CKM angle γ measurements at LHCb

Alexis Vallier

Laboratoire de l'Accélérateur Linéaire, Université Paris-Sud 11, CNRS/IN2P3, Orsay, France.

E-mail: vallier@lal.in2p3.fr

Abstract. The CKM angle γ remains the least known parameter of the CKM mixing matrix. The precise measurement of this angle, as a Standard Model benchmark, is a key goal of the LHCb experiment. We present four recent CP violation studies related to the measurement of γ, including amplitude analysis of $B^{\pm} \to DK^{\pm}$ decays, the ADS/GLW analysis of $B^0 \to DK^{*0}$ decays and the time-dependent analysis of $B_s^0 \to D_s^{\mp}K^{\pm}$ decays.

1. Introduction

The CKM angle γ, defined as $\gamma \equiv \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)$, is the least known CKM parameter. B-factories and the LHCb experiment measured γ with an uncertainty larger than 10° [1, 2, 3]. To compare, global fits like CKMfitter [4] and UTfit [5] obtain an estimation of γ with an error about 2°. This angle is directly measurable through tree processes, without significant loop contribution. Hence the extraction of its value is very clean and has a theoretical relative uncertainty lower than 10^{-7} [6]. Therefore a precise measurement of γ provides an excellent standard candle to check the consistency of the CKM paradigm in the Standard Model and to probe some new physics. The present paper summarises four measurements of γ performed by the LHCb collaboration and presented at the BEACH 2014 conference.

2. Time-integrated measurements of γ

Given its definition, γ is approximately the phase difference between the quark transitions $b \to c\bar{u}s$ and $b \to u\bar{c}s$ and the interference between these two transitions is sensitive to this angle. The interference is obtained by reconstructing the D^0 and $\bar{D}^0$ mesons produced in these decays in an identical final state (Fig. 1). In the case of a three body D meson decay a Dalitz plot analysis can be carried out. This method is called GGSZ [7, 8] and two recent LHCb results are reported in section 2.1. In the case of a two body D meson[1] decay a counting analysis is developed following the so called GLW [9, 10] or ADS [11, 12] methods. A recent ADS/GLW result from LHCb is presented in section 2.2. All of these methods can be applied to the channels $B^{\pm} \to DK^{\pm}$ and $B^0 \to DK^{*0}$. Since these B mesons decays are self-tagged, no time-dependent analysis is required.

[1] in the following D stands for either a D^0 or a $\bar{D}^0$ meson.

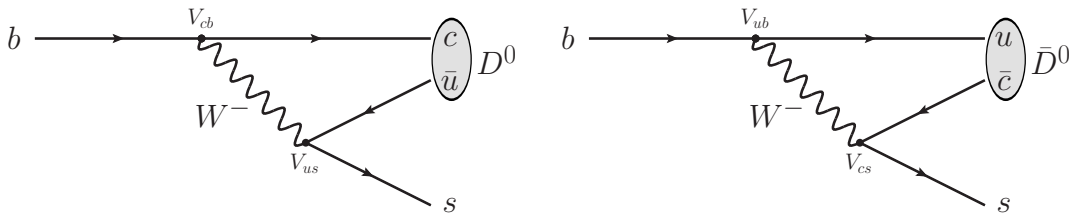

Figure 1. Feynman diagrams of $b \to c\bar{u}s$ (left) and $b \to u\bar{c}s$ (right) decays.

2.1. Measurements with 3-body D meson decays
The $B^\pm \to D(K^0_S h^+ h^-)K^\pm$decay amplitude — h stands for either a charged pion or a charged kaon — can be written as

$$A_{B^\pm}(\mathcal{D}) = A_D(\mathcal{D}) + e^{i(\delta_B \pm \gamma)} A_{\bar{D}}(\mathcal{D}),$$

where A_D ($A_{\bar{D}}$) is the D^0 ($\bar{D}^0$) decay amplitude, $\mathcal{D}$ represents the D meson phase space, δ_B is the strong phase difference and γ is the weak phase difference between the D^0 and $\bar{D}^0$ channels. The D meson phase space is parameterised by two squared invariant masses, for instance $m^2(K^0_S\pi^+)$ and $m^2(K^0_S\pi^-)$ on a D meson Dalitz plot. The sensitivity to γ arises from large asymmetries in some region of the Dalitz plot. In order to evaluate γ, the strong phase variation over the Dalitz plot must be known. This can be done in two different ways: with a model-dependent (MD) method using BaBar's amplitude model [13], or with a model-independent (MI) method using CLEO-c measurements as inputs [14]. Both methods involve fitting the D meson Dalitz plot to extract the polar coordinates $(r_{B^\pm}, \delta_B, \gamma)$. The parameter $r_{B^\pm}$ is the ratio of the magnitudes of the suppressed and favoured B decay amplitudes. The polar coordinates are not estimated directly from the Dalitz fit, but the cartesian coordinates $x_\pm = r_{B^\pm}\cos(\delta_B \pm \gamma)$ and $y_\pm = r_{B^\pm}\sin(\delta_B \pm \gamma)$.

