PROCEEDINGS OF SCIENCE

The first evidence of CP violation in the $B_s \to J/\psi\phi$ system, obtained by CMS

Enrico Lusiani[a,*]

[a] *INFN Padova Section,*
via Marzolo 8, Padova, Italy

E-mail: enrico.lusiani@cern.ch

The study of CP violation is critical for understanding the asymmetry between matter and antimatter in the universe. This talk presents the CP violation in $B_s \to J/\psi\phi$ decays measured with the CMS detector at the LHC using Run 2 data. A full angular analysis of the decay is performed, extracting several key parameters such as the CP-violating phase, the amount of direct CP violation and differences in decay width and mass between mass eigenstates. The study employs an innovative flavour tagging approach, leveraging machine learning to improve accuracy by using information from both sides of the decay.

The XVIth Quark Confinement and the Hadron Spectrum Conference (QCHSC24)
19-24 August, 2024
Cairns Convention Centre, Cairns, Queensland, Australia

*Speaker

PoS(QCHSC24)141

1. Introduction

The decays of B_s^0 mesons provide powerful ways to test the standard model (SM) predictions for *CP* violation (CPV) in the quark sector and search for new physics effects. In the SM, the weak phase ϕ_s, which arises from CPV in the interference between decays with and without mixing of B_s^0 mesons to a *CP* eigenstate, is related to the elements of the Cabibbo–Kobayashi–Maskawa quark mixing matrix [1, 2] by $\phi_s \approx -2\beta_s = -2\arg(-V_{ts}V_{tb}^*/V_{cs}V_{cb}^*)$, ignoring small contributions from penguin diagrams [3]. Global fits to measurements of b-hadron and kaon decays in the context of the SM predict $-2\beta_s \approx -37 \pm 1$mrad [4, 5]. This precise determination makes ϕ_s an excellent probe for beyond-the-SM physics, as its value can be modified by the contribution of new particles to B_s^0 mixing [6–8]. Several experiments have measured ϕ_s via $b \to c\bar{c}s$ transitions in B_s^0 decays [9–26], with no evident deviation from SM-based predictions.

These proceedings present a study of the $B_s^0 \to J/\psi\,\phi(1020)$ decay to the $\mu^+\mu^- K^+K^-$ final state using proton-proton collisions collected by the CMS experiment [27, 28] at $\sqrt{s} = 13$ TeV during 2017–2018, corresponding to an integrated luminosity of 96.5 fb^{-1} [29–31] [32]. The CMS apparatus is a multipurpose, nearly hermetic detector, designed to perform a wide range of particle physics measurements. During Run2, CMS collected over $7.5 \cdot 10^{13}$ $b\bar{b}$ pairs, making it a great fit for B-Physics measurements. For the measurement, about 500 thousands events were used.

2. Event recontruction

Since the final state is mixture of CP eigenstates an angular analysis is used to separate the CP-odd and CP-even components. This measurement uses the transversity basis defined by the three decay angles $\cos\theta_T$, $\cos\psi_T$, and φ_T. To resolve the oscillation, it's also necessary to estimate the B_s^0 flavour at production time, a process known as flavour tagging. There are multiple algorithms for flavour tagging, divided in two categories based on what information they use. Opposite Side (OS) algorithms rely on the fact that b quarks are produced in opposite charge pairs in LHC and look at decays of the second B hadron in the event to estimate the flavour of the signal B_s^0. The three OS algorithms used in this analysis look for example for semileptonic decays into μ or e, or analyse inclusively all the decay products of the OS B by looking inside jets identified as produced by a B. Same Side (SS) algorithms instead look directly at features of the signal B_s^0 to find it's flavour. Only one such algorithm is used in the analysis, which analyses all tracks produced in a cone around the signal B_s^0 to collect informations related to the B_s^0 fragmentation.

All these algorithms were implemented as Neural Networks and trained on Monte Carlo samples reproducing the signal. The advantage of this implementation is that, by choosing the correct network structure and optimization objective, the taggers can also be used to estimate the probability of returning the wrong flavour, which can be further improve the performance if used in the NLL fit. To avoid biases, the output of the tagging algorithm is calibrated on data using the Platt scaling (a linear calibration applied before the tagger output is normalized to a probability). This strategy cancels almost all the systematic effects associated with flavour tagging.

