

Experimental status of CPV in B_s mixing

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Abstract

This proceeding contribution presents the latest measurement of the CP-violation and other physics parameters in the $B_s^0 \rightarrow J/\psi\phi$ decay channel performed by the ATLAS, CMS and LHCb experiments. The measurements are based on a data set collected at the LHC in proton-proton collisions at a center-of-mass energy of 13 TeV. Besides the CP violating phase ϕ_s , the width difference between the B_s^0 meson mass eigenstates $\Delta\Gamma_s$ and the average decay width Γ_s are measured. The measured values are then combined with those collected at 8 TeV. The measurements are consistent with theoretical predictions based on the Standard Model.

1 Introduction

Since no direct evidence of New Physics (NP) has been found at the CERN LHC so far, precision tests of the Standard Model (SM) of particle physics have become increasingly important. A wide program of studies of heavy flavor at the LHC, including studies of CP violation and mixing in b hadrons, is performed by the ATLAS, CMS and LHCb collaborations, and a number of recent results in this field are reviewed in this report¹. However, several other contributions in this conference include some of the new results not covered here. In this regard, B_s^0 meson decays present copious opportunities to probe the consistency of the SM. In this proceeding, the measurement of the CP violating weak phase ϕ_s and the decay width difference $\Delta\Gamma_s$ between the light (B_s^L) and heavy (B_s^H) B_s^0 meson mass eigenstates is presented.

The $B_s^0 \rightarrow J/\psi\phi$ channel is used to measure the CP violation phase ϕ_s which is potentially sensitive to NP. In $B_s^0 \rightarrow J/\psi\phi$ CP violation occurs due to interference between a direct decay

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and a decay with $B_s^0-\bar{B}_s^0$ mixing. In the SM, ϕ_s is related to the elements of the Cabibbo–Kobayashi–Maskawa matrix via $\phi_s \simeq -2\beta_s = -2\text{arg}(-V_{ts}V_{tb}^*/V_{cs}V_{cb}^*)$, neglecting penguin diagram contributions. The current best determination of $-2\beta_s$ from a SM global fit to experimental data is $-36.96_{-0.84}^{+0.72}$ mrad [1]. New physics processes can introduce additional contributions to the box diagrams describing the B_s^0 mixing and can modify this ϕ_s value via the contribution of beyond-the-SM particles. So far, the NP enhancements of the mixing amplitude have been excluded by the precise measurement of the oscillation frequency. However, there is still some room on the order of statistical uncertainty. Since the numerical value of ϕ_s in the SM is predicted very precisely, a deviation from the SM prediction would constitute strong evidence of physics beyond the SM.

2 Measurement of the CP violating phase ϕ_s in $B_s^0 \rightarrow J/\psi\phi$ decays in ATLAS at 13 TeV

The analysis presented here introduces a measurement of the $B_s^0 \rightarrow J/\psi\phi$ decay parameters using 80.5 fb^{-1} of LHC proton–proton (pp) data collected by the ATLAS detector during 2015–2017 at a centre-of-mass \sqrt{s} equal to 13 TeV [2].

The data were collected during periods with different instantaneous luminosities, so several triggers were used in the analysis. All triggers were based on the identification of a decay $J/\psi \rightarrow \mu^+\mu^-$. The K^+K^- pairs of the $B_s^0 \rightarrow J/\psi\phi$ decay are selected in the vicinity of the ϕ resonance. The four-body invariant mass spectra are fitted with signal plus background models using an unbinned extended maximum likelihood fit.

The amplitude analyses are simultaneously performed in the helicity angles, the reconstructed mass, the measured proper decay time, the measured mass uncertainty, the measured proper decay time uncertainty, the measured transverse momentum, and the tagging probability.

