Measurement of CP violating phase $\phi_s$ and control of penguin pollution at LHCb

WALAA KANSO
on behalf of the LHCb collaboration

CPPM, Aix-Marseille Université CNRS/IN2P3, Marseille, France

The study of CP violation in $B^0_s$ oscillations is a key measurement at the LHCb experiment. In this document, we discuss the latest LHCb results on the CP-violating phase, called $\phi_s$, using $B^0_s \rightarrow J/\psi K^- K^+$ and $B^0_s \rightarrow J/\psi \pi^- \pi^+$ channels. To conclude on the presence of New Physics in $\phi_s$, the estimation of the sub-dominant contributions from the Standard Model becomes crucial now. We outline a method to estimate the contribution of penguin diagrams in $\phi_s$. Branching fractions and upper limits of $B^0 (s) \rightarrow J/\psi K_S h^+(h^-) (h^0) = K, \pi$ modes are presented.

PRESENTED AT

8th International Workshop on the CKM Unitarity Triangle (CKM 2014)
8-12 September 2014, Vienna, Austria
1 Introduction

The interference between $B^0_s$ mesons decaying directly via $b \to c\bar{c}s$ transitions to CP eigenstates and those decaying after $B^0_s$-$\bar{B}^0_s$ oscillations gives rise to a CP violating phase called $\phi_s$.

Within the Standard Model, the decay can occur via two main topologies: the predominant tree topology and the sub-leading penguin diagram. New Physics processes, e.g., new particles contributing to the box diagrams, can modify the value of $\phi_s$:

$$\phi^\text{meas}_s = -2\beta_s + \Delta\phi^\text{peng}_s + \delta^\text{NP}$$

The indirect determination via global fit to experimental data gives:

$$-2\beta_s = 2 \arg \left( \frac{V_{ts}V^*_{tb}}{V_{cs}V^*_{cb}} \right) = -0.0363 \pm 0.0013 \ [7].$$

The theoretical uncertainty on $\phi_s$ is mainly due to unknown penguin contributions $\Delta\phi^\text{peng}_s$. The control of penguin pollution is limited by large theoretical uncertainties. Thus, experimental measurements are very useful to constrain the contribution of penguin diagrams. Therefore, we should estimate $\Delta\phi^\text{peng}_s$, otherwise we may incorrectly interpret the Standard Model penguin contributions as signs of New Physics. In Section 2, we summarize the measurement of the CP-violating phase $\phi_s$ in $B^0_s \to J/\psi K^-K^+$. In Section 3, we report on a recent update of the same measurement using $B^0_s \to J/\psi\pi^+\pi^-$. The studies of penguin pollution in $\phi_s$ and $2\beta$ are described in Section 4 and 5 respectively. A recent result on the branching ratio of $B^0_{(s)} \to J/\psi K^0_S h^{(*)+}h^- (h^{(*)} = K, \pi)$ modes is shown in Section 6.

2 $B^0_s \to J/\psi K^-K^+$

The purpose of this analysis is to mainly measure $\phi_s$, the decay width difference $\Delta\Gamma_s$ and $\Gamma_s$. $B^0_s \to J/\psi \to \mu^+ \mu^- \to K^+K^-$ is pseudo-scalar decaying into two vector mesons. The study of this decay requires an angular analysis in order to disentangle CP-odd/CP-even mixture of the final state. After the statistical background subtraction $[3]$, a fit to decay time ($t$) and three angles in helicity frame ($\Omega = \theta_{\mu}, \theta_K, \varphi_h$) is performed in six bins of $m_{KK}$ $[5]$. To account for the detector and selection effects, the decay time acceptance is taken from real data and the angular acceptance is studied in the simulated data. The finite decay time resolution is modelled by a single Gaussian of width $S_\sigma \times \sigma_t$, where $\sigma_t$ is the estimated per event decay time uncertainty, and the scale factor, $S_\sigma$, is measured in a sample of prompt $J/\psi \to \mu^+ \mu^-$. The effective resolution is 45 fs for $B^0_s \to J/\psi \phi$. The $B^0_s$ flavour, at production, is determined by the combination of the same side kaon tagger and the opposite side taggers, which gives the overall tagging power: $\epsilon(1 - 2\omega)^2 = (3.13 \pm 0.23)\%$, where $\epsilon$ indicates the tagging efficiency, and $\omega$ the mistag rate $[14]$. Using 1 $fb^{-1}$ of real data collected in 2011, LHCb obtained:
\[ \phi_s = 0.07 \pm 0.09 \text{ (stat)} \pm 0.01 \text{ (syst)} \]
\[ \Gamma_s = 0.663 \pm 0.005 \text{ (stat)} \pm 0.006 \text{ (syst)} \]
\[ \Delta\Gamma_s = 0.100 \pm 0.016 \text{ (stat)} \pm 0.003 \text{ (syst)} \]