2.1.1. Model-dependent analysis This section presents the model-dependent analysis of the $B^\pm \to D(K^0_S\pi^+\pi^-)K^\pm$ signal, using a sample of proton-proton collision data at a centre-of-mass energy of 7 TeV corresponding to an integrated luminosity of 1 fb^{-1}. Full details can be found in Ref. [15]. The analysis is carried out in two distinct stages. First a fit to the B meson reconstructed invariant mass is performed on the selected $B^\pm \to D(K^0_S\pi^+\pi^-)K^\pm$ and $B^\pm \to D(K^0_S\pi^+\pi^-)\pi^\pm$ candidates. This fit determines the signal and background fractions in the data sample. A total yield of 637 $B^\pm \to D(K^0_S\pi^+\pi^-)K^\pm$ signal events and 8866 events of the $B^\pm \to D(K^0_S\pi^+\pi^-)\pi^\pm$ control channel are found. Then a fit to the Daliz plot determines the CP violation observables $(x_\pm, y_\pm)$. The signal and background yields and the parameters of the B invariant mass probability distribution function are fixed to the values obtained in the first stage. The model used to described the amplitude of the $D^0 \to K^0_S\pi^+\pi^-$ decay over the phase space is the one determined by the BaBar collaboration in Ref. [13]. Fitting simultaneously the distributions in the $D^0 \to K^0_S\pi^+\pi^-$ phase space for the $B^\pm \to D(K^0_S\pi^+\pi^-)K^\pm$ and the $B^\pm \to D(K^0_S\pi^+\pi^-)\pi^\pm$ candidates enables to take into account the variation of efficiency over the phase space. The $B^\pm \to D(K^0_S\pi^+\pi^-)\pi^\pm$ decay is a good proxy to get the efficiency variation, since it has a kinematic topology similar to the signal one and CP violation can be neglected in this channel. The resulting values of the cartesian coordinates are

$$\begin{aligned} x_- &= +0.027 \pm 0.044^{+0.010}_{-0.008} \pm 0.001, & x_+ &= -0.084 \pm 0.045 \pm 0.009 \pm 0.005, \\ y_- &= +0.013 \pm 0.048^{+0.009}_{-0.007} \pm 0.003, & y_+ &= -0.032 \pm 0.048^{+0.010}_{-0.009} \pm 0.008, \end{aligned}$$

where the first uncertainty is statistical, the second systematic and the third due to the amplitude model used to describe the $D^0 \to K^0_S\pi^+\pi^-$ decay. The leading experimental systematic errors are due to the efficiency and background description uncertainties. The constraints obtained on the polar coordinates are $r_{B^\pm} = 0.06 \pm 0.04$, $\delta_B = (115^{+41}_{-51})^\circ$ and $\gamma = (84^{+49}_{-42})^\circ$. These results are consistent with those of the LHCb model-independent analysis based on the same data set [16].

2.1.2. Model-independent analysis This section presents the model-independent analysis of the $B^\pm \to D(K^0_S h^+h^-)K^\pm$ decays, using a sample of proton-proton collision data at a centre-of-mass energy of 7 and 8 TeV corresponding to a total integrated luminosity of 3 fb^{-1}. Full details can be found in Ref. [17]. There is a significant improvement compared to the former results in Ref. [16], thanks to the increased statistics and a better analysis technique. To know the strong phase variation over the $D^0 \to K^0_S h^+h^-$ phase space the measurements made by CLEO-c, in a particular binning scheme, is used [14]. In this way the analysis is a counting experiment in bins of the Dalitz plot. The expected number of D from B^+ events falling in a particular bin labelled $\pm i$ (the $\pm$ sign comes from the phase symmetry with respect to the Dalitz diagonal) can be expressed as

$$N^+_{\pm i} = h^+_B \left[F_{\mp i} + (x_+^2 + y_+^2)F_{\pm i} + 2\sqrt{F_i F_{-i}}(x_+ c_{\pm i} \mp y_+ s_{\pm i})\right], \quad (1)$$

