PROCEEDINGS OF SCIENCE

Studies of *CP* violation at Belle and Belle II

Radek Žlebčík[a,*]

[a] *INFN, via Valerio 2, Trieste, Italy*

E-mail: Radek.Zlebcik@ts.infn.it

We review the Belle II measurements related to the *CP* violation which are based on Belle II data collected between 2019-2022 and corresponding to $365\,\mathrm{fb}^{-1}$. The data were taken in the e^+e^- collisions at the $\Upsilon(4S)$ resonance energy $\sqrt{s} = 10.58\,\mathrm{GeV}$. The discussed results include the time-dependent measurements of the $\sin 2\phi_1$ parameter in tree-dominated and loop-dominated B^0 decays, as well as measurements contributing to the global fit of ϕ_2. All of the presented measurements are statistically limited and are expected to improve with future data taking.

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*Speaker

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1. Introduction

Since the discovery of CP violation in the B^0 meson system in 2001 by the Belle and BaBar experiments [1, 2], the B factories, where $B\bar{B}$ pairs are produced in e^+e^- collisions, have played a crucial role in testing CP symmetry. In the Standard Model, CP violation arises from a complex phase in the Cabibbo-Kobayashi-Maskawa (CKM) matrix [3]. Rather than measuring this phase directly, it is advantageous to study the so-called Unitarity Triangle (UT), which is derived from the CKM matrix, however its angles and sides are well-defined physical observables that do not depend on the phase convention. Since the turn of the millennium, measurements from the B factories and LHCb have significantly improved the precision of the UT parameters [4]. These measurements over-constrain the UT, providing sensitivity to potential deviations from CKM matrix unitarity. Such deviations, predicted in various New Physics scenarios, could manifest, for example, if the triangle's angles do not sum to 180 degrees.

This report presents recent Belle II measurements constraining the UT angles ϕ_1/β and ϕ_2/α. Thanks to the clean event topology of the $e^+e^- \to \Upsilon(4S) \to B\bar{B}$ process, where the 4-momentum conservation between the initial and final states can be exploited, B factories are particularly well-suited for studying final states involving photons, π^0s, or neutrinos[5]. This advantage is evident in the measurement of ϕ_1 using penguin-dominated $b \to s$ transitions, such as $B^0 \to \eta' K_S$, where the Standard Model contribution is suppressed, allowing for enhanced sensitivity to the New Physics.

The B factories are also the driving force in determining the angle ϕ_2, which is extracted from analyses of all charge combinations of the $B \to \pi\pi$, $B \to \rho\pi$, and $B \to \rho\rho$ decays.

2. Measurements of ϕ_1/β

Angle $\phi_1 = \arg[-(V_{cd}V^*_{cb})/(V_{td}V^*_{tb})]$ is the best-known angle of the UT and its precise determination is a standard benchmark for the time-dependent CP violation analysis framework, where both B mesons vertices are measured. The signal B^0 is the fully reconstructed B meson decaying to the CP eigenstate while the other B^0 meson decays inclusively and its flavor is determined using the Flavour tagging algorithm. Compared to Belle or BaBar the Belle II analyses also profit from smaller interaction region (so-called "nano-beam" scheme) which can be used as a constraint in the vertex fitting, leading to better resolution of B vertices [6].

At Belle II we developed a new Flavor tagging algorithm based on the Graph Neural Network (GNN) architecture [7] which is trained on the Monte Carlo simulated data and compared to the category-based flavor tagging which was used at Belle it has 20% higher effective tagging efficiency. The effective tagging efficiencies were calibrated on data using $B \to D^{(*)}\pi$ decays. The performance comparison of the two flavor taggers is shown in Figure 1, where qr is the discriminator between $\bar{B}^0$ ($qr = -1$) and B^0 ($qr = 1$) flavor states.

We used the new GNN flavor tagger to measure the $\sin 2\phi_1$ in the "golden" $B^0 \to J/\psi K_S$ decays mode by fitting the Δt distribution (Figure 1). The Δt is the time difference between the B^0 decay times, where the times are measured in the proper time frames of the B mesons. The measured value of mixing-induced CP violation parameter S, $S = 0.724 \pm 0.035 \pm 0.009$, is in agreement with the world average [4] which is dominated by the LHCb measurement [8]. The Belle II measurement of S is still statistically limited, however, thanks to the usage of the GNN

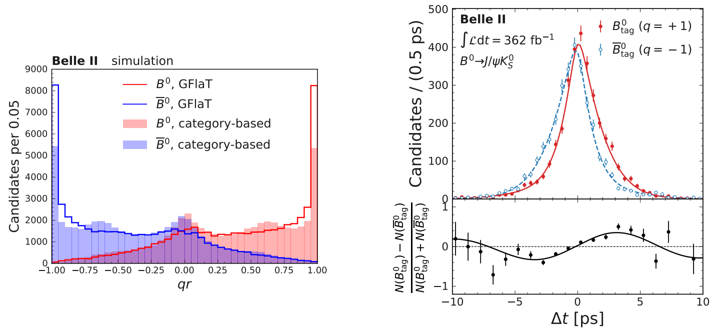

Figure 1: The histogram of the qr discriminator comparing the performance of the GNN and category-based flavor tagger for the MC events (left) and the Δt distribution in the $B^0 \to J/\psi K_S$ decays (right) [7].

flavor tagger the statistical uncertainty is smaller than the one of BaBar result [9] although the Belle II data have lower integrated luminosity.