3 \( B^0_s \to J/\psi\pi^-\pi^+ \)

Another useful channel to measure \( \phi_s \) is \( B^0_s \to J/\psi\pi^-\pi^+ \). This decay is 97.7% dominated by the CP-odd component, at 95 % C.L [4]. Nevertheless, an angular analysis is needed to obtain the small CP-even component. We performed a six-dimensional fit of \( B^0_s \) and \( \pi\pi \) masses, time and the three helicity angles (\( m_{B^0_s}, t, m_{\pi\pi}, \Omega \)). The decay time acceptance is determined in \( B^0 \to J/\psi K^{*0} \) channel and simulation, while \( \Delta\Gamma_s \) and \( \Gamma_s \) are taken from \( B^0 \to J/\psi\phi \). This analysis aims to measure \( \phi_s \) and |\( \lambda \)|, related to the direct CP violation. By following the same methodology as in \( B^0_s \to J/\psi\phi \) channel to determine the effective decay time resolution, we obtained: 40fs. The tagging algorithm achieved a power of: \( \epsilon(1 - 2\omega)^2 = (3.89 \pm 0.25)\% \). It is found that five interfering \( \pi^+\pi^- \) states are required to describe the data. These include the dominant \( f_0(980) \), as well as the \( f_0(1500), f_0(1790), f_2(1270), f_2'(1525) \). The resulting decomposition of the \( \pi^+\pi^- \) invariant mass spectrum is shown in (fig. 1(a)). The projections of angular distributions are shown in fig. 2.

Figure 1: (a): Invariant mass of \( J/\psi\pi^+\pi^- \). The (red) solid line shows the \( B^0_s \), the the (brown) dotted line shows the exponential combinatorial background, the (green) short-dashed line shows the \( B^\pm \) background, the (magenta) dot-dashed line shows the \( B^0 \) signal, the (light blue) dashed line represents some misreconstructed decays, the (black) dot-dashed line is the \( B^0 \to J/\psi K^{*0} \pi^\pm \pi^\mp \) reflection and the (blue) solid line is the total. (b): Unofficial overview of the current experimental constraints in the \( \phi_s-\Delta\Gamma_s \) plane, modified compared to the original [8] to include these results as well as the summer 2014 updates from Atlas [10] and CMS [9].

LHCb analysed 3 fb\(^{-1} \) of \( B^0_s \to J/\psi\pi^-\pi^+ \) collected in 2011 and 2012. Assuming that there is no direct CP-violation (|\( \lambda \)| = 1), the CP violating phase, \( \phi_s \), is:
\[ \phi_s = 0.075 \pm 0.067 \text{ (stat)} \pm 0.008 \text{ (syst)} \]

If the direct CP-violation, represented by \(|\lambda|\), is floating, we obtained:

\[ \phi_s = 0.070 \pm 0.068 \text{ (stat)} \pm 0.008 \text{ (syst)} \]

\[ \lambda = 0.89 \pm 0.05 \text{ (stat)} \pm 0.01 \text{ (syst)} \]

Figure 2: Projections of the three decay angles. The signal fits are shown with (red) dashed lines, the background with a (black) dotted lines, and the (blue) solid lines represent the total fits. The difference between the data and the fits divided by the uncertainty on the data is shown below.

