CP violating phase $\phi_s$ and $\Delta \Gamma_s$ measurements at LHCb

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Recent LHCb measurements of the mixing-induced CP violating phase $\phi_s$ in $B_0^s$ decays through $b \to c\bar{c}s$ transitions are presented. The LHCb Collaboration has published such measurements using $B_0^s \to J/\psi \pi^+ \pi^-$ and $B_0^s \to J/\psi K^+ K^-$ decay modes from 3 fb$^{-1}$ of $pp$ collision data. In the latter decay channel, also $\Gamma_s$, $\Delta m_s$, and the decay width difference, $\Delta \Gamma_s$, are measured. Contributions to this phase from second-order diagrams are obtained from a combined fit using $B_0^s \to J/\psi K^{(*)0}$ and $B^0 \to J/\psi \rho^0$ decays. An observation reported by the LHCb Collaboration of $\bar{B}_s^0 \to \psi(2S) K^+ \pi^-$ decays is presented as well. Finally, world averages for $\phi_s$ and $\Delta \Gamma_s$ by the Heavy Flavor Average Group, using results not only from LHCb but also from ATLAS, CMS, D0 and CDF collaborations, are discussed.

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1. CP violation in the interference between $B^0_s$ mixing and decay

For the $B^0_s$ meson system, a CP violating interference phase $\phi_{d(s)}$ can arise due to the interference between the decay to a CP eigenstate before and after $B^0_s - \bar{B}^0_s$ oscillation (see Figure 1). Experimentally, this phase can be accessed via a time-dependent asymmetry of the $B^0_s$ and $\bar{B}^0_s$ decay rates.

Here we focus on the $B^0_s$ meson system, where the $B^0_s$ meson decays through $b \to c\bar{c}s$ transitions of the non-spectator $b$ quark. In the Standard Model (SM), and taking into account only tree-level contributions, this CP violating phase $\phi_{c\bar{c}s}$ can be written as a function of elements of the Cabibbo-Kobayashi-Maskawa (CKM) matrix [1, 2], as

$$\phi_s = -2 \arg \left( \frac{V^*_{cb}V_{cs}}{V^*_{tb}V_{ts}} \right) \equiv -2 \beta_s. \tag{1.1}$$

The fact that any possible new particle contributing to the “box” diagram (shown in Figure 1) can modify the predicted value for $\phi_s$ [3], and the very precise SM estimation for this phase, $-0.0376^{+0.0008}_{-0.0007}$ rad [4], makes $\phi_s$ an excellent probe to search for possible New Physics (NP).

2. Flavour tagging at LHCb

The knowledge of the production and decay flavour of a reconstructed $B$ meson, flavour tagging, is required in the CP violation studies presented in this talk [5, 6, 7]. In the LHCb experiment, there are two types of flavour taggers: SS (same-side) taggers, focused on the associated production with the signal $B$ meson [8]; and OS (opposite-side) taggers, focused instead on the complementary $b$ quark of the $b\bar{b}$ pair [9]. In CP violation studies, the tagging power of these algorithms represents the effective statistical reduction of the studied sample size, having a direct impact on the sensitivity of the measured CP asymmetries.

A new SSK (same-side kaon) tagger algorithm has been developed by the LHCb Collaboration: based on a pair of neural networks and calibrated using the Run I dataset (consisting of $3 \text{ fb}^{-1}$)

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1 Further references to $\phi_s$ are assumed to be referred to $\phi_{c\bar{c}s}$ through the rest of these proceedings.
of data from $pp$ collisions), an improvement of $\approx 50\%$ of the SSK tagging power w.r.t. the former SSK algorithm is achieved [10].

A new OS tagger focused on $b \to c$ transitions has been developed, the OS-charm tagger, using 3 fb$^{-1}$ of $pp$ data. Including this new tagger along with the OS-electron/muon ($b \to eW$), the OS-kaon ($b \to c \to s$), and the OS vertex charge taggers leads to an absolute gain in OS tagging power of approximately 0.11\% [11].

3. Results from $B^0_s \to J/\psi K^+K^-$ decays

The decay channel $B^0_s \to J/\psi K^+K^-$ is considered as a golden mode to study mixing-induced $CP$ violation effects: not only $\phi_s$ but also other parameters of interest as the mass difference $\Delta m_s$, the decay width and decay width difference $\Gamma_s$ and $\Delta \Gamma_s$, and the modulus of the time-dependent asymmetry ratio $|\lambda|$, can be obtained from the study of these decays. Since the $K^+K^-$ spectrum for masses less than 1.05 GeV/$c^2$ has been found to be dominated by a large resonant P-wave component (corresponding to the $\phi(1020)$ meson), followed by a small fraction (around 2.3\%) of S-wave, an angular analysis is needed to disentangle the different $CP$ components of $B^0_s \to J/\psi\phi$ ($CP$-admixture) decays.

