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CP violation measurements in B to open charm decays at LHCb

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The LHCb experiment at CERN is performing powerful tests of the Standard Model of elementary particles and their interactions, in particular of the flavour sector. These proceedings highlight some recent results that concern CP violation in hadronic B decays. Particular emphasis is given to the determination of the angle γ, related to the complex phase present in the CKM matrix that describes charged-current couplings between the six known types of quarks. Recent measurements of γ in $B^- \to DK^{*-}$ and $B^0_s \to D^{\mp}_s K^{\pm}$ decays both achieve a precision on γ of around $13°$. Together with existing measurements, the updated combined value of all LHCb measurements is determined to be $\gamma = (64.6 \pm 2.8)°$, in good agreement with indirect determinations. Results on time-dependent and flavour-tagged analyses of $B^0 \to D^+D^-$ and $B^0_s \to D^+_s D^-_s$ decays are also presented, as well as an outlook on the performance of the newly upgraded detector and plans for a second LHCb upgrade.

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1. Introduction

All hadrons that contain heavy quarks are unstable because the weak charged current allows decays of heavy quarks to lighter quarks. The strength of the couplings between the three generations of positively charged (*up*-type) and negatively charged (*down*-type) quarks is described in the Standard Model of elementary particles and their interactions by the complex 3×3 Cabibbo–Kobayashi–Maskawa (CKM) matrix. Since this matrix is unitary and the relative phases between the six quark fields are arbitrary, the CKM matrix contains 4 parameters with a physical meaning. Experimentally, the very off-diagonal elements V_{ub} and V_{td} are found to have a large, $O(1)$, complex phase. This phase, in decays where multiple amplitudes contribute, may result in CP violation, observable as decay rate asymmetries between particles and antiparticles.

The magnitude and phase of V_{ub} can be measured through processes in which a b quark decays directly, through so-called "tree" processes, to a u quark. Instead, the magnitude and phase of V_{td} is best measured in decays that involve oscillations between the B^0_d and the $\overline{B}^0_d$ meson, a process that is governed by "loop" diagrams involving virtual t quarks.

Since unitarity predicts a strict relationship between the magnitudes and phases of V_{ub} and V_{td}, the comparison of these measurements provides a strong test of consistency of our current understanding of the Standard Model. New, currently undiscovered, particles could show up as an inconsistency between processes dominated by tree and loop diagrams. At the current precision, no inconsistencies have been established, but this may change in the future as more precise measurements are being performed.

These proceedings describe several recent measurements performed by the LHCb collaboration. LHCb, one of the four large experiments at the Large Hadron Collider, is a single-arm detector instrumented at angles of $10 < \theta < 300$ mrad with respect to the clock-wise running LHC proton beam [1]. Most hadrons with b and c quarks produced in this direction have a high momentum, which helps to identify the decay vertex with the retractable silicon strip detector. Charged particle momenta are measured with a precision in the range of $0.5 - 1.0$ % by measuring their trajectory both upstream and downstream of a warm dipole magnet with an integrated magnetic field of ≈ 4 Tm. Two ring-imaging Cherenkov detectors make it possible to distinguish charged pions from charged kaons in the momentum range of $2 < p < 100$ GeV. During Run 1 (2010-2012), $\approx 3\,\mathrm{fb}^{-1}$ of pp collisions has been collected at centre-of-mass energies ,$\sqrt{s}$, of 7 and 8 TeV, and during Run 2 (2015-2018) another $\approx 6\,\mathrm{fb}^{-1}$ at $\sqrt{s} = 13$ TeV.

2. Measuring γ in $B^- \to DK^{*-}$ decays

The measurement of the angle $\gamma \equiv \arg(-\frac{V_{ud}V^*_{ub}}{V_{cd}V^*_{cb}})$ is possible through studies of CP violation in $B^- \to DK^{(*)-}$ decays, if final states that are common to both D^0 and $\overline{D}^0$ are considered. Amplitudes from both $b \to u$ and $b \to c$ transitions contribute to these decays, with an amplitude ratio $r_B e^{i(\delta_B - \gamma)}$. The strong phase difference δ_B is identical for B^+ and B^- decays, but the weak phase γ changes sign, resulting in a nonzero direct CP asymmetry $A_{CP} \equiv \frac{\Gamma(B^-)-\Gamma(B^+)}{\Gamma(B^-)+\Gamma(B^+)}$.

