

Measurement of CP violation in the B_s^0 system

Kristof De Bruyn on behalf of the LHCb collaboration

Nikhef National Institute for Subatomic Physics,
Science Park 105, 1098 XG Amsterdam, The Netherlands

E-mail: debkr@nikhef.nl

Abstract. Studies of CP violation play a key role in the search for physics beyond the Standard Model. In the B_s^0 system these mainly consist of measurements of mixing-induced CP violation, which arises from the interference between the B_s^0 - \bar{B}_s^0 mixing process and the subsequent decay. This report focusses on two such asymmetry measurements recently published by the LHCb collaboration. The first analysis presents the measurement of a CP violating phase in $B_s^0 \rightarrow \phi\phi$, which is found to be $\phi_{\phi\phi} = -0.17 \pm 0.15(\text{stat}) \pm 0.03(\text{syst})$ rad. The second provides an updated measurement of the B_s^0 - \bar{B}_s^0 mixing phase ϕ_s using the $B_s^0 \rightarrow J/\psi\pi^+\pi^-$ channel. It yields $\phi_s = 0.070 \pm 0.068(\text{stat}) \pm 0.008(\text{syst})$ rad. Both results are consistent with the Standard Model expectations and no indication for direct CP violation was found in either decay mode.

1. Introduction

In the Standard Model (SM), CP violation arises through a single phase in the CKM quark mixing matrix. In decays of neutral B_s^0 mesons to a final state accessible to both B_s^0 and \bar{B}_s^0 , the interference between the amplitude for the direct decay and the amplitude for decay via oscillation leads to time-dependent CP violation. The resulting CP asymmetry can be parametrised in terms of the convention-independent quantity

$$\lambda_f \equiv \frac{q}{p} \frac{A(\bar{B}_s^0 \rightarrow f)}{A(B_s^0 \rightarrow f)} = |\lambda_f| e^{i\phi_f}, \quad (1)$$

where q and p are complex parameters that relate the B_s^0 flavour and mass eigenstates to each other, and A is the decay amplitude. Where accurate SM predictions for λ_f are available, these CP asymmetries provide sensitive tests of the SM flavour sector and thus are excellent probes to search for signs of new physics, well beyond the reach of direct detection methods. Under the assumption that $|q/p| = 1$, as is consistent with current data [1], a deviation of $|\lambda_f|$ from unity would be a measure of direct CP violation in the $B_s^0 \rightarrow f$ mode. As direct CP violation is in general expected to be small, the primary target for mixing-induced CP violation measurements is the decay-mode-dependent complex phase ϕ_f .

This report presents two such asymmetry measurements: the first measurement of a CP violating phase in $B_s^0 \rightarrow \phi\phi$ [2] and an updated measurement of the B_s^0 - \bar{B}_s^0 mixing phase ϕ_s from $B_s^0 \rightarrow J/\psi\pi^+\pi^-$ [3]. Both analyses are performed on a data sample corresponding to an integrated luminosity of 3.0 fb^{-1} of pp collisions, recorded by the LHCb experiment in 2011 and 2012. The LHCb detector [4] is a single-arm forward spectrometer covering the pseudo-rapidity range $2 < \eta < 5$, designed for the study of particles containing b or c quarks. Its vertex locator and tracking system allow for the identification of the secondary vertices associated with the

decay of B_s^0 mesons, and achieve a decay time resolution of about 40 fs. This is small enough to resolve the rapid B_s^0 - \bar{B}_s^0 oscillations and allow for a time-dependent analysis of the above-mentioned modes.

2. Measurement of a CP violating phase in $B_s^0 \rightarrow \phi\phi$

The $B_s^0 \rightarrow \phi\phi$ decay originates from a $\bar{b} \rightarrow \bar{s}s\bar{s}$ transition. In the SM, such a transition is forbidden at tree level and can only proceed via higher order loop diagrams, where it is dominated by the so-called gluonic penguin topologies. The channel is therefore sensitive to possible new heavy degrees of freedom showing up in such loops. The presence of these new physics contributions can be constrained through a measurement of the complex phase $\phi_{\phi\phi}$, defined in Eq. (1). Due to a difference in the structure of the decay amplitude, this weak phase should not directly be compared to the CKM angle ϕ_s measured in $B_s^0 \rightarrow J/\psi h^+ h^-$ decays. Instead, its SM value is limited to be smaller than [5]

$$\phi_{\phi\phi} \approx \left(S_{\phi\phi} \equiv \frac{2 \operatorname{Im}[\lambda_{\phi\phi}]}{1 + |\lambda_{\phi\phi}|^2} \right) \leq 0.02. \quad (2)$$

The experimental measurement at LHCb [2] uses a topological b -trigger to identify potential $B_s^0 \rightarrow \phi\phi$ candidates from a four kaon final state. The subsequent event selection is based on a multivariate analysis trained on a combination of simulated data for the signal and data events from the B_s^0 mass sidebands for the background. Due to differences in the run conditions between 2011 and 2012 and in particular the pile-up, which affects the particle identification performance, the selection procedure is optimised for both years individually and yields 1185 ± 35 (2011) plus 2765 ± 57 (2012) reconstructed $B_s^0 \rightarrow \phi\phi$ decays.

