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Time-dependent CP violation in charmless b decays at LHCb

Louis Henry*†
Universita Milano, Universita Valencia
E-mail: louis.henry@cern.ch

In the B-meson sector, measurements of weak phases not associated with V_{ub} are obtained through time-dependent, flavour-tagged analyses involving $B-\overline{B}$ mixing. In addition to new phases that may enter the mixing loop, charmless B decays have an additional mechanism for unknown particles to induce deviations from the Standard Model expectation due to the sizeable contribution to these decays from penguin topologies. We present the most recent studies of time-dependent CP violation in charmless B decays at the LHCb experiment, including $B_s^0 \to \phi\phi$, one of the "golden channels" for New Physics searches.

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*Speaker.
†On behalf of the LHCb collaboration

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1. Introduction

In the Standard Model (SM), charmless decays of b hadrons are generally suppressed at the tree level, and as such penguin amplitudes containing a virtual-loop contribution can be sizeable or even dominant. These diagrams can in turn interfere with other diagrams, such as the ones related to the $B-\overline{B}$ mixing, giving rise to *CP*-violation (CPV) effects sensitive to new physics (NP).

Experimentally, hadronic charmless decays cover a large range of available number of events, from few observed in the $B_s \to K^0_S K^+ K^-$ mode to hundreds of thousands in the $B^+ \to \pi^+\pi^-\pi^+$ mode. The sensitivity to $B-\overline{B}$ oscillations depends on the LHCb detector ability to estimate correctly the decay time of the B meson, and to assign the correct flavour at production, a process known as *tagging*.

Tagging the flavour at LHCb is done by combining information coming from quarks that hadronised with the b quark ("same-side" tagging) and information from possibly flavour-specific decays of the hadron formed by the other b quark of the $b\overline{b}$ pair ("opposite-side" tagging), as described in detail in Ref. [1]. The effective tagging power in LHCb is around 5 %.

Selection efficiencies usually depend on the displacement of the B decay vertex, and thus on the decay time, which needs to be accurately modelled using simulations and control modes. Furthermore, any measurement depending on the decay time is also affected by the resolution on this quantity, which is of order 0.03 ps in Run I. In order to improve our knowledge on this quantity, the behaviour of the resolution as a function of the decay time is modelled on simulated samples. The results of this modelling are then used to estimate an event-per-event decay-time resolution, which is in turn convolved with the time-dependent PDFs.

2. Time-dependent *CP* violation in $B^0_{(s)} \to h^+h^-$ decays

Decays of the $B^0_{(s)} \to h^+h^-$ type, where h is a kaon or a pion, are dominated by the $b \to d$ and $b \to s$ transitions which are forbidden at tree level in the SM. As the final state is a *CP* eigenstate, it can be accessed from both flavours of the neutral B meson, and as such is sensitive to the time-dependent *CPV* related to B mixing. Additionally, it is necessary to study as well the $K\pi$ final state, as it contributes to the invariant-mass spectra of both h^+h^- modes.

Extracting weak observables from hadronic processes can prove challenging, but exploiting symmetries can allow for a clean measurements of these observables. For instance, the $B^0_s \to \pi^+\pi^-$ and $B^0_s \to K^+K^-$ decays being equivalent under the $d \leftrightarrow s$ symmetry ("U-spin" symmetry), it has been proposed in e.g. [2] to exploit that symmetry for a clean extraction of both the γ and β_s angles. That symmetry can be exploited further by fixing the γ angle from external sources and as such reduce systematic uncertainties on the Φ_s angle from 5° to 0.5° in the LHCb upgrade era [3].

We report the results of the LHCb analysis of the full Run I dataset, published in [4]. The decay-time-dependent width for the $\pi^+\pi^-$and K^+K^-modes is written as

$$A_{CP}(t) = \frac{-C_f \cos(\Delta m_{d,s} t) + S_f \sin(\Delta m_{d,s} t)}{\cosh(\frac{\Delta\Gamma_{d,s}}{2} t) + A^{\Delta\Gamma}_f \sinh(\frac{\Delta\Gamma_{d,s}}{2} t)},$$

where

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$$C_f = \frac{1-\left|\lambda_f\right|^2}{1+\left|\lambda_f\right|^2}, S_f = \frac{2\mathrm{Im}(\lambda_f)}{1+\left|\lambda_f\right|^2}, \text{ and } A_f^{\Delta\Gamma} = -\frac{2\mathrm{Re}(\lambda_f)}{1+\left|\lambda_f\right|^2}.$$

The λ_f observable is defined as

$$\lambda_f = \frac{q}{p}\frac{\overline{A}_f}{A_f},$$

and is related to the mixing parameters of the relevant meson, p and q, and to the difference between the amplitudes of the B and the $\overline{B}$ meson going to the same state f, A_f and $\overline{A}_f$, respectively. Additionally, the time-integrated CP asymmetry of a flavour-specific mode f is defined as

$$A_{CP} = \frac{|\overline{A}_{\overline{f}}|^2 - |A_f|^2}{|\overline{A}_{\overline{f}}|^2 + |A_f|^2}.$$