Earlier measurements of $B^- \to DK^-$ decays have recently been complemented by measurements in the $B^- \to DK^{*-}$ channels [6], using the full Run 1 and Run 2 data sets, where the $K^*(892)^-$ is reconstructed through its decay to $\pi^- K^0_S$. Firstly, the same-sign $B^- \to [K^-\pi^+]_D K^{*-}$

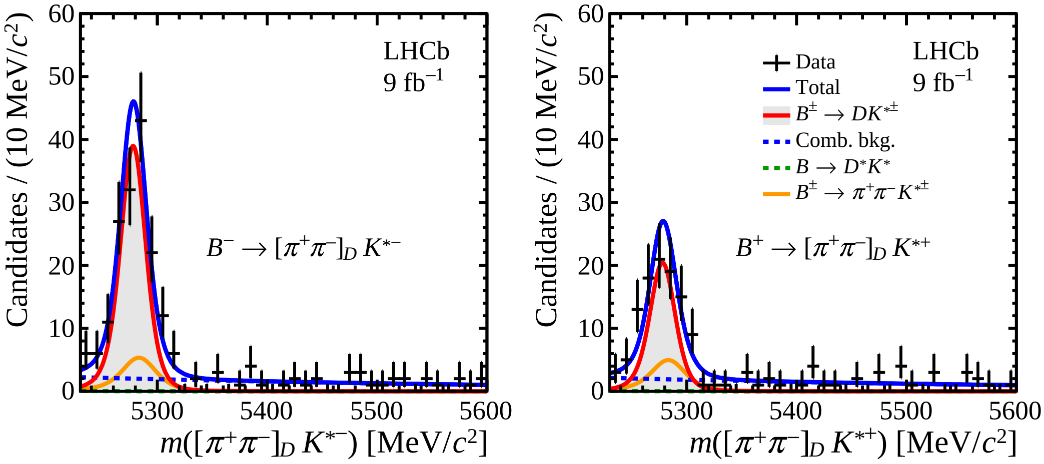

Figure 1: Reconstructed mass spectrum of (left) B^- and (right) B^+ candidates, reconstructed as $B^\pm \to [\pi^+\pi^-]_D K^\pm$.

and $B^- \to [K^-\pi^+\pi^-\pi^+]_D K^{*-}$ provide a high-statistics sample of B decays that has almost no CP asymmetry and serves as a normalisation for the other channels.

The D^0 decays to CP eigenstates K^+K^- and $\pi^+\pi^-$ as well as the quasi-CP-eigenstate $\pi^+\pi^-\pi^+\pi^-$ provide as observables the yield ratio $R_{CP} \equiv \frac{\Gamma(B\to D_{CP})}{\Gamma(B\to D_{SS})} \times \frac{\Gamma(D^0\to SS)}{\Gamma(D^0\to CP)}$, as well as a CP asymmetry $A_{CP} \equiv \frac{\Gamma(B^-)-\Gamma(B^+)}{\Gamma(B^-)+\Gamma(B^+)}$. These two observables are related to γ through the relations $R_{CP} = 1 + r_B^2 + r_B \cos\delta_B \cos\gamma$ and $A_{CP} = 2r_B \sin\delta_B \sin\gamma / R_{CP}$. These relations need to be adjusted for a coherence factor $\kappa = 0.95 \pm 0.06$ to account for dilution from nonresonant $B^- \to D\pi^- K_S^0$ contributions in the K^{*-} window, and a factor $F_{CP} = 0.735 \pm 0.016$ that accounts for the CP-even fraction in $D \to \pi^+\pi^-\pi^+\pi^-$ decays. The large CP asymmetry in this class of decays is evident from the difference in raw yield of B^- and B^+ decays, as illustrated in Fig. 1 for $D \to \pi^+\pi^-$ decays.

Opposite-sign $B^- \to [\pi^-K^+]_D K^{*-}$ and $B^- \to [\pi^-K^+\pi^-\pi^+]_D K^{*-}$, observed for the first time, are strongly suppressed but contribute to the measurement of γ through additional observables. The yield ratio $R_{OS} \equiv \frac{\Gamma(B\to D_{OS})}{\Gamma(B\to D_{SS})}$ is related to γ through the relation $R_{OS} = r_B^2 + r_D^2 + 2r_B \cos(\delta_B + \delta_D)\cos\gamma$, where r_D and δ_D are the amplitude ratio and strong phase difference, respectively, of the Cabibbo-favoured $D^0 \to K^-\pi^+$ and the double-Cabibbo-suppressed $D^0 \to K^+\pi^-$ decay. Further constraints on γ in this channel comes from the CP asymmetry $A_{CP} = 2r_B \sin(\delta_B + \delta_D)\sin\gamma / R_{OS}$.

