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CP violation in B hadron 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 CP violation measurements in B hadron decays, performed by LHCb using the data sample collected during 2011 and 2012.

PACS 12.15.Hh – Determination of Cabibbo-Kobayashi & Maskawa (CKM) matrix.
PACS 13.25.Hw – Decays of bottom mesons.

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]. This mechanism generates CP violation 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. Despite its success in exaplaining the current experimental data, the CKM paradigm is not sufficient to generate the imbalance between matter and anti-matter observed in the Universe. Consequently, additional sources of CP violation are required. The study of B-hadron decays is one of the most promising way to probe the validity of the SM and to search for New Physics. On the one hand, the precise determination of the CKM matrix elements, using measurements of CP violation in decays dominated by tree-level transitions, allows for stringent test of the SM. On the other hand, new particles beyond the SM may enter loop-mediated processes, leading to discrepancies of the CP violation observables with respect to their SM expectation. The LHCb experiment [2] has been designed specifically to perform very precise measurements of CP violation observables in B hadron decays, exploiting the large cross-section of b quark production in p-p collisions at the LHC. In this document we report some of the most recent and most relevant measurements in this sector, performed by LHCb using the data 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.

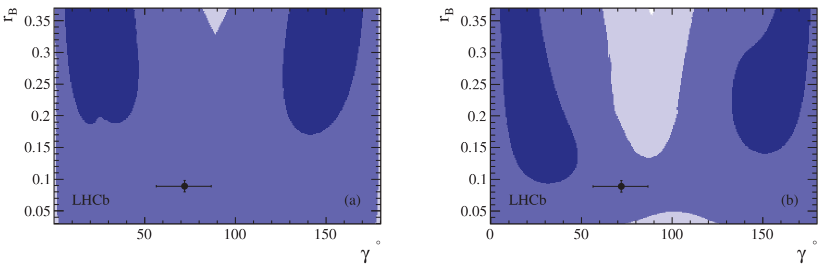

Fig. 1. – Scans of the χ^2 probabilities over the γ-r_B parameter space for the full analysis of $B^+ \to \left[K^0_S K^+ \pi^-\right]_{D^0} h^+$ decays (left) and for the analysis restricted to the $K^{*0} \to K^+\pi^-$ region of the $K^0_S K^+\pi^-$ Dalitz plane. The contours represent the 1σ (dark blue), 2σ (medium blue), and 3σ (light blue) regions.

2. – Determination of the angle γ of the Unitary Triangle

The Unitary Triangle (UT) is the graphical representation of one of the six unitary conditions of the CKM matrix. The measurement of direct CP asymmetries in $B^+ \to D^0 h^+$([1]) (where $h = K, \pi$) allows the precise determination of the angle γ of the UT. Since the $B^+ \to D^0 h^+$ decays are governed by tree-level processes, the determination of γ from these decays is free from both theoretical uncertainties and possible contribution of new physics, providing an unvaluable tool to probe the SM. The strategy for the measurement of direct CP violation at LHCb is in common among all the analyses presented in this document. Firstly a raw asymmetry is determined by means of fits to the invariant mass spectra of the CP-conjugate final states of the decays. Then two kind of corrections have to be applied in order to extract the actual CP asymmetry: a correction due to the detection asymmetry A_{D}, introduced by the different reconstruction efficiencies of the two charge-conjugate final states, and a correction due to the asymmetry in the production rate of B and $\bar{B}$ mesons (A_{P}). For $B^+ \to D^0 h^+$ decays the natural control sample used to determine A_{D} and A_{P} is provided by $B^+ \to J/\psi h^+$ decays. Three methods can be used to extract γ from $B^+ \to D^0\pi^+$ decays [3]: the GLW method, where the D^0 meson decays to CP-eigenstates; the ADS method, where the D^0 meson decays to almost flavour-specific final states; the GGSZ method, where the D^0 meson decays to $K^0_S h^+ h^-$ final states and an analysis over the Dalitz plane of the D^0 is necessary to extract the angle γ. During 2013 LHCb has published a preliminary combination of the measurements involving $B^+ \to D^0 h^+$ decays: results from the GLW and ADS method are based on 2011 data and consider the decays of the D^0 meson to the K^+K^-, $\pi^+\pi^-$, $K^-\pi^+$ and $K^+\pi^-\pi^+\pi^-$ final states; results from the GGSZ method are based on measurements performed on the full sample collected during 2011 and 2012. The combination of all the measurements has been performed using a frequentist analysis and the extracted value corresponds to $\gamma = (67 \pm 12)^\circ$ at 68% CL [4]. More recently LHCb published the determination of γ using $B^+ \to D^0 h^+$ decays where the D^0 meson decays to the $K^0_S K^+\pi^-$ final states. This analysis follows the ADS method, and exploits also the variation of sensitivity on γ over the Dalitz plane of the D^0 meson. The analysis is performed on the full data sample collected during 2011 and 2012. In fig. 1 we report the obtained countour plot with the 1σ, 2σ, and

