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Measurement of γ from $B \to DK$ decays at LHCb

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Abstract. We report results from the first measurements of the CKM angle γ using $B \to DK$ decays with the LHCb experiment. Three well established methods are used to extract the *CP* observables. The updated measurement of γ in the three-body D^0 Dalitz space results in $\gamma = (57 \pm 16)^\circ$. When combining the observables from all $B \to DK$ studies, the best fit value for $\gamma \in [0, 180]^\circ$ is $\gamma = 67.2^\circ$ with $\gamma \in [55.1, 79.1]^\circ$ at 68%CL and $\gamma \in [43.9, 89.5]^\circ$ at 95%CL. This represents the most precise γ values directly measured by a single experiment. Furthermore, a new time-dependent approach using $B_s^0 \to D_s^\pm K^\mp$ decays is used for the first time to measure *CP* observables and future prospects for γ at LHCb are given.

1 Introduction

The CKM parameter $\gamma = \arg(-V_{ud}V_{ub}^*/V_{cd}V_{cb}^*)$ is the least well measured angle of the Unitarity Triangle. So far, the best measurements from single experiments have been performed by the *B*-factories BaBar and Belle. The latest results from both experiments are $\gamma = (69^{+17}_{-16})^\circ$ [1] and $\gamma = (68^{+15}_{-14})^\circ$ [2], respectively.
One of the core physics goals of the LHCb experiment is to precisely measure the CKM angle γ. This can be done by exploiting tree-level processes like $B^\pm \to DK^\pm$ or $B_s^0 \to D_s^\pm K^\mp$, which are sensitive to Standard Model (SM) interactions only. In contrast, it is also possible to extract γ from loop processes such as two or three-body charmless *B* transitions. Potential differences in these results could indicate new physics contributions. Comparing direct measurements to indirect SM fits could also indicate tensions within the SM.
Examples of two different approaches to measure γ are described in these proceedings. First the more traditional time-independent measurements already performed by the *B*-factories in section 2 and then a new, LHCb exclusive, time-dependent way in section 3.

2 Time-Independent measurements using charged B decays

Measuring γ with charged *b*-hadron decays one considers the interference from $b \to u$ and $b \to c$ transitions in $B \to Dh$. Here, *D* is either a D^0 or $\overline{D}^0$ and *h* is a $K^\pm$ or $\pi^\pm$. The interference is ensured by reconstructing the *D* meson in a final state common to D^0 and $\overline{D}^0$, so that the two decay paths $B^+ \to DK^+$ and $B^+ \to \overline{D}K^+$ are indistinguishable [1]. The sensitivity on γ is roughly given by the ratio of the suppressed over the favoured *B* decay amplitude, r_B. The interference additionally is dependent on the relative strong phase difference δ_B of the two *B* amplitudes.
There are three established methods to extract γ from these types of processes, which depend on the *D* final state: the ADS method [3] using quasi flavour-specific, doubly Cabbibo suppressed states (e.g. $D \to K^+\pi^-$ or $D \to K^+\pi^-\pi^+\pi^-$). The *D* final states are chosen so that the decay suppressions (r_B and the *D* system equivalent r_D) are similar between the two interfering *B* amplitudes. The *CP* asymmetries are therefore expected to be large. However, the interference acquires an additional dependence on the strong phase difference in the *D* meson system, δ_D. The GLW method [4, 5] on the other hand, makes use of the *D* meson decaying into a *CP* eigenstate, where one can eliminate the *D* system parameters.
In the GGSZ method [6] three-body self-conjugate *D* final states are studied (e.g. $D \to K_S^0\pi^+\pi^-$ or $D \to K_S^0K^+K^-$). Performing a Dalitz plot analysis of the *D* meson decays leads to a good sensitivity on γ.
LHCb results from the three methods are presented in the following sections. Additionally, a combination of the various observables from the different *B* decay modes is shown in section 2.3, which increases the sensitivity on γ beyond the single measurements.

