RECENT RESULTS OF MEASUREMENT OF CKM ANGLE γ AND CPV IN THE BEAUTY SECTOR AT THE LHCb*

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The Standard Model (SM) description of CP violation can be tested by over-constraining the angles of the Unitary Triangle. Differences in measurements of the Cabibbo–Kobayashi–Maskawa angle γ performed with the tree-level and loop-dominated processes may be evidence for physics not covered by the Standard Model. Recent results of measurements of the CKM angle γ, including one of the most precise determinations of the CKM angle γ in a single measurement obtained in studies of $B^{\pm} \to DK^{\pm}$ with the $D \to K^{\mp}\pi^{\pm}\pi^{\pm}\pi^{\mp}$ decay and results of studies of $B^{\pm} \to Dh^{\pm}$ with the $D \to h^{\pm}h'^{\mp}\pi^{0}$ and $B^{\pm} \to D[K^{\mp}\pi^{\pm}\pi^{\pm}\pi^{\mp}]h^{\pm}$ decays, are presented in these proceedings.

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1. Introduction

The CKM angle $\gamma \equiv \arg(-V_{ud}V^{*}_{ub}/V_{cd}V^{*}_{cb})$ is one of the parameters of the Unitary Triangle. It can be determined experimentally by exploiting the interference between the favoured $b \to c$ and suppressed $b \to u$ quark transition amplitudes. The family of processes where these interferences occur are tree-level decays such as $B \to DK$. Discrepancies between the measurement of the CKM angle γ in tree-level decay (Fig. 1, right) and processes involving loops (Fig. 1, left) would be evidence of physics beyond the Standard Model.

The combined LHCb measurement of CKM angle γ yields: $\gamma = (65.4^{+3.8}_{-4.2})^{\circ}$ [2], which is the most precise result from a single experiment. The precision is dominated by the measurement using $B^{\pm} \to DK^{\pm}$ decays.

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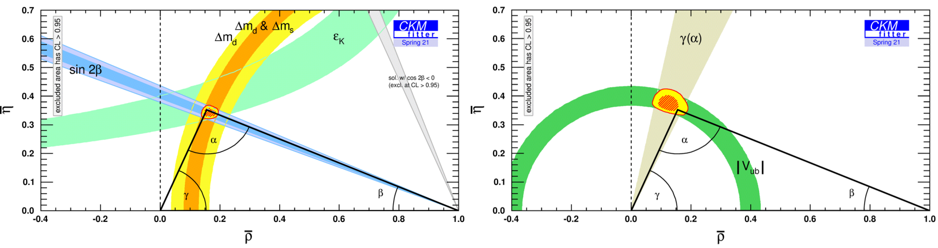

Fig. 1. Result of the measurement of the CKM matrix parameters using all possible modes (left) and tree-level processes only (right) provided by the CKM fit group [1].

2. Studies of $B_s^0 \to D_s^\mp K^\pm \pi^\pm \pi^\mp$ decay

The measurement of the CKM angle γ with $B_s^0 \to D_s^\mp K^\pm \pi^\pm \pi^\mp$ decays is an example of time-dependent measurement at the LHCb [3] where the transition between B_s^0 and $\bar{B}_s^0$ (or B^0 and $\bar{B}^0$) flavour eigenstates to the same final state is exploited to measure the CKM matrix parameters. The full Runs 1 and 2 LHCb data set, 9 fb^{-1}, collected at the centre-of-mass energies of 7, 8, and 13 TeV was used in this study. The analysis result was verified by simultaneous measurement of the CKM angle γ using a model-independent measurement, integrating over the phase space of the decay. A sample of the $B_s^0 \to D_s^\mp \pi^\pm \pi^\pm \pi^\mp$ decay was used in calibrating the flavour-tagging algorithm[1] and to measure Δm_s (B_s^0–$\bar{B}_s^0$ mixing frequency — the difference between mass eigenstates of B_s^0 meson).

The candidates are selected by requirements on variables such as the particle's identification, B_s^0 meson proper time, displace of B_s^0 vertex from primary proton–proton interaction vertex (PV), and output of the Boosted Decision Tree (BDT) algorithm. The mass distributions of the $B_s^0 \to D_s^\mp \pi^\pm \pi^\pm \pi^-$ and $B_s^0 \to D_s^\mp K^\pm \pi^\pm \pi^-$ candidates with the fit result superimposed are shown in Fig. 2.

