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

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**Summary.** — In this document, we will present two recent results from the LHCb Collaboration on the topic of $CP$ violation in beauty-hadron decays: the measurement of the weak phase $\phi_s^{s\bar{s}s}$ in $B_s^0 \to \phi\phi$ decays and a study of $CP$ violation in $B^\pm \to [K^+K^-\pi^+\pi^-]_D h^\pm$ and $B^\pm \to [\pi^+\pi^-\pi^+\pi^-]_D h^\pm$ decays. Then, anticipations on two ongoing analyses by LHCb will be given, in particular regarding time-dependent $CP$ violation in $B^0_{(s)} \to h^+h^{'-}$ decays and the measurement of integrated $CP$ asymmetries in baryonic $\Lambda_b^0 \to ph^-$ decays.

## 1. – Measurement of the weak phase $\phi_s^{s\bar{s}s}$ with $B_s^0 \to \phi\phi$ decays

The $B_s^0 \to \phi\phi$ decay, being a pure Flavour-Changing Neutral Current (FCNC) mode, is an excellent test-bench to searche for Beyond Standard Model (BSM) Physics, since it can only proceed through loop diagrams where new particles not present in the Standard Model (SM) may appear as virtual contributions. In the SM, time-dependent $CP$ violation of the $B_s^0 \to \phi\phi$ decay is characterised by two parameters, $\phi_s^{s\bar{s}s}$ e $|\lambda|$, predicted to have values respectively close to 0 and 1 in the absence of $CP$ violation; these parameters can also be measured in the three possible polarization states of the $\phi\phi$ pair: null, parallel, or perpendicular (0, $\|$, $\perp$). The LHCb Collaboration previously published a measurement of $\phi_s^{s\bar{s}s}$ using part of the data collected during Run 2 [1]; here we will present the result of the analsyis performed on the full Run 2 sample, corresponding to an integrated luminosity of $6\,\text{fb}^{-1}$ [2]. The differential decay rates can be written as:

$$\frac{\mathrm{d}^4\Gamma(t,\vec{\Omega})}{\mathrm{d}t\,\mathrm{d}\vec{\Omega}} \propto \sum_{k=1}^{6} h_k(t) f_k(\vec{\Omega}), \tag{1}$$

where $\vec{\Omega} = (\theta_1, \theta_2, \varphi)$ are the three angles describing the polarisation of the $\phi$ pair in the final state, $f_k(\vec{\Omega})$ are angular functions defined in [1], and $h_k(t)$ temporal functions that depend on the initial flavour of the $B_s^0$ meson, the mass of the light and heavy mass eigenstates, and on the phases and amplitudes $\phi_{s,i}$ and $|\lambda_i|$. By fitting eq. (1) to the angular

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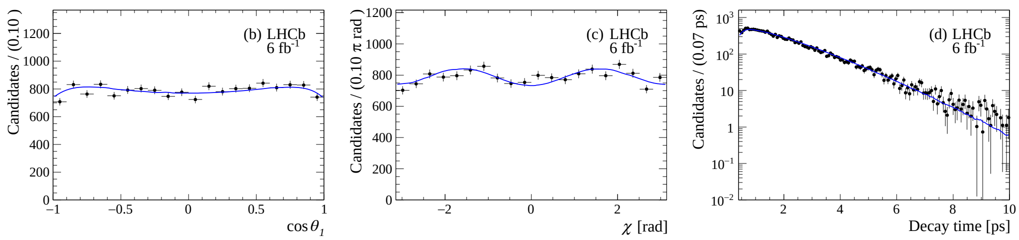


Fig. 1. – Angular and time distributions of $B_s^0 \to \phi\phi$ decays, with the results of the fit superimposed with a blue line.

