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CP Violation in Beauty to Open Charm Decays at LHCb

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A precise measurement of the CKM angle γ is a central goal of the LHCb experiment. During the first two runs of the LHC the LHCb experiment collected $9\,\text{fb}^{-1}$ of data, corresponding to a rich dataset of Beauty and Charm hadron decays. Measurements of CP violation in the decays of B^+ and $B^0_{(s)}$ mesons have been performed with a variety of final states and diverse methods, resulting in world leading sensitivity. These are combined, along with complementary measurements of Charm mixing parameters, to yield a single LHCb value of γ and related parameters. The updated combination for 2024 and a selection of notable inputs are presented, for which $\gamma = (64.6 \pm 2.8)^\circ$.

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1. Time integrated *CP* violation measurements

The weak-phase difference between quark level $b \to c$ and $b \to u$ transitions is, to a very good approximation, equal to γ. Therefore one can exploit the interference between decays corresponding to these transitions to obtain sensitivity to γ. For example one can consider a $B^+ \to DK^+$ decay where D is an admixture of D^0 and $\overline{D}^0$ and decays to some final state f accessible by the decay of either D^0 or $\overline{D}^0$. Charge conjugation is implied throughout. As illustrated by Fig. 1 this will result in an interference term in the equation for the squared-amplitude of a $B^\pm$ decay that depends on $\Delta\delta_B \pm \gamma$, therefore γ can be extracted from a simultaneous measurement of the squared-amplitude of both the B^+ and B^- decays.

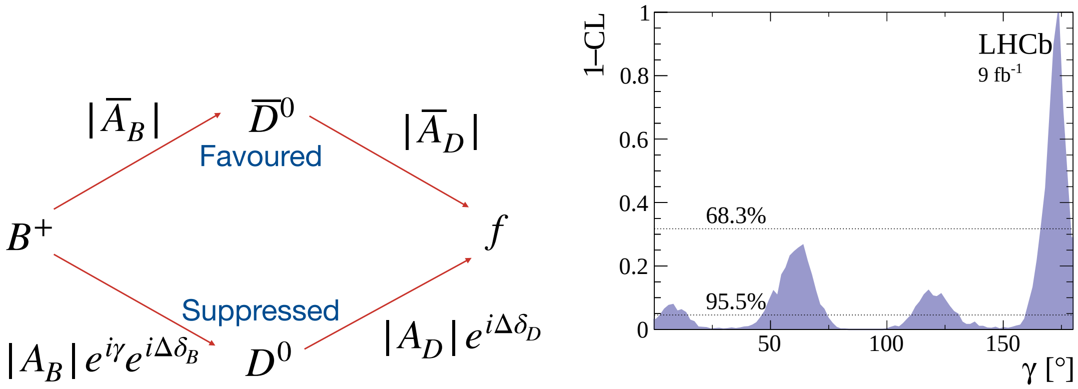

Figure 1: Left: A sketch of the terms contributing to the amplitude of a $B^+ \to DK^+, D \to f$ decay, where f is an arbitrary final state accessible via the decay of a D^0 or $\overline{D}^0$ meson, $\Delta\delta_X$ is the strong-phase difference between the favoured and suppressed X decays. Right: The γ confidence level profile for the measurement of γ in $B^0 \to DK^{*0}, D \to h^+h^{'-}$ $(\pi^+\pi^-)$ decays.

A number of time integrated measurements of γ have been performed since the last update to the LHCb γ combination. A GLW/ADS [1–4] analysis of $B^0 \to DK^{*0}$, $D \to h^+h^{'-}$ $(\pi^+\pi^-)$ decays [5] obtained the confidence level profile shown in Fig. 1. This was a simultaneous measurement of the $D \to K^\pm\pi^\mp(\pi^+\pi^-)$, $D \to \pi^+\pi^-(\pi^+\pi^-)$ and $D \to K^+K^-$ final states.

This measurement alone does not provide a single solution for γ and requires further information for an unambiguous extraction from $B^0 \to DK^{*0}$ decays. This is achieved by combination with a measurement from $B^0 \to DK^{*0}, D \to K^0_S h^+h^-$ decays [6]. This extraction of γ is performed via a simultaneous binned Dalitz analysis of the Dalitz plane of $D \to K^0_S\pi^+\pi^-$ and $D \to K^0_S K^+K^-$ decays [7–10]. Although the total asymmetry across the $D \to K^0_S h^+h^-$ Dalitz planes is low the resonant structure results in large local asymmetries and high sensitivity to γ.

