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CP violation and mixing in beauty with LHCb

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Recent results on time-dependent and time-integrated measurements of CP violation and of meson mixing in the beauty sector are presented, along with prospects for future sensitivities. Large asymmetries in Dalitz plot analyses of $B^{\pm} \to \pi^{\pm}K^{-}K^{+}$ and $B^{+} \to \pi^{+}\pi^{-}\pi^{+}$ decays, including the first observation of CP violation involving a tensor state and the first observation of CP violation in a quasi-two-body interference, are reported. The study of $B_s^0 \to VV$ *time dependent analyses* is also summarised, including the most precise measurements of $\phi_s^{c\bar{c}s}$, $\phi_s^{s\bar{s}s}$ and $\phi^{d\bar{d}s}$.

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1. Introduction

The decays of hadrons containing b-quarks are the systems where CP violation (CPV) in the weak interaction is most evident. The first decay in which direct CPV, a difference between the partial widths of a decay and its CP conjugate, was observed in B mesons is $B^0 \to K^+\pi^-$ [1]. The study of CPV in b hadrons established the CKM mechanism as the origin of the broken CP symmetry and led to Makoto Kobayashi and Toshihide Maskawa being awarded half of the 2008 Nobel Prize in Physics.

The LHC is a copious source of b hadrons. The production cross section of $b-\bar{b}$ pairs at the LHC is in the range of $10^5 - 10^6$ nb. Most of these pairs are produced in the forward region. The LHCb spectrometer is designed to accept particles in the $2 \lesssim |\eta| \lesssim 4$ regime maximising the acceptance of the products of b-hadron decays with excellent vertex reconstruction, to distinguish their displaced secondary vertexes, momentum resolution, for optimal invariant mass reconstruction, and particle identification. LHCb has published a large number of results of CPV and mixing in b hadrons and a review of all of them would be beyond the scope of these proceedings. The focus here is in two subtopics: *direct CPV in charmless 3-body decays* and $B_s^0 \to VV$ *time dependent analyses*. Other recent and very relevant results, such as the first observation of direct CPV in a charmless $B^0 \to VV$ decay [2], or the measurements of CP observables in the $B^0 \to DK^{*0}$ decay [3], including the γ angle, initially contemplated in the presentation, are mentioned for the interested reader to consult the corresponding LHCb publications.

2. Direct CPV in 3-body decays

Charged B meson decays only manifest direct CPV. The decays of charged B mesons into three charmless charged mesons (either kaons or pions) is a field of great interest since in 2012 LHCb observed, in the analysis of 3 fb^{-1} pp collisions, large CP asymmetries in a Dalitz Plot analysis [4]. These asymmetries were not uniformly distributed in phase space and concentrated mainly in the two-body invariant mass region $1.0 < m(h^+h^-) < 1.5$ GeV/c^2. This effect could be explained by long-distance $\pi^+\pi^- \leftrightarrow K^+K^-$ rescattering. Detailed amplitude analyses have been recently published of the $B^\pm \to \pi^\pm K^- K^+$ decay and the $B^\pm \to \pi^\pm\pi^-\pi^+$ decay and are discussed below.

2.1 Amplitude analysis of $B^\pm \to \pi^\pm K^- K^+$ decays

A Dalitz Plot analysis of $B^\pm \to \pi^\pm K^- K^+$ decays with the 3 fb^{-1} data sample of LHC Run-I was completed by LHCb [5]. B meson candidates are reconstructed by requiring three charged tracks forming a good-quality secondary vertex significantly separated from the primary pp vertex. Mass vetoes are applied to remove contributions from two-body D^0 meson decays. Particle identification criteria are used to reduce the crossfeed from other b-hadron decays. The selection is completed with a multivariate boosted decision tree (BDT) whose selection requirement is chosen to maximise the signal significance. Selected candidates are the object of a three-body mass fit to obtain B^+ and B^- yields in the $5.266 < m(\pi^\pm K^+ K^-) < 5.300$ GeV/c^2 region, estimated to be 2052 ± 102 and 1566 ± 84, respectively. A production charge asymmetry of 3.1% is accounted for in the analysis.

