

## Determination of the phase $\phi_s$ at LHCb

Varvara Batozskaya<sup>1,\*,\*\*</sup>

on behalf of the LHCb Collaboration

<sup>1</sup>National Centre for Nuclear Research (NCBJ), Warsaw, Poland

**Abstract.** The determination of the mixing-induced  $CP$ -violating phase  $\phi_s$  in the  $B_s^0 - \bar{B}_s^0$  system is one of the key goals of the LHCb experiment. Using several  $B_s^0$  decay modes it has been measured by the LHCb collaboration exploiting the Run I data set. The first observation of the  $B_s^0 \rightarrow \eta_c \phi$  and  $B_s^0 \rightarrow \eta_c \pi^+ \pi^-$  decay modes which can be used to measure  $\phi_s$  with Run II data is presented.

### 1 Introduction

The  $CP$ -violating phase  $\phi_s$  originates from the interference between the mixing and direct decay of the  $B_s^0$  mesons to  $CP$  eigenstates. Ignoring subleading penguin contributions, the phase  $\phi_s$  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  $2\beta_s = 0.0376_{-0.0007}^{+0.0008}$  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  $\phi_s$  has been independently performed using  $B_s^0 \rightarrow J/\psi K^+ K^-$ ,  $B_s^0 \rightarrow J/\psi \pi^+ \pi^-$  and  $B_s^0 \rightarrow \psi(2S)\phi$  decay channels. All measurements shown in the proceedings use  $3 \text{ fb}^{-1}$  of data collected by the LHCb experiment [4] in  $pp$  collisions during 2011 and 2012.

### 2 Status of $\phi_s$ measurement

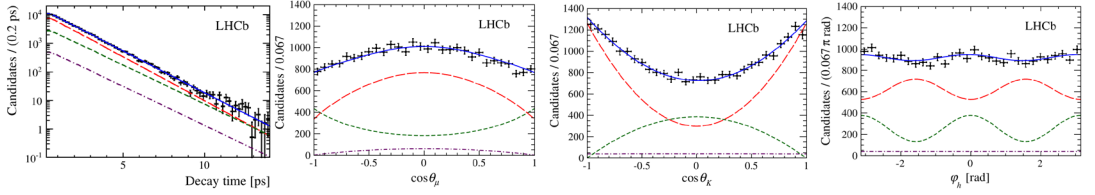
#### 2.1 $\phi_s$ from $B_s^0 \rightarrow J/\psi \phi$ and $B_s^0 \rightarrow J/\psi \pi^+ \pi^-$

The  $B_s^0 \rightarrow J/\psi \phi$  candidates are reconstructed as the decay  $J/\psi \rightarrow \mu^+ \mu^-$  and  $\phi \rightarrow K^+ K^-$  [5]. After applying a full offline and trigger selection,  $95690 \pm 350$  signal candidates of the  $B_s^0 \rightarrow J/\psi \phi$  are obtained. The decay time and angular acceptances, decay time resolution as well as flavour tagging efficiency are taken into account in the fitting procedure. 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. The decay time resolution is estimated using a sample of prompt  $J/\psi K^+ K^-$  combinations produced directly in the  $pp$  interactions and is found to be 46 fs. The combined effective tagging power is  $(3.73 \pm 0.15)\%$  [5].

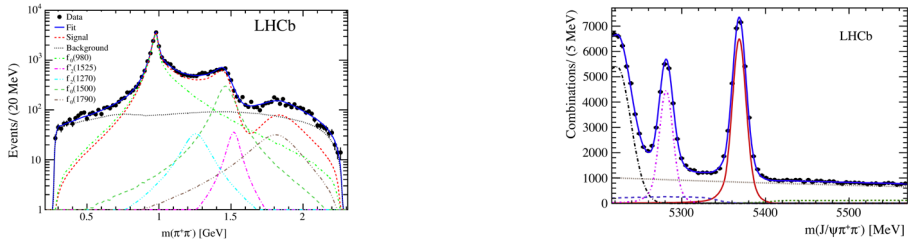
A weighted unbinned maximum likelihood fit is performed using a signal-only Probability Density Function (PDF), as described in [6]. Fig. 1 shows the projections of the decay time and angular

\*e-mail: [varvara.batozskaya@cern.ch](mailto:varvara.batozskaya@cern.ch)

\*\*On leave of absence from JINR, Dubna



**Figure 1.** Decay time and angle distributions for  $B_s^0 \rightarrow J/\psi\phi$  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.



