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Measurements of CP violation and lifetime properties of B mesons at ATLAS

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The ATLAS experiment at the Large Hadron Collider has performed precise measurements of mixing and CP violation in neutral B mesons. The Standard Model predicts the CP-violating mixing phase ϕ_s, to be very small and its SM value is very well constrained, while any measured deviations from SM value can indicate New Physics not described by the SM. The future analyses will profit considerably from the increased statistics expected from the 3000 fb^{-1} of HL-LHC data as well as detector improvements providing better mass and proper decay time resolutions.

This contribution focuses on the latest results from ATLAS, including measurements of CP violation in the $B_s^0 \to J/\psi\phi$ channel, and the prospects of future analyses of the same channel.

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1. Introduction

The ATLAS experiment [1] at the Large Hadron Collider (LHC) [2] has a program dedicated to B physics that includes the search for New Physics (NP) in the measurement of CP violation in the $B_s^0 \to J/\psi\phi$ channel.

The sensitivity to NP is measured via the CP-violating phase ϕ_s that is defined as the weak phase difference between the $b \to c\bar{c}s$ amplitude and the $B_s^0 - \overline{B}_s^0$ mixing amplitude. The SM prediction assuming no NP contribution is $\phi_s = -0.03696^{+0.00072}_{-0.00082}$ rad [3]. Other parameters like the decay width Γ_s and the width difference $\Delta\Gamma_s$ are not highly sensitive to NP, but are important for tests of theoretical predictions ($\Delta\Gamma_s = 0.091 \pm 0.013\,\text{ps}^{-1}$ [4]) and provide the information about the B_s^0 lifetime. The ATLAS Run1 results are consistent with the SM prediction, however the additional are needed to exclude the BSM contribution: $\phi_s = -0.090 \pm 0.078(\text{stat.}) \pm 0.041(\text{syst.})$ rad and $\Delta\Gamma_s = 0.085 \pm 0.011(\text{stat.}) \pm 0.007(\text{syst.})\,\text{ps}^{-1}$ [5].

The time-dependent angular analysis provides an increased precision of determina- tion of these parameters using 80.5 fb^{-1} of LHC proton-proton data collected by the ATLAS detector during 2015–2017 at a centre-of-mass energy $\sqrt{s} = 13$ TeV [6].

2. Data Selection

The reconstructed B_s^0 candidate needs to fulfil several conditions. Each event must pass the trigger requirement based on the $J/\psi \to \mu^+\mu^-$ decay identification with muon transverse momentum thresholds of either 4 or 6 GeV. Each event must contain at least one reconstructed primary vertex for four tracks - two oppositely charged muons and two oppositely charged kaons K^+, K^-. The muon pair is refitted to a common vertex and it must fulfil the fit quality $\chi^2/\text{n.d.o.f.} < 10$. The ATLAS detector has a different mass resolution as a function of the pseudorapidity coordinate. For this reason, the refitted $J/\psi(\mu^+\mu^-)$ candidates are selected in the mass windows according to the pseudorapidity of muons:

- both muons have $|\eta| < 1.05$: $m_{J/\psi} \in (2.959 - 3.229)$ GeV
- both muons have $1.05 < |\eta| < 2.5$: $m_{J/\psi} \in (2.913 - 3.273)$ GeV
- one muon has $|\eta| < 1.05$ and the second has $1.05 < |\eta| < 2.5$: $m_{J/\psi} \in (2.959 - 3.229)$ GeV.

The $\phi \to K^+K^-$ are reconstructed from tracks not identified as muons and fulfil kinematic conditions $p_T > 1$ GeV, $|\eta| < 2.5$ and the invariant mass must lie in a range of $(1.0085 - 1.0305)$ GeV. Then, the B_s^0 candidates are fitted using all combinations of the J/ψ and ϕ candidates with a common vertex. The B_s^0 candidate is accepted and used in the analysis, if the B_s^0 vertex fit quality is $\chi^2/\text{n.d.o.f.} < 3$ and the transverse momentum of B_s^0 is greater than 10 GeV. In total, 2 977 526 B_s^0 candidates are collected within the mass range of $(5.15 - 5.65)$ GeV in Run2. No lifetime cut is used in order to allow precise determination of the properties of the background events.