([1]) Throughout this document the charge conjugation is implied unless explicitly stated.

3σ regions in the γ-r_B plane. On the left the determination over the entire Dalitz plane of the D^0 is reported, while on the right only the region around the $K^{*0}(892) \to K^+\pi^-$ resonance (where the sensitivity on γ is at its maximum) is used to draw the countours [5].

3. – Direct CP violation in B hadron decays dominated by loop diagrams

The contribute of loop topologies to the decay amplitudes can be either a powerful resource either a limitation. In fact, even if new particles beyond the SM may appear in the loops, these topologies introduce theoretical uncertainties, due to QCD interactions between quarks, in the interpretation of the CP violation observables.

Of particular interest is the measurement of the direct CP asymmetries of the $B^0 \to K^+\pi^-$ and $B_s^0 \to \pi^+K^-$ decays, using the data collected during 2011. The production asymmetry is determined directly from data measuring the untagged time-dependent asymmetry of the signals. The correction due to detection asymmetry is extracted from D^*-tagged $D^0 \to K^-\pi^+$ and $D^0 \to K^+K^-$ decays, and untagged $D^0 \to K^-\pi^+$ decays. The final results are $A_{CP}\left(B^0 \to K^+\pi^-\right) = -0.080 \pm 0.007 \pm 0.003$, representing the most precise measurement of this quantity, and $A_{CP}\left(B_s^0 \to \pi^+K^-\right) = 0.27 \pm 0.04 \pm 0.01$ representing the first observation of CP violation in the decays of B_s^0 meson with a significance of more than 5σ [6].

B hadron decays governed by $b \to s\bar{s}s$ transitions are governed only by loop diagrams, thus they can be largely affected by new physics. LHCb performed the measurement of the direct CP asymmetry of the $B^0 \to \phi(K^+K^-)K^{*0}(K^+\pi^-)$ and $B^+ \to \phi(K^+K^-)K^+$ decays using the data collected during 2011. Detection and production asymmetries are determined from the raw asymmetries of $B^0 \to J/\psi K^{*0}$ and $B^+ \to J/\psi K^+$ decays, respectively. Numerical results are $A_{CP}\left(B^0 \to \phi K^{*0}\right) = (1.5 \pm 3.2 \pm 0.5)\%$ [7] and $A_{CP}\left(B^+ \to \phi K^+\right) = (2.2 \pm 2.1 \pm 0.9)\%$ [8], respectively. Both results improved the precision by approximately a factor two with respect to previous world average. In the case of $B^0 \to \phi K^{*0}$, also an amplitude analysis has been performed. With a simulteneous fit to the background subtracted distributions of three helicity angles, K^+K^- invaraint mass spectrum and $K^+\pi^-$ invariant mass spectrum, also the polarization fractions of the $B^0 \to \phi K^{*0}$ decay has been determined. In the model the P-wave and S-wave contributions to the K^+K^- state and to the $K^+\pi^-$ state have been considered. The longitudinal polarization fraction is measured to be $f_{\rm L} = 0.497 \pm 0.019 \pm 0.015$, while the perpendicular polarization fraction is measured to be $f_\perp = 0.221 \pm 0.016 \pm 0.013$ [7]. From the analysis of the $B^+ \to \phi K^+$ decays, performing a simultaenous fit to the ϕK^+ and $\phi\pi^+$ invariant mass spectra, also an upper limit on the branching fraction of the very suppressed $B^+ \to \phi\pi^+$ decay has been established: $BR\left(B^+ \to \phi\pi^+\right) < 1.5(1.8) \times 10^{-7}$ at 68% (95%) of CL.

