PROCEEDINGS OF SCIENCE

Time integrated CP violation in b decays (LHCb)

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CKM (Cabibbo-Kobayashi-Maskawa) mechanism [1] [2], describing the coupling between up-type and down-type quarks through the weak interaction, is the main CP violation contribution to the quark sector of the Standard Model (SM). In particular, the precise measurement of the CKM angle γ sets a benchmark for CP violation. A discrepancy between direct and indirect measurements would exhibit a strong evidence of Physics beyond the SM. The CKMfitter group has notably proven that a $1°$ precision on γ direct measurement would lead to test SM up to dozens of TeV [3]. In this document, we present the last LHCb combination of its various γ measurements, which is currently the most precise determination of γ from a single experiment. Two new analyses are also presented, the first one measuring CP violation in the decays $B^{\pm} \to D^0(\to h^+h^-\pi^+\pi^-)h^{\pm}$ and the second one measuring branching fractions of $B^0 \to \overline{D}^{(*)0}\phi$ and $B_s^0 \to \overline{D}^{(*)0}\phi$ decays, which can later lead to a γ measurement with those channels.

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1. Combinated determination of the CKM angle γ at LHCb [4]

In 2022, the LHCb collaboration performed a new combination of measurements sensitive to the *CP* violation angle γ [4], including all relevant beauty and charm results from the LHCb detector until October 2022 with data from Run 1 and Run 2, corresponding to an integrated luminosity of $9\,\mathrm{fb}^{-1}$. This combination has been processed through the simultaneous determination of γ angle and charm mixing parameters, using a frequentist approach. Auxiliary inputs from HFLAV, BESIII, CLEO and LHCb were added, leading to 173 input observables to determine 52 free parameters among which the γ angle.

The two-dimensional profile likelihood contours in the (γ, r_B^{DK}) plane is given in Fig. 1 for the total combination and for some specified channels. One may notice that $B^+ \to D^0 h^+$ modes are largely dominating the combination, as sensibility to γ is large in such decay, in particular when $h^\pm = K^\pm$. However, no individual channel dominates the measurement, showing the necessity of a complementary approach to constrain γ from a global fit. The p-value distribution is also given in Fig. 1. A moderate tension of 2.2σ appears between B^+ and B^0 modes, highlighting the importance for analysis in new B^0 channels. We enter in a luminosity era enabling to reach a better precision for B^0 and B_s^0 modes.

Finally, the global combination leads to $\gamma = (63.8^{+3.5}_{-3.7})^\circ$, which is compatible with the previous LHCb combination and in agreement with global CKM fit prediction (no discrepancy with SM so far). This is by far the most precise determination of γ from a single experiment. Note that uncertainties are still in the regime of statistical dominance as systematic uncertainties only account for $\approx 1.4^\circ$. Time-integrated methods still dominate the measurement, with $\gamma = 63.3^{+3.7}_{-3.9}$, compared to $\gamma = 79^{+21}_{-23}$ for time-dependent methods. The biggest improvement from the previous combination [5] is due to the analysis with channel $B^\pm \to D^0 h^\pm$ with $D^0 \to K^\pm \pi^\mp \pi^+ \pi^-$ [6].

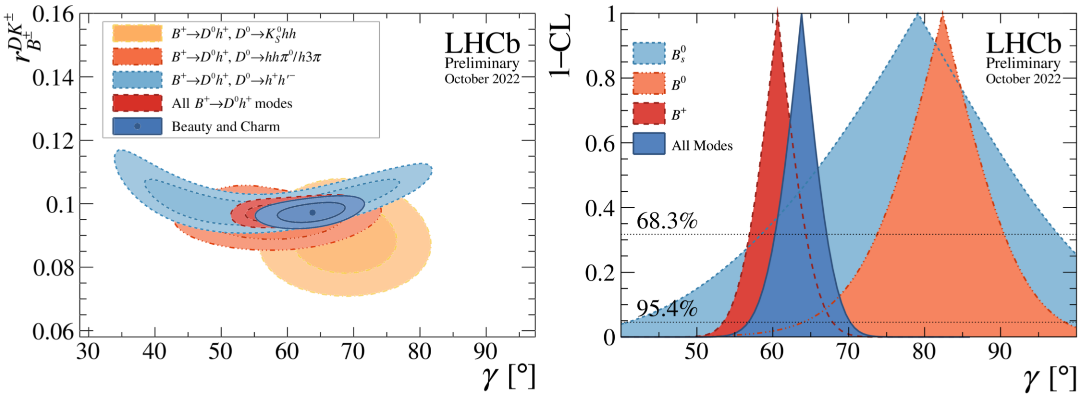

Figure 1: On the left, two-dimensional profile-likelihoods (1σ and 2σ contours) in the (γ, r_B^{DK}) plane. On the right, p-value distribution as a function of γ for the total or partial combination.

