

Measurements of CP violation in B mixing through $B \rightarrow J/\psi X$ decays at LHCb

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B mesons provide an ideal laboratory for measurements of CP violation and searches for CP violation beyond the Standard Model. Recent measurements of the mixing phases of the B_s^0 and B^0 mesons, ϕ_s and $\sin 2\beta$, using decays to $J/\psi X$ final states are presented. In view of future improved measurements, a good understanding of pollution from sub-leading penguin topologies in these decays is needed. Those can be probed using suppressed decays like $B_s^0 \rightarrow J/\psi K_s^0$ and $B_s^0 \rightarrow J/\psi \bar{K}^{*0}$. Recent results using these decay modes are presented.

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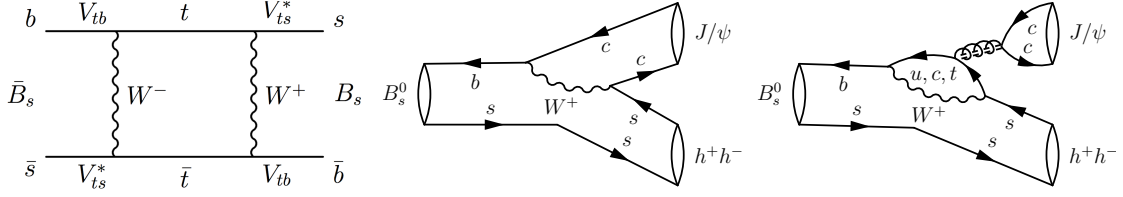


Figure 1: Feynman diagrams showing B_s^0 meson mixing (left) and example $b \rightarrow c\bar{c}s$ transitions via a tree-level (middle) and penguin process (right).

1. CP violation in B mixing and decay

In both the B^0 and B_s^0 meson systems a CP violating phase $\phi_{d,s}$ arises through the interference of $B_{(s)}^0$ mesons decaying via $b \rightarrow c\bar{c}s$ transitions to CP eigenstates and those decaying after oscillation¹. Figure 1 shows examples of these mixing and decay processes for the B_s^0 system. In the Standard Model (SM), ignoring sub-leading penguin processes, ϕ_s is equal to $-2\beta_s$, where $\beta_s \equiv \arg[-(V_{ts}V_{tb}^*)/(V_{cs}V_{cb}^*)]$ with V_{ij} being elements of the quark-mixing matrix [1, 2]. Similarly, in the B^0 system the ϕ_d is equal to 2β , where $\beta \equiv \arg[-(V_{cd}V_{cb}^*)/(V_{td}V_{tb}^*)]$. Global fits to experimental data give precise determinations: $\phi_s = -0.0365 \pm 0.0012$ rad and $\sin 2\beta = 0.771_{-0.041}^{+0.017}$ [3]. These phases could be modified if non-SM particles contribute to the B meson oscillation [4, 5] and, therefore, are the subject of many experimental measurements. Typically the measurements require the study of the CP asymmetry as a function of the B meson decay time, t . The asymmetry is defined as,

$$A_{CP}(t) \equiv \frac{\Gamma_{\bar{B}^0 \rightarrow f} - \Gamma_{B^0 \rightarrow f}}{\Gamma_{\bar{B}^0 \rightarrow f} + \Gamma_{B^0 \rightarrow f}} = \frac{S_f \sin(\Delta m t) - C_f \cos(\Delta m t)}{\cosh(\Delta\Gamma t/2) + A_{\Delta\Gamma} \sinh(\Delta\Gamma t/2)}, \quad (1.1)$$

where $\Gamma_{B^0 \rightarrow f}$ is the rate of the $B^0 \rightarrow f$ decay, $C_f \equiv \frac{1-|\lambda_f|^2}{1+|\lambda_f|^2}$, $S_f \equiv \frac{2\text{Im}(\lambda_f)}{1+|\lambda_f|^2}$ and $A_{\Delta\Gamma} \equiv -\frac{2\text{Re}(\lambda_f)}{1+|\lambda_f|^2}$. Here, Δm is the oscillation frequency of the B meson system, $\Delta\Gamma$ is the width difference between the light and heavy eigenstates of the B system. The parameter $\lambda_f \equiv \frac{q}{p} \frac{\bar{A}_f}{A_f}$ describes CP violation in the interference between mixing and decay, with the CP violating phase defined by $\phi \equiv -\arg(\lambda_f)$.

