Measurement of CP violation and mixing in $B_s^0 \rightarrow J/\psi\phi$ in ATLAS *

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Abstract

An overview of a measurement of time-dependent CP asymmetry parameters in $B_s^0 \rightarrow J/\psi(\mu^+\mu^-)\phi(K^+K^-)$ decays using 80.5 fb^{-1} of integrated luminosity collected with the ATLAS detector from 13 TeV pp collisions at the LHC is presented. A manifestation of the CP violation is an interference between direct and mixing-mediated B_s^0 decays, producing a common final state. In the Standard Model, it is characterized by a phase shift ϕ_s related to the CKM matrix. In the case of $B_s^0 \rightarrow J/\psi\phi$, this shift is predicted to be small, $\phi_s = -0.0363_{-0.0015}^{+0.0016}$ rad. New physics can enhance ϕ_s whilst satisfying all existing constraints. Results presented in this talk are compatible with those obtained from 19.2 fb^{-1} of 7 TeV and 8 TeV data as well as with the Standard Model predictions and other LHC measurements.

Keywords: CP Violation, Bs J/psi Phi, ATLAS, CERN, B Physics, Flavour Physics

1. Introduction

The $B_s^0 \rightarrow J/\psi\phi$ decay channel is expected to be sensitive to new physics contributions in the CP violation. In this channel, CP violation occurs due to interference between direct decays and decays occurring through $B_s^0 - \bar{B}_s^0$ mixing. The frequency of this mixing is characterized by the mass difference ΔM_s between light (B_L) and heavy (B_H) mass eigenstates. The CP violation is described by the weak phase difference ϕ_s between the $B_s^0 - \bar{B}_s^0$ mixing amplitude and the $b \rightarrow ccs$ decay amplitude, the decay width $\Gamma_s = (\Gamma_L^s + \Gamma_H^s)/2$, and the width difference $\Delta\Gamma_s = \Gamma_L^s - \Gamma_H^s$, where Γ_L^s and Γ_H^s are decay widths of B_L and B_H states, respectively. In the Standard Model (SM), the phase ϕ_s is related to CKM quark mixing matrix via the relation

$$\phi_s \simeq -2 \arg \left(-\frac{V_{ts} V_{tb}^*}{V_{cs} V_{cb}^*} \right). \quad (1)$$

Assuming no beyond the SM physics contributions to the B_s^0 mixing and decays, a value of $\phi_s = -0.0363_{-0.0015}^{+0.0016}$ rad is predicted [1]. Many New Physics (NP) models allow a larger value of ϕ_s whilst satisfying all existing constraints, including the precisely measured value of ΔM_s .

The analysis presented here introduces a measurement of parameters describing the CP violation in the $B_s^0 \rightarrow J/\psi\phi$ decay using 80.5 fb^{-1} of LHC pp 13 TeV data collected by the ATLAS detector during 2015 - 2017 [2]. The results are combined with those obtained from the analysis of 19.2 fb^{-1} of data collected at 7 TeV and 8 TeV [3].

2. The ATLAS detector

The ATLAS experiment [4] is a multipurpose particle detector at the LHC. It consists of three main parts: the Inner Detector (ID) immersed in a 2 T axial magnetic field, electromagnetic and hadronic calorimeters, and a Muon Spectrometer (MS), all located within the magnetic field produced by three large superconducting air-core toroid systems.

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Table 1: Tagging performance for the methods used in the analysis, determined by using the sample of $B^\pm$ signal candidates. Uncertainties shown are statistical only. Taken from [2].

Tag method	Efficiency [%]	Effective Dilution [%]	Tagging Power [%]
Tight muon	4.50 ± 0.01	43.8 ± 0.2	0.862 ± 0.009
Electron	1.57 ± 0.01	41.8 ± 0.2	0.274 ± 0.004
Low- p_T muon	3.12 ± 0.01	29.9 ± 0.2	0.278 ± 0.006
Jet	5.54 ± 0.01	20.4 ± 0.1	0.231 ± 0.005
Total	14.74 ± 0.02	33.4 ± 0.1	1.65 ± 0.01

The ID subsystem covers the pseudorapidity region of $|\eta| < 2.5$ and is used for a precise tracking. The ID consists of a silicon pixel detector, a silicon microstrip detector, and a transition radiation tracker. A new Insertable B-Layer was added to the present ID during the Long Shutdown 1. This fourth layer with a radius of 33 mm was placed between a new beam pipe and the current inner pixel layer.

