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MEASUREMENT OF THE PHASE ϕ_s AT THE LHCb*

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One of the key goals of the LHCb experiment is the determination of the CP-violating phase ϕ_s in $\bar{b} \to \bar{c}c\bar{s}$ decays. Its value is predicted to be very small in the Standard Model. The measurements in the $B_s^0 \to J/\psi\phi$, $B_s^0 \to J/\psi\pi^+\pi^-$ and $B_s^0 \to \psi(2S)\phi$ channels are reviewed. The first observation of the $B_s^0 \to \eta_c\phi$ and $B_s^0 \to \eta_c\pi^+\pi^-$ decay modes is presented. These channels can be used to measure ϕ_s with larger data statistics that will be collected during Run 2 by the LHCb experiment.

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1. Introduction

The CP-violating phase ϕ_s originates from the interference between direct B_s^0 meson decays into a CP eigenstate and decays through B_s^0–$\bar{B}_s^0$ mixing to the same final state. If only the dominant "tree level" contributions are included, ϕ_s is related to the elements of the Cabbibo–Kobayashi–Maskawa quark mixing matrix by $\phi_s \simeq -2\beta_s$, where $\beta_s = \arg(-V_{ts}V_{tb}^*/V_{cs}V_{cb}^*)$ [1]. The prediction for $2\beta_s$, determined via a global fit to experimental data within the Standard Model (SM), is $2\beta_s = 0.0376^{+0.0008}_{-0.0007}$ rad [2]. Since the value predicted by the SM is very precise, any significant deviation of the measured value from this prediction would be particularly interesting, as it would indicate a possible contribution of new, unknown particles to the loop diagram describing B_s^0–$\bar{B}_s^0$ mixing. All measurements presented here are obtained using 3 fb^{-1} of pp collisions collected by the LHCb experiment [3] in 2011 and 2012 at a center-of-mass energy of $\sqrt{s} = 7$ TeV and 8 TeV, respectively.

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2. $B_s^0 \to J/\psi\phi$ analysis

In order to measure the phase ϕ_s in the $B_s^0 \to J/\psi\phi$ mode with $J/\psi \to \mu^+\mu^-$ and $\phi \to K^+K^-$, a flavour tagged time-dependent angular analysis is used as described in Ref. [4]. The final state is decomposed into four polarization amplitudes: three P-waves, A_0, $A_\parallel$, $A_\perp$ and one S-wave, A_{S} accounting for the non-resonant K^+K^- configuration. The angular analysis is required to disentangle the interfering CP-even and CP-odd components in the final state which arise due to total spin conservation between two vector resonances coming from a pseudoscalar meson decay.

A sample of 95 690 $\pm$ 350 signal $B_s^0 \to J/\psi\phi$ candidates are obtained after the trigger and off-line selection. The fit procedure takes into account decay time resolution, angular and decay time acceptances as well as the effective tagging power. The decay time acceptance is determined from data, using a prescaled unbiased trigger sample, and a tag and probe technique. A simulated sample is used to determine the angular acceptance. Using prompt $J/\psi K^+K^-$ combinations, the decay time resolution is estimated to be $\sim$ 45 fs. The information from additional same-side and opposite-side particles with respect to the signal candidate is used in the flavour tagging algorithm. It is optimised on simulated samples and calibrated on data, using flavour specific control channels. The obtained effective tagging power is $(3.73 \pm 0.15)\%$ [4].

Using a signal-only PDF, a weighted unbinned likelihood fit is performed as described in Ref. [5]. The signal weights are extracted using the sPlot technique [6]. The fit is divided into six bins of $m(K^+K^-)$ region to allow the measurement of the small ($\sim$ 2%) S-wave amplitude in each bin and to minimize correction factors due to the interference between the different components of the final state. The projections of the decay time and angular distributions are shown in Fig. 1. The measured results are $\phi_s = -0.058 \pm 0.049 \pm 0.006$ rad, $\Gamma_s = 0.6603 \pm 0.0027 \pm 0.0015$ ps^{-1} and $\Delta\Gamma_s = 0.0805 \pm 0.0091 \pm 0.0032$ ps^{-1}, where the first uncertainty is statistical and the second systematic [4]. The quantities Γ_s and $\Delta\Gamma_s$ are the average decay width and the decay width difference between the two mass eigenstates, respectively. This measurement of the CP-violating parameter, ϕ_s, is the single most precise to date and is in agreement with the SM predictions [2, 7]. The dominant source of systematic uncertainty comes from knowledge of the angular and decay time efficiencies.

