figure (a).

The time-dependent angular fits are shown in Figure 1. It is the first time the weak phase in a $b \rightarrow d\bar{s}$ transition has been measured. It is found to be $\phi_s^{d\bar{s}} = -0.10 \pm 0.13 \pm 0.14$[rad] where the first uncertainty is statistical and the second uncertainty is systematic. The largest systematic
uncertainty on the $\phi_d^d$ measurement stems from the acceptance, taken from simulated samples. Direct CP violation in these decays is measured as $|\lambda| = 1.035 \pm 0.034 \pm 0.089$. These results are in agreement with SM predictions.

3. $\phi_s^s$ weak phase in $B^0_s \to \phi\phi$ decays

The $B^0_s \to \phi\phi$ decay [4] is a pseudoscalar decaying to two vectors. This analysis is based on $pp$ collision data corresponding to an integrated luminosity of 5.0 fb$^{-1}$ collected by the LHCb experiment at centre-of-mass energies $\sqrt{s} = 7$ TeV in 2011, 8 TeV in 2012, and 13 TeV from 2015 to 2016. The $\phi\phi$ final state gives rise to P-wave contributions. However, due to the proximity of the $f_0(980)$ resonance to the $\phi$ meson, the analysis consists of P-wave, CP-even S-wave ($f_0 f_0$), CP-odd S-wave ($\phi f_0$) and interference terms. A time-dependent angular analysis is required to disentangle these contributions. The free parameters in the time-dependent fit are the polarisation amplitudes, $A_{||}$, $A_{\perp}$, $A_0$, $A_s$ and $A_{ss}$ and the CP conserving strong phases, $\delta_1$, $\delta_2$, $\delta_s$ and $\delta_{ss}$. In addition, the CP-violating weak phase $\phi_s^s$ and the direct CP violation parameter $|\lambda|$ are measured.

Figure 2. One-dimensional projections of the $B^0_s \to \phi\phi$ fit for (a) the decay time, (b) the angle between the two $\phi$ decay particles, $\Phi$, and (c), (d) the cosine of helicity angles $\theta_1$ and $\theta_2$. The background-subtracted data are given by the black points. The blue solid lines represents the projections of the best fit. The CP-even P-wave, the CP-odd P-wave and S-wave combined with double S-wave components are shown by the red long dashed, green short dashed and purple dot-dashed lines, respectively.

The final time-dependent angular fit includes the decay-time resolution, flavour tagging input (5.8% effective tagging power), angular acceptance and decay-time acceptance. The $B^0_s$ decay widths [5] and the $B^0_s$ oscillation frequency [6] are Gaussian constrained to previous measurements. The results of the fit can be found in Figure 2. The CP-violating phase $\phi_s^s$ is measured as $\phi_s^s = -0.06 \pm 0.13 \pm 0.03$[rad] and the direct CP violation parameter is $|\lambda| = 1.02 \pm 0.05 \pm 0.03$ where the first uncertainties are statistical and the second uncertainties are systematic. The largest systematic uncertainty on the $\phi_s^s$ measurement comes from the fit bias. These measurements of the CP-violating phase and CP-violating parameters are in agreement with previous LHCb measurements [7] and the SM predictions.
In addition to the time-dependent angular analysis, the triple product asymmetries $A_U$ and $A_V$ are measured in a decay time untagged method. These asymmetries are a probe for time (T) violation, which implies CP violation if CPT conservation is assumed. The observables U and V are defined in terms of the helicity angles: $U = \cos \Phi \times \sin \Phi$ and $V = \eta_b \times \sin \Phi$, where $\eta_b = 1$ if $\cos (\theta_1) \times \cos (\theta_2) < 0$, and $\eta_b = -1$ otherwise. The asymmetries are defined in Equation 1.

$$A_U = \frac{N(U > 0) - N(U < 0)}{N(U > 0) + N(U < 0)},$$
$$A_V = \frac{N(V > 0) - N(V < 0)}{N(V > 0) + N(V < 0)}. \tag{1}$$

The asymmetries are measured through a simultaneous fit to the datasets according to the sign of the U(V) observable. The Run 2 results are $A_U = 0.3 \pm 1.6 \pm 0.5\%$ and $A_V = 1.0 \pm 1.6 \pm 0.5\%$ where in both cases the first uncertainty is statistical and the second uncertainty is systematic. These results are in agreement with T conservation. Note that this does not imply that there is no CP violation.

