CP violation at ATLAS

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Abstract. A measurement of several properties of the B_s meson, including the CP-violating weak phase ϕ_s and the mixing-induced width difference $\Delta\Gamma_s$, is performed using the decay $B_s \to J/\psi(\mu^+\mu^-)\phi(K^+K^-)$, from a dataset of 4.9 fb^{-1} of integrated luminosity collected in 2011 by the ATLAS detector at the LHC. The measured parameters are consistent with the world average values and theoretical expectations; in particular ϕ_s is within 1 σ of the expected value in the Standard Model.

1. Introduction

New phenomena beyond the Standard Model (SM) may alter CP violation in B-decays. The CP violation present in the SM cannot account for the dominance of matter in the observable universe, providing a strong motivation for investigating sources of CP violation as they become amenable to experimental investigation. In the $B_s \to J/\psi(\mu^+\mu^-)\phi(K^+K^-)$ decay the CP-violating phase ϕ_s is the weak phase difference between the $B_s^0 - \bar{B}_s^0$ mixing amplitude and the $b \to c\bar{c}s$ decay amplitude. The SM predicts a small value of $\phi_s \simeq -2\beta_s = -0.0368 \pm 0.0018$ rad [2]. Another quantity involved in $B_s^0 - \bar{B}_s^0$ mixing is the width difference $\Delta\Gamma_s = \Gamma_L - \Gamma_H$ between heavy (B_H) and light (B_L) eigenstates. Physics beyond the SM is not expected to affect $\Delta\Gamma_s$ significantly [3]. Extracting $\Delta\Gamma_s$ from data is nevertheless useful as it allows theoretical predictions to be confirmed. The presented analysis uses data collected by the ATLAS experiment in pp collisions at $\sqrt{s}$ = 7 TeV in 2011, corresponding to an integrated luminosity of 4.9 fb^{-1}. The measurement of ϕ_s, the average decay width $\Gamma_s = (\Gamma_L + \Gamma_H)/2$ and the value of $\Delta\Gamma_s$, were performed without any attempt to distinguish the between the B_s and $\bar{B}_s$ (flavour tagging). The CP states were separated statistically through the time-dependence of the decay and angular correlations amongst the final-state particles.

2. ATLAS potential in B_s mixing and CP violation studies

ATLAS has measured the cross sections of the inclusive $b\bar{b} \to J/\psi$ and $pp \to J/\psi$ and found that given the conditions in ATLAS the $b\bar{b} \to J/\psi$ cross section is approximately $0.38 \pm 0.01(\text{stat.}) \pm 0.47(\text{syst.}) \pm 0.03(\text{spin}) \pm 0.01(\text{lumi.})\mu b$, while the $pp \to J/\psi$ cross section is $0.98 \pm 0.02(\text{stat.}) \pm 0.13(\text{stat.}) \pm 0.15(\text{spin}) \pm 0.03(\text{lumi.})\mu b$ [9]. The high ratio of $R = (bb \to J/\psi)/(pp \to J/\psi) = 0.39$ makes it viable to collect all the $(pp \to J/\psi)$ background and fit it in the maximum likelihood, since the alternative method of applying a proper decay time cut to remove the background has the side effect of complicating the fitting proceeding and introducing another type of systematic error.

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3. Candidate Selection

ATLAS is a multipurpose cylindrical particle detector at the Large Hadron Collider [4]. 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 dimuon triggers used for the analysis are based on identification of a $J/\psi \to \mu^+\mu^-$ 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 GeV) to one of the muons. The pairs of muon tracks are refitted to a common vertex and are accepted if the fit χ^2/d.o.f. < 10. The invariant mass of the J/ψ is required to fall in the range (2.959 - 3.229) GeV when both muons entered the barrel ($\mid \eta \mid < 1.05$) or (2.852-3.332) GeV when both muon entered the endcap ($1.05 < \mid \eta \mid < 2.5$) or (2.913-3.273) GeV otherwise. Candidates for $B_s \to J/\psi(\mu^+\mu^-)\phi(K^+K^-)$ are sought by fitting the four tracks to a common vertex resulting in χ^2/d.o.f.< 3, while the invariant mass of the two muons are fixed to the J/ψ mass [5]. In total 131k B_s^0 candidates are collected within a mass range of $\phi \to K^+K^-$ (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 t is determined by the expression: $t = L_{xy}M_B/(cp_{T_B})$, where p_{T_B} 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)[5]. L_{xy} is the displacement in transverse plane of the B_s^0 decay vertex with respect to the primary vertex (PV) projected onto the direction of p_{T_B}. 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. The PV with the smallest d_0 is chosen for the proper decay time calculation, this 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.

