Recent measurements of the time-dependent CP violation are presented. The decays of $B_s^0$ mesons to $J/\psi K^+K^-$ and $J/\psi \pi^+\pi^-$ final states are used to measure CP-violating parameters with proton-proton collision data, corresponding to an integrated luminosity of 1.9 fb$^{-1}$, collected by the LHCb detector at a centre-of-mass energy of 13 TeV in 2015 and 2016.

1 CP violation in the $B_s^0 - \bar{B}_s^0$ system

The LHCb detector$^{1,2}$ is a general purpose detector in the forward region, situated at the Large Hadron Collider at CERN. The broad physics program of the LHCb experiment covers various topics including study of the CP violation (CPV) in $B$ mesons. The CP-violating phase $\phi_s$ arises in the interference between the amplitudes of a $B_s^0$ meson$^6$ decaying via $b \to c\bar{c}s$ transition directly to its final state or after oscillation to a $\bar{B}$ meson. In the Standard Model (SM) ignoring subleading penguin contributions, this phase is constrained via global fits to the experimental data to be $-0.0364 \pm 0.0016$ rad$^3$. This precise prediction makes the measurement of $\phi_s$ interesting since it is possible that new physics processes could modify the phase, if new particles were to contribute to the $B_s^0 - \bar{B}_s^0$ mixing diagrams$^4,5$. The value of $\phi_s$ measured to be significantly different from the SM would be a clear evidence for physics beyond the SM.

2 Measurement of $\phi_s$ at LHCb

Two recent measurements of the phase $\phi_s$ at the LHCb experiment are presented. Both analyses measure the CP-violating phase $\phi_s$ using $B_s^0$ meson decays. One analysis explores the $B_s^0 \to J/\psi K^+K^-$ decay mode$^7$, while the other studies the $B_s^0 \to J/\psi \pi^+\pi^-$ decay$^6$. Since the analysis strategies are very similar, the baseline strategy adopted by both is covered and relevant differences between the two are highlighted.

$^a$The inclusion of charge-conjugate processes is implied throughout this manuscript, unless otherwise noted.
Both analyses use proton-proton collision data collected with the LHCb detector in 2015 and 2016, corresponding to the total integrated luminosity of 1.9 fb\(^{-1}\). A \(B^0_s\) (\(\bar{B}^0_s\)) meson after being produced in a proton-proton collision in the LHCb detector (so-called primary vertex), flies approximately 1 cm before decaying inside the vertex locator, VELO, of the LHCb detector. The excellent resolution of the VELO detector, which is equal to 45.5 (41.5) fs for the \(B^0_s \to J/\psi K^+ K^-\) (\(B^0_s \to J/\psi \pi^+ \pi^-\)) mode, allows to resolve oscillations in the \(B^0_s - \bar{B}^0_s\) system. The decay products of a \(B^0_s\) (\(\bar{B}^0_s\)) meson, \(J/\psi K^+ K^-\) or \(J/\psi \pi^+ \pi^-\) where \(J/\psi\) decays to \(\mu^+ \mu^-\) pair, escape from the decay point of \(B^0_s\) (so-called secondary vertex) through the rest of the detector, traversing the magnet, where tracks of charge particles are bent; tracking stations; Cherenkov detectors, which allows to identify hadron type; calorimeter system and muon stations. The distance between the secondary and primary vertices is translated to the \(B^0_s\) meson decay-time using estimate of its momentum.

CP-violating parameters \(\phi_s\) and \(|\lambda|\) are measured. The \(B^0_s \to J/\psi K^+ K^-\) channel allows measuring lifetime parameters of the \(B^0_s\) meson: the decay-width difference between the heavy and light \(B^0_s\) meson eigenstates, \(\Delta \Gamma_s = \Gamma_L - \Gamma_H\), and the average decay-width of the states, \(\Gamma_s = \frac{\Gamma_L + \Gamma_H}{2}\). However, since \(J/\psi \pi^+ \pi^-\) final state is almost entirely CP-odd, only decays of the heavy \(B^0_s\) meson eigenstate are possible, therefore one can measure \(\Gamma_H\) with \(B^0_s \to J/\psi \pi^+ \pi^-\). In order to disentangle CP-even from CP-odd component, angular analysis is required. For the four-body final state, three independent angles are needed to describe the system. Both analyses make use of helicity angles formalism. In the measurements the decay-width difference between the \(B^0_s\) (\(B_H\)) and \(B^0\) meson is fitted for, in order to keep results independent of the value of \(B^0\) meson width. In this way, the value of the \(\Gamma_{s/H}\) can be extracted using the latest world average of the value of \(\Gamma_{B^0}\).