3. Time-dependent Angular Analysis

$B_s^0 \to J/\psi\phi$ is a decay of pseudoscalar into a pair of vectors where the final state is an admixture of CP-odd (L= 1) and CP-even (L= 0, 2) states. The contribution of the CP-odd non-resonant S-wave $B_s^0 \to J/\psi K^+K^-$ is also included in the model. The differential decay rate depends on amplitudes A_0, $A_\perp$, $A_\parallel$, A_S (and their interferences) and angles ψ_T, ϕ_T, θ_T (the full description of the differential decay rate can be found in Ref. [6]).

To extract the physical parameters of interest, ϕ_s, $\Delta\Gamma_s$, the average decay width Γ_s and the CP-state amplitudes with their phases, an unbinned maximum likelihood (ML) fit in five dimensions (mass m, lifetime t and angles ψ_T, ϕ_T, θ_T). The likelihood function is a combination of signal and background probability density functions,

$$L = \sum_{i=1}^{N} w_i \ln \Bigg[f_s F_s \left(m_i, t_i, \sigma_{t_i}, \Omega_i, p_{\mathrm{T}_i}, P(B|Q)\right) + f_s f_{B^0} F_{B^0} \left(m_i, t_i, \sigma_{t_i}, \Omega_i, p_{\mathrm{T}_i}, P(B|Q)\right) \\ + f_s f_{\Lambda_b} F_{\Lambda_b} \left(m_i, t_i, \sigma_{t_i}, \Omega_i, p_{\mathrm{T}_i}, P(B|Q)\right) \\ + \left(1 - f_s(1 + f_{B^0} + f_{\Lambda_b})\right) F_{bkg} \left(m_i, t_i, \sigma_{t_i}, \Omega_i, p_{\mathrm{T}_i}, P(B|Q)\right) \Bigg], \tag{1}$$

where N is the number of events, w_i is the weight of each event, f_s is the signal fraction, f_{B^0} and f_{Λ_b} are the fraction of B_d and Λ_b wrongly identified as the B_s^0 candidate (these fractions are obtained from the Monte Carlo analysis and are set to be constant). The F_s, F_{B^0}, F_{Λ_b} and F_{bkg} are the probability density function (PDF) describing the signal, B_d^0 background, Λ_b background and other background distributions. The PDFs contain per-candidate conditional probabilities to describe the mass and lifetime resolution, candidate p_{T}, tagging probability and tagging method.

4. Opposite Side Tagging

The initial B_s^0 flavour determination is improved by the opposite side flavour tagging (OST). This method uses the reconstructed decay and a lepton or jet coming from the opposite side B-hadron. The $b \to l$ transition can be diluted by the $b \to c \to l$ transition. The separation power of tagging lepton is obtained by considering a weighted sum of the charge of the tracks in a cone around the lepton.

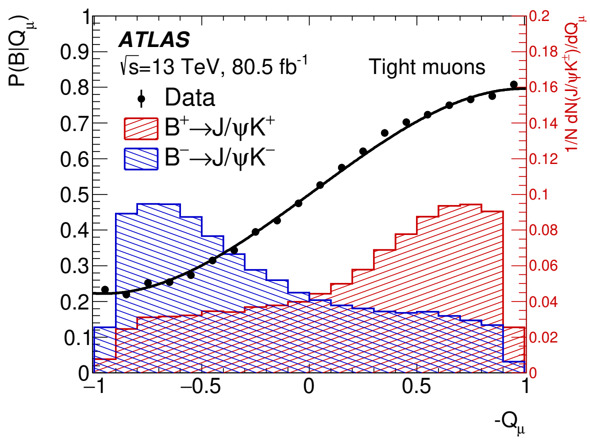

Figure 1: The B^+ tag probability distribution for tight muons(black) and weighted sum of the charge of the tracks in a cone distributions (red and blue) [6].

