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Measurement of the weak mixing phase ϕ_s through time-dependent CP violation in $B_s^0 \to J/\psi\phi$ decay in ATLAS

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In the Standard Model of particle physics, CP violation arises due to a single complex phase in the Cabibbo-Kobayashi-Maskawa (CKM) quark mixing matrix. Testing the validity of the CKM mechanism as a source of CP violation is one of the major experimental challenges in particle physics today. Precise measurement of the CKM parameters therefore constrains the Standard Model, and may reveal effects beyond it. Measurement of the time-dependent decay rates of $B_s^0 \to J/\psi\phi$ provides a theoretically clean method for extracting the CP-violating weak mixing phase ϕ_s. The Standard Model predicts ϕ_s to be very small and it is very well constrained, while in many new physics models large ϕ_s values are expected. Small deviations in a measurement of ϕ_s would be hints for the existence of the new particles. The most recent results on the CP-violating mixing phase ϕ_s and several other parameters describing the B_s^0 meson system are presented from ATLAS, using $\sqrt{s} = 13$ TeV proton-proton collision data from the LHC, are presented.

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1. Introduction

ATLAS [1] is a general purpose detector that measures heavy-flavour properties using its inner dectectors, muon spectrometers and electromagnetic calorimeters. Measuring the properties of heavy-flavour particles has been part of the B physics program of the ATLAS experiment since the start of the proton-proton (pp) collisions at LHC in 2010. The analysis presented here [2] introduces a measurement of the $B_s \to J/\psi\phi$ decay parameters using 80.5 fb^{-1} of LHC pp data collected by the ATLAS detector during 2015 – 2017 at a centre-of-mass energy, $\sqrt{s}$, equal to 13 TeV. The analysis closely follows a previous ATLAS measurement [3] that was performed using 19.2 fb^{-1} of data collected at 7 TeV and 8 TeV and introduces more precise models for both signal and backgrounds.

In the presence of New Physics (NP) phenomena, sources of CP violation in b-hadron decays can arise in addition to those predicted by the Standard Model (SM) [4]. In the $B_s \to J/\psi\phi$ decay, CP violation occurs due to interference between a direct decay and a decay with $B_s - \bar{B}_s^0$ mixing. The oscillation frequency of B_s meson mixing is characterised by the mass difference Δm_s of the heavy (B_H) and light (B_L) mass eigenstates. The CP violating phase ϕ_s is defined as the weak phase difference between the $B_s - \bar{B}_s^0$ mixing amplitude and the $b \to c\bar{c}s$ decay amplitude. In the SM the phase ϕ_s is small and is related to Cabibbo–Kobayashi–Maskawa (CKM) quark mixing matrix elements via the relation $\phi_s \simeq -2\beta_s$, with $\beta_s = \arg[-(V_{ts}V_{tb}^*)/(V_{cs}V_{cb}^*)]$; assuming no NP contributions to B_s mixing and decays, a value of $-2\beta_s = -0.0363^{+0.0016}_{-0.0015}$ rad can be predicted by combining beauty and kaon physics observables [5]. While large NP enhancements of the mixing amplitude have been excluded by the precise measurement of the oscillation frequency [6], the NP couplings involved in the mixing may still increase the size of the observed CP violation by enhancing the mixing phase ϕ_s with respect to the SM value.

Other physical quantities involved in $B_s - \bar{B}_s^0$ mixing are the decay width ($\Gamma_s = (\Gamma_\mathrm{L} + \Gamma_\mathrm{H})/2$) and the width difference ($\Delta\Gamma_s = \Gamma_\mathrm{L} - \Gamma_\mathrm{H}$), where Γ_L and Γ_H are the decay widths of the light and heavy mass eigenstates, respectively. A potential NP enhancement of ϕ_s would also decrease the size of $\Delta\Gamma_s$, though it is not expected to be affected as significantly as ϕ_s [7].