The model-dependent method comprises resonances that potentially contribute to the $B_s^0 \to D_s^\mp K^\pm \pi^\pm \pi^\mp$ decay. The two quasi-independent models cover the $b \to c$ and $b \to u$ type contributions. The complexity of the model was limited using the LASSO technique [5].

The summary of measurements of the CKM matrix parameters, including the CKM angle γ and associated hadronic parameters, together with Δm_s are presented in Table 1. The uncertainties given in Table 1 are statistical, systematic, and due to alternative amplitude models considered.

[1] Algorithms which aim to identify the initial flavour of the neutral particle by investigating flavour at decay, defined by the electric charge of the decay products [4].

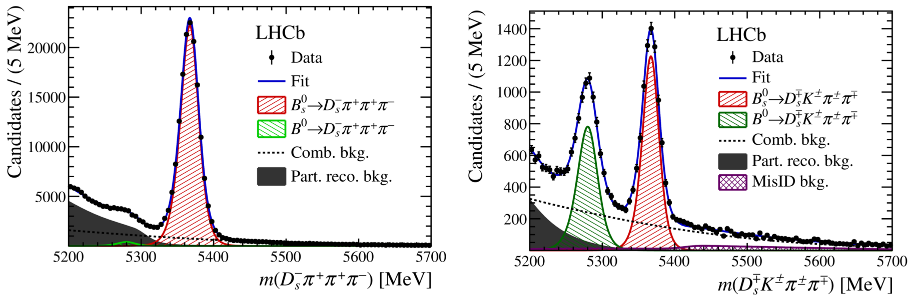

Fig. 2. Invariant mass distributions for the $B_s^0 \to D_s^\mp \pi^\pm\pi^\pm\pi^\mp$ (left) and $B_s^0 \to D_s^\mp K^\pm\pi^\pm\pi^\mp$ (right) candidates with a result of the fit superimposed [3].

Table 1. Results of the model-independent and model-dependent measurements of parameters determined from fits to $B_s^0 \to D_s^\mp K^\pm\pi^\pm\pi^\mp$ candidates.

Parameter	Model-independent	Model-dependent
r	$0.47^{+0.08+0.02}_{-0.08-0.03}$	$0.56 \pm 0.05 \pm 0.04 \pm 0.07$
κ	$0.88^{+0.12+0.04}_{-0.19-0.07}$	$0.72 \pm 0.04 \pm 0.06 \pm 0.04$
δ	$\left(-6^{+10+2}_{-12-4}\right)^\circ$	$(-14 \pm 10 \pm 4 \pm 5)^\circ$
$\gamma - 2\beta_s$	$\left(42^{+19+6}_{-13-2}\right)^\circ$	$(42 \pm 10 \pm 4 \pm 5)^\circ$
Δm_s	$(17.757 \pm 0.007 \pm 0.008)$ ps^{-1}	

3. Studies of $B^\pm \to Dh^\pm(D \to h^\pm h'^\mp \pi^0)$ decays

The LHCb Collaboration measured CP observables in $B^\pm \to Dh^\pm$ decays, where $h^\pm$ is either a kaon or a pion, and the neutral D-meson decay is reconstructed in the three-body final states $K^\pm\pi^\mp\pi^0$, $\pi^\pm\pi^\mp\pi^0$, $K^\pm K^\mp\pi^0$, and $\pi^\pm K^\mp\pi^0$. The most suppressed $B^\pm \to D[\pi^\pm K^\mp\pi^0]K^\pm$ mode is observed for the first time with a significance greater than seven standard deviations [6].

A data sample was collected with the LHCb detector, corresponding to an integrated luminosity of 9 fb^{-1}. The angle γ is probed using ADS (Atwood–Dunietz–Soni, $D \to K^\pm\pi^\mp\pi^0$) or GLW (Gronau–London–Wyle, $D \to \pi^\pm\pi^\mp\pi^0$, $D \to K^\pm K^\mp\pi^0$) modes. The observables are determined by performing a simultaneous fit to the invariant mass of the selected B candidates in sixteen subsamples. The details of the data and total probability density function (PDF), which comprises several components, can be found in Fig. 3.

