Neutral *B*-meson Mixing and *CP* Violation at LHCb

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Abstract. The LHCb detector is a single-arm forward spectrometer that collects data at the LHC, designed for studies of flavour physics with high precision. We present a selection of recent measurements of mixing and CP-violating parameters, including $\sin 2\beta$ and weak phase ϕ_s, using several decays. A good understanding of the pollution from sub-leading penguin topologies in these measurements can be achieved by measuring CP violation and polarization in the decay $B_s^0 \to J/\psi\, \bar{K}^{0*}$ and $B^0 \to J/\psi\, \rho^0$. All results here presented are obtained using the full Run I dataset.

1. Introduction

Studies of *CP* violation with heavy-flavoured hadrons are amongst the main interests of the LHCb collaboration. They can unveil indirect evidence of New Physics, revealing inconsistencies with respect to theoretical predictions based on the validity of the Standard Model (SM). Subtle *CP* violating effects can be searched for by overconstraining the angles and the sides of the CKM unitary triangle.

In this summary, selected results regarding B mesons mixing and *CP* violation are presented, including the measurements of the weak phases φ_d and φ_s and measurements to constrain penguin pollution.

2. LHCb spectrometer

The LHCb experiment (Figure 1) is a dedicated apparatus for studying flavour physics at the LHC at CERN. In particular, the experiment is designed to study *CP* violation and rare decays of beauty and charm particles. It is a single-arm forward spectrometer covering the pseudorapidity range $2<\eta<5$. Thus the LHCb programme is highly complementary to the direct searches performed by the ATLAS and CMS experiments.

The $b\bar{b}$ pair production in proton-proton collisions at the LHC is spatially correlated and occurs predominantly at small angles with respect to the beam axis.

The interaction point is surrounded by the Vertex Locator sub-detector, the role which is to

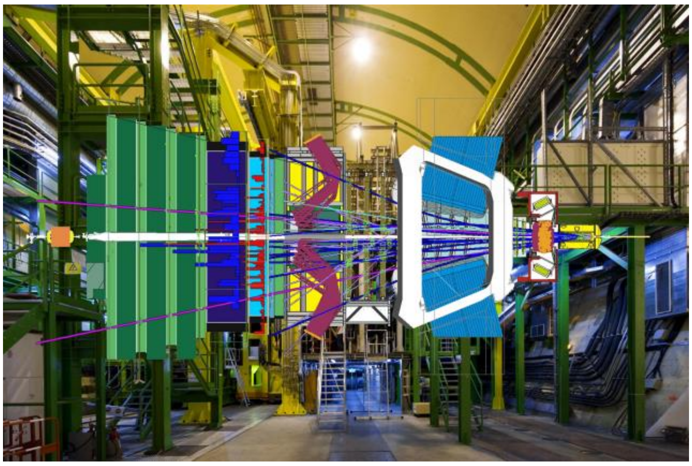

Figure 1. The LHCb forward spectrometer at the LHC with a sample event superimposed.

precisely determine both the position of primary and secondary vertices and allow study of the decays of beauty and charm particles.

In the Run I data taking, during the years 2010-12, LHCb collected data corresponding to an integrated luminosity of 3 fb^{-1} at $\sqrt{s}$ =7 TeV and 8 TeV. The spectrometer achieved an excellent vertex resolution, momentum determination with a precision of $\delta p/p$~0.4-0.6% and very good particle identification of hadrons in the range of 2-100 GeV. A complete description of the LHCb experiment may be found in [1].

3. Weak phase in *B* meson mixing

The phase differences between the amplitude for a direct decay $B^0_{(s)} \to f$ and the amplitude for decay after oscillation $B^0_{(s)} \to \bar{B}^0_{(s)} \to f$ can be expressed by the CKM angles $\phi_d \approx 2\beta$, $\phi_s \approx -2\beta_s$, where: $\beta = \arg\left(-\frac{V_{cd}V^*_{cb}}{V_{td}V^*_{tb}}\right)$ and $\beta_s = \arg\left(-\frac{V_{cb}V^*_{cs}}{V_{tb}V^*_{ts}}\right)$ for the B^0 and B^0_S mesons respectively.

