Journal of Physics: Conference Series

PAPER • OPEN ACCESS

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

To cite this article: Emmy Gabriel and LHCb Collaboration 2019 *J. Phys.: Conf. Ser.* **1137** 012056

IOP Conf. Series: Journal of Physics: Conf. Series **1137** (2019) 012056 doi:10.1088/1742-6596/1137/1/012056

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

Emmy Gabriel

University of Edinburgh, Edinburgh, UK

E-mail: emmy.gabriel@cern.ch

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 $\phi_s^{d\bar{d}}$ from the decay $B_s^0 \to (K^+\pi^-)(K^-\pi^+)$ is discussed, as well as the CP-violating phase $\phi_s^{s\bar{s}}$ from the $B_s^0 \to \phi\phi$ decay. In addition, the $B_s^0 \to \phi\phi$ 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, η, 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. $\phi_s^{d\bar{d}}$ weak phase in $B_s^0 \to (K^+\pi^-)(K^-\pi^+)$ decays

Both the $B_s^0 \to (K^+\pi^-)(K^-\pi^+)$ and $B_s^0 \to \phi\phi$ 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, $\phi_s^{q\bar{q}}$, which is defined as $\phi_s^{q\bar{q}} = -2\beta_s = \Phi_M - 2\Phi_D$. Here, Φ_M is the phase induced by mixing and Φ_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 $B_s^0 \to (K^+\pi^-)(K^-\pi^+)$ 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, δ_i, the CP-violating weak phase, $\phi_s^{d\bar{d}}$, and the direct CP violation is given by $|\lambda|$. The number of amplitudes in the fit depends on the final state

IOP Conf. Series: Journal of Physics: Conf. Series **1137** (2019) 012056 doi:10.1088/1742-6596/1137/1/012056

Table 1. Quasi-two-body decay channels and corresponding polarisation amplitudes contributing to the $B_s^0 \to (K^+\pi^-)(K^-\pi^+)$ 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 (j1, j2), 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
$B_s^0 \to (K^+\pi^-)_0^*(K^-\pi^+)_0^*$	scalar-scalar	0	0	0	1
$B_s^0 \to (K^+\pi^-)_0^*\overline{K}^*(892)^0$	scalar-vector	0	1	0	1
$B_s^0 \to K^*(892)^0(K^-\pi^+)_0^*$	vector-scalar	1	0	0	1
$B_s^0 \to (K^+\pi^-)_0^*\overline{K}_2^*(1430)^0$	scalar-tensor	0	2	0	1
$B_s^0 \to K_2^*(1430)^0(K^-\pi^+)_0^*$	tensor-scalar	2	0	0	1
$B_s^0 \to K^*(892)^0\overline{K}^*(892)^0$	vector-vector	1	1	0, $\parallel$, $\perp$	3
$B_s^0 \to K^*(892)^0\overline{K}_2^*(1430)^0$	vector-tensor	1	2	0, $\parallel$, $\perp$	3
$B_s^0 \to K_2^*(1430)^0\overline{K}^*(892)^0$	tensor-vector	2	1	0, $\parallel$, $\perp$	3
$B_s^0 \to K_2^*(1430)^0\overline{K}_2^*(1430)^0$	tensor-tensor	2	2	0, $\parallel_1$, $\perp_1$, $\parallel_2$, $\perp_2$	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.