The $\overset{(-)}{B^0}$ invariant mass distribution is fitted in data with the signal yields expressed in terms of *CP* observables from which γ is then extracted. The observed per-bin asymmetries and the confidence level profile obtained from the combination with the $B^0 \to DK^{*0}$, $D \to h^+h^{'-}$ $(\pi^+\pi^-)$ measurement are shown in Fig. 2. The value of γ for this combined measurement is $\gamma = (63.2^{+6.9}_{-8.1})°$.

A measurement of γ has also been performed by studying $B^\pm \to DK^{*\pm}$ decays [11]. This is a simultaneous measurement of the $D \to K^\pm\pi^\mp(\pi^+\pi^-)$, $D \to \pi^+\pi^-(\pi^+\pi^-)$, $D \to K^+K^-$ and $D \to K^0_S h^+h^-$ final states, and utilises a similar method to the $B^0 \to DK^{*0}$ measurements. This

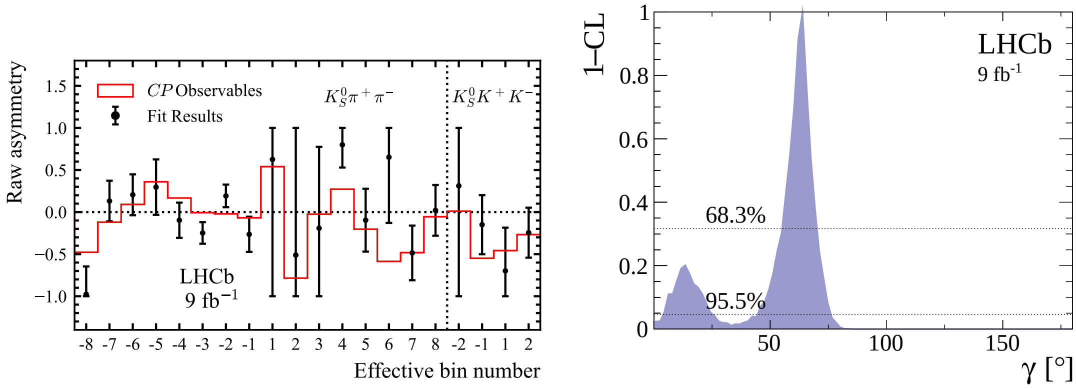

Figure 2: Left: Per-bin asymmetries in $B^0 \to DK^{*0}, D \to K_S^0 h^+h^-$ decays determined by the *CP* fit parameters (red) and signal yields when allowed to float freely (black) with statistical uncertainties. Right: Confidence level profile for γ from a combination of the $B^0 \to DK^{*0}$ measurements.

yields $\gamma = (63 \pm 13)^\circ$ and the first observation of the doubly Cabibbo suppressed $B^\pm \to DK^{*\pm}, D \to \pi^\pm K^\mp(\pi^+\pi^-)$ decay.

2. Time dependent *CP* violation measurements

CP violation can also be observed by studying the interference between a decay with and without mixing. For example for a final state f accessible by the decay of either a B_s^0 or $\overline{B}_s^0$ meson, since the mass eigenstate of the B meson is a superposition of the flavour eigenstates, it will oscillate between the two as it propagates. Therefore if one uses flavour tagging to determine the initial flavour of the B meson, and measures its decay time, the interference between the amplitudes can be measured and *CP* observables extracted. Fig. 3 shows the flavour oscillation in the decay-time distribution of $B_s^0 \to D_s^\mp K^\pm$ decays and the confidence level profile for the Run 1 and Run 2 measurements [12]. This analysis of Run 2 data obtained $\gamma = (74^{+12}_{-11})^\circ$, and when combined with the previous Run 1 result with nuisance parameters updated to match the inputs for the Run 2 analysis, $\gamma = (81^{+12}_{-11})^\circ$. This is the most precise measurement of γ in B_s^0 decays from a single experiment.