From the experimental point of view, main aspects in the analysis are the tagging of the initial B^0 flavour at production and a very good decay-time resolution.
A major improvement in most of the LHCb analyses has been achieved due to the inclusion of a new tagging procedure (so-called "same-side pion" tagger) which deduces the production flavor by exploiting pions produced in the fragmentation of *b* quark in association with the signal *B* meson. All time-dependent studies require a very good decay-time resolution that is related not only to momentum resolution but also to an excellent precision on both primary and secondary vertex reconstruction. In the analyses presented below, the decay time distribution was extensively modeled taking into account different detector conditions (e.g. trigger, reconstruction, beam energy) using real and Monte Carlo data samples. The production and detector asymmetries were determined in separate analyses [2] and taken into account as well. All shown results are obtained using the whole Run I data sample.

3.1. *Measurement of* $sin\,2\beta$

The $B^0 \to J/\psi\, K^0_S$ decay is considered as a "golden mode" for the measurement of $sin\,2\beta$. As the $J/\psi\, K^0_S$ final state is common to both B^0 and $\bar{B}^0$ meson decays, the interference between the amplitudes for the direct decay and for the decay after B^0 oscillation results in a decay-time dependent asymmetry between the decay rates: $A_{CP}(t) = \frac{\Gamma\{B^0 \to J/\psi\, K^0_S\} - \Gamma\{\bar{B}^0 \to J/\psi\, K^0_S\}}{\Gamma\{B^0 \to J/\psi\, K^0_S\} + \Gamma\{\bar{B}^0 \to J/\psi\, K^0_S\}}$, which, neglecting penguin pollution, in the SM can be written as: $A_{CP}(t) \approx -\sin 2\beta \sin \Delta mt \equiv S \sin \Delta mt$, where Δm is the mass differences between the heavy and light mass eigenstates.

The reconstructed mass of the signal events is presented in Figure 2 together with the decay-time asymmetry of tagged *B* mesons [3].

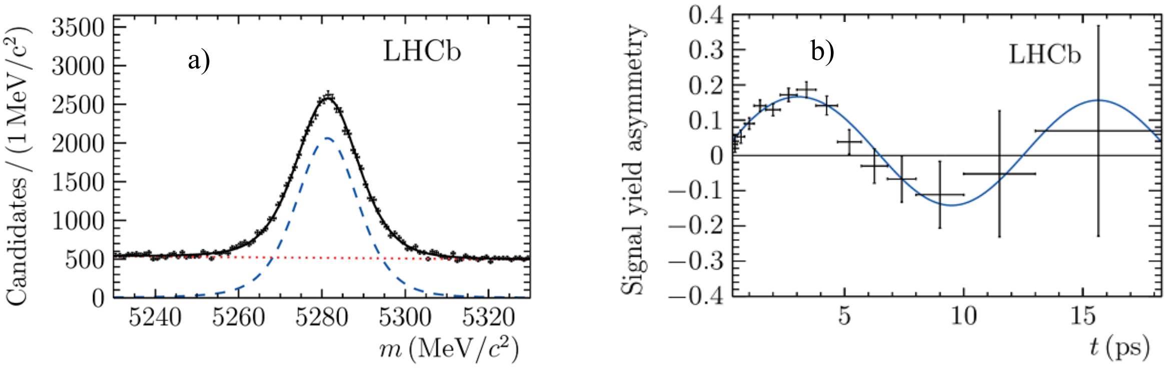

Figure 2. a) Mass distribution of $B^0 \to J/\psi\, K^0_S$ candidates. b) Time dependent asymmetry of signal events [3].

The likelihood fit to the time-dependent *CP* asymmetry, whose model takes into account different experimental conditions, signal with background and tagging decisions, yields the result: $S \equiv \sin 2\beta = 0.731 \pm 0.035(stat) \pm 0.020(syst)$. The value is consistent with the current world average and with the SM and is the most precise time-dependent *CP* violation measurement at hadron colliders obtained to date, with a precision competitive with *B*-factories [4].

3.2. Results on weak phase ϕ_s

The weak phase ϕ_s within the SM is predicted to be very small. The *CP*-violating phase ϕ_s arises from the interference between the amplitude of the mesons B_s^0 decaying directly via $b \to c\bar{c}s$ to *CP* eigenstates and after oscillation $B_s^0 - \bar{B}_s^0$. The LHCb experiment pioneered this measurement with a number of final states and currently dominates the world average [4].