The S parameter is up to a small correction from the "penguin pollution" of the decay amplitude equal to $\sin 2\phi_1$. For the $\sin 2\phi_1$ measurement LHCb has the advantage of a much larger data sample and the higher boost of the B mesons which leads to better Δt resolution. However, in the future, the theoretical uncertainty related to the penguin contribution in the $B^0 \to J/\psi K_S$ decay amplitude can limit the precision of the $\sin 2\phi_1$. Fortunately, penguin contribution can be constrained using $B^0 \to J/\psi \pi^0$ decays where the tree level contribution is color suppressed and therefore, the loop contribution, which is similar as in the $B^0 \to J/\psi K_S$ decays, plays a much larger role. The decay mode includes π^0 in the final states which makes it hardly accessible at LHCb while Belle II is a perfect place for this measurement. The value of S measured by Belle II for this decay mode, $S = -0.88 \pm 0.17 \pm 0.03$, is within the uncertainty compatible with the world average $\sin 2\phi_1$ value and it is the most precise measurement of the S parameter in this decay mode. As the measurement is dominated by statistical uncertainty, with more data we can expect a non-trivial impact of the penguin component in this decay mode. The measured distributions of the ΔE variable (used for the signal selection) and the Δt variable in the $B^0 \to J/\psi \pi^0$ analysis are shown in Figure 2.

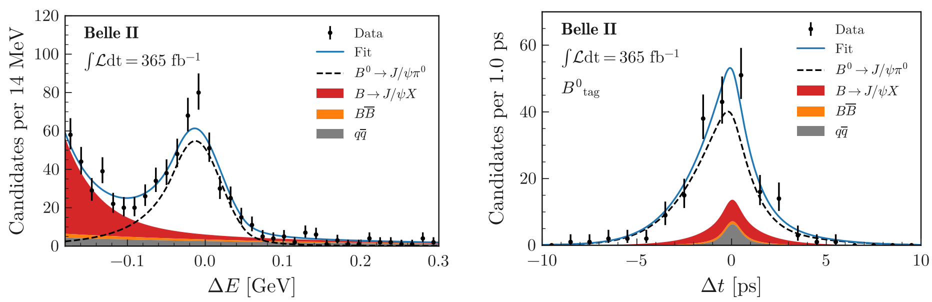

Figure 2: The $\Delta E = E^*_B - E^*_{\rm beam}$ distribution in the $B^0 \to J/\psi \pi^0$ decay (left) and the Δt distribution in the $B^0 \to J/\psi \pi^0$ decay (right) [10].

One of the main goals of the Belle II experiment is to measure the mixing-induced (S) and direct (C) CP violation parameters in the $b \to s$ loop transitions, where the New Physics can be more pronounced. The final states of these processes are only accessible by the e^+e^- B factories and, therefore, represent a unique way to hunt for the deviations of the CP phase w.r.t. the Standard Model predictions. Two well-known examples of these decay modes measured by Belle II are $B^0 \to \eta' K_S$ [11] and $B^0 \to \phi K_S$ [12], where the measured values of S and C are in agreement with the world average $\sin 2\beta$ value, but more data are needed to surpass the precision of the Belle measurements and have tighter constrains on the deviations from the Standard Model.

3. Measurements of ϕ_2/α

The angle $\phi_2 = \arg[-V_{td}V_{tb}^*/V_{ud}V_{ub}^*]$ which is the least known angle of the UT is measured in the $b \to u\bar{u}d$ decays using processes as $B \to \pi\pi$, $B \to \rho\pi$ and $B \to \rho\rho$. The tree-level contribution to the process amplitude is double-Cabibbo suppressed and, therefore, the loop-level contribution has a comparable size and cannot be neglected. To separate the tree-level component from the loop component which has different phase, the Gronau-London isospin relations [13] are used. To fully utilize the power of the isospin relations, the CP violation parameters S, C as well as the branching fractions for all relevant charge combinations of the $B \to \pi\pi$, $B \to \rho\pi$ and $B \to \rho\rho$ processes should be measured. Fortunately, there is some redundancy in the ϕ_2 fit and, for example, the fit can proceed without $S_{\pi^0\pi^0}$, where the absence of the B decay vertex forbids the time-dependent analysis.