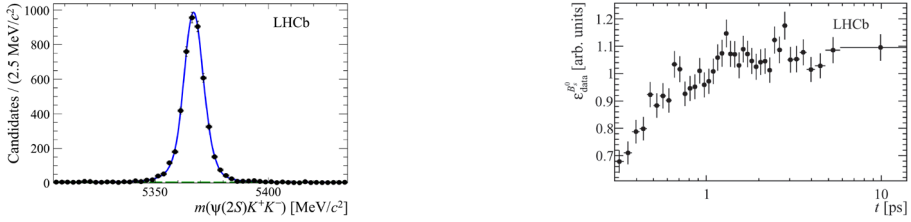
**Figure 2.** (left) Distribution of  $m(\pi^+\pi^-)$  invariant mass with contributing components. (right) Invariant mass of  $J/\psi\pi^+\pi^-$  combinations where the (red) solid curve shows the  $B_s^0$  signal, the (brown) dotted line shows the combinatorial background, other colour lines indicate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

distributions. The final 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 $^{-1}$  [5]. The dominant contribution to the systematic uncertainty is given by the decay time and angular efficiency and background subtraction.

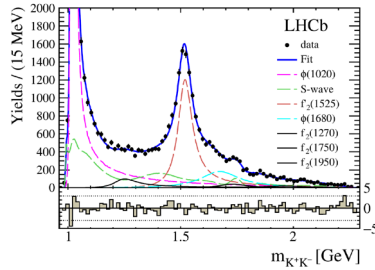
The  $B_s^0 \rightarrow J/\psi\pi^+\pi^-$  decays has also been used by the LHCb collaboration [7] to measure  $\phi_s$ . The decay is similar to the  $B_s^0 \rightarrow J/\psi\phi$  one with a noticeable simplification: the final state being  $CP$ -odd, there is no need for the angular analysis. Five interfering  $\pi^+\pi^-$  states dominated by  $f_0(980)$  component are shown in Fig. 2. After trigger and selection chain  $27100 \pm 200$  signal  $B_s^0 \rightarrow J/\psi\pi^+\pi^-$  candidates are reconstructed (Fig. 2). With the time-dependent amplitude analysis, the measured value of the phase  $\phi_s$  is  $0.070 \pm 0.068 \pm 0.08$  rad. The dominant systematic uncertainty is the one coming from knowledge about  $\pi^+\pi^-$  resonance model. The combination of the  $B_s^0 \rightarrow J/\psi\phi$  and  $B_s^0 \rightarrow J/\psi\pi^+\pi^-$  fit results gives  $\phi_s = -0.010 \pm 0.039$  rad [5].

## 2.2 $\phi_s$ from $B_s^0 \rightarrow \psi(2S)\phi$

Another  $B_s^0$  decay mode with  $\bar{b} \rightarrow \bar{c}c\bar{s}$  transition that has been exploited by the LHCb collaboration to measure the phase  $\phi_s$  is  $B_s^0 \rightarrow \psi(2S)(\rightarrow \mu^+\mu^-)\phi(\rightarrow K^+K^-)$  [8]. The formalism used for this analysis is very close to that of  $B_s^0 \rightarrow J/\psi\phi$  decay [5] where the  $J/\psi$  meson is replaced with  $\psi(2S)$ . The number of signal candidates selected from a fit to the data sample is  $\sim 4700$  (Fig. 3). The decay time acceptance is determined using a control  $B^0 \rightarrow \psi(2S)K^{*0}(\rightarrow K^+\pi^-)$  decay mode as shown in Fig. 3. The first measurement of the  $CP$ -violating parameters in a final state containing the  $\psi(2S)$  resonance is  $\phi_s = -0.23^{+0.29}_{-0.28} \pm 0.02$  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  $B_s^0 \rightarrow J/\psi\phi$  measurement and the SM predictions. The systematic uncertainty is less than 20% of the statistical uncertainty, except for  $\Gamma_s$  where it is close to 60%.