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The events in the aforementioned mass window are the object of an amplitude analysis that employs the isobar model. The amplitude of the process is parameterised as

$$\mathscr{A}(m^2_{\pi^+K^-}, m^2_{K^+K^-}) = \sum_{i=1}^{N} c_i \mathscr{M}_{R_i}(m^2_{\pi^+K^-}, m^2_{K^+K^-}), \tag{2.1}$$

where c_i are complex coefficients and $\mathscr{M}_{R_i}(m^2_{\pi^+K^-}, m^2_{K^+K^-})$ are amplitudes for the i-th intermediate state. The B^- sample is fitted with independent coefficients, $\bar{c}_i$, and the complex conjugate amplitudes $\bar{\mathscr{M}}_{R_i}$. From the results of the two Dalitz Plots the asymmetries (A_{CP}) and fit fractions (FF_i) are obtained as,

$$A_{CPi} = \frac{|\bar{c}_i|^2 - |c_i|^2}{|\bar{c}_i|^2 + |c_i|^2}, \tag{2.2}$$

$$FF_i = \frac{\int \left(|c_i \mathscr{M}_i|^2 + |\bar{c}_i \bar{\mathscr{M}}_i|^2\right) \mathrm{d}m^2_{\pi^\pm K^\mp} \mathrm{d}m^2_{K^+K^-}}{\int \left(|\mathscr{A}_i|^2 + |\bar{\mathscr{A}}_i|^2\right) \mathrm{d}m^2_{\pi^\pm K^\mp} \mathrm{d}m^2_{K^+K^-}}. \tag{2.3}$$

A total of seven contributions are considered in the model of equation 2.1. Three of them in the $\pi^\pm K^\mp$ system: a non-resonant amplitude involving a single-pole form factor and $K^*(892)^0$ and $K_0^*(1430)^0$ contributions. Other four correspond to the K^+K^- system: a dedicated amplitude accounting for the $\pi^+\pi^- \leftrightarrow K^+K^-$ rescattering, along with $\phi(1020)$, $\rho(1450)^0$, $f_2(1270)$ resonances. Additional contributions have not shown to improve the fit agreement with data and their possible appearance is considered among the systematic uncertainties.

The results of the fit are shown in table 1, where two main conclusions can be drawn: first, the main contributions are the non-resonant single pole $B^+ \to (\pi^\pm K^\mp)K^+$ and the $B^+ \to \rho^0(1450)\pi^+$, and second, there is a large CP asymmetry in the K^+K^- rescattering contribution of as much as 66%. These results are in agreement with the inclusive CP asymmetry of (-12.3 ± 2.1)% reported in [4].

Table 1: Results of the $B^\pm \to \pi^\pm K^- K^+$ Dalitz plot analysis. The first uncertainty is statistical and the second systematic.

Contribution	Fit Fraction(%)	A_{CP}(%)
$K^*(892)^0$	$7.5 \pm 0.6 \pm 0.5$	$+12.3 \pm 8.7 \pm 4.5$
$K_0^*(1430)^0$	$4.5 \pm 0.7 \pm 1.2$	$+10.4 \pm 14.9 \pm 8.8$
Single pole	$32.3 \pm 1.5 \pm 4.1$	$-10.7 \pm 5.3 \pm 3.5$
$\rho(1450)^0$	$30.7 \pm 1.2 \pm 0.9$	$-10.9 \pm 4.4 \pm 2.4$
$f_2(1270)$	$7.5 \pm 0.8 \pm 0.7$	$+26.7 \pm 10.2 \pm 4.8$
Rescattering	$16.4 \pm 0.8 \pm 1.0$	$-66.4 \pm 3.8 \pm 1.9$
$\phi(1020)$	$0.3 \pm 0.1 \pm 0.1$	$+9.8 \pm 43.6 \pm 26.6$

Table 2: Results of the $B^\pm \to \pi^\pm \pi^- \pi^+$ Dalitz plot analysis. The first uncertainty is statistical and the second systematic.

