FUTURE CONTRIBUTIONS TO ϕ_s MEASUREMENTS*

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The most recent results on the CP-violating phase ϕ_s measurements in the B_s^0–$\bar{B}_s^0$ system obtained by the LHCb Collaboration with Run 1 data are presented. Thanks to the precise prediction of the ϕ_s value in the frame of the Standard Model, it represents an excellent probe to search for new physics. Current results are compatible with the Standard Model predictions, and their precision will be increased with larger data sets. Further improvement is expected from the inclusion of results obtained using decay modes with smaller branching fractions.

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1. Introduction

The phase ϕ_s can be related to the angle β_s of the unitary CKM triangle of the B_s^0 meson system analogous to β angle in B^0 meson decay [1]. The interference between the mixing and direct decay of B_s^0 mesons to CP eigenstates via $b \to c\bar{c}s$ transitions allows to measure the CP-violating phase, ϕ_s:

$$\phi_s = \phi_{\mathrm{M}} - 2\phi_{\mathrm{D}} = -2\beta_s + \Delta\phi_s^{\mathrm{Peng}} + \delta_s^{\mathrm{NP}}\,, \tag{1}$$

where ϕ_{M} and ϕ_{D} are the mixing and direct phases, respectively. The other components in the ϕ_s determination are higher order "pengiun" diagrams from non-perturbative hadronic effects (Fig. 1) and new physics (NP) contributions that could be difficult to distinguish from "penguins". These components start to play an important role when reaching high precision of the ϕ_s measurement [2].

Including only the dominant "tree-level" contributions (Fig. 1), the phase ϕ_s within the Standard Model (SM) is predicted to be $-2\beta_s$, where $\beta_s = \arg(-V_{ts}V_{tb}^*/V_{cs}V_{cb}^*)$ [3]. An indirect determination of $2\beta_s = 37.6^{+0.8}_{-0.7}$ mrad is obtained using a global fit to experimental data [4].

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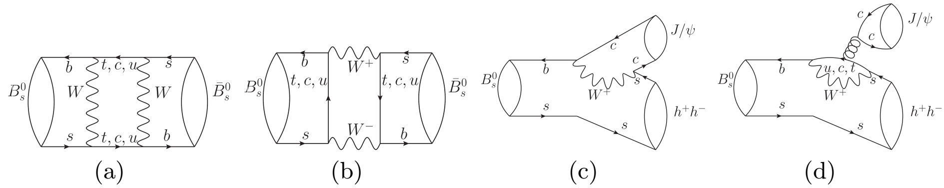

Fig. 1. Feynman diagrams: (a)–(b) $B_s^0 - \bar{B}_s^0$ mixing and contributions to the decay $B_s^0 \to J/\psi h^+h^-$ within the SM, where $h = \pi, K$: (c) "tree-level", and (d) "penguin" diagrams.

The initial measurements of the phase ϕ_s have been performed by the Tevatron experiments: CDF [5] and DØ [6] with large uncertainties. Extensive studies have been made by the LHC experiments: ATLAS [7], CMS [8] and LHCb [9] with Run 1 data collected in 2011 and 2012 at a center-of-mass energy of $\sqrt{s} = 7$ TeV and 8 TeV, respectively. At the LHCb [10], the measurement of the CP-violating phase ϕ_s has independently been performed using $B_s^0 \to D_s^+ D_s^-$ [11], $B_s^0 \to J/\psi\phi$ [9], $B_s^0 \to J/\psi\pi^+\pi^-$ [12], $B_s^0 \to \psi(2S)\phi$ [13], and $B_s^0 \to J/\psi K^+K^-$ with $m(K^+K^-)$ above the $\phi(1020)$ mass [14] decay modes. The world average value shown in Fig. 2 is consistent with the SM predictions but the combined measurement is still far from the SM precision thus leaving still some room for NP effects. Improvements on the sensitivity of ϕ_s are expected from the inclusion of Run 2 data collected in 2015–2019 at a center-of-mass energy of $\sqrt{s} = 13$ TeV that will allow to use the $b \to c$ and $b \to s$ processes with very small branching fraction to constrain the ϕ_s measurement. These proceedings discuss some of those decay modes as a future potential to the determination of the CP-violating phase ϕ_s.

