Measurement of CP-violation parameters in decays of $B^0_s \rightarrow J/\psi \phi$ with the ATLAS detector

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Abstract. A measurement of CP-violating weak phase $\phi_s$ and $B^0_s$ meson decay width difference with $B^0_s \rightarrow J/\psi \phi$ decays in the ATLAS experiment is presented. It is based on integrated luminosity of 14.3 fb$^{-1}$ collected by the ATLAS detector from 8 TeV pp collisions at the LHC. The measured values are statistically combined with those from 4.9 fb$^{-1}$ of 7 TeV collisions data, yielding an overall Run-1 ATLAS result.

1. Introduction

Physics beyond Standard Model (SM) may affect the amount of CP violation in $b$-hadron decays. It is expected that decay $B^0_s \rightarrow J/\psi \phi$ is sensitive to new physics contributions. CP violation in the $B_s^0 \rightarrow J/\psi \phi$ decay occurs due to the interference between direct decays and decays with $B^0_s - \overline{B}^0_s$ mixing. The amount of CP violation is characterized by the $\phi_s$ parameter, which is defined as the weak phase difference between the $B^0_s - \overline{B}^0_s$ mixing amplitude and the $b \rightarrow c\bar{c}s$ decay amplitude. In the SM, the phase $\phi_s$ is predicted to be small; it can be related to Cabibbo-Kobayashi-Maskawa (CKM) matrix elements with the relation $\phi_s \simeq -2\beta_s$, where $\beta_s = \arg\left[-\frac{V_{ts}V_{tb}^*}{V_{ts}V_{tb}^*}\right]$. In the absence of new physics contributions to $B^0_s$ mixing and decays a value of $-2\beta_s = 0.0376^{+0.0008}_{-0.0007}$ rad can be predicted by combining beauty and kaon physics observables [1].

Along with $\phi_s$, the time evolution of $B^0_s - \overline{B}^0_s$ system is defined by the mass difference $\Delta m_s$ of the heavy and light mass eigenstates and decay width difference $\Delta \Gamma_s = \Gamma_L - \Gamma_H$, where $\Gamma_L$ and $\Gamma_H$ are decay widths of the light and heavy states, respectively. The value of $\Delta \Gamma_s$ is predicted to be $0.088 \pm 0.020 \text{ps}^{-1}$ within the SM [2] and is not expected to be significantly affected by new physics contributions.

This paper presents the measurement of $B^0_s \rightarrow J/\psi \phi$ decay parameters using 14.3 fb$^{-1}$ of LHC pp data collected by the ATLAS detector [3] during 2012 at $\sqrt{s} = 8$ TeV [4]. The obtained parameter values are statistically combined with those measured in ATLAS with 4.9 fb$^{-1}$ of 7 TeV collision data [5], yielding an overall Run-1 ATLAS result.
2. Candidate selection and fitting

The analysis is performed using the 14.3 fb$^{-1}$ data sample of $pp$ collisions collected by the ATLAS detector during the $\sqrt{s} = 8$ TeV run of the LHC. The triggers used to select events for this analysis are based on identification of a $J/\psi \rightarrow \mu^+\mu^-$ decay, with muon transverse momentum threshold of either 4 GeV or 6 GeV. The candidates of $B^0 \rightarrow J/\psi(\mu^+\mu^-)\phi(K^+K^-)$ decay are selected by searching for a pair of oppositely charged muon tracks and also a pair of oppositely charged tracks not identified as muons. Muon tracks are refitted to a common vertex and cut on their invariant mass within a defined $J/\psi$ mass region. The fit is further constrained by fixing the invariant mass of the muon pair to the $J/\psi$ mass value [3], all four tracks being refitted to a common vertex with kaon mass hypothesis on the two non-muon tracks and requirement being imposed on the $KK$ invariant mass to fall into a defined $\phi$ mass region.

An unbinned maximum likelihood fit is then performed on the $B^0 \rightarrow J/\psi(\mu^+\mu^-)\phi(K^+K^-)$ event candidates to extract the parameter values. The fit uses information about the reconstructed mass, the measured proper decay time along with its uncertainty, $B^0_s$ flavour tagging probability (see section 3) and the three transversity angles (see ref. [4] for precise definition) of each $B^0 \rightarrow J/\psi\phi$ candidate to separate different CP states.

The likelihood function is defined as a combination of the signal and background probability density functions (PDF). The signal PDF is described as the product of the following components. Mass shape is modelled by a sum of three Gaussian distributions. Decay time error and $p_T$ probability terms are described by gamma functions (unchanged from the 7 TeV ATLAS analysis [3]). The joint PDF for the decay time and the transversity angles for the $B^0 \rightarrow J/\psi(\mu^+\mu^-)\phi(K^+K^-)$ decay is taken according to [7], taking into account non-resonant component $B^0_s \rightarrow J/\psi K^+K^-$, as suggested in [8]. An additional angular sculpting term is used to account for the effect of the detector and kinematic acceptance on the angular distributions. Since flavour tagging probability (see section 3) is distributed differently for signal and background, an additional PDF term describing its distribution for signal is used.

There are three background components in the fit: combinatorial background and two resonant components from $B^0 \rightarrow J/\psi K^{\pm}$ and $\Lambda^0 \rightarrow J/\psi p^+ K^-$ decays mis-reconstructed as $B^0_s \rightarrow J/\psi\phi$. The combinatorial background PDF is constructed with the mass term, proper decay time function, the PDF of the background tagging probability, angular PDF and probability terms for the decay time error and $p_T$. The mass term is an exponential function with a constant term added. The proper decay time PDF is combined from a prompt Gaussian peak to account for combinatorial background events with lifetimes distributed around zero, two positive exponential functions representing a fraction of longer-lived backgrounds with non-prompt $J/\psi$, and a negative exponential function to account for events with poor vertex resolution. The probability terms for the decay time error and $p_T$ are modelled by gamma functions. The background tagging probability PDF is described in section 3. The shape of the background angular distribution arises primarily from detector and kinematic sculpting effects and is described by Legendre polynomial functions fitted to the mass sidebands and fixed in the main fit.

