PROCEEDINGS OF SCIENCE

$B_s^0 \to J/\psi\phi$ in ATLAS

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A measurement of the $B_s^0 \to J/\psi\phi$ decay parameters using $80.5\,\mathrm{fb}^{-1}$ of integrated luminosity collected with the ATLAS detector from 13 TeV proton-proton collisions at the LHC from 2015-2017 is presented. The measured parameters include the CP-violating phase ϕ_s, the width difference $\Delta\Gamma_s$ between the B_s^0 mass eigenstates and the average decay width Γ_s.

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1. Introduction

In the presence of new physics phenomena, sources of CP violation in b-hadron decays can arise in addition to those predicted by the Standard Model. In $B_s^0 \to J/\psi\phi$ decays, CP violation occurs due to interference between the direct decay and the decay after the $B_s^0 - \bar{B}_s^0$ mixing. The oscillation frequency of B_s^0 meson mixing is proportional to the mass difference, Δm_s, between the heavy and light mass eigenstates. The CP-violating phase ϕ_s is defined as 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. In the Standard Model this phase is small and related to the Cabibbo–Kobayashi–Maskawa quark mixing matrix elements via the relation $\phi_s \approx -2\beta_s$, with $\beta_s = \arg[-(V_{ts}V_{tb}^*)/(V_{cs}V_{cb}^*)]$. By combining beauty and kaon physics observables, and assuming no new physics contributions to B_s^0 mixing and decays, a value of $2\beta_s = 0.037(1)$ is predicted [1]. Other physical quantities involved in $B_s^0 - \bar{B}_s^0$ mixing are the average decay width Γ_s and the width difference $\Delta\Gamma_s$ between the light and heavy mass eigenstates.

These proceedings present a measurement of the $B_s^0 \to J/\psi\phi$ decay parameters using 80.5 fb^{-1} of the LHC proton-proton data collected by the ATLAS detector during 2015-2017, at a centre-of-mass energy of 13 TeV [2].

2. Event Selection and Monte Carlo Simulations

This section describes the candidate selection for the decay $B_s^0 \to J/\psi(\mu^+\mu^-)\phi(K^+K^-)$ [2]. The data were collected during periods with different instantaneous luminosity, so several triggers were used in the analysis. All triggers were based on the identification of a $J/\psi \to \mu^+\mu^-$ decay, with transverse momentum (p_T) thresholds of either 4 GeV or 6 GeV for the muons. Data quality requirements were imposed on the data, notably on the performance of the muon spectrometer, inner detector and calorimeter systems of the ATLAS detector.

In addition, each event must contain at least one reconstructed primary vertex, formed from at least four inner detector (ID) tracks, and at least one pair of oppositely charged muon candidates. The muon track parameters are determined from the ID measurement alone. Pairs of oppositely charged muon tracks are re-fitted to a common vertex. In order to account for varying mass resolution in different parts of the detector, the J/ψ candidates are divided into three subsets according to the pseudorapidity η of the muons.

The candidates for the decay $\phi \to K^+K^-$ are reconstructed from all pairs of oppositely charged tracks not identified as muons or electrons. Candidate events for $B_s^0 \to J/\psi(\mu^+\mu^-)\phi(K^+K^-)$ decays are selected by fitting the tracks for each combination of $J/\psi \to \mu^+\mu^-$ and $\phi \to K^+K^-$ to a common vertex. The fit is also constrained by fixing the invariant mass calculated from the two muon tracks to the J/ψ mass. For the $\phi \to K^+K^-$ candidate, the invariant mass of the track pairs must fall within the interval 1.0085 GeV $< m(K^+K^-) <$ 1.0305 GeV. The B_s^0 candidate is required to be within the mass range of 5150-5650 GeV.

For each B_s^0 meson candidate the proper decay time t is estimated using:

$$t = \frac{L_{xy} m_B}{p_{\mathrm{T}_B}},$$

where p_{T_B} is the reconstructed transverse momentum of the B_s^0 meson candidate and m_B denotes the PDG value for the mass of the B_s^0 meson [3]. The transverse decay length, L_{xy}, is the displacement in the transverse plane of the B_s^0 meson decay vertex relative to the primary vertex, projected onto the direction of the B_s^0 transverse momentum.