3. Data, reconstruction, and candidate selection

The data were collected using triggers based on the identification of a $J/\psi \rightarrow \mu\mu$ decay, with transverse momentum (p_T) thresholds of either 4 GeV or 6 GeV for the muons.

Events must contain at least one reconstructed primary vertex, formed from at least four ID tracks, to pass the selection. Also at least one pair of oppositely charged muons reconstructed using information from both the MS and the ID must be present in the event. Pairs of oppositely charged muon tracks are refitted to a common vertex and the pair is accepted if $\chi^2/\text{ndf} < 10$. Varying mass resolution in different parts of the detector is accounted for by the $|\eta(\mu)|$ dependent J/ψ mass cuts. Decays $\phi \rightarrow K^+K^-$ are reconstructed from all pairs of oppositely charged particles with $p_T > 1$ GeV and $|\eta| < 2.5$ that are not identified as muons. Candidates for B_s^0 are selected by fitting the four tracks to a common vertex with J/ψ mass constraint [5]. A candidate is accepted if the vertex fit has $\chi^2/\text{ndf} < 3$ and $|m(K^+K^-) - m_{\text{PDG}}(\phi)| < 11$ MeV. In the case of more than one B_s^0 candidate in the event, the one with the lowest χ^2/ndf is selected.

For each B_s^0 candidate the proper decay time t is calculated:

$$t = \frac{L_{xy} m(B_s^0)}{p_T(B_s^0)},$$

where $p_T(B_s^0)$ is the transverse momentum of the B_s^0 meson and $m(B_s^0)$ is the mass of the B_s^0 meson, taken

from [5]. The transverse decay length L_{xy} is the displacement in the transverse plane of the B_s^0 meson decay vertex with respect to the primary vertex, projected onto the direction of the B_s^0 transverse momentum.

4. Flavour tagging

Initial flavour of (neutral) B_s^0 is inferred using the other B -meson typically produced in the event. Discrimination is provided by measuring the *cone charge* from the semileptonic decay of this meson, which is defined as a p_T -weighted sum of charge of tracks in the cone $\Delta R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2} < 0.5$, i.e.,

$$Q_x = \frac{\sum_i^{N_{\text{tracks}}} q_i \cdot (p_{Ti})^\kappa}{\sum_i^{N_{\text{tracks}}} (p_{Ti})^\kappa},$$

where $x = \{\mu, e, \text{jet}\}$ refers to muon, electron, or jet charge tagging method, respectively. Jet charge is used if no lepton is present in the event. The constant κ is found empirically for each tagging method to achieve the best performance. To study and calibrate used tagging methods, events containing the decays of “self-calibrated” channel $B^\pm \rightarrow J/\psi K^\pm$ were used (flavour of the B -meson at production is provided by the kaon charge). Using this sample, a cone charge is mapped to a probability $P(B|Q_x)$ that a B meson is produced in a state containing a $\bar{b}$ -quark. This information is then used in a fit on a per-candidate basis. If there is no information available for a given B_s^0 meson, a probability of 0.5 is assigned to that candidate.

A strength of a particular flavour tagging method is represented by a dilution $\mathcal{D}(Q_x) = 2P(B|Q_x) - 1$. An efficiency ϵ_x is defined as the fraction of signal events tagged by the method compared to the total number of signal events in the sample. A tagging power is then defined as $T_x = \sum_i \epsilon_{xi} \cdot (2P(B|Q_{xi}) - 1)^2$, where the sum is over the probability distribution in intervals of the cone charge variable. An effective dilution, $D_x = \sqrt{T_x/\epsilon_x}$, is calculated from the measured tagging power and efficiency. A summary of the tagging performance for each method is given in Table 1.

Table 2: Fit results for the selected physical parameters with their statistical and systematic uncertainties, both for the 13 TeV measurement and for the combination with the results obtained from 7 TeV and 8 TeV data. Taken from [2].

Parameter	13 TeV Data			13 TeV and Run 1 combined		
	Value	Stat.	Syst.	Value	Stat.	Syst.
ϕ_s [rad]	-0.068	0.038	0.018	-0.076	0.034	0.019
$\Delta\Gamma_s$ [ps^{-1}]	0.067	0.005	0.002	0.068	0.004	0.003
Γ_s [ps^{-1}]	0.669	0.001	0.001	0.669	0.001	0.001

Figure 1: Mass fit projection for the $B_s^0 \rightarrow J/\psi\phi$ sample. The red line shows the total fit, the dashed magenta line shows the $B_s^0 \rightarrow J/\psi\phi$ signal component, the blue line shows the $B_d^0 \rightarrow J/\psi K^{0*}$ component, while the green line shows the contribution from $\Lambda_b \rightarrow J/\psi p K^-$ events. Below the figure is a ratio plot that shows the difference between each data point and the total fit line divided by the statistical and systematic uncertainties summed in quadrature of that point [2].

