PROCEEDINGS OF SCIENCE

CP violation in beauty with LHCb

Melissa Maria Cruz Torres on behalf of the LHCb collaboration*
Universidad Nacional Autónoma de Honduras - UNAH
E-mail: melissa.maria.cruz.torres@cern.ch/melissa.cruz@unah.edu.hn

The study and search for new sources of *CP* violation in the beauty sector provide not only a better understanding of the phenomenon itself and thus of the matter-antimatter asymmetry in the universe, but to a better understanding of the rich dynamic present in the hadronic environment. Several analyses performed by the LHCb experiment that gather new insights into *CP* violation effects in non-leptonic *b*-hadron decays are presented in this document.

7th Annual Conference on Large Hadron Collider Physics - LHCP2019
20-25 May, 2019
Puebla, Mexico

*Speaker.

PoS(LHCP2019)204

1. Amplitude Analysis of $B^\pm \to \pi^\pm K^- K^+$ decays

Charmless charged three-body B decays, with pions and kaons in their final states, $B^\pm \to h^\pm h^+ h^-$, constitute an excellent scenario for the study of the Charge-Parity (CP) violation phenomenon. In fact, large CP violation effects have been previously reported in the phase space (Daliz plot) of these decays [1]. Particularly, for the decay channel $B^\pm \to \pi^\pm K^- K^+$, a large negative integrated CP asymmetry has been observed by the LHCb collaboration and large CP asymmetries in specific regions of the phase space has also been found [1] [2]. In order to understand the origin of these asymmetries, an amplitude analysis is needed. In this work the amplitude analysis of $B^\pm \to \pi^\pm K^- K^+$ has been performed using the data collected by the LHCb detector in 2011 and 2012 corresponding to an integrated luminosity of 3 fb^{-1}.

The strategy followed consists in performing a maximum likelihood fit to the distribution of events in the Dalitz plot, constructed in the squared mass combination $m^2_{\pi^\pm K^\mp}$ and $m^2_{K^+K^-}$, and allowing for CP violation. The isobar model formalism is used to compose the B^+ decay amplitude $\mathscr{A}$,

$$\mathscr{A}(m^2_{\pi^+K^-}, m^2_{K^+K^-}) = \sum_{i=1}^{N} c_i \mathscr{M}_i(m^2_{\pi^+K^-}, m^2_{K^+K^-}), \tag{1.1}$$

and, similar for the B^- decay amplitude, $\bar{\mathscr{A}}$, where c_i ($\bar{c}_i$ for $\overline{\mathscr{A}}$) represents the coupling to the intermediates states and $\mathscr{M}_i(m^2_{\pi^+K^-}, m^2_{K^+K^-})$ ($\bar{\mathscr{M}}_i(m^2_{\pi^-K^+}, m^2_{K^+K^-})$) is the decay amplitude for the intermediate state i, which accounts for the dynamic part. The CP asymmetry and fit fraction for each component is given by

$$A_{CP_i} = \frac{|\bar{c}_i|^2 - |c_i|^2}{|\bar{c}_i|^2 + |c_i|^2}, \tag{1.2}$$

$$\mathrm{FF}_i = \frac{\int (|c_i \mathscr{M}_i|^2 + |\bar{c}_i \overline{\mathscr{M}}_i|^2) \mathrm{d}m^2_{\pi^\pm K^\mp} \mathrm{d}m^2_{K^+K^-}}{\int (|\mathscr{A}|^2 + |\overline{\mathscr{A}}|^2) \mathrm{d}m^2_{\pi^\pm K^\mp} \mathrm{d}m^2_{K^+K^-}}. \tag{1.3}$$

The total probability density function (PDF) is constructed as the sum of a signal and background components whose relative contributions are determined from the one dimensional fit to the $\pi^\pm K^- K^+$ mass spectrum. Models for the efficiency variation across the Dalitz plot and the several types of background contributions are constructed. Then, the best description of data is tested through a systematic procedure in which all possible known resonant states are tested [3]. For the regions of the phase space that could not be well described, alternative parametrisations were implemented. In total, seven components are obtained [4]; three components in the $\pi^\pm K^\mp$ system and four components in the K^+K^- system, shown in Table 1.