2. *CP* violation in the decays $B^\pm \to D^0(\to h^+h^-\pi^+\pi^-)h^\pm$ [7]

The LHCb collaboration performed the first study of *CP* violation in $B^\pm \to D^0(\to h^+h^-\pi^+\pi^-)h^\pm$ decays [7] ($h = K, \pi$), using the full Run1+2 data. In this analysis, two statistically independent measurements of *CP* parameters are processed, in a phase-space integrated way or through a sophisticated binning of the 5D D^0-decay phase-space.

In the integrated measurement, direct asymmetries $\mathcal{A}$ and double-ratio $\mathcal{R}_{CP}$ are measured and can be defined as a function of γ angle as :

$$\mathcal{A}_h^{KK\pi\pi} \equiv \frac{\Gamma(B^- \to Dh^-) - \Gamma(B^+ \to Dh^+)}{\Gamma(B^- \to Dh^-) + \Gamma(B^+ \to Dh^+)} = \frac{2r_B^{Dh}\kappa sin(\delta_B^{Dh})sin(\gamma)}{1 + (r_B^{Dh})^2 + 2r_B^{Dh}\kappa cos(\delta_B^{Dh})cos(\gamma)}, \quad (1)$$

$$\mathcal{R}_{CP}^{KK\pi\pi} \equiv \frac{R_{KK\pi\pi}}{R_{K\pi\pi\pi}} = 1 + (r_B^{DK})^2 + 2r_B^{DK}\kappa cos(\delta_B^{DK})cos(\gamma), \quad (2)$$

$$R_f \equiv \frac{\Gamma(B^- \to [f]_D K^-) + \Gamma(B^+ \to [f]_D K^+)}{\Gamma(B^- \to [f]_D \pi^-) + \Gamma(B^+ \to [f]_D \pi^+)} \quad (3)$$

where r_B^{Dh} is the amplitude ratio between $B \to D^0 h$ and $B \to \overline{D}^0 h$, δ_B^{Dh} is the B decay strong phase and $\kappa = 2F_+^{KK\pi\pi} - 1$ is calculated from [8] and [9]. The *CP*-violating observables are summarised in Fig. 2 and leads to a γ angle measurements which can be seen in Fig. 3.

CP-violating observable	Fit results
$A_K^{KK\pi\pi}$	$0.093 \pm 0.023 \pm 0.002$
$A_\pi^{KK\pi\pi}$	$-0.009 \pm 0.006 \pm 0.001$
$A_K^{\pi\pi\pi\pi}$	$0.060 \pm 0.013 \pm 0.001$
$A_\pi^{\pi\pi\pi\pi}$	$-0.0082 \pm 0.0031 \pm 0.0007$
$R_{CP}^{KK\pi\pi}$	$0.974 \pm 0.024 \pm 0.015$
$R_{CP}^{\pi\pi\pi\pi}$	$0.978 \pm 0.014 \pm 0.010$

Figure 2: Results of the phase-space integrated measurements. The first uncertainty is statistical, the second systematic.

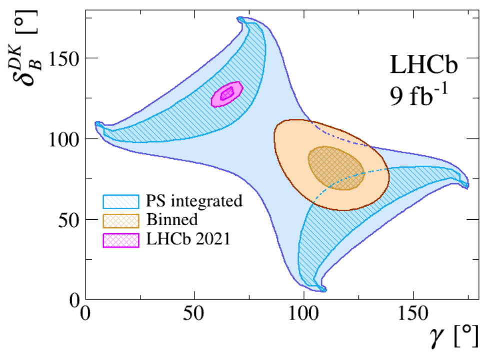

Figure 3: Profile-likelihood contours (1 and 2σ) in the (γ, δ_B^{DK}) plane for binned and integrated measurements.

The second method is performed through the BPGGSZ formalism [10] [11], which consists in defining a binning scheme of the D^0 decay phase-space on which the strong phase difference $\Delta\delta_D$ between D^0 and $\overline{D}^0$ is known for each bin. Here, $\Delta\delta_D$ is known thanks to an existing amplitude analysis [12], which makes this study a model-dependent analysis. However, strong phases will be available from BESIII upcoming $\psi(3770)$ data, leading to a theoretically cleaner model-independent update of this study. The binning scheme is defined in the 2D surface defined by $\Delta\delta_D$ and r_D and has been defined in order to enhance sensitivity to γ. The two-dimensional profile likelihood contours in the (γ, δ_B^{DK}) plane for binned and integrated measurements are given in Fig. 3, leading to a numerical result of $\gamma = (116^{+12}_{-14})^\circ$, which is high compared to the world average but still in the 3σ asymmetric contours. A better measurement is expected with the future model-independent study.

