IL NUOVO CIMENTO **48 C** (2025) 93
DOI 10.1393/ncc/i2025-25093-2

Colloquia: IFAE 2024

Status of CP violation searches in beauty hadron decays at LHCb(*)

Andrea Villa
University of Bologna and INFN - Bologna, Italy

received 2 December 2024

Summary. — The study of CP violation in the decays of b-hadrons has brought a wealth of new discoveries in recent years, with many new source of CP violation being discovered in several decay channels. This field of reasearch is also an excellent way to test the assumptions of the Standard Model, as deviation from the predictions could give hints of physics beyond it. In this document, we will present the latest results from the LHCb Collaboration regarding CP-violating measurements in the decays of beauty hadrons.

1. – Measurement of the CKM angle γ in partially and completely reconstructed $B^{\pm} \to D^{*}h^{\pm}$ decays with $D \to K^0_S h^+ h^-$

In the Standard Model (SM), the Cabibbo-Kobayashi-Maskawa (CKM) matrix describes the phenomenon of *CP* violation in the quark sector. The Unitarity Triangle is one of the possible representations of the CKM matrix, and its internal angle $\gamma \equiv \arg(-V_{ud}V^{*}_{ub}/V_{cd}V^{*}_{cb})$ is an important observable for checking the consistency of the SM, which predicts its value with a precision of $\mathcal{O}(10^{-7})$. Assuming tree-level processes do not include physics beyond the Standard Model, a comparison of direct γ measurements and indirect determinations can be made. One of the most precise measurements of γ can be obtained studying the interference of $b \to c$ and $b \to u$ amplitudes with $B^{\pm} \to (D^{*} \to D^0\gamma/\pi^0)h^{\pm}$ decays, where $h = \pi, K$. In particular, the $D^0 \to K^0_S h^+ h^-$ decays are considered golden channels for this measurement given their rich interference structures. By binning the Dalitz plane, a measurement of γ can be performed provided that strong-phase information for the D decays is available. Such information can be obtained from CLEO and BESIII measurements using quantum correlated $D^0\overline{D}^0$ pairs produced at the $\psi(3770)$ resonance [4,5]. The LHCb Collaboration recently published two distinct papers exploting the $B^{\pm} \to [D\gamma/\pi^0]_{D^*}h^{\pm}$ decays to perform a model-independent measurement of γ [1,2]. The two analyses differ on the reconstruction of the γ and the π^0, with one using the fully reconstructed decay chain and the other using an inclusive approach in which no selection is applied to the two neutral

(*) IFAE 2024 - "Intensity Frontier" session

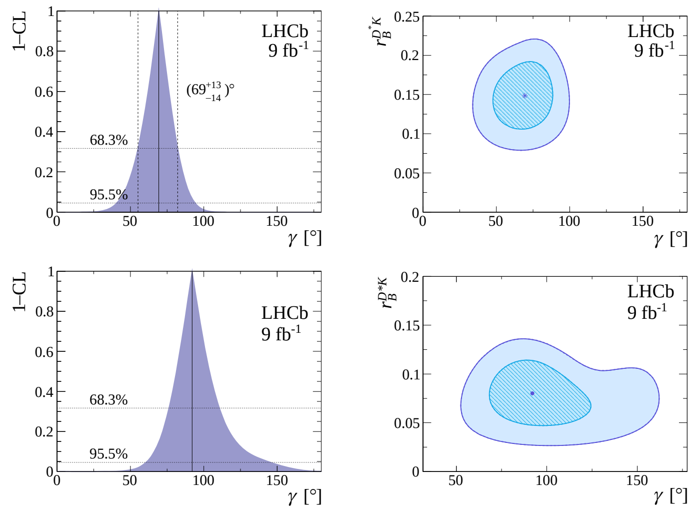

Fig. 1. – Values of γ (left) and 2D projections on the $\gamma - r_B^{D^*K}$ plane of the (top) totally and (bottom) partially reconstructed $B^\pm \to D^* h^\pm$ decays.