In the $\pi^\pm K^\mp$ system, the best description of data is obtained when including the $K^*(892)^0$ and $K^*(1430)^0$ resonances, both found with a CP asymmetry consistent with zero, plus a nonresonant component. The latter, denoted as a single-pole amplitude, provides a phenomenological description of the partonic interaction.

Table 1: Results of the Dalitz plot fit, where the first uncertainty is statistical and the second systematic. The fitted values of c_i ($\bar{c}_i$) are expressed in terms of magnitudes $|c_i|$ ($|\bar{c}_i|$) and phases $\arg(c_i)$ ($\arg(\bar{c}_i)$) for each B^+ (B^-) contribution. The top row corresponds to B^+ and the bottom to B^- mesons.

Contribution	Fit Fraction(%)	A_{CP}(%)	Magnitude (B^+/B^-)	Phase[^{o}] (B^+/B^-)
$K^*(892)^0$	$7.5\pm0.6\pm0.5$	$+12.3\pm\ 8.7\pm\ 4.5$	$0.94\pm0.04\pm0.02$	0 (fixed)
			$1.06\pm0.04\pm0.02$	0 (fixed)
$K_0^*(1430)^0$	$4.5\pm0.7\pm1.2$	$+10.4\pm14.9\pm\ 8.8$	$0.74\pm0.09\pm0.09$	$-176\pm10\pm16$
			$0.82\pm0.09\pm0.10$	$136\pm11\pm21$
Single pole	$32.3\pm1.5\pm4.1$	$-10.7\pm\ 5.3\pm\ 3.5$	$2.19\pm0.13\pm0.17$	$-138\pm\ 7\pm\ 5$
			$1.97\pm0.12\pm0.20$	$166\pm\ 6\pm\ 5$
$\rho(1450)^0$	$30.7\pm1.2\pm0.9$	$-10.9\pm\ 4.4\pm\ 2.4$	$2.14\pm0.11\pm0.07$	$-175\pm10\pm15$
			$1.92\pm0.10\pm0.07$	$140\pm13\pm20$
$f_2(1270)$	$7.5\pm0.8\pm0.7$	$+26.7\pm10.2\pm\ 4.8$	$0.86\pm0.09\pm0.07$	$-106\pm11\pm10$
			$1.13\pm0.08\pm0.05$	$-128\pm11\pm14$
Rescattering	$16.4\pm0.8\pm1.0$	$-66.4\pm\ 3.8\pm\ 1.9$	$1.91\pm0.09\pm0.06$	$-56\pm12\pm18$
			$0.86\pm0.07\pm0.04$	$-81\pm14\pm15$
$\phi(1020)$	$0.3\pm0.1\pm0.1$	$+9.8\pm43.6\pm26.6$	$0.20\pm0.07\pm0.02$	$-52\pm23\pm32$
			$0.22\pm0.06\pm0.04$	$107\pm33\pm41$

