Measurement of $\Delta \Gamma_s$ and the CP-violating weak phase $\phi_s$ in the decay $B^0_s \rightarrow J/\psi \phi$ by ATLAS

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1 Introduction

New phenomena beyond the predictions of the Standard Model (SM) may alter CP violation in $B$-decays. In the decay $B^0_s \rightarrow J/\psi \phi$ the CP-violating phase $\phi_s$ is the weak phase difference between the $B^0_s - \overline{B^0_s}$ mixing amplitude and the $b \rightarrow c \alpha s$ decay amplitude. SM predicts a small value of $\phi_s \simeq -2\beta_s = -0.0368 \pm 0.0018 \text{ rad}$ [1].

Another quantity involved in $B^0_s - \overline{B^0_s}$ mixing is the width difference $\Delta \Gamma_s = \Gamma_L - \Gamma_H$ of heavy ($B_H$) and light ($B_L$) eigenstates. Physics beyond the SM is not expected to affect $\Delta \Gamma_s$ significantly [2]. Extracting $\Delta \Gamma_s$ from data is nevertheless useful as it allows theoretical predictions to be tested [2]. The presented analysis uses data collected by the ATLAS experiment in $pp$ collisions at $\sqrt{s} = 7 \text{ TeV}$ in 2011, corresponding to an integrated luminosity of $\sim 4.9 \text{ fb}^{-1}$. Measurements of $\phi_s$, the average decay width $\Gamma_s = (\Gamma_L + \Gamma_H)/2$ and the value of $\Delta \Gamma_s$, were performed with no flavour tagging to distinguish between the initial $B^0_s$ and $\overline{B^0_s}$ states. The CP states were separated statistically through the time-dependence of the decay and angular correlations amongst the final-state particles.

2 Candidate selection

ATLAS is a multipurpose detector described in details in [3]. The tracking and muon systems are of particular importance in the reconstruction of $B$ mesons. The inner tracking detector consists of a silicon pixel detector, a silicon microstrip detector and a transition radiation tracker; all surrounded by a superconducting solenoid providing a 2 T axial field. The muon spectrometer consists of three superconducting toroids, a system of tracking chambers, and detectors for triggering. The triggers used for this analysis are based on identification of a $J/\psi \rightarrow \mu^+ \mu^-$ decay, with either a 4 GeV transverse momentum ($p_T$) threshold for each muon or an asymmetric configuration that applies a higher $p_T$ threshold ($4 - 10 \text{ GeV}$) to one of the muons. The pairs of muon tracks refitted to a common vertex are accepted if the fit results in $\chi^2/\text{d.o.f.} < 10$ and the invariant mass falls in the range $(2.959 - 3.229) \text{ GeV}(\text{when both muons have } |\eta| < 1.05)$, or $(2.852 - 3.332) \text{ GeV}(\text{both muons within } 1.05 < |\eta| < 2.5)$ or
(2.913 – 3.273) GeV otherwise. Candidates for $B_s^0 \rightarrow J/\psi (\mu^+ \mu^-) \phi(K^+ K^-)$ are sought by fitting the four tracks to a common vertex resulting in $\chi^2$/d.o.f. < 3, while the invariant mass of the two muons was fixed to the $J/\psi$ mass [4]. In total 131k $B_s^0$ candidates are collected within a mass range of $\phi \rightarrow K^+ K^- (1.0085 - 1.0305)$ GeV and $5.15 < m(B_s^0) < 5.65$ GeV, figure 1. For each $B_s^0$ candidate the proper decay time $t$ ('decay time' henceforth) is determined by the expression: $t = L_{xy} M_B / (c p_{TB})$, where $p_{TB}$ is the transverse momentum of the $B_s^0$ candidate and $M_B$ is the mass of the $B_s^0$ meson (5.3663 GeV) [4]. $L_{xy}$ is the displacement in the transverse plane of the $B_s^0$ decay vertex with respect to the primary vertex (PV) projected onto the direction of $p_{TB}$. The position of the PV is refitted following the removal of the tracks used to reconstruct the $B_s^0$ candidate. For the selected events the average number of pileup interactions is 5.6, necessitating a choice of the best candidate for the PV at which the $B_s^0$ is produced. The variable used is a three-dimensional impact parameter $d_0$, calculated as the distance between the line extrapolated from the $B_s^0$ vertex in the direction of the $B_s^0$ momentum, and each PV candidate. The chosen PV is the one with the smallest $d_0$.