To identify, or tag, the flavour of a neutral B_s^0 meson at the point of production, information is extracted using the decay of the other (or opposite) b-hadron that is produced from the pair production of $b\bar{b}$ quarks. This method is called opposite-side tagging (OST). Four types of taggers are used: two types of muons, electrons and when no lepton is found a weighted sum of the charge of the tracks in a jet associated with the opposite-side b-hadron decay is used to provide discrimination. These methods are based on the same discriminating variable called *cone charge*, defined as:

$$Q_x = \frac{\sum_i^N \text{Tracks } q_i \cdot (p_{Ti})^\kappa}{\sum_i^N \text{Tracks } (p_{Ti})^\kappa}, \quad (1)$$

where $x = \{\mu, e, jet\}$ refers to muon, electron, or jet charge, respectively, and the summation is made over a selected set of tracks in a cone of size $\Delta R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2} < 0.5$ around the lepton or jet direction. The constant κ is found empirically for each tagging method. A probability $P(B|Q_x)$ is constructed, which is defined as the probability that a B meson is produced in a state containing a \bar{b} -quark, given the value of the cone charge Q_x . The tagging power of a particular tagging

method is then defined as $T_x = \sum_i \epsilon_{xi} \cdot D^2(Q_{xi})$ where the sum is over the probability distribution in intervals of the cone charge variable, ϵ_x is the tag efficiency, and $D(Q_{xi})$ is the dilution. The efficiency, ϵ_x , of an individual tagging method is defined as the number of signal events tagged by that method divided by the total number of signal events in the sample. The purity of a particular flavour tagging method, called the dilution, is defined as $D(Q_{xi}) = 2P(B|Q_x) - 1$. An effective dilution, $D(Q_{xi}) = \sqrt{T_x/\epsilon_x}$, is calculated from the measured tagging power and efficiency. A summary of the tagging performance for each method is given in Table 1.

Table 1: Summary of tagging performance for the different flavour tagging methods. Taken from [2].

Tag method	ϵ_x [%]	D_x [%]	T_x [%]
Tight muon	4.50 ± 0.01	43.8 ± 0.2	0.862 ± 0.009
Electron	1.57 ± 0.01	41.8 ± 0.2	0.274 ± 0.004
Low- p_T muon	3.12 ± 0.01	29.9 ± 0.2	0.278 ± 0.006
Jet	12.04 ± 0.02	16.6 ± 0.1	0.334 ± 0.006
Total	21.23 ± 0.03	28.7 ± 0.1	1.75 ± 0.01

The results of the main physics parameters obtained from the fit are given in Table 2.

Table 2: Fitted values for the physical parameters of interest with their statistical and systematic uncertainties. Taken from [2].

Parameter	value	Statistical uncertainty	Systematic uncertainty
ϕ_s [rad]	-0.081	0.041	0.020
$\Delta\Gamma_s$ [ps^{-1}]	0.0607	0.0047	0.0022
Γ_s [ps^{-1}]	0.6687	0.0015	0.0018

The obtained parameters are combined with results from ATLAS 8 TeV measurements [3] using a Best Linear Unbiased Estimator method (BLUE). This method uses the measured values and uncertainties of the parameters as well as the correlations between them. The combined values of parameters are shown in Table 3. The two-dimensional likelihood contours in the ϕ_s - $\Delta\Gamma_s$ plane for the ATLAS result based on 7 TeV and 8 TeV data, the result from 13 TeV data, and the combined results are shown in Figure 1.

Table 3: Values of the physical parameters extracted in the combination of 13 TeV results with those obtained from 7 TeV and 8 TeV data. Taken from [2].

Parameter	value	Statistical uncertainty	Systematic uncertainty
ϕ_s [rad]	-0.087	0.036	0.019
$\Delta\Gamma_s$ [ps^{-1}]	0.0641	0.0043	0.0024
Γ_s [ps^{-1}]	0.6697	0.0014	0.0015