2.1 ADS/GLW

The LHCb collaboration has performed analyses in $B^+ \to DK^+$ and $B^+ \to D\pi^+$, where the *D* meson is reconstructed in $K^\pm\,\pi^\mp$, $K^+\,K^-$, $\pi^+\,\pi^-$, $\pi^\pm\,K^\mp$, and $\pi^\pm\,K^\mp\,\pi^+\,\pi^-$ [7, 8] with a dataset corresponding to an integrated luminosity of 1 fb^{-1} at $\sqrt{s} = 7$ TeV. The ADS doubly Cabbibo suppressed modes in $B \to (\pi K)_D K$, $B \to (\pi K\pi\pi)_D K$ and $B \to (\pi K\pi\pi)_D\pi$ are observed for the first time with a significance of $> 10\sigma$, 5.1σ and $> 10\sigma$, respectively. Here $(f)_D$ is the abbreviated form for a *D* meson decaying into

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[1] Charge-conjugation is implied throughout the document, if not stated otherwise.

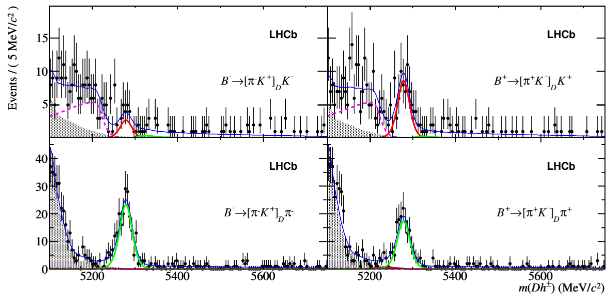

Figure 1. Invariant mass distribution of the two-body ADS suppressed modes in $B \to (\pi K)_D K$ (top) and $B \to (\pi K)_D \pi$ (bottom).

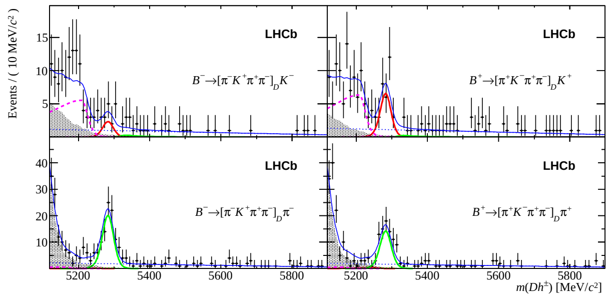

Figure 2. Invariant mass distribution of the four-body ADS suppressed modes in $B \to (\pi K \pi\pi)_D K$ (top) and $B \to (\pi K \pi\pi)_D \pi$ (bottom).

the final state f, $D \to f$. The respective invariant mass distributions are shown in Figure 1 and 2. Using the ADS and GLW methods the following *CP* observables sensitive to γ, r_B, δ_B, r_D and δ_D can be measured: the charge-averaged ratios of $B \to DK$ and $B \to D\pi$

$$R^f_{K/\pi} = \frac{\Gamma(B^- \to DK^-) + \Gamma(B^+ \to DK^+)}{\Gamma(B^- \to D\pi^-) + \Gamma(B^+ \to D\pi^+)} \quad ,$$

where f indicates the D final state, the charge asymmetries

$$A^f_h = \frac{\Gamma(B^- \to Dh^-) - \Gamma(B^+ \to Dh^+)}{\Gamma(B^- \to Dh^-) + \Gamma(B^+ \to Dh^+)} \quad ,$$

and the non charge-averaged ratio of suppressed and favoured D final state

$$R^{\pm}_h = \frac{\Gamma(B^\pm \to Dh^\pm)_{\text{sup}}}{\Gamma(B^\pm \to Dh^\pm)} \quad .$$

The resulting values can be found in the refs. [7, 8] and serve as inputs for the combined γ measurement in section 2.3. Furthermore, direct *CP* violation in $B^\pm \to DK^\pm$ is observed with a total significance of 5.8σ.

2.2 GGSZ

The GGSZ method exploits the three-body $D \to K^0_S h^+ h^-$ Dalitz space in $B^\pm \to DK^\pm$ decays to extract the *CP* observables $x_\pm = r_B \cos(\delta_B \pm \gamma)$ and $y_\pm = r_B \sin(\delta_B \pm \gamma)$. Due to the rich resonance structure of the D decays, this method has proven to be most sensitive one at the B-factories. We report the model-independent measurement

