Latest ATLAS results on ϕ_s

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New Physics effects beyond the predictions of the Standard Model may manifest in the *CP*-violation of *b*-hadron decays. This paper presents the latest analysis of $B_s^0 \rightarrow J/\psi\phi$ decay at the ATLAS experiment, measuring the *CP*-violating phase ϕ_s, the decay width Γ_s and the difference of widths between the mass eigenstates $\Delta\Gamma_s$. The latest results are using integrated luminosity of 14.3 fb^{-1} collected by the ATLAS detector from $\sqrt{s} = 8$ TeV *pp* collisions at the Large Hadron Collider, and are statistically combined with the results from 4.9 fb^{-1} of $\sqrt{s} = 7$ TeV data, leading to:

$$\phi_s = -0.090 \pm 0.078 \,(\text{stat.}) \pm 0.041 \,(\text{syst.}) \text{ rad}$$
$$\Delta\Gamma_s = 0.085 \pm 0.011 \,(\text{stat.}) \pm 0.007 \,(\text{syst.}) \text{ ps}^{-1}$$
$$\Gamma_s = 0.675 \pm 0.003 \,(\text{stat.}) \pm 0.003 \,(\text{syst.}) \text{ ps}^{-1}.$$

The results are also presented in the form of likelihood contours in the $\phi_s - \Delta\Gamma_s$ plane. The measurement includes the transversity amplitudes and corresponding strong phases. All the results are compatible with the Standard Model predictions. The paper is concluded with an overview of the detector performance relevant for this particular analysis in current and future phases of the ATLAS experiment and the Large Hadron Collider.

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1. Introduction

Probing the heavy flavour (HF) sector allows for precision tests of the Standard Model (SM) and thus also provides a tool for searches for New Physics (NP). The NP may alter the *CP*-violation (CPV) in *b*-hadron decays. In decay $B_s^0 \to J/\psi\phi$ the *CP*-violation occurs due to interference between direct decays and decays with $B_s^0 - \bar{B}_s^0$ mixing, with an oscillation frequency characterized by the mass difference Δm_s and related decay width difference $\Delta\Gamma_s$ of the heavy and light mass eigenstates. One of the most sensitive parameters to NP contributions is the CPV phase ϕ_s 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. The SM prediction for ϕ_s is small [1], as it is related to the CKM quark mixing matrix elements: $\phi_s \simeq -2\beta_s = -0.0363^{+0.0016}_{-0.0015}$ rad.

The $B_s^0 \to J/\psi\phi$ decay is described by nine physics parameters: the CPV phase ϕ_s, the average decay width Γ_s and the width difference $\Delta\Gamma_s$, *CP*-state amplitudes $|A_\parallel|$ and $|A_0|$, strong phases $\delta_\parallel$ and $\delta_\perp$, and the S-wave amplitude $|A_S|$ and phase δ_S. The parameters are extracted using statistical analysis of the time-dependent correlations of transversity decay angles $\Omega = (\theta_T, \psi_T, \phi_T)$ in the $B_s^0 \to J/\psi(\mu^+\mu^-)\phi(K^+K^-)$ decay.

2. Data and selection

This paper presents the $B_s^0 \to J/\psi\phi$ analysis [2, 3] using Run-1 *pp* collision data collected by the ATLAS experiment [5]. The data were collected by a set of triggers based on identification of $J/\psi \to \mu^+\mu^-$ decay, with the muons transverse momentum (p_T) thresholds of 4 or 6 GeV. The decay candidates of $B_s^0 \to J/\psi(\mu^+\mu^-)\phi(K^+K^-)$ are constructed from track quadruples, requiring all of the tracks to originate at a common vertex (vertex fit $\chi^2/d.o.f. < 3$), and two of the opposite-charge tracks being identified as muons with invariant mass consistent with J/ψ. The $\phi \to K^+K^-$ candidates are required to have invariant mass within 1.0085 GeV $< m(K^+K^-) <$ 1.0305 GeV, accepting only tracks with p_T above 1 GeV. No B_s^0 decay time cut is applied.

3. Flavour tagging

The precision of the measurement (fit) is significantly increased with the knowledge of the B_s^0 meson production flavour (B_s^0 or $\bar{B}_s^0$). Opposite-side *b*-hadron decays are used to tag the flavour of the signal B_s^0. Three methods were developed, linking the *b*-hadron charge flavour with a p_T-weighted charge of tracks in a cone around muon, electron, or a *b*-jet from the *b*-hadron decay. The tagging is calibrated using self-tagged $B^\pm \to J/\psi K^\pm$ decays reconstructed from the real data, with a selection close to the signal B_s^0 decays. The total tagging power reaches $(1.49 \pm 0.02)\%$.