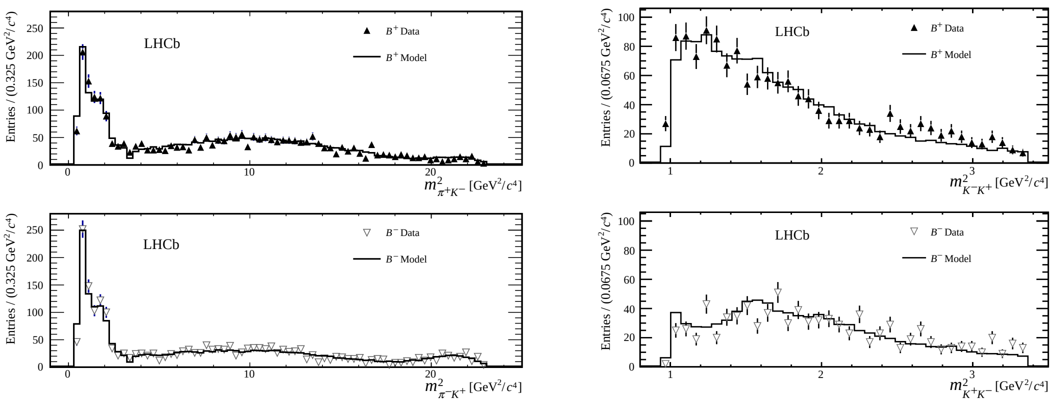

Figure 1: Distribution of $m^2_{\pi^\pm K^\mp}$ (left) and the low $m^2(K^+K^-)$ region (right). Data are represented by points for B^+ and B^- candidates separately, with the result of the fit overlaid.

In the K^+K^- system four component are obtained; a vector and tensor resonances, $\rho(1450)^0$ and $f_2(1270)$, respectively, mainly providing a destructive interference pattern in the Dalitz plot. It is also included a dedicated amplitude for the $\pi\pi \leftrightarrow KK$ rescattering region and the $\phi(1020)$ resonance which improves the description in the K^+K^- threshold but shows itself not to be statistically significant. Particularly, the rescattering amplitude, which acts in the region $0.95 < m(K^+K^-) < 1.42$ GeV/c^2, produces alone a CP asymmetry of $(-66\pm4\pm2)\%$ [4]. This is the largest CP asymmetry observed for a single amplitude. This gives a hint that this asymmetry and the large inclusive CP asymmetry observed for this channel [1], $(-12.3\pm2.1)\%$, must be related [5]. The data projection with the model overlaid is shown in Figure 1, for $m^2_{\pi^\pm K^\mp}$ (left) and the low $m^2(K^+K^-)$ region (right).

2. Amplitude analysis of $B^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$ decays

Another interesting $B^{\pm} \to h^{\pm}h^{+}h^{-}$ channel for *CP* violation studies is the $B^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$ decay mode. Rich structures have been previously reported on its phase space, and a large inclusive *CP* asymmetry has also been measured [1]. For multibody hadronic decays like $B^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$, *CP* violation signatures can be enhanced in specific region of the Dalitz plot [6]. A detailed study of these effects is performed through an amplitude analysis based on a data sample corresponding to an integrated luminosity of 3 fb^{-1} of *pp* collisions recorded by the LHCb detector.

The strategy consists in performing an isobar description of the non S-wave amplitude, and, for the $\pi^{+}\pi^{-}$ S-wave, which possesses a high level of complexity with many resonances contributions and open channels, three complementary approaches; the isobar model, the K-matrix formalism, and a quasi-model-independent procedure.

The results for the non S-wave amplitude include the contribution from the resonant states $\rho(770)^0$, $\omega(782)$ and $\rho(1450)^0$ in the $\pi^{+}\pi^{-}$ P-wave, $f_2(1270)$ in the $\pi^{+}\pi^{-}$ D-wave, and $\rho_3(1690)^0$ in the $\pi^{+}\pi^{-}$ F-wave. An interesting behaviour is observed in the P-wave. A *CP* asymmetry observed around the $\rho(770)^0$ mass changes its sign when projected in regions of the cosine of the helicity angle. This is a characteristic pattern due to the interference between spin-0 and spin-1 objects; the spin-1 $\rho(770)^0$ resonance and a broad spin-0 contribution which is present in this region. The *CP* asymmetry vanishes when integrating over the cosine of the helicity angle, consistent with the theoretical expectations. This represents the first observation of *CP* violation mediated entirely by the interference between hadronic resonances [7] [8]. Also reported is a sizable *CP* asymmetry of around 40% associated with the $f_2(1270)$ resonance. This is observed with a significance of about 15σ [7] [8].