The LHCb Collaboration has performed a time-dependent angular analysis, using 3 fb$^{-1}$ of $pp$ data, of $B^0_s \to J/\psi K^+K^-(\phi)$ decays [5]. Using 95690 $B^0_s \to J/\psi\phi$ signal events, with a tagging power of 3.73 $\pm$ 0.15\% and a decay time resolution of approximately 46 fs, a value for $\phi_s$ of $-0.058 \pm 0.049$ (stat) $\pm 0.006$ (syst) rad is measured. This value, along with the results for $\Delta m_s$, $\Gamma_s$, $\Delta \Gamma_s$ and $|\lambda|$, are shown in Table 1, and found to be compatible with the SM predictions and with no direct $CP$ violation [4, 12]. Also, no polarisation-dependent $CP$ violation is observed [13]. Main contributions of systematic uncertainties come from decay time and angular efficiencies.

4. Results from $B^0_s \to J/\psi \pi^+\pi^-$ decays

The LHCb Collaboration has also measured $\phi_s$ and $|\lambda|$ in $B^0_s \to J/\psi \pi^+\pi^-$ decays [6] using Run I data. In this case, the more complicated $\pi^+\pi^-$ spectrum is found to be dominated by a CP-odd component, where its contribution is higher than 97.7\% at 95\% CL [14]. From a four-dimensional fit to the mass of the $\pi^+\pi^-$ spectrum and the three decay angles of 27100 $B^0_s \to J/\psi \pi^+\pi^-$ signal events, with a tagging power of 3.89 $\pm$ 0.23\% and a decay time resolution of around 40.5 fs, the values $\phi_s = 0.070 \pm 0.068$ (stat) $\pm 0.008$ (syst) rad and $|\lambda| = 0.89 \pm 0.05$ (stat) $\pm 0.01$ (syst) are obtained. No direct $CP$ violation and consistency with SM predictions [4, 12, 15] are found. Systematic uncertainties are mainly dominated by the limited knowledge of the $\pi^+\pi^-$ spectrum.

Results from $B^0_s \to J/\psi K^+K^-$ and $B^0_s \to J/\psi \pi^+\pi^-$ decays, summarised in Table 1, are combined, assuming that the exact same quantities are measured, in the most precise measurements of $\phi_s$ and $|\lambda|$ in $b \to c\bar{c}s$ processes to date: $\phi_s = -0.010 \pm 0.039$ rad and $|\lambda| = 0.957 \pm 0.017$ [5].

5. Contributions to $\phi_s$ due to second-order topologies

As a pure SM effect, second-order contributions to $\phi_s$ due to penguin diagrams (see Figure 2),
Parameter & $B^0_s \to J/\psi K^+ K^-$ & $B^{0*}_s \to J/\psi \pi^+ \pi^-$ & Combination \\
$\phi_s$ [rad] & $-0.058 \pm 0.049 \pm 0.006$ & $0.070 \pm 0.068 \pm 0.008$ & $-0.010 \pm 0.039$ \\
$|\lambda|$ & $0.964 \pm 0.019 \pm 0.007$ & $0.89 \pm 0.05 \pm 0.01$ & $0.957 \pm 0.017$ \\
$\Gamma_s$ [ps$^{-1}$] & $0.6603 \pm 0.0027 \pm 0.0015$ & -- & -- \\
$\Delta\Gamma_s$ [ps$^{-1}$] & $0.0805 \pm 0.0091 \pm 0.0032$ & -- & -- \\
$\Delta m_s$ [ps$^{-1}$] & $17.711 \pm 0.056 \pm 0.011$ & -- & -- \\

Table 1: Summary of LHCb results from the analyses of $B^0_s \to J/\psi K^+ K^-$ and $B^{0*}_s \to J/\psi \pi^+ \pi^-$ decays, and their combination for parameters $\phi_s$ and $|\lambda|$. When two uncertainties are shown, the first is statistical and the second one is systematic.

$\delta_P$, could mimic possible NP effects, $\delta_{NP}$, since

$$ \phi_s \text{ (measured)} = -2\beta_s + \delta_P + \delta_{NP}. \quad (5.1) $$

Figure 2: Tree-level diagram (left) and second-order (penguin) diagram (right) for $B^0_s \to J/\psi \phi$ mode.