4. Maximum likelihood fit

An unbinned maximum likelihood fit is performed to extract the physics parameters. The observables of the fit include the B_s^0 decay time, its per-candidate resolution σ_t, the three decay angles Ω, the $J/\psi\phi$ invariant mass, the tagging probability and the $p_T(B_s^0)$. The likelihood is composed of four components: the signal, combinatorial background and two peaking backgrounds originating from the $B_d^0 \to J/\psi K^{*0}$ and $\Lambda_b^0 \to J/\psi\Lambda(Kp)$ decays. In addition, it includes a Monte Carlo

Par	8 TeV data			7 TeV data			Run1 combined		
	Value	Stat	Syst	Value	Stat	Syst	Value	Stat	Syst
ϕ_s[rad]	−0.110	0.082	0.042	0.12	0.25	0.05	−0.090	0.078	0.041
$\Delta\Gamma_s$[ps^{-1}]	0.101	0.013	0.007	0.053	0.021	0.010	0.085	0.011	0.007
Γ_s[ps^{-1}]	0.676	0.004	0.004	0.677	0.007	0.004	0.675	0.003	0.003
$|A_\parallel(0)|^2$	0.230	0.005	0.006	0.220	0.008	0.009	0.227	0.004	0.006
$|A_0(0)|^2$	0.520	0.004	0.007	0.529	0.006	0.012	0.522	0.003	0.007
$|A_S|^2$	0.097	0.008	0.022	0.024	0.014	0.028	0.072	0.007	0.018
$\delta_\perp$ [rad]	4.50	0.45	0.30	3.89	0.47	0.11	4.15	0.32	0.16
$\delta_\parallel$ [rad]	3.15	0.10	0.05	[3.04, 3.23]		0.09	3.15	0.10	0.05
$\delta_\perp - \delta_S$ [rad]	−0.08	0.03	0.01	[3.02, 3.25]		0.04	−0.08	0.03	0.01

Table 1: Current measurement using data from 8 TeV *pp* collisions, the previous measurement using data taken at centre of mass energy of 7 TeV, and the values for the parameters of the two measurements, statistically combined.

(MC) based weighting factor accounting for decay time trigger efficiency. The signal probability density functions (PDFs) include the angular detector acceptance taken from MC simulations. The combinatorial background PDFs are determined from sidebands, with the angular part fixed to sidebands pre-fit. The PDFs describing the peaking B_d^0 and Λ_b^0 decays are determined from MC simulations.

5. Results

The likelihood fit leads to an extraction of 74900 ± 400 signal candidates. The results of the fit are summarized in Table 1, presenting the main physics parameters describing the signal B_s^0 decay. The Figure 1 shows the likelihood contours in the two potentially most sensitive physics parameters, ϕ_s and $\Delta\Gamma_s$, to NP contributions. The results are consistent with SM.

The systematic uncertainties, not accounted for in the likelihood fit, arises from the following sources: the flavour-tagging calibration, the detector acceptance determination, the residual misalignment of the Inner Detector, the determination of the trigger lifetime bias, the fixation of the background angles shapes, the uncertainties in modeling the peaking B_d^0 and Λ_b^0 backgrounds, the likelihood fit model variations and finally from the intrinsic bias of the default fit model.

6. Future prospects

The $B_s^0 \to J/\psi\phi$ analysis will be updated with the new data from the current run and future upgrades of the ATLAS experiment: Runs 2 and 3 at the LHC and Runs ≥ 4 at the High-Luminosity LHC (HL-LHC) [6]. In order to cope with increased instantaneous luminosity and to keep low p_T thresholds, new trigger strategies are developed. These include Level 1 topological triggers [7], allowing for rough selections based on opening angle, invariant mass etc. of objects already at the hardware trigger level (L1). The second improvement is the Fast hardware Tracker (FTK) [8], implemented as an intermediate step between the L1 and next software-based trigger levels. The FTK will allow for fast preselection based on full reconstruction of the *b*-hadron decays.

