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Time-dependent *CP* violation measurements with *B* decays at LHCb

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Summary. — LHCb is one of the four major experiments operating at the Large Hadron Collider, and is specifically dedicated to the measurement of CP violation and rare decays in the beauty and charm quark sectors. In this report we present some of the latest and most relevant measurements of time-dependent CP violation in B hadron decays, performed by LHCb using the data sample collected during 2011 and 2012.

1. – Introduction

The non-invariance of the weak interactions with respect to the combined application of charge conjugation (C) and parity (P) transformations is explained, within the Standard Model (SM), by the Cabibbo-Kobayashi-Maskawa (CKM) mechanism [1, 2]. This mechanism generates CP violation (CPV) introducing a complex phase in the elements of the so-called CKM matrix, a 3×3 unitary complex matrix, that mixes the mass-eigenstates and flavour-eigenstates of quarks. The precise determination of the parameters of the CKM matrix is one of the most promising way to probe the validity of the SM and to search for New Physics (NP). The measurement of time-dependent CP asymmetries of neutral B meson decays allow the determination of the CKM phases responsible of CPV in B decays. Moreover, the time evolution of neutral B mesons is governed by box diagrams. New particles, not foreseen within the SM, may appear inside the diagrams as virtual contributions, altering the values of the CPV observables with respect to the SM predictions. In this document we present some of the most recent and relevant measurements of time-dependent CPV in B decays, performed by LHCb [3] using p-p collisions collected during 2011 and 2012, corresponding to an integrated luminosity of $1\,\text{fb}^{-1}$ at $\sqrt{s} = 7\,\text{TeV}$ and $2\,\text{fb}^{-1}$ at $\sqrt{s} = 8\,\text{TeV}$, respectively.

The time-dependent CP asymmetry of either a B^0 or a B_s^0 meson decaying into a CP-eigenstate f can be written as

$$A_{CP}(t) = \frac{\Gamma_{\bar{B}\to f}(t) - \Gamma_{B\to f}(t)}{\Gamma_{\bar{B}\to f}(t) + \Gamma_{B\to f}(t)} = \frac{-C_f \cos(\Delta m t) + S_f \sin(\Delta m t)}{\cosh(\frac{\Delta\Gamma t}{2}) + A_{\Delta\Gamma}\sinh(\frac{\Delta\Gamma t}{2})}, \tag{1}$$

where $\Gamma(t)$ represents the time-dependent decay rate of the initial B or $\bar{B}$ meson to the final state f, Δm and $\Delta\Gamma$ are the B meson oscillation frequency and decay width difference respectively, and where the relation $C_f^2 + S_f^2 + A_{\Delta\Gamma}^2 = 1$ holds. With this parameterization, C_f and S_f account for CPV in the decay and in the interference between mixing and decay, respectively, and are related to the elements of the CKM matrix intervening in the decay diagrams.

A crucial experimental aspect in the measurement of C_f and S_f is the determination of the inital flavour of the B meson. The tagging of the inital flavour is performed using both the information from the other b-quark in the event, referred to as opposite side (OS) tagging, as well as the information from kaons and pions associated with the hadronisation of the signal b-quark, referred to as same side (SS) tagging.

2. – Measurement of ϕ_s using $B_s^0 \to J/\psi K^+K^-$ and $B_s^0 \to J/\psi\pi^+\pi^-$ decays

