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Overview of time-integrated *CP* violation in beauty-hadron decays

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Charge-parity (*CP*) violation in the b-quark sector can be investigated by means of the time-integrated decay rates of beauty hadrons into various final states. *CP* violation is a phenomenon that plays a crucial role in understanding the observed matter-antimatter asymmetry in the universe. Several experimental efforts have been made at high-energy physics laboratories in the last decades aiming to measuring the *CP*-violating observables and the elements of the Cabibbo-Kobayashi-Maskawa matrix that describe the Standard Model (SM) and exploring any theoretical implication or hint for new physics beyond the SM. A better knowledge of all these ingredients will provide a strong contribution to unraveling the fundamental symmetries of particle physics and shedding light on the mysterious baryon asymmetry in the universe. This report provides a comprehensive overview of time-integrated *CP* violation in b-sector, analyzing some of the latest results achieved by the LHCb and Belle collaborations and discussing the future projections of these results.

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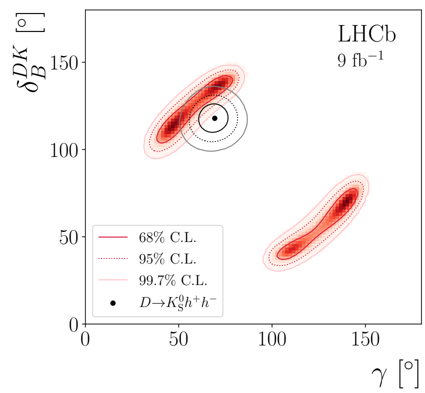
1. Introduction

In the last decades, B-hadron decays have attracted attention due to charge-parity violation phenomena (*CPV*) as well as the sensitivity to new physics in rare B decays. Within the Standard Model (SM), the *CP* symmetry between quarks and antiquarks is broken by a single complex phase in the Cabibbo-Kobayashi-Maskawa (CKM) quark-mixing matrix. The assumption of unitarity for this matrix leads to the condition $V_{ud}V^*_{ub} + V_{cd}V^*_{cb} + V_{td}V^*_{tb} = 0$, where V_{ij} are the complex elements of the CKM matrix [1]. This equation can be visualised as a triangle in the complex plane with angles α, β and γ. A key test of the SM consistency is to verify the unitarity conditions by constraining the CKM matrix with various independent measurements. The magnitudes of the CKM matrix elements are measured from the decay rates of flavor-changing transitions, while the CKM phases are determined through the measurements of *CP* asymmetries [2, 3]. The angle $\gamma \equiv arg[-(V_{ud}V^*_{ub})/(V_{cd}V^*_{cb})]$ play an interesting role since it is the only CKM angle that can be measured in tree-level decays, where the interpretation of physical observables (rates and *CP* asymmetries) is affected by negligible theoretical uncertainties, at the order of 10^{-7} [4]. Therefore, a precision measurement of the angle γ is an optimal SM benchmark, to be compared with indirect determinations from other CKM matrix observables, more sensitive to new physics phenomena beyond the SM.

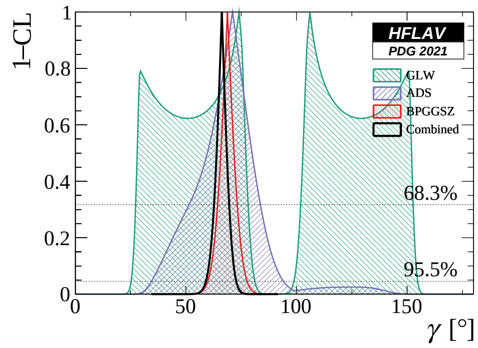
The *CPV* in b-baryon decays is predicted by the SM but, differently for the b-meson scenario, it has been never observed. Thanks to the large production cross-section of b-baryons in pp collisions at the LHC, LHCb is the only experiment capable of expanding our knowledge in this sector.