4. CP-asymmetries in $B^0_{(s)} \rightarrow hh'$

The $B^0_{(s)} \rightarrow hh'$ analysis [8] covers four different final states. The $B^0_s \rightarrow K^+K^-$ and $B^0 \rightarrow \pi^+\pi^-$ decays require a time-dependent analysis, which allows for a measurement of the CP asymmetries as a function of decay time. However, the $B^0 \rightarrow K^+\pi^-$ and $B^0_s \rightarrow \pi^+K^-$ decays can be analysed using a time-integrated measurement. The decays have tree contributions as well as penguin contributions, which could include sources of physics beyond the standard model. The analysis uses pp collision data corresponding to an integrated luminosity of 3 fb$^{-1}$, collected at centre-of-mass energies of 7 and 8 TeV. A simultaneous fit is performed to the $\pi\pi$, $KK$ and $K\pi$ masses, using a flavour-tagged and decay-time dependent fit. In addition, the decay-time acceptance and decay-time resolution are included.

![Figure 3. Time-dependent asymmetries for ($K^±\pi^\mp$) candidates with an invariant mass between 5200 MeV/$c^2$ and 5320 MeV/$c^2$ (a) using the OS-tagging decision and (b) the SS-tagging decision. The line shows the results of the simultaneous fit.](image)

The CP asymmetries for the time-dependent measurement are given in Equation 2, where the observable $C_f = \frac{1 - |\lambda_f|^2}{1 + |\lambda_f|^2}$ quantises the amount of CP violation in decay and $S_f = \frac{2\Im \lambda_f}{1 + |\lambda_f|^2}$ gives the CP violation present in interference between decay and mixing. The decay time asymmetry, $A_f^\Delta$ is given by $A_f^\Delta = \frac{-2\Im \lambda_f}{1 + |\lambda_f|^2}$. For the time-integrated measurements, the observable is given by Equation 3.
\[ A_{CP}(t) = \frac{\Gamma_{B_0^0 \to f(t)} - \Gamma_{B_0^0 \to f(t)}}{\Gamma_{B_0^0 \to f(t)} + \Gamma_{B_0^0 \to f(t)}} = -C_f \cos(\Delta m_{d,s} t + S_f \sin(\Delta m_{d,s} t)) \frac{\Delta \Gamma_f}{\Delta \Gamma_f} \sinh(\frac{\Delta \Gamma_f}{2} t) + A_{\Delta \Gamma_f} \sinh(\frac{\Delta \Gamma_f}{2} t) \] (2)

\[ A_{CP} = \frac{|\bar{A}_f| - |A_f|^2}{|\bar{A}_f|^2 + |A_f|^2} \] (3)

The result of the fit to the time-dependent asymmetries of the \((K\pi)\) mass candidates is shown in Figure 3. Similar fits are performed to the \((KK)\) and \((\pi\pi)\) mass candidates.

The results of this analysis, where the first quoted uncertainty is statistical, and the second is systematic in all cases, are shown in Equation 4.

\[ C_{\pi^+\pi^-} = -0.34 \pm 0.06 \pm 0.01, \]
\[ S_{\pi^+\pi^-} = -0.63 \pm 0.05 \pm 0.01, \]
\[ C_{KK} = 0.20 \pm 0.06 \pm 0.02, \]
\[ S_{KK} = 0.18 \pm 0.06 \pm 0.02, \]
\[ A_{\Delta \Gamma_{KK}} = -0.79 \pm 0.07 \pm 0.10, \]
\[ A_{B_0^0} = -0.084 \pm 0.004 \pm 0.003, \]
\[ A_{B_0^0} = 0.213 \pm 0.015 \pm 0.007. \] (4)

The measurements of \(C_{\pi\pi}, S_{\pi\pi}, A_{CP}^{B_0^0}\) and \(A_{CP}^{B_0^0}\) are the most precise measurements from a single experiment. \(C_{KK}\) and \(S_{KK}\) are in agreement with previous LHCb results. There is a 4σ deviation of \((C_{KK}, S_{KK}, A_{\Delta \Gamma_{KK}})\) from \((0, 0, -1)\), which is the strongest evidence of time-dependent \(CP\) violation in the \(B_0^0\) meson sector to date. In addition, these measurements allow for improved constraints on the CKM matrix unitarity triangle angles.

5. Conclusion

There are many interesting \(CP\) violation results in the charmless \(B\) physics sector at LHCb, of which three recent results have been outlined in this report. LHCb currently leads the world sensitivity in several of these measurements. All results obtained so far are in agreement with the SM predictions. However, an interesting future lies ahead as the data currently being taken can be added to these analyses. In addition, more data will be taken after the upcoming LHCb Upgrade I.

References

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