DETERMINATION OF THE CP-VIOLATING PHASE ϕ_s IN $B_s^0 \to J/\psi\phi$ DECAYS*

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The determination of the CP-violating phase ϕ_s in $B_s^0 \to J/\psi\phi$ decays is one of the key goals of the LHCb experiment. Its value is predicted to be very small in the Standard Model. However, it can be significantly enhanced by contributions from effects of new physics. The most precise measurements of ϕ_s and $\Delta\Gamma_s$ to date are presented. Using a dataset corresponding to 3 fb^{-1} collected at the LHCb during 2011–2012, they are measured to be $\phi_s = -0.010 \pm 0.039$ rad and $\Delta\Gamma_s = 0.0805 \pm 0.0091 \pm 0.0032$ ps^{-1}.

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1. Introduction

Measurements of CP violation are a primary goal of the LHCb experiment [1] at CERN. Checking the expected values of CP-violating parameters and searching for deviations from these expectations improves our knowledge of CP violation. For decays which do not have a trivial phase space, amplitude analyses are essential for measurements of these parameters.

The CP-violating phase ϕ_s is measured with $B_s^0 \to J/\psi\phi$ [5] and $B_s^0 \to J/\psi\pi^+\pi^-$ [9] decays using 3 fb^{-1} of pp collisions collected by LHCb in 2011 and 2012 at $\sqrt{s} = 7$ TeV and 8 TeV, respectively. The result and measurement methodology is reported. In addition, the first estimate on the possibility of observing CP violation in $B_s^0 \to J/\psi\phi$ decays where $J/\psi \to e^+e^-$ is reported.

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2. Measurements of the CP-violating phase ϕ_s

The CP-violating phase, ϕ_s, the average decay width, Γ_s, and the decay width difference, $\Delta\Gamma_s$, between the lighter and heavier B_s^0 mass eigenstates can be measured via the interference between the mixing and direct decay of B_s^0 mesons to CP eigenstates (Figs. 1–2). If only leading penguin contributions are included (Fig. 2), the Standard Model (SM) predicts the CP-violating phase to be $\phi_s \simeq -2\beta_s$, where $\beta_s = \arg(-V_{ts}V_{tb}^*/V_{cs}V_{cb}^*)$ [2]. Using global fits to experimental data, an indirect determination of $2\beta_s = 0.0363^{+0.0012}_{-0.0014}$ rad is obtained [3].

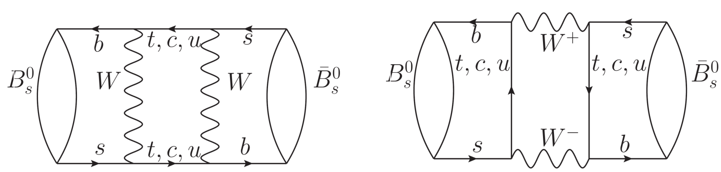

Fig. 1. Feynman diagrams for B_s^0–$\bar{B}_s^0$ mixing within the SM.

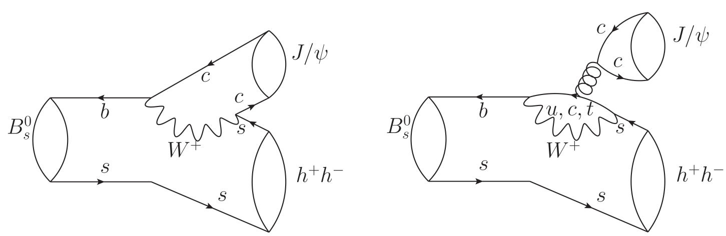

Fig. 2. Feynman diagrams contributing to the decay $B_s^0 \to J/\psi h^+h^-$ within the SM, where $h = \pi, K$: tree-level diagram (left) and penguin diagram (right).

Contributions from physics beyond the SM may affect the measured value of ϕ_s [4]. The CP-violating phase ϕ_s is independently measured using $B_s^0 \to J/\psi\phi$ and $B_s^0 \to J/\psi\pi^+\pi^-$ decay channels.