Parameter	Value	Statistical uncertainty	Systematic uncertainty
ϕ_s [rad]	-0.081	0.041	0.022
$\Delta\Gamma_s$ [ps^{-1}]	0.0607	0.0047	0.0043
Γ_s [ps^{-1}]	0.6687	0.0015	0.0022
$\lvert A_{\parallel}(0)\rvert^2$	0.2213	0.0019	0.0023
$\lvert A_0(0)\rvert^2$	0.5131	0.0013	0.0038
$\lvert A_S(0)\rvert^2$	0.0321	0.0033	0.0046
$\delta_\perp - \delta_S$ [rad]	-0.25	0.05	0.04
Solution (a)			
$\delta_\perp$ [rad]	3.12	0.11	0.06
$\delta_\parallel$ [rad]	3.35	0.05	0.09
Solution (b)			
$\delta_\perp$ [rad]	2.91	0.11	0.06
$\delta_\parallel$ [rad]	2.94	0.05	0.09

Table 1: Fitted values for the physical parameters of interest with their statistical and systematic uncertainties [6]. For variables $\delta_\perp$ and $\delta_\parallel$ the values are given for the two solutions (a) and (b) [6]. For the rest of the variables, the values for the two minima are consistent. The same is true for the statistical and systematic uncertainties of all the variables.

To calibrate the OST, the $B^\pm \to J/\psi K^\pm$ channel is used, where the charge of the kaon determines the flavour of the B meson, providing a self-tagging sample of events. The weighted sum of charge of the tracks in a cone around the lepton and the $B^\pm$ tag probability using the tight muons is shown in Figure 1. The total tag power (figure of merit of the tagger performance) is 1.65 ± 0.01 %. The term $P(B|Q)$ in equation (1) is obtained by applying the $B^\pm$ tag probability on the B_s^0 weighted sum of the charge of the tracks in a cone.

5. Results

The results are presented in Table 1. While for most of the physics parameters, including ϕ_s, $\Delta\Gamma_s$ and Γ_s, the fit determines a single solution with Gaussian behaviour of the projection of the log-likelihood, for the strong-phases $\delta_\parallel$ and $\delta_\perp$, two well-separated local maxima of the likelihood are found (see Figure 2), and shown as Solution (a) and (b) in Table 1. The difference in - $2\Delta\ln(L)$ between the two solutions is 0.03. The two-fold behaviour of the likelihood in the strong phases is the result of an approximate symmetry of the signal PDF and the effect is completely negligible for all other variables, for which the fit values and uncertainty ranges overlap accurately.

The extensive systematic study was performed, further details can be found in Ref. [6]. The major contributions to the total systematic uncertainties are from tagging (function used for fitting the calibration curves, dependency on pile and $B^\pm - B_s^0$ difference), fit bias (stability validated by the pseudo-experiments with default fit results), selection of the best candidate and from background angles model (varying the bin boundaries, invariant mass window and side-band definition).

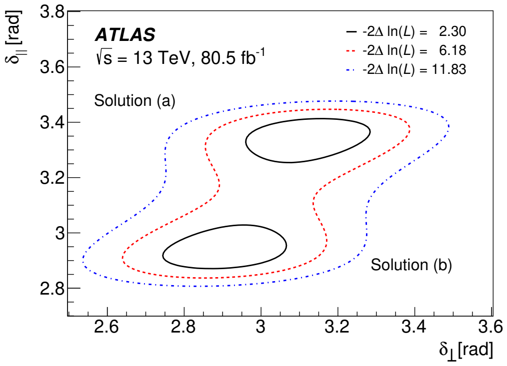

Figure 2: Two-dimensional constraints on the values of $\delta_{||}$ and $\delta_{\perp}$ for Solution (a) and Solution (b) at the level of $-2\Delta\ln(L) = 2.30, 6.18$, and 11.83 respectively. The minimum of the solution (b) is $-2\Delta\ln(L) = 0.03$ higher than the minimum of the Solution (a) [6].