The last measurement of direct CP violation we present is the first evidence of CP violation in charmless three body decays observed by LHCb in the $B^+ \to h^+h^-\pi^+$ decays. The analysis is based on the 2011 data sample, the pion detection asymmetry has been determined using $D_s^+ \to K^+K^-\pi^+$ decays, while the B^+ production asymmetry is determined studying the $B^+ \to J/\psi K^+$ decays. The observed CP asymmetries are $A_{CP}\left(B^+ \to K^+K^-\pi^+\right) = -0.141 \pm 0.040 \pm 0.018 \pm 0.007$ and $A_{CP}\left(B^+ \to \pi^+\pi^-\pi^+\right) = 0.177 \pm 0.021 \pm 0.009 \pm 0.007$ (where the last error represent the error coming from the world average of the CP asymmetry in $B^+ \to J/\psi K^+$ decays) [9]. The significance of a deviation of the two measurements from the absence of CP violation is of 3.2σ and a 4.9σ, respectively. The measurements have been performed also in different regions of the Dalitz plane. Large asymmetries, with opposite sign for the two decays and not

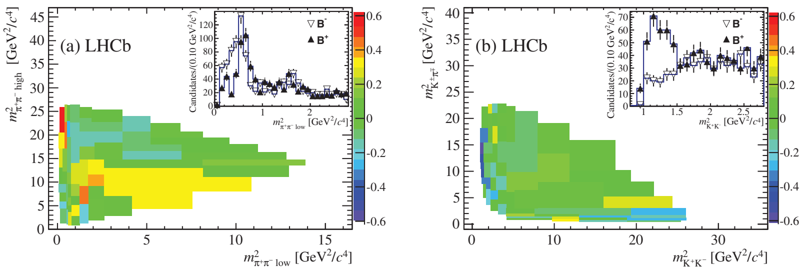

Fig. 2. – Asymmetries of the number of events (including signal and background, not corrected for efficiency) in bins of the Dalitz plot for $B^+ \to \pi^+\pi^-\pi^+$ (left) and $B^+ \to K^+K^-\pi^+$ (right). The inset figures show the projections of the number of events in bins of $m^2_{\pi^+\pi^-}$ for $m^2_{\pi^+\pi^-} < 15\,\mathrm{GeV}^2/c^4$ (left) and in bins of $m^2_{K^+K^-}$ (right).

associated with any resonance, have been observed in the low $\pi^+\pi^-$ invariant mass region and in the low K^+K^- invariant mass region, as evidenced in fig. 2.

4. – CP violation in the $B^0_s - \bar{B}^0_s$ mixing

The oscillation of neutral B mesons between their particle and anti-particle states are sensitive probe of new physics, since the process is governed by second order box diagrams. The semileptonic asymmetry $a^{\mathrm{s}}_{\mathrm{sl}} \equiv [\Gamma(\bar{B}(t) \to f) - \Gamma(B(t) \to \bar{f})]/[\Gamma(\bar{B}(t) \to f) + \Gamma(B(t) \to \bar{f})] \approx \frac{\Delta\Gamma}{\Delta M} \tan\phi_{12}$ contains information on the complex phase ϕ_{12} entering the mixing process ($f = D^-_s\mu^+\nu_\mu$, $\bar{f} = D^+_s\mu^-\bar{\nu}_\mu$, $\Delta\Gamma$ and ΔM are the decay width difference and the mass difference between the two mass eigenstates of the B meson, respectively). Experimentally LHCb, using the data collected during 2011, measured the quantity $A_{\mathrm{meas.}} = [\Gamma(D^-_s\mu^+) - \Gamma(D^+_s\mu^-)]/[\Gamma(D^-_s\mu^+) + \Gamma(D^+_s\mu^-)]$, counting the $D^+_s \to K^+K^-\pi^+$ decays that can be associated with an oppositely charged muon. $A_{\mathrm{meas.}}$ is related to a_{sl} by the relation $A_{\mathrm{meas.}} = a^{\mathrm{s}}_{\mathrm{sl}}/2 + \kappa[A_{\mathrm{P}} - a^{\mathrm{s}}_{\mathrm{sl}}/2]$, where the factor $\kappa \approx 0.2\%$ (related to the time evolution of the B^0_s meson) makes negligible the correction factor containing the production asymmetry A_{P}. The corrections to apply are the detection asymmetry of the $\pi^-\mu^+$ pair and the constribution of the background coming from true D^+_s decays associated with random muons. The final result is $a^{\mathrm{s}}_{\mathrm{sl}} = (-0.06 \pm 0.50 \pm 0.36)\%$ [10], compatible with the previous results obtained by other experiments and with the SM expectation.