3 Analysis and results

The $B_s^0 \rightarrow J/\psi \phi$ decay involves three angular momentum states of the $J/\psi \phi$ system, combined into three polarization amplitudes, longitudinal polarization ($A_0$), and transverse polarization with the linear polarization vectors of the vector mesons parallel ($A_\parallel$) or perpendicular ($A_\perp$) to each other. The first two states are $CP$-even, while the last state is $CP$-odd. Another $CP$-odd state can be produced by a non-resonant $K^+ K^-$ pair or by the decay of the spin-0 $f_0$ meson, resulting in another independent amplitude, the S-wave $A_S$. The time evolution of the four decay amplitudes along with six interference terms is fitted simultaneously with the angular distributions of the cascade decay $B_s^0 \rightarrow J/\psi (\mu^+ \mu^-) \phi(K^+ K^-)$. Three independent angles $\Omega = (\theta_T, \psi_T, \varphi_T)$, are defined in the transversity basis [5]. The $B_s^0 \rightarrow J/\psi \phi$ decay probability is a function of the following physics parameters of interest, $\Delta \Gamma_s, \phi_s, \Gamma_s$, the amplitudes $A_0, A_\parallel, A_S(0)$ and of the related strong phases defined as $\delta_\parallel = \text{arg}(A_\parallel, A_0)$, $\delta_\perp = \text{arg}(A_\perp, A_0)$ and $\delta_S = \text{arg}(A_S, A_0)$. For untagged analysis all terms involving the mass splitting $\Delta m_s$ in the time-dependent amplitudes cancel out [6]. In addition, the time-dependent amplitudes depending on $\delta_\perp$ are multiplied by a small value of $\sin \phi_s$, hence the untagged analysis is not sensitive to $\delta_\perp$. A Gaussian constraint to the external data, $\delta_\perp = (2.95 \pm 0.39)$ rad [7] is therefore applied.

An unbinned maximum likelihood fit uses information of the reconstructed $B_s^0$ candidate mass $m$, decay time $t$, their uncertainties $\sigma_m$ and $\sigma_t$, and the angles $\Omega = (\theta_T, \psi_T, \varphi_T)$. In total 26 parameters are determined, including the eight physics param-
eters of interest mentioned above, while the other quantities describe the $J/\psi\phi$ mass distribution, the decay time and the angular distributions of the background. The single-event likelihood has the form:

$$L \propto w_i \cdot F_{si} + f_s \cdot f_{B^0} \cdot F_{B^0i} + (1 - f_s \cdot (1 + f_{B^0})) \cdot F_{bkgi}$$

where the index $i$ is used for the variables specific for each single-event, $f_s$ is the fraction of signal candidates, $F_{si}$ and $F_{bkgi}$ are probability density functions (PDF) modelling the signal and background. The backgrounds $B^0 \rightarrow J/\psi K^*$ and $B^0 \rightarrow J/\psi K^+\pi^-$ are parametrized separately by $F_{B^0i}$ with $f_{B^0}$ being the fraction of this background events. The weighting factor $w_i$ accounts for a small decay-time dependency of the acceptance, related to a limited resolution in the on-line track reconstruction, details are given in [6]. The PDF describing the signal, $F_s$, has the form:

$$F_{si} = P_s(m_i|\sigma_{m_i}) \cdot P_s(\Omega_i,t_i|\sigma_t) \cdot A(\Omega_i, p_{T_i}) \cdot P_s(p_{T_i})$$