A preliminary combination of 3 fb\(^{-1}\) \(B_s^0 \to J/\psi\pi^-\pi^+\) with 1 fb\(^{-1}\) \(B_s^0 \to J/\psi K^-K^+\), gives:

\[ \phi_s = 0.070 \pm 0.054 \pm 0.011 \]

This measurement is consistent with the Standard Model but there is still room for New Physics. A comparison of the LHCb result with those of other experiments is shown in fig. 1(b).

4 Estimating penguin pollution in \( \phi_s \) with \( B_s^0 \to J/\psi K^{*0} \)

A sample of \( B_s^0 \to J/\psi K^{*0} \) is taken as a control channel because the penguin diagrams are not suppressed in this decay. While in the \( B_s^0 \to J/\psi \phi \) channel, the penguin process is suppressed, by \( \lambda^2 \sim 0.05\), relative to tree diagram. \( a_i \) and \( \theta_i \) are defined as penguin’s parameter for \( B_s^0 \to J/\psi \phi \) [2]. There are two penguin parameters for each of the three polarizations of final states: \( i = 0, \perp \), \( \parallel \):

\[ a_i e^{i\theta_i} = (1 - \frac{\lambda^2}{2}) |V_{ub}|/(\lambda V_{cb}) \left[ \frac{P_q^i + P_{\bar{q}}^i}{P_q^0 + P_{\bar{q}}^0 - P_q^i} \right]. \]

With \( \lambda \sim 0.22\), penguin amplitude is: \( P_q, q = u, t, c \), and the tree amplitude is represented by: \( T_c \). \( a_i \) and \( \theta_i \) are the penguin parameters for \( B_s^0 \to J/\psi K^{*0} \). In order to connect both channels, penguin parameters in \( B_s^0 \to J/\psi \phi \) and \( B_s^0 \to J/\psi K^{*0} \), are supposed equal, using the approximations of SU(3) flavour (quarks \( u, d, s \) are identical):
Therefore, a shift on $\phi_s$ due to penguin diagrams, is calculated for each polarization:

$$
tan(\Delta \phi_s^{\text{peng}}) = \frac{2a_i \cos \theta_i \sin \gamma + a_i^2 \sin 2\gamma}{1 + 2\epsilon a_i \cos \theta_i \cos \gamma + \epsilon^2 a_i^2 \cos 2\gamma},
$$

where $\epsilon = \frac{\lambda^2}{1 - \lambda^2}$. From the experimental point of view, there are two observables for each polarization ($i = 0, \perp, \parallel$): The first one, $H_i$, is proportional to the ratio of branching fractions of the 2 channels, multiplied, respectively, by the corresponding polarization fractions. This requires an angular analysis to disentangle those states. The factor $|A_i|_2^4$ is a critical SU(3) breaking factor calculated theoretically with a big error.

$$
H_i = \frac{1 - 2a_i \cos \theta_i \cos \gamma + a_i^2}{1 + 2\epsilon a_i \cos \theta_i \cos \gamma + \epsilon^2 a_i^2} = \frac{1 - \lambda^2}{\lambda^2} |A_i|_2^4 \frac{f_{J/\psi K^*0}}{f_{J/\psi \phi}} \frac{BR(B^0_s \rightarrow J/\psi K^*)}{BR(B^0_s \rightarrow J/\psi \phi)}
$$

The second observable is the direct CP violation in $B^0_s \rightarrow J/\psi K^*$:

$$
A_i^{CP} = \frac{2a_i \sin \theta_i \sin \gamma}{1 - 2a_i \cos \theta_i \cos \gamma + a_i^2} = \frac{\Gamma_i^{B^0_s}}{\Gamma_i^{B^0_s} + \Gamma_i^{B^0_s}}
$$

$H_i$ and $A_i^{CP}$ form a non trivial system of two equations with two unknowns: $a_i$ and $\theta_i$ that lead to the shift on $\phi_s$, $\Delta \phi_s^{\text{peng}}$. In this channel, an angular analysis is required to calculate the polarization amplitudes. The presence of P and S-wave in the $K\pi$ system has to be studied carefully. Using 0.37 fb$^{-1}$, a fit to mass, angles has been performed and gave [5]:

$$
BR(B^0_s \rightarrow J/\psi K^*0) = (4.4^{+0.5}_{-0.4} \pm 0.8) \times 10^{-5}
$$