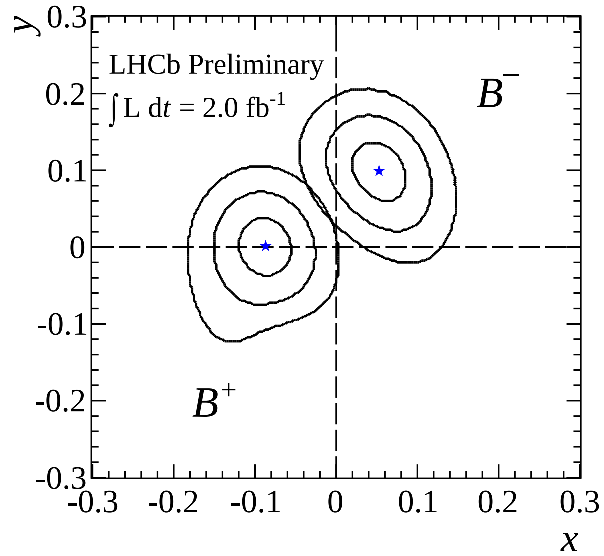

Figure 3. Best fit values (stars) and 1σ, 2σ and 3σ confidence intervals (contours) in the (x,y) plane using the statistical uncertainties and correlations only.

using a dataset corresponding to 2 fb^{-1} of integrated luminosity with a centre of mass energy of $\sqrt{s} = 8\,\text{TeV}$ by the LHCb Collaboration [9], which is the successor of the 1 fb^{-1} publication [10] at $\sqrt{s} = 7\,\text{TeV}$. The variation of the strong phase difference δ_D in bins of the $D \to K^0_S h^+ h^-$ Dalitz plot is taken as an external input from the CLEO collaboration. The resulting numbers for the *CP* violation parameters $x_\pm$ and $y_\pm$ are illustrated in Figure 3 for 2 fb^{-1}, where the combined 3 fb^{-1} values are:

$$\langle x_+ \rangle = (-8.9 \pm 3.1) \times 10^{-2}, \ \langle x_- \rangle = (3.5 \pm 2.9) \times 10^{-2}$$
$$\langle y_+ \rangle = (0.1 \pm 3.7) \times 10^{-2}, \quad \langle y_- \rangle = (7.9 \pm 3.8) \times 10^{-2}.$$

The dominant systematic uncertainties are coming from the assumption of no interference in the control channel and the external hadronic input parameters. However, the results are limited statistically. The underlying physics parameters are extracted using a frequentist approach resulting in $\gamma = (57 \pm 16)^\circ$, $r_B = (8.8^{+2.3}_{-2.4}) \times 10^{-2}$ and $\delta_B = (124^{+15}_{-17})^\circ$. This results competes with the methodically equivalent Belle measurement [11] of $\gamma = (77.4^{+15.1}_{-14.9} \pm 4.1 \pm 4.3)^\circ$ for the current world's most precise single direct measurement of γ.

2.3 Combination

To reach the best possible sensitivity on γ the observables from the ADS, GLW and GGSZ analyses, the amplitudes and ratios from section 2.1 and the combined 3 fb^{-1} *CP* observables from section 2.2, are evaluated at the same time for the $B \to DK$ transitions. Additionally, inputs from the CLEO collaboration [12] and the Heavy Flavour Averaging Group (HFAG) [13] have been used to constrain the hadronic parameters of the D system and the effect of direct *CP* violation in D decays, respectively. A likelihood

Table 1. Best-fit values and confidence intervals for γ, r_B and δ_B from the combination of the $B \to DK$ measurements.

quantity	DK combination
γ	$67.2°$
68% CL	$[55.1, 79.1]°$
95% CL	$[43.9, 89.5]°$
r_B	$114.3°$
68% CL	$[101.3, 126.3]°$
95% CL	$[88.7, 136.3]°$
δ_B	0.0923
68% CL	$[0.0843, 0.1001]$
95% CL	$[0.0762, 0.1075]$

is constructed from the input measurements as follows:

$$\mathcal{L}(\vec{\alpha}) = \prod_i \xi_i(\vec{A}_i^{\text{obs}}|\vec{\alpha}) \quad ,$$

