PROCEEDINGS OF SCIENCE

Measurements of α, β, ϕ_s and B meson lifetime properties at LHCb

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Precision measurements of the Cabibbo-Kobayashi-Maskawa (CKM) matrix are excellent tests of the validity of the Standard Model. They are sensitive to higher energies than can be obtained in direct searches, and thus can constrain New Physics at much higher scales. In this proceeding, the latest updates to the measurements of α, β, ϕ_s and B meson lifetime using data obtained by the LHCb experiment are reviewed.

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1. Introduction

Charge-Parity (CP) violation in charged-current quark transitions is described in the Standard Model (SM) through the Cabibbo-Kobayashi-Maskawa (CKM) mechanism. It stems from the fact that mass and flavor eigenstates do not coincide, allowing to quark flavour transitions with different amplitudes described by the unitary CKM matrix. This matrix can be parametrised by three real numbers and one irreducible complex phase that is responsible for CP violation [1, 2].

Using the unitary property of the CKM matrix, it is possible to define triangles using the six vanishing conditions in the complex plane. Measurements related to two angles of one of the unitary triangles (α, β) and a third (β_s) related to another of the triangles, performed by the LHCb collaboration are presented in these proceedings. These are defined as [1, 2]:

$$\alpha = \arg\left(-\frac{V_{td}V^*_{tb}}{V_{ud}V^*_{ub}}\right), \quad \beta = \arg\left(-\frac{V_{cd}V^*_{cb}}{V_{td}V^*_{tb}}\right), \quad \beta_s = \arg\left(-\frac{V_{ts}V^*_{tb}}{V_{cs}V^*_{cb}}\right). \tag{1}$$

In $B^0_{(s)}$ meson decays to a CP eigenstate, which is denoted by f, CP violation can originate from the interference between the mixing and the decay. The latter can be modelled by an effective Hamiltonian whose mass eigenstates are linear combinations of the two flavour egenstates, $p\,|B^0_s\rangle \pm q\,|\bar{B}^0_s\rangle$, where p and q are complex parameters, normalised such that $|p|^2 + |q|^2 = 1$. The CP asymmetry as a function of decay time is given by

$$A_{CP}(t) = \frac{\Gamma_{\bar{B}\to f}(t) - \Gamma_{B\to f}(t)}{\Gamma_{\bar{B}\to f}(t) + \Gamma_{B\to f}(t)} = \frac{-C_f\cos(\Delta m t) + S_f\sin(\Delta m t)}{\cosh\left(\frac{\Delta\Gamma t}{2}\right) + A^{\Delta\Gamma}_f\sinh\left(\frac{\Delta\Gamma t}{2}\right)}, \tag{2}$$

where $\Delta\Gamma$ and Δm are the width and mass differences of the mass eigenstates of the B system, C_f, S_f and $A^{\Delta\Gamma}_f$ are defined as Eq. 3 and A_f ($\bar{A}_f$) is the decay amplitude for the $B^0_{(s)}$ ($\bar{B}^0_{(s)}$) $\to f$ transition.

$$C_f = \frac{1-|\lambda_f|^2}{1+|\lambda^2_f|}, \quad S_f = \frac{2\Im\lambda_f}{1+|\lambda^2_f|}, \quad A^{\Delta\Gamma}_f = \frac{2\Re\lambda_f}{1+|\lambda^2_f|}, \quad \text{with } \lambda_f = \frac{q}{p}\frac{\bar{A}_f}{A_f}. \tag{3}$$

2. $B^0_{d,s} \to h^+h^-$

Time dependent CP asymmetries in $B^0 \to \pi^+\pi^-$ decays can be related through a GL isospin analysis with $B^0 \to \pi^0\pi^0$ and $B^+ \to \pi^+\pi^0$ decays in order to constrain α [3]. This analysis can be extended taking advantage of the U-spin symmetry that relates this decay with $B^0_s \to K^+K^-$ [4]. It has been shown that the results of $B^0_s \to K^+K^-$ can be used to put stringent constraints on $2\beta_s$ and γ [5]. Finally, information can be added from the semileptonic decays $B^0 \to \pi^-K^+\nu$ and $B^0_s \to K^-l^+\nu$ to reduce the uncertainty on the determination of $2\beta_s$ [6].

In the present analysis the time-dependent CP asymmetries of $B^0 \to \pi^+\pi^-$ and $B^0_s \to K^+K^-$ and the time-integrated CP asymmetries in $B^0 \to K^+\pi^-$ and $B^0_s \to K^-\pi^+$ are measured using the 2015-2016 data sample of the LHCb experiment corresponding to an integrated luminosity of 1.9 fb^{-1} at a centre of mass energy of 13 TeV and are combined with Run 1 results. The results (C_{KK},

S_{KK}, $A^{\Delta\Gamma}_{KK}$) show the first observation of time dependent CP violation in the B^0_s system, excluding the hypothesis of the CP conservation (0,0,-1) by more than 6.5σ [7]:

$$C_{KK} = 0.172 \pm 0.031, \quad S_{KK} = 0.139 \pm 0.032, \quad A^{\Delta\Gamma}_{KK} = -0.897 \pm 0.087 \tag{4}$$