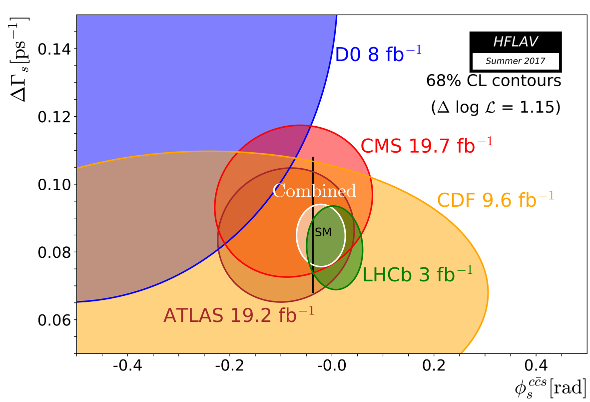

Fig. 2. (Colour on-line) Regions of 68% confidence level in $\Delta\Gamma_s$ and ϕ_s plane obtained from individual contours of CDF, DØ, CMS, ATLAS and LHCb measurements and the combined contour (solid line and shaded area) [15]. The expectation within the SM [4] is shown as a black thin rectangle.

2. Observation of the $B_s^0 \to \eta_c\phi$ decay

For the first time the LHCb Collaboration has observed the decay $B_s^0 \to \eta_c\phi$, where the η_c meson is reconstructed in the $p\bar{p}$, $K^+K^-\pi^+\pi^-$, $\pi^+\pi^-\pi^+\pi^-$ and $K^+K^-K^+K^-$ decay modes and the $\phi(1020)$ in the K^+K^- decay mode using Run 1 data [16]. The $B_s^0 \to J/\psi\phi$ decay with the same final states is used as a normalization channel. The interference between the η_c and purely nonresonant contributions is taken into account using an amplitude model to simultaneously fit the four hadrons and $p\bar{p}$ mass distributions (Fig. 3). The branching fractions are measured to be $\mathcal{B}(B_s^0 \to \eta_c\phi) = [5.01 \pm 0.53 \pm 0.27 \pm 0.63] \times 10^{-4}$ and $\mathcal{B}(B_s^0 \to \eta_c\pi^+\pi^-) = [1.76 \pm 0.59 \pm 0.12 \pm 0.29] \times 10^{-4}$. In both cases, the first uncertainty is statistical and the second is systematic. The third uncertainty is due to the limited knowledge of the branching fractions of the normalisation channel. In the future, with significant improvement of the hadronic trigger efficiencies [17], these decay modes may become of interest to add sensitivity to the measurement of ϕ_s.