$B_s^0 \rightarrow \phi\phi$ is a vector-vector final state and thus requires an angular analysis to disentangle the CP-even and CP-odd contributions to its decay amplitude. In addition, also contributions from non-resonant final states, split in a vector-scalar type (S-wave) and a scalar-scalar type (double S-wave) component, are included in the analysis. The angular analysis is performed in the helicity frame, illustrated in Fig. 1.

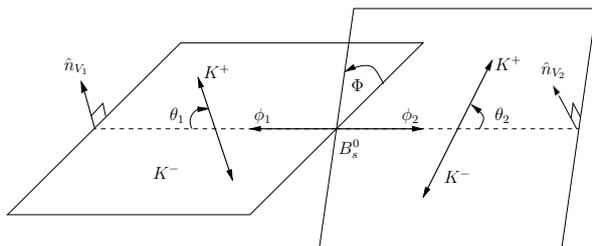


Figure 1. Helicity framework for the angular analysis of the $B_s^0 \rightarrow \phi\phi$ decay. The angle Φ , used in the construction of the two *triple product asymmetries*, is the angle between the decay planes of the two ϕ mesons.

For the time-dependent analysis, knowledge of the initial flavour of the B_s^0 meson is required. This analysis uses both information from the other b -quark in the event, referred to as opposite side tagging, as well as information from kaons that can be associated with the hadronisation of the signal b -quark, referred to as same side kaon tagging. The effective tagging power is measured to be $(5.33 \pm 0.37)\%$ for the 2011 data and $(5.44 \pm 0.30)\%$ for the 2011 data. The reader is referred to Ref. [2] for further details regarding the analysis and the construction of the used likelihood. The results from the time-dependent analysis of the data are

$$\begin{aligned} \phi_{\phi\phi} &= -0.17 \pm 0.15 \text{ (stat)} \pm 0.03 \text{ (syst)} \text{ rad} , \\ |\lambda_{\phi\phi}| &= 1.04 \pm 0.07 \text{ (stat)} \pm 0.03 \text{ (syst)} . \end{aligned} \quad (3)$$

The value of $\phi_{\phi\phi}$ is found to be compatible with the SM expectation.

In addition, also the T-odd *triple product asymmetries* can be used — in conjunction with the CPT theorem — to deduce information about CP violation in the $B_s^0 \rightarrow \phi\phi$ mode. These time-integrated quantities are defined in terms of the angular observables only. Starting from the trigonometric functions

$$U \equiv \sin(\Phi) \cos(\Phi), \quad V \equiv \sin(\pm\Phi), \quad (4)$$

where Φ is the angle between the decay planes of the two ϕ mesons, as shown in Fig. 1, they are defined as

$$\begin{aligned} \mathcal{A}_U &\equiv \frac{\Gamma(U > 0) - \Gamma(U < 0)}{\Gamma(U > 0) + \Gamma(U < 0)}, \\ \mathcal{A}_V &\equiv \frac{\Gamma(V > 0) - \Gamma(V < 0)}{\Gamma(V > 0) + \Gamma(V < 0)}, \end{aligned} \quad (5)$$

and measured to be

$$\begin{aligned} \mathcal{A}_U &= -0.003 \pm 0.017 \text{ (stat)} \pm 0.006 \text{ (syst)}, \\ \mathcal{A}_V &= -0.017 \pm 0.017 \text{ (stat)} \pm 0.006 \text{ (syst)}. \end{aligned} \quad (6)$$

Also these results are compatible with the SM expectation.

3. Update on the measurement of ϕ_s in $B_s^0 \rightarrow J/\psi\pi^+\pi^-$

The $B_s^0\text{-}\bar{B}_s^0$ mixing phase ϕ_s is a gold plated probe to search for new physics. Its SM value is precisely known [6],

$$\phi_s^{\text{SM}} = -0.0364 \pm 0.0016 \text{ rad}, \quad (7)$$

and it is experimentally well accessible through the $B_s^0 \rightarrow J/\psi K^+K^-$ and $B_s^0 \rightarrow J/\psi\pi^+\pi^-$ decay modes. LHCb has recently updated its 1 fb^{-1} analysis [7] for the $B_s^0 \rightarrow J/\psi\pi^+\pi^-$ mode, which now includes the full LHC run 1 data [3].

The measurement sample uses high momentum muons to identify potential $B_s^0 \rightarrow J/\psi\pi^+\pi^-$ candidates from a $\mu^+\mu^-\pi^+\pi^-$ final state. The subsequent event selection is based on a multivariate analysis trained on a combination of simulated data for the signal and data events from the B_s^0 mass sidebands for the background. The final selection achieves a signal purity of 79.6% in the $\pm 20 \text{ MeV}$ mass window around the B_s^0 peak, with a total signal yield of 27100 ± 200 events.