In each $h^+h^{(\prime)-}$ spectrum, the model takes into account event species related to both B and B_s contributions, as well as background events from random associations of tracks (combinatorial background) and partially reconstructed events from B to 3-body decays. Additionally, components from other signal modes, where one of the final-state mesons is misidentified, have to be carefully modelled using simulated events. A simultaneous extended likelihood fit to the invariant-mass, decay time, decay-time uncertainty, tagging decision, and mistag probability is performed on the dataset, as shown in Fig. 1, and yields

$$\begin{aligned}
C_{\pi\pi} &= -0.34 \pm 0.06 \pm 0.01, & S_{\pi\pi} &= -0.63 \pm 0.05 \pm 0.01 \\
C_{KK} &= 0.20 \pm 0.06 \pm 0.02, & S_{KK} &= 0.18 \pm 0.06 \pm 0.02, \\
A^{\Delta\Gamma}(KK) &= -0.79 \pm 0.07 \pm 0.10 \\
A_{CP}(B) &= -0.084 \pm 0.004 \pm 0.003, A_{CP}(B_s) = 0.213 \pm 0.015 \pm 0.007
\end{aligned}$$

Compared with former LHCb measurements [5, 6], uncertainties are improved by a factor 2 to 3, depending on the observable. Statistical-only uncertainties are also competitive or even better than current PDG values [7]. Finally, the strongest evidence to date of time-dependent *CPV* in the B_s sector is obtained, with more than 4σ discrepancy between $(C_{KK}, S_{KK}, A_{KK}^{\Delta\Gamma})$ and $(0,0,-1)$ (*CP* conserved).

3. Measurement of $\phi_s^{d\overline{d}}$ in $B_s^0 \to K^{*0}\overline{K}^{*0}$ decays

The $B_s^0 \to K^{*0}\overline{K}^{*0}$ decay, observed by LHCb for the first time in 2011 [8], is dominated by gluonic penguin diagrams. As such, the study of this mode is complementary to that of processes dominated by electroweak penguins, involved in the so-called "*B* anomalies". The weak phase in this mode, $\phi_s^{d\overline{d}}$, is equal in the SM to that of $b \to c\overline{c}s$ transitions, measured to be

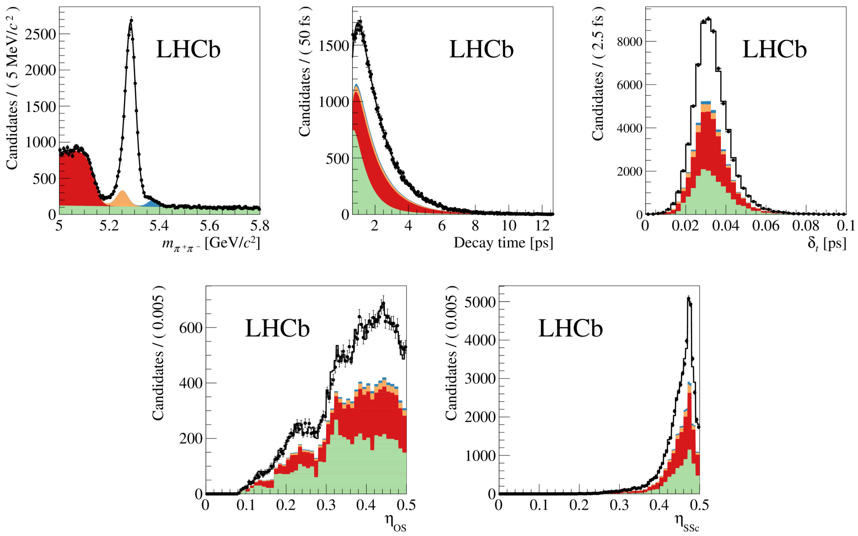

Figure 1: Simultaneous fits to (top,left) $m_{\pi\pi}$, (top,middle) the decay time, (top, right) the uncertainty on the decay time, (bottom left) the mistag probability of the opposite-side tagger, and (bottom, right), the mistag probability of the same-side tagger. The $B^0 \to \pi^+\pi^-$ signal is in white, the $B_s^0 \to \pi^+\pi^-$ in blue, the $B^0 \to K^+\pi^-$ background in orange, the combinatorial background in green, and the 3-body B decays background in red.

$$\phi_s^{c\bar{c}} = -0.021 \pm 0.031 \text{ rad}.$$

We report the results of the analysis performed on the full Run I dataset of the LHCb experiment, published in [9], which updates a previous analysis that was performed using only the 2011 dataset [10]. The new analysis considers 19 different amplitudes, including some tensor components for the first time, as reported in Fig. 2.