$f_L = 0.50 \pm 0.08 \pm 0.02$, $f_\parallel = 0.19^{+0.10}_{-0.08} \pm 0.02$

In order to determine penguin pollution in $B^0_s \rightarrow J/\psi \phi$, a measurement of the direct CP violation, in $B^0_s \rightarrow J/\psi K^*$, is needed. To do so, one has to split the data sample into $K^+\pi^-$ and $K^0\pi^+$. A direct CP violation measurement and an update, with 3 fb$^{-1}$, of the branching ratio and polarization fractions are ongoing.
5 Estimating penguin pollution in $2\beta$ with $B_s^0 \to J/\psi K^0_S$

$B_s^0 \to J/\psi K^0_S$ is the ultimate tool for controlling penguin diagrams in $B^0 \to J/\psi K^0_S$. This requires a CP analysis in $B_s^0 \to J/\psi K^0_S$ [2]. LHCb published a previous analysis of $B_s^0 \to J/\psi K^0_S$ with 1 fb$^{-1}$ of real data [6].

$$BR(B_s^0 \to J/\psi K^0_S) = (1.97 \pm 0.23) \times 10^{-5}, \tau_{eff} = 1.75 \pm 0.12(\text{stat})\pm0.07(\text{syst}) \text{ ps}$$

A CP analysis is ongoing, as well as an update of the branching ratio with full LHC run 1 data.

6 $B^0_{(s)} \to J/\psi K^0_S h^{(i)}+ h^- \ (h^{(i)} = K, \pi)$

This analysis could help, with high statistics, in the measurement of $\phi_s$. It’s also interesting for spectroscopy measurements and the search for exotics [1].

New branching fraction measurements of $B^0_{(s)} \to J/\psi K^0_S h^{(i)}+ h^- \ (h^{(i)} = K, \pi)$ have been performed with 1 fb$^{-1}$ of real data. The channel $B^0 \to J/\psi K^0_S K\pi$ is confirmed and first observations of $B^0 \to J/\psi K^0_S K\pi$ and $B^0 \to J/\psi K^0_S K\pi$ are published with more than 7$\sigma$.

In the first place, $B^0 \to J/\psi K^0_S K\pi$ has been measured relative to $B^0 \to J/\psi K^0_S$. Using $B^0 \to J/\psi K^0_S K\pi$ updated branching fraction, all others modes are measured as you can see below:

$$B(B^0 \to J/\psi \bar{K}^0 K^{\pm}\pi^\mp) = (11 \pm 5(\text{stat}) \pm 3(\text{syst}) \pm 1(\text{PDG}) \times 10^{-6},$$

$$< 21 \times 10^{-6} \text{ at } 90\% \text{ CL},$$

$$< 24 \times 10^{-6} \text{ at } 95\% \text{ CL},$$

$$B(B^0 \to J/\psi K^0 K^+K^-) = (20.2 \pm 4.3(\text{stat}) \pm 1.7(\text{syst}) \pm 0.8(\text{PDG}) \times 10^{-6},$$

$$B(B^0_s \to J/\psi \bar{K}^0 K^{\pm}\pi^-) = (2.4 \pm 1.4(\text{stat}) \pm 0.8(\text{syst}) \pm 0.1(f_{/f_d}) \pm 0.1(\text{PDG}) \times 10^{-5},$$

$$< 4.4 \times 10^{-5} \text{ at } 90\% \text{ CL},$$

$$< 5.0 \times 10^{-5} \text{ at } 95\% \text{ CL},$$

$$B(B^0 \to J/\psi \bar{K}^0 K^{\pm}\pi^\mp) = (91 \pm 6(\text{stat}) \pm 6(\text{syst}) \pm 3(f_{/f_d}) \pm 3(\text{PDG}) \times 10^{-5},$$

$$B(B^0 \to J/\psi \bar{K}^0 K^+K^-) = (5 \pm 9(\text{stat}) \pm 2(\text{syst}) \pm 1(f_{/f_d}) \times 10^{-6},$$

$$< 12 \times 10^{-6} \text{ at } 90\% \text{ CL},$$

$$< 14 \times 10^{-6} \text{ at } 95\% \text{ CL}.$$

7 Epilogue

While completing these proceedings, several important new results have been obtained. LHCb updated the measurement of the CP-violating phase $\phi_s$ with 3 fb$^{-1}$ [12], and put limits on penguin effects in $\phi_s$ [11]. The shift in $\phi_s$ is limited to be within
the interval $[-1.05^\circ, 1.18^\circ]$ at 95% C.L. HFAG collaboration updated the the $\phi_s$-$\Delta\Gamma_s$ plane [13].