and decay-time distributions of reconstructed $B_s^0 \to \phi\phi$ decays it is then possible to obtain the experimental values of $\phi_s^{s\bar{s}s}$ and $|\lambda|$, either integrated or polarization-dependent. The initial flavour of the $B_s^0$ meson is inferred by flavour-tagging algorithms [3], which are calibrated using $B^+ \to J/\psi K^+$ and $B_s^0 \to D_s^- \pi^+$ decays, while the angular and temporal efficiencies are evaluated using samples of fully simulated signal events by means of an iterative procedure that corrects data-simulation discrepancies. The angular and decay-time distributions are shown in fig. 1. The results of the fit to the total sample are:

$$\phi_s^{s\bar{s}s} = -0.042 \pm 0.075 \pm 0.009, \quad (2)$$

$$|\lambda| = 1.004 \pm 0.030 \pm 0.009, \quad (3)$$

where the first uncertainty is statistical and the second systematic. When combined with the previous Run 1 results, the final values are $\phi_s^{s\bar{s}s} = -0.074 \pm 0.069$ and $|\lambda| = 1.009 \pm 0.030$, both compatible with the SM predictions and the world's best estimates of these observables. No dependence on the polarization state is observed. In fig. 2 the experimental values of $\phi_s^{s\bar{s}s}$ are shown for Run 1, Run 2, and their combination.

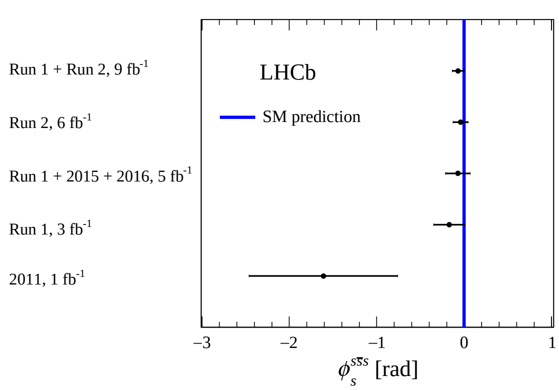


Fig. 2. – Values of $\phi_s^{s\bar{s}s}$ obtained with the Run 1 and Run 2 samples, and their combination.

## 2. – Study of $CP$ violation in $B^{\pm} \to [K^+K^-\pi^+\pi^-]_D h^{\pm}$ and $B^{\pm} \to [\pi^+\pi^-\pi^+\pi^-]_D h^{\pm}$ decays

A powerful tool to study $CP$ violation in the SM constists of contraining the apex of the Unitary Triangle (UT), which is a geometrical representation of the unitary conditions of the Cabibbo–Kobayashi–Maskawa quark-mixing matrix. One of the three angles of the UT, $\gamma = \arg(-V_{ud}V_{ub}^*/V_{cd}V_{cb}^*)$, is notable for being the only one that can be measured directly with tree-level processes, making it an excellent benchmark that can be compared with other indirect measurements of $\gamma$ that are more likely to be affected by physics beyond the SM.

The $B^+ \to D^0h^+$ decay (plus its charge-conjugated analog), where $h = K, \pi$ consitute a promising channel to measure $\gamma$ since it can proceed either through favoured or suppressed Cabibbo transitions, the interference of which provides sensitivity to $\gamma$. The choice of selecting $D^0$ mesons by their decays into the final state $K^+K^-\pi^+\pi^-$, with its rich resonant structure and final state made of only charged particles, has the potential to enhance the sensitivity to $\gamma$, once the amplitude and strong phases of the $D^0$ decay are included from external measurements [4, 5].

In a recent paper by the LHCb Collaboration [6], a study of $CP$ violation is performed on $B^{\pm} \to D^0h^{\pm}$ decays, with $D^0 \to K^+K^-\pi^+\pi^-$ and $D^0 \to \pi^+\pi^-\pi^+\pi^-$, using the full Run 1 and 2 datasets collected by the experiment, corresponding to an integrated lumonosity of $9\,\text{fb}^{-1}$. $CP$ asymmetries of the decays are measured in bins of the $D^0$ phase space, and the results are interpreted as limits on $\gamma$ and other underlying physics parameters. The overall amplitude of the decay can be written as

$$\mathcal{A}_{B^-}(\Phi) = \mathcal{A}_{B^-}^{D^0h^-}\left(\mathcal{A}_{D^0}(\Phi) + r_B^{Dh}\exp\big(i(\delta_B^{Dh} - \gamma)\big)\mathcal{A}_{\overline{D}^0}(\Phi)\right), \tag{4}$$