2. Direct measurements of the CKM angle γ

The CKM angle γ can be measured directly using tree-level b-hadron decays, exploiting the interference between $b \to u$ and $b \to c$ transitions [5]. In particular, the measurement of the direct *CPV* in $B^{\mp} \to DK^{\mp}$ decays provide the most stringent constraints on the γ angle, assuming the D meson decays in a final state, f, accessible from both flavour states. The relative phase between the two decay amplitudes has both the *CP*-conserving (δ_B^{DK}) and *CP*-violating (γ) contributions. Since γ is shared by all these decays, the best precision is obtained from their combination in several decay modes. Different approaches can be followed to perform this measurement: the GLW method exploits decays of the D meson to *CP* eigenstates, the ADS technique considers favored and doubly Cabibbo-suppressed D decays while the BPGGSZ method requires D decays to self-conjugate final states such as $K^0_s h^+ h^-$, measuring the *CP* asymmetries over the phase space. One of the latest analysis performed by the LHCb Collaboration is based on the BPGGSZ approach, investigating the differences in the phase-space distributions of $B^{\pm}$ meson decays. The Dalitz plot technique is used for interpreting the results in terms of physics observables of the D-meson decay. The strong phase (δ_B^{DK}) is taken as external input from the measurements performed by the CLEO and BESIII collaborations, using the quantum correlated pairs of D meson produced in the $\psi(3770)$ decays [6]. This approach leads to the most precise measurement, from single experiment, of the γ angle, determining a value of $(68.7^{+5.2}_{-5.1})^{\circ}$ [7]. The result is in a good agreement with the other analyses based on the different methods and turns out to be crucial for solving the two-fold ambiguity in the parameter space [8] in their result, as shown in Figure 1a. LHCb collaboration performed a



(a) Confidence region in the (δ_B^{DK}, γ) plane for both $B^\mp \to D^{(*)}K^\mp$ LHCb analyses [7, 8].



(b) One dimensional profile likelihood scans of the 1-CL distribution for γ from the combination using different methods [12].

combination of γ measurements obtained with several $B \to Dh$ modes using data collected during the first two runs of the LHC. The results are obtained using a frequentist approach and external inputs from other experiments. The combined γ value is $(65.4^{+3.8}_{-4.2})^\circ$ which result to be the highest precision measurement from a single experiment to date [9]. Similar combinations have been performed also with the Belle and Belle II results, using a model-independent Dalitz plot analysis of $B^+ \to D^0(K_S^0 h^- h^+)h^+$ decays, with $(h = K, \pi)$. This is the first measurement that simultaneously uses Belle and Belle II data, corresponding to an integrated luminosity of 711 fb^{-1} and 128 fb^{-1}, respectively. The combined results is $\gamma = (78.4 \pm 11.5)^\circ$ [10], which is compatible with the LHCb result within one standard deviation. In addition, the Belle II collaboration performed also a GLS measurement using the $B^\pm \to D^0 h^\pm$ $(h = \pi, K)$ where the D^0 meson decays into $K_S^0 K^\pm \pi^\mp$ final state [11]. Even if this measurement is not able to solve the two-fold ambiguity in the γ determination it provides an important constraint when combined in the global fits. A combination of all the γ measurements obtained with the various methods is shown in Figure 1b.

3. *CP* violation in charmless b-meson decays

Charmless b-meson decays are an fundamental sector for investigating the *CPV*, testing the SM predictions, and searching for new physics effects. Key characteristic of this kind of decays is that they receive contributions from the both tree-level and penguin processes with amplitudes of the same size, making them more sensitive to the effect of virtual particles not accounted for in the SM. Furthermore, these decays produce a wide variety of final states, including kaons, pions, and other light hadrons, providing a rich experimental landscape for testing the *CPV* across different channels.

3.1 Direct *CP* violation in two-body B decays

The charmless two-body B decays, with a kaon and pion in the final state, are an optimal test-bed for the isospin symmetry [13]. Isospin symmetry breaking (ISB) arises when the masses of u and d quarks, which are assumed to be equal in the absence of isospin breaking, deviate slightly. Understanding isospin symmetry and its breaking is crucial for precision tests of the SM and for interpreting experimental results. The LHCb collaboration measured the time-integrated *CP* asymmetry in the $B \to K\pi$ decays obtaining $\mathcal{A}^{CP}_{B^0} = (-8.24 \pm 0.03_{stat} \pm 0.03_{syst})\%$ [14] and $\mathcal{A}^{CP}_{B^+} = (2.5 \pm 1.5_{stat} \pm 0.6_{syst} \pm 0.3_{ext})\%$ [15]. These results lead to

$$\Delta\mathcal{A}^{CP}(K\pi) \equiv \mathcal{A}^{CP}(B^+ \to K^+\pi^0) - \mathcal{A}^{CP}(B^0 \to K^\pm\pi^\mp) \neq 0$$

by more than 8 standard deviations, confirming the anomalous difference between the direct *CP* asymmetries of the $B^0 \to K^+\pi^-$ and $B^+ \to K^+\pi^0$ decays, known as the $K\pi$ puzzle.