Similarly the CKM angles β and β_s can be measured by studying the decay-time dependent asymmetries in $B^0_{(s)} \to D^+_{(s)} D^-_{(s)}$ decays [13]. From a study of these decays one can extract *CP* observables that depend on $\beta_{(s)}$,

$$S_f = -\frac{2|\lambda_f|\sin(-2\beta_d)}{1+|\lambda_f|^2}, \quad C_f = \frac{1-|\lambda_f|^2}{1+|\lambda_f|^2}, \quad \text{where} \quad \lambda_f = \frac{q}{p}\frac{\overline{A}_f}{A_f}, \quad 2\beta_d = \arg\lambda_f, \tag{1}$$

and A_f, $\overline{A}_f$ are the decay amplitudes of $B^0_{(s)}$, $\overline{B}^0_{(s)}$ to the final state f and the ratio q/p described the mixing of $B^0_{(s)}$ mesons.

For $B^0 \to D^+D^-$ the Run 2 measurement corresponds to the first rejection of *CP* symmetry in a single measurement of $B^0 \to D^+D^-$ decays. The extracted *CP* observables, when combined with the corresponding Run 1 result, are

$$S_{D^+D^-} = -0.55 \pm 0.09 \qquad C_{D^+D^-} = 0.16 \pm 0.09. \tag{2}$$

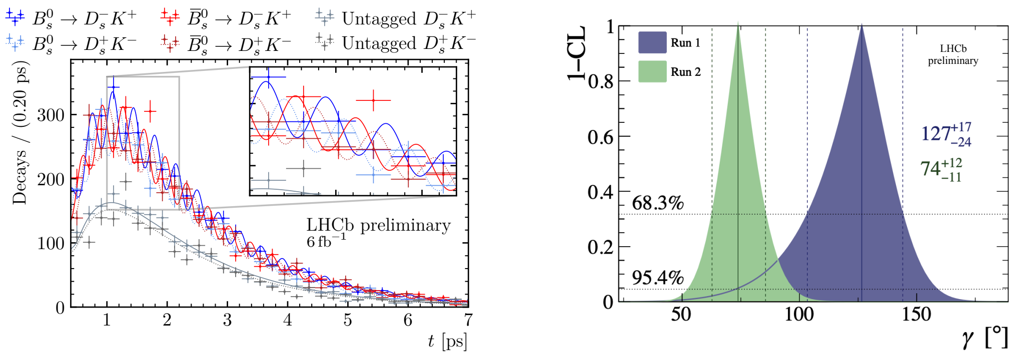

Figure 3: Left: Decay-time distribution of signal $B_s^0 \to D_s^{\mp} K^{\pm}$ candidates per final state and tagging category. Right: Confidence level profiles for γ from Run 1 & 2 $B_s^0 \to D_s^{\mp} K^{\pm}$ measurements.

The measurement of $B_s^0 \to D_s^+ D_s^-$ decays is consistent with *CP* symmetry. The extracted *CP* observables, when combined with the corresponding Run 1 result, are

$$-2\beta_s = -0.05 \pm 0.09 \text{ rad} \qquad |\lambda_{D_s^+ D_s^-}| = 1.05 \pm 0.10. \tag{3}$$

3. The 2024 γ combination

As described in Ref. [14] the LHCb collaboration combines all measurements of γ and relevant parameters to obtain a single LHCb value. This has recently been expanded to a general Beauty and Charm combination where the complementary sensitivities of Beauty and Charm measurements is exploited to optimise sensitivity, particularly to Charm mixing parameters [15]. The 2024 iteration is a combination of 19 LHCb B decay measurements, of which four are new and three supersede previous measurements, and 11 LHCb D decay measurements, one of which is new and another supersedes a previous measurement. 27 auxiliary inputs from LHCb, HFLAV, CLEO-c and BESIII are used, one of which is new and two are updated values. The 2024 combination yields the result $\gamma = (64.6 \pm 2.8)^\circ$ [16], which corresponds to a decrease in uncertainty of 0.7° since the 2022 iteration [17].

The updated per B-species values of γ are shown in Tab. 1. Fig. 4 shows the confidence level profile for the total combination and breakdowns in various categories to illustrate how different sources of measurements contribute to the total combination. Sensitivity in all B-species has greatly increased and the tension between the neutral and charged B meson measurements is significantly reduced. Due to the new results from B^0 measurements the B^0 central value has shifted much closer to the B^+ value, and with the updated $B_s^0 \to D_s^{\mp} K^{\pm}$ measurement the contributions from B_s^0 mesons are more consistent with each other which has resulted in a significantly lower total uncertainty. There is some tension between the time dependent and time integrated methods, however due to the relatively low efficiency of flavour tagging required for time dependent measurements it is difficult to obtain similar sensitivity as with time integrated methods.