The signal mass density $P_s(m_i|\sigma_{m_i})$ is modelled as a Delta function smeared by a Gaussian with a per-candidate mass resolution $\sigma_{m_i}$. Similarly, each of ten terms of the signal time and angular dependence, $P_s(\Omega_i,t_i|\sigma_t)$, is convoluted with a Gaussian with a per-candidate resolution $\sigma_t$. The angular sculpting of the detector and kinematic cuts on the angular distributions is included in the likelihood function through $A(\Omega_i, p_{T_i})$. This is calculated using a four-dimensional binned acceptance method, applying an event-by-event efficiency according to the transversity angles ($\theta_T, \psi_T, \phi_T$) and the $p_{T_B}$. The acceptance was calculated from the $B_s^0 \rightarrow J/\psi \phi$ MC events. The background PDF has the following composition:

$$F_{bkgi} = P_b(m_i) \cdot P_b(\sigma_{m_i}) \cdot P_b(t_i|\sigma_t) \cdot P_b(\theta_T) \cdot P_b(\psi_T) \cdot P_b(\phi_T) \cdot P_b(\sigma_t) \cdot P_b(p_{T_i})$$

The decay time function $P_b(t_i|\sigma_t)$ is parameterised as a Delta function, two positive exponentials and a negative exponential. These functions are smeared with the same resolution function as the signal decay time-dependence. The prompt peak models the combinatorial background events, which are expected to have reconstructed lifetime distributed around zero. The two positive exponentials represent a fraction of longer-lived backgrounds with non-prompt $J/\psi$, combined with hadrons from the primary vertex or from a $B/D$ hadron in the same event. The negative exponential takes into account events with poor vertex resolution. The shape of the background angular distributions, $P_b(\theta_T), P_b(\psi_T)$, and $P_b(\phi_T)$ arising primarily from detector and kinematic sculpting are described by the empirical functions with nuisance parameters determined in the fit. The correlations between the background angular shapes are neglected, but a systematic error arising from this simplification was evaluated. The background mass model,
$P_b(m)$ is a linear function. Mis-reconstructed $B^0 \rightarrow J/\psi K^*$ and $B^0 \rightarrow J/\psi K^+\pi^-$ (non-resonant) decays, are parametrized separately. The fractions of these components are fixed in the likelihood fit to values $(6.5 \pm 2.4\%)$ and $(4.5 \pm 2.8\%)$, calculated using MC events. Mass and angles have fixed shapes determined from the MC studies. The decay time is described by an exponential smeared with per-candidate Gaussian errors. Finally, the terms $P_{s,b}(\sigma_{m_i})$, $P_{s,b}(\sigma_{t_i})$ and $P_{s,b}(p_{T_i})$ are introduced to account for differences between signal and background per-candidate mass and decay time uncertainties and values of transverse momenta, details are given in [6].

Systematic uncertainties are assigned by considering effects not accounted for in the likelihood fit. The impact of inner detector residual misalignments was estimated using events simulated with perfect and distorted geometries. Systematics due to limitations of the fit model were determined by 1000 pseudo-experiments generated with variations in the signal and background mass model, resolution model, background lifetime and background angles models. Systematics due to $B^0 \rightarrow J/\psi K^*0$ and $B^0 \rightarrow J/\psi K\pi$ arise from the uncertainties of the PDG decay probabilities, ref. [4].

In the absence of initial state flavour tagging the PDF is invariant under the simultaneous transformations: $\{\phi_s, \Delta \Gamma_s, \delta_\perp, \delta_\parallel, \delta_S\} \rightarrow \{-\phi_s, \Delta \Gamma_s, \pi - \delta_\perp, -\delta_\parallel, -\delta_S\}$ leading to a fourfold ambiguity. As the constraint on $\delta_\perp$ is taken from the LHCb measurement [7], that quotes only two solutions with a positive $\phi_s$ and two $\Delta \Gamma_s$ values symmetric around zero, two of the four minima fitted in the present non-flavour tagged analysis are excluded from the results presented here. Additionally a solution with negative $\Delta \Gamma_s$ is excluded following the LHCb measurement [8] which determines the $\Delta \Gamma_s$ to be positive. The measured values, for the single minimum resulting from these constraints, are given in Table 1. The second strong phase, $\delta_\parallel$, is fitted very close to its symmetry point at $\pi$. Pull studies, based on pseudo-experiments using input values determined from the fit to data, return a non-Gaussian pull distribution for this parameter. For this reason the result for $\delta_\parallel$ is given in the form of a 1$\sigma$ confidence interval $[3.04, 3.24]$ rad. The strong phase of the $S$-wave component is fitted relative to $\delta_\perp$, as $\delta_\perp - \delta_S = (0.03 \pm 0.13)$ rad. The fraction of $S$-wave $KK$ or $f_0$ contamination is measured

