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CP violation in *B* decays to charmonia at LHCb

CP violation in B decays to charmonia at LHCb

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Abstract. $B^0_{(s)}$ meson decays to states containing a charmonium meson are theoretically clean modes to measure the weak mixing phases ϕ_d and ϕ_s, one of the key goals of the LHCb experiment. The current status of measurements of these observables performed by the LHCb collaboration is presented. The future perspectives, as well as the expected precision that will be achieved from LHCb, are also discussed.

1. Introduction

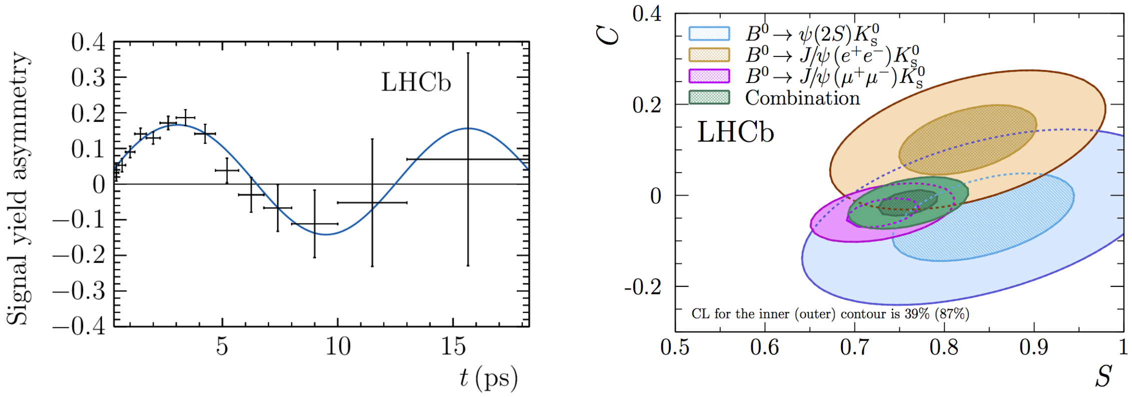
Measurements of time-dependent CP asymmetries in the B^0 and B^0_s systems using $b \to c\bar{c}s$ transitions, *e.g.* decay modes involving a charmonium meson in the final state, are sensitive to the CKM phases $\beta \equiv \arg[-(V_{cd}V^*_{cb})/(V_{td}V^*_{tb})]$ and $\beta_s \equiv \arg[-(V_{ts}V^*_{tb})/(V_{cs}V^*_{cb})]$, respectively. The interference between the $B^0_{(s)}$ mixing and decay processes introduces the CP-violating observables ϕ_d and ϕ_s. Within the Standard Model (SM), and neglecting subleading decay diagrams, they can be identified with $\phi_d = 2\beta$ and $\phi_s = -2\beta_s$. These observables are precisely predicted from global fits to experimental data, and deviations from these predictions would indicate New Physics (NP) contributions entering the loops describing the $B^0_{(s)}$ mixing. On the other side, the experimental constraints on these phases put stringent limits on NP models. The LHCb detector [1, 2], having an excellent decay time resolution of $\sim 45\,\text{fs}$ [3] and a tagging power of the $B^0_{(s)}$ flavour at production of $\sim 4\%$ [4], has been designed to perform leading measurements of these CP-violating observables, requiring flavour-tagged time-dependent angular (or amplitude) analyses. All measurements presented here used samples of pp collisions data collected by the LHCb experiment at $\sqrt{s} = 7\,\text{TeV}$ and $\sqrt{s} = 8\,\text{TeV}$ during Run 1.

2. Status of ϕ_d measurement

The $B^0 \to J/\psi K^0_S$ decay channel is the golden mode for the measurement of ϕ_d. The LHCb collaboration measured $\sin\phi_d = 0.731 \pm 0.035 \pm 0.020$ using $B^0 \to J/\psi(\to \mu^+\mu^-)K^0_S(\to \pi^+\pi^-)$ decays, where the first uncertainty is statistical and the second systematic [5]. The signal yield asymmetry as a function of the B^0 decay time is shown in Fig. 1(a). The analysis provides the most precise measurement of ϕ_d at an hadronic collider with the result having a similar precision to the single measurements by the BaBar [6] and Belle [7] collaborations.