The decays governed by $b \to c\bar{c}s$ transitions are referred to as "golden modes" for the determination of ϕ_s, since subleading corrections from penguin amplitudes in these processes are expected to be very small. Neglecting penguins, the term C_f equals zero, and S_f is equal to $\sin(-2\beta_s)$ (where $-2\beta_s \equiv \phi_s$). Exploiting the full sample collected during Run 1, LHCb reconstructed 27100 ± 200 $B_s^0 \to J/\psi\pi^+\pi^-$ decays and 95690 ± 350 $B_s^0 \to J/\psi K^+K^-$ decays. The J/ψ vector meson is reconstructed using the decay $J/\psi \to \mu^+\mu^-$ in both analyses. The $B_s^0 \to J/\psi K^+K^-$ decay proceeds predominantly via the $B_s^0 \to J/\psi\phi$, with $\phi \to K^+K^-$, hence the final state is a superposition of CP-even and CP-odd states. Since the measurement of ϕ_s requires to disentangle the two CP states, an angular analysis of the final products of the decay is necessary in order to determine the relative orbital angular momentum of the J/ψ and ϕ mesons. Hence the value of ϕ_s is extracted from data by means of a simultaneous fit to the tagged decay time and 3 helicity angles spectra of background subtracted signal candidates. The initial flavour of the B meson is determined using both OS and SS tagging techniques, achieving an effective tagging power of $(3.73 \pm 0.15)\%$. A further complication arises from the fact that the $J/\psi K^+K^-$ final state can also be produced the K^+K^- pair in a CP-odd S-wave configuration. The contribution of such a component is determined performing the analysis in 6 bins of the K^+K^- invariant mass. The full fit allows the determination of the width parameters Γ_s and $\Delta\Gamma_s$ of the B_s^0 meson. Final results are $\phi_s^{c\bar{c}s} = -0.058 \pm 0.049(\text{stat.}) \pm 0.006(\text{syst.})$ rad, $\Gamma_s = 0.6603 \pm 0.0027(\text{stat.}) \pm 0.0015(\text{syst.})$ ps^{-1} and $\Delta\Gamma_s = 0.0805 \pm 0.0091(\text{stat.}) \pm 0.0032(\text{syst.})$ ps^{-1} [4].

In the analysis of the $B_s^0 \to J/\psi\pi^+\pi^-$ decays the CP-even and CP-odd components are disentangled by means of an amplitude analysis of the $\pi^+\pi^-$ invariant mass spectrum in conjunction with a full angular analysis of the final state. The model adapted to the $\pi^+\pi^-$ invariant mass spectrum contains 5 resonances: the dominant $f_0(980)$ as well as the $f_0(1500)$, $f_0(1790)$, $f_2(1270)$, and $f_2(1525)$. The $B_s^0 \to J/\psi\pi^+\pi^-$ mode results to be consistent with a fully CP-odd final state, with an estimated CP-even contribution smaller than 2.3% at 90% C.L. Both OS and SS taggers are used to determine the initial flavour of the B_s^0 meson, with an effective tagging power of $(3.89 \pm 0.25)\%$. The

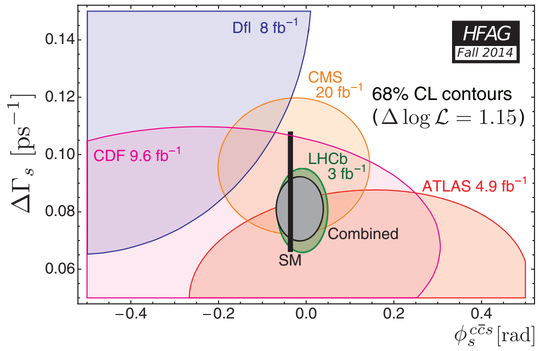

Fig. 1. – Experimental 68% confidence-level contours in the $\phi_s^{c\bar{c}s}$-$\Delta\Gamma_s$ plane. Measurements from ATLAS, CMS, CDF, D0 and LHCb collaborations are reported, together with the combined contour determined by HFAG [6]. The SM prediction is represented by the thin black rectangle.

determination of ϕ_s is achieved with a simulatenous fit to the spectra of the $J/\psi\pi^+\pi^-$ invariant mass, the tagged decay time, the $\pi^+\pi^-$ invariant mass, and 3 helicity angles. The result is $\phi_s^{c\bar{c}s} = 0.070 \pm 0.068(\text{stat.}) \pm 0.008(\text{syst.})$ rad [5]. In fig. 1 the experimental status is summarised in the ϕ_s-$\Delta\Gamma_s$ plane. The result from LHCb, which dominates the world average, is the combination of the two analyses presented in this document and is $\phi_s^{c\bar{c}s} = -0.010 \pm 0.039$ rad.