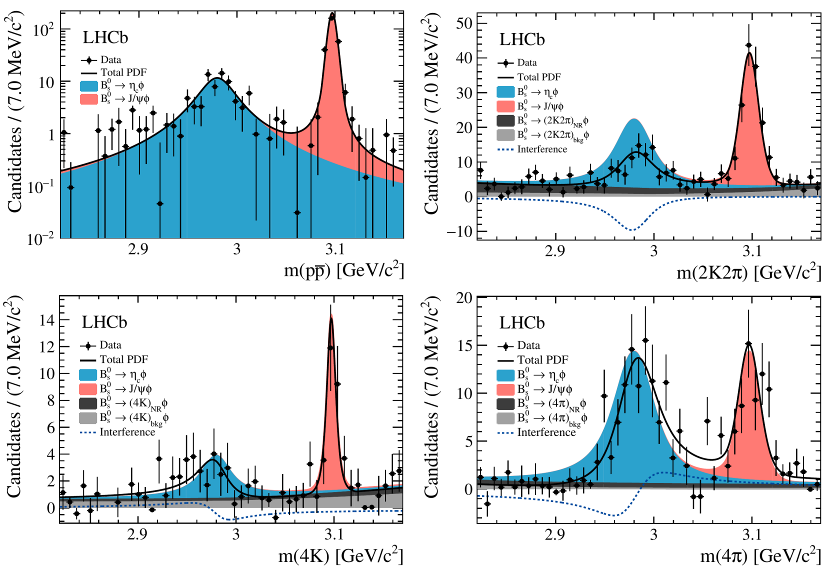

Fig. 3. (Colour on-line) Invariant mass distributions for selected $p\bar{p}$, $K^+K^-\pi^+\pi^-$, $K^+K^-K^+K^-$ and $\pi^+\pi^-\pi^+\pi^-$ candidates presented as the left peak (blue area). The normalization channel shows as the right peak (red area). The nonresonant contributions and background candidates describe by dark and light grey area, respectively.

3. The $B_s^0 \to J/\psi\eta$ effective lifetime

The B_s^0 effective lifetime has been measured by the LHCb Collaboration using CP-even $B_s^0 \to J/\psi\eta(\to \gamma\gamma)$ decay mode, with $J/\psi \to \mu^+\mu^-$ and $\eta \to$

$\gamma\gamma$ using Run 1 data [18]. As ϕ_s is measured to be small and assuming CP conservation, the effective lifetime corresponds to the lifetime of the light B_s^0 mass eigenstate, $\tau_L \propto \Gamma_L$. The invariant mass resolution is approximately 48 MeV/c^2 (Fig. 4) causing the overlap of the B_s^0 signal mode with the $B^0 \to J/\psi\eta$ background component. The effective lifetime for ~ 3000 signal candidates is measured to be $\tau_{\rm eff} = 1.479 \pm 0.034 \pm 0.011$ ps. The result is consistent with, and has a similar precision to, the other CP-even lifetime measurements [19, 20].

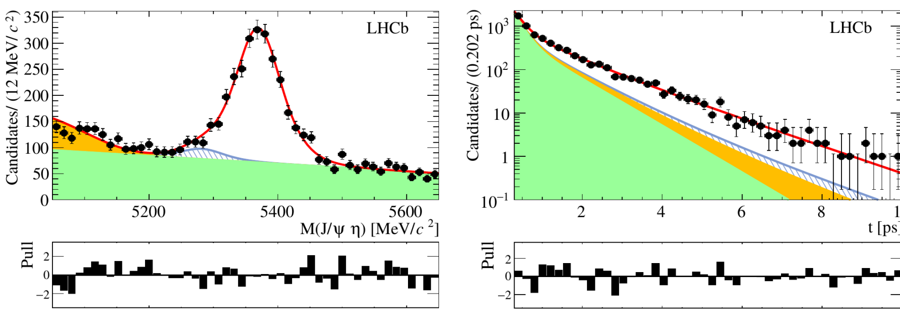

Fig. 4. (Colour on-line) Distributions of $J/\psi\eta$ invariant mass (left) and decay time (right) for selected $B_s^0 \to J/\psi\eta$ decays. Combinatorial background (light grey/green), background from $B^0 \to J/\psi\eta$ decays (hatched/blue) and partially reconstructed background (dark grey/orange) are shown.

4. Observation of the $B_s^0 \to \phi\pi^+\pi^-$ decays

The first observation of the inclusive decay $B_s^0 \to \phi(\to K^+K^-)\pi^+\pi^-$ has been performed by the LHCb Collaboration [21]. Figure 5 shows the result of the final fit to the $m(K^+K^-\pi^+\pi^-)$ distribution. The B_s^0 yield is found to be around 700 signal candidates. Since the $\pi^+\pi^-$ spectrum includes several resonances, an amplitude analysis to the $\pi^+\pi^-$ mass and decay angle distributions is used to separate out exclusive contributions to the B_s^0 meson decays (Fig. 5). The $B_s^0 \to \phi\phi$ is used as a normalization channel for both the inclusive and exclusive decays. The decays $B_s^0 \to \phi f_0(980)$, $B_s^0 \to \phi f_2(1270)$ and $B_s^0 \to \phi\rho^0$ are observed with a significance of 8σ, 5σ and 4σ, respectively. The measurement of their branching fractions is $\mathcal{B}(B_s^0 \to \phi f_0(980)) = [1.12 \pm 0.16^{+0.09}_{-0.08} \pm 0.11] \times 10^{-6}$, $\mathcal{B}(B_s^0 \to \phi f_2(1270)) = [0.61 \pm 0.13^{+0.12}_{-0.05} \pm 0.06] \times 10^{-6}$ and $\mathcal{B}(B_s^0 \to \phi\rho^0) = [2.7 \pm 0.7 \pm 0.2 \pm 0.2] \times 10^{-7}$, where the first uncertainty is statistical, the second is systematic, and the third is related to the knowledge of the normalization channel branching fraction. The measurements are consistent with the SM predictions and, in the case of the $B_s^0 \to \phi\rho^0$, they provide a constraint on possible contributions from NP effects [22].