4. Analysis and results

The $B_s \to J/\psi(\mu^+\mu^-)\phi(K^+K^-)$ decay involves three CP states of the $J/\psi\phi$ system, combined into three polarisation amplitudes, A_0, $A_\parallel$ and $A_\perp$. The first two states are CP-even, while the last state is CP-odd. Other CP-odd states 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 inference terms is fitted simultaneously with the angular distributions and the reconstructed proper decay time of the cascade decay $B_s \to J/\psi(\mu^+\mu^-)\phi(K^+K^-)$. Three independent angles $\Omega = (\theta_T, \psi_T, \phi_T)$, are defined in the transversity basis [6]. The interesting parameters of the $B_s \to J/\psi(\mu^+\mu^-)\phi(K^+K^-)$ decay are $\delta_\parallel = \arg(A_\parallel, A_0)$, $\delta_\perp = \arg(A_\perp, A_0)$ and $\delta_s = \arg(A_s, A_0)$. For untagged analysis all terms involving the mixing frequency Δm_s in the time-dependant amplitudes cancel out [1]. Also the time-dependent amplitudes depending on $\delta_\perp$ are multiplied by a small value $\sin\phi_s$, 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 is therefore applied [8]. An unbinned maximum likelihood fit uses information of the reconstructed B_s^0 candidate mass m, proper decay time t, their uncertainties σ_m and σ_t, and the angles $\Omega = (\theta_T, \psi_T, \phi_T)$. In total 26 parameters are determined, including the eight physics parameters of interest mentioned above, while the other quantities describe the $J/\psi\phi$ mass distribution, the proper decay time and the angular distributions of the background. The event likelihood has the form:

$$\mathcal{L} \propto w_i \cdot f_s \cdot \mathcal{F}_s i + f_s \cdot f_{B_i^0} + (1 - f_s \cdot (1 + f_{B^0})) \cdot \mathcal{F}_{bkgi} \tag{1}$$

where the index i is used for the variables specific for each event, f_s is fraction of signal candidates, $\mathcal{F}_{si}$ and $\mathcal{F}_{bkgi}$ are probability density functions (PDF) modelling the signal and background. The backgrounds $B^0 \to J/\psi K^*$ and $B^0 \to J/\psi K^+\pi^-$ are parametrised separately by $\mathcal{F}_{B^0_i}$ 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 [1]. The PDF describing the signal, $\mathcal{F}_s$, has the form:

$$\mathcal{F}_{si} = P_s(m_i \mid \sigma_{m_i}) \cdot P_s(\sigma_{m_i}) \cdot P_s(\Omega_i, t_i \mid \sigma_{t_i}) \cdot A(\Omega_i, p_{T_i}) \cdot P_s(p_{T_i}) \tag{2}$$

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

$$\mathcal{F}_{bkgi} = P_b(m_i) \cdot P_b(\sigma_{m_i} \cdot P_b(\sigma_{m_i}) \cdot P_b(t_i \mid \sigma_{t_i}) \cdot P_b(\theta_T) \cdot P_b(\psi_T) \cdot P_b(\phi_T) \cdot P_b(\sigma_{t_i}) \cdot P_b(p_{T_i}) \tag{3}$$