These proceedings will first review the experimental measurements of the CP violating phases, focussing on recent analyses of $B \rightarrow J/\psi X$ decays ($J/\psi \rightarrow \mu^+\mu^-$) from the LHCb collaboration that have been obtained using 3.0 fb^{-1} of pp collision data recorded at a centre-of-mass energies of $\sqrt{s} = 7$ and 8 TeV at the Large Hadron Collider. As will become clear, the increasing precision of these measurements now make it essential to test the assumption that $b \rightarrow c\bar{c}s$ penguin processes are small and therefore have little contribution to the CP violating phases. As such, the second half of the proceedings will focus on the latest experimental developments in this area.

2. $\sin 2\beta$ from $B^0 \rightarrow J/\psi K_S^0$

The time-dependent analysis of the CP asymmetry in $B^0 \rightarrow J/\psi K_S^0$ decays allows a measurement of $\sin 2\beta$. The latest result [6] from the LHCb collaboration used 41560 flavour-tagged candidates (Figure 2 (a)) to measure the parameters $S_{J/\psi K_S^0} = +0.731 \pm 0.035 \pm 0.020$ and $C_{J/\psi K_S^0} =$

¹Charge-conjugation is implicit unless stated otherwise.

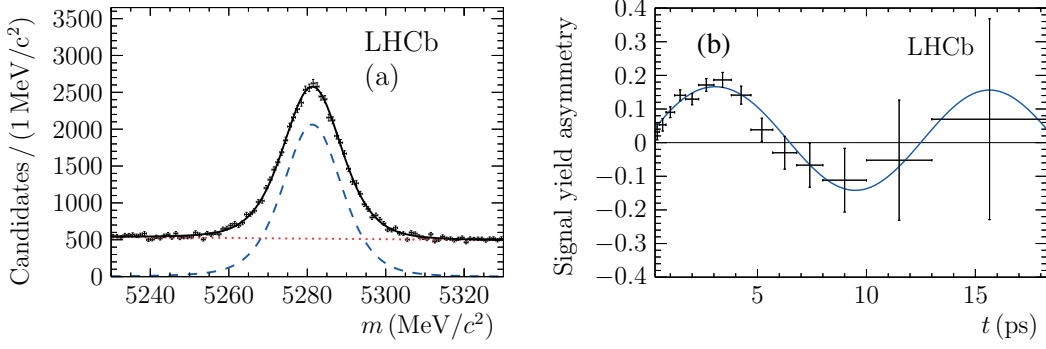


Figure 2: (a) Distribution of the $J/\psi K_S^0$ invariant mass for $B^0 \rightarrow J/\psi K_S^0$ candidates with the signal (blue-dotted line) and background (red-dotted) components of the maximum likelihood fit shown. (b) The signal asymmetry as a function of B^0 decay time.

$-0.038 \pm 0.032 \pm 0.005$, where $S_{J/\psi K_S^0} \approx \sin 2\beta$ and the first uncertainty is of statistical origin and the second is systematic. The correlation between the parameters is $\rho(S, C) = 0.483$. Figure 2(b) shows the signal asymmetry as a function of the decay time, where the sinusoidal oscillation is clearly visible. The dominant systematic uncertainty comes from knowledge of the tagging asymmetry of the background events. The result is consistent with the existing world average and of similar precision to existing measurements, as shown in Figure 3(a).

3. ϕ_s from $B_s^0 \rightarrow J/\psi K^+ K^-$ and $B_s^0 \rightarrow J/\psi \pi^+ \pi^-$

In the B_s^0 system the measurement of ϕ_s can be performed via a time-dependent analysis of $B_s^0 \rightarrow J/\psi \phi$ ($\phi \rightarrow K^+ K^-$) and $B_s^0 \rightarrow J/\psi \pi^+ \pi^-$ decays. In these cases the final states are admixtures of both CP -odd and CP -even components such that the decay angle information must also be used to disentangle the CP states. This gives rise to a rich structure and allows the simultaneous determination of many B_s^0 mixing parameters from the $B_s^0 \rightarrow J/\psi \phi$ decay, such as $\phi_s, \Delta m_s, \Gamma_s, \Delta \Gamma_s, |\lambda_f|$. The LHCb collaboration has measured these parameters using 96 000 $B_s^0 \rightarrow J/\psi \phi$ decays [8] with an effective tagging efficiency of $\sim 3.0\%$, leading to $\phi_s = -0.058 \pm 0.049 \pm 0.006$ rad and $|\lambda| = 0.964 \pm 0.019 \pm 0.007$. Only a 2% contribution from the $K^+ K^-$ S-wave is found in a $60 \text{ MeV}/c^2$ window around the $\phi(1020)$ meson. The main systematic uncertainties on the measurement of ϕ_s comes from the description of the angular efficiency of the LHCb detector and event selection requirements.