3. Branching fractions of $B^0 \to \overline{D}^{(*)0}\phi$ and $B_s^0 \to \overline{D}^{(*)0}\phi$ [13]

In [13], the first evidence for the decay $B^0 \to \overline{D}^{(*)0}\phi$ has been measured, with a branching ratio to be:

$$\mathcal{B}(B^0 \to \overline{D}^0\phi) = (7.7 \pm 2.1 \pm 0.7 \pm 0.7) \times 10^{-7}, \quad (4)$$

$$\mathcal{B}(B^0 \to \overline{D}^{*0}\phi) = (2.2 \pm 0.5 \pm 0.2 \pm 0.2) \times 10^{-6}, \quad (5)$$

where the first uncertainty is statistical, the second systematic and the third is due to the normalisation mode $B^0 \to \bar{D}^0 K^+ K^-$. This leads to a 3.6$\sigma$ significance on $B^0 \to \bar{D}^0 \phi$ and 4.3σ significance on $B^0 \to \bar{D}^{*0}\phi$. A combined study of the two decay modes, with inputs on $\mathcal{B}(B^0 \to \bar{D}^{(*)0}\omega)$ from world average, leads to the first determination of the $\omega - \phi$ mixing angle δ in b-hadron decays, to be :

$$tan^2(\delta) = (3.6 \pm 0.7 \pm 0.4) \times 10^{-3}, \tag{6}$$

which is consistent with the world average [14].

An updated measurement of the branching ratio of the $B_s^0 \to \bar{D}^{(*)0}\phi$ was also performed, giving :

$$\mathcal{B}(B_s^0 \to \bar{D}^0 \phi) = (2.30 \pm 0.10 \pm 0.11 \pm 0.20) \times 10^{-5}, \tag{7}$$

$$\mathcal{B}(B_s^0 \to \bar{D}^{*0} \phi) = (3.17 \pm 0.16 \pm 0.17 \pm 0.27) \times 10^{-5}, \tag{8}$$

where uncertainties are similarly defined than for $B^0 \to \bar{D}^{(*)0}\phi$, with the same normalisation mode. Note that those results are consistent with the previous LHCb results [15]. The combined fit used to perform those four branching fraction measurements are shown in Fig. 4.

This last updated measurement is of particular interest because $B_s^0 \to \bar{D}^{*0}\phi$ and $B_s^0 \to D^{*0}\phi$ are two color-suppressed interfering diagrams with amplitudes similar in size, analogous to the decay $B^0 \to \bar{B}^0 K^{*0}$, which is already used to process a γ angle measurement. Using $B_s^0 \to \bar{D}^{*0}\phi$ to measure γ would give an additional method with B_s^0 decay, complementary with $B_s^0 \to D_s^+ K$. The expected sensitivity on γ with this decay has been estimated in [16] to 8° to 19° with the LHCb dataset.

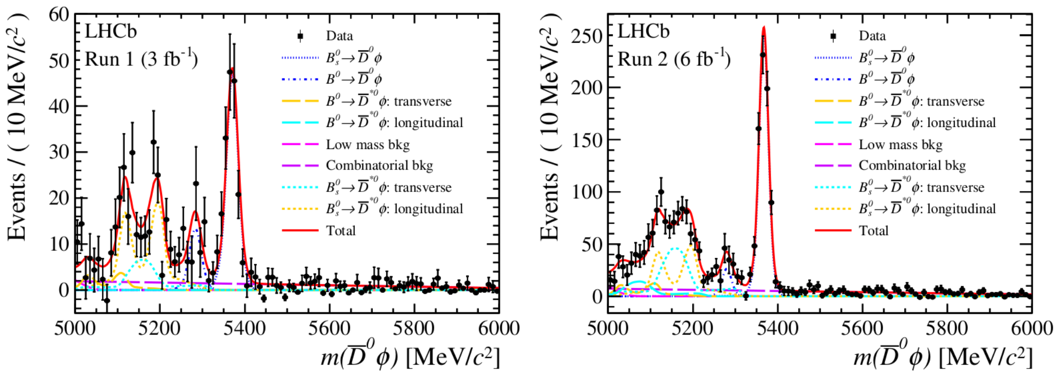

Figure 4: Distribution and fit of weighted $m_{D\phi}$ for (left) Run 1 data and (right) Run 2 data.

4. Conclusion

Precise measurement of the CKM angle γ is currently one of the main challenge in flavour physics and in the research for new physics beyond the SM. LHCb experiment provides the most precise value in the last combination [4]. New studies with other channels are still necessary, in particular in B^0 and B_s^0 decays. In this context, a first γ measurement has been performed with the channels $B^\pm \to D^0(\to h^+h^-\pi^+\pi^-)h^\pm$ [7], to be improved with a model-independent study when strong phase measurements will be available. A first evidence for $B^0 \to \bar{D}^{(*)0}\phi$ as also been processed, as well as an updated measurement of the $B_s^0 \to \bar{D}^{(*)0}\phi$ branching fraction leading to an additional mode for γ study. Finally, there is room for improvement with upcoming Run 3 analysis as all measurements are still limited by statistics.

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