3.2.1 $B_s^0 \to J/\psi\,\phi$. The "golden mode" for the ϕ_s measurement is the decay $B_s^0 \to J/\psi\,\phi$, counterpart of $B^0 \to J/\psi\, K_S^0$. The decays of B_s^0 and $\bar{B}_s^0$ mesons proceed through tree (which is dominant) and penguin (that is suppressed) diagrams.
The final state includes the vector meson $\phi(1020)$ that is in *P*-wave configuration and, depending on the relative momentum of the ϕ and J/ψ, *CP*-even and *CP*-odd components are expected. Their disentanglement is done by means of an angular analysis in the helicity basis. The mass distribution for $J/\psi\,(\to \mu^+\mu^-)K^-K^+$ candidates is shown in Figure 3a, when a huge number of about $96 \cdot 10^3$ signal events enables a precise angular analysis ($\cos\theta_K$ distribution is shown in Figure 3b) [5].

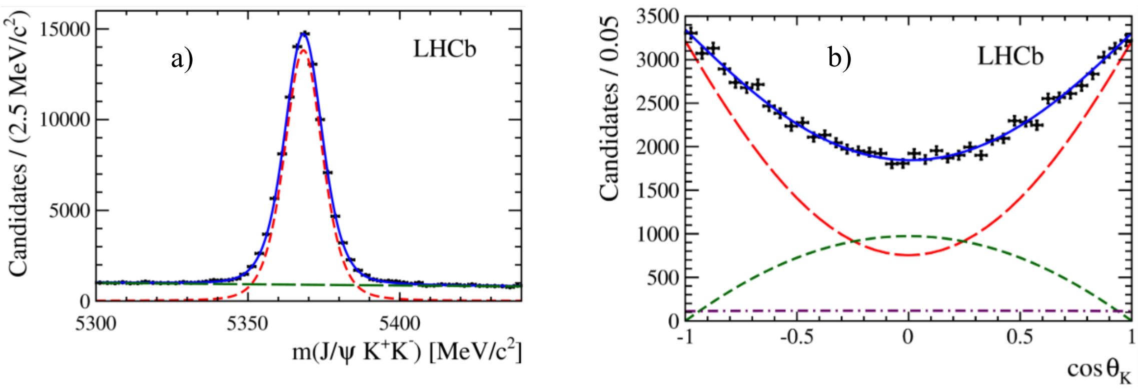

Figure 3. a) Mass distribution of the J/ψKK events. The B^0 signal component is shown by the red dashed line and the combinatorial background by the green long-dashed line. b) Distribution of $\cos\theta_K$ with the fit projection. The solid blue line shows the total signal contribution, which is composed of CP-even (long-dashed red), CP-odd (short-dashed green) and S-wave (dotted-dashed purple) components [5].

The main physics parameters (Δm_s, Γ_S, $\Delta\Gamma_S$, ϕ_S, $|\lambda|$ and polarization amplitudes) were obtained from a maximum likelihood fit to the decay-time and angle distributions, yielding: $\phi_s = -0.058 \pm 0.049 \pm 0.006$ rad, $\Delta\Gamma_S = 0.805 \pm 0.0027 \pm 0.0015\, ps^{-1}$, $\Delta m_s = 17.711^{+0.055}_{-0.057} + 0.011\, ps^{-1}$. The parameter $|\lambda|$ is consistent with unity, implying no evidence for direct *CP* violation.
The combination of the results obtained in the $B_s^0 \to J/\psi K^-K^+$ and $B_s^0 \to J/\psi\,\pi^-\pi^+$ analyses [6] makes the measurement of ϕ_s the most precise result to date, in agreement with the SM prediction [7].

3.2.1 $B_s^0 \to D_s^+ D_s^-$. This channel also proceeds via $b \to c\bar{c}s$ transitions. As the final state does not include vector mesons, an angular analysis is unnecessary. From the Run I data sample about 3350 flavour tagged signal events were reconstructed. The mass distribution and decay time of the candidates are presented in Figure 4a and 4b respectively [8].