LHCb also measured ϕ_d using the $B^0 \to J/\psi(\to e^+e^-)K^0_S(\to \pi^+\pi^-)$ and $B^0 \to \psi(2S)(\to \mu^+\mu^-)K^0_S(\to \pi^+\pi^-)$ decay modes, improving the precision on $\sin 2\beta$ by $\sim 20\%$ [8]. The combination of the LHCb measurements, shown in Fig. 1(b), results in

$\sin\phi_d = 0.760 \pm 0.034$. The world average is given by $\sin\phi_d = 0.691 \pm 0.017$ [9], to be compared with the SM prediction of $\sin\phi_d = 0.740^{+0.020}_{-0.025}$ [10, 11].



(a) (b)

Figure 1. (Colours online) Panel (a): signal yield asymmetry determined in the flavour-tagged time-dependent analysis of $B^0 \to J/\psi K^0_S$ decays. Panel (b): combination of LHCb measurements of ϕ_d. Within the SM, $C \sim 0$ and $S \sim 2\beta$. LHCb combination gives $S = 0.760 \pm 0.034$ and $C = -0.017 \pm 0.029$.

3. Status of ϕ_s measurement

The golden mode for the measurement of ϕ_s is the $B^0_s \to J/\psi(\to \mu^+\mu^-)\phi(\to K^+K^-)$ decay channel, that can be precisely measured at hadronic colliders only. The final state involves two vector mesons, motivating a time-dependent angular analysis in order to disentangle the *CP*-odd and *CP*-even components. Moreover, a K^+K^- S-wave amplitude, of the order of $\sim 2\%$, is present under the ϕ region. The advantage in performing such angular analysis is the possibility to also measure the B^0_s mixing parameters. The LHCb collaboration performed the analysis of the $B^0_s \to J/\psi(\to \mu^+\mu^-)\phi(\to K^+K^-)$ decay channel [12] obtaining the results shown in Table 1. The result of the angular analysis is reported in Fig. 2(a). It has also been possible to test the dependence of the ϕ_s value on the polarisation of the final state. No evidence for a polarisation-dependent *CP*-violation is found for $B^0_s \to J/\psi\phi$ decays.

Table 1. Parameters determined from the flavour-tagged time-dependent angular analysis of the $B^0_s \to J/\psi\phi$ decay channel. The results are the most precise determinations of these parameters to date.

Parameter	Value
ϕ_s	$-58 \pm 49 \pm 6\,\text{mrad}$
$\Delta\Gamma_s$	$0.0805 \pm 0.0091 \pm 0.0032\,\text{ps}^{-1}$
Γ_s	$0.6603 \pm 0.0027 \pm 0.0015\,\text{ps}^{-1}$
$\lvert\lambda\rvert$	$0.964 \pm 0.019 \pm 0.007$

As suggested in Ref. [13], the full $m(K^+K^-)$ spectrum in $B^0_s \to J/\psi K^+K^-$ decays can be used to increase the sensitivity on ϕ_s. The LHCb collaboration performed the time-dependent amplitude analysis of $B^0_s \to J/\psi(\to \mu^+\mu^-)K^+K^-$ decays using the $m(K^+K^-) > 1.05\,\text{GeV}$

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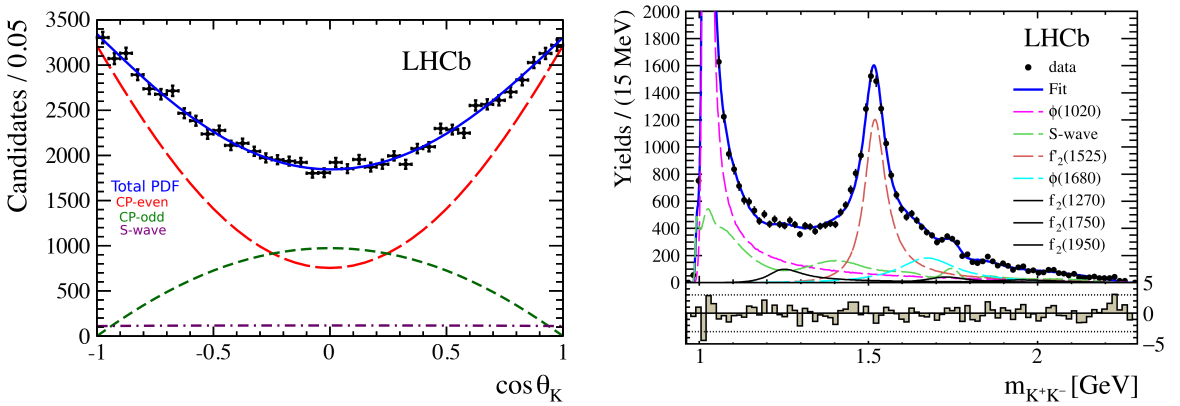
range, *i.e.* above the ϕ resonance region [14]. The amplitude fit is shown in Fig. 2(b). The results, reported in Table 2, have uncertainties two times larger than the $B_s^0 \to J/\psi\phi$ decay channel analysis. The combination of the results obtained in the two $m(K^+K^-)$ ranges is $\phi_s = -25 \pm 45 \pm 8\,\text{mrad}$.

