Improved constraints on $\gamma$: CKM2014 update

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I report on an updated combination of all currently available tree-level measurements of the CKM angle $\gamma$ from LHCb. This combination currently gives LHCb’s most precise value of $\gamma = (73^{+9}_{-10})^\circ$ obtained from $B \to DK$-like decays. For the first time in a single experiment, the uncertainty has dropped below $10^\circ$. When using $B \to D\pi$ decays in addition, the situation becomes non-Gaussian which makes the confidence intervals more difficult to interpret.

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1 Introduction

The CKM angle $\gamma = \arg \left[-V_{ud}V_{ub}^*/(V_{cd}V_{cb}^*)\right]$ is a central parameter describing the CKM matrix. It can be measured using two different approaches. One is using loop-induced decays, which can give rise to effects of New Physics. The other approach is the topic of these proceedings and is purely based on tree level decays. This last property turns $\gamma$ into one of the corner stones of CKM physics.

At LHCb, $\gamma$ is measured using a large variety of decay channels. The best sensitivity is achieved through a combination of measurements that determine $\gamma$ along with several other hadronic parameters. The input measurements provide sensitivity to $\gamma$ through the interference of $b \to u$ and $b \to c$ amplitudes, as described in more detail in Ref. [1]. Determining the additional hadronic parameters from data results in a small systematic uncertainty on the measurement of $\gamma$. The presented update [2] improves over the previous combinations [1,3] by adding more decay channels and updating selected channels to the full available dataset of 3 fb$^{-1}$. Tab. 1 gives the input measurements considered in this combination. Among the inputs is the first constraint of $\gamma$ from the time-dependent analysis of $B_0^0 \to D_s^\pm K^\mp$ [4]. Being the only time-dependent method considered so far at LHCb, it is affected by very different experimental systematic uncertainties, which bases the $\gamma$ average on a healthy range of measurements.

Table 1: LHCb Input measurements. The symbol $h$ denotes either a kaon or a pion, and the acronyms denote the initials of authors first proposing the measurements in Refs. [5–14].

| Decay                  | Acronym       | $\sigma$ fb$^{-1}$ |
|------------------------|--------------|-------------------|
| $B^+ \to Dh^+$, $D \to hh$ | GLW/ADS      | 1                  |
| $B^+ \to Dh^+$, $D \to K\pi\pi\pi$ | ADS          | 1                  |
| $B^+ \to DK^+$, $D \to K_0^0 hh$ | model-independent GGSZ | 3 |
| $B^+ \to DK^+$, $D \to K_0^0 K\pi$ | GLS          | 3                  |
| $B^0 \to DK^{*0}$, $D \to hh$ | GLW/ADS      | 3                  |
| $B^0_\s \to D^\pm_\s K^\pm$ | time-dependent | 1                  |

2 Two combinations

Two combinations are prepared, referred to as the “robust” and “full” combinations. The robust combination only contains observables measured in $B \to DK$-like systems, which are the traditional channels being used to measure $\gamma$. Compared to $B \to D\pi$-like systems they offer larger interference, and therefore are very robust against systematic effects. The robust combination provides the main result for $\gamma$.

The full combination adds information from the $B \to D\pi$ system. This is motivated by the fact that LHCb has a large set of $\gamma$-sensitive observables in $B \to D\pi$ decays,
although their sensitivity to $\gamma$ is suppressed compared to the $B \to DK$-like decays. The reason for this is that the amplitude ratio, which governs the interference effects and therefore the sensitivity, is expected to be a factor $\approx 15$ smaller than for the $B \to DK$-like systems. At the same time, the available data samples are usually a factor 10 larger in $B \to D\pi$ decays. The full combination is more sensitive to several effects. The most prominent of these is $D^0-D^0$ mixing \cite{20,22}, which we fully correct for in both combinations, taking into account the $D^0$ decay time acceptances of the individual measurements. We also correct at first order for possible $CP$ violation in the $D^0$ system using information from the Heavy Flavor Averaging Group (HFAG) \cite{23}. Furthermore, in order to ensure our combination is not sensitive to mixing and $CP$ violation in $K^0$ decays \cite{24}, we exclude observables where such effects may be non-negligible. Due to the larger data samples, the relative impact of the systematic uncertainties is larger than in the robust combination, although both of the current combinations are still statistically limited. Finally, a small value of the amplitude ratio $r^{D\pi}_D$ that is not significantly different from zero, is known to affect the coverage of the frequentist methods used here.

### 3 Statistical Procedure

The combination follows a frequentist treatment described in detail in Ref. \cite{1}, in which the nuisance parameters are kept at their best fit values (known as the "plug-in" method). The results obtained using $B \to DK$-like decays alone are also cross-checked using a Bayesian approach assuming a flat prior.