where $\mathcal{A}_{B^-}^{D^0h^-}$ is the amplitude of the favoured $B^- \to D^0h^-$ decay, $\mathcal{A}_{D^0}$ ($\mathcal{A}_{\overline{D}^0}$) is the amplitude of the $D^0$ ($\overline{D}^0$) decay, $r_B^{Dh}$ is the magnitude of the ratio of the $B^-$ and $B^+$ decay amplitudes, and $\delta_B^{Dh}$ is the strong-phase difference of the amplitudes. The parameter $\Phi$ labels the bin in the 5-dimensional phase-space of the decay. The following $CP$-violating observables can be defined:

$$x_{\pm}^{Dh} = r_B^{Dh}\cos\big(\delta_B^{Dh} \pm \gamma\big), \tag{5}$$

$$y_{\pm}^{Dh} = r_B^{Dh}\sin\big(\delta_B^{Dh} \pm \gamma\big), \tag{6}$$

which can be used to parametrise the yields of $B^{\pm}$ candidates in each phase-space bin. In summary, counting the signal events and thus the $CP$ asymmetries, both in the total sample and in each phase-space bin, allows limits on $\gamma$, $\delta_B^{DK}$, $r_B^{DK}$, $\delta_B^{D\pi}$, and $r_B^{D\pi}$ to be established. The results of the analysis are:

$$\delta_B^{DK} = (81^{+14}_{-13})^{\circ}, \qquad \delta_B^{D\pi} = (298^{+62}_{-118})^{\circ}, \tag{7}$$

$$r_B^{DK} = 0.110^{+0.020}_{-0.020}, \qquad r_B^{D\pi} = 0.0041^{+0.0054}_{-0.0041}, \tag{8}$$

$$\gamma = (116^{+12}_{-14})^{\circ}, \tag{9}$$

where the uncertainties combine statistical and systematic sources (the errors are completely dominated by the former). In fig. 3 the contour plots of these observables are shown, compared with a previous LHCb determination performed combining the results from many $B$ and $D$ decays [7].

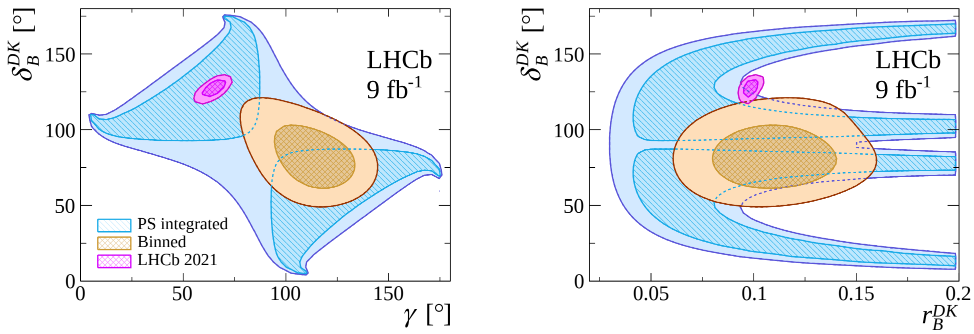


Fig. 3. – Contour plots of $\gamma$ *vs.* $\delta_B^{DK}$ (left) and $r_B^{DK}$ *vs.* $\delta_B^{DK}$ (right). The results of this analysis are shown with blue and yellow regions for the phase-space integrated and binned analysis, respectively. In magenta the results of a more comprehensive analysis [7] are reported.

## 3. – Measurement of time-dependent *CP* asymmetries in $B^0_{(s)} \to h^+ h^{'-}$ decays

The study of *CP* violation in charmless decays of $B^0_{(s)}$ mesons to charged two-body final states represents a powerful tool to test the Cabibbo-Kobayashi-Maskawa (CKM) picture of the quark-flavour mixing in the SM. In addition, since they are highly sensitive to potential new physics effects occurring through loop transitions, they allow the presence of BSM physics to be investigated.

