PROCEEDINGS OF SCIENCE

Time-dependent CP violation at LHCb

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The LHCb experiment has conducted precision measurements of time-dependent CP violation (TD-CPV) in key decay modes, including $B^0 \to \psi K^0_S$, $B^0_s \to J/\psi K^+ K^-$, and $B^0_s \to D^{\mp}_s K^{\pm}$ allowing extraction of CKM phases β, β_s, and γ. In the charm sector, where CP asymmetries are expected to be highly suppressed, TD-CPV analyses in $D^0 \to K^{\mp}\pi^{\pm}$ and $D^0 \to \pi^+\pi^-\pi^0$ decays provide sensitive tests of the Standard Model (SM). These measurements offer world-leading constraints on CP-violating parameters and show no significant deviations from SM predictions.

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1. Introduction

In the Standard Model of particle physics (SM), the Cabibbo-Kobayashi-Maskawa matrix ($V_{\rm CKM}$) rules the dynamic of quark flavours [1, 2]. It also encodes all the phenomena distinguishing matter from antimatter, namely the asymmetry under the combined action of the charge-conjugation and parity operations (*CP*). The SM requires the $V_{\rm CKM}$ matrix to be unitary. This constraint provides powerful tests of the SM internal consistency because redundant verifications are possible. Any deviations observed between $V_{\rm CKM}$ parameters measured in tree-level-dominated decays (considered SM benchmarks) and those in loop-dominated decays would provide indirect evidence for potential new physics. This proceeding presents measurements of the following phases of $V_{\rm CKM}$ elements: $\beta \equiv -\arg[(V_{cd}V_{cb}^*)/(V_{td}V_{tb}^*)]$, $\gamma \equiv -\arg[(V_{ud}V_{ub}^*)/(V_{cd}V_{cb}^*)]$, and $\beta_s \equiv -\arg[(V_{cs}V_{cb}^*)/(V_{ts}V_{tb}^*)]$ [3]. The LHCb experiment has recently updated their determinations studying the time-dependent *CP* violation (TD-CPV) in the $B^0 \to \psi K^0_{\rm S}$, $B^0_s \to D_s^\mp K^\pm$, and $B^0_s \to J/\psi K^+K^-$ decays, respectively. The study of *CP* violation in the D^0 sector is also relevant: this is the unique meson comprising only up-type quarks. According to the SM, the *CP* asymmetries in the charm sector are suppressed to the level of $10^{-4} - 10^{-3}$ [4]. Although the theory predictions face non-perturbative QCD contributions, which are difficult to compute, eventual CPV enhancements would be signs of new physics. No TD-CPV has been observed in the charm sector so far. This proceeding reports LHCb searches for TD-CPV with $D^0 \to K^\pm\pi^\mp$ and $D^0 \to \pi^+\pi^-\pi^0$ decays.

The LHCb experiment is a single-arm forward spectrometer designed to exploit the unique heavy-flavour factory that is the LHC at CERN [5]. The high production cross-sections of $b\bar{b}$ and $c\bar{c}$ quark pairs allow studies of all beauty hadrons and provide datasets containing millions of charm candidates [6, 7]. LHCb operates with low trigger thresholds for hadrons, muons and photons [8] and takes advantage of excellent momentum resolution, decay-time resolution, and particle identification performance [9]. These capabilities enable world-leading measurements in the TD-CPV sector, despite the complexity of flavour tagging, namely the identification of the $B^0_{(s)}$ flavour at production, which is challenging in a hadron collider environment, as detailed in Ref. [10].

