PROCEEDINGS OF SCIENCE

Measurements of CKM γ from tree-level decays at LHCb

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Measurements from tree level decays of the angle γ of the Cabibbo–Kobayashi–Maskawa matrix are one of the primary goals of the LHCb experiment. Results from the most recent LHCb γ combination will be presented first, followed by a few representative measurements not yet included in the combination. Future prospects conclude these proceedings.

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1. The LHCb CKM γ combination

The angle γ of the Cabibbo–Kobayashi–Maskawa (CKM) matrix is measured in decays which are sensitive to the interference between the favoured $b \to c$ and the suppressed $b \to u$ transition amplitudes. These are proportional to V_{cb} and V_{ub}, respectively. The amplitude ratio is written as $A_{sup}/A_{fav} = r_B e^{i\delta_B \pm \gamma}$, where the + (−) sign occurs if the initial state contains a $\bar{b}$ (b) quark, r_B is the magnitude ratio and δ_B their CP–conserving strong–phase difference. In term of the elements of the CKM matrix, γ is defined as $\arg[-\frac{V_{ud}V^*_{ud}}{V_{cb}V^*_{cb}}]$. γ can be measured in tree-level decay or inferred from global CKM fits. Any disagreement between the two determinations would indicate physics beyond the Standard Model. The 2022 LHCb γ combination [1] uses 16 different measurements as input involving $B^\pm$, B^0 and B^0_s mesons. Typical decay modes are $B^\pm \to Dh^\pm$ or $B^0 \to DK^{*0}$, where D is a mixture of the D^0 $\bar{D}^0$ flavour eigenstates and h is a π or a K. Typical D meson decays are $D \to \pi^+\pi^-$, $D \to K^+K^-$, $D \to \pi^-K^+$ or $D \to K^0_s\pi^+\pi^-$. The LHCb γ combination result from a fit with 173 observables and 52 free parameters. The most relevant of these are γ, shared between all decays, (r_B,δ_B) pairs, specific for each considered beauty meson decay and the x and y charm mixing parameters. Given the χ^2 value at the best fit point and the number of degrees of freedom the fit probability is about 80 %. The γ value obtained is $63.8^{+3.5}_{-3.7}$, shown in Fig. 1. This is the most precise determination from a single experiment. It is worth to notice that the x and y measurements obtained from the fit are the most precise determinations to date. These were taken as auxiliary inputs from HFLAV [2] in previous γ combinations. In the following sections we will

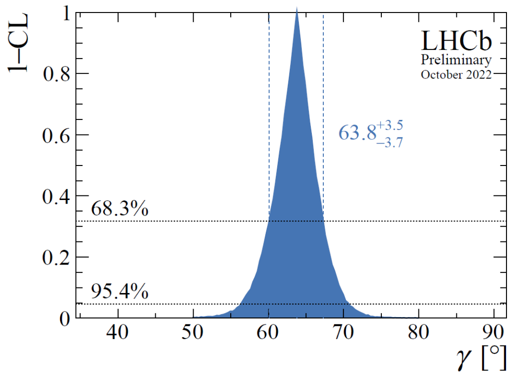

Figure 1: One dimensional 1 - CL profile for γ from all inputs used in the combination.

present a few recent measurements not yet included in the combination. Except where explicitly stated, these additional measurements are based on an integrated luminosity of 9 fb^{-1} collected during the LHC Run 1 and Run 2.

