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Measurements of CP violation in neutral B mesons at LHCb

N. Belloli([1])([2])

([1]) *INFN, Sezione di Milano Bicocca - Milano, Italy*
([2]) *Dipartimento di Fisica, Università degli Studi di Milano Bicocca - Milano, Italy*

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Summary. — During 2011 and 2012 the LHCb detector collected data coming from proton-proton collision corresponding to an integrated luminosity of $1\,\mathrm{fb}^{-1}$ at a center-of-mass energy of $7\,\mathrm{TeV}$ and $2\,\mathrm{fb}^{-1}$ at a center-of-mass energy of $8\,\mathrm{TeV}$, respectively. Using this data sample LHCb can measure with an unprecedented precision the parameters associated to the CKM matrix. In the neutral B meson system, CP violation is induced from the interference of decay with or without mixing, with possible implications in the search for physics beyond the Standard Model. Recent results obtained by LHCb Collaboration are presented, which give access to the β and ϕ_s parameters, in particular the analysis of the decays $B^0 \to J/\psi K^0_s$, $B^0_s \to J/\psi K^+K^-$ and $B^0_s \to J/\psi \pi^+\pi^-$. Finally the first LHCb measurements of CP violation in the channels $B^0 \to D^+D^-$ and $B^0_s \to D^+_s K^-$ are presented.

1. – Introduction

One of the main goal of the LHCb experiment [1] at CERN's Large Hadron Collider (LHC) is the precision measurement of CP violation observables in decays of mesons containing b quarks. The comparison of these measurements with predictions from the Standard Model (SM) of particle physics tests the model itself and can reveal the presence of contributions from physics Beyond the Standard Model. This contribution illustrates LHCb measurements of CP-violating observables. All the measurements discussed were performed using Run I data samples, corresponding to an integrated luminosity of $3\,\mathrm{fb}^{-1}$. In the SM the Cabibbo-Kobayashi-Maskawa (CKM) quark mixing matrix [2, 3], parametrizes transitions between the three quark families in charge current interactions. It is described by four independent parameters, namely three real rotation angles and one complex phase. A value for this phase which is different form zero can induce CP-violating asymmetries in processes in which two or more amplitudes with different weak phases interfere. Precision measurement of such asymmetries can test the SM predictions and hint at the underlying dynamics of BSM physics. The CKM mechanism gives rise to three possible sources of CP violation asymmetries:

- *CP violation in decay* is caused when, considering a flavor specific final state, a difference exists between a process and its CP conjugate

- *CP violation in mixing* is caused when mass eigenstates are different with respect to *CP* eigenstates

- *CP violation in interference* is caused when, considering a *CP* final state, an interference occurs between the decay with or without mixing.

2. – Measurement of $\sin(2\beta)$ in $B^0 \to J/\psi K_s^0$

In the "golden" mode $B^0 \to J/\psi K_s^0$ the final state is common to both the B^0 and the $\bar{B}^0$ meson decays, so the interference between the amplitudes for the direct decay and for the decay after B^0-$\bar{B}^0$ oscillation results in a decay-time–dependent *CP* asymmetry between the time-dependent decay rates of B^0 and $\bar{B}^0$ mesons. Through the measurement of this asymmetry, two *CP* observables can be obtained, one related to direct *CP* violation C and one to the *CP* violation in interference S. Since the $B^0 \to J/\psi K_s^0$ decay is dominated by a $b \to \bar{c}cs$ transition, *CP* violation in decay is expected to be negligible at the current level of experimental precision, allowing to identify the parameter S with $\sin(2\beta)$, where β is one of the angles of the CKM triangle. The analysis is performed with $B^0 \to J/\psi K_s^0$ candidates reconstructed in the $J/\psi \to \mu^+\mu^-$ and $K_s^0 \to \pi^+\pi^-$ final states. This measure requires knowledge of the initial flavor of each reconstructed B^0 meson. To infer this piece of information a combination of algorithms, namely the opposite-side (OS) and same-side pion (SSπ), are used [4-6], after being calibrated on the flavor specific control channels $B^+ \to J/\psi K^+$ and $B^0 \to J/\psi K^{*0}$, respectively. The *CP* observables obtained from a decay-time-dependent fit on signal tagged events are measured to be $S = 0.731 \pm 0.035(\text{stat.}) \pm 0.020(\text{syst.})$ and $C = -0.038 \pm 0.032(\text{stat.}) \pm 0.005(\text{syst.})$ [7]. This result has a similar precision to, and is in good agreement with previous measurement performed by BaBar and Belle [8, 9].