2. TD-CPV in the $B^0_{(s)}$ sector

Due to flavour-eigenstate mixing, the mass eigenstates of the $B^0_{(s)} - \bar{B}^0_{(s)}$ system can be written as $|B^0_{(s)L,H}\rangle = |B^0_{(s)}\rangle q \pm |\bar{B}^0_{(s)}\rangle p$, where p and q are complex numbers. Assuming *CPT* symmetry and no CPV in the mixing [11] the asymmetry between neutral mesons produced as $B^0_{(s)}$ or $\bar{B}^0_{(s)}$ and decaying to the final state f at the proper time t can be written as [3]:

$$A_{CP}(t) = \frac{\Gamma(\bar{B}^0_{(s)} \to f, t) - \Gamma(B^0_{(s)} \to f, t)}{\Gamma(\bar{B}^0_{(s)} \to f, t) + \Gamma(B^0_{(s)} \to f, t)} = \frac{S_f \sin(\Delta m_{(s)} t) - C_f \cos(\Delta m_{(s)} t)}{\cosh\left(\frac{\Delta\Gamma_{(s)}}{2} t\right) + A_f^{\Delta\Gamma} \sinh\left(\frac{\Delta\Gamma_{(s)}}{2} t\right)},$$

where $\Delta m_{(s)}$ and $\Delta\Gamma_{(s)}$ are the mass and decay-width differences between the $B^0_{(s)L}$ and $B^0_{(s)H}$ eigenstates; $C_f = (1 - |\lambda_f|^2)/(1 + |\lambda_f|^2)$, $S_f = 2{\rm Im}[\lambda_f]/(1 + |\lambda_f|^2)$, $A_f^{\Delta\Gamma} = -2{\rm Re}[\lambda_f]/(1 + |\lambda_f|^2)$, $\lambda_f = (q\bar{A}_f)/(pA_f)$ where A_f ($\bar{A}_f$) is the instantaneous amplitude of the $B^0_{(s)} \to f$ ($\bar{B}^0_{(s)} \to f$) decay.

If f is a *CP* eigenstate, C_f encodes the CPV in the decay and S_f encodes the CPV in the interference of decays with and without mixing. An equivalent set of observables is given by the magnitude $|\lambda_f|$ and phase $\phi_{(s)} \equiv \arg[\lambda_f]$. The decays $B^0 \to J/\psi K^0_S$ and $B^0_s \to J/\psi\phi$ are considered golden modes because their total amplitudes are dominated by Feynman diagrams involving only mixing and tree-level decays. In these cases, the SM predicts $(C_f, S_f) = (0, \sin[\pm 2\beta_{(s)}])$, namely $(|\lambda_f|, \phi_{(s)}) = (1, \pm 2\beta_{(s)})$, up to subleading loop contributions [12]. The decays $B^0_s \to D^\mp_s K^\pm$ and $\bar{B}^0_s \to D^\pm_s K^\mp$ are also governed by mixing and tree-level processes. Both the final states $f = D^-_s K^+$ and $\bar{f} = D^+_s K^-$ are allowed for the B^0_s and $\bar{B}^0_s$ mesons. Following the formalism introduced above, two time-dependent asymmetries are possible. The SM predicts: $S_f = 2r_f \sin(\delta - (\gamma - 2\beta_s))/(1 + r_f^2)$, $A^{\Delta\Gamma}_f = -2r_f \cos(\delta - (\gamma - 2\beta_s))/(1 + r_f^2)$, $S_{\bar{f}} = -2r_f \sin(\delta + (\gamma - 2\beta_s))/(1 + r_f^2)$, $A^{\Delta\Gamma}_{\bar{f}} = -2r_f \cos(\delta + (\gamma - 2\beta_s))/(1 + r_f^2)$, $C_f = (1 - r_f^2)/(1 + r_f^2) = -C_{\bar{f}}$, where $r_f \equiv |\lambda_f|$ and δ is the strong-phase difference between $\bar{A}_f$ and A_f.

These LHCb measurements share similar features. Event selection leverages Boosted Decision Tree (BDT) algorithms to efficiently suppress combinatorial background [13]. Fits to the invariant-mass distribution are used to statistically subtract all the residual background components (*sPlot* technique [14]). The asymmetry parameters are obtained from a second fit to the resulting signal distributions, considering flavour tagging and decay time. Data-driven techniques are used to calibrate both the mistag probability and the decay-time resolution, using flavour-specific decays (*e.g.* $B^0_s \to D^-_s \pi^+$, $B^+ \to \psi K^+$) and prompt samples of background candidates that mimic the signal.