To study the detector response, estimate backgrounds, and model systematic effects, 100 M Monte Carlo (MC) simulated $B_s^0 \to J/\psi\phi$ events were generated. In order to account for the varying number of proton-proton interactions per bunch crossing (pile-up) and trigger configurations during data-taking, the MC events were weighted to reproduce the same pile-up and trigger conditions as in data. Additionally, background samples of both exclusive ($B_d^0 \to J/\psi K^{0*}$ and $\Lambda_b \to J/\psi p K^-$) and inclusive ($b\bar{b} \to J/\psi X$ and $pp \to J/\psi X$) decays were simulated. For validation studies related to flavour tagging, events with $B^\pm \to J/\psi K^\pm$ exclusive decays were also simulated.

3. Flavour Tagging

To identify (tag) the flavour of a neutral B meson at the point of production, information is extracted using the decay of the other (opposite) b-hadron that is produced from the pair production of b and $\bar{b}$ quarks. This method is called opposite-side tagging (OST). The OST algorithms define a discriminating variable Q_x, based on charge information and sensitive to the flavour of the opposite-side b-hadron. The algorithms thus provide a probability $P(B|Q_x)$ that a signal B meson in a given event is produced with a given flavour. The calibration of the OST algorithms proceeds using $B^\pm \to J/\psi K^\pm$ candidate decays, where the charge of the kaon determines the flavour of the B meson. This provides a self-tagging calibration sample. Once calibrated, the OST algorithms are applied to the $B_s^0 \to J/\psi\phi$ candidate events, providing a probability of a certain event containing a B_s^0 or $\bar{B}_s^0$ state respectively. Four different OST algorithms are used and in case of events tagged with multiple methods, the OST method is selected in the following order: tight muon, low-p_T muon, electron and jet tagging. Lepton and jet tagging by definition have no overlap, while the ordering of electron and muon tagging is found to have negligible effect. The probabilities determined by the flavour tagging are finally used as input to the maximum likelihood fit of the $B_s^0 \to J/\psi\phi$ events.

4. Results

This section details the results of this analysis [2]. It describes the maximum likelihood fit to be applied to the data before giving an overview of the obtained results. A short discussion of systematic uncertainties is also given.

4.1 Maximum Likelihood Fit

An unbinned maximum likelihood fit is performed on the selected events in order to extract the physics parameters describing the $B_s^0 \to J/\psi(\mu^+\mu^-)\phi(K^+K^-)$ decay. The fit uses information on the reconstructed mass m, the measured proper decay time t, mass uncertainty σ_m, proper decay time uncertainty σ_t, transverse momentum p_T, the tagging probability, $P(B|Q_x)$, and the three so-called transversity angles $\Omega = (\theta_T, \psi_T, \phi_T)$ of each candidate event. These angles are defined in the rest frames of the final state particles. The x-axis is determined by the momentum of the ϕ meson and the x-y plane is defined by the K^+K^- system. The three angles are defined as follows:

- θ_T is the angle between $\vec{p}(\mu^+)$, the momentum of μ^+, and the normal to the x-y plane, in the J/ψ rest frame,