3. – Measurement of ϕ_d using the $B^0 \to J/\psi K^0_S$ decay

The $B^0 \to J/\psi K^0_S$ decay proceeds through $b \to c\bar{c}s$ transitions analogously to the two decays discussed in the previous section. The same considerations regarding the contributions from subleading penguin amplitudes hold in this case, making this decay the "golden mode" for the determination of $\sin(2\beta)$. In the SM and assuming $C_f = 0$ the term S_f of eq. (1) is $S_f = \sin(2\beta)$ (where $2\beta \equiv \phi_d$). Neutral kaons are reconstructed using the decay $K^0_S \to \pi^+\pi^-$ in two different ways: "long-long" K^0_S are reconstructed from pairs of pions with hits in the vertex detector, while "down-down" K^0_S are reconstructed from pairs of pions without hits in the vertex detector. Using the full sample of p-p collisions collected during Run 1 LHCb reconstructed 41560 ± 270 tagged $B^0 \to J/\psi K^0_S$ decays. Both OS and SS taggers are used to determine the inital flavour of B^0 candidates. The CPV terms are determined from data by means of a simultaneous fit to the invariant mass and tagged decay time spectra of the reconstructed candidates. The results are: $S_f = 0.731 \pm 0.035(\text{stat.}) \pm 0.020(\text{syst.})$ and $C_f = -0.038 \pm 0.032(\text{stat.}) \pm 0.005(\text{syst.})$ [7]. Fixing $C_f = 0$ the fit returns $S_f = \sin(2\beta) = 0.746 \pm 0.030(\text{stat.})$. This is the most precise time-dependent CPV measurement at a hadron collider to date.

4. – Constraints to hadronic uncertainties in $b \to c\bar{c}s$ transitions

Due to improving precision of the measurements, constraining the contributions from subleading penguin amplitudes to these decays is becoming increasingly important in the determination of the B^0 and B^0_s mixing phases. A common strategy used to constrain the effect of penguin pollution is to measure the time-dependent CP asymmetries in decays where the contributions of such diagrams are enhanced. Using the data sample collected during Run 1 LHCb reconstructed 17650 ± 200 $B^0 \to J/\psi\pi^+\pi^-$ decays. The same analysis performed on $B_s^0 \to J/\psi\pi^+\pi^-$ decays is used. From the amplitude analysis of the $\pi^+\pi^-$ invariant mass spectrum, the contribution of the dominant $B^0 \to J/\psi\rho^0$ decays has been extracted. Using the time-dependent CP asymmetry of this decay and assuming the validity of U-spin symmetry (*i.e.* the invariance of strong interactions under the quark exchange $s \leftrightarrow d$), a constraint on the effect of penguin amplitudes on the determination of ϕ_s from $B_s^0 \to J/\psi\phi$ decays has been evaluated: $\Delta\phi_s = 0.0009 \pm 0.0098$ rad [8]. The uncertainty on the extracted value of $\Delta\phi_s$ is small if compared with the current precision on ϕ_s, but will have to become more precise as the measurements improve.

Analysing the full data sample of Run 1 LHCb reconstructed 908 ± 36 $B_s^0 \to J/\psi K_S^0$ decays (summing together the K_S^0 reconstructed as "long-long" and "down-down"). The time-dependent CP asymmetry of this decay has been measured following the same strategy used for the $B^0 \to J/\psi K_s^0$ decay. Numerical results are: $C_f = -0.28 \pm 0.41(\text{stat.}) \pm 0.08(\text{syst.})$, $S_f = -0.08 \pm 0.40(\text{stat.}) \pm 0.08(\text{syst.})$ and $A_{\Delta\Gamma} = 0.49^{+0.77}_{-0.65}(\text{stat.}) \pm 0.06(\text{syst.})$ [9]. For the moment, the large statistical uncertainties provide very weak constraints on the effect of penguin amplitudes in the determination of ϕ_d.