5. Maximum likelihood fit

To extract the parameters characterising the decay, an unbinned maximum likelihood fit is performed on 3 210 429 B_s^0 candidates passing the selection and collected within a mass range of $5.15 \text{ GeV} < m(B_s^0) < 5.65 \text{ GeV}$. The fit uses information about the reconstructed mass m , the measured proper decay time t , the measured proper decay time uncertainty σ_t , the tagging probability $P(B|Q_x)$, and the transversity angles $(\theta_T, \psi_T, \phi_T)$ of each B_s^0 candidate. The likelihood function is defined as a combination of the Probability Density Functions (PDF) describing the signal (including a non-resonant S -wave state $B_s^0 \rightarrow J/\psi K^+ K^-$), backgrounds from B_d^0 mesons and Λ_b baryons misidentified as B_s^0 candidates, and the combinatorial background distributions.

Systematic uncertainties are evaluated for effects that

Figure 2: Proper decay time fit projection for the $B_s^0 \rightarrow J/\psi\phi$ sample. The red line shows the total fit while the magenta dashed line shows the total signal. The total background is shown as a blue dashed line with a long-dashed grey line showing the prompt J/ψ background. Below the figure is a ratio plot that shows the difference between each data point and the total fit line divided by the statistical and systematic uncertainties summed in quadrature of that point [2].

are not accounted for in the likelihood fit. Following sources were identified and are described in detail in [2]: flavour tagging, angular acceptance method, ID alignment, fit model used, trigger efficiency, B_d^0 and Λ_b contributions, and limitation of the data modelling. For each parameter, the total systematic uncertainty is obtained by adding these contributions in quadrature.

6. Results

The fit results are compatible with those obtained from 19.2 fb^{-1} of 7 TeV and 8 TeV data analysis. A Best Linear Unbiased Estimator (BLUE) method [6] is used to perform a combination of the current measurements with the previous analysis. Selected parameters of the fit results and the obtained combined results together with their uncertainties are given in Table 2. Fit

Figure 3: Fit projections for the transversity angle ϕ_T (top), $\cos \theta_T$ (middle), and $\cos \psi_T$ (bottom). In all three plots the red solid line shows the total fit, the $B_s^0 \rightarrow J/\psi\phi$ signal component is shown by the magenta dashed line and the blue dotted line shows the contribution of all background components. Below each figure is a ratio plot that shows the difference between each data point and the total fit line divided by the statistical and systematic uncertainties summed in quadrature of that point [2].

projections of mass, lifetime, and transversity angles between final state particles are shown in Figure 1, 2, and 3 respectively. The two dimensional likelihood contours in the $\phi_s - \Delta\Gamma_s$ plane for the both measurements and the combined results are shown in Figure 4.

7. Summary

A measurement of the time-dependent CP asymmetry parameters in $B_s^0 \rightarrow J/\psi(\mu^+\mu^-)\phi(K^+K^-)$ decays using 80.5 fb $^{-1}$ of integrated luminosity collected with the

Figure 4: Likelihood 68% confidence level contours in the $\phi_s - \Delta\Gamma_s$ plane, showing ATLAS results for 7 TeV and 8 TeV data (blue dashed-dotted curve), for 13 TeV data (green dashed curve) and for 13 TeV data combined with 7 TeV and 8 TeV (red solid curve) data. In all contours the statistical and systematic uncertainties are combined in quadrature and correlations are taken into account. Taken from [2].

ATLAS detector from 13 TeV pp collisions at the LHC is presented. Results are compatible with those obtained from 19.2 fb $^{-1}$ of 7 TeV and 8 TeV data analysis and both measurements are statistically combined to the following results:

$$\begin{aligned}\phi_s &= -0.076 \pm 0.034(\text{stat.}) \pm 0.019(\text{syst.}) \text{ rad} \\ \Delta\Gamma_s &= 0.068 \pm 0.004(\text{stat.}) \pm 0.003(\text{syst.}) \text{ ps}^{-1} \\ \Gamma_s &= 0.669 \pm 0.001(\text{stat.}) \pm 0.001(\text{syst.}) \text{ ps}^{-1}\end{aligned}$$

Both the new measurement and the combination are still consistent with the Standard Model predictions as well as with the other LHC measurements.

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