where i denotes the different measurements, $\vec{A}_i^{\text{obs}}$ the observables, ξ_i the probability density functions (PDFs) of the observables $\vec{A}_i$ and $\vec{\alpha}$ is the set of parameters (γ, r_B, etc.). For most of the PDFs ξ_i a multidimensional Gaussian is assumed taking correlations into account. Whenever highly non-Gaussian behaviour is present, ξ_i is replaced by the experimental likelihood.
The confidence intervals are calculated using a frequentist method. Its coverage is not guaranteed from first principles, so the coverage is tested. It is found that the coverage is almost correct so that the results are scaled according to the small differences. Additionally, the confidence intervals are cross-checked and found to be consistent with a method inspired by Berger and Boos [14]. In this method the values of the nuisance parameters are sampled from a uniform distribution covering a multidimensional confidence belt C_β, instead of fixing the nuisance parameters to their best-fit values. C_β is chosen such that the corresponding corrections to the p-value are negligible. For more details on the inputs, the statistical procedures and the validation of the results, see [14–16]. The best fit values and confidence intervals for γ, r_B and δ_B are listed in Table 1, all values are modulo 180°. The $1 - \text{CL}$ curve for γ and the two-dimensional likelihood projection for γ and r_B are shown in Figure 4 and 5, respectively. The 68% CL interval for γ can be translated to $\gamma = (67 \pm 12)°$. This preliminary result has a lower uncertainty compared to the latest results from BaBar [1] and Belle [2].

3 Time-dependent measurement in $B_s^0 \to D_s^\pm K^\mp$ decays

A different approach to extract γ is to use neutral B mesons and perform a time-dependent measurement of the CP parameters. This can be done using tree-level $B_s^0 \to D_s^\pm K^\mp$ decays. The sensitivity to γ arises from the interference of both B mesons, B_s^0 and $\bar{B}_s^0$, decaying into the same final state: $D_s^+ K^-$ or $D_s^- K^+$. Note that the D_s final states are not of major importance in this method. Each decay amplitude is roughly of the same order of magnitude, thus the expected interference is large $r_B^{D_sK} = 0.37$.

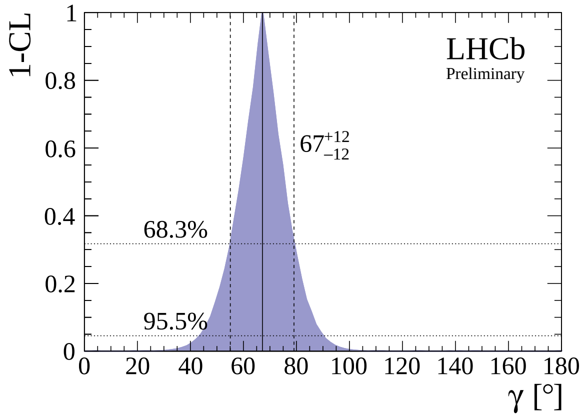

Figure 4. $1 - \text{CL}$ curve for γ from the combined ADS/GLW 1 fb^{-1} and GGSZ 3 fb^{-1} measurements. The 1σ and 2σ confidence interval can be read off at the intersections of the blue curve with the dotted lines labelled 68.3 % and 95.5 %, respectively.

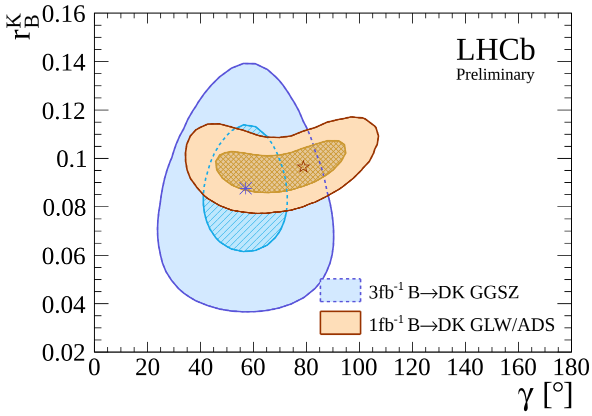

Figure 5. Best-fit values (markers) and contours where the difference in log-likelihood corresponds to 1σ and 2σ. The 3 fb^{-1} GGSZ and 1 fb^{-1} ADS/GLW analyses are shown separately in blue and orange.