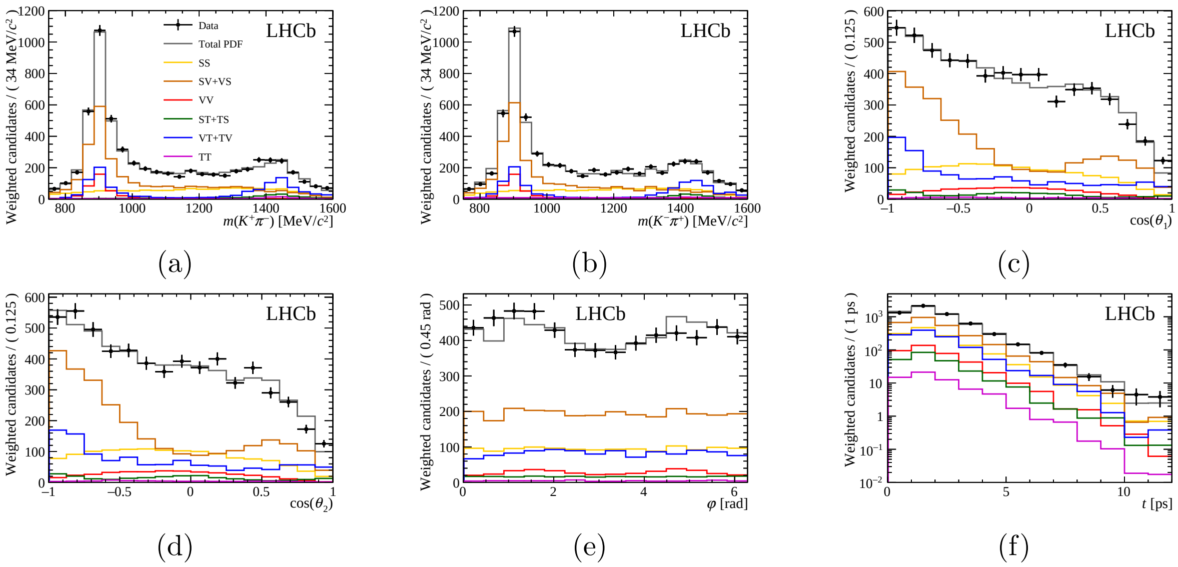
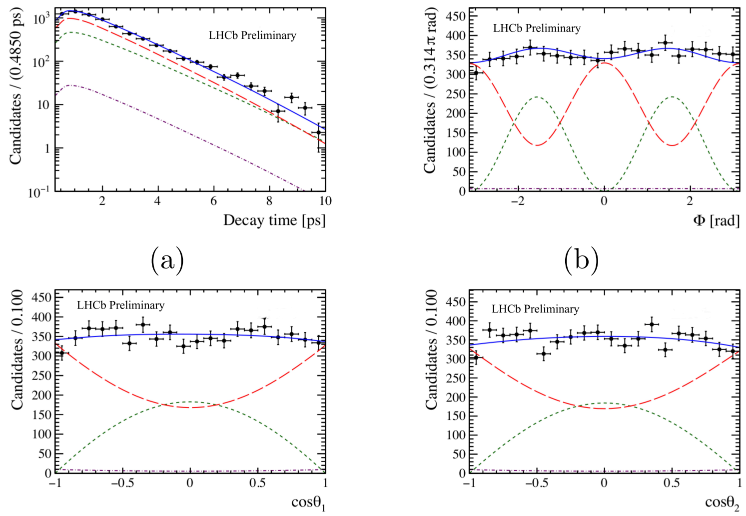


Figure 1. One-dimensional projections of the $B_s^0 \to (K^+\pi^-)(K^-\pi^+)$ fit to (a), (b) the two (Kπ) invariant masses, (c), (d) the two (Kπ) decay plane angles $\cos(\theta_1)$ and $\cos(\theta_2)$, (e) the angle between the two (Kπ) decay planes, ϕ, and (f) the decay-time. The top solid line represents 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 $b \to d\bar{d}$ transition has been measured. It is found to be $\phi_s^{d\bar{d}} = -0.10 \pm 0.13 \pm 0.14$[rad] where the first uncertainty is statistical and the second uncertainty is systematic. The largest systematic uncertainty on the $\phi_s^{d\bar{d}}$ 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. $\phi_s^{s\bar{s}}$ weak phase in $B_s^0 \to \phi\phi$ decays

The $B_s^0 \to \phi\phi$ decay [4] is a pseudoscalar decaying to two vectors. This analysis is based on *pp* collision data corresponding to an integrated luminosity of $5.0\,\mathrm{fb}^{-1}$ collected by the LHCb experiment at centre-of-mass energies $\sqrt{s} = 7\,\mathrm{TeV}$ 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 ϕ meson, the analysis consists of P-wave, *CP*-even S-wave ($f_0 f_0$), *CP*-odd S-wave (ϕf_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, $A_\parallel$, $A_\perp$, A_0, A_s and A_{ss} and the *CP* conserving strong phases, δ_1, δ_2, δ_s and δ_{ss}. In addition, the *CP*-violating weak phase $\phi_s^{s\bar{s}}$ and the direct *CP* violation parameter $|\lambda|$ are measured.



(a) (b) (c) (d)

Figure 2. One-dimensional projections of the $B_s^0 \to \phi\phi$ fit for (a) the decay time, (b) the angle between the two ϕ decay particles, Φ, and (c), (d) the cosine of helicity angles θ_1 and θ_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_s^0 decay widths [5] and the B_s^0 oscillation frequency [6] are Gaussian constrained to previous measurements. The results of the fit can be found in Figure 2. The *CP*-violating phase $\phi_s^{s\bar{s}}$ is measured as $\phi_s^{s\bar{s}} = -0.06 \pm 0.13 \pm 0.03$[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 $\phi_s^{s\bar{s}}$ 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.

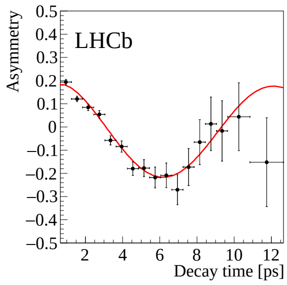
In addition to the time-dependent angular analysis, the triple product asymmetries A_U and A_V are measured in a decay time untagged method. These asymmetries are a probe for time (T) violation, which implies *CP* violation if *CPT* conservation is assumed. The observables U and V are defined in terms of the helicity angles: $U = \cos\Phi \times \sin\Phi$ and $V = \eta_\theta \times \sin\Phi$, where $\eta_\theta = 1$ if $\cos(\theta_1) \times \cos(\theta_2) < 0$, and $\eta_\theta = -1$ otherwise. The asymmetries are defined in Equation 1.