An important improvement impacting the $B_s^0 \to J/\psi\phi$ analysis is the upgrade of the tracking system: compared to Run-1, the current tracker includes in addition the Insertable B-layer
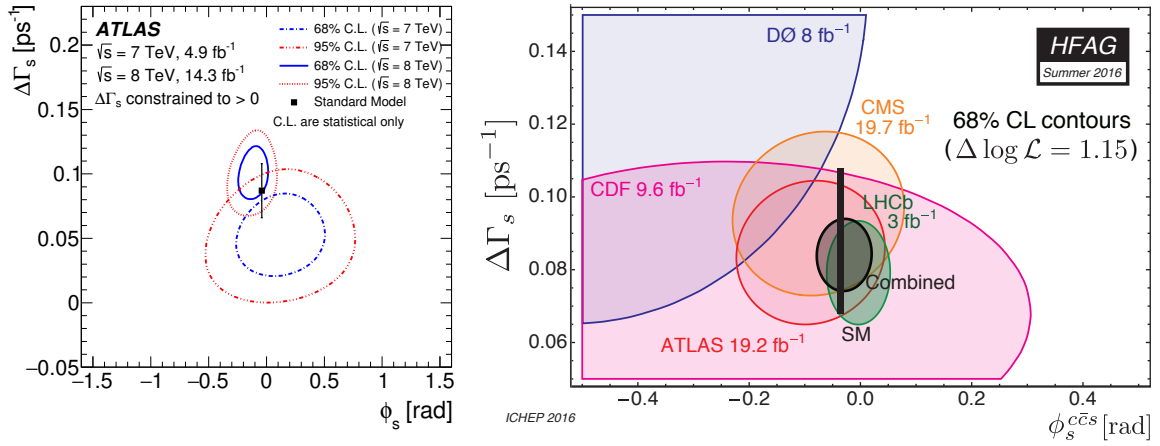
Figure 1: Likelihood contours in the $\phi_s - \Delta\Gamma_s$ plane for individual results from 7 TeV and 8 TeV data (left). The blue line shows the 68% likelihood contour, while the red dotted line shows the 95% likelihood contour (statistical errors only). The SM prediction is taken from [1], at this scale the uncertainty on ϕ_s is not visible on the figure. The statistical combination of the two ATLAS results is shown on the right figure, together with the 68% likelihood contours from the D0, CDF, CMS and LHCb measurements. The right figure, taken from Ref. [4], also presents the combined result of all the experiments.
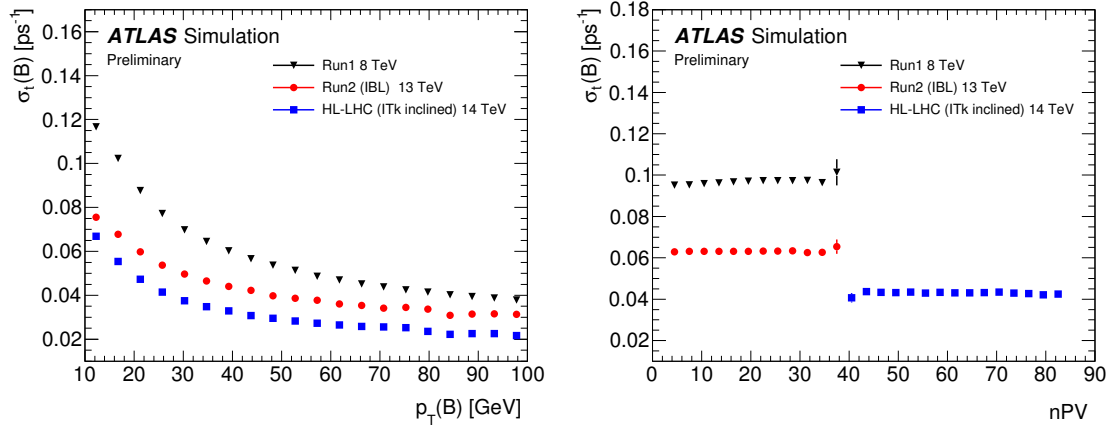

Figure 2: The B_s^0 proper decay time resolution σ_t as a function of the transverse momentum p_T of the B_s^0 meson (left) and the number of reconstructed primary vertices (right), shown for three detector layouts and pp collision conditions: the ATLAS detector layout and pile-up conditions of 2012 (Run-1, black), the ATLAS detector with the additional pixel layer (IBL) and with the pile-up conditions of 2015 (Run-2, red), and the upgraded ATLAS detector with the all-silicon ITk tracker (inclined layout) and with the pile-up of $\langle\mu\rangle = 200$ (HL-LHC, blue). The proper decay time uncertainty is extracted for $B_s^0 \rightarrow J/\psi(\mu^+\mu^-)\phi(K^+K^-)$ decay candidates from simulated events, and is calculated per-candidate by propagating the uncertainties in track and primary vertex parameters as well as the uncertainties from the B_s^0 candidate decay vertex fit. The vertical axis gives the average value of the per-candidate decay time uncertainties for the B_s^0 candidates within the p_T bin. The p_T thresholds on the tracks are 5.5 GeV for the muon candidates and 1 GeV for the kaon candidates. The right figure demonstrates the stability of the decay time resolution at the high pile-up environment expected at HL-LHC.

(IBL) [9]. Before the HL-LHC starts operating, the ATLAS tracking system will be replaced by a fully semiconductor-based tracker (ITk) [10]. Studies of the IBL and ITk performance have been performed [11], showing that the resolution of the reconstruction of the B_s^0 decay time, a key parameter driving the precision of the ϕ_s measurement, improves as illustrated on Figures 2.

7. Summary

An analysis of the $B_s^0 \to J/\psi\phi$ decay has been performed, extracting the *CP*-violating asymmetry parameters in that decay. The measurement uses 14.3 fb^{-1} of $\sqrt{s} = 8$ TeV *pp* collision data sample collected at the ATLAS experiment at the LHC, and the results are statistically combined with the previous analysis using 4.9 fb^{-1} of 7 TeV collision data. The measured values of the *CP*-violating asymmetry parameters are consistent with the Standard Model prediction. The analysis will continue at $\sqrt{s} = (13 - 14)$ TeV centre of mass energy *pp* collisions, while upgrades and in the tracking and muons systems as well as new trigger strategies will improve precision and will help to cope with the high-luminosity environment.

8. Acknowledgement

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