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



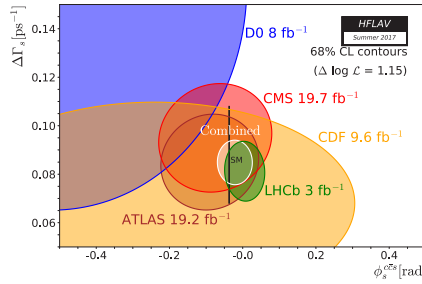
**Figure 4.** Distribution of the  $m(J/\psi K^+K^-)$  invariant mass with contributing components.

### 2.3 $\phi_s$ from $B_s^0 \rightarrow J/\psi K^+K^-$ in high $m(K^+K^-)$ range

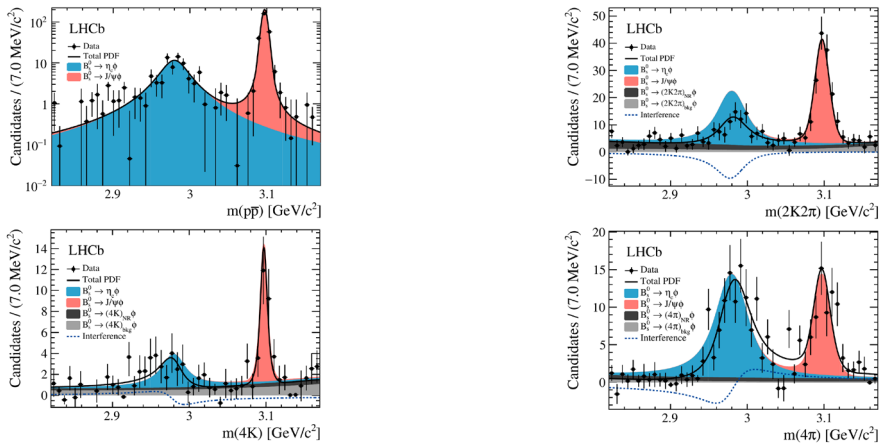
The first measurement of the phase  $\phi_s$  has been performed in the  $B_s^0 \rightarrow J/\psi K^+K^-$  decay with  $K^+K^-$  invariant mass higher than 1050 MeV/c<sup>2</sup> [9] that is above the  $\phi(1020)$  resonance region. The important difference between both decay analyses is that modelling 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 [8] by using a control channel  $B^0 \rightarrow J/\psi K^{*0}$ . 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  $\phi(1020)$  transversity states,  $K^+K^-$  S-wave,  $f_2(1270)$ ,  $f_2'(1525)$ ,  $\phi(1680)$  and the combination of the two high-mass  $f_2(1750)$  and  $f_2(1950)$  states. The  $CP$ -violating parameters measurement of  $B_s^0 \rightarrow J/\psi K^+K^-$  in high  $m(K^+K^-)$  region is  $\phi_s = 0.119 \pm 0.107 \pm 0.034$  rad,  $\Gamma_s = 0.650 \pm 0.006 \pm 0.004$  ps<sup>-1</sup> and  $\Delta\Gamma_s = 0.066 \pm 0.018 \pm 0.006$  ps<sup>-1</sup>. The largest contribution to systematic uncertainty results from the resonance fit model. The combination with the  $B_s^0$  decay fit results in the  $\phi(1020)$  region gives  $\phi_s = -0.025 \pm 0.045 \pm 0.008$  rad that improves a precision of the  $\phi_s$  measurement by more than 9%.