Contribution	Fit fraction (10^{-2})	A_{CP} (10^{-2})	B^+ phase (°)	B^- phase (°)
Isobar model				
$\rho(770)^0$	$55.5 \pm 0.6 \pm 2.5$	$+0.7 \pm 1.1 \pm 1.6$	—	—
$\omega(782)$	$0.50 \pm 0.03 \pm 0.05$	$-4.8 \pm 6.5 \pm 3.8$	$-19 \pm 6 \pm 1$	$+8 \pm 6 \pm 1$
$f_2(1270)$	$9.0 \pm 0.3 \pm 1.5$	$+46.8 \pm 6.1 \pm 4.7$	$+5 \pm 3 \pm 12$	$+53 \pm 2 \pm 12$
$\rho(1450)^0$	$5.2 \pm 0.3 \pm 1.9$	$-12.9 \pm 3.3 \pm 35.9$	$+127 \pm 4 \pm 21$	$+154 \pm 4 \pm 6$
$\rho_3(1690)^0$	$0.5 \pm 0.1 \pm 0.3$	$-80.1 \pm 11.4 \pm 25.3$	$-26 \pm 7 \pm 14$	$-47 \pm 18 \pm 25$
S-wave	$25.4 \pm 0.5 \pm 3.6$	$+14.4 \pm 1.8 \pm 2.1$	—	—
Rescattering	$1.4 \pm 0.1 \pm 0.5$	$+44.7 \pm 8.6 \pm 17.3$	$-35 \pm 6 \pm 10$	$-4 \pm 4 \pm 25$
σ	$25.2 \pm 0.5 \pm 5.0$	$+16.0 \pm 1.7 \pm 2.2$	$+115 \pm 2 \pm 14$	$+179 \pm 1 \pm 95$
K-matrix				
$\rho(770)^0$	$56.5 \pm 0.7 \pm 3.4$	$+4.2 \pm 1.5 \pm 6.4$	—	—
$\omega(782)$	$0.47 \pm 0.04 \pm 0.03$	$-6.2 \pm 8.4 \pm 9.8$	$-15 \pm 6 \pm 4$	$+8 \pm 7 \pm 4$
$f_2(1270)$	$9.3 \pm 0.4 \pm 2.5$	$+42.8 \pm 4.1 \pm 9.1$	$+19 \pm 4 \pm 18$	$+80 \pm 3 \pm 17$
$\rho(1450)^0$	$10.5 \pm 0.7 \pm 4.6$	$+9.0 \pm 6.0 \pm 47.0$	$+155 \pm 5 \pm 29$	$-166 \pm 4 \pm 51$
$\rho_3(1690)^0$	$1.5 \pm 0.1 \pm 0.4$	$-35.7 \pm 10.8 \pm 36.9$	$+19 \pm 8 \pm 34$	$+5 \pm 8 \pm 46$
S-wave	$25.7 \pm 0.6 \pm 3.0$	$+15.8 \pm 2.6 \pm 7.2$	—	—
QMI				
$\rho(770)^0$	$54.8 \pm 1.0 \pm 2.2$	$+4.4 \pm 1.7 \pm 2.8$	—	—
$\omega(782)$	$0.57 \pm 0.10 \pm 0.17$	$-7.9 \pm 16.5 \pm 15.8$	$-25 \pm 6 \pm 27$	$-2 \pm 7 \pm 11$
$f_2(1270)$	$9.6 \pm 0.4 \pm 4.0$	$+37.6 \pm 4.4 \pm 8.0$	$+13 \pm 5 \pm 21$	$+68 \pm 3 \pm 66$
$\rho(1450)^0$	$7.4 \pm 0.5 \pm 4.0$	$-15.5 \pm 7.3 \pm 35.2$	$+147 \pm 7 \pm 152$	$-175 \pm 5 \pm 171$
$\rho_3(1690)^0$	$1.0 \pm 0.1 \pm 0.5$	$-93.2 \pm 6.8 \pm 38.9$	$+8 \pm 10 \pm 24$	$+36 \pm 26 \pm 46$
S-wave	$26.8 \pm 0.7 \pm 2.2$	$+15.0 \pm 2.7 \pm 8.1$	—	—