The experimental differential decay-time rate for an initial \(B^0_s\) meson as a function of decay time and angles is given as

\[
\frac{d^4 \Gamma}{dt \, d\Omega} \propto \sum_{k=1}^{10} \varepsilon(t, \Omega) f_k(\Omega) h_k(t) \otimes G(t|\sigma_t),
\]

where \(\varepsilon(t, \Omega)\) is efficiency as a function of decay-time and angular observables, \(f_k(\Omega)\) are angular functions, \(G(t|\sigma_t)\) is experimental decay-time resolution and the decay-time-dependent functions \(h_k(t)\) for the decay of \(B^0_s\) meson produced as \(B^0_s\) meson are given as

\[
h_k(t) = \frac{3}{4\pi} e^{-\Gamma t} \left( a_k \cosh \frac{\Delta \Gamma t}{2} + b_k \sinh \frac{\Delta \Gamma t}{2} + c_k \cos(\Delta m t) + d_k \sin(\Delta m t) \right).
\]

For an initial \(B^0_s\) at production, the signs of \(c_k\) and \(d_k\) should be reversed. The end goal is to perform a simultaneous maximum likelihood fit to the decay-time and three angles in order to extract CP-violating parameters. As can be seen from the equation 1, there are several experimental inputs that are required for the time-dependent fit to be performed: efficiency, decay-time resolution of the detector and the knowledge of the flavour of the \(B^0_s\) meson at production. The details on these inputs are given in the following.

### 2.1 Selection and mass fit

The time-dependent angular fit is performed on background-subtracted data. For both decays under study a corresponding boosted decision tree, BDT, is used to select signal and reject background candidates. The BDTs are trained using data sidebands as background proxy and simulated events as signal proxy. After the training, the optimal cut is found and applied on the data sample.

In case of \(\Lambda_b \to J/\psi p^+ K^-\) decays, it can happen that the proton in the final state is mis-identified as a kaon and resulting \(J/\psi K^+ K^-\) wrong combination might end up peaking under the signal peak. Since this contribution is significant for the \(B^0_s \to J/\psi K^+ K^-\) mode.
it is subtracted by injected negatively weighted simulated sample of $\Lambda_b \to J/\psi p^+ K^-$ decays with the total weight equal to the expected contribution of the $\Lambda_b$ background. Other peaking background contributions coming from decays $B^0 \to J/\psi K^+ K^-$, $B^0 \to J/\psi \pi^+ \pi^-$ and $B^0 \to J/\psi K^+ K^0(\to K^+ \pi^-)$ are either vetoed using particle identification requirements or accounted for directly in the mass fit.

In order to disentangle combinatorial background events from signal candidates the signal weights are used. Those weights are obtained using the sPlot procedure\(^{11}\), which assigns a weight to each event based on the probability density function (PDF) that is used to describe the invariant mass spectra and are later used to statistically subtract the background contribution. The invariant mass distributions of $J/\psi K^+ K^-$ and $J/\psi \pi^+ \pi^-$ are shown in Fig. 1 together with the analytical shapes that are used to extract signal weights.

### 2.2 Decay time resolution

The decay-time resolution of the detector directly affects the precision of the measured CP-violating parameters. Therefore, detailed understanding of the time resolution is required. The decay-time error that is estimated on an event-by-event basis during the reconstruction step is underestimated and therefore requires calibration. In order to perform decay-time resolution calibration both analyses use a prompt data sample that consists of $J/\psi \to \mu^+ \mu^-$ candidates that originate from the primary vertex and therefore have zero lifetime. The decay-time distribution of prompt $B^0_s \to J/\psi K^+ K^-$ candidates is shown in Fig. 2 (a). Events with negative lifetime are present which can only be possible due to the resolution effect of the detector. This is used to assess the effective decay-time resolution of the detector. In order to correct the decay-time uncertainty estimation, a binned procedure is implemented where the prompt sample is divided in several subsamples with different values of the per-event error. In each subsample the effective resolution is assessed by fitting the decay-time distribution. The result of this procedure is shown in Fig. 2 (b). The relation between the effective resolution and the per-event error is parametrised with a linear dependency and the linear calibration parameters are extracted using a $\chi^2$ fit.

### 2.3 Reconstruction and selection efficiency

The geometry of the detector together with the selection requirements cause non-uniform efficiency as a function of the observables (three helicity angles and decay-time). In the case of $B^0_s \to J/\psi \pi^+ \pi^-$ decay, the invariant mass of two pions is also an observable in the fit and the efficiency as a function of it is studied separately. For both decay modes, efficiency as a function of decay angles is evaluated using simulated samples and then taken into account in the final fit. The non-uniform shape of the efficiency as a function of decay-time is caused by biasing.