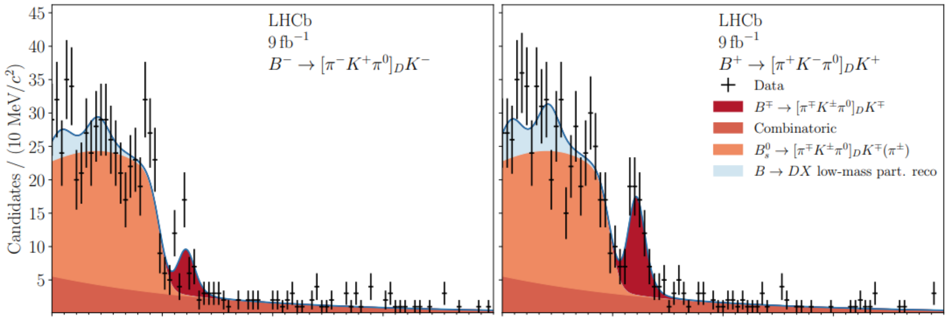

Fig. 3. Mass distributions of the $B^\pm \to DK^\pm$ candidates, separated by the charge of B candidate [6].

The result of the analysis are interpreted in terms of γ and associated hadronic parameters. Confidence intervals are evaluated using the profile likelihood method where the χ^2 function is evaluated at each point in parameter space to determine $\Delta\chi^2$ with respect to the best-fit point. Due to trigonometric ambiguities, there are up to four solutions in the range of $0 < \gamma < 180°$. The global minimum χ^2 is found at $\gamma = (145^{+9}_{-39})°$; however, one of the local minima $\gamma = (56^{+24}_{-19})°$ is also consistent with the LHCb γ combination (Fig. 4).

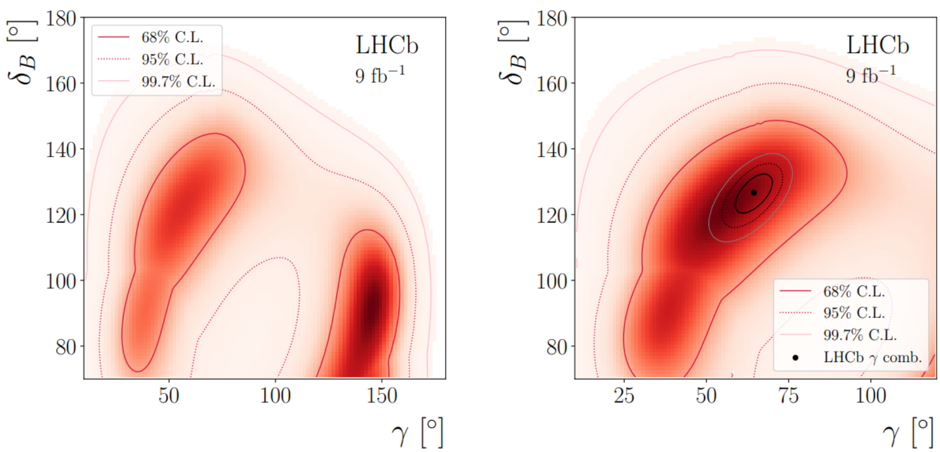

Fig. 4. Confidence regions of the strong phase, δ_B *versus* the CKM angle, on the left, γ shows (left) two solutions; on the right, the solution consistent with the recent LHCb γ combination [6].

4. Studies of $B^\pm \to D[K^\mp\pi^\pm\pi^\pm\pi^\mp]h^\pm$

Studies of $B^\pm \to D[K^\mp\pi^\pm\pi^\pm\pi^\mp]h^\pm$ are experimentally attractive considering the high branching fraction, and exclusively charged particles in the final state [7]. Studying the decay rates of different regions (bins) of the $D \to K^\mp\pi^\pm\pi^\pm\pi^\mp$ phase space instead of the inclusive decay can increase sensitivity to the CKM angle γ. This is a consequence of the different values of the mean strong-phase difference in each bin, which removes trigonometric ambiguities. Moreover, coherence factor is higher in the regions than in the decay phase-space taken as a whole [8].

The observables used to determine γ and related hadronic parameters are the ratios of rates of the opposite-sign (kaon from D and bachelor $h^\pm$ have an opposite sign) to the like-sign (the same sign of kaon from D and $h^\pm$) $B^\pm \to Dh^\pm$ decays in each phase-space bin.

Figure 5 shows invariant mass distribution of $B^\pm \to D[K^\mp\pi^\pm\pi^\pm\pi^\mp]h^\pm$ for $h = \pi, K$, and each of B charge. The analysis results is the CKM angle γ determined as $\gamma = (54.8^{+6.0+0.6+6.7}_{-5.8-0.6-4.0})^\circ$.

