CP Violation in b Hadrons at LHCb

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The most recent results on CP violation in b hadrons obtained by the LHCb Collaboration with Run I and years 2015-2016 of Run II are reviewed. The different types of violation are covered by the studies presented in this paper.

Keywords: CP violation; Heavy Flavours.

1. Introduction

The violation of the CP symmetry is predicted in the Standard Model (SM) weak sector and closely related to the existence of at least three flavour families. However, other sources of CP violation are likely to intervene to explain the excess of matter over antimatter in the universe. For what concerns the quarks, the SM-based CP violating phase is embedded in the Cabibbo-Kobayashi-Maskawa (CKM) matrix^{1,2}:

$$V_{CKM} = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix} \quad (1)$$

involving couplings within and between quark generations, because the eigenstates of the weak interaction are different from the mass eigenstates. The magnitude of the CKM elements is not evenly distributed, though: the modules of the diagonal elements (within-generation couplings) are one while the strength decreases as one departs from the diagonal. The weakest couplings are thus between the first and third generation, namely V_{td} and V_{ub} . The unitarity condition, $V_{CKM}V_{CKM}^\dagger = \mathbf{1}$, imposes six independent relations, of which one is of particular interest, $V_{ud}V_{ub}^* +$

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$V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$, involving a sum of elements of similar magnitude and defining the “ B^0 triangle” or Unitarity Triangle, and a second one, $V_{us}V_{ub}^* + V_{cs}V_{cb}^* + V_{ts}V_{tb}^* = 0$, although being an unbalanced squeezed triangle, involves the angle intervening in the B_s^0 meson oscillations, $\beta_s = \arg\left(\frac{-V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}\right)$.

To probe CP violation, rate asymmetries of decays $B \rightarrow f$ are measured, involving amplitudes such as $A_f = \langle f|H_{eff}|B\rangle$, $A_{\bar{f}} = \langle \bar{f}|H_{eff}|B\rangle$, $\bar{A}_f = \langle f|H_{eff}|\bar{B}\rangle$ and $\bar{A}_{\bar{f}} = \langle \bar{f}|H_{eff}|\bar{B}\rangle$. $\bar{B}$ and $\bar{f}$ denote the charge conjugates of the b hadron and the final state, respectively. H_{eff} is the effective Hamiltonian describing the decay. Physics beyond SM may intervene, in box or loop diagrams, as contributions to H_{eff} and thus impact directly on the asymmetries.

LHCb research program has focused on CP violation in the decays, in the neutral B mesons mixing, and in the interference of decays and mixing. Recent results spanning the three categories are reviewed in this paper.

2. CP violation in mixing

Neutral B mesons oscillate between B_q^0 and $\bar{B}_q^0$ states ($q = d, s$)^a. The oscillation dynamics can be written as:

$$i\frac{d}{dt}\begin{pmatrix} |B_q^0(t)\rangle \\ |\bar{B}_q^0(t)\rangle \end{pmatrix} = \left[\begin{pmatrix} M_{11}^q & M_{12}^q \\ M_{12}^{q*} & M_{22}^q \end{pmatrix} - \frac{i}{2} \begin{pmatrix} \Gamma_{11}^q & \Gamma_{12}^q \\ \Gamma_{12}^{q*} & \Gamma_{22}^q \end{pmatrix} \right] \begin{pmatrix} |B_q^0(t)\rangle \\ |\bar{B}_q^0(t)\rangle \end{pmatrix}, \quad (2)$$

where M_{ij}^q and Γ_{ij}^q are elements of the mass and decay matrices. We note $\phi_{12}^q = \arg(-M_{12}^q/\Gamma_{12}^q)$ and $\phi_M^q = \arg(M_{12}^q)$. The eigenstates of the Hamiltonian are noted as $|B_{L,H}^0\rangle = p|B^0\rangle \pm q|\bar{B}^0\rangle$, where L and H stand for light and heavy, respectively. In the SM, CP violation in mixing ϕ_{12}^q is expected to be very small (or said otherwise, $|\frac{q}{p}| \approx 1$) and thus an intervention of new heavy particles could be detected through a substantial deviation from the null prediction.