| Par.         | Value | Stat. | Syst. | Par.         | Value | Stat. | Syst. |
|--------------|-------|-------|-------|--------------|-------|-------|-------|
| $\phi_s$(rad) | 0.22  | 0.41  | 0.10  | | $|A_0(0)|^2$ | 0.528 | 0.006 | 0.009 |
| $\Delta \Gamma_s$(ps$^{-1}$) | 0.053 | 0.021 | 0.010 | | $|A_\parallel(0)|^2$ | 0.220 | 0.008 | 0.007 |
| $\Gamma_s$(ps$^{-1}$) | 0.677 | 0.007 | 0.004 | | $|A_S(0)|^2$ | 0.02  | 0.02  | 0.02  |

Table 1. Fitted values for the physics parameters along with their statistical and systematic uncertainties.
Figure 1. Mass and decay time fit projections for the $B_s^0$ candidates. The pull distribution at the bottom shows the difference between the data and fit value normalised to the data uncertainty.

to be consistent with zero, at $|A_S(0)|^2 = 0.02 \pm 0.02$. The two-dimensional likelihood contours in the $\phi_s - \Delta \Gamma_s$ plane for the 68%, 90% and 95% confidence intervals are produced using a profile likelihood method and are shown in figure 2. The systematic errors are not included in figure 2 but as seen from table 1 they are small compared to the statistical errors. The ATLAS measured parameters of the $B_s^0 \rightarrow J/\psi \phi$ decay, using $4.9 \text{fb}^{-1}$ of integrated luminosity collected in 2011, are consistent with the world average values and with theoretical expectations, in particular $\phi_s$ is within 1$\sigma$ of the expected value in the Standard Model.
Figure 2. Likelihood contours in the $\phi_s - \Delta \Gamma_s$ plane, statistical errors only. The green band is the theoretical prediction of mixing-induced $CP$ violation.

References

[1] UTfit Collaboration, M. Bona et al., Constraints on new physics from the quark mixing unitarity triangle, Phys.Rev.Lett. 97 (2006) 151803, [hep-ph/0605213].

[2] A. Lenz and U. Nierste, Theoretical update of $B^0_s - \bar{B}^0_s$ mixing, JHEP 0706 (2007) 072, [hep-ph/0612167].

[3] ATLAS Collaboration, The ATLAS Experiment at the CERN Large Hadron Collider, JINST 3 (2008) S08003.

[4] Particle Data Group Collaboration, K. Nakamura et al., Review of particle physics, J.Phys.G G37 (2010) 075021. (And 2011 partial update for the 2012 edition).

[5] A. S. Dighe, I. Dunietz, and R. Fleischer, Extracting CKM phases and $B^0_s - \bar{B}^0_s$ mixing parameters from angular distributions of nonleptonic $B$ decays, Eur.Phys.J. C6 (1999) 647–662, [hep-ph/9804253].

[6] ATLAS Collaboration, Time-dependent angular analysis of the decay $B^0_s \rightarrow J/\psi \phi$ and extraction of $\Delta \Gamma_s$ and the $CP$-violating weak phase $\phi_s$ by ATLAS, arXiv:1208.0572.

[7] LHCb Collaboration, R. Aaij et al., Measurement of the $CP$-violating phase $\phi_s$ in the decay $B^0_s \rightarrow J/\psi \phi$, Phys.Rev.Lett. 108 (2012) 101803, [arXiv:1112.3183].

[8] LHCb Collaboration, R. Aaij et al., Determination of the sign of the decay width difference in the $B^0_s$ system, Phys.Rev.Lett. 108 (2012) 241801, [arXiv:1202.4717].