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CP violation with the ATLAS and CMS experiments

PoS(LHCP2021)052

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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 and CMS, using $\sqrt{s}$ = 13 TeV proton-proton collision data from the LHC, are presented.

The Ninth Annual Conference on Large Hadron Collider Physics - LHCP2021
7-12 June 2021
Online

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1. Introduction

ATLAS [1] and CMS [2] are general purpose detectors that measure heavy-flavour properties using their inner detectors, muon spectrometers and electromagnetic calorimeters. Measuring the properties of heavy-flavour particles has been part of the B physics program of the ATLAS and CMS experiments since the start of the proton-proton (pp) collisions at the LHC in 2010. The ATLAS analysis presented here [3] 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, $\sqrt{s}$ = 13. The CMS analysis presented here [4] shows a measurement of the same decay using 96.4 fb^{-1} of *pp* data collected by the CMS detector during 2017 – 2018 at a centre-of-mass energy, $\sqrt{s}$ = 13.

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) [5]. 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 ($B_{\rm H}$) and light ($B_{\rm L}$) 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 [6]. While large NP enhancements of the mixing amplitude have been excluded by the precise measurement of the oscillation frequency [7], 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 ($\Gamma_s = (\Gamma_{\rm L} + \Gamma_{\rm H})/2$) and the width difference ($\Delta\Gamma_s = \Gamma_{\rm L} - \Gamma_{\rm H}$), where $\Gamma_{\rm L}$ and $\Gamma_{\rm H}$ 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 [8].

2. Flavour Tagging

Opposite side tagging is used to infer the initial flavour of the B meson by producing a probability of whether it is a particle or anti-particle. ATLAS uses 4 methods selecting the one with the most power available in each event, "Tight Muons", Electron, "Low-p_T Muon" and Jet. The effeciency, dilution and power of these can be seen in Table 1 (left) with the CMS muon tagging details separated down by data sample in Table 1 (right).

3. 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

Tag method	Signal efficiency [%]	Background efficiency [%]
Tight muon	4.06 ± 0.06	3.21 ± 0.01
Electron	1.86 ± 0.04	1.48 ± 0.01
Low-p_T muon	2.95 ± 0.05	2.70 ± 0.01
Jet	12.1 ± 0.1	9.41 ± 0.02
Untagged	79.1 ± 0.3	83.20 ± 0.05

Data sample	ε_{tag} (%)	ω_{tag} (%)	P_{tag} (%)
2017	45.7 ± 0.1	27.1 ± 0.1	9.6 ± 0.1
2018	50.9 ± 0.1	27.3 ± 0.1	10.5 ± 0.1

Table 1: A Table showing the tagging methods used in the ATLAS analysis [3] (left). A Table showing the tagging power of the samples used in the CMS analysis [4] (right).

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 $\Omega = (\theta_T, \psi_T, \phi_T)$ are defined in Ref. [3]. In both analysis the likelihood was taken as independent of the invariant mass of K^+K^- pair.

4. Results

The full simultaneous unbinned maximum-likelihood fit contains nine physical parameters: $\Delta\Gamma_s$, ϕ_s, Γ_s, $|A_0(0)|^2$, $|A_{\parallel}(0)|^2$, $\delta_{||}$, $\delta_{\perp}$, $|A_S(0)|^2$ 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.

The function finds two minima in the ATLAS data sample, these minima show identical values for the primary physical quantities ϕ_s, $\Delta\Gamma_s$, Γ_s and helicity amplitudes, while different values for strong phases $\delta_{||}$ and $\delta_{\perp}$, both results are presented in Table 2 (left). The CMS results are also presented in Table 2 (right).

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
$\|A_{\parallel}(0)\|^2$	0.2213	0.0019	0.0023
$\|A_0(0)\|^2$	0.5131	0.0013	0.0038
$\|A_S(0)\|^2$	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

Parameter	Fit value	Stat. uncer.	Syst. uncer.
ϕ_s [mrad]	−11	± 50	± 10
$\Delta\Gamma_s$ [ps^{-1}]	0.114	± 0.014	± 0.007
Δm_s [$\hbar$ ps^{-1}]	17.51	$^{+0.10}_{-0.09}$	± 0.03
$\|\lambda\|$	0.972	± 0.026	± 0.008
Γ_s [ps^{-1}]	0.6531	± 0.0042	± 0.0024
$\|A_0\|^2$	0.5350	± 0.0047	± 0.0048
$\|A_\perp\|^2$	0.2337	± 0.0063	± 0.0044
$\|A_S\|^2$	0.022	$^{+0.008}_{-0.007}$	± 0.016
$\delta_\parallel$ [rad]	3.18	± 0.12	± 0.03
$\delta_\perp$ [rad]	2.77	± 0.16	± 0.04
$\delta_{S\perp}$ [rad]	0.221	$^{+0.083}_{-0.070}$	± 0.048

Table 2: A Table showing the physical parameters measured in the ATLAS dataset [3] (left). A Table showing the physical parameters measured in the CMS dataset [4]. (Right)

Both experiments performed a statistical combination of their new results with those obtained in Run1 [9, 10] using the BLUE method. This method uses the measured values and uncertainties of the parameters as well as the correlations between them. These can been seen as contours in Fig. 1.