Measurement of $\sin(2\beta)$ with $B^0 \to \psi K^0_S$ decays This analysis [15] exploits the Run2 dataset of LHCb, corresponding to an integrated luminosity of 6 fb^{-1}. The charmonium modes $J/\psi \to \mu^+\mu^-$, $J/\psi \to e^+e^-$, and $\psi(2S) \to \mu^+\mu^-$, are considered. They correspond to 306000, 24000, and 43000 signal candidates, respectively. The main systematic uncertainties are due to the $\Delta\Gamma = 0$ assumption [11] and the flavour-tagging calibration. The final results are $C_{\psi K^0_S} = 0.008 \pm 0.012 \pm 0.003$ and $S_{\psi K^0_S} = 0.717 \pm 0.013 \pm 0.008$, where the first uncertainty is statistical and the second one is systematic. The same convention is assumed hereon, when two uncertainties are quoted. These measurements are more precise than the previous world average. The combinations with the previous LHCb results yield $C^{\text{Run1+2}}_{\psi K^0_S} = 0.004 \pm 0.012$ and $S^{\text{Run1+2}}_{\psi K^0_S} = 0.724 \pm 0.014$, in agreement with the SM predictions [16, 17].

Measurement of ϕ_s with $B^0_s \to J/\psi K^+K^-$ decays This analysis [18] uses the data collected during the Run2 of LHCb (6 fb^{-1}). The invariant mass of the K^+K^- pair is selected in the vicinity of the $\phi(1020)$ resonance. The yield of signal candidates is 350000 decays. Since the ϕ is a vector meson, an angular analysis is performed to disentangle the *CP*-even and the *CP*-odd contributions to the B^0_s decay. The combination of the LHCb analyses with Run1 and Run2 data yields: $|\lambda_{J/\psi\phi}| = 0.990 \pm 0.010$, $\phi_s^{J/\psi\phi} = -0.044 \pm 0.020$ rad, whose total uncertainties are dominated by the statistical contribution. This is the most precise determination of these quantities to date. The combination of all LHCb measurements of ϕ_s in $b \to c\bar{c}s$ transitions is $\phi_s^{c\bar{c}s} = -0.031 \pm 0.018$ rad in agreement with the precise SM prediction [16, 17].

A measurement of $\Delta\Gamma_s$ The B^0_s decay-width difference, $\Delta\Gamma_s$ is usually precisely determined with $B^0_s \to J/\psi\phi$ decays. Indeed, the LHCb analysis in Ref. [18] measured $\Delta\Gamma_s^{J/\psi\phi} = 0.087 \pm 0.012 \pm$

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0.009. However, the $\Delta\Gamma_s$ measurements reported by the ATLAS, CMS, and LHCb experiments are in tension between each other [11]. LHCb has recently measured $\Delta\Gamma_s$ also using $B_s^0 \to J/\psi\eta'$ and $B_s^0 \to J/\psi f_0(980)$ decays. The small value of ϕ_s means that *CP*-even modes, such as the former, determine the light mass eigenstate lifetime $(1/\Gamma_L)$ while *CP*-odd modes, such as the latter, measure the heavy mass eigenstate lifetime $(1/\Gamma_H)$, within 0.2 fs^{-1} [19]. The analysis [20] used the total integrated luminosity collected by LHCb (9 fb^{-1}) and its result is $\Delta\Gamma_s = 0.087 \pm 0.012 \pm 0.009$ ps^{-1}. This precision is not competitive with the world average [11], but the alternative approach may help to resolve the current experimental tensions.

