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Measurement of the CP-violating phase ϕ_s in the $B_s^0 \to J/\psi\phi$ decay with the ATLAS detector

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In the presence of New Physics phenomena, sources of CP violation can arise in addition to those predicted by the Standard Model. The $B_s^0 \to J/\psi\phi$ decay can provide a very precise measurement of the CP-violating phase ϕ_s, the decay width Γ_s and the difference of widths between the mass eigenstates $\Delta\Gamma_s$. Results presented here use data of pp collisions at $\sqrt{s}$ = 13 TeV corresponding to 80.5 fb^{-1} of integrated luminosity collected by ATLAS at the Large Hadron Collider in years 2015–2017, and are statistically combined with the previous measurements with 19.2 fb^{-1} data with 7 and 8 TeV energy leading to

$$\begin{aligned}
\phi_s &= -0.087 \pm 0.036 \text{ (stat.)} \pm 0.021 \text{ (syst.)}\\
\Gamma_s &= 0.6703 \pm 0.0014 \text{ (stat.)} \pm 0.0018 \text{ (syst.)}\\
\Delta\Gamma_s &= 0.0657 \pm 0.0043 \text{ (stat.)} \pm 0.0037 \text{ (syst.)}.
\end{aligned}$$

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1. Introduction

CP violation (CPV) occurs in the $B_s^0 \to J/\psi\phi$ decay due to the interference between the direct decay and the decay with $B_s^0 - \bar{B}_s^0$ mixing. Physical quantities involved in the CP violation and mixing include phase ϕ_s and decay widths Γ_L and Γ_H of the light and heavy mass eigenstates. New Physics (NP) phenomena can increase the size of ϕ_s and potentially also decrease the size of $\Delta\Gamma_s = \Gamma_L - \Gamma_H$ [1]. The phase ϕ_s is related to the CKM matrix elements via relation $\phi_s \simeq 2\arg[(V_{ts}V_{tb}^*)/(V_{cs}V_{cb}^*)]$, and can be precisely predicted in the Standard Model (SM). The predicted value is very small with uncertainty at the level of 3% ($\phi_s^{\text{CKMFitter}} = -0.03696^{+0.00072}_{-0.00082}$ rad [2], $\phi_s^{\text{UTfit}} = -0.03700 \pm 0.00104$ rad [3]).

2. Data selection

In total 80.5 fb^{-1} of integrated luminosity of pp collisions were collected by the ATLAS detector [4] in the years 2015–2017 during Run 2. Results are statistically combined with the 19.2 fb^{-1} dataset of Run 1 [5]. Several triggers, 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 were used. Data quality requirements are imposed on the data, notably on the performance of the muon spectrometer (MS), inner detector (ID) and calorimeter systems. Each $B_s^0 \to J/\psi(\mu^+\mu^-)\phi(K^+K^-)$ candidate must contain at least one reconstructed primary vertex, formed from at least four ID tracks, and at least one pair of oppositely charged muon candidates. Dimuon pairs are refitted to a common vertex, requiring $\chi^2/\text{ndof} < 10$ and one of three different m($\mu\mu$) windows around J/ψ mass based on muons pseudorapidity (accounting for varying mass resolution in different parts of the ATLAS detector). For the reconstruction of ϕ meson, two oppositely charged hadron tracks with $p_{\text{T}} > 1$ GeV in the ID are used, applying a mass window $m(KK) \in (1008.5, 1030.5)$ MeV. The secondary vertex is reconstructed from the J/ψ and ϕ candidates with $m(\mu\mu)$ constrained to the average J/ψ mass [6], requiring $m(B_s^0) \in (5150, 5650)$ MeV and $\chi^2/\text{ndof} < 3$. For events with multiple B_s^0 candidates, the one with the smallest χ^2/ndof is selected.

3. Opposite-side tagging

Knowledge of $B_s/\bar{B}_s$ flavour at production significantly increases the sensitivity of the likelihood fit model to ϕ_s. Four types of taggers are used to build per-candidate B_s flavour probability $P(B|Q)$ that is propagated into the likelihood function. Two muon taggers (at two identification criteria working points), electron and b-jet taggers. All are based on the charge of p_{T}-weighted tracks in a ΔR cone around the opposite-side (OS) primary object (μ, e, b-jet) Q_X defined as:

$$Q_X = \frac{\Sigma_i^{N_{tracks}} p_{\text{T}i}^{\kappa} q_i}{\Sigma_i^{N_{tracks}} p_{\text{T}i}^{\kappa}}.$$

Calibration of the tagger proceeds using self-tagged data of $B^\pm \to J/\psi K^\pm$ decays. The tagging performance can be described by the total tagging power and tagging efficiency with values 1.75 ± 0.01 % and 21.23 ± 0.03 %, respectively.