The LHCb Collaboration published a paper in 2018 [8] presenting a measurement of time-dependent *CP* asymmetries in $B^0 \to \pi^+\pi^-$ and $B^0_s \to K^+K^-$ decays, as well as time-integrated *CP* asymmetries in $B^0 \to K^+\pi^-$ and $B^0_s \to \pi^+K^-$ decays, using the full Run 1 dataset corresponding to $2\,\text{fb}^{-1}$ of integrated luminosity. Another measurement, using only part of the Run 2 data collected until 2016, reported the first observation of time-dependent *CP* violation in $B^0_s$ decays [9]. An effort to perform a measurement on the full Run 2 dataset is currently ongoing. The time-dependent *CP* asymmetry of a $B^0_{(s)}$ meson to a *CP* eigenstate $f$ can be written as:

$$A_{CP}(t) = \frac{\Gamma_{\overline{B}^0_{(s)}\to f}(t) - \Gamma_{B^0_{(s)}\to f}(t)}{\Gamma_{\overline{B}^0_{(s)}\to f}(t) + \Gamma_{B^0_{(s)}\to f}(t)} = \frac{-C_f \cos(\Delta m_{d(s)} t) + S_f \sin(\Delta m_{d(s)} t)}{\cosh\left(\frac{\Delta\Gamma_{d(s)}}{2} t\right) + A_f^{\Delta\Gamma} \sinh\left(\frac{\Delta\Gamma_{d(s)}}{2} t\right)}, \tag{10}$$

where $\Delta m_{d(s)}$ and $\Delta\Gamma_{d(s)}$ are the mass and width differences of the $B^0_{(s)}$–$\overline{B}^0_{(s)}$ mass eigenstates. The observables $C_f$, $S_f$, parameterise *CP* violation in the decay and in the interference between mixing and decay, respectively. The quantities $C_f$, $S_f$ and $A_f^{\Delta\Gamma}$ must satisfy the condition $(C_f)^2 + (S_f)^2 + (A_f^{\Delta\Gamma})^2 = 1$, therefore the value of $A_f^{\Delta\Gamma}$ obtained in the analysis can be used as a cross-check to validate the procedure.

The time-integrated *CP* asymmetry for a $B^0_{(s)}$ decay to a flavour-specific final state $f$, such as $B^0 \to K^+\pi^-$ and $B^0_s \to \pi^+K^-$, is defined as

$$A_{CP} = \frac{\left|\overline{A}_{\overline{f}}\right|^2 - \left|A_f\right|^2}{\left|\overline{A}_{\overline{f}}\right|^2 + \left|A_f\right|^2}, \tag{11}$$

TABLE I. – *Values of the statistical uncertainties of the* $B^0_{(s)} \to h^+ h^{'-}$ *CP violation observables (left column) in the previous analysis* [9] *(middle column) and expected values with the full Run 2 dataset (right column).*

| Observable | Previous precision | Expected precision |
|---|---|---|
| $A_{CP}(B^0 \to K^+\pi^-)$ | $3 \times 10^{-3}$ | $2 \times 10^{-3}$ |
| $A_{CP}(B^0_s \to K^+K^-)$ | $13 \times 10^{-3}$ | $7 \times 10^{-3}$ |
| $C_{\pi\pi}$ | $4.5 \times 10^{-3}$ | $3 \times 10^{-2}$ |
| $S_{\pi\pi}$ | $4.2 \times 10^{-3}$ | $2 \times 10^{-2}$ |
| $C_{KK}$ | $3.4 \times 10^{-3}$ | $2 \times 10^{-2}$ |
| $S_{KK}$ | $3.4 \times 10^{-3}$ | $2 \times 10^{-2}$ |

where $A_f$ ($\overline{A}_{\overline{f}}$) is the amplitude of the $B^0_{(s)} \to f$ ($\overline{B}^0_{(s)} \to \overline{f}$) decay. The analysis consists of performing an unbinned maximum-likelihood simultaneous fit to the distributions of invariant mass, decay time, and flavour-tagging variables of the four samples ($K^+K^-$, $\pi^+\pi^-$, $K^+\pi^-$, $\pi^+K^-$) to obtain both the time-dependent and time-integrated asymmetries. With the inclusion of the remaining part of the Run 2 dataset to the analysis, meaning an increase in the sample size of a factor 3, the precision on the $CP$-violating observables is expected to reach the levels shown in table I.