2.1. The $B_s^0 \to J/\psi K^+K^-$ analysis

The weak phase ϕ_s is extracted using a tagged time-dependent angular fit to $B_s^0 \to J/\psi(\mu^+\mu^-)K^+K^-$ candidates as described in Ref. [5]. The final state is decomposed into four amplitudes: three P-wave, A_0, $A_\parallel$, $A_\perp$ and one S-wave, A_S accounting for the non-resonant K^+K^- configuration. It is a superposition of CP-even states, $\eta_i = +1$ for $i \in 0, \parallel$ and CP-odd states, $\eta_i = -1$ for $i \in \perp, S$ states. The phase ϕ_s is defined by $\phi_s = -\arg(\lambda)$, where $\lambda = \lambda_i/\eta_i$ and $\lambda_i = \frac{q}{p}\frac{\bar{A}_i}{A_i}$. The complex parameters p and q describe the relation between mass and flavour eigenstates: $|B_{L,H}\rangle = p|B_s^0\rangle \pm q|\bar{B}_s^0\rangle$ and $p^2 + q^2 = 1$.

The reconstruction of $B_s^0 \to J/\psi K^+K^-$ candidates proceeds using the decays $J/\psi \to \mu^+\mu^-$ combined with a pair of oppositely charged kaons. After the trigger and full off-line selection, $95\,690 \pm 350$ signal candidates of the $B_s^0 \to J/\psi K^+K^-$ are obtained [5]. The fit procedure takes into account decay time and angular acceptances, decay-time resolution as well as efficiency of flavour tagging. The decay-time resolution is estimated using prompt $J/\psi K^+K^-$ combinations and is found to be 46 fs. The decay-time acceptance is determined from data, using a prescaled unbiased trigger sample and a tag-and-probe technique. The angular acceptance is determined using a Monte Carlo sample. The flavour tagging algorithm uses information from additional same-side and opposite-side particles with respect to the signal candidate. It is optimised on Monte Carlo samples and calibrated on data, using flavour specific control channels. The obtained effective tagging power is $(3.73 \pm 0.15)\%$ [5].