Table 2. Parameters determined from the time-dependent angular analysis of the $B_s^0 \to J/\psi K^+K^-$ decay channel, with $m(K^+K^-) > 1.05\,\text{GeV}$.

Parameter	Value
ϕ_s	$119 \pm 107 \pm 34\,\text{mrad}$
$\Delta\Gamma_s$	$0.066 \pm 0.018 \pm 0.010\,\text{ps}^{-1}$
Γ_s	$0.650 \pm 0.006 \pm 0.004\,\text{ps}^{-1}$
$\lvert\lambda\rvert$	$0.994 \pm 0.018 \pm 0.006$



(a) (b)

Figure 2. (Colours online) Panel (a): angular distribution of $B_s^0 \to J/\psi K^+K^-$ decays in the ϕ region. The CP-even, CP-odd and S-wave components are shown in the legend. Panel (b): amplitude fit results of $B_s^0 \to J/\psi K^+K^-$ decays. Above the ϕ region, the decay amplitude mainly proceeds through the $f_2'(1525)$ resonance.

The LHCb collaboration measured ϕ_s also using the $B_s^0 \to J/\psi\pi^+\pi^-$ [15] and $B_s^0 \to \psi(2S)\phi$ [16] decay channels, and using open-charm [17] and charmless decay modes [18]. The most precise contribution to the world average $\phi_s = -21 \pm 31\,\text{mrad}$ [9], shown in Fig. 3(a), is given by LHCb and its value is consistent with the SM prediction $\phi_s^{\text{SM}} = -37.6^{+0.7}_{-0.8}\,\text{mrad}$ [19, 20]. The large experimental uncertainty, far from the theoretical precision, leaves room for NP contributions in the B_s^0 mixing sector.

4. Control of penguin effects

As the experimental precision improves, the penguin pollution involving hadronic effects [21, 22] must be controlled. The experimental values of ϕ_d and ϕ_s can be written as

$$\phi_d^{\text{exp}} = 2\beta + \Delta\phi_d^{\text{pen}} + \Delta\phi_d^{\text{NP}}, \tag{1}$$

$$\phi_s^{\text{exp}} = -2\beta_s + \Delta\phi_s^{\text{pen}} + \Delta\phi_s^{\text{NP}}, \tag{2}$$

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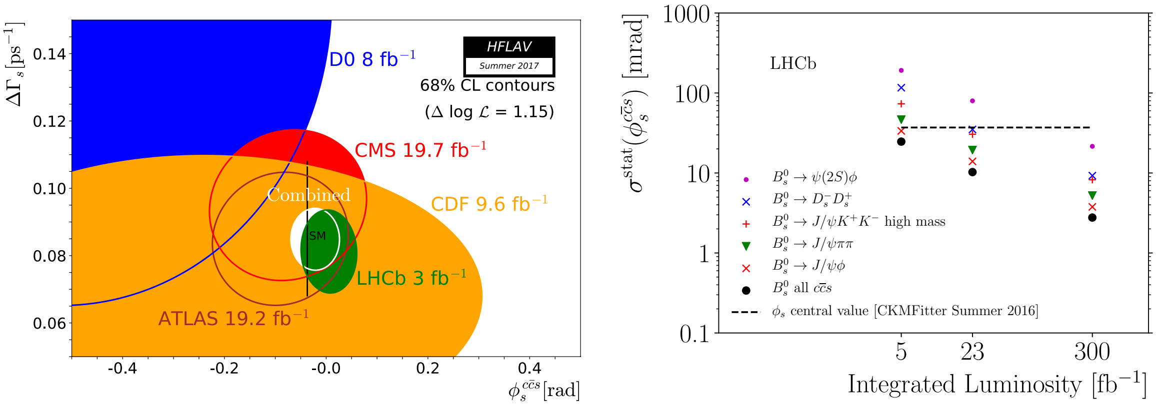