In the case of $B_s^0 \rightarrow J/\psi \pi^+ \pi^-$ a four-dimensional amplitude analysis is performed to understand structure in the full $\pi^+ \pi^-$ spectrum, finding it to be $> 97.7\%$ CP -odd @ 95% CL [9] with the main systematic uncertainty coming from the $\pi^+ \pi^-$ resonance model. The measured values of the CP parameters from this analysis are [10] $\phi_s = 0.070 \pm 0.068 \pm 0.008$ rad and $|\lambda| = 0.894 \pm 0.05 \pm 0.01$. Assuming CP violation in decay is the same in both the $K^+ K^-$ and $\pi^+ \pi^-$ modes is it possible to combining the measurements [8] giving the most precise determinations of the parameters $\phi_s = -0.010 \pm 0.039$ rad and $|\lambda| = 0.957 \pm 0.017$, where statistical and systematic uncertainties have been combined in quadrature. Figure 3(b) shows the current status of all mea-

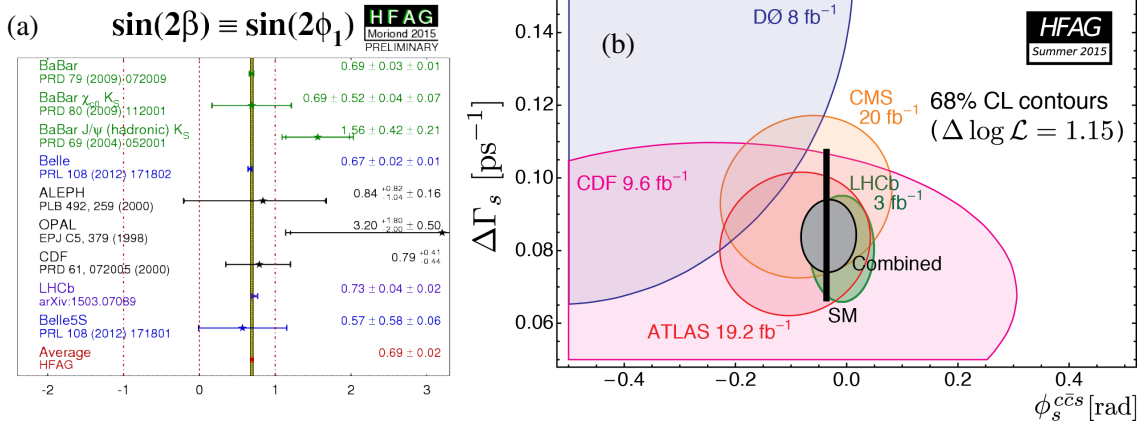


Figure 3: Summary of measurements and the global fit result for (a) $\sin 2\beta$ and (b) ϕ_s and $\Delta\Gamma_s$ [7].

measurements of ϕ_s and $\Delta\Gamma_s$ and the global fit, which is consistent with the SM predictions [3, 11, 12], indicating that any contributions from beyond-the-SM physics is small.

4. Controlling penguin pollution

The contributions to $\phi_{d,s}$ from penguin decay topologies are suppressed by $\varepsilon = |V_{us}|^2/(1 - |V_{us}|^2) \approx 0.05$ relative to the tree decay and, as discussed in Section 1, assumed to be negligible. Given the precision with which $\phi_{d,s}$ are now known and the projected sensitivity in the near-future it is essential that such ‘‘penguin pollution’’ is constrained before trying to use these CP violating phases in searches for new physics. Since the shift in $\phi_{d,s}$ from such contributions are difficult to calculate due to the non-perturbative nature of QCD it is crucial to make experimental measurements of the size of the penguin contribution. Various approaches exist to deal with this problem [13, 14, 15, 16, 17, 18]. One technique is to measure the CP violating phase for different polarisations of the final state, any observed differences then being interpreted as due to the pollution. This approach has been applied to the analysis of $B_s^0 \rightarrow J/\psi \phi$ decays [8] and no evidence of a polarisation-dependent CP violating phase is observed. The second is to study decays where the penguin-to-tree ratio is not suppressed, as is discussed in more detail below.

