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

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Recent LHCb measurements of the mixing-induced CP violating phase ϕ_s in B_s^0 decays through $b \to c\bar{c}s$ transitions are presented. The LHCb Collaboration has published such measurements using $B_s^0 \to J/\psi\pi^+\pi^-$ and $B_s^0 \to J/\psi K^+K^-$ decay modes from 3 fb^{-1} of pp collision data. In the latter decay channel, also Γ_s, Δm_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 $B_s^0 \to J/\psi\bar{K}^{*0}$ 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 ϕ_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_s^0 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.

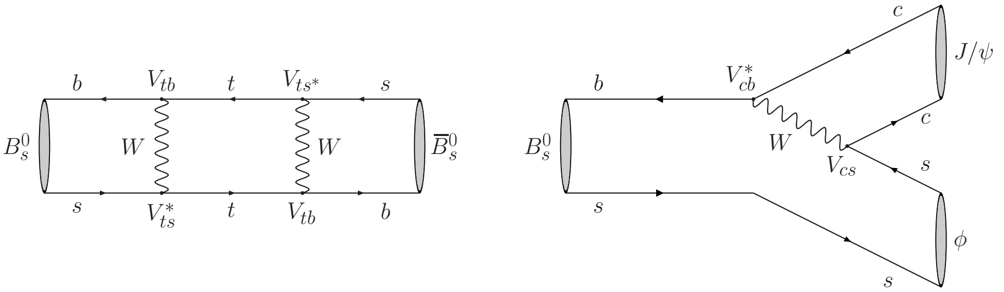

Figure 1: "Box" diagram (left) of $B_s^0 - \bar{B}_s^0$ oscillations, and $B_s^0 \to J/\psi\phi$ mode tree-level diagram (right).

Here we focus on the B_s^0 meson system, where the B_s^0 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 $\phi_s^{c\bar{c}s}$ can be written as a function of elements of the Cabibbo-Kobayashi-Maskawa (CKM) matrix [1, 2], as[1]

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

The fact that any possible new particle contributing to the "box" diagram (shown in Figure 1) can modify the predicted value for ϕ_s [3], and the very precise SM estimation for this phase, $-0.0376^{+0.0008}_{-0.0007}$ rad [4], makes ϕ_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 fb^{-1}

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[1] Further references to ϕ_s are assumed to be referred to $\phi_s^{c\bar{c}s}$ through the rest of these proceedings.

of data from pp collisions), an improvement of ≈ 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 ($b \to cW$), 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 $B_s^0 \to J/\psi K^+K^-$ decays

The decay channel $B_s^0 \to J/\psi K^+K^-$ is considered as a *golden* mode to study mixing-induced *CP* violation effects: not only ϕ_s but also other parameters of interest as the mass difference $\Delta \mathrm{m}_s$, the decay width and decay width difference Γ_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 $B_s^0 \to J/\psi\phi$ (*CP*-admixture) decays.

The LHCb Collaboration has performed a time-dependent angular analysis, using 3 fb^{-1} of pp data, of $B_s^0 \to J/\psi K^+K^-(\phi)$ decays [5]. Using 95690 $B_s^0 \to J/\psi\phi$ signal events, with a tagging power of $3.73 \pm 0.15\%$ and a decay time resolution of approximately 46 fs, a value for ϕ_s of -0.058 ± 0.049 (stat) ± 0.006 (syst) rad is measured. This value, along with the results for $\Delta \mathrm{m}_s$, Γ_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 $B_s^0 \to J/\psi\pi^+\pi^-$ decays

The LHCb Collaboration has also measured ϕ_s and $|\lambda|$ in $B_s^0 \to J/\psi\pi^+\pi^-$ 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 $B_s^0 \to J/\psi\pi^+\pi^-$ signal events, with a tagging power of $3.89 \pm 0.23\%$ and a decay time resolution of around 40.5 fs, the values $\phi_s = 0.070 \pm 0.068\ (\mathrm{stat}) \pm 0.008\ (\mathrm{syst})$ rad and $|\lambda| = 0.89 \pm 0.05\ (\mathrm{stat}) \pm 0.01\ (\mathrm{syst})$ 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 $B_s^0 \to J/\psi K^+K^-$ and $B_s^0 \to J/\psi\pi^+\pi^-$ decays, summarised in Table 1, are combined, assuming that the exact same quantities are measured, in the most precise measurements of ϕ_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 ϕ_s due to second-order topologies