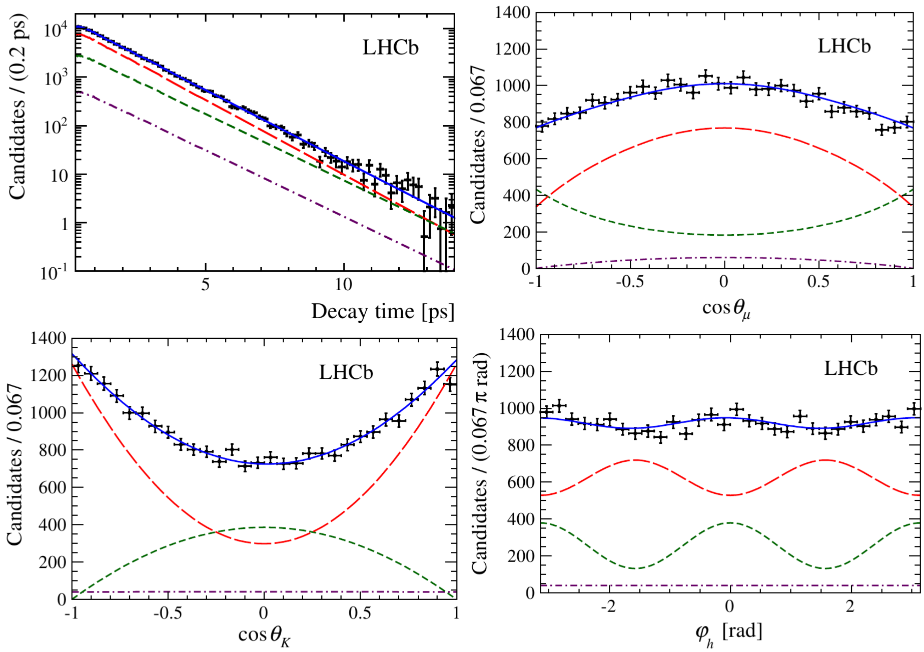

Fig. 3. (Colour on-line) Decay-time and helicity-angle distributions for $B_s^0 \to J/\psi(\mu^+\mu^-)K^+K^-$ decays (black markers) with the one-dimensional projections of the Probability Density Function (PDF) at the maximal likelihood fit. The solid (blue) line shows the total signal contribution, which is composed of CP-even (long-dashed/red), CP-odd (short-dashed/green) and S-wave (dot-dashed/purple) contributions.

A weighted unbinned likelihood fit is performed using a signal-only PDF, as described in Ref. [6]. The signal weights are determined using the sPlot method [7]. The data is divided into six independent invariant K^+K^- mass bins. This improves the statistical sensitivity and allows to resolve the two-fold ambiguity of $B_s^0 \to J/\psi K^+K^-$ differential decay rate, in particular the sign of $\Delta\Gamma_s$, as is described in [8]. The projections of the decay-time and angular distributions are shown in Fig. 3. The final results of the maximum likelihood fit are $\phi_s = -0.058 \pm 0.049 \pm 0.006$ rad, $\Gamma_s = 0.6603 \pm 0.0027 \pm 0.0015\ \mathrm{ps}^{-1}$ and $\Delta\Gamma_s = 0.0805 \pm 0.0091 \pm 0.0032\ \mathrm{ps}^{-1}$, where the first uncertainty is statistical and the second systematic [5].

2.2. The $B_s^0 \to J/\psi\pi^+\pi^-$ analysis and combined results

The $B_s^0 \to J/\psi\pi^+\pi^-$ analysis [9] is similar to the $B_s^0 \to J/\psi K^+K^-$ one with a noticeable simplification: the final state being CP-odd, there is no need for the angular analysis. After trigger and selection $27\,100 \pm 200$ signal $B_s^0 \to J/\psi\pi^+\pi^-$ candidates are found in the analysis. The decay time resolution is 40.3 fs and the effective tagging power is $(3.89 \pm 0.25)\%$. The result of the simultaneous fit to both $B_s^0 \to J/\psi K^+K^-$ and $B_s^0 \to J/\psi\pi^+\pi^-$ is $\phi_s = -0.010 \pm 0.039$ rad [5].

The measurements of the CP-violating phase ϕ_s and $\Delta\Gamma_s$ are the most precise to date and are in agreement with the SM predictions [3, 10]. Figure 4 compares the measured value of ϕ_s with other independent measurements [11].

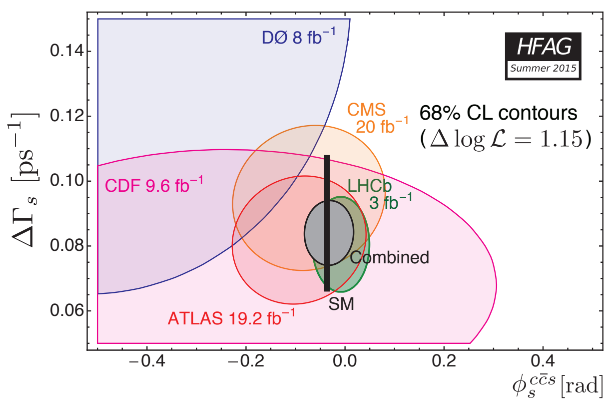

Fig. 4. 68% confidence level regions in $\Delta\Gamma_s$ and ϕ_s plane obtained from individual contours of CDF, D0, CMS, ATLAS and LHCb and the combined contour (solid line and shaded area) [12]. The expectation from the SM [3] is shown as a black thin rectangle.

2.3. The $B_s^0 \to J/\psi(e^+e^-)\phi$ analysis

In order to increase the statistics of the data and to improve the accuracy of the measurement of the CP-violating phase ϕ_s, the analysis of the $B_s^0 \to J/\psi\phi$ decay, where $J/\psi \to e^+e^-$, is performed.