4.1 $B_s^0 \rightarrow J/\psi \bar{K}^* (892)^0$ and $B^0 \rightarrow J/\psi \rho^0$

A suitable channel where the penguin amplitude is not suppressed relative to the tree is $B_s^0 \rightarrow J/\psi \bar{K}^* (892)^0$ [13, 15, 16]. The amplitudes for this mode and $B_s^0 \rightarrow J/\psi \phi$ are given by,

$$A(B_s^0 \rightarrow (J/\psi \bar{K}^{*0})_f) = -\lambda \mathcal{A}_f \left[1 - a_f e^{i\theta_f} e^{i\gamma} \right], \quad A(B_s^0 \rightarrow (J/\psi \phi)_f) = (1 - \lambda^2/2) \mathcal{A}'_f \left[1 + \varepsilon a'_f e^{i\theta'_f} e^{i\gamma} \right], \quad (4.1)$$

where f represents the polarisation of the final state, γ is an angle of the CKM triangle and $\mathcal{A}_f^{(i)}$ is a CP -conserving hadronic matrix element. The parameters $a_f^{(i)}$ and $\theta_f^{(i)}$ are the magnitude and phase of the penguin amplitude, respectively. The first stage towards constraining the size of the penguin phase is to perform an angular analysis of the $B_s^0 \rightarrow J/\psi \bar{K}^{*0}$ decay products. This allows

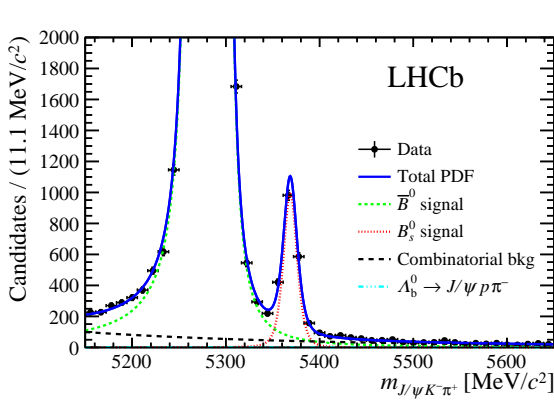


Figure 4: Distribution of $J/\psi K^*0$ invariant mass for all $B_s^0 \rightarrow J/\psi K^*0$ candidates.

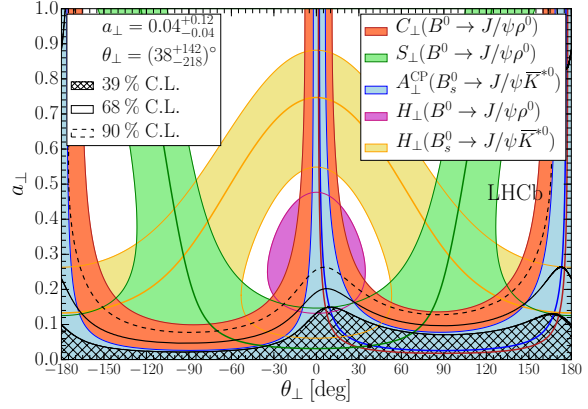


Figure 5: Limits on the penguin parameters a_\perp and θ_\perp obtained from intersecting contours derived from CP asymmetries and branching fraction measurements in $B_s^0 \rightarrow J/\psi K^*0$ and $B^0 \rightarrow J/\psi \rho^0$. Superimposed are the confidence-level contours from a χ^2 fit to the data.

the branching fraction of the decay to be measured along with the polarisation fractions of the final state. By separating the sample into B_s^0 and \bar{B}_s^0 subsets, the CP asymmetries for each polarisation can also be measured after accounting for production and detection asymmetries [19, 20]. The LHCb collaboration has recently published [21] the results of this analysis using a sample of 1800 $B_s^0 \rightarrow J/\psi K^*0$ signal events as seen in Figure 7. The branching fraction is measured to be $\mathcal{B}(B_s^0 \rightarrow J/\psi K^*0) = (4.13 \pm 0.16 \pm 0.25 \pm 0.24 (f_s/f_d)) \times 10^{-5}$ and the CP asymmetries are all consistent with zero at a precision of $\sim 10\%$, dominated by the statistical uncertainty.

