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Overview of CPV parameter φ_s determination

Varvara Batozskaya on behalf of the LHCb Collaboration

National Centre for Nuclear Research (NCBJ), Warsaw, Poland

Abstract

The one of main goals of the LHCb experiment is the measurement of the mixing-induced CP-violating phase φ_s in the $B_s^0 - \bar{B}_s^0$ system. It has been measured exploiting the Run I data set, using several decay channels. The most recent results obtained analyzing $B_s^0 \to J/\psi K^+K^-$ candidates in the K^+K^- mass region above the $\varphi(1020)$ resonance are presented. The measurements using the same final state with the $m(K^+K^-)$ at the $\varphi(1020)$ and $B_s^0 \to J/\psi\pi^+\pi^-$, as well as using the $B_s^0 \to \psi(2S)\varphi$ decay are discussed.

Corresponding Author:
Varvara Batozskaya
varvara.batozskaya@cern.ch

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1. Introduction

The CP-violating phase φ_s originates from the interference between the mixing and direct decay of B_s^0 mesons to CP eigenstates. Ignoring subleading penguin contributions, the phase φ_s within the Standard Model (SM) is predicted to be $-2\beta_s$ where $\beta_s = \arg(-V_{ts}V_{tb}^*/V_{cs}V_{cb}^*)$ [1]. An indirect determination of $2\beta_s = 0.0376^{+0.0008}_{-0.0007}$ rad is obtained using a global fit to experimental data [2]. Any deviation from this prediction would be a clear sign, so-called New Physics effects, strongly motivating the need for precise experimental measurements of this quantity [3]. The measurement of CP-violating phase φ_s has been independently performed using $B_s^0 \to J/\psi K^+K^-$, $B_s^0 \to J/\psi\pi^+\pi^-$ and $B_s^0 \to \psi(2S)\varphi$ decay modes. All measurements shown in the proceedings use 3 fb^{-1} of data collected by the LHCb experiment [4] in pp collisions during 2011 and 2012.

2. Measurements of the CP-violating phase φ_s

2.1. φ_s from $B_s^0 \to J/\psi\varphi$

A tagged time-dependent angular fit to $B_s^0 \to J/\psi\varphi$ candidates is applied to extract the CP-violating phase φ_s [5]. The final state of the decay is an admixture of CP-even states, $\eta_i = +1$ for $i \in \{0, \|\}$ and CP-odd states, $\eta_i = -1$ for $i \in \{\perp, \mathrm{S}\}$. It is decomposed into four amplitudes: three P-waves, A_0, $A_\parallel$, $A_\perp$ and one S-wave, A_S accounting for the nonresonant K^+K^- configuration. The phase is determined by $\varphi_s = -\arg(\lambda)$ where $\lambda = \lambda_i/\eta_i$ and $\lambda_i = \frac{q}{p}\frac{\bar{A}_i}{A_i}$. In the absence of CP violation in decay, $\lambda = 1$. The complex parameters p and q describe the relation between flavour and mass eigenstates: $|B_{\mathrm{L,H}}\rangle = p|B_s^0\rangle \pm q|\bar{B}_s^0\rangle$ and $p^2 + q^2 = 1$.

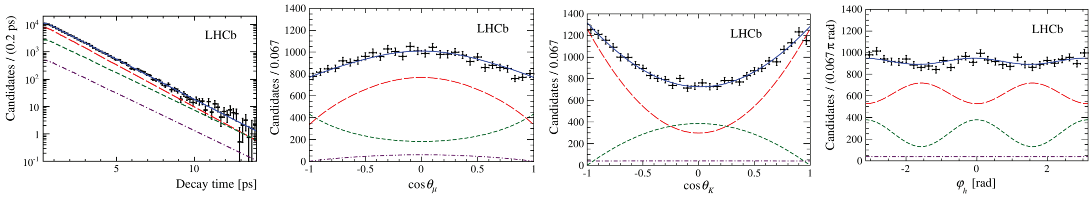

Figure 1: Decay time and angle distributions for $B_s^0 \to J/\psi\varphi$ decays (black markers) with the one-dimensional projections of the PDF. The solid blue line shows the total signal contribution, which is composed of CP-even (long-dashed red), CP-odd (short-dashed green) and S-wave (dotted-dashed purple) contributions.