where c_i and s_i are the averaged cosine and sine of the strong phase difference in bin i (CLEO-c inputs), F_i is the expected fraction of pure D^0 events in bin i taking into account the efficiency profile over the phase space, and h^+_B is a normalisation factor. The F_i parameters are determined from the $B^0 \to D^{*\pm}\mu^\mp\nu_\mu$ control mode. This is an excellent proxy because the sample has a high purity, a high statistics and the D^0 meson is tagged thanks to the slow pion in the $D^{*+} \to D^0\pi^+$ decay. Some corrections are applied from simulated data to account for reconstruction and selection discrepancies between the $B^0 \to D^{*\pm}\mu^\mp\nu_\mu$ and the $B^\pm \to DK^\pm$ decays. The fit is performed in two steps. First the phase space integrated $B^\pm$ mass fit determines the total signal yields (around 2600) and fixes the model used in the second step. This last fit is made in each Dalitz bin with all the parameters in Eq. (1) fixed but the normalisation factor and the $(x_\pm, y_\pm)$ observables. The resulting values of the cartesian coordinates (Fig. 2) are the most precise to date:

$$\begin{aligned} x_- &= (2.5 \pm 2.5 \pm 1.0 \pm 0.5) \times 10^{-2}, & x_+ &= (-7.7 \pm 2.4 \pm 1.0 \pm 0.4) \times 10^{-2}, \\ y_- &= (7.5 \pm 2.9 \pm 0.5 \pm 1.4) \times 10^{-2}, & y_+ &= (-2.2 \pm 2.5 \pm 0.4 \pm 1.0) \times 10^{-2}, \end{aligned}$$

where the first uncertainty is statistical, the second systematic and the third due to the experimental knowledge of the (c_i, s_i) parameters. Compared to the 1 fb^{-1} measurement [16], the statistical uncertainty is reduced thanks to the larger data sample, the experimental systematic is reduced by using the new control mode $B^0 \to D^{*\pm}\mu^\mp\nu_\mu$, and the (c_i, s_i) systematic is also improved by the increased LHCb sample size. The results are: $r_{B^\pm} = 0.080^{+0.019}_{-0.021}$, $\gamma = (62^{+15}_{-14})^\circ$ and $\delta_B = (62^{+14}_{-15})^\circ$.

2.2. Measurements with 2-body D meson decays

This section presents the ADS/GLW analysis of the $B^0 \to DK^{*0}$ decays, using a sample of proton-proton collision data at a centre-of-mass energy of 7 and 8 TeV corresponding to a total integrated luminosity of 3 fb^{-1}. Full details can be found in Ref. [18]. Compared to the $B^\pm \to DK^\pm$ decays, both Cabibbo favoured and suppressed diagrams are color suppressed, which brings about a higher interference amplitude (r_{B^0} is larger than $r_{B^\pm}$). Hence a better sensitivity to γ is expected. However this neutral channel is experimentally more challenging. For the GLW modes the D mesons are reconstructed in two CP eigenstate: K^+K^- and $\pi^+\pi^-$.

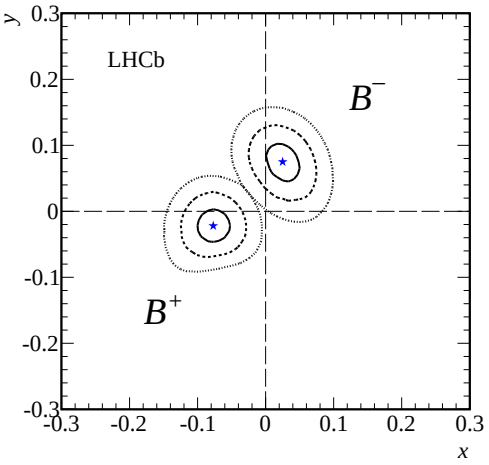

Figure 2. Confidence levels at 39.3%, 86.5% and 98.9% probability for (x_+, y_+) and (x_-, y_-) as measured in $B^\pm \to DK^\pm$ decays (statistical uncertainties only). The parameters (x_+, y_+) relate to B^+ decays and (x_-, y_-) refer to B^- decays. The stars represent the best fit central values.

