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γ measurements in ADS and GLW(-like) decays at LHCb

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These proceedings present recent LHCb measurements of the CKM angle γ in ADS and GLW(-like) decays. These include measurements of CP observables in $B^\pm \to D^{(*)}h^\pm$ with $D \to h^+h^-$ and $B^\pm \to Dh^\pm$ with $D \to h^\pm h^\mp \pi^0$ decays. A CP asymmetry measurement in $\Lambda_b^0 \to DpK^-$ decays with $D \to K\pi$ is also presented, where the suppressed mode is observed for the first time. All of the results are obtained using the full LHCb dataset collected during Run 1 (2011-2012) and Run 2 (2015-2018), corresponding to an integrated luminosity of 9 fb^{-1}.

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PoS(CKM2021)115

1. Introduction

The unitarity of the CKM matrix [1, 2], describing the quark mixing, can be represented by a particular triangle in the complex plane. The weak phase $\gamma \equiv \arg(-V_{ud}V_{ub}^*/V_{cd}V_{cb}^*)$ is the only angle which is accessible at tree level and has a negligible theoretical uncertainty. Direct measurements of γ at tree level are benchmarks of the Standard Model, whereas indirect determinations consist of global fits to the unitary triangle, assuming a closed triangle, and involve inputs containing loop processes through which New Physics could potentially contribute. Therefore, a key goal of the LHCb experiment is to improve direct measurements of γ using tree-level decays in order to look for any discrepancy with respect to the indirect determination of γ. The value of the indirect determination is $\gamma = (65.66^{+0.90}_{-2.65})^\circ$, while the direct measurement gives $\gamma = (72.1^{+5.4}_{-5.7})^\circ$ as of Summer 2019 [3], before the results presented at this conference were published. The analyses presented use the dataset collected by the LHCb experiment in proton-proton collisions during Run 1 (2011-2012) and Run 2 (2015-2018), corresponding to an integrated luminosity of 9 fb^{-1}.

2. Measurement of γ in $B^\pm \to DK^\pm$

The most sensitive decays in the measurement of γ are $B^\pm \to DK^\pm$, where the D meson is a superposition of D^0 and $\bar{D}^0$ states. The interference between $b \to c\bar{u}s$ and $b \to u\bar{c}s$ transitions gives sensitivity to γ, and both the D^0 and $\bar{D}^0$ should be able to decay to the same final state in order for the interference to arise and lead to a measurement of γ. The first family of processes that can be used are those where one of the D^0 or $\bar{D}^0$ decays is Cabibbo-favoured and the other doubly-Cabibbo-suppressed, such as $D^0 \to K^-\pi^+$ and $\bar{D}^0 \to K^-\pi^+$, and are referred to as ADS decays [4]. The ratio of yields between the favoured and suppressed decays, as well as the rate asymmetries between B^- and B^+, are related to the physics parameters of interest r_B, δ_B and γ:

$$R_{ADS} = \frac{\Gamma(B^- \to [\pi^-K^+]_D K^-)}{\Gamma(B^- \to [K^-\pi^+]_D K^-)} = r_B^2 + r_D^2 + 2r_B r_D \cos(\delta_B + \delta_D)\cos(\gamma), \tag{1}$$

$$A_{ADS} = \frac{\Gamma(B^- \to DK^-) - \Gamma(B^+ \to DK^+)}{\Gamma(B^- \to DK^-) + \Gamma(B^+ \to DK^+)} = \frac{2r_B r_D \sin(\delta_B + \delta_D)\sin(\gamma)}{R_{ADS}}, \tag{2}$$

where r_B is the ratio between the amplitudes of the suppressed and favoured B decays and δ_B the corresponding strong-phase difference. The D decay parameters r_D and δ_D are taken as external inputs [5]. Due to the similar magnitude of the amplitudes between the two interfering paths for the decay, large interference, and hence *CP* violation, can occur. A second family of D decay modes that can be exploited are the *CP*-eigenstates $D \to K^-K^+$ and $D \to \pi^-\pi^+$, referred to as GLW modes [6, 7]. Due to the fact that the overall amplitudes of the two decay paths are of different sizes, the amount of *CP* violation that is observable is relatively smaller.