particles, resulting in a higher selection efficiency at the cost of larger background contamination. Both analyses employ the full Run 1+2 dataset from LHCb of proton-proton collisions at energies of 7, 8, and 13 TeV, corresponding to a total integrated luminosity of approximately 9 fb^{-1}. The analysis involves dividing the Dalitz plots into bins that maximize sensitivity to γ. By comparing the yields of decays originating from B^+ and B^- mesons, a determination of both the physical and *CP*-violating observables is possible. The physical paramenters include γ, $r_B^{D^*h}$, and $\delta_B^{D^*h}$, the latter two being respectively the ratio of the magnitudes of the suppressed and favoured $B^\pm$ decays and the strong-phase difference between them. The *CP*-violating paramenters can be defined from the physical ones and comprise $x_\pm^{D^*h} \equiv r_B^{D^*h}\cos\big(\delta_B^{D^*h} \pm \gamma\big)$, $y_\pm^{D^*h} \equiv r_B^{D^*h}\sin\big(\delta_B^{D^*h} \pm \gamma\big)$, and $\xi \equiv r_B^{D^*\pi}/r_B^{D^*K}\exp\big[i(\delta_B^{D^*\pi} - \delta_B^{D^*K})\big]$. The two analyses provide different sensitivities to the two sets of observables. The results for the physical observables from the totally (on the left) and partially (on the right) reconstructed analysis are the following (also shown in fig. 1):

$$
\begin{aligned}
\gamma &= (69^{+13}_{-14})^\circ, & \gamma &= (92^{+21}_{-17})^\circ,\\
r_B^{D^*K} &= 0.15 \pm 0.03, & r_B^{D^*K} &= 0.080^{+0.022}_{-0.023},\\
r_B^{D^*\pi} &= 0.01 \pm 0.01, & r_B^{D^*\pi} &= 0.009^{+0.005}_{-0.007},\\
\delta_B^{D^*K} &= (311 \pm 14)^\circ, & \delta_B^{D^*K} &= (310^{+15}_{-20})^\circ,\\
\delta_B^{D^*\pi} &= (37 \pm 37)^\circ, & \delta_B^{D^*\pi} &= (304^{+37}_{-38})^\circ,
\end{aligned}
$$

which are compatible with each other and with the world average value. It can be seen how the fully reconstructed analysis provides a better sensitivity to γ despite having a signal yield lower by about one order of magnitude than the partially reconstructed. Together, these two measurements provide the most precise estimate of γ from the $B^\pm \to D^* h^\pm$ decay channels, which will significantly improve the precision of the combination with the other LHCb measurements.

2. – Measurement of CP violation parameters in $B_s^0 \to J/\psi K^+K^-$ decays in the vicinity of the $\phi(1020)$ resonance

The interference between B_s^0-mixing and -decay amplitudes to CP eigenstates with a $c\bar{c}$ resonance in the final state gives rise to a measurable CP-violating phase ϕ_s, which is particularly sensitive to physics beyond the standard model (SM). In the SM, neglecting subleading loop contributions in $b \to c\bar{c}s$ transitions, ϕ_s is predicted to be equal to $-2\beta_s$, where $\beta_s \equiv \arg[-(V_{ts}V_{tb}^*)/(V_{cs}V_{cb}^*)]$ and V_{ij} are elements of the Cabibbo-Kobayashi-Maskawa (CKM) quark-flavor-mixing matrix. Global fits to experimental data, under the assumption of the CKM paradigm, give $-2\beta_s = (-0.0368^{+0.0009}_{-0.0006})$ rad. This precise indirect determination makes the measurement of ϕ_s an excellent probe for physics beyond the SM, especially for models contributing to $B_s^0 - \overline{B}_s^0$ mixing. Several experiments have measured ϕ_s, the B_s^0 decay width Γ_s, and the decay-width difference $\Delta\Gamma_s$ in B_s^0 decays via $b \to c\bar{c}s$ transitions. The measurements lead to the current world average of $\phi_s^{c\bar{c}s} = (-0.049 \pm 0.019)$ rad, which is dominated by the LHCb results in $B_s^0 \to J/\psi h^+h^-$ ($h = K, \pi$) decays using $5\,\text{fb}^{-1}$ of data collected at center-of-mass energies of $\sqrt{s} = 7, 8 and 13\,\text{TeV}$ [6]. An updated measurement of $\phi_s^{c\bar{c}s}$ has been performed by the LHCb Collaboration with $B_s^0 \to J/\psi K^+K^-$ decays using the full Run 2 dataset collected in 2015-2018, corresponding to an integrated luminosity of $6\,\text{fb}^{-1}$ at $\sqrt{s} = 13\,\text{TeV}$ [3]. The measurement supersedes that in ref. [6] and is combined with the LHCb result using $3\,\text{fb}^{-1}$ of Run 1 data [7]. The paper involves the study of the decay $B_s^0 \to J/\psi K^+K^-$, focusing on events around the $\phi(1020)$ resonance by selecting K^+K^- candidates with an invariant mass in the range $[990, 1050]$ MeV$/c^2$. The dataset has been further split into 48 independent bins of $m(K^+K^-)$, trigger category, and year of data-taking, in each of which a maximum likelihood invariant-mass fit has been performed to obtain signal weights. To obtain a measurement of ϕ_s, a weighted simultaneous fit to the distribution of the decay time and helicity angles $(\cos\theta_K, \cos\theta_\mu, \phi_h)$ is performed in the 48 bins; the fit depends on the physics parameters ϕ_s, $|\lambda|$, $\Gamma_s - \Gamma_d$, $\Delta\Gamma_s$, Δm_s, and A_k. The parameters λ and A_k can be defined for the different polarisation states of the K^+K^- system $(0, \|, \perp, S)$. The PDF used for the simultaneous fit includes corrections for the decay-time resolution, the decay-time and angular efficiencies, and the flavour tagging performance, and contains terms for the S- and P-wave contributions, as well as the inferference of the two. The results of the analysis are:

$$
\begin{aligned}
\phi_s &= (-0.039 \pm 0.022 \pm 0.006) \text{ rad}, \\
\Delta\Gamma_s &= (0.0845 \pm 0.0044 \pm 0.0024) \text{ ps}^{-1}, \\
\Gamma_s - \Gamma_d &= -0.0056^{+0.0013}_{-0.0015} \pm 0.0014 \text{ ps}^{-1},
\end{aligned}
$$

which are the most precise measurement of these 3 parameters to date, and are consistent with SM predictions and previous measurements; no dependence on the polarisation state of the K^+K^- system has been observed, and no CP violation is found in the $B_s^0 \to J/\psi K^+K^-$ decay. The summary of all LHCb measurements of ϕ_s and $\Delta\Gamma_s$ and their combination are shown in fig. 2.

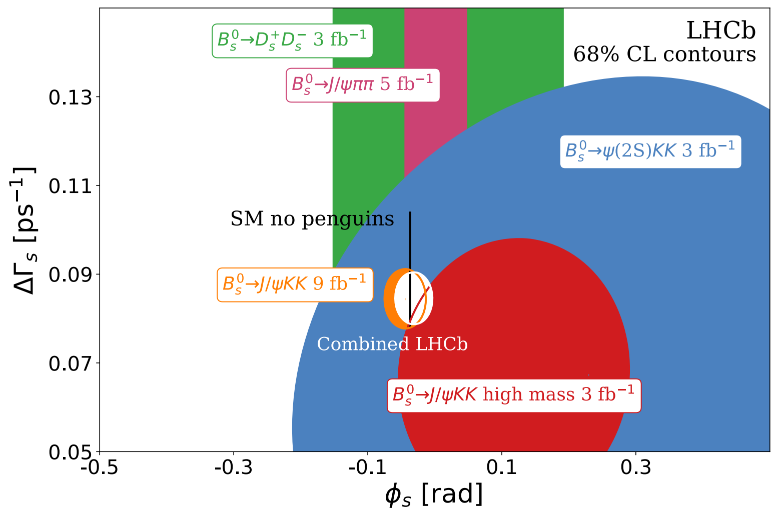

Fig. 2. – Summary of LHCb measurements of ϕ_s and, wherever applicable, $\Delta\Gamma_s$, in $b \to c\bar{c}s$ transitions and their average.

3. – Measurement of $D^0 - \overline{D}^0$ mixing and search for CP violation with $D^0 \to K^+\pi^-$ decays

Flavor-changing neutral currents (FCNCs) and CP violation in charm quark decays are highly suppressed by the Glashow-Iliopoulous-Maiani (GIM) mechanism and the smallness of the elements of the Cabibbo-Kobayashi-Maskawa (CKM) matrix connecting the generations of quarks involved. Accurate measurements of these suppressed processes are critical for testing the limits of the Standard Model, where the role of long-distance QCD contributions is still unclear, and potentially identifying signs of New Physics beyond it. The time evolution of the decay $D^0(t) \to K^+\pi^-$ allows to study all of the effects described above, as it receives contributions from the amplitudes of both the doubly Cabibbo-suppressed $D^0 \to K^+\pi^-$ decay and the Cabibbo-favoured $\overline{D}^0 \to K^+\pi^-$ decay following a $D^0 - \overline{D}^0$ oscillation. The rate of mixing between D^0 and $\overline{D}^0$ is ruled by the mixing parameters $x_{12} = 2|M_{12}|/\Gamma$ and $y_{12} = |\Gamma_{12}|/\Gamma$, where M_{12} and Γ_{12} are the entries of the two matrices that govern the time evolution of the $D^0 - \overline{D}^0$ system, and Γ is the decay width of the D^0 meson. Taking the ratio of the $D^0(t) \to K^+\pi^-$ decay rate and the $\overline{D}^0 \to K^+\pi^-$ rate allows to reduce the dependence of the results from the value of the D^0 lifetime; to do this the following decay-time ratios are defined:

$$R^+_{K\pi} = \frac{\Gamma(D^0(t) \to K^+\pi^-)}{\Gamma(\overline{D}^0(t) \to K^+\pi^-)}, \qquad R^-_{K\pi} = \frac{\Gamma(\overline{D}^0(t) \to K^-\pi^+)}{\Gamma(D^0(t) \to K^-\pi^+)},$$

which, thanks to the smallness of the mixing elements x_{12} and y_{12}, can be expanded up to second order as

$$R^\pm_{K\pi} \approx R_{K\pi}(1 \pm A_{K\pi}) + \sqrt{R_{K\pi}(1 \pm A_{K\pi})}(c_{K\pi} \pm \Delta c_{K\pi})t + (c'_{K\pi} \pm \Delta c'_{K\pi})t^2,$$

where the parameters $R_{K\pi}$, $A_{K\pi}$, $c_{K\pi}$, $\Delta c_{K\pi}$, $c'_{K\pi}$, and $\Delta c_{K\pi}$ are defined as:

$$R_{K\pi} = \frac{1}{2}\left(\left|A_{\overline{f}}/\overline{A}_{\overline{f}}\right|^2 + \left|\overline{A}_f/A_f\right|^2\right) \qquad A_{K\pi} = \frac{\left|A_{\overline{f}}/\overline{A}_{\overline{f}}\right|^2 - \left|\overline{A}_f/A_f\right|^2}{\left|A_{\overline{f}}/\overline{A}_{\overline{f}}\right|^2 + \left|\overline{A}_f/A_f\right|^2},$$

$$c_{K\pi} \approx y_{12}\cos\phi_f^\Gamma \cos\Delta_f + x_{12}\cos\phi_f^M \sin\Delta_f \qquad c'_{K\pi} \approx \frac{1}{4}(x_{12}^2 + y_{12}^2),$$

$$\Delta c_{K\pi} \approx x_{12}\sin\phi_f^M \cos\Delta_f - y_{12}\sin\phi_f^\Gamma \sin\Delta_f \qquad \Delta c'_{K\pi} \approx \frac{1}{2}x_{12}y_{12}\sin\left(\phi_f^M - \phi_f^\Gamma\right),$$

where A_f denotes the decay amplitude of a D^0 meson going into the f final state (and similarly for the $\overline{A}$ and $\overline{f}$ variants). The observable $A_{K\pi}$, in particular, offers a rigorous null test of the SM, as it is theoretically predicted with a precision of $\mathcal{O}\left(10^{-5}\right)$. The LHCb Collaboration has performed a measurement of $R^{\pm}_{K\pi}(t)$ using the full Run 2 dataset, corresponding to an integrated luminosity of $6\,\text{fb}^{-1}$ [8]. The measurement supersedes the previous results obtained on the 2015-2026 subsample of the Run 2 dataset [9] and performs a combination with the Run 1 measurement. The analysis has been carried out studying $D^{*+} \to D^0\pi^+$ decays, where the sign of the low-momentum pion (called *soft* pion) allows to infer the flavour of the D^0 meson at production. The dataset is then split into a right-sign (RS) category, which contains the decays $D^0 \to K^-\pi^+$, and a wrong-sign (WS) category, which contains the $D^0 \to K^+\pi^-$ decays([1]) After the event selection, the dataset is further divided into disjoint sets by final state ($K^+\pi^-$ and $K^-\pi^+$), year of data taking (2015-2016, 2017, 2018), and D^0 decay time. In each of these bins, the WS-to-RS yield ratios are determined with simultaneous χ^2 fits to the invariant-mass distribution of WS, RS, and ghost particles([2]). The raw WS-to-RS ratios are corrected for known sources of possible bias, namely the contamination of doubly misidentified D^0 decays and the removal of common candidates from the WS sample, as well as the soft pion detection asymmetry and the production asymmetry of the D^{*+} meson. Another source of bias considered is the contamination from secondary decays, which can bias the decay-time distribution towards higher values. After all the necessary corrections have been computed and applied, the measured ratios and average decay times in each bin (shown in fig.3) are fitted with the expected decay-time function to extract the best-fit parameters from the Run 2 sample, which are found to be