The OS and SS tagger are combined in a single probability, relying on the fact that the signal and opposite side are independent in our events. The combined flavour tagging framework achieves a tagging power of $P_{tag} = 5.6\%$ when applied to the B_s^0 data sample, which is among the highest ever recorded at LHC and a ×3/4 improvement compared to the previous CMS analysis in this channel.

The flavour tagging framework is validated in the $B^0 \to J/\psi\, K^*(892)^0$ control channel, containing about 2M events. The time-dependent mixing asymmetry is measured to extract the flavour mixing oscillation frequency Δm_d with a precision of ≈ 1‰ (comparable with the first generation of B factories). The validation is repeated in each of the sample subsets using a specific tagger, and excellent agreement with world-averages is observed. The time-integrated mixing is also measured for each tagger and their dependency on the expected tagging dilution is compared. The dependency between the measured A_{mix} and the estimated $\mathcal{D}_{tag}$ is found to be well described by a linear relationship, indicating that all four techniques behave in the same predictable way.

3. Maximum likelihood fit

The parameter estimation for this analysis is made using an unbinned maximum likelihood fit on the signal and background components. The background sources considered in the fit are the combinatorial background and $B^0 \to J/\psi\, K^*(892)^0$ events mistakenly reconstructed as $B_s^0 \to J/\psi\, \phi(1020)$, while $\Lambda_b \to J/\psi\, pK^-$ were found to be negligible.

The signal includes the differential decay rate described by time-dependent and angular functions ([33]), plus terms related to the angular and time acceptance and the time resolution.

The angular acceptance is estimated in simulated events using Kernel Density Estimation. The simulated data samples are corrected to match the data using an iterative procedure to simultaneously correct the kinematics of the final state particles and the differences in the physics parameters set in the MC with respect to what measured in the data. The time resolution instead is measured in data using the $B^0 \to J/\psi\, K^*(892)^0$ control sample using simulated samples to correct for the meson flavour and ultimately fitted using Bernstein polynomials. In the NLL fit, the angular acceptance is included as part of the model, while the the time resolution, to speed up the fit, is included as a weight.

4. Results

The CP violation phase is measured to be $\phi_s = -73 \pm 23(\text{stat}) \pm 7(\text{syst})$, while the decay width difference is measured to be $\Delta\Gamma_s = 0.0761 \pm 0.0043(\text{stat}) \pm 0.0019(\text{syst})$. The $|\lambda|$ parameter is measured to be $|\lambda| = 1.011 \pm 0.014(\text{stat}) \pm 0.012(\text{syst})$, consistent with no direct CP violation ($|\lambda| = 1$). The average of the heavy and light B_s^0 mass eigenstate decay widths is determined to be $\Gamma_s = 0.6613 \pm 0.0015(\text{stat}) \pm 0.0028(\text{syst})\text{ps}^{-1}$, consistent with the world-average value. The mass difference between the heavy and light B_s^0 meson mass eigenstates is measured to be $\Delta m_s = 17.757 \pm 0.035(\text{stat}) \pm 0.017(\text{syst})\, \hbar\text{ps}^{-1}$, consistent with the world-average value. The uncertainties in all these measured parameters are dominated by the statistical component. The results are in agreement with the earlier CMS result at a centre-of-mass energy of 8 TeV [14] and therefore combined. The two sets of results are combined using their respective correlation matrices, with their respective systematic uncertainties treated as uncorrelated. Due to the high difference in statistical power between the two results the sensitivity gain is small. The combined results for the CP-violating phase and lifetime difference between the two mass eigenstates are:

PoS(QCHSC24)141

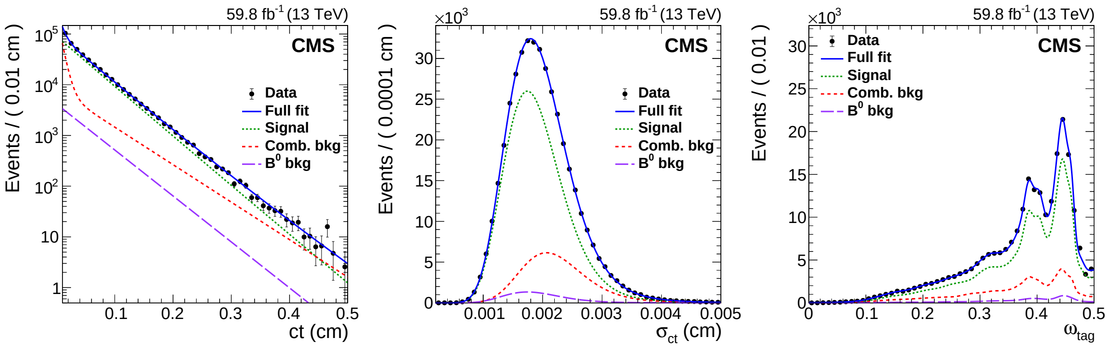

Figure 1: Distributions of the proper decay time ct, its uncertainty σ_{ct}, and mistag probability $\omega_{\rm tag}$ of the selected candidates for the ST trigger category (2018 data). The projections of the fitted model are also shown.

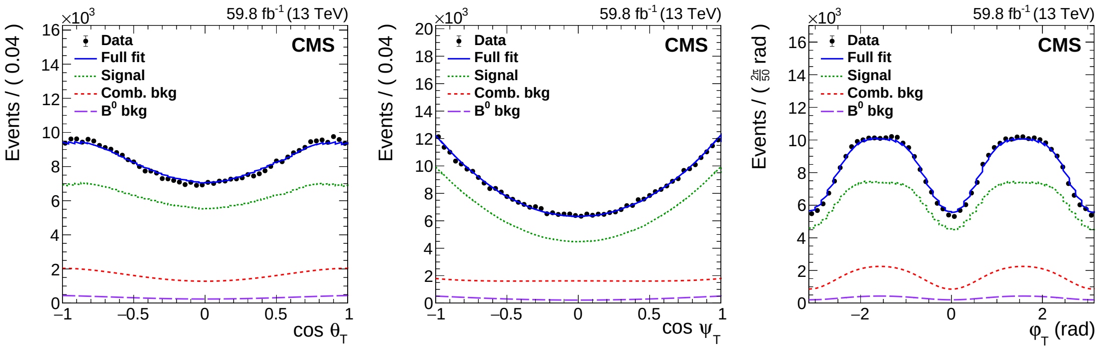

Figure 2: Angular observables distributions of the selected candidates and fit projection for the ST trigger category (2018 data). The projections of the fitted model are also shown.

$$\phi_{\rm s} = -74 \pm 23 \text{ mrad}$$

$$\Delta\Gamma_{\rm s} = 0.0780 \pm 0.0045 \text{ ps}^{-1}.$$

Figure 3 shows the two-dimensional $\phi_{\rm s}$ vs. $\Delta\Gamma_{\rm s}$ contour at 68% CL for the combined results, alongside the SM-based prediction and the latest results from other LHC experiments.

The combined $\phi_{\rm s}$ value exhibits a deviation from zero of 3.2 standard deviations, providing the first evidence for mixing-induced CPV in $\rm B_s^0 \to J/\psi\, \phi(1020)$ decays.

References

[1] N. Cabibbo, *Unitary symmetry and leptonic decays*, *Phys. Rev. Lett.* **10** (1963) 531.

[2] M. Kobayashi and T. Maskawa, *CP violation in the renormalizable theory of weak interaction*, *Prog. Theor. Phys.* **49** (1973) 652.

[3] M.Z. Barel, K. De Bruyn, R. Fleischer and E. Malami, *In pursuit of new physics with $B^0 \to J/\psi K^0$ and $B_s^0 \to J/\psi\, \phi(1020)$ decays at the high-precision frontier*, *J. Phys. G* **48** (2021) 065002 [2010.14423].