3. ADS/GLW analysis in $B^\pm \to D^{(*)}h^\pm$, $D \to h^+h^-$

The first analysis presented [8] is of an ADS/GLW measurement using $B^\pm \to D^{(*)}h^\pm$, $D \to h^+h^-$ decays ($h \in \{\pi, K\}$). Both fully and partially reconstructed $B^\pm \to D^{(*)}h^\pm$ decays are used as signal, with D^* decaying to the $D\pi^0$ or $D\gamma$ final states and where the neutral pion or photon is not reconstructed. The partial reconstruction method provides larger yields with respect to fully reconstructing the D^* decay given the low efficiency for neutral pions and photons at LHCb. The ADS $B^\pm \to D^* h^\pm$ modes are measured for the first time at LHCb and the first observation of the ADS $B^\pm \to [D\pi^0]_{D^*}\pi^\pm$ decay with a significance of 6.1 standard deviations is reported. An extended maximum likelihood fit to the Dh invariant mass is used to determine 28 *CP* observables, which are all measured with world-best precision. The fit is performed simultaneously in 16 independent samples corresponding to the categories defined by the charge of the B candidate, the companion particle hypothesis and the four D decay modes. The invariant-mass distribution for the $B^\pm \to D^{(*)}K^\pm$ suppressed mode is shown in Fig. 1 for B^- (left) and B^+ (right) candidates, with the fit result superimposed.

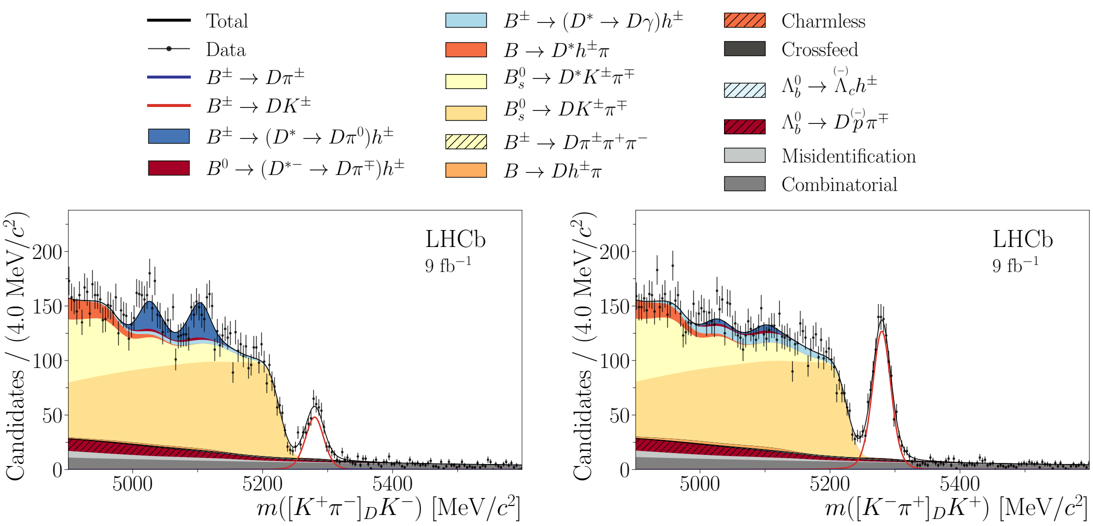

Figure 1: Invariant-mass distribution for the suppressed mode for B^- (left) and B^+ (right) decays with the fit result superimposed. This figure is one of a series which can be found in Ref. [8] and the different fit components are listed in the legend.

The $B^\pm \to D^* h^\pm$ signals are at a lower reconstructed mass due to the missing particle and clear *CP* asymmetries are visible. The $B^\pm \to [D\pi^0]_{D^*}K^\pm$ decays are dominant on the left for B^-, whereas there are more $B^\pm \to [D\gamma]_{D^*}K^\pm$ decays on the right for B^+. This is due to the strong-phase difference of 180° between $D^* \to D\pi^0$ and $D^* \to D\gamma$ decays, which makes their CP asymmetries opposite. Using the relations between the observables and the physics parameters, the space in (r_B, δ_B, γ) compatible with the values obtained for the *CP* observables can be determined and is shown in Fig. 2 for $B^\pm \to DK^\pm$ (left) and $B^\pm \to D^*K^\pm$ (right). The solution for γ is multiple-valued and in order to resolve the situation, the $B^\pm \to Dh^\pm$ results are combined with the $B^\pm \to Dh^\pm$, $D \to K_s^0 hh$ analysis [9], which is single-valued and breaks the multiple solutions. The combination yields a value of $\gamma = (61.8 \pm 4.0)^\circ$. Concerning the $B^\pm \to D^*K^\pm$ results, the multiple solutions are not broken yet and work is ongoing on the corresponding $D \to K_s^0 hh$ decays in order to be able to add a constraint which would allow a standalone determination of γ from $B \to D^* h$ decays.