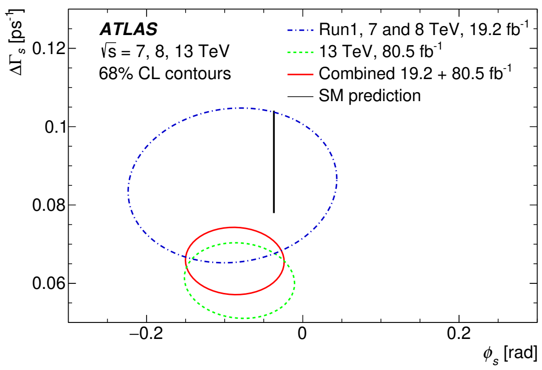

Figure 3: Contours of 68% confidence level (CL) in the $\phi_s - \Delta\Gamma_s$ plane, showing ATLAS results for 7 TeV and 8 TeV data, for 13 TeV data and for 13 TeV data combined with 7 TeV and 8 TeV data [6]. The Standard Model prediction is shown as a black rectangle.

The results using only ATLAS Run2 data (Table 1) were combined with ATLAS Run1 results [5], yielding to

$$\phi_s = -87 \pm 36(\text{stat.}) \pm 21(\text{syst.})\ \text{mrad}$$
$$\Delta\Gamma_s = 65.7 \pm 4.3(\text{stat.}) \pm 3.7(\text{syst.})\ \text{ns}^{-1}$$
$$\Gamma_s = 670.3 \pm 1.4(\text{stat.}) \pm 1.8(\text{syst.})\ \text{ns}^{-1}.$$

Both Run1 and Run2 ATLAS results and their combination are shown in Figure 3.

6. High Luminosity LHC Prospects

The ATLAS detector will provide more data during Run3 at the LHC and Run4 at the High Luminosity LHC (HL-LHC). New trigger strategies are developed to keep low-p_T thresholds with the expected increase of instantaneous luminosity. Measurement of the CP violation using $B_s^0 \to J/\psi\phi$ channel will benefit from the new ATLAS tracking system, fully semiconductor-based tracker (ITk) [7]. Studies of the Insertable B-Layer (IBL) [8] and ITk performance have been performed, showing that the resolution of the reconstruction of the B_s^0 decay time (driving the precision of the CP-violation phase ϕ_s) will be improved (see Figure 4).

To estimate the precision of the ϕ_s and $\Delta\Gamma_s$ measurements, pseudo-MC experiments based on the Run1 $B_s^0 \to J/\psi\phi$ analysis with three triggers scenarios: two muons with $p_T > 10$ GeV ("conservative"), one muon with $p_T > 10$ GeV and another with $p_T > 6$ GeV ("intermediate") as well as two muons with $p_T > 6$ GeV ("high yield") have been considered yielding to B_s^0 statistics to be increased 18, 60 and 100 times w.r.t. the yield obtained in 2012. The number of B_s^0 signal events and the proper time resolution σ_t are scaled with the integrated luminosity while the B_s^0 flavour tagging power is not scaled in the calculation of the ϕ_s and $\Delta\Gamma_s$ uncertainties. Also systematic uncertainties (the likelihood fit model description, B_s^0 flavour tagging calibration, detector acceptance description, detector alignment and peaking background contributions) are

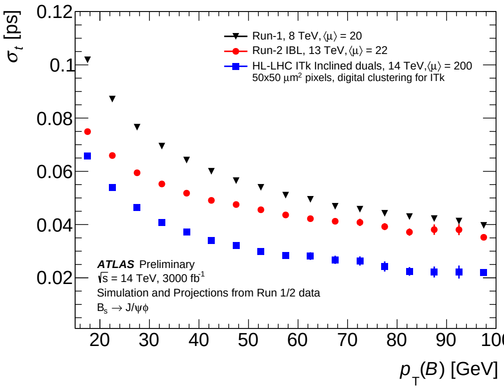

Figure 4: Dependence of the proper decay time resolution of the B_s^0 meson of the signal $B_s^0 \to J/\psi\phi$ decay on B_s^0 p_T [9]. All samples use 6 GeV muon p_T cuts.