Decay	Mode	j_1	j_2	Allowed values of h	Number of amplitudes
$B_s^0 \to (K^+\pi^-)_0^*(K^-\pi^+)_0^*$	scalar-scalar	0	0	0	1
$B_s^0 \to (K^+\pi^-)_0^*\overline{K}^*(892)^0$	scalar-vector	0	1	0	1
$B_s^0 \to K^*(892)^0(K^-\pi^+)_0^*$	vector-scalar	1	0	0	1
$B_s^0 \to (K^+\pi^-)_0^*\overline{K}_2^*(1430)^0$	scalar-tensor	0	2	0	1
$B_s^0 \to K_2^*(1430)^0(K^-\pi^+)_0^*$	tensor-scalar	2	0	0	1
$B_s^0 \to K^*(892)^0\overline{K}^*(892)^0$	vector-vector	1	1	0, $\parallel$, $\perp$	3
$B_s^0 \to K^*(892)^0\overline{K}_2^*(1430)^0$	vector-tensor	1	2	0, $\parallel$, $\perp$	3
$B_s^0 \to K_2^*(1430)^0\overline{K}^*(892)^0$	tensor-vector	2	1	0, $\parallel$, $\perp$	3
$B_s^0 \to K_2^*(1430)^0\overline{K}_2^*(1430)^0$	tensor-tensor	2	2	0, $\parallel_1$, $\perp_1$, $\parallel_2$, $\perp_2$	5

Figure 2: Amplitudes considered in the model to describe the $B_s^0 \to K^{*0}\overline{K}^{*0}$ phase space. The $j_{1,2}$ quantities designate the spin of the first (second) $K\pi$ pair, and h is the helicity of the state.

The angle $\phi_s^{d\bar{d}}$ is measured for the first time, and its value

$$\phi_s^{d\bar{d}} = -0.10 \pm 0.13 \pm 0.14\,\text{rad},$$

where the first uncertainty is statistical and the second is systematic, is compatible with the SM expectations.

4. Measurement of $\phi_s^{s\bar{s}}$ in $B_s^0 \to \phi\phi$ decays

As the $B^0_{(s)} \to K^{*0}\overline{K}^{*0}$ decays, the $B_s^0 \to \phi\phi$ decay is dominated by a gluonic penguin amplitude. However, the underlying transition is $b \to s\bar{s}s$, and as such the time-dependent *CPV* is related to the $\phi_s^{s\bar{s}}$ angle, which is predicted to be smaller than 0.02 rad in the SM [11, 12]. A previous LHCb analysis has measured

$$\phi_s^{s\bar{s}} = -0.17 \pm 0.15 \pm 0.03\,\text{rad},$$

where the first uncertainty is statistical, and the second is systematic [13].

We report the results of the analysis described in [14], and performing an amplitude analysis on data collected from 2011 to 2016, for a total luminosity of more than $4\,\text{fb}^{-1}$. The analysis does not find a significant $B^0 \to \phi\phi$ component, and sets the world's best upper limit on that decay

$$B(B^0 \to \phi\phi) < 2.7 \times 10^{-8} (90\%\text{CL}).$$

Additionally, the $B_s^0 \to \phi\phi$ amplitude is measured as a sum of three terms, denoted with the 0, $\perp$, $\|$ subscripts and whose parameters are measured to be

$$\begin{aligned} |A_0|^2 &= 0.381 \pm 0.007 \pm 0.012, \\ |A_\perp|^2 &= 0.290 \pm 0.008 \pm 0.007, \\ \delta_\perp &= 2.818 \pm 0.178 \pm 0.073\,\text{rad}, \\ \delta_\| &= 2.559 \pm 0.045 \pm 0.033\,\text{rad}, \end{aligned}$$

which is is good agreement with previous measurements.

Finally, the *CP*-violating parameters λ and $\phi_s^{s\bar{s}}$ are measured to be

$$\begin{aligned} \lambda &= 0.99 \pm 0.05 \pm 0.01, \\ \phi_s^{s\bar{s}} &= -0.073 \pm 0.115 \pm 0.027\,\text{rad}. \end{aligned}$$

As a result, no significative *CPV* is found, and the results are compatible with the SM.

5. Perspectives

Time-dependent *CPV* in charmless *b*-meson decays is a sensitive probe of NP, due to both the suppression of tree-level amplitudes in these decays and to the precision of SM predictions. The LHCb experiment is already contributing to these measurements, with the leading precision in the $B^0_{(s)} \to h^+h^-$ modes and the first measurement of $\phi_s^{d\bar{d}}$, using the $B^0 \to K^{*0}\overline{K}^{*0}$ decay channel. All measurements in these proceedings are statistically limited, and in most cases systematic uncertainties are dominated by contributions that are statistical in nature, such as the size of simulated samples. As a result, the full potential of the LHCb experiment will unfold in the coming years, starting with the inclusion of the full Run 2 dataset ($9\,\text{fb}^{-1}$) and especially with the upgrade, planned to start taking data in 2021.

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