PROCEEDINGS OF SCIENCE

Measurement of *CP* violation in B_s^0 decays at CMS

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These proceedings describe the measurement of the *CP*-violating phase ϕ_s using $B_s^0 \to J/\psi\,\phi(1020)$ decays with the CMS experiment at $\sqrt{s}$ = 13 TeV. The measurement is based on a data sample collected in 2017–2018 corresponding to an integrated luminosity of 96.4 fb^{-1}. A dedicated tagging trigger and an opposite-side muon flavour tagger based on deep learning techniques have been used in this analysis, significantly increasing the fraction of tagged events. The decay width (mass) difference $\Delta\Gamma_s$ (Δm_s) between the light and heavy B_s^0 mass eigenstates, the B_s^0 average decay width Γ_s and the *CP* violation observable $|\lambda|$ are also measured. The combination with the results obtained by CMS at $\sqrt{s}$ = 8 TeV is also presented.

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1. Introduction

The weak phase ϕ_s is a *CP*-violating phase arising from the interference between direct B_s^0 decays to a *CP* final state of $c\bar{c}s\bar{s}$ and decays through B_s^0–$\overline{B}_s^0$ mixing to the same final state. It generates a time-dependent *CP* asymmetry which can be expressed as

$$a_{CP}(t) = \frac{d\Gamma/dt(\overline{B}_s^0 \to f) - d\Gamma/dt(B_s^0 \to f)}{d\Gamma/dt(\overline{B}_s^0 \to f) + d\Gamma/dt(B_s^0 \to f)} \propto \sin(\phi_s)\sin(\Delta m_s t)\,,$$

where $d\Gamma/dt(i \to f)$ is the time-dependent decay rate of an initial state i to decay into the final state f, and Δm_s is the mass difference between the light and heavy B_s^0 mass eigenstates. The Standard Model (SM) relates ϕ_s to the elements of the CKM matrix as $\phi_s \simeq -2\beta_s = -2\arg(-V_{\text{ts}}V_{\text{tb}}^*/V_{\text{cs}}V_{\text{cb}}^*)$ where β_s is one of the angles of the B_s^0 unitary triangles. Assuming no physics beyond the SM (BSM) in the B_s^0 decay and mixing, β_s can be determined very precisely by CKM global fits, leading to a predicted ϕ_s value of $\phi_s \simeq -2\beta_s = -36.96\,^{+0.72}_{-0.84}$ mrad [1]. New physics can change the value of ϕ_s up to ~100% via new particles contributing to the B_s^0 mixing [2], so that any reduction of the experimental uncertainties directly leads to a better sensitivity for BSM effects. An overview of the experimental state-of-the-art and the most recent world-average value is shown in Fig. 1. These proceedings presents the most recent measurement of ϕ_s performed by the CMS collaboration [3] using $B_s^0 \to J/\psi\,\phi(1020)$ decays in proton-proton (pp) collisions at $\sqrt{s} = 13$ TeV [4]. In this channel, no direct *CP* violation (*CPV*) is predicted by the SM. Several other interesting observable can be measured, such as Δm_s, the decay width difference $\Delta\Gamma_s$ between the light and heavy B_s^0 mass eigenstates, the B_s^0 average decay width Γ_s and the *CP* violation observable $|\lambda|$. This latter parameter is defined as $\lambda = (q/p)(\overline{A}_f/A_f)$, where A_f ($\overline{A}_f$) is the decay amplitude of the B_s^0 ($\overline{B}_s^0$) meson to the final state f, and the parameters p and q relate the mass and flavour eigenstates through $B_s^H = p\left|B_s^0\right\rangle - q\left|\overline{B}_s^0\right\rangle$ and $B_s^L = p\left|B_s^0\right\rangle + q\left|\overline{B}_s^0\right\rangle$.