Belle and Belle II are the only experiments able to measure all relevant final states of isospin-related charmless decays, including neutral particles in the final state. The isospin sum-rule [16] relation for the $B \to K\pi$ decay modes is a strong validity test of the SM:

$$I_{K\pi} = \mathcal{A}_{K^+\pi^-} + \mathcal{A}_{K^0\pi^+} + \frac{\mathcal{B}(K^0\pi^+)}{\mathcal{B}(K^+\pi^-)}\frac{\tau_{B^0}}{\tau_{B^+}} - 2\mathcal{A}_{K^+\pi^0}\frac{\mathcal{B}(K^+\pi^0)}{\mathcal{B}(K^+\pi^-)}\frac{\tau_{B^0}}{\tau_{B^+}} - 2\mathcal{A}_{K^0\pi^0}\frac{\mathcal{B}(K^0\pi^0)}{\mathcal{B}(K^+\pi^-)} = 0,$$

where $\mathcal{B}$, $\mathcal{A}$, and τ are the branching fractions, direct *CP* asymmetries, and lifetimes of B mesons, respectively. Time-integrated results are combined with time-dependent measurements to obtain the best sensitivity of $\mathcal{A}_{K^0_S\pi^0} = -0.01 \pm 0.12_{\rm stat} \pm 0.05_{\rm syst}$ and $I_{K\pi} = -0.03 \pm 0.13_{\rm stat} \pm 0.05_{\rm syst}$ [17].

3.2 Direct *CP* violation in three-body B decays

The direct *CPV* measurement in $B^\pm \to h^\pm h^+ h^-$ decays, where $h = \pi, K$, has been performed by the LHCb collaboration using the dataset collected during the second LHC run and corresponding to to 5.9 fb^{-1} [18]. The A^{CP} values obtained are:

$$\mathcal{A}^{CP}_{B^\pm\to\pi^\pm\pi^+\pi^-} = (+8.0 \pm 0.4 \pm 0.3 \pm 0.3)\%, \quad \mathcal{A}^{CP}_{B^\pm\to K^\pm\pi^+\pi^-} = (+1.1 \pm 0.2 \pm 0.3 \pm 0.3)\%,$$
$$\mathcal{A}^{CP}_{B^\pm\to\pi^\pm K^+K^-} = (-11.4 \pm 0.7 \pm 0.3 \pm 0.3)\%, \quad \mathcal{A}^{CP}_{B^\pm\to K^\pm K^+K^-} = (-3.7 \pm 0.2 \pm 0.2 \pm 0.3)\%,$$

where the first uncertainty is statistical, second systematic and the third is due the *CP* asymmetry of the $B^\pm \to J/\psi K^\pm$ decay, used as control channel. The $\mathcal{A}^{CP}$ of the $B^\pm \to \pi^\pm\pi^+\pi^-$ and $B^\pm \to K^\pm K^+K^-$ have been measured for the first time with a significance of 14.1 and 8.5 standard deviations, respectively. The result on the $B^\pm \to K^\pm\pi^+\pi^-$ is compatible with the no-*CPV* hypothesis while the value of $\mathcal{A}^{CP}_{B^\pm\to\pi^\pm K^+K^-}$ is found compatible with the previous results. For each decay mode, the *CP* asymmetry is also studied as function of the three-body phase space through a in a Dalitz analysis, considering nine kinematic regions. Significant localized *CP* asymmetries are observed due to rescattering and resonance interference processes. In the $B^\pm \to \pi^\pm\pi^+\pi^-$ channel, the highest *CP* asymmetry ever measured is observed in one of this regions with a value of $\mathcal{A}_{CP} = (+74.5 \pm 2.7_{stat} \pm 1.8_{syst} \pm 0.3_{J/\psi K})\%$. In addition an indication of the $\chi_{c0}(1P)$ resonance, and of the corresponding *CP* violation, is observed in the high $\pi^+\pi^-$ region for the first time.

3.3 Direct *CP* violation in $B \to PV$ decays

LHCb performed a measurement of the direct *CPV* in charmless B decays to a pseudo-scalar and a vector resonance ($B \to PV$) using the data collected during the second LHC run and corresponding to 5.9 fb^{-1} [19]. A new model-independent method based on the angular distributions is employed to measure *CP* asymmetries in low mass and narrow vector resonances. Five different $B \to PV$ decay modes, with three charged tracks in the final state are studied, considering the $\rho(770)^0$,

$K^*(892)^0$ and $\phi(1020)$ resonances. An asymmetry of $\mathcal{A}^{CP} = (+15.0 \pm 1.9_{stat} \pm 1.1_{syst})\%$ is observed for the first time in the $B^\pm \to \rho(770)^0 K^\pm$ decay, with a significance of 6.8 standard deviation. For the other modes, the results are consistent with the no-*CPV* hypothesis.