For the S-wave, a good agreement between the three approaches is obtained, both in its magnitude and phase. A large *CP* asymmetry is reported in the low $m(\pi^{+}\pi^{-})$ region, but more data and experimental investigations, as well as theoretical input, is needed to understand this underlying dynamic further.

3. Measurements of *CP* asymmetries in charmless four-body Λ_b^0 and Ξ_b^0

Rich structures and large evidence of *CP* violation effects have been found in *K*, *B* and *D* mesons. Nevertheless, *CP* violation has not been observed in the baryon sector. Studies conducted by the LHCb collaboration reported indications of *CP* asymmetries in the decay channel $\Lambda_b^0 \to p\pi^{-}\pi^{+}\pi^{-}$ through the *Triple-product asymmetry* technique [9]. Thus, the study of copiously produced baryonic decays can bring not only an overall understanding of the *CP* violation phenomenon itself but to a comprehensive interpretation of these results.

This analysis report the *CP* violation measurements performed on the charmless four-body Λ_b^0 and Ξ_b^0 baryon decays with the 2011 and 2012 of data collected by the LHCb experiment corresponding to an integrated luminosity of 3 fb^{-1}. The abundant production of these particles in *pp* collisions at the LHC allows of precision measurements at LHCb.

The following six four-body charmless decays were analysed [10]: $\Lambda_b^0 \to p\pi^{-}\pi^{+}\pi^{-}$, $\Lambda_b^0 \to pK^{-}\pi^{+}\pi^{-}$, $\Lambda_b^0 \to pK^{-}K^{+}\pi^{-}$, $\Lambda_b^0 \to pK^{-}K^{+}K^{-}$, $\Xi_b^0 \to pK^{-}\pi^{+}\pi^{-}$ and $\Xi_b^0 \to pK^{-}\pi^{+}K^{-}$, which can be summarised as $X_b^0 \to phh^{'}h^{''}$, where X_b^0 stands for Λ_b^0 or Ξ_b^0 and $h^{'}$, $h^{''}$ for pions or kaons.

These decays channels proceed through $b \to d, s$ neutral currents transitions or charged-current $b \to u$ transition, whose interference gives rise to a weak phase difference. These b-flavoured baryons are also characterised by a rich, resonant structure in the two- or three-body baryonic and non-baryonic invariant-mass spectra. These features can enhance *CP*-violation effect in the region around resonances due to strong-phase differences induced by the interference of these intermediate states.

The observable measured is $\Delta A \equiv A^{CP}_{\mathrm{no-c}} - A^{CP}_{\mathrm{c}}$, where A^{CP}_{c} refers to the *CP* asymmetry measured in a reference channel which leads to the same or very similar final state and no *CP* violation is expected in the SM. The asymmetry measured in the charmless decays is denoted as $A^{CP}_{\mathrm{no-c}}$. Strategically this observable has the advantage that, to first order, tracking detection and b-baryon production asymmetries are cancelled out.

A total of eighteen measurements are reported in the analysis. These include *CP*-asymmetries measured in the phase space as well in selected local regions. The specific regions are chosen to include the low invariant mass, lower than 2 GeV/c^2, in the baryonic pair, *i.e* $p\pi^{\pm}$ or pK^{-}, and the low invariant mass on the pairing of the two other tracks. In the latter in order to include several known resonances in the $\pi^+\pi^-, K^{\pm}\pi^{\mp}$ or the KK pair. Measurements are also performed in selected regions that contain specific quasi-two-body, and three-body decays.