2.2 Amplitude Analysis of $B^+ \to \pi^+\pi^-\pi^+$ decays

A similar study is performed by LHCb in the Dalitz Plot of $B^+ \to \pi^+\pi^-\pi^+$ decays. The same 3 fb^{-1} Run-I sample is considered [6]. The event selection also vetoes D^0 decays and applies an offline selection with multivariate algorithms to separate the signal from background formed from random combinations of tracks and discriminate from other B decays with misidentified final state particles. A $5.249 < m(\pi^+\pi^-\pi^+) < 5.317$ GeV/c^2 mass window is considered with a combined signal yield of 20600 ± 1600 events.

The amplitude analysis of these events is background subtracted from the $B^+ \to K^+\pi^+\pi^-$ background which is reweighted to a known amplitude model [7]. The analysis is performed in the high and low mass $(\pi^+\pi^-)$ pairs with Bose-symmetry enforced in the model. Again, the isobar approach is considered except for the S-wave contribution. Six contributions are considered: a double $\rho(770)^0 - \omega(782)$ term, $f_2(1270)$, $\rho(1450)^0$, $\rho_3(1690)^0$ resonances and the S-wave. For the S-wave three alternative approaches were considered: first, an Isobar model, including a rescattering component and a pole for the $f_0(500)$. Second, the K-matrix approach, considering overlapping S-wave states: $f_0(500)$, $f_0(980)$, $f_0(1370)$, $f_0(1500)$, $f_0(1710)$. This approach is unitary by construction and takes into account all open channels. Third and finally, a Quasi-Model-Independent (QMI) approach that fits the magnitude and phase of the S-wave in regions of the Dalitz Plot.

The results of the amplitude analysis are shown in table 2. The phases of the different contributions are measured relative to the $\rho(770)^0$ and the results show agreement between the three S-wave approaches. The largest phase difference ($\sim 52^o$) between B^+ and B^- is in $f_2(1270)$. This phase difference is at the origin of some of the large CP asymmetries seen in the Dalitz Plot. With respect to fit fractions the $\rho(770)^0$ (~ 0.56) and S-wave (~ 0.26) contributions are dominant and there is a significant $f_2(1270)$ (~ 0.09) contribution. CPV significance tests were performed from the change in negative log-likelihood between the baseline fit and alternative fits where the probed CP asymmetry is not allowed. In particular, for the large CPV asymmetries ($\sim 40\%$) observed in the $f_2(1270)$ and the S-wave a significance of more than 10 standard deviations is found. This is the first observation of CPV involving a tensor state. The study of the helicity angle distributions reveals CPV in the interference of the S and P-waves with more than 25 standard deviations significance. This is the first observation of CPV in a quasi-two-body interference. There is also clear CP asymmetry in the low $m(\pi^+\pi^-)$ region below the $\rho(770)^0$ mass. This asymmetry is positive and flips sign at the K^+K^- threshold. On the contrary, there is not a significant asymmetry effect in the $\rho - \omega$ mixing.

3. $B_s^0 \to VV$ time-dependent analyses

The study of mixing neutral meson decays into CP-eigenstates that are available to both B_s^0 and $\overline{B}_s^0$ produces interference between the direct decay and the decay after $B_s^0 - \overline{B}_s^0$ mixing. The final-state dependent observable phase $\phi_s = \phi_M - 2\phi_D$, where ϕ_M is the mixing phase and ϕ_D the decay phase, and the direct CP-violation parameter λ are accessible in time-dependent amplitude analyses. Both magnitudes are excellent probes of different modes that propose physics beyond the Standard Model (NP). Two families of complementary final states are considered: tree-dominated decays corresponding to $b \to sc\bar{c}$ transitions, such as $B_s^0 \to J/\psi K^+K^-$ and $B_s^0 \to J/\psi\pi^+\pi^-$ decays, in which no NP is expected in ϕ_D, and loop-dominated decays ($b \to ss\bar{s}$ and $b \to sd\bar{d}$ transitions), such as $B_s^0 \to \phi\phi$ and $B_s^0 \to K^{*0}\overline{K}^{*0}$ decays, which are particularly sensitive to NP in ϕ_D.