(a) (b)

Figure 3. (Colours online) Panel (a): HFLAV combination of ϕ_s and $\Delta\Gamma_s$ from different experiments. Panel (b): scaling of the statistical precision on ϕ_s from different B_s^0 decay channels.

where $\Delta\phi^{\text{pen}}$ indicates contributions from doubly Cabibbo-suppressed diagrams in the decay amplitudes, and $\Delta\phi^{\text{NP}}$ indicates NP contributions. Therefore, it is important to control penguin effects that could mimic NP contributions in case ϕ^{exp} shows any deviations from the SM prediction.

The $\Delta\phi^{\text{pen}}$ shift arises from hadronic effects and it is difficult to compute due to the non-perturbative nature of the QCD processes involved. A strategy to constrain the effects of the subleading penguin diagrams has been defined [23], exploiting $\text{SU}(3)_f$-related modes, where penguin diagrams are Cabibbo-allowed: $\Delta\phi_d^{\text{pen}}$ can be constrained using the $B_s^0 \to J/\psi K_S^0$ decay mode, and $\Delta\phi_s^{\text{pen}}$ can be constrained using the $B^0 \to J/\psi\rho^0$ and $B^0 \to J/\psi\overline{K}^{*0}$ decay modes. The penguin parameters can then be converted into the golden modes counterparts to obtain the expected shifts in the ϕ_d and ϕ_s values. A small shift $\Delta\phi_d^{\text{pen}} = -(1.10^{+0.70}_{-0.85})^\circ$ has been measured. Given the experimental precision of $\sigma(\phi_d) \sim 1.6^\circ$, one needs to improve the $\Delta\phi_d^{\text{pen}}$ measurement when more statistics will be available. $\Delta\phi_s^{\text{pen}}$ has been measured for the three different polarisations of the $J\psi\phi$ final state, obtaining shift values that are a factor of ten less than the current experimental precision of $\sigma(\phi_s) \sim 0.03\,\text{rad}$.

5. Conclusions and future perspectives

The LHCb collaboration, using Run 1 data, measured the ϕ_d phase with a precision that is competitive with the results from the B-factories, and provided the most precise measurement of the ϕ_s observable. New results using Run 2 data and new B decay modes to charmonium states will allow updated measurements of CP-violating effects. The statistical uncertainty on the weak mixing phases, $\sigma_{\text{stat}}(\phi_{d,s})$, depends not only on the integrated luminosity, but also on the tagging power ϵ_{tag} of the experiment: $\sigma_{\text{stat}}(\phi_{d,s}) \propto 1/\sqrt{\epsilon_{\text{tag}}N}$, where N is the number of events in the corresponding decay channel.

The LHCb collaboration will provide a measurement of $\sin\phi_d$ with a precision of 0.006 with an integrated luminosity of $50\,\text{fb}^{-1}$ from Upgrade I, competitive with the precision that will be reached by the Belle II collaboration.

The LHCb experiment is a unique place to measure the ϕ_s observable, which is particularly interesting given the currently large experimental uncertainty. Future contributions to the ϕ_s measurement will also be possible using decay modes into CP-eigenstates, such as $B_s^0 \to$

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$\eta_c(1S)\phi$ [24] and $B_s^0 \to J/\psi\eta$ [25] decay channels. The projections of the expected statistical uncertainty on ϕ_s that will be obtained by the LHCb experiment after LHC Run 2, after LHCb Phase I Upgrade, and after an eventual Phase II Upgrade that will enable the LHCb experiment to run in the High-Luminosity-LHC conditions, are reported in Fig. 3(b). The expected precision on ϕ_s combining all decay modes is ~ 10 mrad after Upgrade I and ~ 3 mrad after Upgrade II.

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