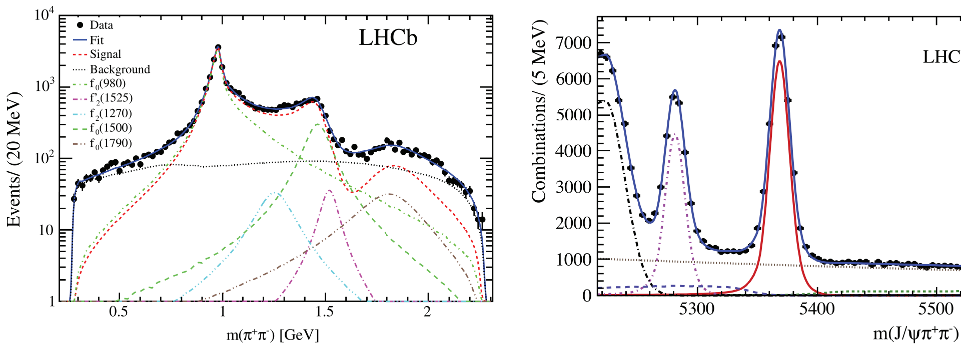

Figure 2: (left) Distribution of $m(\pi^+\pi^-)$ invariant mass with contributing components. (right) Invariant mass of $J/\psi\pi^+\pi^-$ combinations where the (red) solid curve shows the B_s^0 signal, the (brown) dotted line shows the combinatorial background, other colour lines indicate different reconstructed background contributions.

The $B_s^0 \to J/\psi\varphi$ candidates are reconstructed as the decay $J/\psi \to \mu^+\mu^-$ combined with a pair of oppositely charged kaons. After applying a full offline and trigger selection, 95690 ± 350 signal candidates of the $B_s^0 \to J/\psi\varphi$ are obtained [5]. The decay time and angular acceptances, decay time resolution as well as flavour tagging efficiency are taken into account in the fitting procedure. The decay time resolution is estimated using a large sample of prompt $J/\psi K^+K^-$ combinations produced directly in the pp interactions and is found to be 46 fs. Using a prescaled unbiased trigger sample and a tag and probe technique the decay time acceptance is determined from data. The angular acceptance is determined using simulated events that a subjected to the same trigger and selection criteria as the data. The flavour of the produced B_s^0 candidate is identified using two independent tagging algorithms: same side and opposite side. The flavour tagging algorithms are optimised on simulations and calibrated on data using flavour specific control channels. The combined effective tagging power is $(3.73 \pm 0.15)\%$ [5].

A weighted unbinned maximum likelihood fit is performed using a signal-only Probability Density Function (PDF), as described in Ref. [6]. The signal weights are extracted using the sPlot technique [7]. The data set is divided into six independent invariant K^+K^- mass bins that allows the measurement of the small S-wave amplitude in each bin and minimizes correction factors in the interference terms of the PDF [8]. The projections of the decay time and angular distributions are shown in Fig. 1. The final results are $\varphi_s = -0.058 \pm 0.049 \pm 0.006$ 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 is systematic [5]. The dominant contribution to the systematic uncertainty is contributed by the decay time and angular efficiency and background subtraction.

2.2. φ_s from $B_s^0 \to J/\psi\pi^+\pi^-$

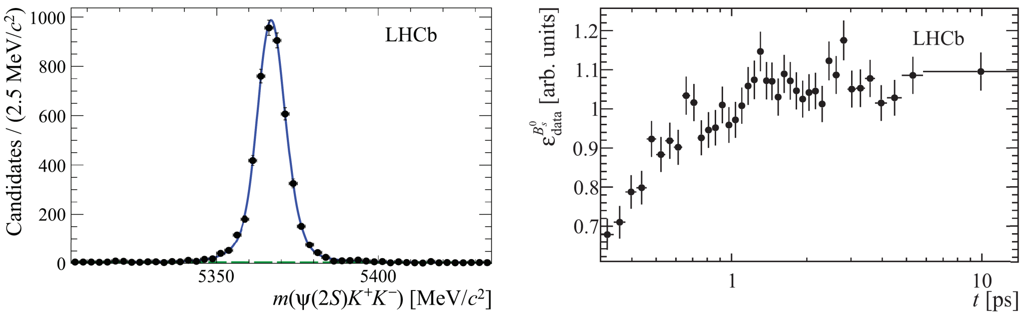

Figure 3: Distribution of the $m(\psi(2S)K^+K^-)$ invariant mass for the selected $B_s^0 \to \psi(2S)\varphi$ candidates and decay time acceptance in arbitrary units.