3.1 The $B_s^0 \to J/\psi K^+K^-$ and $B_s^0 \to J/\psi \pi^+\pi^-$ decays

A total of 1.9 fb^{-1} (2015: 0.3 fb^{-1} and 2016: 1.6 fb^{-1}) Run-II data were recently analysed by LHCb [8, 9]. The K^+K^- pairs of the $B_s^0 \to J/\psi K^+K^-$ decay are selected in the vicinity of the $\phi(1020)$ resonance and, therefore, show a modest S-wave contribution. The $B_s^0 \to J/\psi \pi^+\pi^-$ is dominated by $B_s^0 \to J/\psi f_0(980)$ decays. The selection of signal events over the combinatorial background is performed with a BDT using kinematic variables. The four-body invariant mass spectra are fitted with signal plus background models yielding ~ 117000 $B_s^0 \to J/\psi K^+K^-$ and ~ 33500 $B_s^0 \to J/\psi \pi^+\pi^-$ candidates.

The amplitude analyses are simultaneously performed in the helicity angles and decay time, and also in the $m(\pi^+\pi^-)$ mass for $B_s^0 \to J/\psi \pi^+\pi^-$ decays, requiring careful study of angular and decay-time efficiencies, time resolution and flavour tagging. The decay-time resolution is found to be $\sigma_{eff}(B_s^0 \to J/\psi K^+K^-) \approx 45.5$ fs and $\sigma_{eff}(B_s^0 \to J/\psi \pi^+\pi^-) \approx 41.5$ fs and a 30% higher tagging power than Run-1 has been achieved. The decay-time and angular efficiencies are estimated with simulation and corrected with data methods.

The results of the analyses are in agreement with previous measurements and SM predictions. Other than $\phi_s^{c\bar{c}s}$ [1] and $|\lambda|$, magnitudes such as Γ_H, the decay width of the high mass eigenstate, Γ_s, the average decay width and $\Delta\Gamma_s$, the difference between the decay-width of the high-mass and low-mass eigenstates, are also extracted from in the amplitude analysis. In the $B_s^0 \to J/\psi K^+K^-$ the measured values are $\phi_s^{c\bar{c}s} = -83 \pm 41 \pm 6$ mrad, $|\lambda| = 1.012 \pm 0.016 \pm 0.006$, $\Gamma_s - \Gamma_d = -0.0041 \pm 0.0024 \pm 0.0015$ ps^{-1} (Γ_d is the decay width of the B^0 meson, which appears here because the time acceptance uses a B^0 decay mode as a control sample) and $\Delta\Gamma_s = 0.077 \pm 0.008 \pm 0.003$ ps^{-1}. In the $B_s^0 \to J/\psi \pi^+\pi^-$ decay the measurements are $\phi_s^{c\bar{c}s} = -57 \pm 60 \pm 11$ mrad, $|\lambda| = 1.01^{+0.08}_{-0.06} \pm 0.03$ and $\Gamma_H - \Gamma_d = -0.050 \pm 0.004 \pm 0.004$ ps^{-1}. All of the above taken into account, the LHCb average, considering the previous Run-I analyses, are $\phi_s^{c\bar{c}s} = -41 \pm 25$ mrad, $|\lambda| = 1.093 \pm 0.010$, $\Gamma_s = 0.6562 \pm 0.0021$ ps^{-1} and $\Delta\Gamma_s = 0.0816 \pm 0.0048$ ps^{-1}. The universal combination with other experiments made by HFLAV [11] gives: $\phi_s^{c\bar{c}s} = -55 \pm 21$ mrad and $\Delta\Gamma_s = 0.0764 \pm 0.0024$ ps^{-1}. After these LHCb measurement and the first ATLAS measurement with Run 2 data [15] the improvement in the experimental uncertainty of the $\phi_s^{c\bar{c}s}$ average is from $31 \to 21$ mrad whereas the uncertainty in the $\Delta\Gamma_s$ average is $0.005 \to 0.0034$ ps^{-1}.