In the search for possible NP, the estimation of this effect (known as penguin pollution) becomes mandatory with the upgrade of current generation detectors, where the sensitivity continues to improve.

Since second-order contributions are suppressed w.r.t. the tree-level in $B^0_s \to J/\psi \phi$ decays by approximately a factor 95% and are difficult to calculate in perturbative QCD (pQCD) [13, 16], an alternative strategy [17, 18] is followed. The decay amplitude of the $B^0_s \to J/\psi \phi$ mode can be written as a function of some hadronic parameters (henceforth referred to as penguin parameters), which can be related (under SU(3) flavour symmetry assumptions) to observables in control channels where second-order contributions are not suppressed. The main idea is to obtain these penguin parameters in the control channels via the measurement of certain observables.

5.1 Using $B^0_s \to J/\psi \bar{K}^{*0}$ as a control channel

An angular analysis of $B^0_s \to J/\psi K^- \pi^+$ decays (3 fb$^{-1}$) has been published by the LHCb Collaboration [19], where the $K^- \pi^+$ spectrum is found to be broadly dominated by the $\bar{K}(892)^{*0}$ resonance. Hence, focusing on the $B^0_s \to J/\psi \bar{K}^{*0}$ mode, direct CP asymmetries and polarisation
These results, dominated by the input from the state to obtain the parameters needed to estimate the penguin pollution to $\phi_i$. Since the final state $J/\psi K^{*0}$ is not a CP eigenstate, a decay-time-integrated and flavour-averaged analysis is performed, using 1808 $B^0 \rightarrow J/\psi K^{*0}$ signal events. Polarisation-dependent results are summarised in Table 2. The branching fraction is measured to be $\beta(B^0 \rightarrow J/\psi K^{*0}) = (4.14 \pm 0.18 \text{ (stat)} \pm 0.26 \text{ (syst)} \pm 0.24 \text{ (f/d/f_s)}) \times 10^{-5}$. Simulation-based corrections to the angular acceptance are applied, being these the main source of systematic uncertainties. Production and detection asymmetries are taken into account [20, 21].

5.2 Combination with results from $B^0 \rightarrow J/\psi\rho^0$ decays

From a combined fit using not only inputs from the $B^0 \rightarrow J/\psi K^{*0}$ analysis but from the $B^0 \rightarrow J/\psi\rho^0$ mode as well [22], LHCb Collaboration has reported the following values for the penguin pollution to the CP violating $\phi_i$ phase in $b \rightarrow c\bar{c}s$ processes, $\delta_P$, in each final polarisation state [19],

$$
\begin{align*}
\delta_P^0 & = 0.000 \pm 0.0004 \pm 0.0004 \text{ rad,} \\
\delta_P^\parallel & = 0.001 \pm 0.0014 \pm 0.008 \text{ rad,} \\
\delta_P^\perp & = 0.003 \pm 0.0014 \pm 0.008 \text{ rad.}
\end{align*}
$$

These results, dominated by the input from the CP asymmetries in $B^0 \rightarrow J/\psi\rho^0$ decays, were found to be small and well under control. A plot from the fit for the parallel (||) final polarisation state to obtain the penguin parameters $a_{\parallel}$ and $\theta_{\parallel}$ is shown in Figure 3.

6. Observation of $\bar{B}^0 \rightarrow \psi(2S)K^+\pi^-$ decays

The LHCb Collaboration published recently the observation (3 fb$^{-1}$) of $\bar{B}^0 \rightarrow \psi(2S)K^+\pi^-$ decays [23]. This mode is analogous to the $B^0 \rightarrow J/\psi K^{*0}$ channel, except for the $c\bar{c}$ quark pair hadronising into the heavier $\psi(2S)$ meson, but also being reconstructed into a dimuon final state. Hence, penguin pollution to $\phi_i$ when it is measured using $B^0 \rightarrow \psi(2S)X$ modes (such as $B^0 \rightarrow \psi(2S)K^+K^-$ decays) may be estimated from $B^0 \rightarrow \psi(2S)K^{*0}$ decays, since $\delta_P$ depends on the hadronisation of the final state. An additional motivation for this analysis is the search for exotic states: the LHCb Collaboration reported a couple of years ago the observation of the $Z(4430)^-$ tetraquark in $B^0 \rightarrow \psi(2S)K^+\pi^-$ decays [24], which is the $B^0$ counterpart of this mode.
In this analysis, the fraction of events and the longitudinal polarisation fraction for the $K^{*0}$ meson are measured, $f(K^{*0})$ and $f_L$ respectively, along with the neutral $B$ meson mass difference, and with the normalised branching fractions $\mathcal{B}(B_s^0 \rightarrow \psi(2S)K^+\pi^-)$ and $\mathcal{B}(B_s^0 \rightarrow \psi(2S)K^{*0})$. Using 239 $\bar{B}_s^0 \rightarrow \psi(2S)K^+\pi^-$ signal events, a four-dimensional fit to the $K^+\pi^-$ invariant mass and the three decay angles is performed, leading to the following results,