As a pure SM effect, second-order contributions to ϕ_s due to penguin diagrams (see Figure 2),

Parameter	$B_s^0 \to J/\psi K^+K^-$	$B_s^0 \to J/\psi\pi^+\pi^-$	Combination
ϕ_s [rad]	$-0.058 \pm 0.049 \pm 0.006$	$0.070 \pm 0.068 \pm 0.008$	-0.010 ± 0.039
$\lvert\lambda\rvert$	$0.964 \pm 0.019 \pm 0.007$	$0.89 \pm 0.05 \pm 0.01$	0.957 ± 0.017
Γ_s [ps^{-1}]	$0.6603 \pm 0.0027 \pm 0.0015$	–	–
$\Delta\Gamma_s$ [ps^{-1}]	$0.0805 \pm 0.0091 \pm 0.0032$	–	–
Δm_s [ps^{-1}]	$17.711 \pm 0.056 \pm 0.011$	–	–

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

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

$$\phi_s\ (\text{measured}) = -2\beta_s + \delta_{\rm P} + \delta_{\rm NP}. \tag{5.1}$$

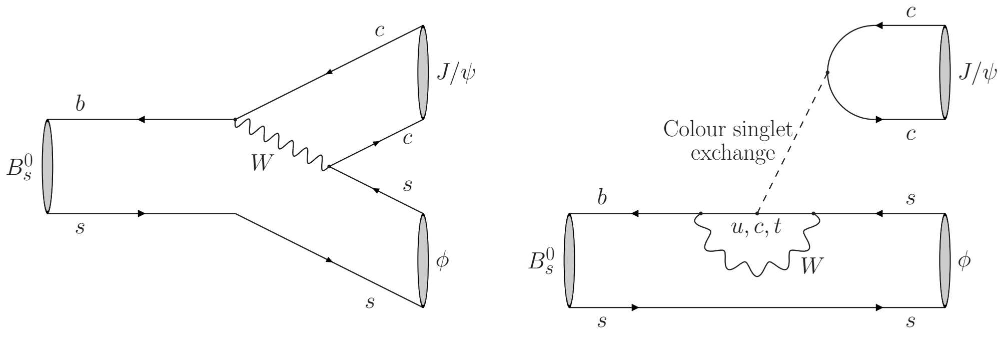

Figure 2: Tree-level diagram (left) and second-order (*penguin*) diagram (right) for $B_s^0 \to J/\psi\phi$ mode.

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 $B_s^0 \to J/\psi\phi$ 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 $B_s^0 \to J/\psi\phi$ 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 $B_s^0 \to J/\psi\bar{K}^{*0}$ as a control channel

An angular analysis of $B_s^0 \to J/\psi K^-\pi^+$ 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 $B_s^0 \to J/\psi\bar{K}^{*0}$ mode, direct *CP* asymmetries and polarisation

Parameter	Longitudinal ($i = L$)	Parallel ($i = \parallel$)	Perpendicular ($i = \perp$)
f_i	$0.497 \pm 0.025 \pm 0.025$	$0.179 \pm 0.027 \pm 0.013$	–
A_i^{CP}	$-0.048 \pm 0.057 \pm 0.020$	$0.171 \pm 0.152 \pm 0.028$	$-0.049 \pm 0.096 \pm 0.025$

Table 2: Results from the $B_s^0 \to J/\psi \overline{K}^{*0}$ analysis for direct CP asymmetries A^{CP} and polarisation fractions f in the three different final polarisation states i: longitudinal (L), parallel ($\parallel$) and perpendicular ($\perp$). The perpendicular polarisation fraction is not directly obtained from the fit as the three polarisation fractions are normalised to unity by definition. First uncertainties are stastistical, second are systematic.

fractions are measured for each final polarisation state, along with a measurement of its branching fraction. All these observables are furtherly used to determine the *penguin* parameters needed to estimate the *penguin pollution* to ϕ_s.