The measurements of $C_{\pi\pi}$, $S_{\pi\pi}$, $A^{B^0}_{CP}$ and $A^{B^0_s}_{CP}$ are the most accurate measurements to date [7] and are compatible with previous results provided by B-factories [8, 9]. Specifically, the values obtained for $C_{\pi\pi}$ and $S_{\pi\pi}$, which are of great importance for the isospin analysis necessary to constrain α [3], were as follows [7],

$$C_{\pi\pi} = -0.320 \pm 0.038, \quad S_{\pi\pi} = -0.672 \pm 0.034. \tag{5}$$

The world average of α is provided by HFLAV2021 through an isospin analysis which uses time dependent CP violation parameters in $B_d \to \pi^+\pi^-, \pi^+\pi^-\pi^0, \rho\pi, \rho\rho$ decays. The confidence interval for the value of α can be seen in Fig. 1, where the results are split by decay mode. The current world average is $(85.4^{+4.8}_{-4.3})^\circ$ [10].

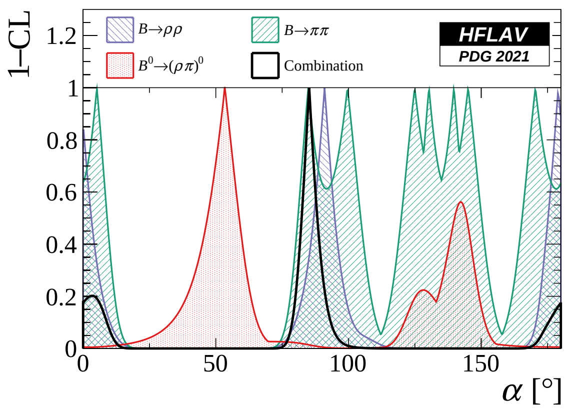

Figure 1: World average of α in terms of 1-CL split by decay mode [10].

3. CPV in $B^0_d \to D^*D$

This analysis constitutes the first measurement of CP violation in $B \to D^*D$ at LHCb and uses the full Run 1 and Run 2 data set, corresponding to an integrated luminosity of 9 fb^{-1}. These decays are mediated by a $b \to c\bar{c}d$ transition sensitive to 2β. In this decay, a penguin diagram with a different phase ($V^*_{tb}V_{td}$) from the dominant tree contribution ($V^*_{cb}V_{cd}$) is expected to contribute to a few percent to the measurement of an effective phase β_{eff} [12]. Therefore a difference between $S_{c\bar{c}s}$ and $S_{c\bar{c}d}$ greater than expected could indicate the existence of beyond Standard Model physics.

The final state of this decay is not a CP eigenstate ($f \neq \bar{f}$), therefore the decay parameters of Eq. 3 are combined to $\{S, C\}_{D^*,D} = \frac{1}{2}(\{S, C\}_f + \{S, C\}_{\bar{f}})$ and $\Delta\{S, C\}_{D^*,D} = \frac{1}{2}(\{S, C\}_f - \{S, C\}_{\bar{f}})$. In absence of new physics (NP) and ignoring higher order contributions in SM, $S = \sin 2\beta$ while $C, A, \Delta C, \Delta S$ vanish [11].

The result excludes the hypothesis of CP conservation by more than 10σ and is the most precise single measurement of the CP parameters in $B^0 \to D^*D$ decays as can be seen in Fig. 2. The

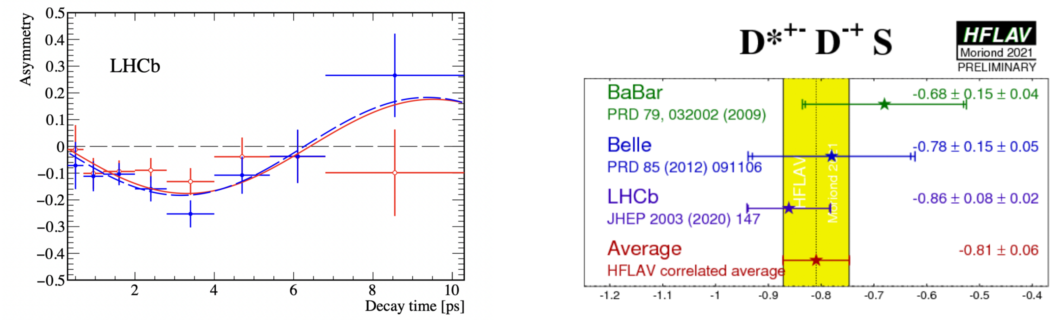

Figure 2: The time-dependent asymmetry between B^0 and $\bar{B}^0$ decay rates to $D^{*-}D^{+}$ (red empty dot) and $D^{*+}D^{-}$ (blue full dot) final states is shown in the left figure, where the flavour of the B meson at production is obtained by tagging. On the right plot is displayed the current world average for the CP observable S in $D^{*}D$ final state [10].

result of S is compatible with the LHCb combination in the golden transition $b \to [c\bar{c}]s$ transtions ($S = 0.76 \pm 0.034$ [13]). The rest of CP observables are compatible with zero as expected [11].