Measurement of γ with $B_s^0 \to D_s^{\mp}K^{\pm}$ decays This analysis [21] concerns the data collected in LHCb Run2. The $D_s^{\mp}$ mesons are reconstructed considering five final states: $\pi^+\pi^+\pi^-$, $K^{\mp}\pi^+\pi^-$, $\phi\pi^{\mp}$, $K^{*0}(892)K^{\mp}$. The total inclusive signal yield is 20100. The measured asymmetry parameters are: $C_f = -C_{\bar{f}} = 0.791 \pm 0.061 \pm 0.022$, $A_f^{\Delta\Gamma} = -0.051 \pm 0.134 \pm 0.037$, $A_{\bar{f}}^{\Delta\Gamma} = -0.303 \pm 0.125 \pm 0.036$, $S_f^{\Delta\Gamma} = -0.571 \pm 0.084 \pm 0.023$, $S_{\bar{f}}^{\Delta\Gamma} = -0.503 \pm 0.084 \pm 0.025$. Combining these results and taking $2\beta_s = -\phi_s$ as input from Ref. [18], the following quantities are determined: $r_f = 0.327 \pm 0.038$, $\delta = (346.9 \pm 6.6)^\circ$, and $\gamma = (74 \pm 11)^\circ$.

3. TD-CPV in the D^0 sector

Mixing and CPV in $D^0 \to K^{\pm}\pi^{\mp}$ decays The total amplitude A_f $(\bar{A}_{\bar{f}})$ of the $D^0 \to K^-\pi^+$ $(\bar{D}^0 \to K^+\pi^-)$ mode is dominated by a Cabibbo-Favoured (CF) transition. The amplitude $\bar{A}_f$ $(A_{\bar{f}})$ of the $\bar{D}^0 \to K^-\pi^+$ $(D^0 \to K^+\pi^-)$ mode is ruled by the interference of a doubly-Cabibbo-suppressed (DCS) decay with D mixing followed by a CF decay. Two time-dependent ratios between the just mentioned decay categories can be constructed: $R^+_{K\pi}(t) = \Gamma(D^0 \to K^+\pi^-)/\Gamma(\bar{D}^0 \to K^+\pi^-)$, $R^-_{K\pi}(t) = \Gamma(\bar{D}^0 \to K^-\pi^+)/\Gamma(D^0 \to K^-\pi^+)$. Due to the smallness of the charm mixing parameters, such ratios can be expanded to the second power of the decay time according to [22]:

$$R^{\pm}_{K\pi} = R_{K\pi}(1 \pm A_{K\pi}) + \sqrt{R_{K\pi}(1 \pm A_{K\pi})}(c_{K\pi} + \Delta c_{K\pi})t/\tau_{D^0} + (c'_{K\pi} + \Delta c'_{K\pi})(t/\tau_{D^0})^2,$$

where: τ_{D^0} is the D^0 lifetime [3], $R_{K\pi} = (|A_{\bar{f}}/\bar{A}_{\bar{f}}|^2 + |\bar{A}_f/A_f|^2)/2$, $A_{K\pi}$ is the *CP* asymmetry of the DCS decay, which is expected to be null in the SM, $c_{K\pi}$ and $c'_{K\pi}$ depend on the mixing parameters, $\Delta c_{K\pi}$ encodes the CPV in the mixing, and $\Delta c'_{K\pi}$ the CPV in the interference of decay with and without mixing. The new measurement of these quantities by LHCb exploits the Run2 data sample [23]. The D flavour at production is tagged selecting flavour-conserving prompt-$D^{*+} \to D^0\pi^+$ decays. The $R^{\pm}_{K\pi}$ ratios are determined by measuring the signal yields in 18 quasi-equally populated bins of decay time with fits to the $D^{*\pm}$ invariant mass. The total yields are 412 million for the CF decays and 1.6 million for the suppressed ones. The main challenges are due to experimental effects caused by the reconstruction of low-momentum pions (*ghosts*), the final-state detection asymmetries, and the decay-time bias caused by the presence of $D^{*\pm}$ from decays of B mesons. Precise studies and corrections of these effects have halved the systematic uncertainties compared to the previous LHCb results from Run1 data. The combination of the two analyses provided the following results: $R_{K\pi} = (342.7 \pm 1.9) \times 10^{-5}$, $A_{K\pi} = (-6.6 \pm 5.7) \times 10^{-3}$, $c_{K\pi} = (52.8 \pm 3.3) \times 10^{-4}$, $\Delta c_{K\pi} = (2.0 \pm 3.4) \times 10^{-4}$, $c'_{K\pi} = (12.0 \pm 3.5) \times 10^{-6}$, $\Delta c'_{K\pi} = (-0.7 \pm 3.6) \times 10^{-6}$, whose total uncertainties are statistically dominated and 40% smaller than the previous best measurements.