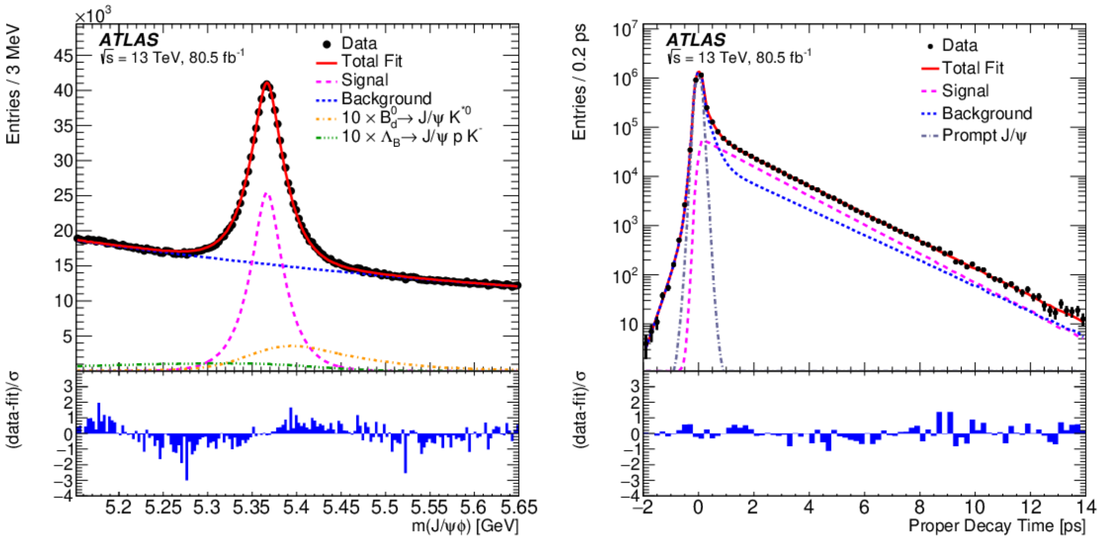

Figure 1: (Left) Mass fit projection for the $B_s^0 \to J/\psi\phi$ sample. The red line shows the total fit, the short-dashed magenta line shows the $B_s^0 \to J/\psi\phi$ signal component, the combinatorial background is shown as a blue dotted line, the orange dash-dotted line shows the $B_d^0 \to J/\psi K^{0*}$ component, and the green dash-dot-dot line shows the contribution from $\Lambda_b \to J/\psi p K^-$ events. (Right) Proper decay time fit projection for the $B_s^0 \to J/\psi\phi$ sample. The red line shows the total fit while the short-dashed magenta line shows the total signal. The total background is shown as a blue dotted line, and a long-dashed grey line shows the prompt J/ψ background component. Below each figure a ratio plot is given 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]

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- ϕ_T is the angle between the x-axis and the projection of $\vec{p}(\mu^+)$ onto the x-y plane, in the J/ψ rest frame,
- ψ_T is the angle between $\vec{p}(K^+)$ and $-\vec{p}(J/\psi)$.

The likelihood function is defined as a combination of the signal and background PDFs as follows:

$$\begin{aligned}\log \mathcal{L} = \sum_{i=1}^{N} w_i \log[& f_s \mathcal{F}_s(m_i, t_i, \sigma_{m_i}, \sigma_{t_i}, \Omega_i, P_i(B|Q_x), p_{T_i}) \\ & + f_s f_{B^0} \mathcal{F}_{B^0}(m_i, t_i, \sigma_{m_i}, \sigma_{t_i}, \Omega_i, P_i(B|Q_x), p_{T_i}) \\ & + f_s f_{\Lambda_b} \mathcal{F}_{\Lambda_b}(m_i, t_i, \sigma_{m_i}, \sigma_{t_i}, \Omega_i, P_i(B|Q_x), p_{T_i}) \\ & +(1 - f_s(1 + f_{B^0} + f_{\Lambda_b}))\mathcal{F}_{\mathrm{bkg}}(m_i, t_i, \sigma_{m_i}, \sigma_{t_i}, \Omega_i, P_i(B|Q_x), p_{T_i})],\end{aligned}$$

where N is the number of selected candidates, w is a weighting factor to account for the trigger efficiency. The terms $\mathcal{F}_s$, $\mathcal{F}_{B^0}$, $\mathcal{F}_{\Lambda_b}$ and $\mathcal{F}_{\mathrm{bkg}}$ are the PDFs modelling the signal, B^0 background, Λ_b background and other backgrounds respectively. The term f_s is the fraction of signal candidates and f_{B^0} and f_{Λ_b} are the background fractions of B^0 mesons and Λ_b baryons misidentified as B_s^0 candidates, calculated relative to the number of signal events. A detailed discussion of these functions can be found in [2].