$$f_L = 0.524 \pm 0.056 \pm 0.029,$$

$$f(K^{*0}) = 0.645 \pm 0.049 \pm 0.049,$$

$$\frac{\mathcal{B}(B_s^0 \rightarrow \psi(2S)K^+\pi^-)}{\mathcal{B}(B^0 \rightarrow \psi(2S)K^+\pi^-)} = (5.38 \pm 0.36 \pm 0.22 \pm 0.31 \ (f_i/f_d)\%) \%,$$

$$\frac{\mathcal{B}(B_s^0 \rightarrow \psi(2S)K^{*0})}{\mathcal{B}(B^0 \rightarrow \psi(2S)K^{*0})} = (5.58 \pm 0.57 \pm 0.40 \pm 0.32 \ (f_i/f_d)\%) \%,$$

$$M(B_s^0) - M(B^0) = 87.45 \pm 0.44 \pm 0.09 \text{ MeV}/c^2,$$

which have been found to be compatible with previous studies [19, 25, 26], and where the first uncertainties are statistical and the second are systematic. The latter are dominated by the amplitude model used for the fit. Apart from $B_s^0 \rightarrow \psi(2S)K^{*0}$ decays, no other significant structure is found in the four-body mass spectrum.

7. Summary and prospects

The latest combination [27] by the Heavy Flavor Average Group (HFAG), including results from ATLAS, CMS, CDF, D0 and LHCb collaborations (the latter includes not only results from the analysis of $B_s^0 \rightarrow J/\psi K^+K^-$ and $B_s^0 \rightarrow J/\psi \pi^+\pi^-$ decays but also from the $B_s^0 \rightarrow D^+D_s^-$ mode [7]) leads to the following world averages (see Figure 4) of $\phi_s$ and $\Delta\Gamma_s$,

$$\phi_s = -0.033 \pm 0.033 \text{ rad},$$

$$\Delta\Gamma_s = 0.083 \pm 0.006 \text{ ps}^{-1},$$
which are fully compatible with SM estimations [4, 12].

\[
\phi_s = -0.0376^{+0.0008}_{-0.0007} \text{ rad}, \\
\Delta \Gamma_s = 0.088 \pm 0.020 \text{ ps}^{-1}.
\]

In order to improve the sensitivity and reduce the statistical uncertainty of these measurements, the LHCb Collaboration also plans to study additional time-dependent decay modes, such as \(B_s^0 \to \psi(2S)K^+K^-\) and \(B_s^0 \to J/\psi(e^+e^-)K^+K^-\) decays, and to update current \(B_s^0 \to J/\psi K^+K^-\) and \(B_s^0 \to J/\psi \pi^+\pi^-\) studies including \(pp\) collisions data from Run II as well. For the High Luminosity (HL) LHC era (scheduled for 2028), statistical uncertainties more than five times smaller than present ones are expected for these \(\phi_s\) measurements [28].

8. Conclusions

In these proceedings, Run I LHCb results for the \(CP\) violating phase \(\phi_s\), \(|\lambda|\), and for the decay width difference \(\Delta \Gamma_s\) from \(B_s^0 \to J/\psi \pi^+\pi^-\) and \(B_s^0 \to J/\psi K^+K^-\) decay modes are presented, as well as results for the decay width and mass differences \(\Gamma_s\) and \(\Delta m_s\). Results have been found to be fully compatible with SM estimations. An LHCb estimation of the second-order contributions to the \(\phi_s\) phase, measured in \(B_s^0 \to J/\psi K^{*0}\) and \(B^0 \to J/\psi \rho^0\) channels and known as \textit{penguin pollution}, is also presented, being found to be not larger than 21 mrad and well under control. An observation of the decay channel \(\bar{B}_s^0 \to \psi(2S)K^+K^-\) by the LHCb Collaboration is also described in this document, where the normalised branching fractions, \(K^{*0}\) longitudinal polarisation fraction and ratio, and neutral \(B\) meson mass difference are measured and found to be compatible with previous studies. Finally, world average results on \(\phi_s\) and \(\Delta \Gamma_s\) obtained by the HFAG are presented, along with the most relevant prospects by the LHCb Collaboration.

References

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