4. *CP* violation in b-baryon decays

In the last two decades, the B-factories and the LHCb collaboration have successfully established the CKM mechanism and the *CPV* in the b-meson decays. The violation of the *CP* symmetry is required also to explain the observed asymmetry between baryons and anti-baryons in the Universe, named Baryon Asymmetry of the Universe (BAU) [20]. Even if the SM allows *CPV* for b-baryon decays, the CKM mechanism is not strong enough to fully explain the BAU observed in the universe, requiring new physics for additional sources of *CPV*. At the current state of art the *CPV* in the b-baryon sector remains a largely unexplored area. Thanks to the large production cross-section of b-baryons in pp collisions at the LHC, LHCb is the only experiment capable of extending our knowledge in this sector. The first hint of this phenomenon has been obtained using a sample of $\Lambda_b^0 \to p\pi^-\pi^+\pi^-$ decays [21], proving that this kind of measurement is already within the reach of LHCb experiment, thanks to the large dataset collected during the the first two runs of LHC. This analysis uses both triple-product asymmetries and the unbinned energy test method. The highest significances of *CP* asymmetry are 2.9 standard deviations from triple product asymmetries and 3.0 standard deviations for the energy test method. Once the global p-value is considered, all results are consistent with no *CP* violation. Parity violation is observed at a significance of 5.5 standard deviations for the triple product asymmetry method and 5.3 standard deviations for the energy test method.

5. Future perspectives

The prospect of time-integrated measurements in the LHCb Upgrade II experiment and the Belle II experiment holds great significance in the field of particle physics. The data collected in the future runs will be characterised by a significant increase of the available statistics allowing high precision measurements in the key physics channels and the investigation of high-multiplicity or suppressed decay modes.

The sensitivity to the *CP* observables is largely affected by difference in rates of the B and $\bar{B}$ processes. Therefore, a precise control of the detection and charged-particle identification asymmetries is required. The corresponding systematic uncertainties are expected to scale with the integrated luminosity. In the next decade, many experiments will provide important contributions on deepening the *CPV* knowledge.

The Belle II experiment will collect data from e^+e^- collisions at the $\Upsilon(4S/5S)$ and corresponding to 50 ab^{-1} [22]. With high reconstruction efficiencies and resolutions of neutral and charged particles, Belle II has the unique capability of studying all relevant final states of isospin-related charmless decays. This capability will allow, for example, to test the SM through isospin sum-rules at unprecedented precision.

The LHCb Upgrade II phase will collect data from pp collisions at 13-14 TeV, corresponding to 50 fb^{-1}, granting larger statistics in charged-track decay modes for all the b-hadron species [23].

Since many three-body B meson and b-baryonic decay modes involve loop-level transitions, they will be very sensitive to New Physics contributions. Furthermore, the upgraded calorimeter will enhance the LHCb capabilities in selecting decay channels with neutral particles in the final state while addition of magnet-side stations and the TORCH system will allow a better separation of the low-momentum proton and kaons, reducing the physics backgrounds.

With the HL-LHC era, both ATLAS and CMS collaborations will join the search for *CPV* effects exploiting b-decays with muons in the final states. Both experiments will reach an instantaneous luminosity up to $2^{34} cm^{-2}s^{-1}$ and collecting $\sim 300\ fb^{-1}$. Such a large dataset will grant them to be competitive in several measurements.

A fundamental role will be played by the BESIII collaboration, performing quantum correlated measurements at the $\psi(3770)$. These measurements will provide the necessary model-independent inputs needed in several time-integrated *CPV* analyses. In fact, precise measurements performed by the BESIII collaboration will allow to reduce uncertainty on γ, due to external inputs, by $\sim 50\%$. Nevertheless, further analyses with larger datasets will be crucial for not limiting the γ sensitivity.

6. Summary

This article report the recent achieved results on time-integrated *CP* violation measurements with b-hadrons decays. The results, obtained from the LHCb and Belle II experiments, cover the direct γ measurements, the *CPV* in charmless B meson decays. The new LHCb combined value of γ angle reached the 4° precision and many new *CP* asymmetries have been observed for the first time. In addition, a first hint of *CPV* in the baryons sector was obtained by the LHCb experiment. In the next decade, many experiments will provide important contributions to this field thanks to the larger datasets collected and the upgraded detectors.

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