In order to resolve the B_s^0 oscillations, a good time resolution is mandatory. For the analysis of $B_s^0 \to D_s^\pm K^\mp$ decays at LHCb [17] it is determined from Monte Carlo (MC) simulations. The difference of the reconstructed and the true decay time is fitted with a resolution model, which is the sum of three Gaussians. To account for differences in data and simulations we scale the Gaussian's widths according to $B_s^0 \to D_s\,\pi$ MC and a data sample of "fake" B_s^0 constructed from prompt D_s mesons which are combined with a random π. We assume that the differences between $B_s^0 \to D_s^\pm K^\mp$ and the control channel $B_s^0 \to D_s\,\pi$ are negligible for the relevant quantities. The resulting effective time resolution is estimated as $\sigma_t \approx 50\,\text{fs}$. Another crucial part is the determination of the time acceptance, which is also obtained from MC. The invariant mass distribution of the B_s^0 candidates is fitted using an unbinned maximum likelihood method in order to get weights, which separate signal from background components. The full mass-fit is

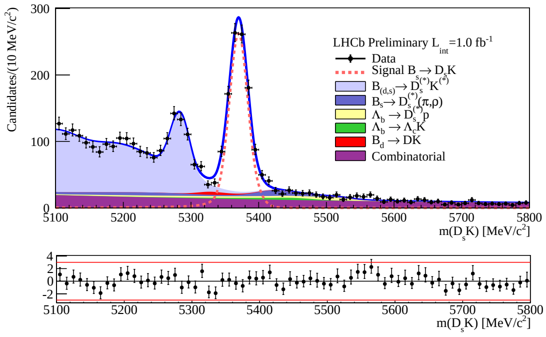

Figure 6. Invariant mass distribution of B_s^0 candidates together with the signal and background components and the full fit. Below the corresponding pulls are shown.

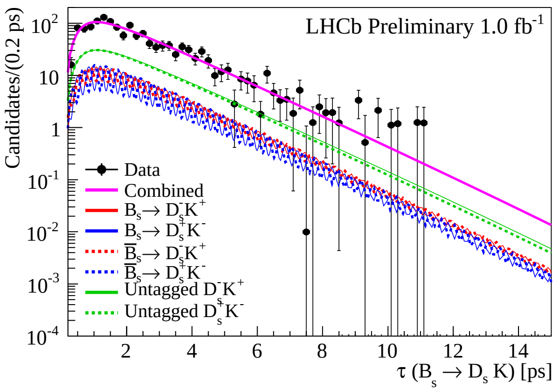

Figure 7. Fit to the weighted decay time distribution, showing all fit components separately.

shown in Figure 6. The weighted decay time distribution is then fitted using the *sFit* [18] technique, where the fit determines the corresponding *CP* observables. The resulting values can be found in [17] and the decay time fit is shown in Figure 7. The weighing procedure is cross-checked with a conventional 2-dimensional fit in the invariant mass and decay time.
It is found that correlations within the systematics have a non-negligible effect on extracting the actual *CP* parameters $\gamma + \beta_s$, where β_s is the B_s^0 mixing phase. Measuring the *CP* parameters marks the first important step towards a time-dependent estimation of γ from $B_s^0 \to D_s^{\pm} K^{\mp}$ decays.

4 Conclusions and prospects

We reported several measurements of γ with the LHCb experiment. Up to now, the GGSZ analysis is the most sensitive single measurement of $\gamma = (57 \pm 16)^\circ$ using the full combined 3 fb^{-1} LHCb dataset. Exploiting the ADS/GLW method on 1 fb^{-1} of LHCb data in $B \to Dh$ with two- and four-body D decays leads to the observations of the corresponding suppressed ADS modes with significances greater than 5σ. Furthermore, *CP* observables are provided by the analyses from which γ can be extracted.
Combining all *CP* observables from the $B \to DK$ measurements the resulting LHCb result is $\gamma = (67 \pm 12)^\circ$, which is more precise than recent BaBar [1] and Belle [2] results. Further improvements are expected with the analyses updated to the full available dataset. When more channels, which were not discussed throughout these proceedings are analysed with the current or with a future dataset, the sensitivity on γ will increase by including these to the combined measurement. Then LHCb will be able to compare γ estimations from tree-level and loop-level processes.
In the future we expect to decrease the uncertainty on γ to $\delta\gamma \sim O(1^\circ)$ [19] using a dataset of 50 fb^{-1} and combining different decay channels. This dataset is planed to be recorded within the coming decade.

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