Since the final state $J/\psi \overline{K}^{*0}$ is not a *CP* eigenstate, a decay-time-integrated and flavour-averaged analysis is performed, using 1808 $B_s^0 \to J/\psi \overline{K}^{*0}$ signal events. Polarisation-dependent results are summarised in Table 2. The branching fraction is measured to be $\mathscr{B}(B_s^0 \to J/\psi \overline{K}^{*0}) = (4.14 \pm 0.18\ (\mathrm{stat}) \pm 0.26\ (\mathrm{syst}) \pm 0.24\ (\mathrm{f_d/f_s})) \times 10^{-5}$. 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 $B^0 \to J/\psi \rho^0$ decays

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

$$\begin{aligned}
\delta_\mathrm{P}^0 &= 0.000\ ^{+0.009}_{-0.011}\ ^{+0.004}_{-0.009}\ \mathrm{rad},\\
\delta_\mathrm{P}^\parallel &= 0.001\ ^{+0.010}_{-0.014} \pm 0.008\ \mathrm{rad},\\
\delta_\mathrm{P}^\perp &= 0.003\ ^{+0.010}_{-0.014} \pm 0.008\ \mathrm{rad}.
\end{aligned}$$

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

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

The LHCb Collaboration published recently the observation (3 fb^{-1}) of $\bar{B}_s^0 \to \psi(2S)K^+\pi^-$ decays [23]. This mode is analogous to the $B_s^0 \to J/\psi \overline{K}^{*0}$ 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 ϕ_s when it is measured using $B_s^0 \to \psi(2S)X$ modes (such as $B_s^0 \to \psi(2S)K^+K^-$ decays) may be estimated from $\bar{B}_s^0 \to \psi(2S)K^{*0}$ decays, since δ_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 $B^0 \to \psi(2S)K^+\pi^-$ decays [24], which is the B^0 counterpart of this mode.

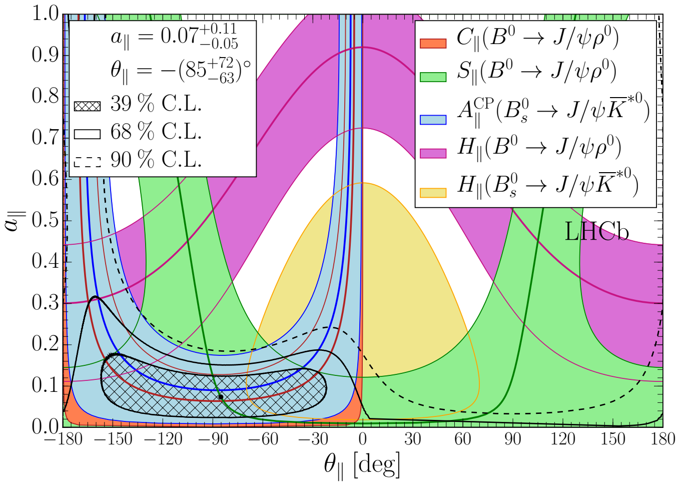

Figure 3: Projection of the fit to $B^0_s \to J/\psi\bar{K}^{*0}$ and $B^0 \to J/\psi\rho^0$ in the parallel final polarisation state.