For $D^0 \to K_S^0\pi^+\pi^-$ and $D^0 \to K_S^0 K^+K^-$ decays, the strong phase varies strongly over the phase space of the decay, and the data are therefore divided into 16 and 4 bins, respectively, using external input from CLEO [3] and BESIII [4, 5]. A simultaneous fit is applied to all bins to measure $x_\pm = r_B \cos(\delta_B \pm \gamma)$ and $y_\pm = r_B \sin(\delta_B \pm \gamma)$.

A combined fit to all D^0 modes discussed results in $\gamma = (63 \pm 13)^\circ$, $r_B^{DK^{*\pm}} = 0.103 \pm 0.010$, and $\delta_B^{DK^{*\pm}} = (47^{+14}_{-12})^\circ$, where the error includes both statistical and systematic uncertainties. This is the most precise measurement in this channel, but not the most precise single measurement of γ.

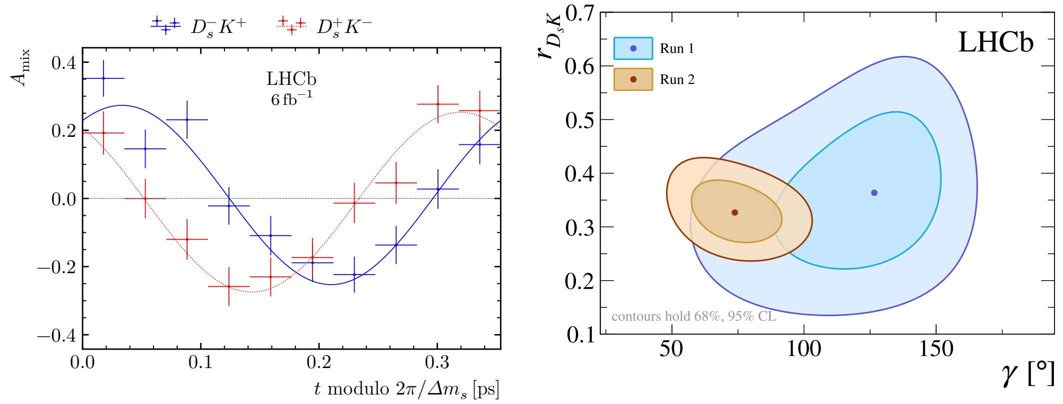

Figure 2: (left) Asymmetry of the flavour-tagged $B_s \to D_s^{\mp} K^{\pm}$ signal, as a function of the decay time modulus the B_s^0 oscillation frequency. (right) 2D-projection of the confidence levels in the angle γ and the amplitude ratio $r_{D_s K}$, compared between the present Run 2 result and the earlier Run 1 result.

3. Measuring γ in $B_s^0 \to D_s^{\mp} K^{\pm}$ decays

Another recent measurement of γ by LHCb [6] exploits the fast $B_s^0 - \overline{B}{}_s^0$ oscillations. The $D_s^- K^+$ final state is accessible both directly from a B_s^0 decay through a $b \to c$ transition or by mixing to $\overline{B}{}_s^0$ followed by a $b \to u$ transition. The resulting interference gives rise to a CP asymmetry that is proportional to $\gamma - 2\beta_s$, where $-2\beta_s = \phi_s = -31 \pm 18$ mrad is the CP-violating phase of B_s^0 mixing, small and well-measured in other B_s^0 decays [7].

The measurement of the CP asymmetry in this decay requires the tagging of the B_s^0 flavour at the moment of production, through a combination of measurements of the fragmentation particles that accompany the produced B meson (same-side tagging) with measurements of the "other" B meson produced in the dominant $b\bar{b}$ production process (opposite-side tagging). The combined efficacy of these flavour taggers has been measured to be $\varepsilon D^2 = 6.1$ %, calibrated on the large $B_s^0 \to D_s^- \pi^+$ data set.

In this analysis, using 6 fb^{-1} of pp collisions of Run 2 data, the D_s^- is reconstructed in three final states, $K^- K^+ \pi^-$, $\pi^- \pi^+ \pi^-$, $K^- \pi^+ \pi^-$. A 2D fit to $m(B)$ and $m(D)$ results in a total signal yield of 20949 ± 180. A decay-time dependent fit is then used to measure the time-dependent CP asymmetry, shown in Fig. 2.

The five measured asymmetry variables are used to determine γ, the ratio of amplitudes $r_{D_s K}$, and the strong phase difference δ. The results, compatible with an earlier Run 1 measurement, are $\gamma = (74 \pm 12)^\circ$, $\delta = (346.9^{+6.8}_{-6.6})^\circ$, $r_{D_s K} = 0.327^{+0.039}_{-0.037}$.