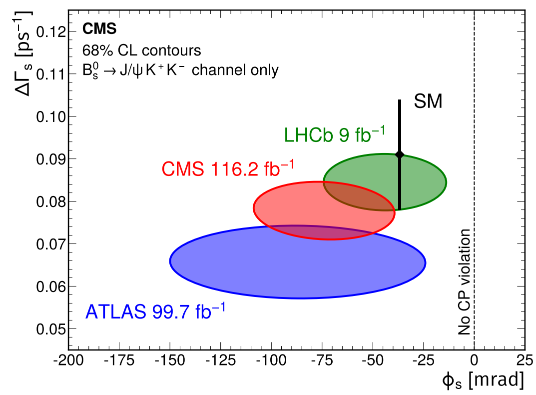

Figure 3: The two-dimensional 68% CL contours in the ϕ_s-$\Delta\Gamma_s$ plane for the combined CMS (red), ATLAS (blue) [26], and LHCb (green) [20] results. Results refer only to $B_s^0 \to J/\psi\, K^+K^-$ measurements. The contours account for both statistical and systematic uncertainties. The SM prediction neglects possible contributions from higher-order penguin diagrams and is represented by the thin black band, with the central value indicated with the black diamond [4, 5, 34].

[4] CKMfitter collaboration, *Predictions of selected flavour observables within the standard model*, Phys. Rev. D **84** (2011) 033005 [1106.4041].

[5] UTfit collaboration, *New UTfit analysis of the unitarity triangle in the Cabibbo–Kobayashi–Maskawa scheme*, Rend. Lincei Sci. Fis. Nat. **34** (2023) 37 [2212.03894].

[6] CDF collaboration, *Observation of B_s^0-$\bar{B}_s^0$ oscillations*, Phys. Rev. Lett. **97** (2006) 242003 [hep-ex/0609040].

[7] C.-W. Chiang, A. Datta, M. Duraisamy, D. London, M. Nagashima and A. Szynkman, *New physics in $B_s^0 \to J/\psi\, \phi(1020)$: a general analysis*, JHEP **04** (2010) 031 [0910.2929].

[8] M. Artuso, G. Borissov and A. Lenz, *CP violation in the B_s^0 system*, Rev. Mod. Phys. **88** (2016) 045002 [1511.09466].

[9] D0 collaboration, *Measurement of B_s^0 mixing parameters from the flavor-tagged decay $B_s^0 \to J/\psi\, \phi(1020)$*, Phys. Rev. Lett. **101** (2008) 241801 [0802.2255].

[10] D0 collaboration, *Measurement of the CP-violating phase $\phi_s^{J/\psi\phi}$ using the flavor-tagged decay $B_s^0 \to J/\psi\, \phi(1020)$ in 8 fb^{-1} of $p\bar{p}$ collisions*, Phys. Rev. D **85** (2012) 032006 [1109.3166].

[11] CDF collaboration, *First flavor-tagged determination of bounds on mixing-induced CP violation in $B_s^0 \to J/\psi\, \phi(1020)$ decays*, Phys. Rev. Lett. **100** (2008) 161802 [0712.2397].

[12] CDF collaboration, *Measurement of the CP-violating phase $\beta_s^{J/\psi\phi}$ in $B_s^0 \to J/\psi\, \phi(1020)$ decays with the CDF II detector*, Phys. Rev. D **85** (2012) 072002 [1112.1726].

[13] CDF collaboration, *Measurement of the bottom-strange meson mixing phase in the full CDF data set*, *Phys. Rev. Lett.* **109** (2012) 171802 [1208.2967].

[14] CMS collaboration, *Measurement of the CP-violating weak phase ϕ_s and the decay width difference $\Delta\Gamma_s$ using the $B_s^0 \to J/\psi\,\phi(1020)$ decay channel in pp collisions at $\sqrt{s} = 8$ TeV*, *Phys. Lett. B* **757** (2016) 97 [1507.07527].

[15] CMS collaboration, *Measurement of the CP-violating phase ϕ_s in the $B_s^0 \to J/\psi\,\phi(1020) \to \mu^+\mu^-\,K^+K^-$ channel in proton-proton collisions at $\sqrt{s} = 13$ TeV*, *Phys. Lett. B* **816** (2021) 136188 [2007.02434].

[16] LHCb collaboration, *Measurement of the CP-violating phase ϕ_s in $\bar{B}_s^0 \to J/\psi\,\pi^+\pi^-$ decays*, *Phys. Lett. B* **713** (2012) 378 [1204.5675].