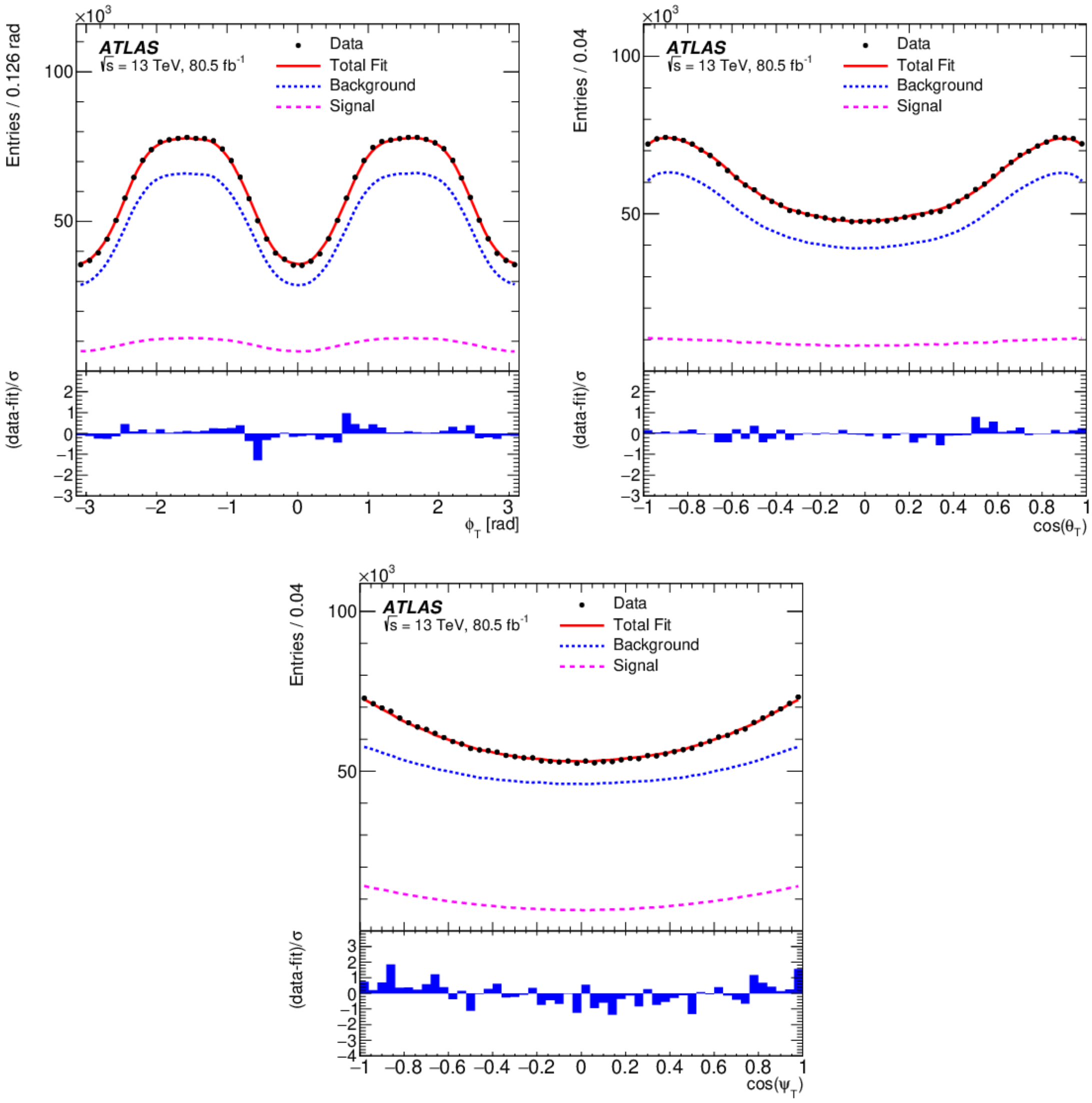

Figure 2: Fit projections for the transversity angles ϕ_T (top left), $\cos\theta_T$ (top right), and $\cos\psi_T$ (bottom). In all three plots the red solid line shows the result of the total fit, the $B_s^0 \to J/\psi\phi$ signal component is shown by the magenta dashed line and the blue dotted line shows the contribution of all background components. A ratio plot below each figure shows 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].