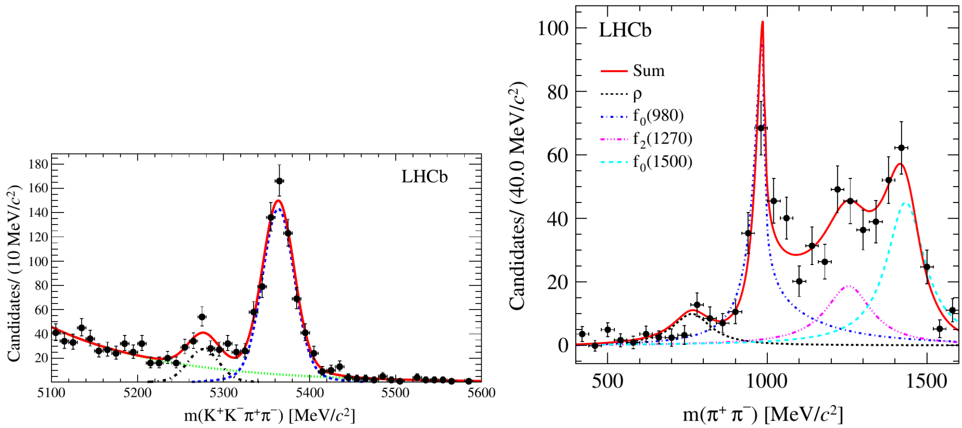

Fig. 5. (Colour on-line) (Left) Distribution of $K^+K^-\pi^+\pi^-$ invariant mass where the dashed (blue) line is the B_s^0 signal, the dotted (green) line shows the combinatorial background and the dot-dashed (black) line indicates the B^0 component. (Right) Distributions of $\pi^+\pi^-$ invariant mass with contributing components.

5. Summary

The recent measurements of the CP-violating phase ϕ_s in the B_s^0 meson system, dominated by the LHCb experiment, are compatible with the SM predictions. The addidtional data from Run 2 of the LHC is expected to improve the current precision significantly. New decay modes have been investigated to either measure CP-violating effects or make preparations for such measurements in the future. The statistical sensitivity of the ϕ_s measurement after the LHCb Phase 1 upgrade in 2021–2029, with an integrated luminosity of 46 fb^{-1}, is expected to be ~ 0.01 rad, close to the present the-

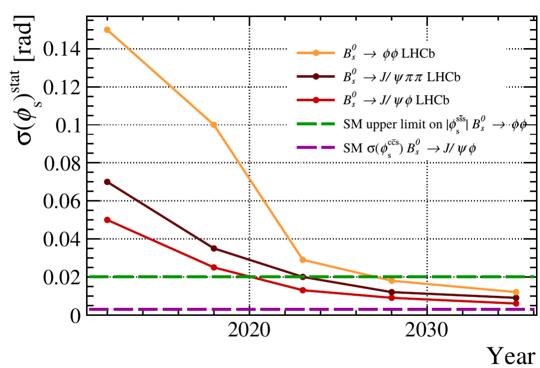

Fig. 6. Projection of how precision on ϕ_s from LHCb measurements will scale as a function of time for different decay modes. Information taken from Ref. [23].

oretical uncertainty (Fig. 6) [24]. As the experimental precision improves, the higher order "penguin" contributions to the B_s^0 decays need to be kept under control and are expected to be no greater than 20 mrad [25, 26].

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