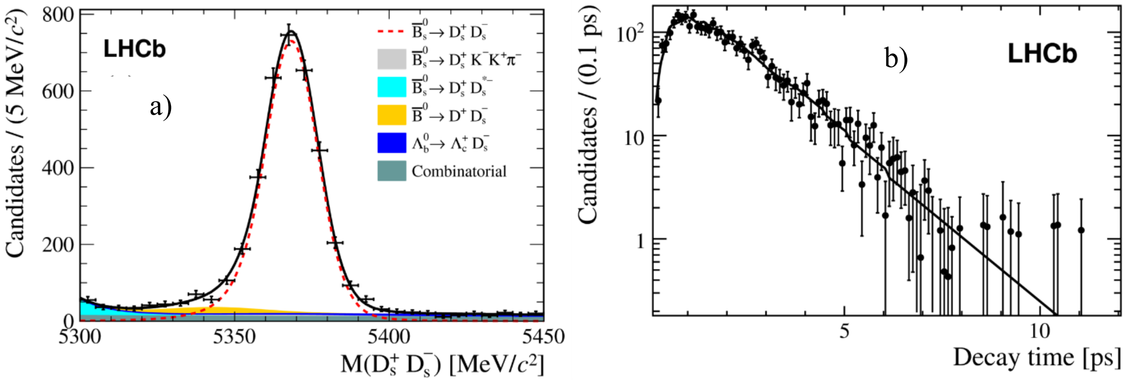

Figure 4. a) Invariant mass distribution of $D_s^+ D_s^-$ events. b) Distribution of the decay time for signal events along with the fit. Discontinuities in the fit line shape are a result of the binned acceptance [8].

The first measurement with this decay mode, obtained by means of a time-dependent study, yields the result: $\phi_s(D_s^+ D_s^-) = 0.02 \pm 0.17(stat) \pm 0.02(syst)$ and $|\lambda| = 0.91^{+0.18}_{-0.15}(stat) \pm 0.02(syst)$, that is consistent with the SM.

3.2.1 $B_s^0 \to \phi\phi$. This is a penguin-dominated process that proceeds via $b \to ss\bar{s}$ transition. As such, it is an excellent probe for New Physics, since new, heavy particles may enter the quantum loops.

More than 4000 signal events were observed in the LHCb Run I data sample [9]. The presence of vector mesons in the final state requires a time-dependent angular analysis. The result yields: $\phi_s(\phi\phi) = -0.17 \pm 0.15(stat) \pm 0.03(syst)$. It's worth noting, that this channel will greatly benefit from the new LHCb trigger in Run II and the obtained precision is expected to improve considerably.

4. Constraining the penguin pollution

The measured value of weak phases, arising from the interference between neutral B meson mixing and decay, is effectively the sum of a term that contains CKM angle β_s, a hadronic term related to gluonic penguin diagrams δ_P and a possible New Physics (NP) contribution δ_{NP}: $\phi_s(measured) = -2\beta_s + \delta_P + \delta_{NP}$. For this reason, before claiming NP discovery, we need to constrain the SM gluonic part, which is colloquially called "penguin pollution". A novel method of constraining the gluonic part δ_P directly from the measurement was proposed [10] and firstly performed by LHCb [11].

In order to constrain penguin contribution in $B_s^0 \to J/\psi\,\phi$ and $B^0 \to J/\psi\,K_S^0$ we need to find control channels, where processes with gluonic loop are not suppressed with respect to dominant tree diagram (see the Figure 5).

This method of obtaining the estimator for δ_P, referred to as "effective approach" can be described by following steps:

- identifying penguin parameters related to the $B_s^0 \to J/\psi\,\phi$ and $B^0 \to J/\psi\,K_S^0$ decays,
- measurement of certain observables in control channels, such as $B^0 \to J/\psi\,\rho^0$ and $B_s^0 \to J/\psi\,\bar{K}^{0*}$,
- relating them with the penguin parameters by assuming SU(3) flavour symmetry.

This approach requires measurement of the branching fractions, direct asymmetries and polarisation fractions, which all depend on the penguin parameters. The analysis is based on the helicity basis, whose amplitudes are rotated into transversity ones that correspond to the different parity eigenstates.

The angular distributions for the $B_s^0 \to J/\psi\,\bar{K}^{0*}$signal events are presented in Figure 6. The transversity amplitudes of the angular method depend on the $K^-\pi^+$mass, so the analysis is performed in different bins of $m_{K^-\pi^+}$ and finally summed over all contributions.