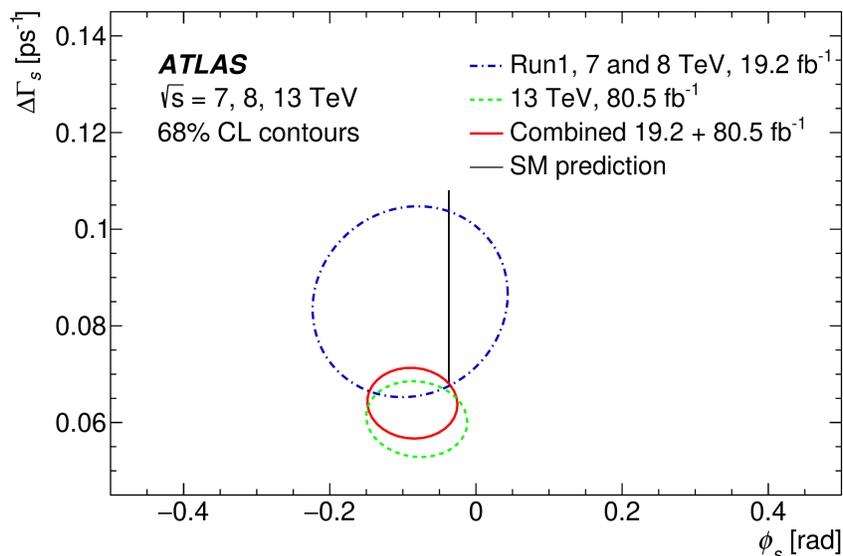


Figure 1: Contours of 68% confidence level in the ϕ_s - $\Delta\Gamma_s$ plane, showing ATLAS results for 7 TeV and 8 TeV data (blue dashed-dotted curve), for 13 TeV data (green dashed curve) and for 13 TeV data combined with 7 TeV and 8 TeV (red solid curve) data. The Standard Model prediction is shown as a very thin black rectangle. In all contours the statistical and systematic uncertainties are combined in quadrature and correlations are taken into account. Taken from [2].

3 LHCb Updated measurement of time-dependent CP violating observables in $B_s^0 \rightarrow J/\psi\phi$ decays

The measurement reported is based on a data sample of proton–proton collisions recorded by the LHCb experiment at a centre-of-mass energy of 13 TeV in 2015 and 2016, corresponding to an integrated luminosity of 0.3 fb^{-1} and 1.6 fb^{-1} , respectively [4].

The B_s^0 candidates are reconstructed by combining the J/ψ candidate with the K^+K^- pair. The invariant mass of the K^+K^- pair, $m(K^+K^-)$, must be in the range 990–1050 MeV. The selection of signal events over the combinatorial background is performed with a BDT using kinematic variables. The $m(\mu^+\mu^-K^+K^-)$ distribution is fitted using an unbinned maximum-likelihood fit to the sample.

The amplitude analyses are simultaneously performed in the helicity angles and decay time requiring a careful study of angular and decay-time efficiencies, time resolution, and flavor tagging. The decay-time resolution is found to be $\sigma_{\text{eff}} \simeq 45.54$ fs and a 30% higher tagging power than 8 TeV has been achieved. The decay-time and angular efficiencies are estimated with simulation and corrected with data methods. It is worth saying, in this analysis the quantity $\Gamma_s - \Gamma_d$ is measured instead of Γ_s .

The determination of the initial flavor of the B_s^0 meson, called tagging, used two classes of algorithms: the opposite side (OS) tagger and the same-side kaon (SSK) tagger. The tagging algorithms each provide a flavor-tagging decision and an estimate of the probability that the decision is incorrect (mistag) for each reconstructed B_s^0 candidate. The mistag probability, w , is defined in the range from 0 to 0.5. Each tagger has a corresponding tagging power given by $\epsilon_{\text{tag}} D^2$, where ϵ_{tag} is the fraction of tagged candidates and $D = 1 - 2w$ is the dilution induced on the amplitude of the B_s^0 oscillation. The combined estimated mistag probability and the corresponding uncertainties are obtained by combining the individual calibrations for the OS and SSK tagging and propagating their uncertainties. The effective tagging power and efficiency for these both OS and SSK tagged candidates is given in Table 4.

Table 4: Overall tagging performance. Taken from [4].