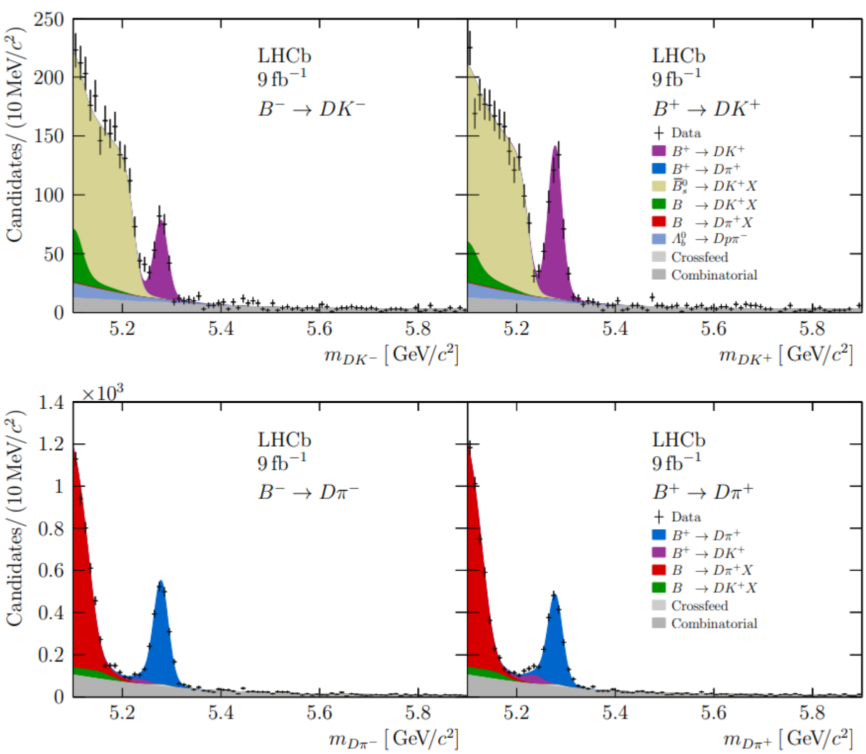

Fig. 5. Invariant mass distributions of the $B^\pm \to DK^\pm$ (top) and $B^\pm \to D\pi^\pm$ (bottom) candidates, divided by the charge of the B hadron (B^- — left, B^+ — right) with a result of the fit superimposed [7].

5. The CKM angle γ combination and conclusions

The studies of 16 decay modes result in the most precise determination of the CKM angle γ provided by the LHCb Collaboration: $\gamma = (65.4^{+3.8}_{-4.2})^\circ$. Compared to the previous combination in 2018 [9], there are two new ($B_s^0 \to D_s^\mp K^\pm \pi^\pm \pi^\mp$ and $B \to DK^{*0}$) and five updated results over the Run 2 data sample [2]. The LHCb Collaboration provides the CKM angle γ measurement (Fig. 6, left) and results with the breakdown into the initial B state (Fig. 6, right) [2].

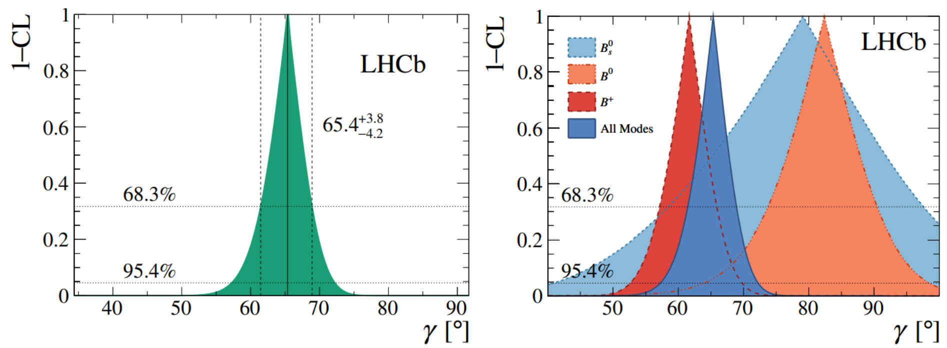

Fig. 6. The 1-CL scan of the CKM angle γ for combination — left, the 1-CL scan of the CKM angle γ with the breakdown into different initial B state — right [2].

The results of studies of $B^\pm \to D[K^\mp\pi^\pm\pi^\pm\pi^\mp]h^\pm$ and $B^\pm \to Dh^\pm(D \to h^\pm h'^\mp\pi^0)$ are not yet included in the combination, however, these measurements, as well as ongoing studies performed by the LHCb Collaboration, are an excellent prospect for the future measurement of the CKM angle γ. The expected precision of the CKM angle γ after Runs 3 and 4 is around 1° [10].

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