Species	Value [°]	68.3% CL Uncertainty [°]	95.4% CL Uncertainty [°]
B^+	63.4	$^{+3.2}_{-3.3}$	$^{+6.4}_{-6.5}$
B^0	64.6	$^{+6.5}_{-7.5}$	$^{+12}_{-17}$
B^0_s	75	$^{+10}_{-11}$	± 20
All	64.6	± 2.8	$^{+5.5}_{-5.7}$

Table 1: Central values and uncertainties of γ per B-species and the total combination for the 2024 LHCb Beauty and Charm combination.

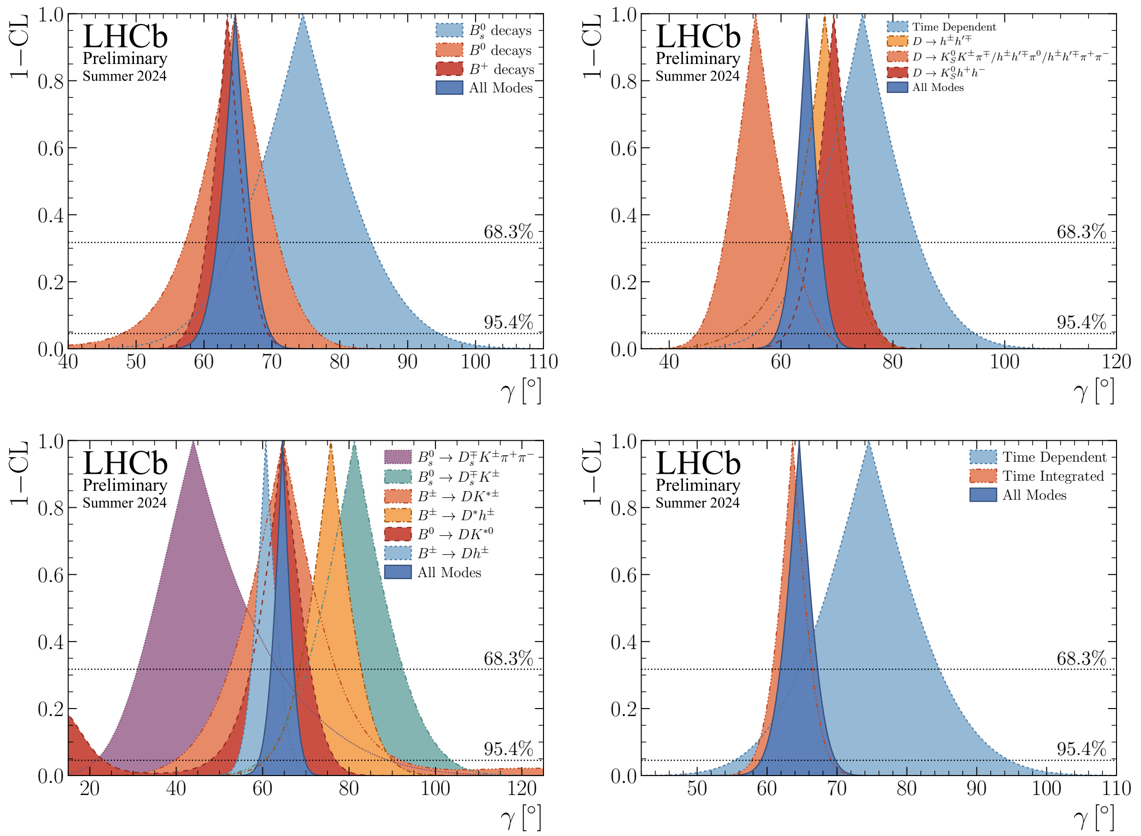

Figure 4: One-dimensional profile-likelihood scans of the confidence level distribution for γ. Top left: inputs split by contributions from B^0_s, B^0, and B^+ mesons. Top right: inputs split by contributions from time-dependent modes, 2-body D decays , $D \to K^0_S h^+ h^-$ decays, and other multibody D decays. Bottom left: inputs split by contributions per B-decay. Bottom right: inputs split by contributions from time-dependent and time-integrated measurements.

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