The results for the integrated *CP*-asymmetry are the following [10]:

$$
\begin{aligned}
\Delta A^{CP}(\Lambda_b^0 \to p\pi^-\pi^+\pi^-) &= (+1.1 \pm 2.5 \pm 0.6)\,\%,\\
\Delta A^{CP}(\Lambda_b^0 \to pK^-\pi^+\pi^-) &= (+3.2 \pm 1.1 \pm 0.6)\,\%,\\
\Delta A^{CP}(\Lambda_b^0 \to pK^-K^+\pi^-) &= (-6.9 \pm 4.9 \pm 0.8)\,\%,\\
\Delta A^{CP}(\Lambda_b^0 \to pK^-K^+K^-) &= (+0.2 \pm 1.8 \pm 0.6)\,\%,\\
\Delta A^{CP}(\Xi_b^0 \to pK^-\pi^+\pi^-) &= (-17 \pm 11 \pm 1)\,\%,\\
\Delta A^{CP}(\Xi_b^0 \to pK^-\pi^+K^-) &= (-6.8 \pm 8.0 \pm 0.8)\,\%.
\end{aligned}
$$

Measurements for the two-body low invariant-mass region:

$$
\begin{aligned}
\Delta A^{CP}(\Lambda_b^0 \to p\pi^-\pi^+\pi^-) &= (+3.7 \pm 4.1 \pm 0.5)\,\%,\\
\Delta A^{CP}(\Lambda_b^0 \to pK^-\pi^+\pi^-) &= (+3.5 \pm 1.5 \pm 0.5)\,\%,\\
\Delta A^{CP}(\Lambda_b^0 \to pK^-K^+\pi^-) &= (+2.7 \pm 2.3 \pm 0.6)\,\%.
\end{aligned}
$$

Measurements in specific regions of the phase space containing quasi two-body or three-body resonances:

$$\Delta A^{CP}(\Lambda_b^0 \to pa_1(1260)^-) = (-1.5 \pm 4.2 \pm 0.6)\,\%,$$
$$\Delta A^{CP}(\Lambda_b^0 \to N(1520)\rho(770)^0) = (+2.0 \pm 4.9 \pm 0.4)\,\%,$$
$$\Delta A^{CP}(\Lambda_b^0 \to \Delta(1232)^{++}\pi^-\pi^-) = (+0.1 \pm 3.2 \pm 0.6)\,\%,$$
$$\Delta A^{CP}(\Lambda_b^0 \to pK_1(1410)^-) = (+4.7 \pm 3.5 \pm 0.8)\,\%,$$
$$\Delta A^{CP}(\Lambda_b^0 \to \Lambda(1520)\rho(770)^0) = (+0.6 \pm 6.0 \pm 0.5)\,\%,$$
$$\Delta A^{CP}(\Lambda_b^0 \to N(1520)K^*(892)^0) = (+5.5 \pm 2.5 \pm 0.5)\,\%,$$
$$\Delta A^{CP}(\Lambda_b^0 \to \Delta(1232)^{++}K^-\pi^-) = (+4.4 \pm 2.6 \pm 0.6)\,\%,$$
$$\Delta A^{CP}(\Lambda_b^0 \to \Delta(1520)\phi(1020)) = (+4.3 \pm 5.6 \pm 0.4)\,\%,$$
$$\Delta A^{CP}(\Lambda_b^0 \to (pK^-)_{highmass}\phi(1020)) = (-0.7 \pm 3.3 \pm 0.7)\,\%.$$

In all cases the first uncertainty is statistical and the systematic. No significant *CP* violation is observed.

4. Measurements of the *CP*-violating phase ϕ_s from $B_s^0 \to J/\psi\pi^+\pi^-$ decays in 13 TeV *pp* collisions

For neutral decays, like $B_s^0 \to J/\psi\pi^+\pi^-$, *CP* violation effects can result from the interference of the direct decay and the $B_s^0 - \overline{B}_s^0$ mixing. This decay channel, thus, allows for *CP*-violation studies and the extraction of the *CP* violating phase ϕ_s, which can be expressed as -2arg$[V_{ts}V_{tb}^*/V_{cs}V_{cb}^*]$ in terms of the Cabibbo-Kobayashi-Maskawa matrix elements [11].