Figure 1 – Distribution of the invariant mass of selected (a) $B^0_s \to J/\psi K^+ K^-$ and (b) $B^0_s \to J/\psi \pi^+ \pi^-$ decays. The color-coding of PDFs is explained on each plot.
Figure 2 – (a) Decay-time distribution of the prompt $B^0_s \rightarrow J/\psi K^+ K^-$ calibration sample with the result of an unbinned maximum likelihood fit overlaid in blue. The overall resolution is represented by the dashed red line. (b) Variation of the effective decay-time resolution, $\sigma_{\text{eff}}$, as a function of the estimated per-candidate decay-time uncertainty, $\delta_t$. The red line shows the result when fitting a linear function. The shaded histogram shows the normalized distribution of $\delta_t$.

selection introduced already in the trigger stage and is described with cubic splines. Since simulation is not completely reliable in modeling of trigger response, a data-driven method is used. The control channel $B^0 \rightarrow J/\psi K^{*0}(\rightarrow K^+ \pi^-)$ is used since it has a well-known lifetime and kinematics of the decay is similar to the signal channels. Signal candidates of the control channel are selected following the selection procedure used for the signal channel. Then the decay-time acceptance is evaluated and corrected by the ratio of acceptances in simulated signal and control channels to take into account differences between the two channels. The final efficiency is represented in the following form:

$$
\varepsilon_{B^0_s}(t) = \varepsilon_{B^0_s}(t) \times \frac{\varepsilon_{B^0_s}(t)}{\varepsilon_{B^0_{s\text{sim}}}(t)}.
$$

The differential decay-time rate is then multiplied with evaluated efficiency as shown in equation 1.

3 Results

Taking into account all the inputs described above, a time-dependent maximum likelihood fit is performed in order to extract the parameters of interest. The corresponding background-subtracted data distributions with fit projections for the $B^0_s \rightarrow J/\psi K^+ K^-$ channel are shown in Fig. 3 and in Fig. 4 for the $B^0_s \rightarrow J/\psi \pi^+ \pi^-$ decay mode. Table 1 summarises parameter estimates obtained by the both analyses.

| Parameter | $B^0_s \rightarrow J/\psi K^+ K^-$ | $B^0_s \rightarrow J/\psi \pi^+ \pi^-$ |
|-----------|-------------------------------|-------------------------------|
| $\phi_s$, rad | $-0.080 \pm 0.041 \pm 0.006$ | $-0.057 \pm 0.060 \pm 0.011$ |
| $|\lambda|$ | $1.006 \pm 0.016 \pm 0.006$ | $1.01^{+0.08}_{-0.06} \pm 0.03$ |
| $\Gamma_{s/H} - \Gamma_{B^0_s}$, ps$^{-1}$ | $-0.0041 \pm 0.0024 \pm 0.0015$ | $-0.050 \pm 0.004 \pm 0.004$ |
| $\Delta \Gamma_s$, ps$^{-1}$ | $0.0772 \pm 0.0077 \pm 0.0026$ | - |
Using a minimum \( \chi^2 \) fit, the presented results are combined with all the previous measurements of the \( \phi_s \) phase performed by the LHCb experiment\(^{12,13,14,15}\). The combined values are

\[
\phi_s = -0.040 \pm 0.025 \text{ rad}, \\
|\lambda| = 0.991 \pm 0.010, \\
\Gamma_s - \Gamma_{B^0} = -0.0024 \pm 0.0018 \text{ ps}^{-1}, \\
\Delta \Gamma_s = 0.0813 \pm 0.0048 \text{ ps}^{-1}.
\]

The results are compatible with the SM expectations and with no CPV in the decay modes under study.

References

1. Alves Jr., A. A. and others, JINST 3, S08005 (2008)
2. Aaij, R. and others, Int. J. Mod. Phys. A 30, 1530022 (2015)
3. Charles, J. and others, Phys. Rev. D 84, 033005 (2011).
4. Buras, Andrzej J., PoS EPS-HEP2009, 024 (2009).
5. Chiang, Cheng-Wei and Datta, Alakabha and Duraisamy, Murugeswaran and London, David and Nagashima, Makiko and others, JHEP 04, 031 (2010)
6. Aaij, Roel and others arXiv 1903.05530 (2019)
7. Aaij, Roel and others LHCb-PAPER-2019-013
8. Aaij, R. and others, Phys. Rev. D 87, 112010 (2013)
9. Liu, Xin and Wang, Wei and Xie, Yuehong, Phys. Rev. D 89, 094010 (2014).
10. Breiman, L. and Friedman, J. H. and Olshen, R. A. and Stone, C. J., Classification and regression trees 1984
11. Pivk, Muriel and Le Diberder, Francois R., Nucl. Instrum. Methods A 555, 356-369 (2005)
12. Aaij, R. and others, Phys. Lett. B 736, 186 (2014)
13. Aaij, R. and others, Phys. Lett. B 762, 253 (2016)
14. Aaij, R. and others, Phys. Rev. Lett. 113, 211801 (2014)
15. Aaij, R. and others, JHEP 08, 037 (2017)
Figure 3 – Decay-time and helicity-angle distributions for background subtracted $B^0_s \to J/\psi K^+ K^-$ decays$^7$ with the one-dimensional projections of the PDF. The solid blue line shows the total signal contribution, which contains CP-even (long-dashed red), CP-odd (short-dashed green) and S-wave (dotted-dashed purple) contributions.

Figure 4 – Decay-time and helicity-angle distributions for background subtracted $B^0_s \to J/\psi \pi^+ \pi^-$ decays$^8$ with the one-dimensional projections of the PDF. The solid blue line shows the total signal contribution.