4. LHCb combination of γ measurements

The measurements of γ have been combined to provide an updated LHCb average of γ [8]. The average is determined through a frequentist fit with 198 input variables and 53 free parameters. Nuisance parameters are treated with the "plug-in" method. The average of all measurements results in a value of $\gamma = (64.6 \pm 2.8)^\circ$, and a P-value of 20.8 %. The quoted uncertainty includes an estimated contribution of 1.4° systematic error and is in good agreement with indirect determinations

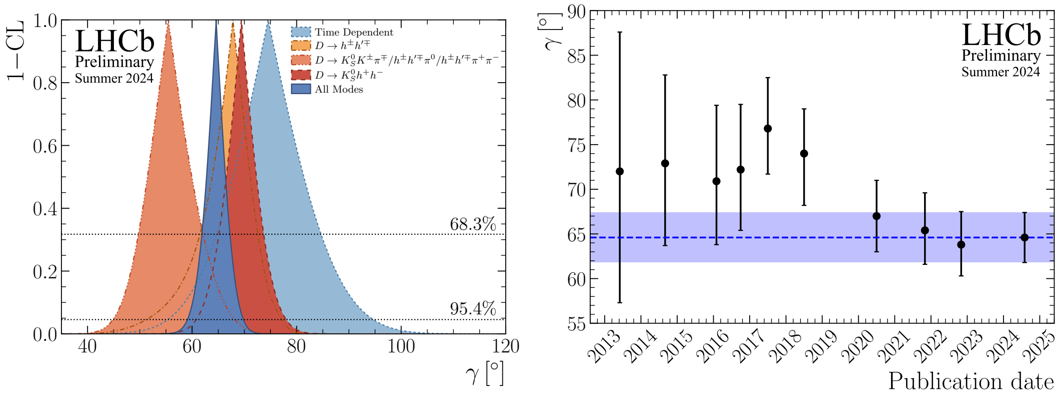

Figure 3: (left) LHCb combinations of γ measurements split by decay mode. (right) History of LHCb γ average determinations.

from CKMfitter, $\gamma = (66.0^{+0.7}_{-1.9})^\circ$ [9], and UTfit, $\gamma = (64.9 \pm 1.4)^\circ$ [10]. Intermediate averages, using different decay modes are in good agreement, as illustrated in Fig. 3, together with a graph of the LHCb γ average as a function of time.

5. CP violation in $B^0 \to D^+D^-$ and $B^0_s \to D^+_s D^-_s$ decays

Studies of CP violation in B decays to double charm are of particular interest to disentangle the contributions of tree, penguin, exchange and penguin annihilation amplitudes, and thus reduce the theoretical uncertainties in other determinations of CKM parameter, in particular that of the angle $\beta \equiv \arg(-\frac{\mathrm{V_{cd}V^*_{cb}}}{\mathrm{V_{td}V^*_{tb}}})$.

A time-dependent and flavour-tagged analysis of $B^0 \to D^+D^-$ decays of $6\,\mathrm{fb}^{-1}$ of LHCb Run 2 data results in a measurement of the sine- and cosine- components of the asymmetry oscillations as $S_{D^+D^-} = -0.552 \pm 0.100 \pm 0.010$, and $C_{D^+D^-} = 0.128 \pm 0.103 \pm 0.010$ [11]. These measurements are in agreement with the SM prediction of tree-only contributions that $S_{D^+D^-} = -\sin 2\beta$, and $C_{D^+D^-} = 0$. For the $B^0_s \to D^+_s D^-_s$ decays, a measurement using the same dataset finds $\phi_s = -0.086 \pm 0.106 \pm 0.028$ rad, and $|\lambda_{D^+_s D^-_s}| = 1.145 \pm 0.126 \pm 0.031$, in agreement with the SM expectations.

6. Outlook and conclusions

Measurements of the CKM angle γ have reached an unprecedented precision and constitute a strong test of the flavour sector of the Standard Model of elementary particles and their interactions. The LHCb collaboration has radically upgraded its detector since the end of Run 2 and is since 2024 collecting data at an instantaneous luminosity that is higher by a factor five. Moreover, the trigger is now fully defined in software and allows to collect hadronic B decays with approximately twice the efficiency as before. It is therefore expected that by the end of Run 4 in 2033, a precision of 0.8° can be achieved on γ [12]. Another increase of a factor of 7.5 in instantaneous luminosity will be possible with the second upgrade of the LHC detector, starting in 2036. Under the assumption that external measurements of the strong phases in D^0 decays will continue to improve in precision, an accuracy of 0.3° on γ appears feasible.

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