Category	$\epsilon_{\text{tag}}(\%)$	D^2	$\epsilon_{\text{tag}} D^2(\%)$
OS only	11.4	0.078	0.88 ± 0.04
SSK only	42.6	0.032	1.38 ± 0.30
OS & SSK	23.8	0.104	2.47 ± 0.15
Total	77.8	0.061	4.73 ± 0.34

The measured values are:

$$\begin{aligned}
 \phi_s &= -0.083 \pm 0.041 \pm 0.006 \text{ rad}, \\
 \Gamma_s - \Gamma_d &= -0.0041 \pm 0.0024 \pm 0.0015 \text{ ps}^{-1}, \\
 \Delta\Gamma_s &= 0.077 \pm 0.008 \pm 0.003 \text{ ps}^{-1},
 \end{aligned}
 \tag{2}$$

These results are combined with related 8 TeV LHCb measurements, taking into account all statistical correlations, all systematic errors and their correlations, and correlations between different run periods. In the 8 TeV measurement, Γ_s was measured instead of $\Gamma_s - \Gamma_d$, hence a linear transformation is taken into account in the combination, constraining Γ_d to the known value [5].

The combined results are

$$\begin{aligned}
 \phi_s &= -0.080 \pm 0.032 \text{ rad} , \\
 \Gamma_s &= 0.6570 \pm 0.0023 \text{ ps}^{-1} , \\
 \Delta\Gamma_s &= 0.0784 \pm 0.0062 \text{ ps}^{-1} .
 \end{aligned}
 \tag{3}$$

4 CMS Measurement of the CP violating phase ϕ_s in the $B_s^0 \rightarrow J/\psi\phi \rightarrow \mu^+\mu^-K^+K^-$ channel in proton-proton collisions at $\sqrt{s}=13$ TeV

The CP violating weak phase ϕ_s , and the decay width difference $\Delta\Gamma_s$ between the light and heavy B_s^0 mass eigenstates are measured with the CMS detector at the LHC in a sample of reconstructed $B_s^0 \rightarrow J/\psi\phi \rightarrow \mu^+\mu^-K^+K^-$ decays. The measurement is based on a data set corresponding to an integrated luminosity of 96.4 fb^{-1} , collected in proton-proton collisions at a center-of-mass energy of 13 TeV in 2017-2018 [6]². Compared to the previous measurement [7], this analysis benefits from a data set collected at higher center-of-mass energy, as well as from a novel opposite-side (OS) muon flavor tagger, taking advantage of machine learning techniques, which allowed reaching unprecedented tagging power. It also uses a specialized trigger, requiring an additional muon, which improves the tagging efficiency at the cost of the reduced number of signal events.

A trigger optimized for the detection of b hadrons decaying to J/ψ mesons is used to collect the data sample. Besides, a third muon is required. This additional muon is important to infer the flavor of the B_s^0 meson at production. Selections have been optimized using the *TMVA* package. The ϕ candidates are selected if the track pair, K^+K^- , of the $B_s^0 \rightarrow J/\psi\phi$ decays has an invariant mass within 10 MeV of the world-average $\phi(1020)$ meson mass.

An unbinned extended maximum-likelihood is performed by including the information on the B_s^0 candidate invariant mass, the three decay angles of the reconstructed B_s^0 candidate, the flavor tag decision, the mistag fraction, the proper decay length of the B_s^0 candidate, and its proper decay length uncertainty.

The flavor of the B_s^0 candidate at production is determined with an OS flavor tagging algorithm. The tagging efficiency ϵ_{tag} is defined as the fraction of the total number of events which are tagged. The mistag fraction w_{tag} is defined as the ratio between the number of wrongly tagged events to the total number of tagged events, and it is used to compute the dilution $D = 1 - 2w_{tag}$, which is a measure of the performance degradation due to mistagged events. The tagging power $P_{tag} = \epsilon_{tag}D^2$ is the effective tagging efficiency. The final flavor tagging performance is shown in Table 5.

The results of the fit with their statistical and systematic uncertainties are given in Table 6.

²The preliminary results shown in this contribution are superseded in this paper [arXiv:2007.02434](https://arxiv.org/abs/2007.02434)[hep-ex], Submitted to Phys. Lett. B.