A similar analysis of $B_s^0 \to J/\psi\pi^+\pi^-$ decays has been also performed at the LHCb [8] to measure ϕ_s. Here, the angular analysis is not needed because the final state has found to be $> 97.7\%$ completely CP-odd with $f_0(980)$ representing the dominant component [9]. A combined fit using both $B_s^0 \to J/\psi\phi$ and $B_s^0 \to J/\psi\pi^+\pi^-$ events gives the result of $\phi_s = 0.010 \pm 0.039$ rad [4].

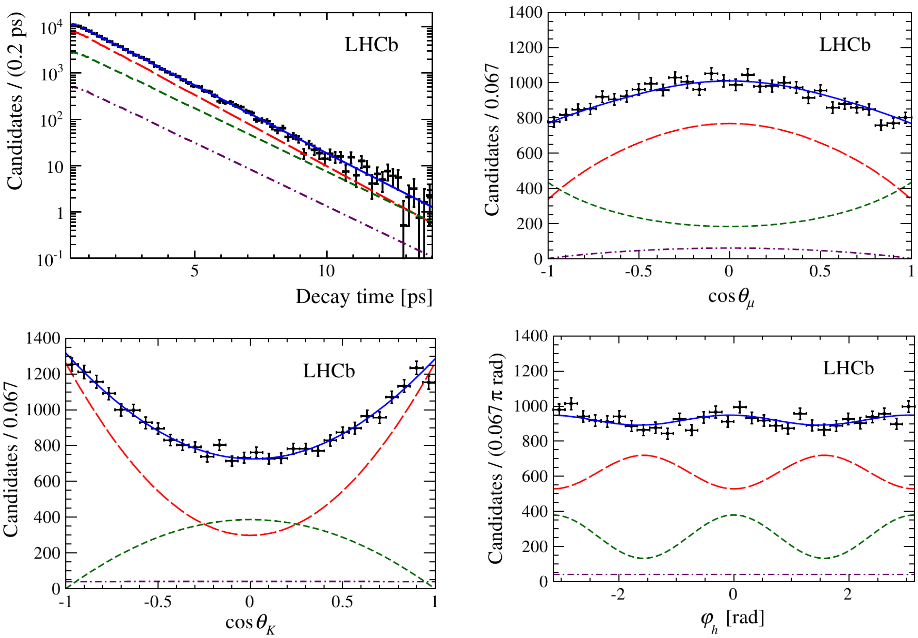

Fig. 1. (Colour on-line) One-dimensional projections of $B_s^0 \to J/\psi\phi$ data (black markers) for decay-time and three helicity angles. The total signal contribution (solid/blue) is composed of CP-even (long-dashed/red), CP-odd (short-dashed/green) and S-wave (dotted-dashed/purple) contributions.

3. $B_s^0 \to \psi(2S)\phi$ analysis

Another B_s^0 decay mode that has been exploited by the LHCb to measure the phase ϕ_s is $B_s^0 \to \psi(2S)\phi$ with $\psi(2S) \to \mu^+\mu^-$ and $\phi \to K^+K^-$ [10]. This decay has been studied for the first time using an analysis method very similar to that used for the $B_s^0 \to J/\psi\phi$ decay mode reported in Ref. [4]. The number of signal candidates obtained from a fit to the data sample is ~ 4700 (Fig. 2). For the selection, a boosted decision tree, trained using simulated signal events and a background sample from the high-mass sideband, has been used. The decay time acceptance is determined using the control channel $B^0 \to \psi(2S)K^*$ with $K^* \to K^+\pi^-$. Figure 2 shows the decay time acceptance, which is defined as the product of the acceptance of the control channel and the ratio of acceptances of the simulated signal and control mode after full selection chain. The first measurement of the CP-violating phase ϕ_s in a final state containing the $\psi(2S)$ resonance is $\phi_s = -0.23^{+0.29}_{-0.28} \pm 0.02$ rad. Moreover, the mixing observables Γ_s and $\Delta\Gamma_s$ are measured to be $\Gamma_s = 0.668 \pm 0.011 \pm 0.006$ ps^{-1} and $\Delta\Gamma_s = 0.066^{+0.041}_{-0.044} \pm 0.007$ ps^{-1}. The results are consistent with previous measurements and the SM predictions. The systematic uncertainty is less than 20% of the statistical uncertainty, except for Γ_s where it is close to 60%.