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

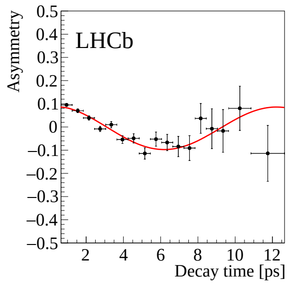
The asymmetries are measured through a simultaneous fit to the datasets according to the sign of the U(V) observable. The Run 2 results are $A_U = 0.3 \pm 1.6 \pm 0.5\%$ and $A_V = 1.0 \pm 1.6 \pm 0.5\%$ where in both cases the first uncertainty is statistical and the second uncertainty is systematic.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

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

The $B^0_{(s)} \to hh'$ analysis [8] covers four different final states. The $B^0_s \to K^+K^-$ and $B^0 \to \pi^+\pi^-$ decays require a time-dependent analysis, which allows for a measurement of the *CP* asymmetries as a function of decay time. However, the $B^0 \to K^+\pi^-$ and $B^0_s \to \pi^+K^-$ 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 $3\,\text{fb}^{-1}$, 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.



(a)



(b)

Figure 3. Time-dependent asymmetries for $(K^\pm\pi^\mp)$ 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.

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 $S_f = \frac{2\text{Im}\lambda_f}{1+|\lambda_f|^2}$ gives the *CP* violation present in interference between decay and mixing. The decay time asymmetry, $A_f^{\Delta\Gamma}$ is given by $A_f^{\Delta\Gamma} = -\frac{2\text{Re}\lambda_f}{1+|\lambda_f|^2}$. For the time-integrated measurements, the observable is given by Equation 3.

$$A_{CP}(t) = \frac{\Gamma_{\bar{B}^0_{(s)}\to f}(t) - \Gamma_{B^0_{(s)}\to f}(t)}{\Gamma_{\bar{B}^0_{(s)}\to f}(t) + \Gamma_{B^0_{(s)}\to f}(t)} = \frac{-C_f\cos(\Delta m_{d,s}t + S_f\sin(\Delta m_{d,s}t))}{\cosh(\frac{\Delta\Gamma_{d,s}}{2}t) + A_f^{\Delta\Gamma}\sinh(\frac{\Delta\Gamma_{d,s}}{2}t)} \quad (2)$$

$$A_{CP} = \frac{|\bar{A}_{\bar{f}}|^2 - |A_f|^2}{|\bar{A}_{\bar{f}}|^2 + |A_f|^2} \quad (3)$$

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.

$$\begin{aligned}
C_{\pi^+\pi^-} &= -0.34 \pm 0.06 \pm 0.01,\\
S_{\pi^+\pi^-} &= -0.63 \pm 0.05 \pm 0.01,\\
C_{K^+K^-} &= 0.20 \pm 0.06 \pm 0.02,\\
S_{K^+K^-} &= 0.18 \pm 0.06 \pm 0.02,\\
A^{\Delta\Gamma}_{K^+K^-} &= -0.79 \pm 0.07 \pm 0.10,\\
A^{B^0}_{CP} &= -0.084 \pm 0.004 \pm 0.003,\\
A^{B^0_s}_{CP} &= 0.213 \pm 0.015 \pm 0.007.
\end{aligned} \quad (4)$$

The measurements of $C_{\pi\pi}$, $S_{\pi\pi}$, $A^{B^0}_{CP}$ and $A^{B^0_s}_{CP}$ 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_s 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

[1] Cheng H and Chua C 2009 *Phys. Rev.* D **80** 114026
[2] Y Shimizu M T and Yamamoto K 2013 *Phys. Rev.* D **87** 056004
[3] Aaij R *et al.* (LHCb collaboration) 2018 *JHEP* **03** 140
[4] 2018 Measurement of CP violation in the $B^0_s \to \phi\phi$ decay and search for the $B^0 \to \phi\phi$ decay Tech. rep. CERN URL `https://cds.cern.ch/record/2314360`
[5] Aaij R *et al.* (LHCb collaboration) 2015 *Phys. Rev. Lett.* **114**(4) 041801
[6] Aaij R *et al.* 2013 *New Journal of Physics* **15** 053021
[7] Aaij R *et al.* (LHCb collaboration) 2014 *Phys. Rev. D* **90**(5) 052011
[8] Aaij R *et al.* (LHCb collaboration) 2018 *Phys. Rev. D* **98**(3) 032004