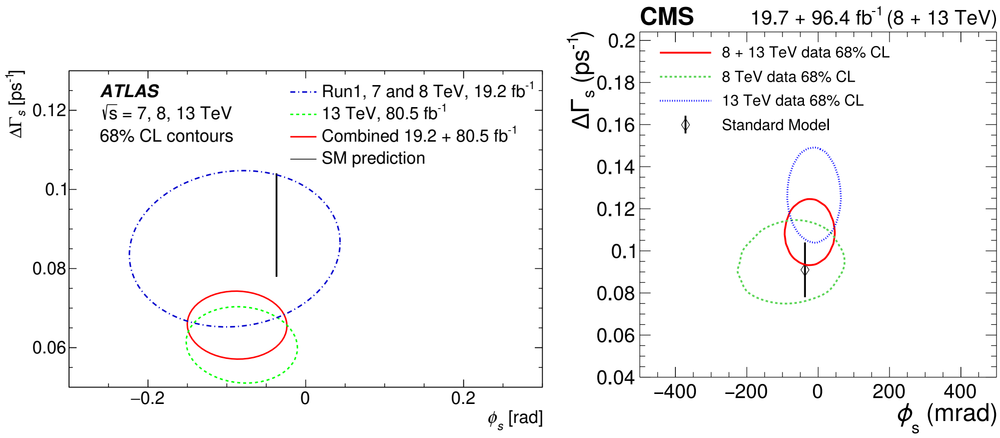

Figure 1: A figure showing the physical parameters when combined with Run 1 using the ATLAS data (left) and the CMS data (right)

The Heavy Flavour Averaging Group has contour plots showing a comparision of results from different analyses [11], these can be seen in Fig. 2. Results on ϕ_s are compatible between ATLAS and CMS and with SM, while there are some tensions in $\Delta\Gamma$ results.

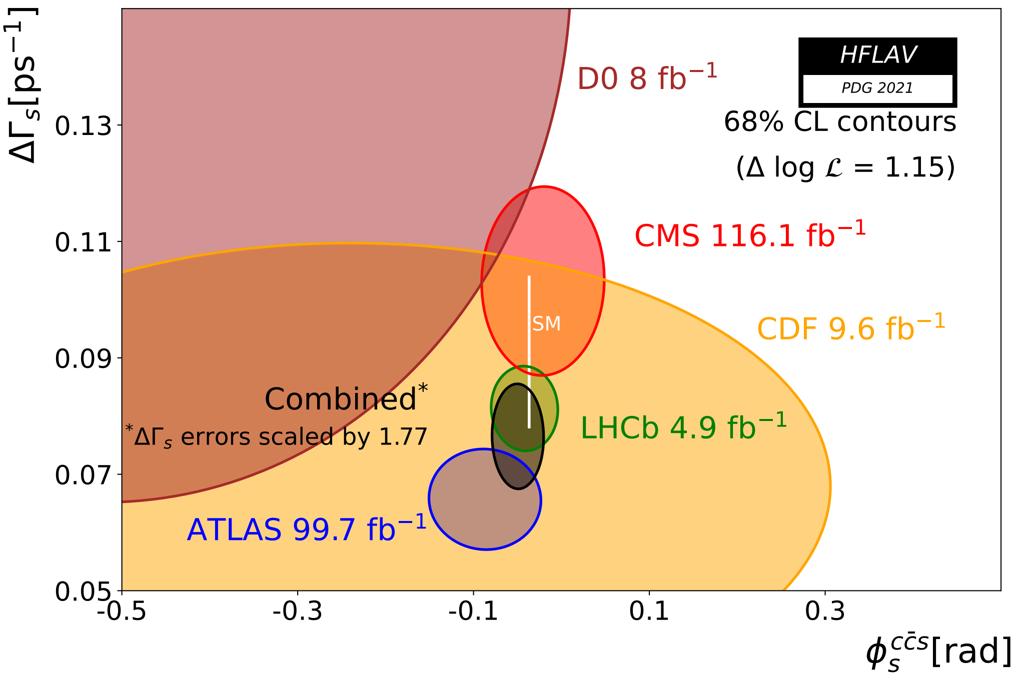

Figure 2: The FLAV plots show the contours of ATLAS, CMS, CDF, D0 and LHCb [11].

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