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 $\mathscr{B}(\bar{B}^0_s \to \psi(2S)K^+\pi^-)$ and $\mathscr{B}(\bar{B}^0_s \to \psi(2S)K^{*0})$. Using 239 $\bar{B}^0_s \to \psi(2S)K^+\pi^-$ signal events, a four-dimensional fit to the $K^+\pi^-$ invariant mass and the three decay angles is performed, leading to the following results,

$$\begin{aligned}
f_L &= 0.524 \pm 0.056 \pm 0.029, \\
f(K^{*0}) &= 0.645 \pm 0.049 \pm 0.049, \\
\frac{\mathscr{B}(\bar{B}^0_s \to \psi(2S)K^+\pi^-)}{\mathscr{B}(B^0 \to \psi(2S)K^+\pi^-)} &= (5.38 \pm 0.36 \pm 0.22 \pm 0.31\ (f_s/f_d))\%, \\
\frac{\mathscr{B}(\bar{B}^0_s \to \psi(2S)K^{*0})}{\mathscr{B}(B^0 \to \psi(2S)K^{*0})} &= (5.58 \pm 0.57 \pm 0.40 \pm 0.32\ (f_s/f_d))\%, \\
M(\bar{B}^0_s) - M(B^0) &= 87.45 \pm 0.44 \pm 0.09\ \mathrm{MeV/c^2},
\end{aligned}$$

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 $\bar{B}^0_s \to \psi(2S)K^{*0}$ 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 $B^0_s \to J/\psi K^+K^-$ and $B^0_s \to J/\psi\pi^+\pi^-$ decays but also from the $B^0_s \to D^+_s D^-_s$ mode [7]) leads to the following world averages (see Figure 4) of ϕ_s and $\Delta\Gamma_s$,

$$\begin{aligned}
\phi_s &= -0.033 \pm 0.033\ \mathrm{rad}, \\
\Delta\Gamma_s &= \quad 0.083 \pm 0.006\ \mathrm{ps}^{-1},
\end{aligned}$$

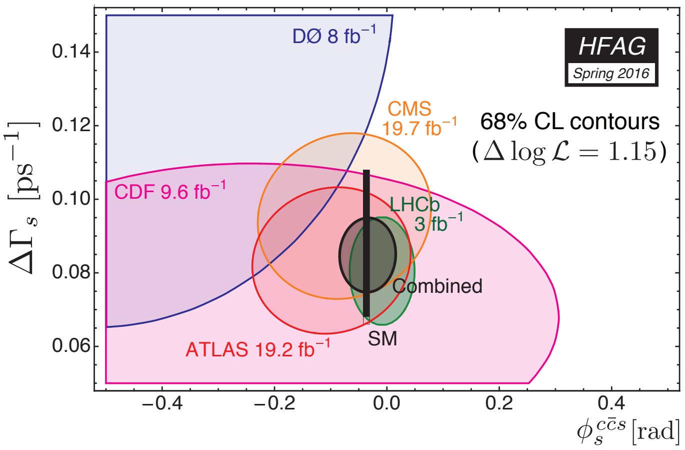

Figure 4: World average fit results to ϕ_s and $\Delta\Gamma_s$ from HFAG.

which are fully compatible with SM estimations [4, 12],

$$\begin{aligned} \phi_s &= -0.0376\ ^{+0.0008}_{-0.0007}\ \text{rad}, \\ \Delta\Gamma_s &= \quad 0.088 \pm 0.020\ \text{ps}^{-1}. \end{aligned}$$

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 $B_s^0 \to J/\psi(\to e^+e^-)K^+K^-$ 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 ϕ_s measurements [28].

8. Conclusions

In these proceedings, Run I LHCb results for the *CP* violating phase $\phi_s^{c\bar{c}s}$, $|\lambda|$, 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 Γ_s and Δm_s. Results have been found to be fully compatible with SM estimations. An LHCb estimation of the second-order contributions to the ϕ_s phase, measured in $B_s^0 \to J/\psi\bar{K}^{*0}$ and $B^0 \to J/\psi\rho^0$ channels and known as *penguin pollution*, is also presented, being found to be not larger than 21 mrad and well under control. An observation of the decay channel $\bar{B}_s^0 \to \psi(2S)K^+\pi^-$ 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 ϕ_s and $\Delta\Gamma_s$ obtained by the HFAG are presented, along with the most relevant prospects by the LHCb Collaboration.

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