For the ADS modes the D mesons are reconstructed in the $K^+\pi^-$ and $K^-\pi^+$ final states. From these decays several observables sensitive to γ can be built. For instance in the GLW modes the CP asymmetries

$$A_d^{hh} \equiv \frac{\Gamma(\bar{B}^0 \to D(h^+h^-)\bar{K}^{*0}) - \Gamma(B^0 \to D(h^+h^-)K^{*0})}{\Gamma(\bar{B}^0 \to D(h^+h^-)\bar{K}^{*0}) + \Gamma(B^0 \to D(h^+h^-)K^{*0})} = \frac{2r_{B^0}\kappa \sin\delta_B \sin\gamma}{1 + r_{B^0}^2 + 2r_{B^0}\kappa\cos\delta_B\cos\gamma}$$

are measured. The parameter κ is the coherence factor introduced to account for the effect of the non resonant $B^0 \to DK^+\pi^-$ contribution in the K^{*0} signal region. And in the ADS mode the ratio of suppressed $B^0 \to D(\pi^+K^-)K^{*0}$ to favoured $B^0 \to D(K^+\pi^-)K^{*0}$ partial widths are measured separately for B^0 and $\bar{B}^0$:

$$\begin{aligned} R_d^+ &\equiv \frac{\Gamma(B^0 \to D(\pi^+K^-)K^{*0})}{\Gamma(B^0 \to D(K^+\pi^-)K^{*0})} = \frac{r_{B^0}^2 + r_D^2 + 2r_{B^0}r_D\kappa\cos(\delta_B + \delta_D + \gamma)}{1 + r_{B^0}^2 r_D^2 + 2r_{B^0}r_D\kappa\cos(\delta_B - \delta_D + \gamma)}, \\ R_d^- &\equiv \frac{\Gamma(\bar{B}^0 \to D(\pi^-K^+)\bar{K}^{*0})}{\Gamma(\bar{B}^0 \to D(K^-\pi^+)\bar{K}^{*0})} = \frac{r_{B^0}^2 + r_D^2 + 2r_{B^0}r_D\kappa\cos(\delta_B + \delta_D - \gamma)}{1 + r_{B^0}^2 r_D^2 + 2r_{B^0}r_D\kappa\cos(\delta_B - \delta_D - \gamma)}. \end{aligned}$$

The parameters r_D and δ_D are the magnitude ratio and the phase difference, respectively, between the amplitudes of the $D^0 \to K^+\pi^-$ and $D^0 \to K^-\pi^+$ decays. The significances of the combined B^0 and $\bar{B}^0$ signals for the $B^0 \to D(K^+K^-)K^{*0}$, $B^0 \to D(\pi^+\pi^-)K^{*0}$ and $B^0 \to D(\pi^+K^-)K^{*0}$ decay modes are 8.6 σ, 5.8 σ and 2.9 σ respectively. Once the production and efficiency asymmetries are taken into account the results are:

$$\begin{aligned} A_d^{KK} &= -0.20 \pm 0.15 \pm 0.02, & R_d^+ &= 0.06 \pm 0.03 \pm 0.01, \\ A_d^{\pi\pi} &= -0.09 \pm 0.22 \pm 0.02, & R_d^- &= 0.06 \pm 0.03 \pm 0.01, \end{aligned}$$

where the first uncertainties are statistical and the second systematic. $A_d^{\pi\pi}$, R_d^+ and R_d^- are first measurements and the A_d^{KK} result supersedes the former LHCb one [19]. From these measurements the value of r_{B^0} (proper to the $B^0 \to DK^{*0}$ channel) is found to be $r_{B^0} = 0.240^{+0.055}_{-0.048}$. This is the most precise measurement to date.

3. Time-dependent measurement of γ

This section presents the time-dependent analysis of the $B_s^0 \to D_s^\mp K^\pm$ decays, using a sample of proton-proton collision data at a centre-of-mass energy of 7 TeV corresponding to an integrated

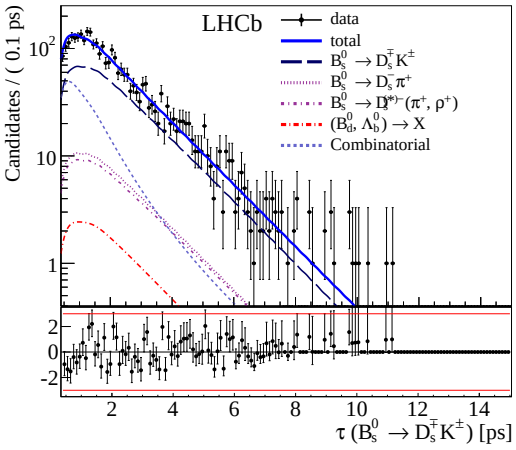

Figure 3. Result of the decay-time *cFit* to the $B_s^0 \to D_s^\mp K^\pm$ candidates.