2. $B^0 \to DK^{*0}$ with self-conjugate $D \to K^0_s h^+h^-$ decays

The $B^0 \to DK^{*0}$ decay has a lower branching fraction with respect to $B^\pm \to DK^\pm$, that has the largest impact on γ. But in the former case the interference between the favoured, $b \to c$, and suppressed, $b \to u$, amplitudes is a factor 3 larger than in the later. LHCb performed a recent measurement [3] in this channel considering the charm meson decay $D \to K^0_s h^+h^-$, with $h = \pi$ or K. The flavour of the B^0 / $\bar{B}^0$ meson at the point of decay is unambiguously provided by the charge of the kaon from the $K^{*0} \to K^+\pi^-$ decay. A binning scheme is defined in the Dalitz plane given by $m^2(K_s^0 h-)$ $m^2(K_s^0 h+)$, the invariant mass squared of the $K_s^0 h^\pm$ system, with 16 bins for $h = \pi$ and 4 bins for $h = K$. The observed raw asymmetry is shown in Fig. 2. The extracted value of γ is $(49^{+22}_{-19})^\circ$, consistent with the γ combination reported in the first paragraph. The cosine and the sine of the strong-phase difference between the D^0 and $\bar{D}^0$ decays in each bin of the Dalitz plane are taken as external constraint from BESIII [4] and CLEO [5] data. These data are precise enough not to limit the accuracy of this LHCb measurement. This γ determination is dominated by statistical uncertainties as systematic are about 1/10 smaller. Hence the accuracy will improve as the overall LHCb integrated luminosity will increase.

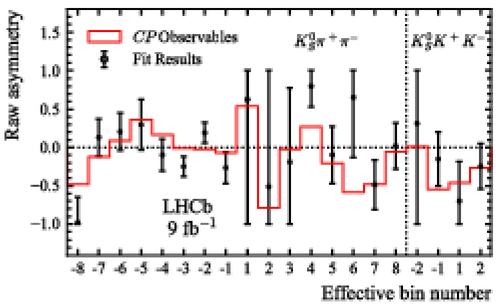

Figure 2: Raw asymmetry in each Dalitz plane bin. It is determined using the fitted CP violation observables (red histogram) and the results of an alternative fit where the signal yield in each Dalitz plot bin is a free parameter (black points).

3. $B^0 \to DK^{*0}$ using two- and four-body D decays

The $B^0 \to DK^{*0}$ with two- and four-body D decays is also used to measure γ. In the four-body mode the sensitivity to γ is due to the interference in the admixture of Cabibbo-favoured (D^0) $K^-\pi^+\pi^+\pi^-$ and doubly Cabibbo-suppressed ($\bar{D}^0$) $K^-\pi^+\pi^+\pi^-$ decays. The charge of the kaon from the $K^{*0} \to K^+\pi^-$ decay is used to determine the flavour of the B^0 / $\bar{B}^0$ meson. To perform this measurement [6] observables that allow the cancellation of a large number of systematic uncertainties related to the reconstruction and selection of the signal candidates are defined. In addition also the K^+K^-, $\pi^+\pi^-$ and $\pi^+\pi^-\pi^+\pi^-$ final states are considered. From the observables defined, the fitted value of γ is $(63.3 \pm 7.2)^\circ$. To date this is the most stringent limit on γ from B^0 decays, the result is consistent with the combination presented in the first section. For most of the considered observables the statistical uncertainties are dominant so the accuracy will improve as the overall LHCb integrated luminosity will increase.

4. $B^\pm \to D^* h^\pm$ with partial D^* reconstruction

The $B^\pm \to D^* h^\pm$ decay with partial D^* reconstruction is also used [7]. In this case the γ or the π^0 from the D^* decay are ignored and the D is reconstructed as $K_s^0 h^+ h^-$ with $h = \pi$ or K. The B^- decay via D^0 ($\bar{D}^0$) proceeds with the favoured (suppressed) amplitude and interference can occur because the final state particles are identical. A measurement of γ is obtained from the distribution

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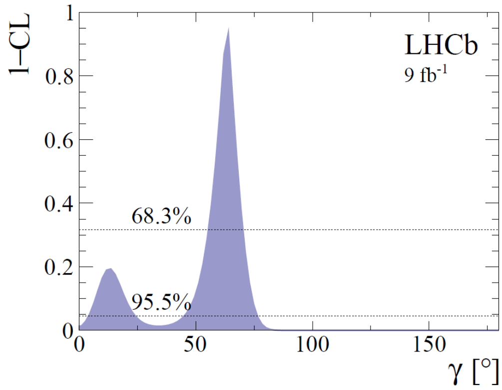

Figure 3: Confidence intervals at 68.3 % and 95.5 % for the CKM angle γ from all observables used in the $B^0 \to DK^{*0}$ using two- and four-body D decays measurement.