For both B^0 and B_s^0 , semileptonic (and thus flavour-specific) decays are used to obtain

$$A_{sl}^q = \frac{\Gamma(\bar{B}_q^0 \rightarrow B_q^0 \rightarrow f) - \Gamma(B_q^0 \rightarrow \bar{B}_q^0 \rightarrow \bar{f})}{\Gamma(\bar{B}_q^0 \rightarrow B_q^0 \rightarrow f) + \Gamma(B_q^0 \rightarrow \bar{B}_q^0 \rightarrow \bar{f})} = -2 \left(\left| \frac{q}{p} \right| - 1 \right) \quad (3)$$

Experimentally, LHCb analyses measure the time-dependent yield asymmetry of the decay states^{3,4}:

$$\frac{N(B_q^0 \rightarrow f, t) - N(\bar{B}_q^0 \rightarrow \bar{f}, t)}{N(B_q^0 \rightarrow f, t) + N(\bar{B}_q^0 \rightarrow \bar{f}, t)} = A_D + \frac{A_{sl}^q}{2} - \left(A_P + \frac{A_{sl}^q}{2} \right) \frac{\cos(\Delta M_q t)}{\cosh(\Delta \Gamma_q t/2)} \quad (4)$$

where ΔM_q and $\Delta \Gamma_q$ are the mass and width differences, A_P and A_D are the B -meson production asymmetry and the combined decay products detection asymmetry. For B_s^0 , the time-dependent term cancels due to the fast oscillations. In the B^0 case, a time-depend fit is necessary.

^a $B_d^0 = B^0$ throughout the paper.

Using $B^0 \rightarrow D^-(\rightarrow K\pi\pi)\mu^+\nu X$, $B^0 \rightarrow D^{*-}(\rightarrow D^0(K\pi)\pi)\mu^+\nu X$, and $B_s^0 \rightarrow D_s^-(\rightarrow K K\pi)\mu^+\nu X$ decay chains, the LHCb measurements are ^{3,4}:

$$A_{sl}^d = (-0.02 \pm 0.19(\text{stat}) \pm 0.30(\text{syst}))\%, \quad A_{sl}^s = (0.39 \pm 0.26(\text{stat}) \pm 0.20(\text{syst}))\%,$$

where the systematic (second) uncertainty is dominated by the size of the control samples used in the determination of the detection asymmetry. These numbers are compatible with the SM-based expectations of orders 10^{-4} and 10^{-5} , respectively ⁵.

3. CP violation in decay

CP violation in decay occurs whenever $|A_f|^2 \neq |\bar{A}_{\bar{f}}|^2$. This requires flavor-specific B decays and could happen only if A_f contains at least two amplitudes with different strong δ_i and weak φ_i phases. In that case, $|\bar{A}_{\bar{f}}|^2 - |A_f|^2 = -4|A_1||A_2|\sin(\delta_1 - \delta_2)\sin(\varphi_1 - \varphi_2)$. The extraction of the parameter of interest, the weak phase difference $\varphi_1 - \varphi_2$, is thus limited by the knowledge of the strong phase difference. However, various fitting techniques involving ratios of branching fractions and asymmetries are used to circumvent this limitation.

3.1. CKM γ angle

The angle $\gamma = \arg\left(\frac{-V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)$ is the least constrained angle of the Unitarity Triangle and is the subject of extensive LHCb studies involving $B \rightarrow DK$ decays ⁶.

The principle of the measurement relies on the use of the interference of tree favored $b \rightarrow c(\bar{u}s)$ (A_B) and suppressed $b \rightarrow u(\bar{c}s)$ ($A_B r_B e^{i(\delta_B - \gamma)}$, r_B is the suppression factor and δ_B is the relative strong phase) decays leading to final states of the type $B \rightarrow DX_s$ where D is a charm meson and X_s a strange system (K , K^* , $K\pi$, $K\pi\pi\pi$, ...). The charm meson decays to a final state accessible by both D and $\bar{D}$ through allowed (A_D) and suppressed ($A_D r_D e^{i\delta_D}$) amplitudes. Since more than two decades, several methods have initially been proposed for $B^+ \rightarrow DK^+$ ^{7,8,9,10} to extract the angle for observables including charge asymmetries and ratio of branching fractions which definition may vary depending on the type of D decay (CP eigenstate, flavour eigenstate, multibody). Beside the generalization of the paradigm to final states involving D^* or more complex X_s system, alternative methods have been developed with other B mesons, such as $B_s^0 \rightarrow D_s^\mp K^\pm$ ¹¹. The most recent LHCb combination of measurements ⁶ gives an average of $\gamma = (76.8_{-5.7}^{+5.1})^\circ$, which dominates the world average, $(76.2_{-5.0}^{+4.7})^\circ$ ¹².

3.2. CP violation in baryonic decays

A pioneering study has been performed on four-body decays of the Λ_b^0 baryon, $\Lambda_b^0 \rightarrow p\pi^- h^+ h^-$ ($h = \pi, K$) ¹³. For four-body modes, a useful observable which has been chosen for CP studies is the triple scalar product $C_{\hat{T}} = \vec{p}_p \cdot (\vec{p}_{h_1^-} \times \vec{p}_{h_2^+})$ ¹⁴. $h_1 = \pi$ and $h_2 = K$ for $\Lambda_b^0 \rightarrow p\pi^- K^+ K^-$, and $h_1 = h_2 = \pi$ for $\Lambda_b^0 \rightarrow p\pi^- \pi^+ \pi^-$.