### 2.4 Global combination

The  $CP$ -violating phase and lifetime parameters have been measured by several experiments, namely four analysis using the  $B_s^0 \rightarrow J/\psi\phi$  final state from CDF [10], D0 [11], ATLAS [12] and CMS [13] collaborations and five analysis using different final states performed by the LHCb collaboration, four of which discussed here. The world average result of  $\phi_s$  and  $\Delta\Gamma_s$  measurements from the Heavy Flavour Averaging Group [14] is shown in Fig. 5. They found  $\phi_s = -0.021 \pm 0.031$  rad and  $\Delta\Gamma_s =$



**Figure 5.** 68% confidence level regions in  $\Delta\Gamma_s$  and  $\phi_s$  plane obtained from individual contours of CDF, D0, CMS, ATLAS and LHCb measurements and the combined contour (solid line and shaded area) [14]. The expectation within the SM [2] is shown as a black thin rectangle.



**Figure 6.** Invariant mass distributions for selected  $p\bar{p}$ ,  $K^+K^-\pi^+\pi^-$ ,  $K^+K^-K^+K^-$  and  $\pi^+\pi^-\pi^+\pi^-$  combinations.

$0.085 \pm 0.006 \text{ ps}^{-1}$  that is dominated by the measurements from LHCb collaboration and is consistent with the SM predictions.

### 3 Future contributions for measuring $\phi_s$

#### 3.1 $\phi_s$ from $B_s^0 \rightarrow \eta_c\phi$

For the first time the LHCb collaboration has observed the  $B_s^0 \rightarrow \eta_c\phi$  decay mode, with  $\eta_c \rightarrow K^+K^-\pi^+\pi^-$ ,  $K^+K^-K^+K^-$ ,  $\pi^+\pi^-\pi^+\pi^-$  and  $p\bar{p}$  [19]. This decay is another  $b \rightarrow c\bar{c}s$  transition that could be used to measure  $\phi_s$ . The interference between the  $\eta_c$  and purely nonresonant contributions is taken into account using an amplitude model for simultaneously fit the four hadrons and  $p\bar{p}$  mass distributions (Fig. 6). The branching fraction is normalized to the  $J/\psi$  mode and found to be  $\mathcal{B}(B_s^0 \rightarrow \eta_c\phi) = [5.01 \pm 0.53(\text{stat}) \pm 0.27(\text{syst}) \pm 0.63(\mathcal{B})] \times 10^{-4}$ . First evidence for the  $B_s^0 \rightarrow \eta_c\pi^+\pi^-$  decay mode has also been reported, with a branching fraction of  $\mathcal{B}(B_s^0 \rightarrow \eta_c\pi^+\pi^-) = [1.76 \pm 0.59(\text{stat}) \pm 0.12(\text{syst}) \pm 0.29(\mathcal{B})] \times 10^{-4}$ .

## 4 Summary

The most precise measurement of  $CP$ -violating phase  $\phi_s$  and lifetime parameters in the  $B_s^0$  system has been performed using Run I data collected by LHCb experiment. So far all results are compatible with the SM prediction. 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  $B_s^0 \rightarrow J/\psi\phi$  channel, inclusion of new decay modes have been investigated. For example, the  $B_s^0 \rightarrow J/\psi(\rightarrow e^+e^-)\phi$  channel not only could bring about 10% of the  $\mu^+\mu^-$  mode statistics, but it will be also an important verification of the  $B_s^0 \rightarrow J/\psi(\rightarrow \mu^+\mu^-)\phi$  as kinematics for both channels are expected to be identical. The statistical sensitivity to  $\phi_s$  measurement after the LHCb upgrade, with an integrated luminosity of  $46 \text{ fb}^{-1}$ , is expected  $\sim 0.01$  rad that will be close to the present theoretical uncertainty [20]. As the measurement precision improves, the penguin pollution contributions to the  $B_s^0$  meson decays have to be kept under control [21, 22].

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