A time-dependent amplitude analysis is performed to determine the resonant structure in the B_s^0 and $\overline{B}_s^0 \to J/\psi\pi^+\pi^-$ decays [12]. Three possible polarizations are identified due to the spin-1 J/ψ meson in the final state, namely, longitudinal, parallel and perpendicular transversity amplitudes. The total decay amplitude of B_s^0 ($\overline{B}_s^0$) at a decay time equal to zero, is expressed then as the coherent sum of the transversity amplitudes in the $\pi^+\pi^-$ system and one nonresonant component. Each amplitude is denoted as A_i ($\overline{A}_i$). The parameter λ_i which relates *CP* violation in the interference between decay and mixing associated with the polarization of state i is defined as

$$\lambda_i \equiv \frac{q}{p}\frac{\overline{A}_i}{A_i}, \tag{4.1}$$

where p and q relates the mass and flavour eigenstate. the total decay amplitude is expressed as $A = \Sigma A_i$ and $\bar{A} = \Sigma \frac{q}{p}\bar{A}_i$. From eq. 4.1, it follows that the $\bar{A} = \Sigma\lambda_i A_i$, and thus, $\bar{A} = \Sigma\eta_i|\lambda_i|e^{-\phi_s^i}A_i$, where η_i is the *CP* eigenvalue of the state. Then, from the assumption that *CP* violation is the same for all amplitudes, the *CP*-violating phase can be determine as

$$\phi_s \equiv -arg(\lambda). \tag{4.2}$$

Two types of solutions are found to best describe the $m_{\pi^+\pi^-}$ spectra, one with positive interference between the contributing resonant states and the other one with negative interference.

Table 2: Several model fits ranked as function of the likelihood value. Positive or negative interferences, Int, among the contributing resonances are indicated. The Solutions are indicated by #.

#	Resonance content	Int	$-2\ln\mathscr{L}$
I	$f_0(980)+f_0(1500)+f_0(1790)+f_2(1270)+f_2'(1525)$+NR	$-$	-4850
II	$f_0(980)+f_0(1500)+f_0(1710)+f_2(1270)+f_2'(1525)$+NR	+	-4834
III	$f_0(980)+f_0(1500)+f_0(1790)+f_2(1270)+f_2'(1525)$+NR	+	-4830
IV	$f_0(980)+f_0(1500)+f_0(1790)+f_2(1270)+f_2'(1525)$	$-$	-4828
V	$f_0(980)+f_0(1500)+f_0(1710)+f_2(1270)+f_2'(1525)$	$-$	-4706

These solutions, summarised in Table 2, are ranked as a function of the negative likelihood value, $-2ln\mathscr{L}$, being Solution I better than Solution II by four standard deviations. The measurements are performed using Solution I as baseline; however, Solution II is taken for systematic studies. The fit results for the *CP*-violating parameters using Solution I are shown in Table 3.

Table 3: Fit results for the *CP*-violating parameters for Solution I. The first uncertainties are statistical, and the second systematic. The last three columns show the statistical correlation coefficients for the three parameters.

	Fit result	Correlation		
Parameter		$\Gamma_H-\Gamma_{B^0}$	$\lvert\lambda\rvert$	ϕ_s
$\Gamma_H-\Gamma_{B^0}$ (ps^{-1})	$-0.050\pm0.004\pm0.004$	1.000	0.022	0.038
$\lvert\lambda\rvert$	$1.01^{+0.08}_{-0.06}\pm0.03$	0.022	1.000	0.065
ϕ_s (rad)	$-0.057\pm0.060\pm0.011$	0.038	0.065	1.000

The quantity $\Gamma_H-\Gamma_{B^0}$ is the decay-width difference between the heavier mass B_s^0 eigenstate and B^0 meson. The results in Table 3 are combined with the previous measurements performed on the same decay channel by the LHCb collaboration using 7 TeV and 8 TeV of *pp* collisions. The combined value for ϕ_s is 0.002 $\pm$ 0.044 $\pm$ 0.013 and $|\lambda| = 0.949\pm0.036\pm0.019$.