## 4. – Measurement of integrated $CP$ asymmetries in $\Lambda^0_b \to ph^-$ decays

The baryonic decays $\Lambda^0_b \to pK^-$ and $\Lambda^0_b \to p\pi^-$ can be described with Feynman diagrams very similar to the ones for the $B^0 \to K^+\pi^-$ decay, where $CP$ violation has already been observed [9]. Thus, they are promising channels in the quest to search for the yet-unobserved $CP$ violation in baryon decays. In addition, the relevant contribution of loop diagrams to the decay amplitudes, where new particles or interactions can contribute, make them sensitive to New Physics effects. The LHCb Collaboration published a paper in 2018 [10] presenting a measurement of integrated $CP$ asymmetries in these two decays with Run 1 data, that resulted in $A_{CP}(\Lambda^0_b \to pK^-) = (-2.0 \pm 1.3 \pm 1.9)\%$ and $A_{CP}(\Lambda^0_b \to p\pi^-) = (-3.5 \pm 1.7 \pm 2.0)\%$, consistent with the conservation of $CP$ symmetry. Repeating the analysis with the Run 2 dataset, containing 4 times more data than Run 1, will reduce the statistical uncertainties by a factor 2.

The analysis starts with the measurement of the raw asymmetries in the dataset,

$$A_{\text{raw}}(\Lambda^0_b \to ph^-) = \frac{N(\Lambda^0_b \to ph^-) - N(\overline{\Lambda}^0_b \to h^+\overline{p})}{N(\Lambda^0_b \to ph^-) + N(\overline{\Lambda}^0_b \to h^+\overline{p})}, \tag{12}$$

from which the $CP$ asymmetry can be obtained as

$$\begin{aligned} A_{CP}(\Lambda^0_b \to ph^-) = & A_{\text{raw}}(\Lambda^0_b \to ph^-) - A_P(\Lambda^0_b) - A_{\text{PID}}(ph^-) \\ & - A_{\text{det}}(p) - A_{\text{det}}(h) - A_{\text{trig}}(ph^-), \end{aligned} \tag{13}$$

where $A_P(\Lambda^0_b)$ is the production asymmetry of the $\Lambda^0_b$ baryon in $pp$ collisions, $A_{\text{PID}}(ph^-)$ is the asymmetry introduced by the Particle Identification (PID) requirements of the selection, $A_{\text{det}}(f)$ is the detection asymmetry of a particle $f$ interacting with the detector material, and $A_{\text{trig}}(ph^-)$ is the asymmetry arising from the trigger selection. Computing all the instrumental asymmetries above and subtracting them from $A_{\text{raw}}$ thus allows $A_{CP}$ to be measured.

The analysis on the full Run 2 dataset will benefit from new methods that were developed to compute $A_{\text{trig}}$, and the recent precise measurement of $A_P$ with Run 1 data by LHCb [11]. Moreover, the addition of fiducial cuts to the sample to reject regions not properly covered by PID calibration samples will help in reducing the uncertainties on $A_{\text{PID}}$. All things considered, the expected statistical precisions on $A_{CP}$ from the Run 2 sample are 0.75% for $\Lambda_b^0 \to pK^-$ and 0.95% for $\Lambda_b^0 \to p\pi^-$, a factor 2 better than the previous LHCb results.

## 5. – Conclusions

In this document, recent results from the LHCb Collaboration regarding *CP* violation in beauty hadron decays have been presented: a world's best measurement of $\phi_s^{s\bar{s}s}$ in $B_s^0 \to \phi\phi$ decays and a measurement of $\gamma$ (among other parameters) from $B^\pm \to D^0 h^\pm$ decays. In addition, two anticipations have been given of upcoming analyses, namely on time-dependent *CP* violation in $B_{(s)}^0 \to h^+ h^{'-}$ decays and integrated *CP* asymmetries in $\Lambda_b^0 \to ph^-$ decays. When finalised, they will contribute to extend our undestanding of *CP* violation in the decay of beauty hadrons. All of these add to the body of evidence establishing LHCb's performances as a precision machine, capable to perform stringent tests of the Standard Model and indirect seaches of physics beyond it.

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