The second stage then relates these experimental observables to the penguin parameters in both $B_s^0 \rightarrow J/\psi K^*0$ and $B_s^0 \rightarrow J/\psi \phi$. A χ^2 fit is performed to measure values for the penguin parameters using the assumption of SU(3) flavour symmetry ($a'_f = a_f$ and $\theta'_f = \theta_f$), a light-cone sum rule calculation [22] of $|\mathcal{A}'_f/\mathcal{A}_f|$ and $\gamma = (3.2^{+6.3}_{-7.0})^\circ$ [3]. These are subsequently translated into values for the penguin phase shift that are shown to be consistent with zero, albeit with large uncertainties of ~ 0.050 rad.

The dominate systematic uncertainty from the theoretical calculation of $|\mathcal{A}'_f/\mathcal{A}_f|$ can be removed and the overall statistical uncertainty reduced by including complementary information on the CP violating phases measured by the LHCb collaboration in each polarisation state of the $B^0 \rightarrow J/\psi \rho^0$ ($\rho^0 \rightarrow \pi^+ \pi^-$) channel [23]. Figure 5 shows the constraints from each measurement for one polarisation state. The central values of the parameters are measured using a χ^2 fit, the result of which is shown by the black contours in Figure 5. Again, the penguin phase shifts are found to be consistent with zero, but now determined to a precision of ~ 0.015 rad through the additional information from the $B^0 \rightarrow J/\psi \rho^0$ channel. This should be compared with the current experimental precision on $\phi_{d,s}$ that are at ~ 0.030 rad.

4.2 $B_s^0 \rightarrow J/\psi K_s^0$

The golden mode for controlling the penguin phase shift to ϕ_d is $B_s^0 \rightarrow J/\psi K_s^0$. This is re-

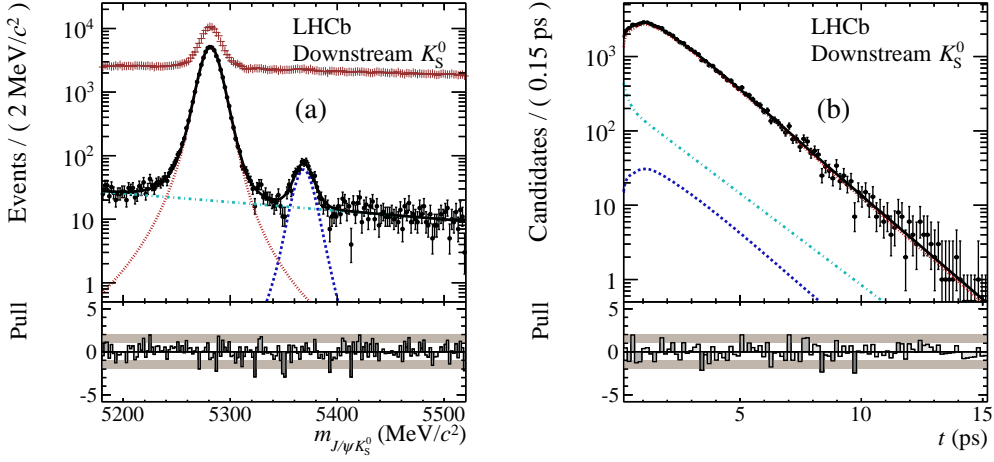


Figure 6: Distributions of (a) $J/\psi K_S^0$ invariant mass and (b) decay time of $B_s^0 \rightarrow J/\psi K_S^0$ candidates. In (a) the distribution before (red) and after (black) the machine learning selection is applied are shown.

lated to $B^0 \rightarrow J/\psi K_S^0$ via the U-spin symmetry of strong interactions [13] but is CKM suppressed making it more difficult to observe the decay. The LHCb collaboration has recently [24] used machine learning techniques to suppress backgrounds from combinatorics and mis-reconstructed $B^0 \rightarrow J/\psi K^{*0}$ decays to observe $B_s^0 \rightarrow J/\psi K_S^0$. Figure 6 shows the distribution of invariant mass and B_s^0 decay time for a subset of $B_s^0 \rightarrow J/\psi K_S^0$ candidates. In total ~ 900 signal events are found with an effective tagging efficiency of $\sim 4\%$. These are used to measure the decay time dependent CP violation observables $A_{\Delta\Gamma}, C, S$ defined in Equation (1.1). All are found to be consistent with zero. The large statistical uncertainty on these measurements is insufficient to constrain the size of the penguin shift to ϕ_d but this proof-of-principle measurement indicates what is possible with future datasets collected by LHCb.