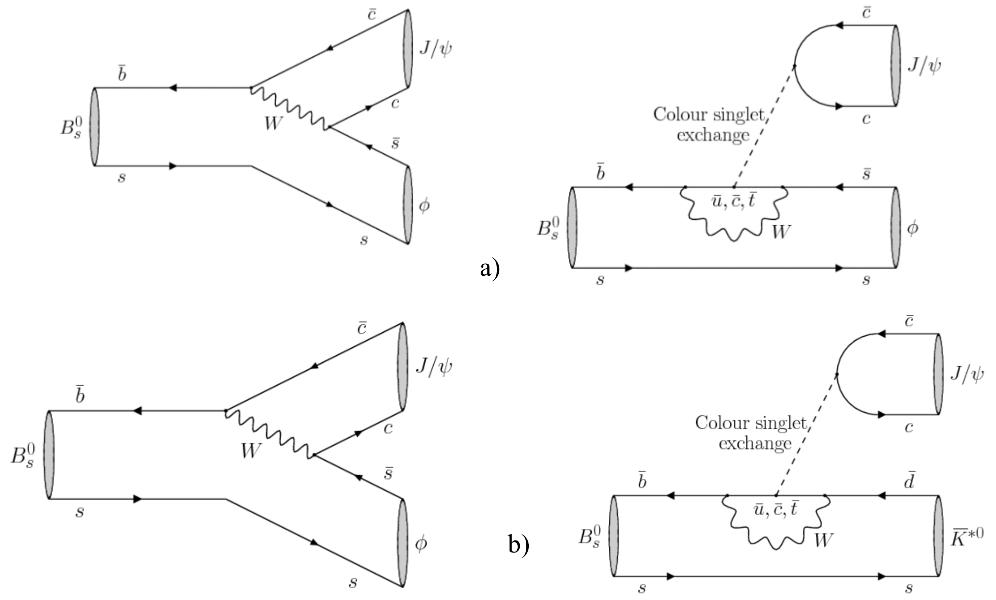

Figure 5. a) The dominant tree and suppressed loop diagrams contributing to the weak phase ϕ_s measurement via $B_s^0 \to J/\psi\,\phi$. b) The diagrams of the control channel $B_s^0 \to J/\psi\,\bar{K}^{0*}$ which contains amplitudes of comparable order.

The penguin parameters are measured and translated into phase shift δ_P. The value obtained is consistent with zero but with large systematic uncertainties coming from theoretical assumptions. They can be further reduced by using the $B^0 \to J/\psi\,\rho^0$ decay mode. The mass distributions for the two mentioned channels are shown in Figure 7.

Direct and mixing-induced time-dependent *CP* violation is observed in the case of $B^0 \to J/\psi\,\rho^0$ decay which parameters depend on the phase ϕ_d. So quantifying the gluonic contribution requires an interplay between the high precision determination of ϕ_d and ϕ_s.

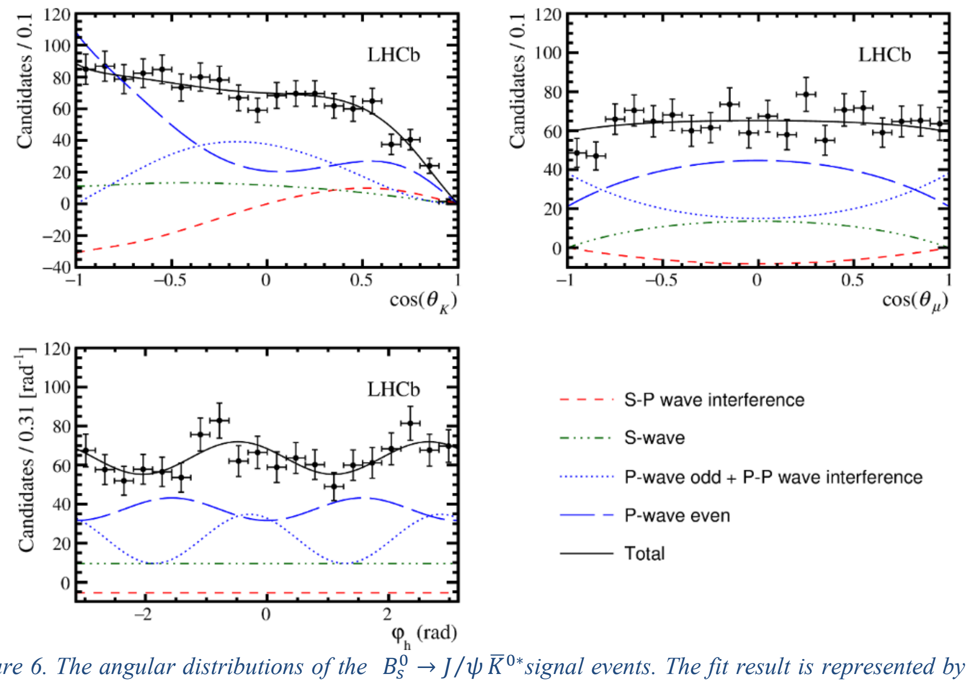

Figure 6. The angular distributions of the $B_s^0 \to J/\psi\,\bar{K}^{0*}$ signal events. The fit result is represented by the solid black line and the contributions from the different amplitude components are described in the legend [11].