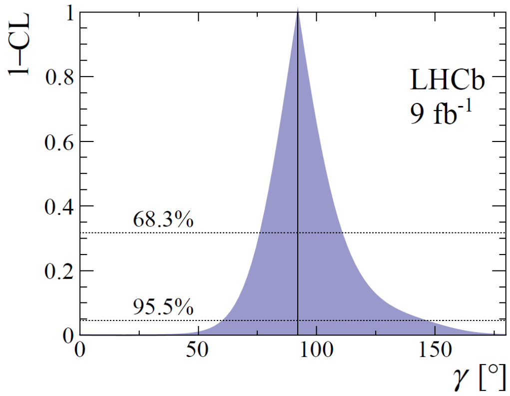

Figure 4: Confidence intervals at 68.3 % and 95.5 % for the CKM angle γ from $B^\pm \to D^* h^\pm$ with partial D^* reconstruction.

of the reconstructed $B^\pm$ events in the D Dalitz plane, the result is shown in Fig. 4. The measurement is consistent with the γ combination average. The total systematic uncertainty is approximately a factor of 2 smaller than the statistical uncertainty. As for the measurement in Sec. 2, the accuracy of the inputs from BESIII and CLEO is not limiting the sensitivity. So the accuracy will improve further as the overall LHCb integrated luminosity will increase.

5. $B_s^0 \to D_s^\mp K^\pm$ decays

The $B_s^0 \to D_s^\mp K^\pm$ decay is sensitive to γ because of the interference of the decays amplitudes with or without mixing. This analysis [8] is complementary to the ones presented in the previous sections because it involves a different beauty meson, a B_s^0, it is time-dependent and it requires flavour tagging. It is performed using a 6 fb^{-1} data sample corresponding to the LHC Run 2. In this measurement γ is extracted from the measurement of the B_s^0 and $\bar{B}_s^0$ decay rates in $D_s^\mp K^\pm$. The decay-time acceptance is obtained from the $B_s^0 \to D_s^- \pi^+$ control channel up to small corrections obtained from the ratio of the decay-time acceptances in $B_s^0 \to D_s^\mp K^\pm$ and $B_s^0 \to D_s^- \pi^+$ simulations. The

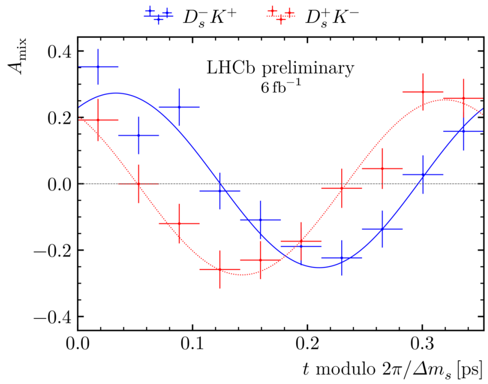

Figure 5: Mixing asymmetry for the (blue) $D_s^- K^+$ and the (red) $D_s^+ K^-$ final states, folded into one mixing period, $2\pi/\Delta m_s$. In both plots, the curves show the result of the decay-time fit.

mixing asymmetry is shown in Fig. 5. The phase shift between the $D_s^- K^+$ and $D_s^+ K^-$ components is well visible. The measured value of γ is $(74 \pm 11)^\circ$, in good agreement with the γ combination.

6. Future prospects

The LHCb γ combination is obtained from more than 10 different measurements and the current result is $(63.8^{+3.5}_{-3.7})^\circ$. This result does not yet include the measurements presented in Sec. 2 to 5. An updated combination will be provided by the end of Summer 2024. This direct measurement has to be compared to the global CKM fit results from CKMfitter [9], $(65.29^{+0.72}_{-1.86})^\circ$. Clearly the direct measurement is not yet competitive. However in the coming years the LHCb integrated luminosity will steadily increase. So by the end of the LHCb physics program, in mid 2040, an accuracy of 0.35° is expected. This is at least a factor 2 better than the current global CKM fit result.

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