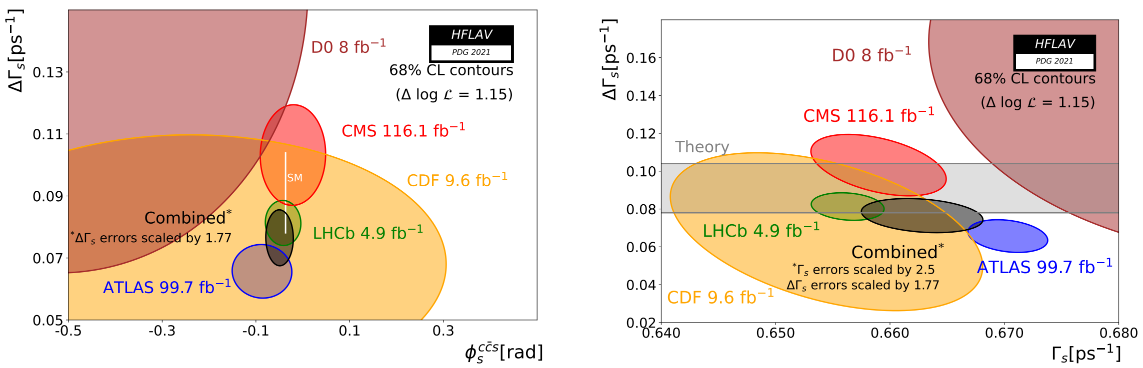

Figure 1: Overview of the experimental state-of-the-art for ϕ_s, $\Delta\Gamma_s$, and Γ_s, showing the latest results from ATLAS, CMS, CDF, D0, and LHCb, together with their combined contour, and the SM predictions. Figures from [5]. The references to the individual results can also be found din Ref. [5].

2. Analysis overview

The analysis is performed with a time-dependent and flavour-tagged angular analysis of the $\mu^+\mu^-\ K^+K^-$ final state, using data collected in pp collisions at $\sqrt{s} = 13$ TeV during 2017–2018 corresponding to an integrated luminosity of $96.4\,\mathrm{fb}^{-1}$. Since the final state is a mixture of *CP* eigenstates, an angular analysis is used to separate the *CP*-odd and *CP*-even components. The transversity basis is used, which is defined by the three decay angles θ_T, ψ_T, and φ_T [6]. Events are first selected by a trigger that requires a $J/\psi \to \mu^+\mu^-$ candidate plus an additional (third) muon. The additional muon can be used to infer the flavour of the B_s^0, via $b \to \mu^- X$ decays of the other b hadron in the event. This trigger strategy improves the fraction of tagged events ("tagging efficiency") at the cost of a reduced number of signal events. The sensitivity of the analysis may or may not depend on the tagging information, depending on the physics parameter. Therefore, the precision of the measurement can either depend on the number of signal events $N_{B_s^0}$ or the effective statistics $N_{B_s^0} \times P_{\mathrm{tag}}$, where P_{tag} is a rescaled efficiency that takes into account the mistagged events called "tagging power". As a result, while based on a similar number of B_s^0 candidates as the previous CMS measurement [7], this new analysis doubles the precision in the determination of ϕ_s. At the same time, the precision on parameters that do not benefit from the tagging information, such as $\Delta\Gamma_s$ and Γ_s, is comparable to that in the previous measurement. Candidates are further selected with several requirements optimized to maximize the signal purity $N_{\mathrm{sig}}/(N_{\mathrm{sig}} + N_{\mathrm{bkg}})$. The prompt background[1] is reduced with an additional requirement on the proper decay length of $ct > 70\ \mu$m. A total of 65 500 B_s^0 candidates are selected. The invariant-mass distribution for the selected candidates is shown in Fig. 3 (top left).

3. Flavour tagging

The B_s^0 flavour at production time is inferred with an opposite side (OS) muon tagging algorithm developed in simulated $B_s^0 \to J/\psi\,\phi(1020)$ events and calibrated in data using self-tagging $B^+ \to J/\psi\,K^+$ decays[2]. The tagging muon candidate is selected with loose kinematic requirements, after excluding the b meson candidate tracks. To further reduce the background from light hadrons (mainly charged kaons and pions) a Deep Neural Network (DNN) discriminator has been trained with muon candidates from simulated samples. The loose selection, combined with the requirement of a third muon at trigger level, leads to a very high tagging efficiency of $\epsilon_{\mathrm{tag}} \approx 50\%$. The mistag probability ω_{evt} is evaluated on per-event basis with a dedicated fully connected DNN[3], constructed in such a way that the output score is equal to the mistag probability. This approach requires almost no calibration and leads to very small systematic uncertainties. The calibration results for the 2017 and 2018 B^+ data are shown in Fig. 2. A tagging efficiency of ≈50% and a tagging power of ≈10% are achieved in both the 2017 and 2018 data samples.

4. Maximum-likelihood fit

The differential decay rate is described by a set of time-dependent and angular functions [8]. Possible contributions of $B_s^0 \to J/\psi\,f_0(980)$ and non-resonant $B_s^0 \to J/\psi\,K^+K^-$ decays are taken into account by including a term for an additional S-wave amplitude in the decay model. The fit model also includes the background parametrization, which contains two terms to model both

[1] Candidates reconstructed from prompt $J/\psi \to \mu^+\mu^-$ plus two random charged tracks.

[2] The flavour of the B^+ meson is given by the charge of the kaon.

[3] This is a different DNN than the one used to select the muon candidates.