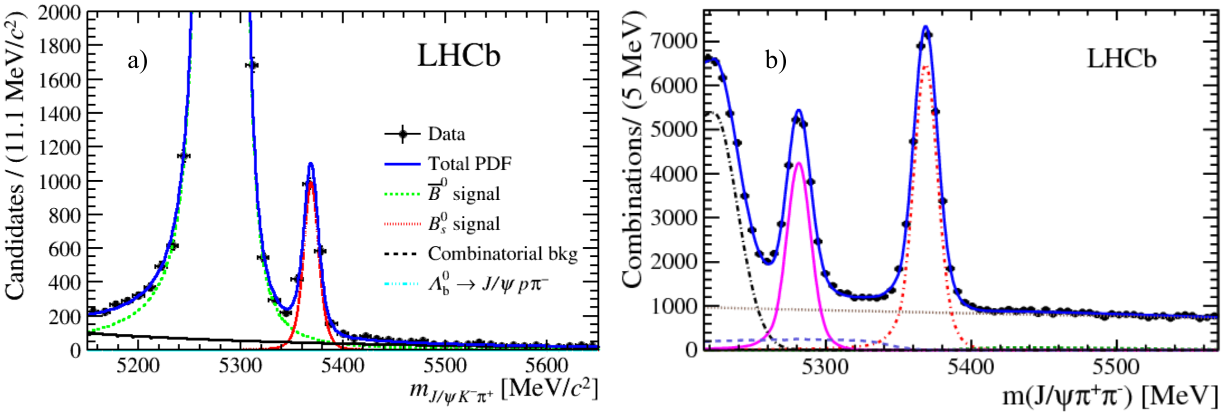

Figure 7. a) The $J/\psi\, K^-\pi^+$invariant mass distributions with the sum of fit projections (blue line) in $m_{K^-\pi^+}$ and $\cos\theta_\mu$ bins. The contributions of different components are detailed in the legend. b) The $J/\psi\,\pi^+\pi^-$invariant mass distributions. The purple solid line represents the B^0signal, the red dot-dash is $B_s^0 \to J/\psi\,\pi^+\pi^-$, the dotted brown – combinatorial background.

Combining the control channels, we measured the weak phase ϕ_s in the different polarisation states and the shift that comes from penguin pollution. For each polarization states $(0, \parallel, \perp)$ the phase shifts in $B_s^0 \to J/\psi\,\phi$ due to penguin pollution are: $\delta_p^0 = 0.000^{+0.009}_{-0.011}\,(stat)\,^{+0.004}_{-0.009}\,(syst)$ rad, $\delta_p^{\parallel} = 0.001^{+0.010}_{-0.014}\,(stat) \pm 0.008\,(syst)$ rad and $\delta_p^{\perp} = 0.003^{+0.010}_{-0.014}\,(stat) \pm 0.008\,(syst)$ rad. The results are in agreement with the SM and gluonic term appeared to be small.

5. Summary

The LHCb experiment, designed to study *CP* violation and rare decays of beauty and charmed hadrons produced in proton-proton collisions at the LHC, has performed a plethora of high-precision measurements, largely surpassing in many cases the knowledge from previous experiments.
Especially the principal *CP*-violating parameters, such as the weak mixing phases in both B^0 and B_s^0 sectors, yields the results: $\sin 2\beta = 0.731 \pm 0.035(stat) \pm 0.020(syst)$ and $\phi_s = -0.058 \pm 0.049(\mathrm{stat}) \pm 0.006(\mathrm{syst})$ rad. Sensitivity for ϕ_s will further increase after Run II and the LHCb Upgrade.

Constraints on penguin pollution were put using measurements of the hadronic parameters in the control channels. Such pioneering results showed that they are small within the present uncertainties, but further data will be needed to constrain such quantities to the required level of precision.

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