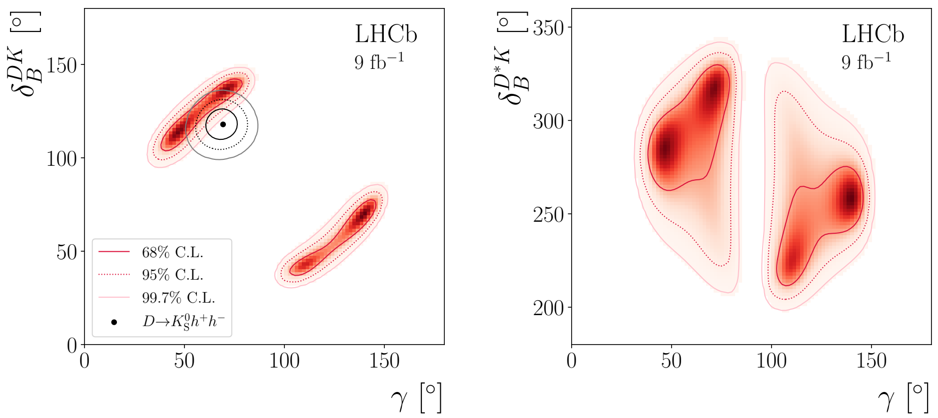

Figure 2: Confidence regions in the (δ_B,γ) space obtained for $B^\pm \to DK^\pm$ (left) and $B^\pm \to D^*K^\pm$ (right) .

4. ADS and quasi-GLW analysis in $B^\pm \to Dh^\pm$, $D \to h^\pm h^\mp \pi^0$

The second analysis [10] studies $B^\pm \to Dh^\pm$, where $D \to h^\pm h^\mp \pi^0$, for which *CP* observables can be formed in a similar way from rate ratios and asymmetries. The $\pi^-\pi^+\pi^0$ and $K^-K^+\pi^0$ final states are admixtures of *CP*-even and *CP*-odd eigenstates, referred to as quasi-GLW modes, which are mostly *CP*-even. Due to the opposite *CP* asymmetries of the two different types of eigenstates, the overall asymmetry is diluted when integrating over phase space and dilution factors are taken as external inputs. For the ADS decays $B^\pm \to [\pi^\pm K^\mp \pi^0]_D h^\pm$, the rate ratios of the suppressed and favoured modes are measured. The invariant-mass distribution for the suppressed $B^\pm \to DK^\pm$ mode is shown in Fig. 3 for B^- (left) and B^+ (right). This constitutes the first observation of this mode with a significance of 7.8 standard deviations.

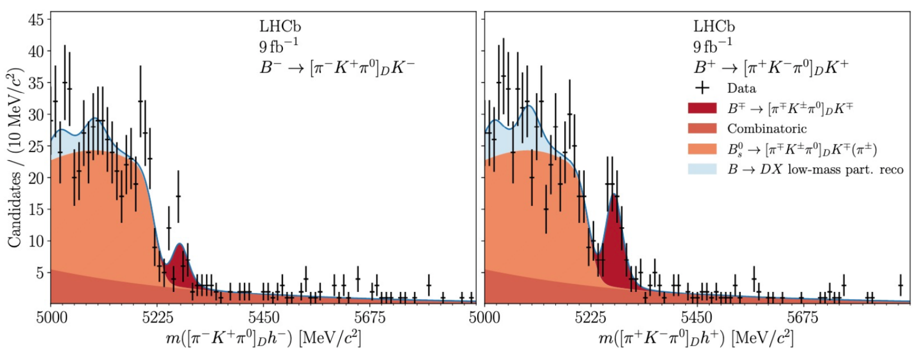

Figure 3: Invariant-mass distribution for the suppressed mode for B^- (left) and B^+ (right) decays. The fit result is superimposed and the different components are visible.

Using the profile likelihood method, confidence regions are obtained in terms of the physics parameters. The multiple solutions obtained are shown in Fig. 4 (left). While the global minimum is found to be at $\gamma = (145^{+9}_{-39})^\circ$, a second solution shown in Fig. 4 (right) is in good agreement with the current value of γ obtained from the 2021 LHCb combination [11]: $\gamma = (56^{+24}_{-19})^\circ$, $\delta_B = (122^{+19}_{-23})^\circ$, $r_B = (9.3^{+1.0}_{-0.9}) \times 10^{-2}$.