3.2 The $B_s^0 \to \phi\phi$ and $B_s^0 \to K^{*0}\overline{K}^{*0}$ decays

The time-dependent analysis of $B_s^0 \to \phi\phi$ with Run-1 (3 fb^{-1}) and a fraction of Run-2 (2 fb^{-1}) data has been also recently presented by LHCb [10]. The analysis strategy is very similar to the one presented above and considers 3 helicity angles and the decay time of the meson. In this case the focus is on ϕ_s, $|\lambda|$ and the longitudinal polarisation fractions and the Γ_s, $\Delta\Gamma_s$ and and m_s values are inputted from external sources.

A yield of ~ 8500 signal events is obtained after the offline selection of the analysed sample. The results of the CP-violating phase being: $\phi_s^{s\bar{s}s} = -0.073 \pm 0.115 \pm 0{,}027$ rad and $|\lambda| = 0.99 \pm$

[1] The subscript in ϕ_s indicates the quark content of the b-quark decay.

0.05 ± 0.01. The longitudinal polarisation fraction of charmless $B \to VV$ decays was expected to be large based on the $V-A$ nature of the weak interaction and quark helicity conservation. This is far from being the case and some modes, $B_s^0 \to \phi\phi$ among them, show small polarisation. This analysis confirms that giving $f_L = 0.381 \pm 0.007 \pm 0.012$.

An analysis presented by LHCb in 2018 [12], determined in $B_s^0 \to (K^+\pi^-)(K^-\pi^+)$ decays (mainly $K^{*0}\overline{K}^{*0}$) $\phi_s^{d\bar{d}s} = -0.10 \pm 0.13 \pm 0.14$ rad, and $|\lambda| = 1.035 \pm 0.034 \pm 0.089$. The prospects of this analysis are to improve these measurements after the LHCb upgrade reaching precisions that would require to account for penguin pollution from subleading amplitudes. This is achieved by studying the U-spin partner $B^0 \to K^{*0}\overline{K}^{*0}$. The first untagged time-integrated LHCb analysis of $B^0 \to K^{*0}\overline{K}^{*0}$ has been recently published with the complete Run-I (3 fb^{-1}) data [13]. The study assumes $\Delta\Gamma \approx 0$ and negligible CPV. It is remarkable that the longitudinal polarisation of this mode is high as compared to $B_s^0 \to K^{*0}\overline{K}^{*0}$: $f_L = 0.724 \pm 0.051 \pm 0.016$ and $f_L = 0.240 \pm 0.031 \pm 0.025$, respectively.

The branching ratio of the $B^0 \to K^{*0}\overline{K}^{*0}$ is measured for the first time in LHCb with the best precision of $(8.04 \pm 0.87 \pm 0.41) \times 10^{-7}$. Using averages $y = \Delta\Gamma_s/(2\Gamma_s) = 0.064 \pm 0.005$ and $\phi_s = -0.021 \pm 0.031$ from [11] the magnitude:

$$R_{sd} = \frac{\mathscr{B}(B_s^0 \to K^{*0}\overline{K}^{*0}) f_L(B_s^0 \to K^{*0}\overline{K}^{*0})}{\mathscr{B}(B^0 \to K^{*0}\overline{K}^{*0}) f_L(B^0 \to K^{*0}\overline{K}^{*0})} \frac{1-y^2}{1+y\cos\phi_s},$$

is found to be $R_{sd} = 3.43 \pm 0.38$ at variance with the theoretical prediction of $R_{sd} = 16.4 \pm 5.2$ [14].

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