5. – Measurement of the flavour specific semileptonic asymmetry a_{sl}^d

Using the full sample collected during Run 1, LHCb measured the flavour-specific semileptonic asymmetry a_{sl}^d, that is proportional to the phase responsible of CPV in the mixing ϕ_d^{12}. LHCb reconstructed semileptonic B^0 decays using the $D^-\mu^+$ and $D^{*-}\mu^+$ final states, with $D^- \to K^+\pi^-\pi^-$ and $D^{*-} \to \bar{D}^0(\to K^+\pi^-)\pi^-$. Fitting simultanously the number of observed charge conjugate final states as a function of the decay time, it is possible to extract the value of a_{sl}^d. This technique is particularly useful at hadronic machines, since it does not require to determine the initial flavour of the B^0 meson. The result is $a_{sl}^d = (-0.02 \pm 0.19(\text{stat.}) \pm 0.30(\text{syst.}))\%$ [10], that is the most precise measurement to date of this quantity.

6. – Measurements of ϕ_s using charmless decays

Charmless B decays provide an important complementary tool with respect to decays governed by $b \to c\bar{c}s$ transitions in the search for NP. These decays are dominated by penguin transitions, where new particles not present in the SM may appear. Any discrepancy between the CPV phases determined from charmless decays and from $b \to c\bar{c}s$ transitions may reveal the presence of NP. Using the full sample of p-p collisions collected during Run 1, LHCb measured the B_s^0 mixing phase in $B_s^0 \to \phi(K^+K^-)\phi(K^+K^-)$ decays, that occur only through $b \to s\bar{s}s$ loop transitions. Since the final state contains two vector mesons, in order to disentangle the CP-even and CP-odd components, a full angular analysis is required as for the $B_s^0 \to J/\psi K^+K^-$ decay. The value of ϕ_s is determined from a simultaneous fit to the tagged decay time and 3 helicity angles of background subtracted signal candidates. The initial falvour of the B_s^0 is determined using both OS and SS taggers. The result is $\phi_s^{s\bar{s}s} = -0.17 \pm 0.15(\text{stat.}) \pm 0.03(\text{syst.})$ rad [11], in agreement with the SM and with the measurements from $b \to c\bar{c}s$ transitions.

Another analysis that allows the determination of ϕ_s relies on the measurements of the time-dependent CP asymmetries in the $B^0 \to \pi^+\pi^-$ and $B_s \to K^+K^-$ decays. The measurement is based on the sample collected by LHCb during 2011, where the CP asymmetries are extracted from a 2-dimensional fit to the invariant mass and tagged decay time spectra [12]. In order to extract ϕ_s (as well as the CKM phase γ) a Bayesian analysis has been performed, combining the measurements of the time-dependent CP asymmetries and the branching ratios of the $B^0 \to \pi^+\pi^-$ and $B_s \to K^+K^-$ decays with the measurement of other two-body charmless B decays. The method assumes also the validity of the U-spin and isospin symmetries. The dependence of the stability of ϕ_s and γ against various levels of U-spin breaking has been studied. Numerical results, considering up to 50% non-factorisable U-spin breaking contributions, are $\phi_s = -0.12^{+0.14}_{-0.16}$ rad and $\gamma = (63.5^{+7.2}_{-6.7})^\circ$ [13]. The results are compatible with the SM and with the measurements of the same quantities from decays dominated by tree-level transitions.

7. – Conclusions

We have presented the most recent measurements of time-dependent CPV performed by the LHCb experiment. The results here shown comprise the measurement of ϕ_s, using $B_s^0 \to J/\psi K^+K^-$ and $B_s^0 \to J/\psi\pi^+\pi^-$ decays, and that of ϕ_d using the $B^0 \to J/\psi K_S^0$ decay. Studies of the influence of penguin pollution to these determinations have been performed measuring time-dependent CPV in $B^0 \to J/\psi\pi^+\pi^-$ and $B_s^0 \to J/\psi K_S^0$ decays. The B_s^0 mixing phase has been also measured using charmless B decays where the contribution of loop diagrams is large. The analysis of the $B_s^0 \to \phi\phi$ decays and of two-body charmless B decays revealed so far no discrepancies with respect to the measurements performed using decays dominated by tree-level transitions. Finally, we have presented the measurement of the semileptonic asymmetry a_{sl}^d. No evidence of discrepancies with respect to the SM prediction is observed.

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