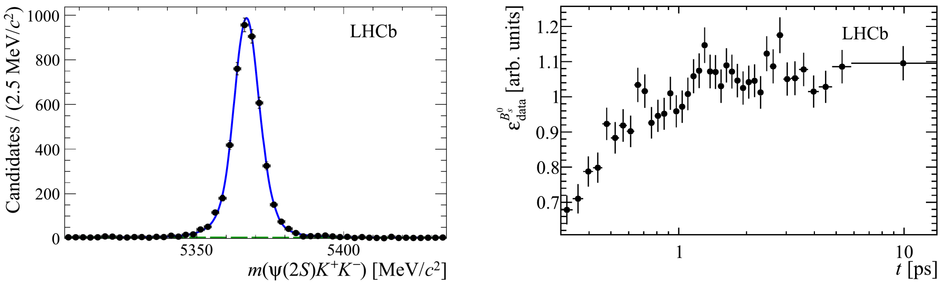

Fig. 2. Distribution of $m(\psi(2S)K^+K^-)$ for the selected $B_s^0 \to \psi(2S)\phi$ candidates and decay time efficiency in arbitrary units.

4. $B_s^0 \to \eta_c\phi$ analysis

The first observation of the $B_s^0 \to \eta_c\phi$ decay has been performed at the LHCb [11]. The decay proceeds dominantly through the $\bar{b} \to \bar{c}c\bar{s}$ transition, like the $B_s^0 \to J/\psi\phi$ mode and it could be used to measure ϕ_s. The η_c meson

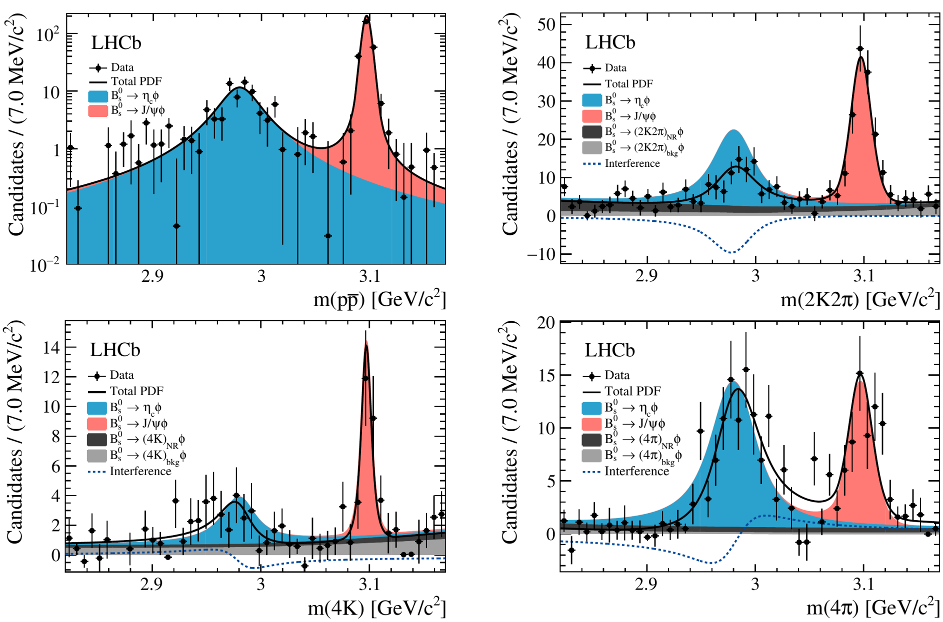

Fig. 3. Invariant mass distributions for selected $p\bar{p}$, $K^+K^-\pi^+\pi^-$, $K^+K^-K^+K^-$ and $\pi^+\pi^-\pi^+\pi^-$ candidates [11]. Different contributions are shown in the legend.