4. ϕ_s related news and status

The phase difference ϕ_s, is a CP-violating observable originated from the interference between the direct decay and the decay through mixing of B_s^0 meson to CP eigenstates proceeding through a $b \to c\bar{c}s$ transition where $\phi_s \approx -2\beta_s$ ignoring BSM and subleading contributions in SM.

The LHCb collaboration measured ϕ_s in $B_s \to J/\psi(\mu^+\mu^-)\phi(K^+K^-)$ [14] and $B_s \to J/\psi(\mu^+\mu^-)\pi^+\pi^-$ [15] using Run 1, 2015 and 2016 data taking, corresponding to an integrated luminosity of 4.9 fb^{-1}. Furthermore, ϕ_s was measured in $B_s \to D_s^+D_s^-$ [16], $B_s \to J/\psi K^+K^-$ (high mass) [17] and $B_s \to \psi(2S)\phi$ [18] using the Run 1 data set. Measurements of ϕ_s in $J/\psi(\mu^+\mu^-)\phi$ have also been performed by ATLAS [19], CMS [20], CDF [21] and D0 [22] collaborations. The world average of all these measurements is $\phi_s = (-0.050 \pm 0.019)$ rad, $\Delta\Gamma_s = (0.082 \pm 0.005)$ ps^{-1} and $\Gamma_s = (0.6628 \pm 0.0035)$ ps^{-1} [10] as displayed in Fig. 3 [10]. The current SM prediction for $-2\beta_s = -37^{+0.7}_{-0.8}$ mrad [23] and $\Delta\Gamma_s = 0.091 \pm 0.013$ ps^{-1} [24].

For the first time the LHCb collaboration performed a measurement of ϕ_s using a flavour-tagged time dependent and angular analysis of the $J/\psi(e^+e^-)\phi(K^+K^-)$ final state using Run 1 (3fb^1) data. The yield of the $B_s^0 \to J/\psi(e^+e^-)\phi$ sample corresponds to about 10% of the $B_s^0 \to J/\psi(\mu^+\mu^-)\phi$ mode [25]. The main difference between these analyses is that electrons radiate a much larger fraction of their energy through bremsstrahlung photons when travelling through the detector material which has a large impact on the resolution of the reconstructed invariant mass of both the di-electron pair and the B_s^0 candidate.

The CP violating phase and lifetime parameters of the B_s^0 system are measured to be $\phi_s = 0.00 \pm 0.28 \pm 0.07$ rad, $\Delta\Gamma_s = 0.115 \pm 0.045 \pm 0.011$ ps^{-1} and $\Gamma_s = 0.608 \pm 0.018 \pm 0.012$ ps^{-1} where the first uncertainty is statistical and the second systematic [25]. These results are consistent with previous measurements [14, 18], SM prediction and show no evidence of CP violation in the interference between B_s^0 meson mixing and decay. In addition, it constitutes an important check

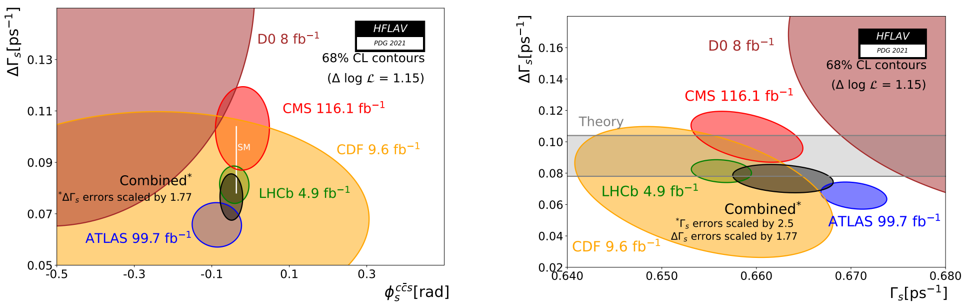

Figure 3: $(\phi_s, \Delta\Gamma_s)$ plane (left) and $(\Gamma_s, \Delta\Gamma_s)$ plane (right) whith individual 68% confidence-level contours from measurements of ATLAS, CMS, CDF, D0 and LHCb and the combined contour (black solid line and shaded area), as well as the Standard Model predictions.

for the result with muons because the systematic uncertainties of the measurements are mostly independent.

5. Future prospects

Statistical uncertainties and data driven systematics will be reduced with the LHCb upgrade. The uncertainties of ϕ_s using $B_s \to J/\psi\phi$ are expected to be reduced to 14 mrad by the first Upgrade of the LHCb Experiment, while a second upgrade planned to operate in the high-luminosity LHC is expected to collect 300 fb^{-1} and reduce the uncertainties to 4 mrad. The uncertainty of $\sin 2\beta$ using the golden channel $B^0 \to J/\psi K^0_S$ is expected to be reduced to 0.003 using the same 300 fb^{-1} data set. These improvements must be complemented by an even greater effort in the understanding of the subdominant contributions in the SM in order to translate into a better understanding of the NP dynamics.

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