The analysis of $B_s^0 \to J/\psi\pi^+\pi^-$ decays has been also performed by the LHCb collaboration [9]. The decay is similar to the $B_s^0 \to J/\psi\varphi$ one with a noticeable simplification: the final state being CP-odd, there is no need for the angular analysis. Fig. 2 shows the five interfering $\pi^+\pi^-$ states dominated by $f_0(980)$ component. After trigger and selection chain 27100 ± 200 signal $B_s^0 \to J/\psi\pi^+\pi^-$ candidates are reconstructed (Fig. 2). With the time-dependent amplitude analysis, the measured value of the phase φ_s is $0.070 \pm 0.068 \pm 0.08$ rad. The dominant systematic uncertainty is coming from knowledge about $\pi^+\pi^-$ resonance model. The combination of the $B_s^0 \to J/\psi\varphi$ and $B_s^0 \to J/\psi\pi^+\pi^-$ fit results gives $\varphi_s = -0.010 \pm 0.039$ rad [5].

2.3. φ_s from $B_s^0 \to \psi(2S)\varphi$

Another B_s^0 decay mode with $\bar{b} \to \bar{c}c\bar{s}$ transition that has been exploited by the LHCb collaboration to measure φ_s is $B_s^0 \to \psi(2S)(\to \mu^+\mu^-)\varphi(\to K^+K^-)$ [10]. The formalism used for this analysis is very close to that of $B_s^0 \to J/\psi\varphi$ decay [5] where the J/ψ meson is replaced with $\psi(2S)$. The number of signal candidates selected from a fit to the data sample is ~ 4700 (Fig. 3). The decay time acceptance is determined using a control $B^0 \to \psi(2S)K^{*0}(\to K^+\pi^-)$ decay mode. Fig. 3 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 trigger and selection chain. The first measurement of the CP-violating parameters in a final state containing the $\psi(2S)$ resonance is $\varphi_s = -0.23^{+0.29}_{-0.28} \pm 0.02$ rad, $\Gamma_s = 0.668 \pm 0.011 \pm 0.006$ ps^{-1} and $\Delta\Gamma_s = 0.066^{+0.041}_{-0.044} \pm 0.007$ ps^{-1}. The fit result is consistent with $B_s^0 \to J/\psi\varphi$ measurement 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%.

2.4. φ_s from $B_s^0 \to J/\psi K^+K^-$ in high $m(K^+K^-)$ range

The first measurement of the phase φ_s has been performed in the $B_s^0 \to J/\psi K^+K^-$ decay with K^+K^- invariant mass larger than 1050 MeV/c^2 [11] that is above the $\varphi(1020)$ resonance region. This decay has been studied using an analysis method very similar to that used for the $B_s^0 \to J/\psi\varphi$ decay mode reported in Ref. [5]. The important difference between both decay analyses is that modelling of the $m(K^+K^-)$ distribution is included to distinguish different resonant and nonresonant contributions. The decay time acceptance is determined with the same method as described in Ref. [10] by using a control channel $B^0 \to J/\psi K^{*0}$. The K^+K^- mass spectrum is fitted by considering the different contributions found in the time-dependent amplitude analysis as shown in Fig. 4. The final fit has been performed allowing eight independent sets of CP-violating parameters: three corresponding to $\varphi(1020)$ transversity states, K^+K^- S-wave, $f_2(1270)$, $f_2^{'}(1525)$, $\varphi(1680)$ and the combination of the two high-mass $f_2(1750)$ and $f_2(1950)$ states. The CP-violating parameters measurement of $B_s^0 \to J/\psi K^+K^-$ in high $m(K^+K^-)$ region is $\varphi_s = 0.119 \pm 0.107 \pm 0.034$ rad, $\Gamma_s = 0.650 \pm 0.006 \pm 0.004$ ps^{-1} and $\Delta\Gamma_s = 0.066 \pm 0.018 \pm 0.006$ ps^{-1}. The largest contribution to systematic uncertainty results from the resonance fit model. The combination with the B_s^0 decay fit results in the $\varphi(1020)$ region gives $\varphi_s = -0.025 \pm 0.045 \pm 0.008$ rad, $\Gamma_s = 0.6588 \pm 0.0022 \pm 0.0015$ ps^{-1} and $\Delta\Gamma_s = 0.0813 \pm 0.0073 \pm 0.0036$ ps^{-1} that improves a precision of the φ_s measurement by more than 9%.