[17] LHCb collaboration, *Measurement of CP violation and the B_s^0 meson decay width difference with $B_s^0 \to J/\psi\,K^+K^-$ and $B_s^0 \to J/\psi\,\pi^+\pi^-$ decays*, *Phys. Rev. D* **87** (2013) 112010 [1304.2600].

[18] LHCb collaboration, *Measurement of the CP-violating phase ϕ_s in $\bar{B}_s^0 \to J/\psi\,\pi^+\pi^-$ decays*, *Phys. Lett. B* **736** (2014) 186 [1405.4140].

[19] LHCb collaboration, *Precision measurement of CP violation in $B_s^0 \to J/\psi\,K^+K^-$ decays*, *Phys. Rev. Lett.* **114** (2015) 041801 [1411.3104].

[20] LHCb collaboration, *Improved measurement of CP violation parameters in $B_s^0 \to J/\psi\,K^+K^-$ decays in the vicinity of the $\phi(1020)$*, *Phys. Rev. Lett.* **132** (2024) 051802 [2308.01468].

[21] LHCb collaboration, *Measurement of the CP-violating phase ϕ_s in $\bar{B}_s^0 \to D_s^+D_s^-$ decays*, *Phys. Rev. Lett.* **113** (2014) 211801 [1409.4619].

[22] LHCb collaboration, *First study of the CP-violating phase and decay-width difference in $B_s^0 \to \psi\,\phi$*, *Phys. Lett. B* **762** (2016) 253 [1608.04855].

[23] ATLAS collaboration, *Time-dependent angular analysis of the decay $B_s^0 \to J/\psi\,\phi(1020)$ and extraction of $\Delta\Gamma_s$ and the CP-violating weak phase ϕ_s by ATLAS*, *JHEP* **12** (2012) 072 [1208.0572].

[24] ATLAS collaboration, *Flavor tagged time-dependent angular analysis of the $B_s^0 \to J/\psi\,\phi(1020)$ decay and extraction of $\Delta\Gamma_s$ and the weak phase ϕ_s in ATLAS*, *Phys. Rev. D* **90** (2014) 052007 [1407.1796].

[25] ATLAS collaboration, *Measurement of the CP-violating phase ϕ_s and the B_s^0 meson decay width difference with $B_s^0 \to J/\psi\,\phi(1020)$ decays in ATLAS*, *JHEP* **12** (2016) 072 [1601.03297].

[26] ATLAS collaboration, *Measurement of the CP-violating phase ϕ_s in $B_s^0 \to J/\psi\,\phi(1020)$ decays in ATLAS at 13 TeV*, *Eur. Phys. J. C* **81** (2021) 342 [2001.07115].

[27] CMS collaboration, *The CMS experiment at the CERN LHC*, *JINST* **3** (2008) S08004.

[28] CMS collaboration, *Development of the CMS detector for the CERN LHC Run 3*, *JINST* **19** (2024) P05064 [2309.05466].

[29] CMS collaboration, *Precision luminosity measurement in proton-proton collisions at $\sqrt{s}$ = 13 TeV in 2015 and 2016 at CMS*, *Eur. Phys. J. C* **81** (2021) 800 [2104.01927].

[30] CMS collaboration, *CMS luminosity measurement for the 2017 data-taking period at $\sqrt{s}$ = 13 TeV*, CMS Physics Analysis Summary CMS-PAS-LUM-17-004 (2018).

[31] CMS collaboration, *CMS luminosity measurement for the 2018 data-taking period at $\sqrt{s}$ = 13 TeV*, CMS Physics Analysis Summary CMS-PAS-LUM-18-002 (2019).

[32] CMS collaboration, *Evidence for CP violation and measurement of CP-violating parameters in $B^0_s \to J/\psi\ \phi(1020)$ decays in pp collisions at $\sqrt{s}$ = 13 TeV*, 2412.19952.

[33] A.S. Dighe, I. Dunietz, H.J. Lipkin and J.L. Rosner, *Angular distributions and lifetime differences in $B^0_s \to J/\psi\ \phi(1020)$ decays*, *Phys. Lett. B* **369** (1996) 144 [hep-ph/9511363].

[34] A. Lenz and G. Tetlalmatzi-Xolocotzi, *Model-independent bounds on new physics effects in non-leptonic tree-level decays of B-mesons*, *JHEP* **07** (2020) 177 [1912.07621].