This channel can be analysed exactly in the same way as $\mu^+\mu^-$ mode to extract the CP-violating phase since it has similar kinematics. However, the reconstruction of the J/ψ with electrons in the final state leads to experimental problems that are specific to this decay mode:

— The momentum determination of an electron pair is worse than muons since the e^+e^- irradiate Bremsstrahlung photons which leads to a degraded J/ψ and B_s^0 mass resolution;

— The identification of electrons from the signal is complicated by the presence of a large electromagnetic and hadronic background in the electromagnetic calorimeter;

— The $B_s^0 \to J/\psi(e^+e^-)\phi$ mode has a different trigger strategy from the channel with muons in the final state as it is mainly based on hadronic and electromagnetic trigger lines.

The invariant mass distribution of the muon and electron systems is shown in Fig. 5. The $\mu^+\mu^-$ mass distribution is very narrow and has a small tail on the left-hand side which is fitted using a Crystal Ball function. On the other hand, the e^+e^- mass distribution is asymmetric with a tail reflecting Bremsstrahlung photons which have not been reconstructed. Both on-line

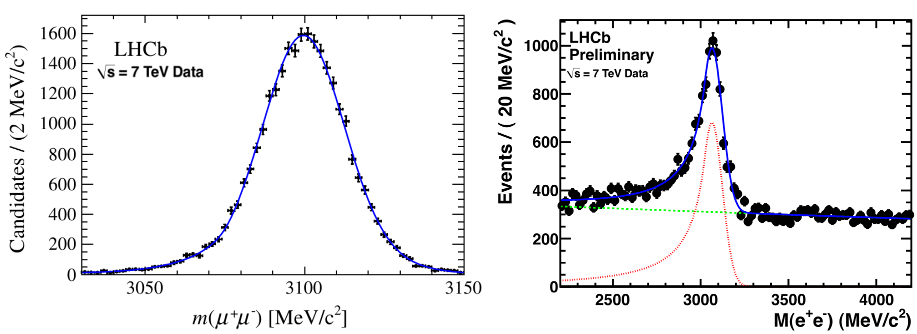

Fig. 5. (Colour on-line) The invariant mass distributions of the muon (left) and electron (right) pairs for the 2011 dataset. Data are shown by black markers. In the case of the $\mu^+\mu^-$ system, the solid (blue) line represents a model that was fitted to the background subtracted invariant mass distribution. For the e^+e^- system, the solid (blue) line shows the total fit, the signal and combinatorial background components are given by dotted (red) line and dashed (green) line, respectively.

and off-line selection efficiency is reduced for $J/\psi \to e^+e^-$. The estimated yield of reconstructed events in the $J/\psi \to e^+e^-$ decay channel is about 10% with respect to the $\mu^+\mu^-$ decay mode.

3. Summary

Using $B_s^0 \to J/\psi K^+K^-$ and $B_s^0 \to J/\psi\pi^+\pi^-$ decays selected from the data corresponding to 3 fb^{-1} of integrated luminosity, LHCb performed the world most precise measurement of $\phi_s = -0.010 \pm 0.039$ 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}. The results are compatible with the SM and put stronger constraints on possible SM extensions in the B_s^0–$\bar{B}_s^0$ mixing phase. The statistical sensitivity to ϕ_s measurement after Run 2, with an integrated luminosity of 8 fb^{-1} for 2015–2018, is expected to be twice better compared to Run 1. The sensitivity after the LHCb upgrade, with expected integrated luminosity of 46 fb^{-1}, will be close to the present theoretical uncertainty [13].

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 golden channels, inclusion of other modes will be required. The $B_s^0 \to J/\psi(e^+e^-)\phi$ channel not only could bring about 10% of the $\mu^+\mu^-$ mode statistics, but it will be also an important verification of the golden channel as kinematics for both channels are expected to be identical.

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