The main fit parameters include the CP-violating phase ϕ_s, the average decay width Γ_s and the decay width difference $\Delta\Gamma_s$. In addition, the amplitudes, $|A_{||}|^2$ and $|A_0|^2$ to be precise, and the strong phases, $\delta_\perp$ and $\delta_{||}$, of the CP states are determined. Also, the quantity $|A_S|^2$ and strong phase δ_S of the S wave are estimated by the likelihood fit.

4.2 Systematic Uncertainties

Various systematic uncertainties are estimated. The impact of these systematics is outlined in Table 1. A detailed account of these systematics is given in [2].

Table 1: This table summarises the systematic effects considered in the analysis. The respective uncertainties are assigned to the various physics parameters [2].

	ϕ_s $[10^{-3}$ rad$]$	$\Delta\Gamma_s$ $[10^{-3}$ ps$^{-1}]$	Γ_s $[10^{-3}$ ps$^{-1}]$	$\lvert A_\parallel(0)\rvert^2$ $[10^{-3}]$	$\lvert A_0(0)\rvert^2$ $[10^{-3}]$	$\lvert A_S(0)\rvert^2$ $[10^{-3}]$	$\delta_\perp$ $[10^{-3}$ rad$]$	$\delta_\parallel$ $[10^{-3}$ rad$]$	$\delta_\perp - \delta_S$ $[10^{-3}$ rad$]$
Tagging	19	0.4	0.3	0.2	0.2	1.1	17	19	2.3
Acceptance	0.5	< 0.1	< 0.1	1.0	0.8	2.6	30	50	11
ID alignment	0.8	0.2	0.5	< 0.1	< 0.1	< 0.1	11	7.2	< 0.1
Best candidate selection	0.5	0.4	0.7	0.5	0.2	0.2	12	17	7.5
Background angles model:									
Choice of fit function	2.5	< 0.1	0.3	1.1	< 0.1	0.6	12	0.9	1.1
Choice of p_T bins	1.3	0.5	< 0.1	0.4	0.5	1.2	1.5	7.2	1.0
Choice of mass interval	0.4	0.1	0.1	0.3	0.3	1.3	4.4	7.4	2.3
Dedicated backgrounds:									
B_d^0	2.3	1.1	< 0.1	0.2	3.0	1.5	10	23	2.1
Λ_b	1.6	0.3	0.2	0.5	1.2	1.8	14	30	0.8
Fit model:									
Time res. sig frac	1.4	1.1	0.5	0.5	0.6	0.8	12	30	0.4
Time res. p_T bins	0.7	0.5	0.8	0.1	0.1	0.1	2.2	14	0.7
S-wave phase	0.2	< 0.1	< 0.1	0.3	< 0.1	0.3	11	21	8.4
Fit bias	4.1	1.7	0.9	1.4	< 0.1	1.5	19	0.9	7.0
Total	20	2.5	1.6	2.3	3.5	4.5	50	79	18

Table 2: This table shows the values of the main physics parameters obtained by the likelihood fit after combination with the Run 1 measurement results along with their statistical and systematic uncertainties [2].