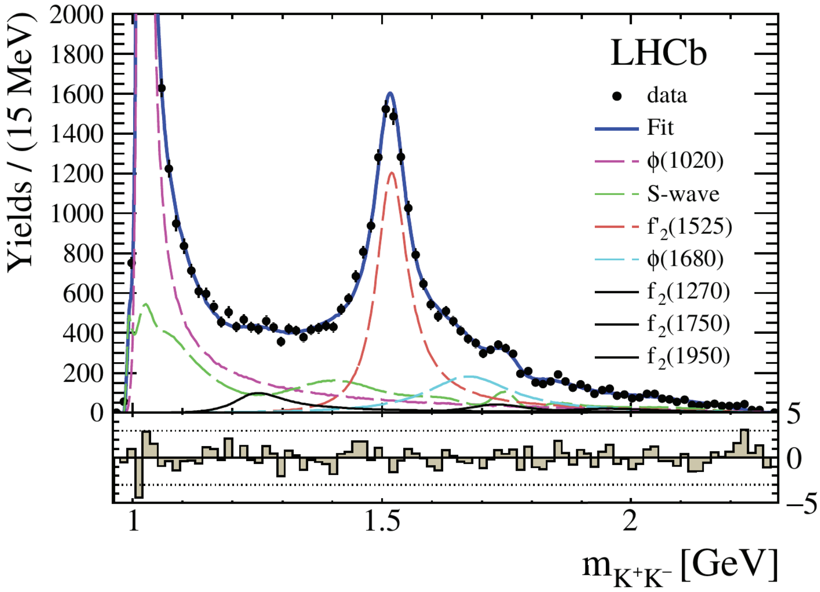

Figure 4: Distribution of the $m(J/\psi K^+K^-)$ invariant mass with contributing components.

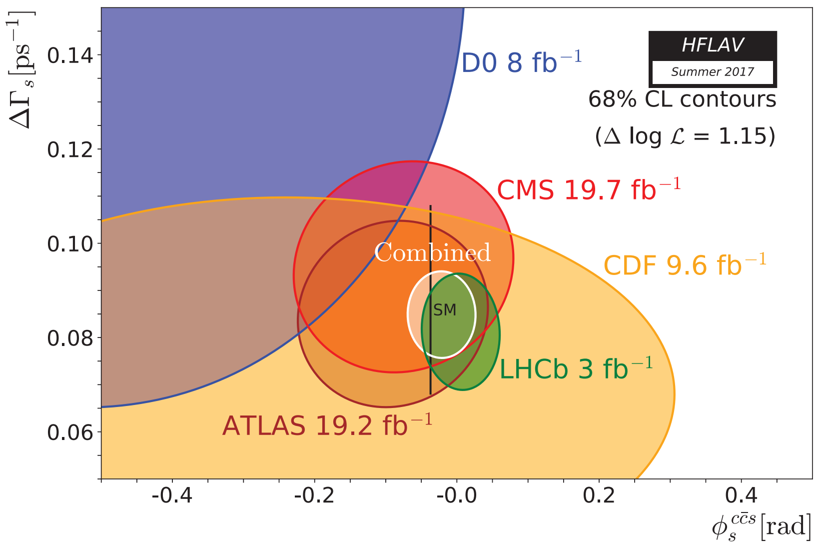

Figure 5: 68% confidence level regions in $\Delta\Gamma_s$ and φ_s plane obtained from individual contours of CDF, D0, CMS, ATLAS and LHCb measurements and the combined contour (solid line and shaded area) [16]. The expectation within the SM [2] is shown as a black thin rectangle.

2.5. Global combination

The CP-violating phase and lifetime parameters have been measured by several experiments, namely four analysis using the $B_s^0 \to J/\psi\varphi$ final state from CDF [12], D0 [13], ATLAS [14] and CMS [15] collaborations and five analysis using different final states performed by the LHCb collaboration, four of which discussed here. The world average result of φ_s and $\Delta\Gamma_s$ measurements from the Heavy Flavour Averaging Group [16] is shown in Fig. 5. They find $\varphi_s = -0.021 \pm 0.031$ rad and $\Delta\Gamma_s = 0.085 \pm$

0.006 ps^{-1} that is dominated by the measurements from LHCb collaboration and is consistent with the SM predictions.

3. Summary

The most precise measurement of CP-violating phase φ_s and lifetime parameters in the B_s^0 system has been performed using data collected by the LHCb experiment during Run I. So far all results are compatible with the Standard Model predictions. In order to reach an uncertainty of the measurement comparable or even better than the theoretical uncertainty of the SM prediction aside from improvements in available luminosity for the $B_s^0 \to J/\psi\varphi$ channels, inclusion of new decay modes have been investigated. For example, the $B_s^0 \to J/\psi(\to e^+e^-)\varphi$ channel not only could bring about 10% of the $\mu^+\mu^-$ mode statistics, but it will be also an important verification of the $B_s^0 \to J/\psi(\to \mu^+\mu^-)\varphi$ as kinematics for both channels are expected to be identical. The statistical sensitivity to φ_s measurement after the LHCb upgrade, with an integrated luminosity of 46 fb^{-1}, is expected ~0.01 rad that will be close to the present theoretical uncertainty [17]. As the measurement precision improves, the penguin polluion contributions to the B_s^0 meson decays have to been kept under control [18, 19].

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