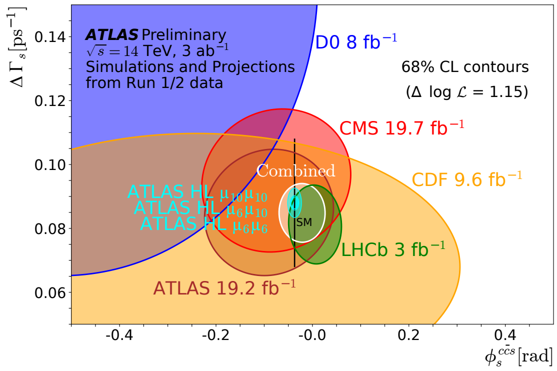

Figure 5: Current experimental summary of the ϕ_s measurements with superimposed ATLAS HL-LHC extrapolations, including both the projected statistical and systematic uncertainties [9].

considered in the study, the expected improvement in the systematic uncertainties should lead to $\delta_{\phi_s}(\text{syst.}) \approx 0.003$ rad and $\delta_{\Delta\Gamma_s}(\text{syst.}) \approx 0.0005$ ps^{-1} for an integrated luminosity of 3000 fb^{-1}, so the future $B_s^0 \to J/\psi\phi$ analysis is therefore expected to be statistically limited. The simulations predict improvement of the ϕ_s and $\Delta\Gamma_s$ statistical uncertainty by a factor ranging between 9× to 20× and 4× to 10×, respectively. The 68% CL contours for the three scenarios (Figure 5) include the combination of statistical and systematic uncertainties.

7. Summary

A measurement of the *CP* asymmetry parameters in $B_s^0 \to J/\psi(\mu^+\mu^-)\phi(K^+K^-)$ decays in 80.5 fb^{-1} data sample of *pp* collisions collected with the ATLAS detector during the 13 TeV LHC run between years 2015 and 2017 was performed. The results shown in Figure 6 are consistent with those obtained in the previous analysis using 7 TeV and 8 TeV ATLAS data [5] and also with the

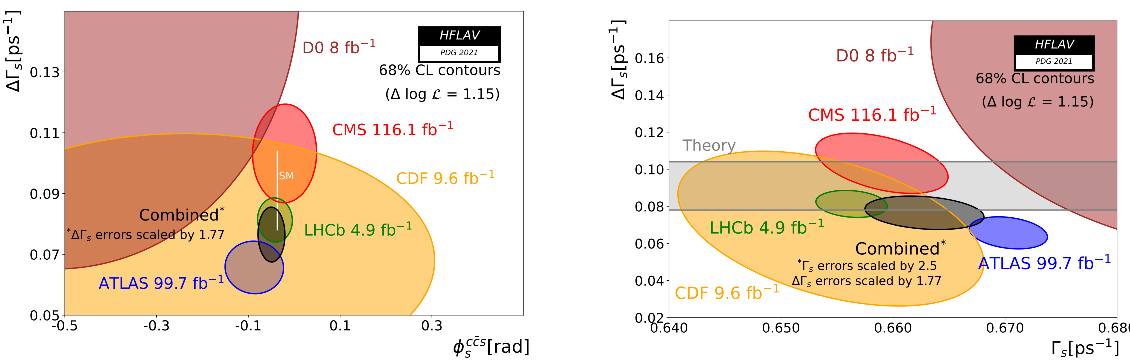

Figure 6: The individual 68% confidence-level contours of ATLAS, CMS, CDF, D0 and LHCb, their combined contour (black solid line and shaded area), as well as the Standard Model predictions (very thin white rectangle) [10].

Standard Model predictions within 2σ, see Figure 6.

Future analyses of the $B_s^0 \to J/\psi\phi$ decay will benefit from the increased statistics during HL-LHC that is expected to be approximately 3000 fb^{-1}. The simulated improvement accounts to the designed ATLAS tracking system (ITk) and to the new trigger strategies. In the most optimistic scenario (using muon trigger thresholds of 6 GeV), the expected statistical uncertainty of ϕ_s is 20 times smaller w.r.t. ATLAS Run1 results, the statistical uncertainty of $\Delta\Gamma_s$ is 10 times smaller.

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