The proper decay time function $P_b(t_i \mid \sigma_{t_i})$ 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 proper decay time-dependence. The prompt peak describes the combinatorial background events, which are expected to have reconstructed lifetimes distributed around zero. The two positive exponentials represent the fraction of longer-lived backgrounds with non-prompt J/ψ, 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 a particularly badly measured vertex. The shapes of the background angular distributions, $P_b(\theta_T)$, $P_b(\psi_T)$, and $P_b(\phi_T)$ arise primarily from detector and kinematic sculpting are described by the empirical functions (equations 4 to 6) 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 $B^0 \to J/\psi K^*$ and $B^0 \to J/\psi K^+\pi^-$ (non-resonant) decays, are parametrised 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 proper decay time is described by an exponential, convoluted by 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 proper decay time uncertainties and values of transverse momenta [1].

$$f(\cos\theta_T) = \frac{a_0 - a_1 cos^2(\theta_T)}{2a_0 - 2a_1/3} \tag{4}$$

$$f(\varphi_T) = \frac{1 + b_1 cos(2\varphi_T + b_0)}{2\pi} \tag{5}$$

$$f(\cos\psi_T) = \frac{c_0 + c_1 cos^2(\psi_T)}{2c_0 + 2c_1/3} \tag{6}$$

Systematic uncertainties are assigned by considering effects not accounted for in the likelihood fit. The impact of inner detector residual misalignments were 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

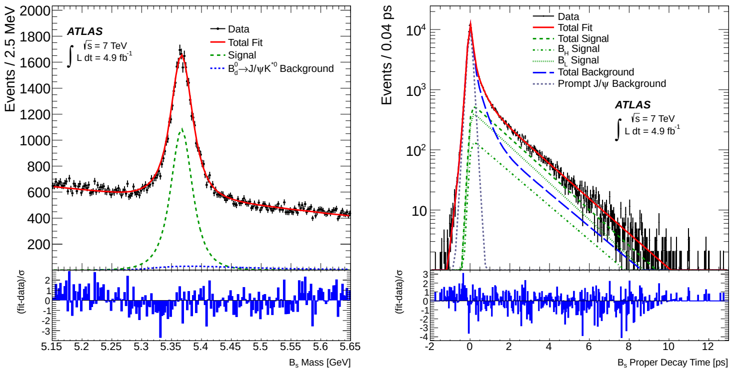

Figure 1. Mass and proper decay time fit projections for the B_s^0 candidates. The pull distribution at the bottom shows the difference between data and fit value normalised to the data uncertainty.[1]

due to $B^0 \to J/\psi K^{*0}$ and $B^0 \to J/\psi K\pi$ arise from the uncertainties of the PDG decay probabilities [5].

In the absence of initial state flavour tagging the PDF is invariant under the simultaneous transformations: $\{\phi_s, \Delta\Gamma_s, \delta_\perp, \delta_\|, \delta_s\} \to \{-\phi_s, \Delta\Gamma_s, \pi - \delta_\perp, -\delta_\|, -\delta_s\}$ 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 ϕ_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.

Par.	Value	Stat.	Syst.
ϕ_s(rad)	0.22	0.41	0.10
$\Delta\Gamma_s(ps^{-1})$	0.053	0.21	0.010
$\Gamma_s(ps^{-1})$	0.0677	0.007	0.004
$\mid A_0(0) \mid^2$	0.528	0.006	0.009
$\mid A\|(0) \mid^2$	0.220	0.008	0.007
$\mid A_s(0) \mid^2$	0.02	0.02	0.02

Table 1. Fitted values for the physics parameters along with their statistical and systematic uncertainties.[1]

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 to be consistent with zero at $\mid A_s(0) \mid^2 = 0.02 \pm 0.02$. 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 as shown in figure 3. The systematic errors are not included in figure 3 but as seen from table 1 they are small compared to the statistical errors. The ATLAS measured parameters are consistent with the world average values and with theoretical expectation in particular ϕ_s is within 1σ of the expected value in the SM.