2. ATLAS detector and Monte Carlo simulation

The ATLAS detector consists of three main components: an inner detector (ID) tracking system immersed in a 2 T axial magnetic field, electromagnetic and hadronic calorimeters, and a muon spectrometer (MS). The inner tracking detector covers the pseudorapidity range $|\eta| < 2.5$, and consists of silicon pixel, silicon micro-strip, and transition radiation tracking detectors. The ID is surrounded by a high-granularity liquid-argon (LAr) sampling electromagnetic calorimeter. A steel/scintillator tile calorimeter provides hadronic coverage in the central rapidity range. The end-cap and forward regions are equipped with LAr calorimeters for electromagnetic and hadronic measurements. The MS surrounds the calorimeters and provides a system of tracking chambers and detectors for triggering. A full description can be found in Refs. [1, 8, 9].

The muon and tracking systems are of particular importance in the reconstruction of $B_s$meson candidates. Only data collected when both these systems were operating correctly and when the LHC beams were declared to be stable are used in the analysis. The data were collected during

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periods with different instantaneous luminosity; therefore several triggers were used in the analysis. All of them 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.

3. Reconstruction and candidate selection

The reconstruction and candidate selection for the decay $B_s \to J/\psi(\mu^+\mu^-)\phi(K^+K^-)$ proceeds as follows; each event 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 that are reconstructed using information from the MS and the ID.

A maximum-likelihood fit is used to extract the J/ψ mass and the corresponding mass resolution for these three subsets, and in each case the signal region is defined symmetrically around the fitted mass and so as to retain 99.7% of the J/ψ candidates identified in the fits.

The candidates for the decay $\phi \to K^+K^-$ are reconstructed from all pairs of oppositely charged tracks with $p_{\mathrm{T}} > 1$ GeV and $|\eta| < 2.5$ that are not identified as muons. Candidate events for $B_s \to J/\psi(\mu^+\mu^-)\phi(K^+K^-)$ 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. A quadruplet of tracks is accepted for further analysis if the vertex fit has a χ^2/n.d.f. < 3. For the $\phi \to K^+K^-$ candidate the invariant mass of the track pairs (using a kaon mass hypothesis) must fall within the interval 1.0085 GeV $< m(K^+K^-) <$ 1.0305 GeV. The interval, chosen using Monte Carlo (MC) simulation, is selected to retain 98% of true $\phi \to K^+K^-$ decays. The B_s candidate with the lowest χ^2/n.d.f. is selected in cases where more than one candidate passes all selections. In total 3 210 429 B_s candidates are collected within the mass range of 5.150–5.650 GeV.

The mean number of interactions per crossing is 30, necessitating a choice of the best candidate for the primary vertex at which the B_s meson is produced. The variable used is the three-dimensional impact parameter a_0, which is calculated as the minimum distance between the line extrapolated from the reconstructed B_s meson vertex in the direction of the B_s momentum, and each primary vertex candidate. The chosen primary vertex is the one with the smallest a_0.

For each B_s 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 meson candidate and m_B denotes the mass of the B_s meson. The transverse decay length, L_{xy}, is the displacement in the transverse plane of the B_s meson decay vertex with respect to the primary vertex, projected onto the direction of the B_s transverse momentum. The primary vertex position is recalculated after removing any tracks used in the B_s meson candidate to avoid biasing L_{xy}.

4. Maximum likelihood fit

An unbinned maximum-likelihood fit is performed on the selected events to extract the parameter values of the $B_s \to J/\psi(\mu^+\mu^-)\phi(K^+K^-)$ decay. 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, and the transversity angles Ω of each $B_s \to J/\psi\phi$ decay candidate. The measured proper decay time uncertainty σ_t is calculated from the covariance matrix associated with the vertex fit of each candidate event. The transversity angles $\Omega = (\theta_{\mathrm{T}}, \psi_{\mathrm{T}}, \phi_{\mathrm{T}})$ are defined in Ref. [2]. The likelihood is independent of the K^+K^- mass distribution. The likelihood function is defined as a combination of the signal and background probability density functions as:

$$\begin{aligned}\ln \mathscr{L} = \sum_{i=1}^{N} w_i \cdot \ln[f_{\mathrm{s}} \cdot \mathscr{F}_{\mathrm{s}}(m_i, t_i, \sigma_{m_i}, \sigma_{t_i}, \Omega_i, P_i(B|Q_x), p_{\mathrm{T}_i}) + f_{\mathrm{s}} \cdot f_{B^0} \cdot \mathscr{F}_{B^0}(m_i, t_i, \sigma_{m_i}, \sigma_{t_i}, \Omega_i, P_i(B|Q_x), p_{\mathrm{T}_i})\\ + f_{\mathrm{s}} \cdot f_{\Lambda_b} \cdot \mathscr{F}_{\Lambda_b}(m_i, t_i, \sigma_{m_i}, \sigma_{t_i}, \Omega_i, P_i(B|Q_x), p_{\mathrm{T}_i})\\ + (1 - f_{\mathrm{s}} \cdot (1 + f_{B^0} + f_{\Lambda_b}))\mathscr{F}_{\mathrm{bkg}}(m_i, t_i, \sigma_{m_i}, \sigma_{t_i}, \Omega_i, P_i(B|Q_x), p_{\mathrm{T}_i})],\end{aligned}$$

where N is the number of selected candidates, w_i is a weighting factor to account for the trigger efficiency, and $\mathscr{F}_{\mathrm{s}}$, $\mathscr{F}_{B^0}$, $\mathscr{F}_{\Lambda_b}$ and $\mathscr{F}_{\mathrm{bkg}}$ are the probability density functions (PDFs) modelling the signal, B^0 background, Λ_b background, and the other background distributions, 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 candidates calculated relative to the number of signal events. These background fractions are fixed to their expectation from the MC simulation and varied as part of the systematic uncertainties. The mass m_i, the proper decay time t_i and the decay angles Ω_i are the values measured from the data for each event i. Further details can be found in Ref. [2].

5. Results

The full simultaneous unbinned maximum-likelihood fit contains nine physical parameters: $\Delta\Gamma_s$, ϕ_s, Γ_s, $|A_0(0)|^2$, $|A_{\|}(0)|^2$, $\delta_{\|}$, $\delta_{\perp}$, $|A_S(0)|^2$ and δ_S. The other parameters in the likelihood function are the B_s signal fraction f_s, parameters describing the $J/\psi\phi$ mass distribution, parameters describing the decay time plus angular distributions of background events, parameters used to describe the estimated decay time uncertainty distributions for signal and background events, and scale factors between the estimated decay time uncertainties and their true uncertainties. In addition there are also nuisance parameters describing the background and acceptance functions that are fixed at the time of the fit.

Multiplying the total number of events supplied to the fit with the extracted signal fraction and its statistical uncertainty provides an estimate for the total number of B_s meson candidates of $477\,240 \pm 760$. The results and correlations of the physics parameters obtained from the fit are given in Table 1. Fit projections of the mass and proper decay time are given in Figure 1.

The values from the 13 TeV analysis are consistent with those obtained in the previous analysis using 7 TeV and 8 TeV ATLAS data [3].

6. Conclusion

The new ATLAS result is consistent with previous LHC Run 1 results from LHCb [10] and CMS [11], using the $B_s \to J/\psi\phi$ decay, and with the SM, as shown in Figure 2. The ATLAS result presented in this paper gives the most stringent measurement on parameters ϕ_s, $\Delta\Gamma_s$, Γ_s and the helicity functions parameters of the $B_s \to J/\psi\phi$ decay from a single measurement.

Parameter	Value	Statistical uncertainty	Systematic uncertainty
ϕ_s[rad]	-0.096	0.036	0.024
$\Delta\Gamma_s$[ps^{-1}]	0.070	0.004	0.003
Γ_s[ps^{-1}]	0.668	0.001	0.002
$\lvert A_{\parallel}(0)\rvert^2$	0.221	0.002	0.003
$\lvert A_0(0)\rvert^2$	0.518	0.001	0.004
$\lvert A_S\rvert^2$	0.041	0.003	0.006
$\delta_{\perp}$ [rad]	3.191	0.105	0.067
$\delta_{\parallel}$ [rad]	3.323	0.062	0.088
$\delta_{\perp} - \delta_S$ [rad]	-0.229	0.041	0.019

Table 1: Values of the physical parameters extracted in the combination of 13 TeV results with those obtained from 7 TeV and 8 TeV data.