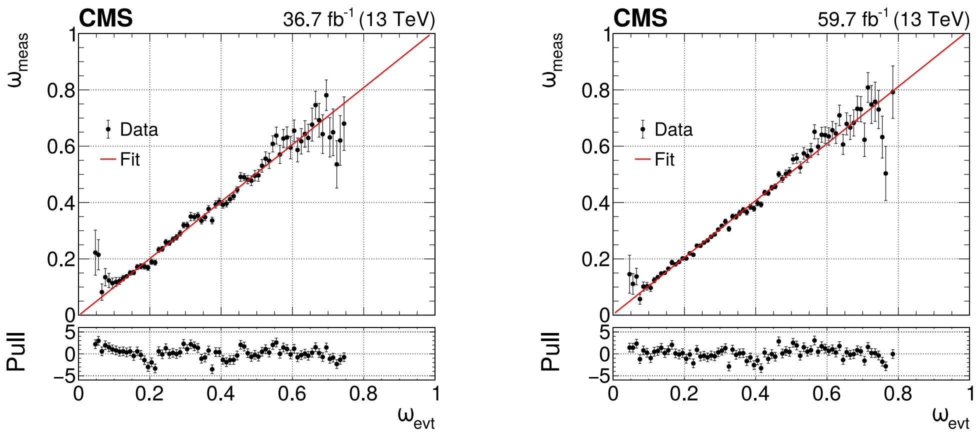

Figure 2: Results of the calibration of the per-event mistag probability ω_{evt} based on $B^+ \to J/\psi\, K^+$ decays from the 2017 (left) and 2018 (right) data sample. The solid line shows a linear fit to data (solid markers). Figures from [4].

the combinatorial background and the peaking background from $B^0 \to J/\psi\, K^{*0} \to \mu^+\mu^-\, K^+\pi^-$ where the pion is misidentified as a kaon. The peaking background from $\Lambda_b^0 \to J/\psi\, K^- p \to \mu^+\mu^-\, K^- p$ was estimated to be negligible. Efficiency functions model the dependence of the signal reconstruction efficiency on the proper decay length and the three angles of the transversity basis. An unbinned multidimensional extended maximum-likelihood fit is performed on the combined data samples using 8 observables as input: the B_s^0 candidate invariant-mass, the three decay angles, the proper decay length of the B_s^0 and its uncertainty, the flavour tag decision, and the mistag probability. The measured number of B_s^0 signal events from the fit is 48 500 ± 250.

5. Results

The distributions of the input observables and the corresponding fit projections are shown in Fig. 3. The *CPV* phase is measured $\phi_s = -11 \pm 50\,(\text{stat}) \pm 10\,(\text{syst})$ mrad, the decay width difference is measured $\Delta\Gamma_s = 0.114 \pm 0.014\,(\text{stat}) \pm 0.007\,(\text{syst})\ \text{ps}^{-1}$. The $|\lambda|$ parameter is measured $|\lambda| = 0.972 \pm 0.026\,(\text{stat}) \pm 0.008\,(\text{syst})$ consistent with no direct *CP* violation ($|\lambda| = 1$) The average decay width is determined to be $\Gamma_s = 0.6531 \pm 0.0042\,(\text{stat}) \pm 0.0026\,(\text{syst})\ \text{ps}^{-1}$, consistent with the world-average value [9]. The mass difference is measured to be $\Delta m_s = 17.51\,^{+0.10}_{-0.09}\,(\text{stat}) \pm 0.03\,(\text{syst})\ \hbar\text{ps}^{-1}$, consistent with the theoretical prediction [2], and in slight tension with the world-average value [9]. The uncertainties in all these measured parameters are dominated by the statistical component. This analysis represents the first measurement by CMS of the mass difference Δm_s and the direct *CP* observable $|\lambda|$. The results are in agreement with the earlier CMS result at a $\sqrt{s} = 8$ TeV [7]. The two sets of results are combined using their respective correlation matrices, with their respective systematic uncertainties treated as uncorrelated. The combined results for the *CP*-violating phase and lifetime difference between the two mass eigenstates are:

$$\phi_s = -21 \pm 44\,(\text{stat}) \pm 10\,(\text{syst})\ \text{mrad},$$
$$\Delta\Gamma_s = 0.1032 \pm 0.0095\,(\text{stat}) \pm 0.0048\,(\text{syst})\ \text{ps}^{-1}.$$

The two-dimensional ϕ_s vs. $\Delta\Gamma_s$ likelihood contours at 68% confidence level for the individual and combined results are shown in Fig. 4. The results are in agreement with each other and with the SM predictions [1, 2].