Contamination from $B^0_d \rightarrow J/\psi K^{*0}$ and $\Lambda^0 \rightarrow J/\psi p^+ K^-$ events mis-reconstructed as $B^0_s \rightarrow J/\psi\phi$ is described by their mass, transversity angle and lifetime distributions. The mass shapes, transversity angle distributions and the fractions of these contributions are evaluated from MC simulation and are fixed in the main fit, transversity angle distributions being as well described by Legendre polynomial functions. The $B^0_d (\Lambda^0)$ lifetime is accounted for by adding an additional exponential term, scaled by the ratio of $B^0_d (\Lambda^0)$ and $B^0_s$ masses. The decays of $B^0_s \rightarrow J/\psi K^+\pi^-$ as well as their interference with $B^0_d \rightarrow J/\psi K^{*0}$ are not accounted for in the main fit, they are treated as an additional source of systematic uncertainty.
3. Flavour tagging
The use of information about the initial flavour of the decaying $B^0$ meson, although not absolutely necessary for the $\phi_s$ parameter extraction, significantly reduces the uncertainty of its measured value. This information can be obtained from the opposite-side $B$ meson that contains the other pair-produced $b$-quark in the event. This is referred to as opposite-side tagging (OST). To study and calibrate the OST methods, events containing $B^{\pm} \rightarrow J/\psi K^{\pm}$ decays can be used, where the flavour of the $B^{\pm}$ meson is provided by the kaon.

Several methods are available to determine the opposite side $b$-quark flavour. The measured charge of a lepton from a semileptonic decay of the $B$ meson provides strong separation power; however there is dilution from neutral $B$ meson oscillations as well as cascade $b \rightarrow c \rightarrow \ell$ decays. The separation power may be enhanced by measuring the weighted sum of the track charges within a cone around the lepton, weighting function and cone parameter being optimized for different tagging methods. In case of absence of leptons, the weighted sum of the charge of tracks in a jet associated with the opposite-side $b$-hadron decay is used.

The distributions of tag charge for $B^{\pm} \rightarrow J/\psi K^{\pm}$ events for the two most powerful methods are shown in figure 1.

![Figure 1: Tag charge distribution for $B^{\pm} \rightarrow J/\psi K^{\pm}$ events for muon (a) and electron (b) based tagging.](image)

These distributions define the probabilities of having a value of $Q$ of the charge variable for the given $B$ flavour, i.e. $P(Q|B^+)$ and $P(Q|B^-)$. The probability of having the $B$ flavour given the charge $Q$ is therefore $P(B|Q) = P(Q|B+)/P(Q|B^- + P(Q|B^-) + P(Q|B^-))$ and $P(B|Q) = 1 - P(B|Q)$. The distributions of $P(B|Q)$ are fitted firstly for the sideband data, thus obtaining the PDF of the background tagging probability. Then, the $B^0$ signal region is fitted fixing the background component parameters as well as the background fraction to obtain the signal tagging probability PDF. These PDFs are used in the main fit as described in the previous section.

4. Results
Fit result projected onto the mass and lifetime of $B^0_s$ candidate is shown in figure 2. The extracted $B^0_s \rightarrow J/\psi \phi$ parameter values combined with those from the 7 TeV analysis provide an overall Run-1 ATLAS result [3]:

$$\phi_s = -0.090 \pm 0.078 \text{ (stat.)} \pm 0.041 \text{ (syst.)} \text{ rad}$$
$$\Delta \Gamma_s = 0.085 \pm 0.011 \text{ (stat.)} \pm 0.007 \text{ (syst.)} \text{ ps}^{-1}$$
$$\Gamma_s = 0.675 \pm 0.003 \text{ (stat.)} \pm 0.003 \text{ (syst.)} \text{ ps}^{-1}$$

Figure 3 shows the likelihood contours on the $\phi_s - \Delta \Gamma_s$ plane for ATLAS 7 and 8 TeV results, as well as their combination, results from other experiments, the world average and
SM prediction [9]. One can see that the two ATLAS results agree with each other, and their combination is in agreement with other experiments and SM.

Figure 2: Fit result projected onto the mass (a) and lifetime (b) of $B_s^0$ candidate [4]

![Figure 2](image1.png)

(a)  
(b)  

Figure 3: Likelihood contours on the $\phi_s - \Delta \Gamma_s$ plane for ATLAS 7 and 8 TeV results (a) [4] and those statistically combined compared with other experiments, the world average and SM prediction (b) [9]

![Figure 3](image2.png)

(a)  
(b)  

References

[1] Charles J et al. 2011 Phys. Rev. D 84 033005
[2] Artuso M, Borissov G and Lenz A 2016 Rev. Mod. Phys. 88(4) 045002
[3] ATLAS Collaboration 2008 JINST 3 S08003
[4] ATLAS Collaboration 2016 JHEP 08 147
[5] ATLAS Collaboration 2014 Phys. Rev. D 90(5) 052007
[6] Olive K A et al. (Particle Data Group) 2014 Chin. Phys. C 38 090001
[7] Dighe A S, Dunietz I and Fleischer R 1999 Eur. Phys. J. C 6 647–62
[8] Stone S and Zhang L 2009 Phys. Rev. D 79 074024
[9] Amhis Y et al. 2016 arXiv:1412.7515