4. Maximum Likelihood Fit

The $B_0 \to J/\psi\phi$ decay is described by nine physics parameters: the CPV phase ϕ_s, decay width and width difference $\Delta\Gamma_s$ and Γ_s, two CP-state amplitudes $|A_0(0)|^2$ and $|A_\parallel(0)|^2$, two strong phases $\delta_\parallel$ and $\delta_\perp$, and S-wave amplitude and phase $|A_S(0)|^2$ and δ_S. The mass difference Δm_s was fixed to the world average value [6] and λ value is taken as unity (no direct CPV). The parameters are extracted using the maximum likelihood fit of the time-dependent correlations of transversity decay angles $\Omega = (\theta_T, \psi_T, \phi_T)$. The fit also uses B_s^0 mass (m_i) for the better signal-background separation, conditional observables: σ_{m_i}, σ_{t_i}, $p_{\mathrm{T}i}$ to properly describe resolution and variables related to the OS tagging. The likelihood is defined as follows, comprising proper decay time efficiency w_i and signal ($\mathcal{F}_s$), combinatorial background ($\mathcal{F}_{bkg}$) and peaking backgrounds ($\mathcal{F}_{B_d^0}$, $\mathcal{F}_{\Lambda_b}$) components:

$$\begin{aligned}
\ln \mathcal{L} = \sum_{i=1}^{N_{events}} \{ & w_i \cdot \ln(f_\mathrm{s} \cdot \mathcal{F}_\mathrm{s}(m_i, t_i, \sigma_m, \sigma_t, \Omega_i, P(B|Q), p_{\mathrm{T}_i}) \\
& + f_\mathrm{s} \cdot f_{B_d^0} \cdot \mathcal{F}_{B_d^0}(m_i, t_i, \sigma_m, \sigma_t, \Omega_i, P(B|Q), p_{\mathrm{T}_i}) \\
& + f_\mathrm{s} \cdot f_{\Lambda_b} \cdot \mathcal{F}_{\Lambda_b}(m_i, t_i, \sigma_m, \sigma_t, \Omega_i, P(B|Q), p_{\mathrm{T}_i}) \\
& + (1 - f_\mathrm{s} \cdot (1 + f_{B_d^0} + f_{\Lambda_b})) \cdot \mathcal{F}_\mathrm{bkg}(m_i, t_i, \sigma_m, \sigma_t, \Omega_i, P(B|Q), p_{\mathrm{T}_i}))\}
\end{aligned}$$

5. Results

Values of the measured physical parameters are shown in Table 1. There are two possible solutions due to convergence of strong phases $\delta_{||}$ and $\delta_\perp$. Fit projections, including ratio plots, are shown in Figure 1 for the mass, the proper decay time and the transversity angles. Below each figure is a ratio plot showing the difference between data and fit divided by the statistical and systematic uncertainties summed in quadrature. The deviations of ratio plots are within 2σ, which confirms that the total uncertainties cover any discrepancy between the data and the fit model. The comparison with other experiments and the predicted values from the SM is shown in Figure 2. The dominant systematic uncertainty on ϕ_s comes from the tagging procedure.

Parameter	Solution (a)			Solution (b)		
	Value	Statistical uncertainty	Systematic uncertainty	Value	Statistical uncertainty	Systematic uncertainty
ϕ_s [rad]	−0.087	0.036	0.021	−0.087	0.036	0.021
$\Delta\Gamma_s$ [ps^{-1}]	0.0657	0.0043	0.0037	0.0657	0.0043	0.0037
Γ_s [ps^{-1}]	0.6703	0.0014	0.0018	0.6704	0.0014	0.0018
$\lvert A_\parallel(0)\rvert^2$	0.2220	0.0017	0.0021	0.2218	0.0017	0.0021
$\lvert A_0(0)\rvert^2$	0.5152	0.0012	0.0034	0.5152	0.0012	0.0034
$\lvert A_S\rvert^2$	0.0343	0.0031	0.0045	0.0348	0.0031	0.0045
$\delta_\perp$ [rad]	3.22	0.10	0.05	3.03	0.10	0.05
$\delta_\parallel$ [rad]	3.36	0.05	0.09	2.95	0.05	0.09
$\delta_\perp - \delta_S$ [rad]	−0.24	0.05	0.04	−0.24	0.05	0.04

Table 1: Values of the physical parameters extracted in the combination of solution (a) and solution (b) of 13 TeV results with those obtained from 7 TeV and 8 TeV data [5].