$$R_{K\pi} = (343.1 \pm 1.9 \pm 0.7) \times 10^{-5} \qquad A_{K\pi} = (-7.1 \pm 5.5 \pm 2.4) \times 10^{-3},$$

$$c_{K\pi} = (51.4 \pm 3.3 \pm 1.1) \times 10^{-4} \qquad c'_{K\pi} = (13.1 \pm 3.5 \pm 1.2) \times 10^{-6},$$

$$\Delta c_{K\pi} = (3.0 \pm 3.3 \pm 1.3) \times 10^{-4} \qquad \Delta c'_{K\pi} = (-1.9 \pm 3.5 \pm 1.4) \times 10^{-6},$$

where the first uncertainty is statistical and the second systematic. The results are consistent with the hypothesis of *CP* conservation and are the most precise measurements of these observables to date.

([1]) The inclusion of charge-conjugated processes is implied in this analysis.
([2]) Ghost particles are fake tracks generated by combining a track stub in the vertex detector with another track stub produced by a different particle in the tracking stations downstream of the magnet.

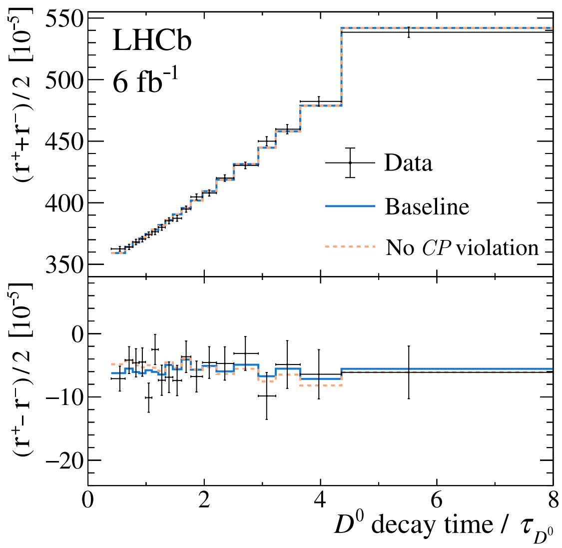

Fig. 3. – Half sum and half difference of measured WS-to-RS yields ratio for the $K^+\pi^-$ and $K^-\pi^+$ final states as a function of decay time. Projections of fits where CP-violation effects are allowed (solid line) or forbidden (dotted line) are overlaid.

4. – Conclusions

In this document, four of the most recent results by the LHCb Collaboration on the topic of CP violation in b-hadron decays have been showcased: a measurement of the CKM angle γ with partially and completely reconstructed $B^\pm \to (D^* \to D\gamma/\pi^0)h^\pm$ decays, with $D \to K^0_S h^+h^-$, a search for CP violation with $B^0_s \to J/\psi K^+K^-$ with a K^+K^- invariant-mass around the $\phi(1020)$ resonance, and a measurement of $D^0 - \overline{D}^0$ mixing and CP-violating parameters with $D^0 \to K^+\pi^-$ decays. They all represent world-best measurements and confirm the position of the LHCb experiment at the precision frontier regarding the study of hadrons containing heavy quarks.

REFERENCES

[1] LHCb Collaboration, *JHEP*, **02** (2024) 118.
[2] LHCb Collaboration, *JHEP*, **12** (2023) 013.
[3] LHCb Collaboration, *Phys. Rev. Lett.*, **132** (2024) 051802.
[4] CLEO Collaboration, *Phys. Rev. D*, **82** (2010) 112006.
[5] BESIII Collaboration, *Phys. Rev. D*, **102** (2020) 052008.
[6] LHCb Collaboration, *Eur. Phys. J. C*, **79** (2019) 706.
[7] LHCb Collaboration, *Phys. Rev. Lett.*, **114** (2015) 041801.
[8] LHCb Collaboration, *Measurement of $D^0 - \overline{D}^0$ mixing and search for CP violation with $D^0 \to K^+\pi^-$ decays*, arXiv:2407.18001 (2024).
[9] LHCb Collaboration, *Phys. Rev. D*, **97** (2018) 031101.