Parameter	Value	Stat.	Syst.
ϕ_s [rad]	−0.087	0.037	0.019
$\Delta\Gamma_s$ [ps^{-1}]	0.0640	0.0042	0.0024
Γ_s [ps^{-1}]	0.6698	0.0014	0.0015
$\lvert A_{\lvert\lvert}\rvert^2$	0.2221	0.0018	0.0022
$\lvert A_0\rvert^2$	0.5149	0.0012	0.0031
$\lvert A_S\rvert^2$	0.0343	0.0032	0.0044
$\delta_\perp$ [rad]	3.21	0.10	0.05
$\delta_{\lvert\lvert}$ [rad]	3.36	0.05	0.08
$\delta_\perp - \delta_S$ [rad]	−0.24	0.05	0.02

4.3 Results

The results of the physics parameters obtained from the fit on Run 2 events are combined with the Run 1 measurement, taking into account correlations of systematic effects. The values obtained from this procedure are given in Table 2. Fit projections, including the ratio plots, are shown in Figure 1 for the mass and proper decay time and in Figure 2 for the three transversity angles. The ratio plots show the difference between each data point and the total fit line divided by the statistical and systematic uncertainties summed in quadrature of that point. The deviations in the ratio plots are within 2σ, which demonstrates that the systematic uncertainties are properly evaluated and cover the model deviations. A comparison with other experiments and theoretical predictions can be seen in Figure 3. It demonstrates that the results for ϕ_s is consistent with the Standard Model prediction, while Γ_s shows tension of the order of 3σ.

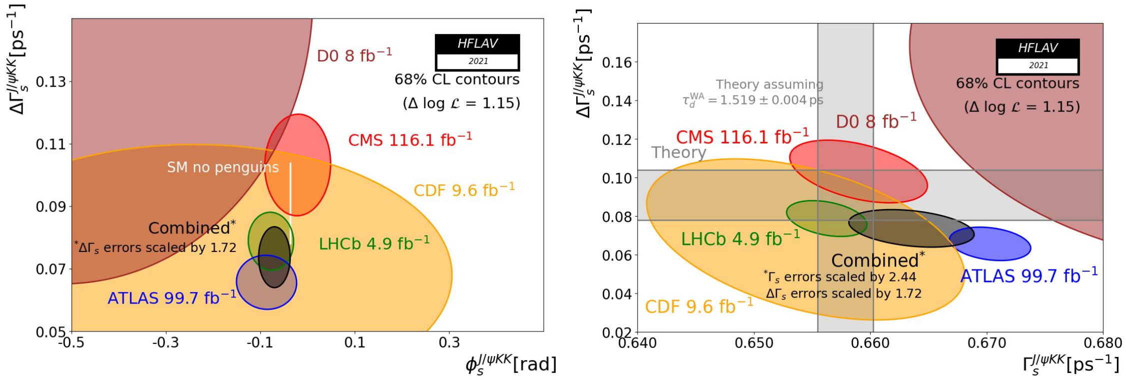

Figure 3: This figure displays the contours in the ϕ_s-$\Delta\Gamma_s$ plane (left) and the Γ_s-$\Delta\Gamma_s$ plane, showing the results of ATLAS and other experiments alongside theoretical predictions. The plots are taken from [4].

5. Summary

This article presents a measurement of the time-dependent CP asymmetry parameters in $B_s^0 \to J/\psi\phi$ decays from a data sample 80.5 fb^{-1} of pp collisions collected with the ATLAS detector during the 13 TeV LHC Run 2. The values from the 13 TeV analysis are consistent with those obtained in the previous ATLAS analysis using 7 TeV and 8 TeV data. The two measurements are statistically combined. The CP-violating phase ϕ_s is measured to be $-0.087 \pm 0.036(\text{stat.}) \pm 0.021(\text{syst.})$, the decay width difference between heavy and light B_s^0 mass eigenstates, $\Delta\Gamma_s = 0.0657 \pm 0.0043(\text{stat.}) \pm 0.0037(\text{syst.})\ \text{ps}^{-1}$, and the average decay width, $\Gamma_s = 0.6703 \pm 0.0014(\text{stat.}) \pm 0.0018(\text{syst.})\ \text{ps}^{-1}$. The measurement of the CP-violating phase ϕ_s is consistent with the Standard Model prediction, and improves on the precision of previous ATLAS measurements, while for the average decay width, Γ_s, the comparison of the 13 TeV result with the current world combined value reveals a tension at the level of 3σ.

References

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