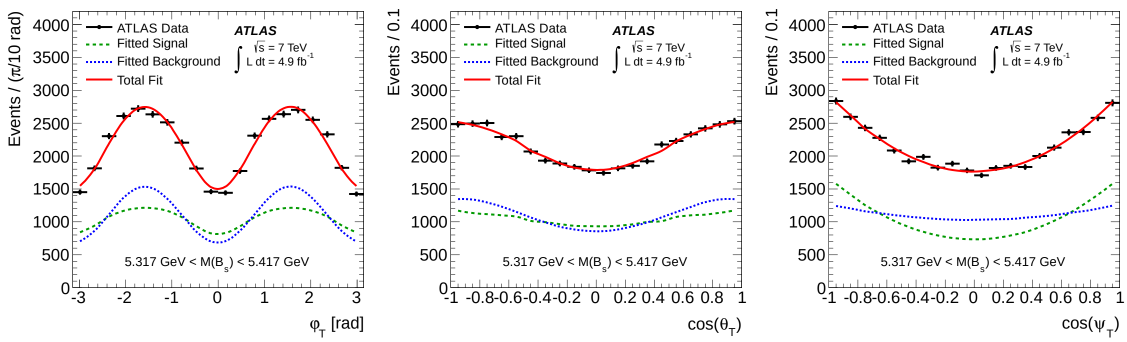

Figure 2. Fit projections for the 3 transversity angles measured in the analysis.[1]

5. Comparison with other results

The heavy flavour averaging group (HFAG) has included the ATLAS result in their world average, bringing the world average into close agreement with the SM prediction (see figure 3). The comparison shown in figure 3 of Γ_s and $\Delta\Gamma_s$ measurements display agreement with other measurements, theoretical prediction and show a competitive accuracy is obtained.

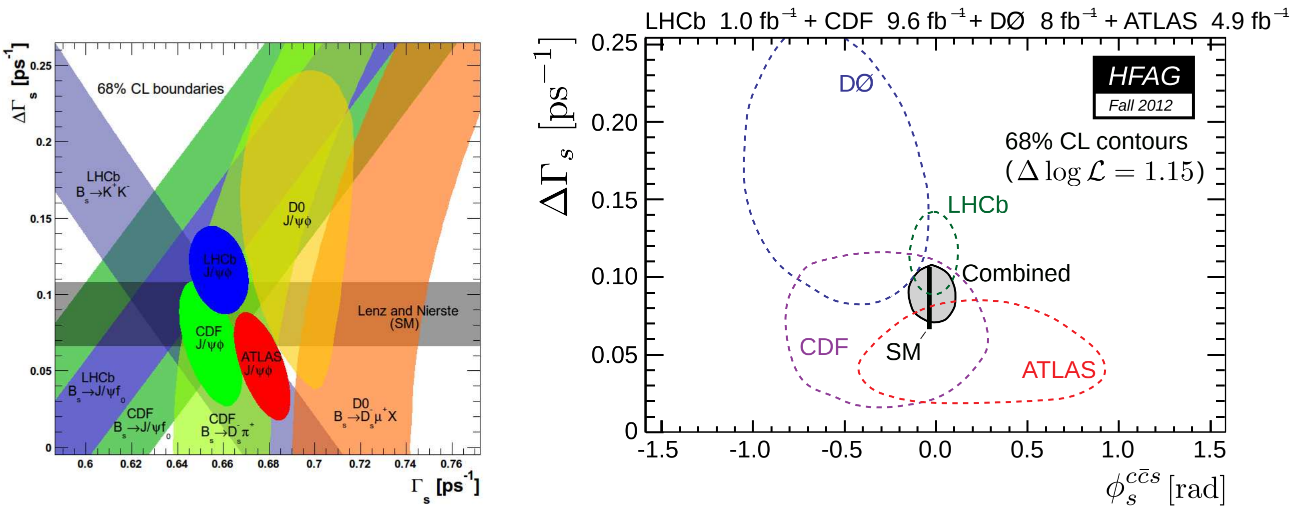

Figure 3. Contour Plots comparing the parameters with those measured at other experiments. Note the other experiments include tagging while the ATLAS contour does not.[1]

Future publications released by ATLAS will increase accuracy by including tagging information, measuring the angles defined in the helicity basis (which produces simpler acceptance sculpting) and incorporating subsequent datasets to increase statistical information.

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