ACKNOWLEDGEMENTS

I would like to thank the organizers of CKM2014 for the nice atmosphere during the workshop in Vienna and my LHCb colleagues who helped in the preparation of this talk.

References

[1] R. Aaij et al. [LHCb Collaboration], “Observation of the $B^0_s \to J/\psi K^0_s K^{\pm}\pi^{\mp}$ decay,” JHEP 1407, 140 (2014) [arXiv:1405.3219 [hep-ex]].

[2] S. Faller, R. Fleischer and T. Mannel, “Precision Physics with $B^0_s \to J/\psi \phi$ at the LHC: The Quest for New Physics,” Phys. Rev. D 79 (2009) 014005 [arXiv:0810.4248 [hep-ph]].

[3] Yuehong Xie, “sFit: a method for background subtraction in maximum likelihood fit,” arXiv:0905.0724.

[4] R. Aaij et al. [LHCb Collaboration], “Measurement of the CP-violating phase $\phi_s$ in $B^0_s \to J/\psi \pi^+\pi^-$ decays,” Phys. Lett. B 736, 186 (2014) [arXiv:1405.4140 [hep-ex]].

[5] R. Aaij et al. [LHCb Collaboration], “Measurement of the $B^0_s \to J/\psi K^{*0}$ branching fraction and angular amplitudes,” Phys. Rev. D 86, 071102 (2012) [arXiv:1208.0738 [hep-ex]].

[6] R. Aaij et al. [LHCb Collaboration], “Measurement of the effective $B^0_s \to J/\psi K^0_S$ lifetime,” Nucl. Phys. B 873, 275 (2013) [arXiv:1304.4500 [hep-ex]].

[7] J. Charles, O. Deschamps, S. Descotes-Genon, R. Itoh, H. Lacker, A. Menzel, S. Monteil and V. Niess et al., Phys. Rev. D 84, 033005 (2011) [arXiv:1106.4041 [hep-ph]].

[8] Y. Amhis et al. [Heavy Flavor Averaging Group Collaboration], “Averages of B-Hadron, C-Hadron, and tau-lepton properties as of early 2012,” arXiv:1207.1158 [hep-ex].

[9] CMS Collaboration [CMS Collaboration], “Measurement of the CP-violating weak phase phi-s and the decay width difference DeltaGamma-s using the Bs to J/psiPhi(1020) decay channel,” CMS-PAS-BPH-13-012.
[10] G. Aad et al. [ATLAS Collaboration], Phys. Rev. D 90, 052007 (2014) [arXiv:1407.1796 [hep-ex]].

[11] R. Aaij et al. [LHCb Collaboration], “Measurement of the CP-violating phase $\beta$ in $B^0 \to J/\psi\pi^+\pi^-$ decays and limits on penguin effects,” arXiv:1411.1634 [hep-ex].

[12] R. Aaij et al. [LHCb Collaboration], “Precision measurement of CP violation in $B_s^0 \to J/\psi K^- K^+$ decays,” arXiv:1411.3104.

[13] Y. Amhis et al., “Averages of b-hadron, c-hadron, and tau-lepton properties as of early 2012,” arXiv:1207.1158 and online update at http://www.slac.stanford.edu/xorg/hfag.

[14] R. Aaij et al. [LHCb Collaboration], “Measurement of CP violation and the $B^0$ meson decay width difference with $B_s^0 J/\psi K^+ K^-$ and $B_s^0 J/\psi^+ \pi^-$ decays,” Phys. Rev. D 87, no. 11, 112010 (2013) [arXiv:1304.2600 [hep-ex]].