4.3 $\bar{B}_s^0 \rightarrow \psi(2S)K^+\pi^-$

The LHCb collaboration has recently observed [25] the $\bar{B}_s^0 \rightarrow \psi(2S)K^+\pi^-$ decay, measuring the ratio of branching ratios $\mathcal{B}(\bar{B}_s^0 \rightarrow \psi(2S)K^+\pi^-)/\mathcal{B}(\bar{B}_s^0 \rightarrow \psi(2S)K^+\pi^-) = 5.38 \pm 0.36$ (stat) ± 0.22 (syst) ± 0.31 (f_s/f_d)%. Figure 7 shows the distributions of $\psi(2S)K^+\pi^-$ and $K^+\pi^-$ invariant masses from the sample. Using a four-dimensional amplitude analysis the fraction of decays proceeding via an intermediate $K^*(892)^0$ meson is measured to be 0.645 ± 0.049 (stat) ± 0.049 (syst) and its longitudinal polarisation fraction, $f_0 = 0.524 \pm 0.056$ (stat) ± 0.029 (syst). No exotic $Z^+ \rightarrow \psi(2S)\pi^+$ component [26] was observed with the current data sample but this mode could prove useful in the future to help understand the nature of the exotic charmonium states. In addition, using the same technique as discussed in Section 4.1, this mode could help to constrain the size of penguin pollution to the CP violating phase in $B_s^0 \rightarrow \psi(2S)\phi$ decays.

5. Summary

These proceedings have presented the latest measurements of CP violation in B meson mixing using $B \rightarrow J/\psi X$ decays collected by the LHCb experiment during pp collision runs at the LHC

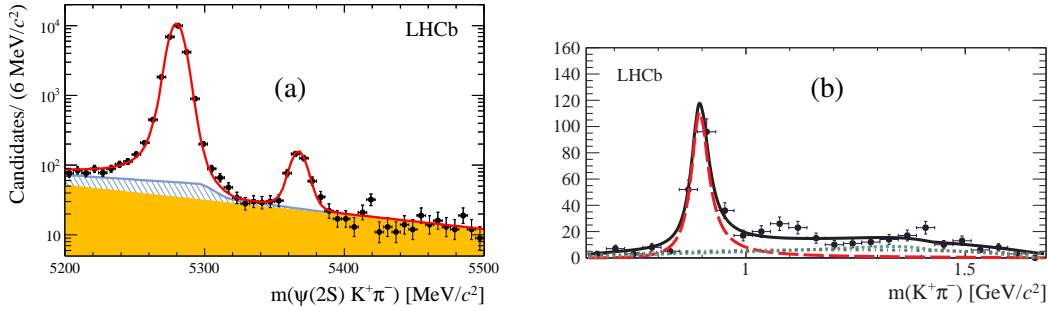


Figure 7: Distributions of (a) $\psi(2S)K^+\pi^-$ and (b) $K^+\pi^-$ invariant masses of $\bar{B}_s^0 \rightarrow \psi(2S)K^+\pi^-$ candidates. In (b) the contributions from the $K^*(892)^0$ (red-dashed), NR (green-dotted) and background (grey-dashed-dotted) components are visible.

at $\sqrt{s} = 7$ and 8 TeV. These represent the most precise determination of the CP violating phase ϕ_s using $B_s^0 \rightarrow J/\psi \phi$ and $B_s^0 \rightarrow J/\psi \pi^+\pi^-$ decays along with a very competitive measurement of the corresponding phase in the B^0 system using $B^0 \rightarrow J/\psi K_S^0$ decays. With this improved precision it is now essential that contributions to these decay processes from suppressed, but hard-to-calculate, penguin diagrams are under control. By making use of B meson decays where the penguin decay processes are not suppressed relative to the tree-level contribution (such as $\bar{B}_s^0 \rightarrow J/\psi K^{*0}$, $B^0 \rightarrow J/\psi \rho^0$ and $B_s^0 \rightarrow J/\psi K_S^0$) the LHCb collaboration has been able to constrain the size of the so-called penguin pollution, finding it to be small. The collaboration looks forward to collecting even more data during Run-2 of the LHC and beyond, where making further precision measurements of CP violating parameters will be essential as we search for signs of beyond-the-SM physics.

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