Fig. 1. Invariant mass spectrum for (left) $p\pi^-\pi^+\pi^-$ and (right) $p\pi^-K^+K^-$.

In the latter case, the ambiguity for the choice of h_1 is removed by selecting the fastest π^- in the Λ_b^0 rest frame, π_{fast}^- . CP conjugation applied to $C_{\hat{T}}$ gives $-\vec{p}_{\pi^-} \cdot (\vec{p}_{h_1^+} \times \vec{p}_{h_2^-}) = -\overline{C}_{\hat{T}}$. Therefore, for CP symmetry to be conserved, any observable depending on $C_{\hat{T}}$ should be unchanged under the substitution $C_{\hat{T}} \rightarrow -\overline{C}_{\hat{T}}$. Experimentally, the following yield asymmetries have been chosen: $A_{\hat{T}}(C_{\hat{T}}) = \frac{N(C_{\hat{T}} > 0) - N(C_{\hat{T}} < 0)}{N(C_{\hat{T}} > 0) + N(C_{\hat{T}} < 0)}$, $\overline{A}_{\hat{T}}(\overline{C}_{\hat{T}}) = \frac{N(-\overline{C}_{\hat{T}} > 0) - N(-\overline{C}_{\hat{T}} < 0)}{N(-\overline{C}_{\hat{T}} > 0) + N(-\overline{C}_{\hat{T}} < 0)}$. Defining the difference, $a_{CP}^{\hat{T}-\text{odd}} = \frac{1}{2}(A_{\hat{T}} - \overline{A}_{\hat{T}})$ ¹⁵, the test consists in probing deviations from zero of $a_{CP}^{\hat{T}-\text{odd}}$. Figure 1 shows the invariant mass spectra of the $p\pi^-h^+h^-$ systems. Both $\Lambda_b^0 \rightarrow p\pi^-h^+h^-$ signals are observed for the first time, with yields of 6646 ± 105 ($h = \pi$) and 1030 ± 56 ($h = K$) events.

$a_{CP}^{\hat{T}-\text{odd}}$ is then studied as a function of the angle Φ between the planes formed by $(p, K^-(\pi_{fast}^-))$ and (π_{slow}^-, K^+) , where we note that $C_{\hat{T}} \propto \sin(\Phi)$. In the case of $\Lambda_b^0 \rightarrow p\pi^-\pi^+\pi^-$, substantial deviation from zero is observed, as illustrated in Fig. 2, with a combined significance of 3.3σ . This is the first evidence of CP violation in the decay of a baryon. With the current statistics, no significant deviation is seen for $\Lambda_b^0 \rightarrow p\pi^-K^+K^-$.

4. CP violation in interferences between mixing and decay

When neutral B mesons decay to a eigen CP final state, the possibility of oscillation implies that the measured asymmetry probing the interference of mixing and decay must be studied as a function of the decay time:

$$A_{CP}(t) = \frac{\Gamma(B_q^0(t) \rightarrow f_{CP}) - \Gamma(\overline{B}_q^0(t) \rightarrow f_{CP})}{\Gamma(B_q^0(t) \rightarrow f_{CP}) + \Gamma(\overline{B}_q^0(t) \rightarrow f_{CP})} = \frac{S_f \sin(\Delta M_q t) - C_f \cos(\Delta M_q t)}{\cosh(\Delta \Gamma_q t/2) + A_f^{\Delta \Gamma} \sinh(\Delta \Gamma_q t/2)} \quad (5)$$

Fig. 2. Variation of (top) $a_P^{\hat{T}-\text{odd}} = \frac{1}{2}(A_{\hat{T}} + \bar{A}_{\hat{T}})$ and (bottom) $a_{CP}^{\hat{T}-\text{odd}}$ as a function of $|\Phi|$ for $\Lambda_b^0 \rightarrow p\pi^-\pi^+\pi^-$.

where $C_f = \frac{1-|\lambda_f|^2}{1+|\lambda_f|^2}$, $S_f = \frac{2\Im(\lambda_f)}{1+|\lambda_f|^2}$, $A_f^{\Delta\Gamma} = -\frac{2\Re(\lambda_f)}{1+|\lambda_f|^2}$ and $\lambda_f = \frac{q}{p} \frac{\bar{A}_f}{A_f}$. For the B^0 meson, the denominator is equal to 1, since $\Delta\Gamma_d/\Gamma_d \ll 1$. Following the discussion in Sec. 2, $\left|\frac{q}{p}\right| = 1$. If only one amplitude contributes to the decay, $\lambda_f = e^{i\Phi_q} = e^{i(\Phi_M - 2\Phi_D)}$ (and thus $C_f = 0$), where Φ_M and Φ_D are the weak mixing and decay phases, respectively. For both B^0 and B_s^0 , one can reasonably assume that $\Phi_M \simeq 0$. Experimentally, except for the mixing phase simplification, the quantities S_f , C_f , and ΔM_q (and $A_f^{\Delta\Gamma}$, $\Delta\Gamma_q$ for B_s^0) are extracted without prior assumption.