is reconstructed into $p\bar{p}$, $K^+K^-\pi^+\pi^-$, $K^+K^-K^+K^-$ and $\pi^+\pi^-\pi^+\pi^-$ final states. All modes are normalized to the J/ψ mode with the same final states. In both the four hadrons and $p\bar{p}$ cases, the total decay amplitude has been calculated. The interference between the η_c and purely non-resonant contributions is taken into account using an amplitude model for simultaneously fit the four hadrons and $p\bar{p}$ mass distributions (Fig. 3). The branching fraction is found to be $\mathcal{B}(B_s^0 \to \eta_c\phi) = (5.01 \pm 0.53(\text{stat.}) \pm 0.27(\text{syst.}) \pm 0.63(\mathcal{B})) \times 10^{-4}$, where the latter is the largest uncertainty and it is due to the limited knowledge of the external branching ratio used for normalisation. First evidence of the $B_s^0 \to \eta_c\pi^+\pi^-$ decay mode has been also presented, with a branching fraction of $\mathcal{B}(B_s^0 \to \eta_c\pi^+\pi^-) = (1.76 \pm 0.59(\text{stat.}) \pm 0.12(\text{syst.}) \pm 0.29(\mathcal{B})) \times 10^{-4}$.

5. Global combination

The CP-violating phase ϕ_s has been measured by several experiments, namely four analysis using the $B_s^0 \to J/\psi\phi$ final state from CDF [12], D0 [13], ATLAS [14] and CMS [15] collaborations and four analysis using different final states performed by the LHCb Collaboration, three of which discussed here. The global combination of ϕ_s and $\Delta\Gamma_s$ measurements from the Heavy Flavour Averaging Group [16] is shown in Fig. 4. They find $\phi_s = -0.030 \pm 0.033$ rad and $\Delta\Gamma_s = 0.085 \pm 0.006$ ps^{-1}, which is dominated by the measurements from the LHCb Collaboration and are consistent with the SM predictions.

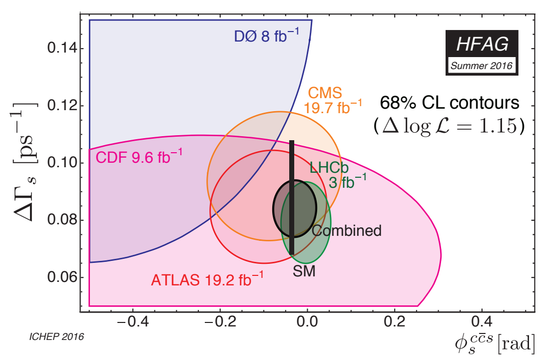

Fig. 4. 68% confidence level regions in $\Delta\Gamma_s$ and ϕ_s plane obtained from individual contours of CDF, D0, CMS, ATLAS and LHCb measurements and the combined contour (solid line and shaded area) [16]. The expectation from the SM [2] is shown as a black thin rectangle.

6. Summary

The most precise measurement of the CP-violating phase ϕ_s and mixing parameters in the B_s^0 system has been performed using data collected by the LHCb experiment during Run 1, corresponding to an integrated luminosity of 3 fb^{-1}. So far, all measurements are consistent with predictions from the Standard Model. To improve the experimental precision of the measurements, the analysis of other $\bar{b} \to \bar{c}c\bar{s}$ decay modes are being pursued, like the study of $B_s^0 \to J/\psi\phi$ decay mode with $J/\psi \to e^+e^-$.

After Run 2, corresponding to an integrated luminosity of 8 fb^{-1}, the statistical sensitivity of ϕ_s is expected to be two times better than for Run 1, using the $B_s^0 \to J/\psi\phi$ decay only. After the LHCb upgrade with an integrated luminosity of 50 fb^{-1}, the sensitivity will be closer to the theoretical uncertainty [17]. As the precision improves, it will be essential to control pollution due to loop-diagrams, so-called penguins, contributing to the decay that can hide contributions from physics beyond the SM [18, 19].

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