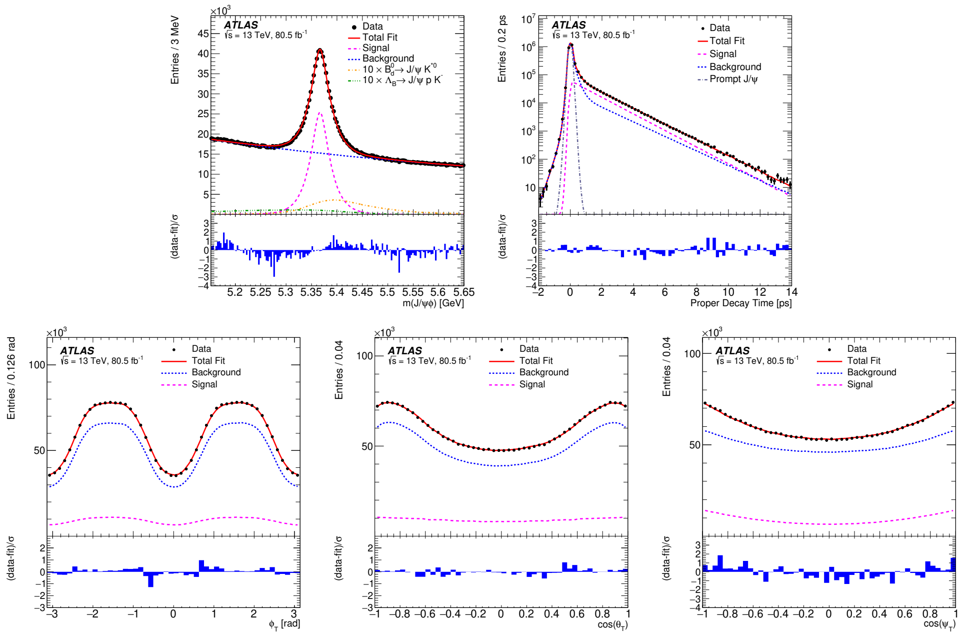

Figure 1: Mass and proper decay time (top), the transversity angles ϕ_T, $\cos(\theta_T)$, and $\cos(\psi_T)$ (bottom) projections of the final fit and its components[5].

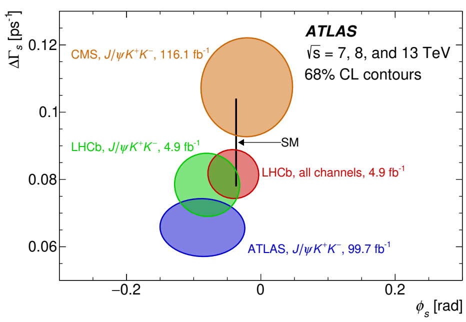

Figure 2: Contours of 68% confidence level in the $\phi_s - \Delta\Gamma_s$ plane [5], including results from CMS (orange) and LHCb (green) using the $B_s \to J/\psi\phi$ decay only and LHCb (red) for all the channels. The SM prediction [7, 8] is shown as a thin black rectangle. In all contours the statistical and systematic uncertainties are combined in quadrature.

6. Summary

Results of the ATLAS measurement with 80.5 fb^{-1} data are statistically combined with the previous results with 19.2 fb^{-1} data. The value of the most sensitive parameter to the New Physics phenomena ϕ_s is presented: $\phi_s = -0.087 \pm 0.036(\text{stat.}) \pm 0.021(\text{syst.})$. Results are generally consistent with the Standard Model prediction and LHCb and CMS measurements, with the exception of $\Delta\Gamma_s$ that shows 3σ tension with respect to the current world combined value.

7. Acknowledgement

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