Table 5: OS muon tagger performance using events in 2017 and 2018 data sets. Taken from [6].

Data set	$\epsilon_{tag}(\%)$	$w_{tag}(\%)$	$P_{tag}(\%)$
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 6: Results of the fit to data with the statistical and systematic uncertainties. Taken from [6].

Parameter	Fit result	Stat. uncer.	Syst. uncer.
ϕ_s [rad]	-0.011	± 0.050	± 0.010
$\Delta\Gamma_s$ [ps^{-1}]	0.114	± 0.014	± 0.007
Γ_s [ps^{-1}]	0.6531	± 0.0042	± 0.0024

The results presented are further combined with the earlier CMS result at the center-of-mass energy of $\sqrt{s} = 8$ TeV [7], using the *IMINUIT* python interface of the *MINUIT2* minimization package. The combined results for the CP violating phase and the lifetime difference between the two mass eigenstates are:

$$\begin{aligned}
 \phi_s &= -0.021 \pm 0.045 \text{ rad}, \\
 \Delta\Gamma_s &= 0.1074 \pm 0.0097 \text{ ps}^{-1}.
 \end{aligned}
 \tag{4}$$

The two-dimensional ϕ_s - $\Delta\Gamma_s$ likelihood contours at 68% confidence level (CL) for the individual and combined results, as well as the SM prediction, are shown in Figure 2. The results are in agreement with each other and with the SM predictions.

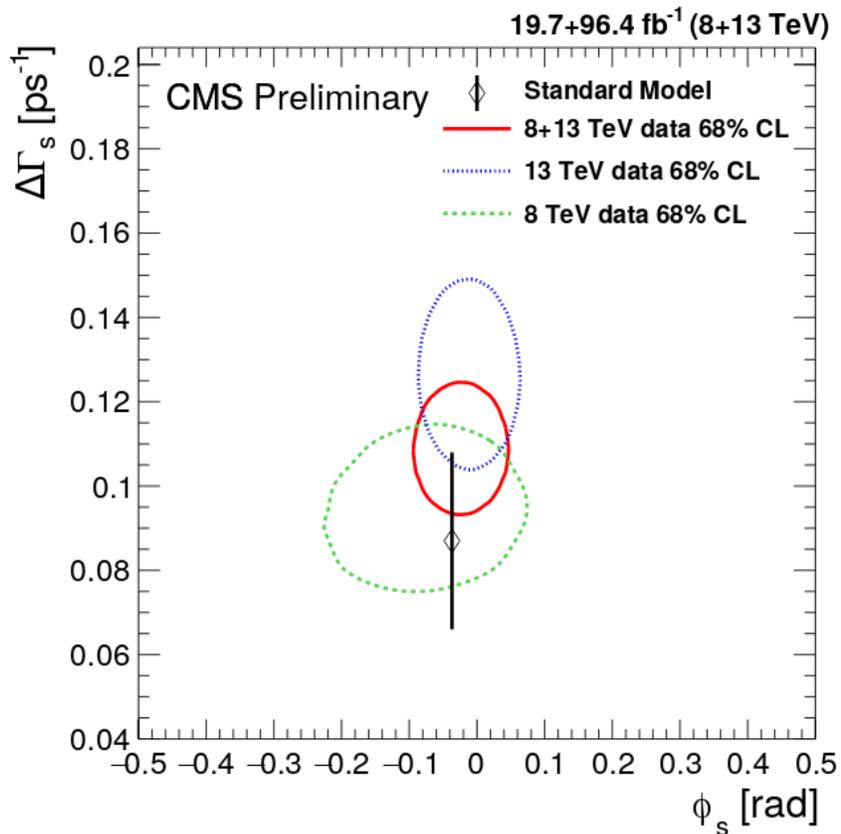


Figure 2: The two-dimensional likelihood contours at 68% CL in the ϕ_s - $\Delta\Gamma_s$ plane, for the CMS 8 TeV (dashed green line), 13 TeV (dashed blue line), and the combined (solid red line) results. The SM prediction is shown as the black rectangle. Taken from [6].

5 Acknowledgements

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