### 4 Results

The result of the robust combination is given in Tab. \ref{tab:results} and illustrated in Figs.\ref{fig:robust} and Fig.\ref{fig:bayesian}. Both frequentist and Bayesian intervals agree very well. The coverage was tested for the frequentist interval and found to be accurate. The fit probability is 89.4%. The robust frequentist values are regarded as the nominal result: $\gamma = (73\pm_{10}^9)$.$^\circ$.

| Observable | Central value $^{[\circ]}$ | Intervals $^{[68\%]}$ | Intervals $^{[95\%]}$ |
|------------|--------------------------|---------------------|---------------------|
| Frequentist | $\gamma$ | 72.9 | [63.0, 82.1] | [52.0, 90.5] |
| Bayesian   | $\gamma$ | 71.9 | [61.9, 81.8] | [50.9, 91] |

Table 2: Confidence and credibility regions and central values for $\gamma$ extracted from the robust combination.
Figure 1: 1 − CL curves for the robust combination (left), and for both robust and full combinations (right).

Figure 2: The 1D posterior PDF in the robust combination. Dark and light regions show the 68% and 95% probability intervals, respectively.

The full combination is more difficult to interpret. It exhibits a sharp maximum at $\gamma = 78.9^\circ$, and a secondary maximum at a value similar to the maximum of the robust combination (Tab. 3). This sharp maximum corresponds to an unexpectedly large value of the amplitude ratio $r^D_{\pi^B}$, $r^D_{\pi^B} = 0.027$. This is regarded as a fluctuation, but nevertheless enhances the impact of the $B^+ \rightarrow D\pi^+$ system. It makes the situation visibly non-Gaussian. As a consequence, the 68% CL interval is misleadingly small, while at 95% CL the intervals agree well between both combinations. This is illustrated in Fig. 1 (right), which shows both robust and full combinations in the same plot. The coverage of the intervals of the full combination was also tested, and as expected from the fact that $r^D_{\pi^B}$ is still consistent with zero, the intervals were found to undercover a
bit, i.e. the reported intervals are too small. It is expected that the ambiguity in $r^{D\pi}_B$, which causes the non-Gaussian behavior, could be resolved by a GGSZ-type analysis of $B^+ \to D\pi^+$ decays.

Table 3: Confidence intervals and central values for the full combination. The two columns correspond to the two minima found by the fit. The most probable value is given in the left column, corresponding to a large value of $r^{D\pi}_B$.

| quantity | full |
|----------|------|
| $\gamma (^{\circ})$ | 78.9 | 72.8 |
| 68% CL ($^{\circ}$) | [71.5, 84.7] | |
| 95% CL ($^{\circ}$) | [54.6, 91.4] | |
| $r^{D\pi}_B$ | 0.027 | 0.006 |
| 68% CL | [0.016, 0.034] | [0.005, 0.007] |
| 95% CL | [0.001, 0.040] | |

5 Discussion

Following the presentation there was a discussion about the following points:

- Why is the $B \to DK$-like “robust” combination regarded as the nominal result, rather than the more complete “full” combination? — At this point, LHCb doesn’t have enough data to measure $r^{D\pi}_B$ significantly different from zero, which affects the statistical coverage of the “full” combination. The result is still correct, only much more difficult to interpret. But the $B^+ \to D\pi^+$ system is a perfect test bed to show up the obstacles on the way to a high precision measurement of $\gamma$ in $B^+ \to DK^+$.

- What drives the large $r^{D\pi}_B$ minimum? — It is driven by two analyses taken together: $B^+ \to Dh^+, D \to hh$ [15] and $B^+ \to Dh^+, D \to K\pi\pi\pi$ [16]. If either one is dropped, the fit converges to a lower value of $r^{D\pi}_B$.

- Does LHCb plan to make a GGSZ type measurement in $B^+ \to D\pi^+$? — Yes.

- Why did the precision on $\gamma$ decrease by so much when the auxiliary inputs were updated? — This was tracked down to a sizable shift in the parameter $R_D(K\pi)$ in the latest HFAG average compared to previous ones.

6 Conclusion

Observables measured by LHCb that have sensitivity at tree-level to the CKM angle $\gamma$, along with supplementary information from other experiments, are combined to
determine an improved constraint on $\gamma$. The effect of $D^0$-$\bar{D}^0$ mixing on the decay rate is taken into account, with consideration of the experimental decay time acceptances of the individual measurements. When all observables are combined, we find

$$\gamma = (73^{+9}_{-10})^\circ,$$

using $B \to DK$-like decays only. This result is more precise than the combination of the results of the $B$ factories Babar and Belle \[25\].

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