A important prerequisite for the time-dependent CP analysis of the $B_s^0 \rightarrow J/\psi\pi^+\pi^-$ mode is a precise determination of its CP content. An amplitude analysis in combination with information from the Dalitz plane was used [8] to identify the resonant contributions in the three-body final state. It was found that five interfering $\pi^+\pi^-$ states are required to describe the data. These include the dominant $f_0(980)$ as well as the $f_0(1500)$, $f_0(1790)$, $f_2(1270)$, and $f_2(1525)$. The resulting decomposition of the $\pi^+\pi^-$ invariant mass spectrum is shown in Fig. 2. The $B_s^0 \rightarrow J/\psi\pi^+\pi^-$ mode is consistent with being fully CP odd, where the CP even contribution is smaller than 2.3% at 90% C.L. Consequently, the full $\pi^+\pi^-$ mass spectrum can be used to perform the CP analysis.

For the time-dependent analysis knowledge of the initial flavour of the B_s^0 meson is required. Also here, both opposite side tagging and same side kaon tagging are used. The effective tagging power is measured to be $(3.89 \pm 0.25)\%$. The reader is referred to Ref. [3] for further details regarding the analysis and the construction of the used likelihood. Contrary to its $B_s \rightarrow J/\psi K^+K^-$ counterpart, the $B_s \rightarrow J/\psi\pi^+\pi^-$ analysis cannot determine $\Delta\Gamma_s$. Instead, the 1 fb^{-1} results from $B_s \rightarrow J/\psi K^+K^-$ [7],

$$\begin{aligned} \Gamma_s &= 0.663 \pm 0.005 \text{ (stat)} \pm 0.006 \text{ (syst)} \text{ ps}^{-1}, \\ \Delta\Gamma_s &= 0.100 \pm 0.016 \text{ (stat)} \pm 0.003 \text{ (syst)} \text{ ps}^{-1}, \end{aligned} \quad (8)$$

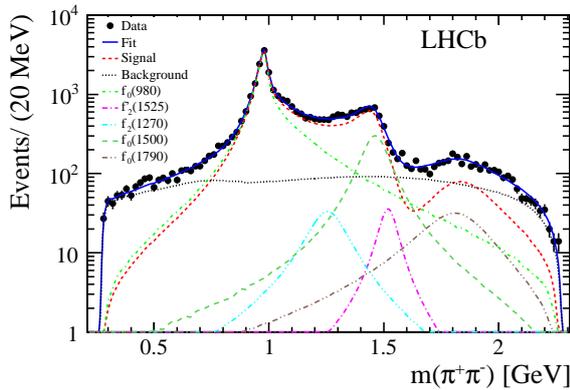


Figure 2. Decomposition of the $\pi^+\pi^-$ invariant mass spectrum for candidates in the ± 20 MeV mass window around the B_s^0 peak.

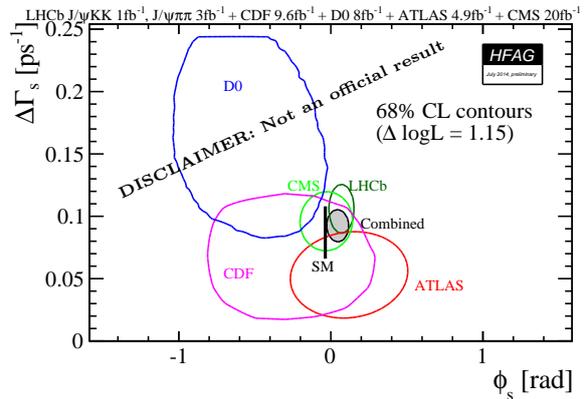


Figure 3. Unofficial overview of the current experimental constraints in the $\phi_s - \Delta\Gamma_s$ plane, modified compared to the original [9] to include these results as well as the summer 2014 updates from Atlas [10] and CMS [11].

are used as Gaussian constraints in the likelihood. The results from the time-dependent analysis of the data are

$$\begin{aligned}\phi_s &= 0.070 \pm 0.068 \text{ (stat)} \pm 0.008 \text{ (syst)} \text{ rad} , \\ |\lambda| &= 0.89 \pm 0.05 \text{ (stat)} \pm 0.01 \text{ (syst)} .\end{aligned}\tag{9}$$

The value of ϕ_s is found to be compatible with the SM expectation. An unofficial overview of the current experimental constraints in the $\phi_s - \Delta\Gamma_s$ plane, modified compared to the original [9] to include these results as well as the summer 2014 updates from Atlas [10] and CMS [11], is shown in Fig. 3. This shows that new physics contributions, if present, are necessarily small and will thus be challenging to find. Further experimental improvements should help settle this matter.

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