6. Future prospects

The CMS Collaboration is currently working on improving the sensitivity of the analysis by analyzing the same dataset including also another trigger selection that requires a displaced $J/\psi \to \mu^+\mu^-$ candidate plus two charged tracks with invariant-mass around the $\phi(1020)$ resonance (assuming for both of them the charged kaon mass). In this data sample, additional flavour tagging techniques will be used alongside the OS muon algorithm, such as OS electron and OS jet taggers. The feasibility of same-side tagging techniques is also currently being studied. The number of signal candidates is expected to increase by a factor ∼10, while the effective statistics $N_{B_s^0} \times P_{\text{tag}}$ highly depends on the final tagging performance and is expected to improve by at least a factor of two. CMS expects large improvements in the precision of the measurement of $\Delta\Gamma_s$ and Γ_s. The sensitivity on ϕ_s is going to be still far from the precision of the theoretical prediction and dominated by statistical uncertainties, but systematic uncertainties will start to become more relevant.

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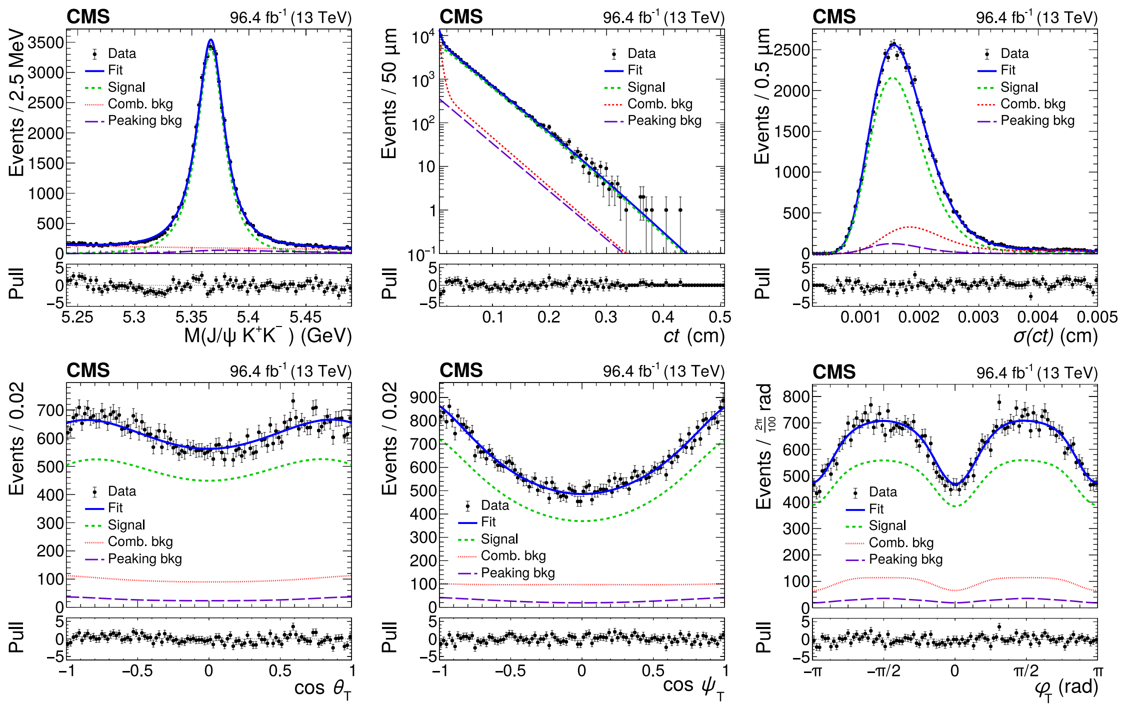

Figure 3: Distributions of the fit input observable for the $B_s^0 \to J/\psi\,\phi(1020) \to \mu^+\mu^-\,K^+K^-$ candidates in data. First row: the invariant-mass distribution (left), ct distribution (middle) and its uncertainty (right). Bottom row: the angular distributions $\cos\theta_T$ (left), $\cos\psi_T$ (middle) and φ_T (right). The blue line represents the fit to data projection. Figures from [4].

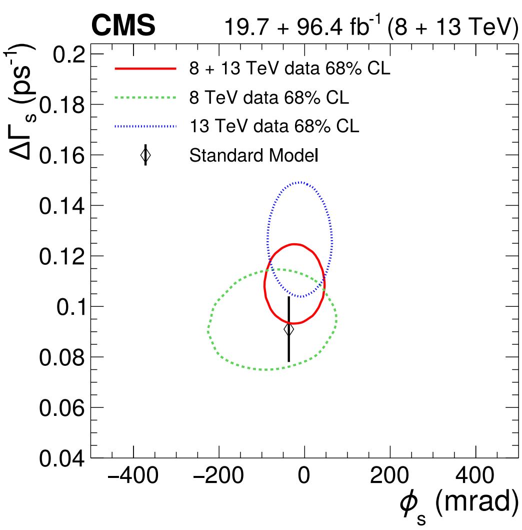

Figure 4: The 2D likelihood contours at 68% CL for the CMS 8 TeV (dashed line), 13 TeV (dotted line), and combined (solid line) results. The SM prediction is shown with the diamond marker [1, 2]. Figures from [4].