4.1. β_s and β measurements

The $b \rightarrow c\bar{c}s$ tree decays are the reference modes for extracting the CKM angles $\beta = \arg\left(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right)$ ($\Phi_d = -2\beta$ for B^0) and $\beta_s = \arg\left(-\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}\right)$ ($\Phi_s = -2\beta_s$ for B_s^0).

Table 1 shows all the modes used over the past years and the corresponding measurements for Φ_s . The most recent one, relying on the decay $B_s^0 \rightarrow J/\psi K^+ K^-$ in the region $m(K^+ K^-) > m_\phi$, is the first with a tensor resonance ($f_2(1525)$) dominating the spectrum. With the current statistics, all the measurements agree with recent SM-based fits 20 , $-0.0365^{+0.0013}_{-0.0012}$.

Table 1. LHCb Φ_s measurements, with their respective statistical (first) and systematic (second) uncertainties.

Final state	Φ_s (rad)	Reference
$J/\psi \pi^+ \pi^-$ (including f_0)	$+0.070 \pm 0.068 \pm 0.008$	Phys.Lett.B B736 186 (2014)
$D_s^+ D_s^-$	$+0.02 \pm 0.17 \pm 0.02$	Phys.Rev.Lett.113 211801 (2014)
$J/\psi K^+ K^-$ (including ϕ)	$-0.058 \pm 0.049 \pm 0.006$	Phys.Rev.Lett.114 041802 (2015)
$\psi(2S)\phi$	$+0.23^{+0.29}_{-0.28} \pm 0.02$	Phys.Lett.B B762, 252-262 (2016)
$J/\psi K^+ K^-$ (above ϕ)	$+0.119 \pm 0.107 \pm 0.034$	JHEP08 (2017) 037

Fig. 3. Quark tree and loop (“penguin”) diagrams of the $B^0_{(s)} \rightarrow hh$ decays.

For β , the Run 1 data LHCb measurement with the golden mode $B^0 \rightarrow J/\psi (\rightarrow \mu^+ \mu^-) K^0_S$, $\sin(2\beta) = 0.731 \pm 0.035(\text{stat}) \pm 0.020(\text{syst})$ ¹⁶ has been recently completed by measurements based on the decays $B^0 \rightarrow J/\psi (\rightarrow e^+ e^-) K^0_S$ and $B^0 \rightarrow \psi(2S) (\rightarrow \mu^+ \mu^-) K^0_S$ ¹⁷, resulting in a combined average of $\sin(2\beta) = 0.760 \pm 0.034$, still in agreement with predictions²⁰, $0.771^{+0.017}_{-0.041}$.

4.2. Two body $B^0_{(s)} \rightarrow hh$

The two body $B^0_{(s)}$ decays involve tree and loop diagram contributions, Fig. 3. The extraction of any weak phase, here $2\beta_s$ or γ , requires some assumptions, such as U-spin symmetry¹⁸, which inexactness limits the accuracy of the results. A recent simultaneous fit of the four channels $B^0 \rightarrow \pi^+ \pi^-$, $B^0 \rightarrow K^+ \pi^-$, $B^0_s \rightarrow K^+ K^-$, and $B^0_s \rightarrow K^+ \pi^-$ ¹⁹ led to the measurements: $C_{\pi\pi} = -0.243 \pm 0.069$, $S_{\pi\pi} = -0.681 \pm 0.060$, $C_{KK} = 0.236 \pm 0.062$, $S_{KK} = 0.216 \pm 0.062$ and $A_{KK}^{\Delta\Gamma} = -0.751 \pm 0.075$. The notable large values of the C_f coefficients are due to a sizeable CP violation in the decay produced by the interference of tree and loop diagrams. Since the significance for $(C_{KK}, S_{KK}, A_{KK}^{\Delta\Gamma})$ to differ from $(0, 0, 1)$ is 4.7σ , LHCb establishes strong evidence for CP violation in $B^0_s \rightarrow K^+ K^-$.

5. Summary

Important progress has been done in the measurement of CP violation at LHCb with Run I and beginning of Run II data, leading to a better constraint of the Unitarity Triangle and opening new routes such as CP violation in Baryon decays. But the needed accuracies, for a sensible comparison between indirect and direct determinations of the angles, will only be reached following the LHCb Phase I upgrade during the next decade. As an illustration, the expected Phase I upgrade accuracy for the angle γ is $\sim 1^\circ$, while the indirect constraint, based on loop-level processes, gives $\gamma = (66.9^{+0.94}_{-3.44})^\circ$ ²⁰. A clear indication of New Physics may show up at this stage.

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