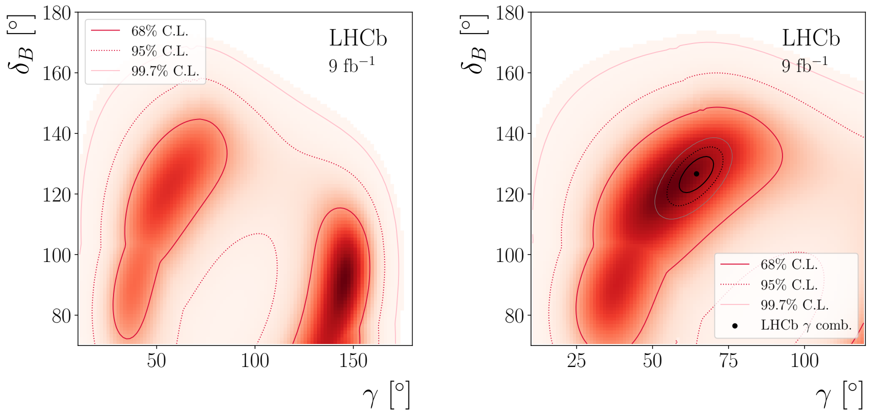

Figure 4: Confidence regions in the (δ_B,γ) space showing the multiple solutions obtained for γ within 180° (left) and the solution which is consistent with the LHCb 2021 γ combination [11] (right).

5. *CP* asymmetry measurement in $\Lambda_b^0 \to DpK^-$, $D \to K\pi$

The last analysis presented [12] consists of a study of $\Lambda_b^0 \to DpK^-$, $D \to K^\pm\pi^\mp$ decays and presents the first observation of the suppressed decay. The branching fraction ratio between the favoured and suppressed modes is measured and a *CP* asymmetry measurement of the suppressed mode is performed. The invariant-mass distributions are shown in Fig. 5 for $\Lambda_b^0 \to [K^+\pi^-]_D pK^-$ (left) and $\bar{\Lambda}_b^0 \to [K^-\pi^+]_D \bar{p}K^+$ (right) suppressed decays.

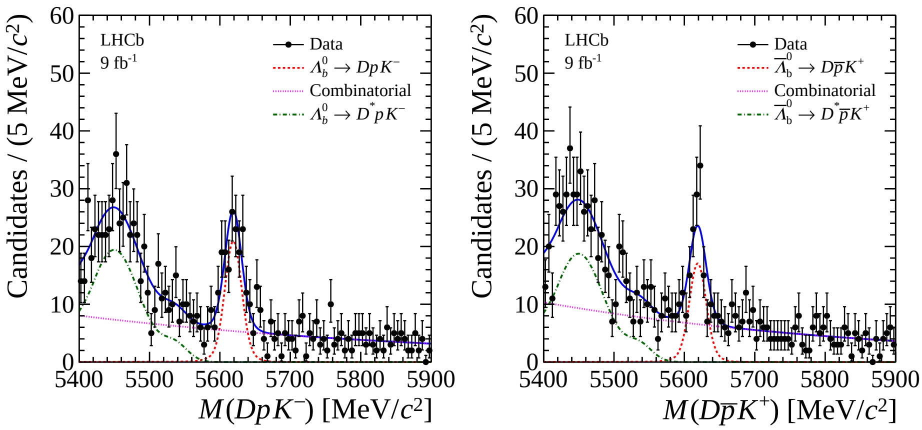

Figure 5: Invariant-mass distribution for the suppressed $\Lambda_b^0 \to [K^+\pi^-]_D pK^-$ (left) and $\bar{\Lambda}_b^0 \to [K^-\pi^+]_D \bar{p}K^+$ (right) decays, with the fit projection superimposed.

While the asymmetry is found to be compatible with zero, higher yields and more decay modes will improve the sensitivity to γ as more data is collected in the future, this being the first measurement of an ADS mode in a baryon decay.

6. Conclusion and outlook

Recent measurements from the LHCb experiment add strong constraints on the CKM angle γ and the LHCb combination [11] yields the most precise measurement from a single experiment with a precision of about 4°. This was the expected sensitivity for Run 1 and Run 2 which is achieved while many ongoing analyses, such as using $B^{\pm} \to DK^{*\pm}$ decays [13], are yet to be published using the full LHCb dataset. The overall strategy is to cover all B and D decay combinations in order to improve the sensitivity to γ. It is important to perform analyses in sub-dominant channels as systematic uncertainties and backgrounds are different and therefore provide further constraints and cross-checks. With more data to be collected during Run 3 and beyond, this will allow measurements of γ with a precision of better than 1° [14, 15] and to further test the Standard Model.

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PoS(CKM2021)115