3. – Measurement of *CP* violation in $B^0 \to D^+D^-$

In the decay $B^0 \to D^+D^-$, *CP* violation is caused by the interference between the direct decay into *CP*-even final state D^+D^- and the decay to the same final state with or without B^0-$\bar{B}^0$ mixing. The two *CP* observables S and C that describe this violation are related to the B^0 mixing phase ϕ_d and a phase shift $\Delta\phi_d$ from the decay amplitude via $S/\sqrt{1-C^2} = -\sin(\phi_d + \Delta\phi_d)$. In the SM at tree-level $\phi_d = 2\beta$, where β is an angle of the unitary triangle, while $\Delta\phi_d$ represents the contribution from higher-order standard model corrections. The measurement of the decay-time–dependent decay rate gives access to *CP* observables. Two classes of flavor tagging algorithms are used: OS and a combination of same-side proton (SSp) and same-side pion taggers [10]. These algorithms are calibrated using a flavor specific channel, namely $B^0 \to D_s^+ D^-$. The effective tagging efficiency, which represents the statistical reduction factor in a tagged analysis, results to be $\epsilon_{\text{eff}} = (8.1 \pm 0.6)\%$, the highest to date in tagged *CP* violation measurement at LHCb. From a decay-time–dependent fit on signal tagged candidates, the *CP* observables are measured to be $S = -0.54^{+0.17}_{-0.16}(\text{stat.}) \pm 0.05(\text{syst.})$ and $C = 0.26^{+0.18}_{-0.17}(\text{stat.}) \pm 0.02(\text{syst.})$ [11]. This result excludes the conservation of *CP* symmetry by 4.0 standard deviations. Combining this result with the one obtained in $B^0 \to J/\psi K_s^0$ for the phase ϕ_d the value of the phase shift can be constrained to $\Delta\phi_d = -0.16^{+0.19}_{-0.21}$ rad, thus implying only a small contribution from higher-order standard model corrections.

4. – Measurement of the phase ϕ_s from $B_s^0 \to J/\psi K^+K^-(\pi^+\pi^-)$

The final state $J/\psi K^+K^-$ is accessible to the decay of both B_s^0 and $\bar{B}_s^0$. The interference between the decay amplitudes and the mixing amplitude can give rise to a *CP*-violating phase ϕ_s. The precise prediction for ϕ_s coming from SM makes this measurement sensitive to possible contributions from BSM physics in B_s^0-$\bar{B}_s^0$ mixing. A time-dependent angular analysis for the four final state particles is required to separate *CP* odd and *CP* even contributions. The initial flavor of the beauty meson at the time of its production is derived using a combination of OS and same-side kaon (SSk) tagging algorithms. The combination of this measurement [12] with an earlier LHCb measurement of ϕ_s using the decay mode $B_s^0 \to J/\psi\pi^+\pi^-$ [13] yielded $\phi_s = -0.010 \pm 0.039$ rad. This is the most precise measurement from a single experiment to date and it is in excellent agreement with SM predictions.

5. – Measurement of *CP*y violation in $B_s^0 \to D_s^+K^-$

CP violation in the decay $B_s^0 \to D_s^+K^-$ occurs due to the interference of mixing and decay amplitudes. The *CP*-violating observables are related to the weak phase $(\gamma + \phi_s)$, where γ represents the least-well known angle of the CKM matrix. A comparison between the value of the CKM angle γ measured from tree-level decays and the CKM parameters measured in loop-level provides a consistency check of the SM. The measurement of the decay-time–dependent rates for the four possible configurations of B-flavor and final state gives access to the *CP*-violating observables. A simultaneous fit in the B_s^0 mass, the D_s^- mass and the log-likelihood difference between pion and kaon hypothesis for the companion particle is used to separate signal from background events. To derive the initial flavor of B mesons, a combination of two flavor-tagging algorithms are used, namely OS and SS, which are calibrated using the control channel $B_s^0 \to D_s^-\pi^+$. Constraining the value of ϕ_s in the weak phase $(\gamma+\phi_s)$, to the LHCb measurement $\phi_s = -0.010\pm0.039$ rad, it is possible to obtain the value for $\gamma = (127^{+17}_{-22})^\circ$ (68.3% CL) [14]. This result is compatible with the γ combination obtained from other LHCb measurements excluding the $B_s^0 \to D_s^+K^-$ one.

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