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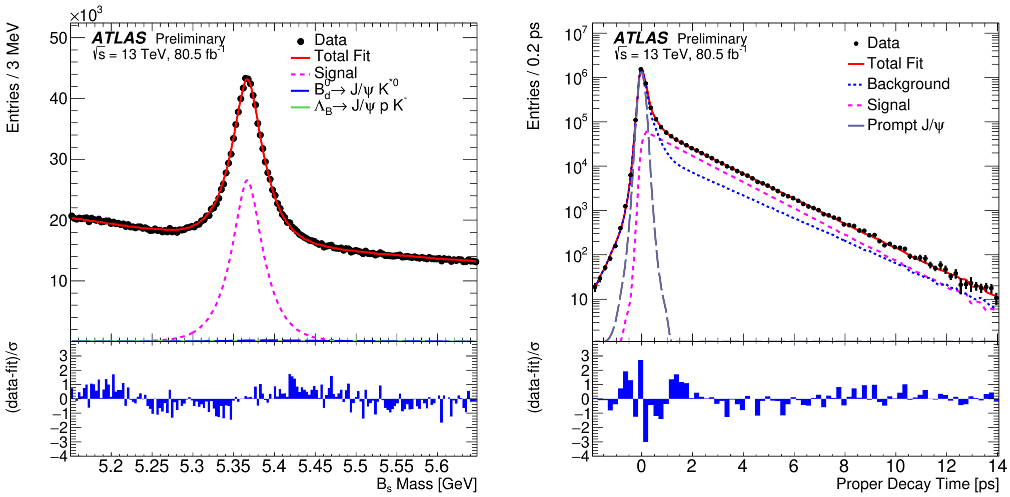

Figure 1: (Left) Mass fit projection for the $B_s \to J/\psi\phi$ sample, from Ref. [2]. The red line shows the total fit, the dashed magenta line shows the $B_s \to J/\psi\phi$ signal component, the blue line shows the $B_d \to J/\psi K^{0*}$ component, while the green line shows the contribution from $\Lambda_b \to J/\psi p K^-$ events. (Right) Proper decay time fit projection for the $B_s \to J/\psi\phi$ sample, from Ref. [2]. The red line shows the total fit while the magenta dashed line shows the total signal.

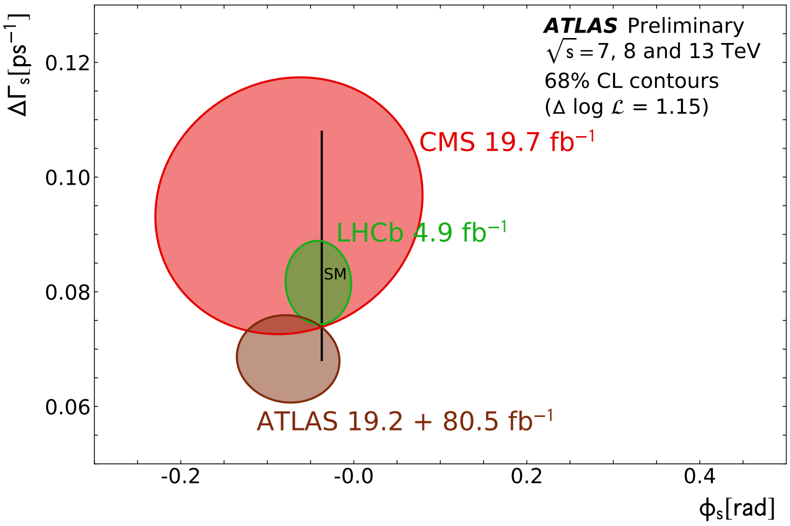

Figure 2: Likelihood 68% confidence level contours in the $\phi_s - \Delta\Gamma_s$ plane, including results from LHCb [10] (green) and CMS [11] (red) using 7 TeV and 8 TeV data. The brown contour shows the ATLAS [2] result for $\sqrt{s} = 13$ TeV combined with the results for $\sqrt{s} = 7$ TeV and 8 TeV. In all contours the statistical and systematic uncertainties are combined in quadrature. Figure from Ref. [2].

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