The parameter is $c'_{K\pi}$ is different from 0 with a significance of 3.5σ: this is the first evidence of a quadratic term related to the D^0 mixing. No CPV evidence is found.

Search for TD-CPV in $D^0 \to \pi^+\pi^-\pi^0$ decays For a D^0 meson decaying to a *CP* eigenstate, f_{CP}, the time-dependent asymmetry can be expanded to first order in the D^0 decay time, t, as $A^{CP}_{f_{CP}}(t) \approx a^{\rm dir}_{f_{CP}} + \eta_{f_{CP}}\Delta Y(t/\tau_{D^0})$, where $a^{\rm dir}_{f_{CP}}$ encodes the direct *CP* asymmetry, $\eta_{f_{CP}}$ is the eigenvalue of the final state, and the gradient ΔY, involving indirect *CP* violation and mixing parameters, is independent of the final state [24]. In general, phase-space integrated analyses of multi-body decays have diluted sensitivity to ΔY due to a mixture of *CP*-even and *CP*-odd contributions from intermediate states: $\Delta Y^{\rm eff}_f = (2F^f_+ - 1)\Delta Y$. In this case, the *CP*-even fraction of the final state was measured by the CLEO-*c* experiment to be $F^{\pi\pi\pi}_+ = 0.973 \pm 0.017$ [25] providing almost undiluted sensitivity. This analysis [26] use the data collected by LHCb from 2012 to 2018 (7.7 fb^{-1}). The total signal yield is 3.77 million candidates. The D^0 flavour is tagged exploiting the $D^{*+} \to D^0\pi^+$ decay chain. The data sample is divided into 21 quasi-equally populated bins depending on the decay time. In each bin, the raw *CP* asymmetry is extracted with a fit to the invariant-mass difference $\Delta m \equiv m(D^{*+}) - m(D^0)$. The nuisance asymmetries due to experimental effects are reduced to a negligible level thanks to a detailed kinematic-weighting procedure. The effective observable $\Delta Y^{\rm eff}_f$ is obtained with a linear fit to the $A^{CP}_{f_{CP}}(t)$ values and then corrected for the dilution factor, $F^{\pi\pi\pi}_+$, taken as external input. The analysis strategy is validated using the $D^0 \to K^-\pi^+\pi^0$ decays, where CPV is expected to be suppressed compared to the signal mode. Indeed, $\Delta Y_{K\pi\pi} = (-1.7 \pm 1.8 \pm 3.5) \times 10^{-4}$ is measured to be compatible with 0 in the validation case. The result for the signal case is: $\Delta Y_{\pi\pi\pi} = (-1.3 \pm 6.3 \pm 2.4) \times 10^{-4}$. No evidence for *CP* violation is found. This study represents the first measurement of TD-CPV in the singly Cabibbo-suppressed decay $D^0 \to \pi^+\pi^-\pi^0$.

4. Conclusions

Several results are still being produced with the data collected by LHCb in Run1 and Run2. Concerning the TD-CPV sector, recent LHCb results provided world-leading measurements of the $\sin(2\beta)$ and ϕ_s observables. New measurements of $B \to DK$ decays are continuously improving the constraints on the CKM angle γ. LHCb is still exploiting its enormous charm data sample to chase new evidence of CPV. No discrepancy from the SM expectations has been observed so far. Increasing the sensitivity to CPV observables is crucial for rigorously testing the CKM paradigm. The main source of current uncertainties is statistical. The UpgradeD LHCb detector has already started to collect data with the potential to more than double its sample size within the next two years [27].

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