5. Summary

Four interesting analyses are presented in this document. Three of them were performed with the Run I (2011 and 2012) data collected by the LHCb experiment, and one with the data collected in 2015 and 2016. It is reported the amplitude analysis of two charmless B decays, $B^\pm \to \pi^\pm K^+K^-$ and $B^\pm \to \pi^\pm\pi^+\pi^-$, where interesting signatures of *CP* violation are studied. In the $B^\pm \to \pi^\pm K^+K^-$ channel a large *CP* asymmetry of $(-66\pm4\pm2)\%$ is observed for the expected $\pi\pi \leftrightarrow KK$ rescattering region, giving an indication of the effect of the dynamically produced strong phase differences between amplitudes with different weak phases, and thus the role of the strong rescattering. This represents the first amplitude analysis ever performed on this decay mode. On the other hand, for the $B^\pm \to \pi^\pm\pi^+\pi^-$ channel, three complementary approaches were implemented in the study of the rich structures observed in its phase space. The first observation of *CP* violation mediated entirely by the interference between hadronic resonances is reported, as well as the first observation of *CP* violation is associated with a tensor resonance. Studies of *CP* violation in the b baryonic sector and a new measurement of the *CP*-violating phase in the quark level $b \to c\bar{c}s$ are also presented. In general, the LHCb experiment has a broad program in search of *CP* asymmetries in b- and c hadrons. With the addition of the complete Run II data, more detailed and precise measurements will be possible.

References

[1] LHCb collaboration, Aaij, R. and others, *Measurement of CP violation in the three-body phase space of charmless $B^{\pm}$ decays*. Phys. Rev. D90, 112004 (2014).

[2] Belle collaboration, Hsu, C. L. and others, *Measurement of branching fraction and direct CP asymmetry in charmless $B^+ \to K^+K^-\pi^+$ decays at Belle*. Phys. Rev. D96, 031101(R) (2017).

[3] Particle Data Group, Tanabashi, M. and others, *Review of particle physics*. `http://pdg.lbl.gov/`, Phys. Rev. D98, 030001 (2018).

[4] LHCb collaboration, Aaij, R. and others, *Amplitude analysis of $B^{\pm} \to \pi^{\pm}K^+K^-$ decays*. arXiv.1905.09244 [hep-ex].

[5] L. Wolfenstein, *Final state interactions and CP violation in weak decays*. Phys. Rev. D43, 151 (1991).

[6] Alvarenga Nogueira, J. H. and Bediaga, I. and Cavalcante, A. B. R. and Frederico, T. and Lourenço, O., *CP violation: Dalitz interference, CPT, and final state interactions*. Phys. Rev. D92, 054010 (2015).

[7] LHCb collaboration, Aaij, R. and others, *Amplitude analysis of $B^+ \to \pi^+\pi^+\pi^-$ decays*. LHCb-PAPER-2019-017.

[8] LHCb collaboration, Aaij, R. and others, *Observation of several sources of CP violation in $B^+ \to \pi^+\pi^+\pi^-$ decays*. LHCb-PAPER-2019-018.

[9] LHCb collaboration, Aaij, R. and others, *Measurement of matter-antimatter differences in beauty baryon decays*. Nature Phys. 13, 391-396 (2017).

[10] LHCb collaboration, Aaij, R. and others, *Measurement of CP asymmetries in charmless four-body Λ_b and Ξ_b^0 decays*. arXiv.1903.06792v1 [hep-ex].

[11] Kobayashi, Makoto and Maskawa, Toshihide, *CP Violation in the Renormalizable Theory of Weak Interaction*. Prog. Theor. Phys. 49, 652-657 (1973).

[12] LHCb collaboration, Aaij, R. and others, *Measurements of the CP-violating phase ϕ_s from $B_s^0 \to J/\psi\pi^+\pi^-$ decays in 13 TeV pp collisions*. Phys. Rev. B 797 (2019).