5. – CP violation in the interference between mixing and decay

When a B hadron decays to a CP-eigenstate final state f, CP violation may manifest thanks to the non-zero difference between the complex phase appearing in the decay amplitudes and the complex phase appearing in the mixing amplitudes. In this case we refer to mixing-induced CP violation. The CP violation observable is the time-dependent CP asymmetry defined as $A_{CP}(t) \equiv [\Gamma(\bar{B}(t) \to f) - \Gamma(B(t) \to f)]/[\Gamma(\bar{B}(t) \to f) + \Gamma(B(t) \to f)] = [S_f \sin\Delta Mt - C_f \sin\Delta Mt]/[\cosh\frac{\Delta\Gamma t}{2} + A_{\Delta\Gamma}\sinh\frac{\Delta\Gamma t}{2}]$, where the C_f and S_f coefficients account for CP violation in the decay and in the interference between mixing and decay, respectively. The crucial aspect of the measurements of this time-dependent asymmetry is the determination of the initial flavour of the signal B meson (the so-called "flavour tagging"). It is obtained using a multivariate algorithm that analyses the underlying event.

Using the data collected during 2011 LHCb measured the C_f and S_f coefficients of the $B_s^0 \to K^+K^-$ and $B^0 \to \pi^+\pi^-$ decays [11]: $C_{KK} = 0.14 \pm 0.11 \pm 0.03$, $S_{KK} = 0.30 \pm 0.12 \pm 0.04$ (with a statistical correlation coefficient of 0.02); $C_{\pi\pi} = -0.38 \pm 0.15 \pm 0.02$, $S_{\pi\pi} = -0.71 \pm 0.13 \pm 0.02$ (with a statistical correlation coefficient of 0.38). These measurements are of particular interest, since they have been used (combined with other quantities of $B^+ \to \pi^+\pi^0$ and $B^0 \to \pi^0\pi^0$ decays) in order to determine the angle γ of the UT and the B_s^0 meson mixing phase. The combination has been published in ref. [12] determining $\gamma = (63.5^{+7.2}_{-6.7})^\circ$ and $-2\beta_s = -0.12^{+0.14}_{-0.16}$ rad, at 68% probability.

The S coefficient of the time-dependent CP asymmetry of B_s^0 decays governed by $b \to c\bar{c}s$ transitions is proportional to $\sin\phi_s$. The weak phase ϕ_s is a parameter of primary importance in testing the CKM paradigms. In fact, the theoretical determination of ϕ_s is almost free from uncertainties. Analysing the decays of B_s^0 mesons to $J/\psi K^+K^-$ and $J/\psi\pi^+\pi^-$ final states, reconstructed from the data collected during 2011, LHCb measured $\phi_s(J/\psi K^+K^-) = 0.07 \pm 0.09 \pm 0.01$ rad [13] and $\phi_s(J/\psi\pi^+\pi^-) = -0.14^{+0.17}_{-0.16} \pm 0.01$ rad [14], respectively. The study of the $J/\psi K^+K^-$ final state required a full analysis of the helicity angles, in order to disentangle the CP-even and the CP-odd components in the final state. On the contrary, the $J/\psi\pi^+\pi^-$ final state does not require the full angular analysis. In fact, analysing the $B_s^0 \to J/\psi\pi^+\pi^-$ decays reconstructed using the data sample collected during 2011 and 2012, LHCb found the final state to be compatible with being completely CP-odd [15]. A combination of the two ϕ_s measurements has been also performed obtaining $\phi_s(b \to c\bar{c}s) = 0.01 \pm 0.07 \pm 0.01$ rad [13], that is compatible with the SM predictions.

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