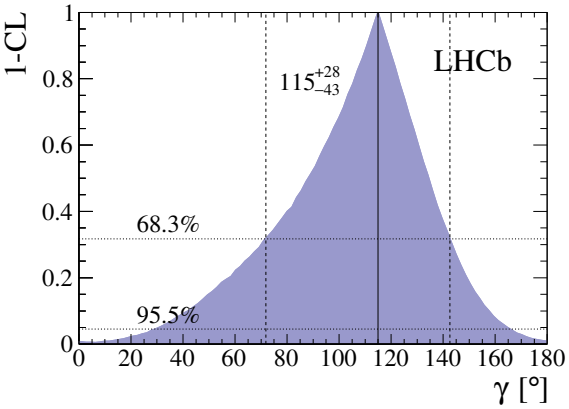

Figure 4. Frequentist interpretation of the γ measurement in term of confidence interval.

luminosity of 1 fb^{-1}. Full details can be found in Ref. [20]. In addition to the same tree level processes as in the time-integrated analysis (Fig. 1), the effect of the B_s mixing occurs. Hence the interference between mixing and decay amplitudes in $B_s^0 \to D_s^\mp K^\pm$ is sensitive to the CP violating phase $(\gamma - 2\beta_s)$ where $\beta_s \equiv \arg(-V_{ts}V_{tb}^*/V_{cs}V_{cb}^*)$. The time-dependent decay rates depend on the CP observables

$$C_f = \frac{1-r_{D_sK}^2}{1+r_{D_sK}^2}, \qquad A_f^{\Delta\Gamma} = \frac{-2r_{D_sK}\cos(\delta-(\gamma-2\beta_s))}{1+r_{D_sK}^2}, \quad A_{\bar{f}}^{\Delta\Gamma} = \frac{-2r_{D_sK}\cos(\delta+(\gamma-2\beta_s))}{1+r_{D_sK}^2},$$
$$S_f = \frac{2r_{D_sK}\sin(\delta-(\gamma-2\beta_s))}{1+r_{D_sK}^2}, \quad S_{\bar{f}} = \frac{-2r_{D_sK}\sin(\delta+(\gamma-2\beta_s))}{1+r_{D_sK}^2},$$

where r_{D_sK} is the magnitude of the amplitude ratio $|A(\bar{B}_s^0 \to D_s^- K^+)/A(B_s^0 \to D_s^- K^+)|$, δ the strong phase difference and $(\gamma - 2\beta_s)$ the weak phase difference. This analysis uses an independent measurement of ϕ_s [21] and assumes $\phi_s = -2\beta_s$ to interpret the results in terms of γ. To discriminate the signal and background components a 3D fit is performed on the B_s and D_s masses along with the log-likelihood difference between the kaon and pion hypothesis for the companion particle ($K^\pm$ for $B_s^0 \to D_s^\mp K^\pm$ signal and π^+ for $B_s^0 \to D_s^- \pi^+$ control mode). Then the output of this multivariate fit is used for the decay-time fit. Two fits are performed: a background subtracted fit, called *sFit*, using the *sWeights* [22, 23] determined by the multivariate fit; and a classical fit, called *cFit* (Fig. 3) where all signal and background time distributions are described. The results of these two fits are in excellent agreement:

Parameter	*sFit* fitted value	*cFit* fitted value
C_f	$0.52 \pm 0.25 \pm 0.04$	$0.53 \pm 0.25 \pm 0.04$
$A_f^{\Delta\Gamma}$	$0.29 \pm 0.42 \pm 0.17$	$0.37 \pm 0.42 \pm 0.20$
$A_{\bar{f}}^{\Delta\Gamma}$	$0.14 \pm 0.41 \pm 0.18$	$0.20 \pm 0.41 \pm 0.20$
S_f	$-0.09 \pm 0.31 \pm 0.06$	$-1.09 \pm 0.33 \pm 0.08$
$S_{\bar{f}}$	$-0.36 \pm 0.34 \pm 0.06$	$-0.36 \pm 0.34 \pm 0.08$

The first uncertainties are statistical and the second systematic. The main sources of systematic arise from the trigger-induced time-dependent efficiency, Γ_s and $\Delta\Gamma_s$. These results can be interpreted as a confidence interval $\gamma = (115^{+28}_{-43})^\circ$ at 68% CL (Fig. 4). This is the first measurement of γ with $B_s^0 \to D_s^\mp K^\pm$ decays.

4. Conclusion

The latest LHCb results on the CKM angle γ are reported: the model dependent GGSZ analysis of $B^{\pm} \to DK^{\pm}$ decays, the update to the full available data set of the model indepent GGSZ analysis of $B^{\pm} \to DK^{\pm}$ decays, the ADS/GLW analysis of $B^0 \to DK^{*0}$ decays and the first γ measurement with $B_s^0 \to D_s^{\mp}K^{\pm}$decays. Using these results and the corresponding improvements, the next combination of the LHCb γ measurements should yield a significant reduction of the uncertainty.

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