Recently, Belle II measured the branching fraction and the direct CP asymmetry in the $B^0 \to \pi^+\pi^-$ decays [14]. This process with four photons in the final state benefits from good Belle II calorimeter and the clear event topology, while at LHCb the background suppression would be very challenging. The measured values of branching fraction and direct CP asymmetry, $\mathcal{B} = (1.26 \pm 0.20 \pm 0.11) \times 10^{-6}$ and $A_{CP} = 0.06 \pm 0.30 \pm 0.06$, are consistent with the world average [4]. Thanks to the superior detector performance and GNN flavor tagger, these values have higher precision than the world average values and, especially, surpass the Belle determination [15]. An example of the fit projections for the ΔE and $M_{\rm bc}$ variables is shown in Figure 3. The global

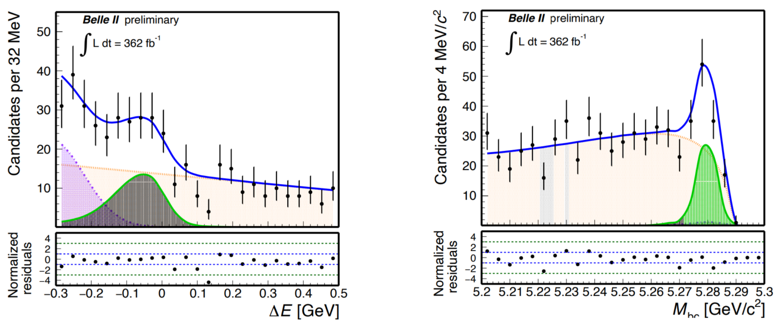

Figure 3: The $\Delta E = E_B^* - E_{\rm beam}^*$ distribution (left) and the $M_{\rm bc} = \sqrt{(E_{\rm beam}^*)^2 - (p_B^*)^2}$ distribution (right) in the $B^0 \to \pi^+\pi^-$ decays [14]. The signal component in the fit is depicted as green line.

maximum likelihood fit is performed in 4 variables, the ΔE, $M_{\rm bc}$, the continuum suppression variable and the wrong tag probability.

In addition to the $B^0 \to \pi^0\pi^0$ decay, Belle II also measured the branching fractions of the other two charge combinations, i.e. $B^0 \to \pi^+\pi^-$ and $B^+ \to \pi^+\pi^0$ [16], where the measurement of the $B^0 \to \pi^+\pi^-$ decay rate has the world-leading accuracy.

The ϕ_2 value can be also constrained uning the $B \to \rho\rho$ decays, where compared to the $B \to \pi\pi$ decays, the $B \to \rho\rho$ decays have fewer ambiguities in the ϕ_2 angle values [4].

Belle II measured *CP* violation parameters and the branching fraction for the $B^0 \to \rho^+\rho^-$ decays [17], where the vector meson ρ^+ decays to $\pi^+\pi^0$. The experimental signature of this decay mode is two tracks and four photons which makes it challenging for LHCb. Belle II performed full angular time-dependent analysis, measuring parameters S and C as well as the branching fraction $\mathcal{B}$ and the longitudinal polarization f_L of the ρ mesons (see Figure 4). The measured values

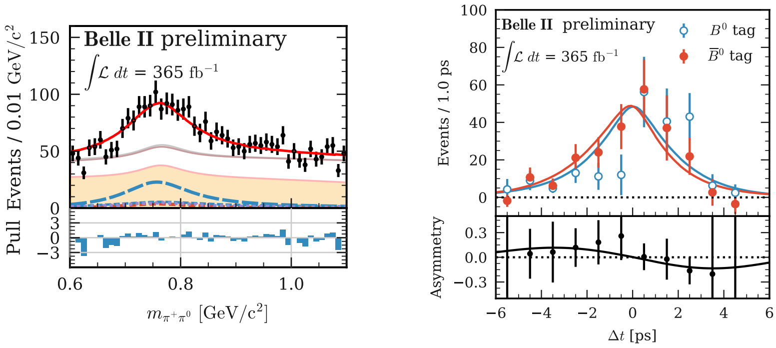

Figure 4: On the left is the histogram of the ρ^+ invariant mass, the main background originates from the light quark processes (orange band) and other $B\bar{B}$ decays (red hatched band). The plot is the Δt distribution in the $B^0 \to \rho^+\rho^-$ decays [17].

$S = -0.26 \pm 0.19 \pm 0.08$, $C = -0.02 \pm 0.12^{+0.06}_{-0.05}$ and $\mathcal{B} = (2.88^{+0.23+0.29}_{-0.22-0.27}) \times 10^{-5}$ are consistent with Belle and BaBar measurements. The longitudinal polarization of ρ^+, $f_L = 0.921^{+0.024+0.017}_{-0.025-0.015}$, is about 2σ lower than the world average value [4].

We tested the impact of the Belle II $B^0 \to \rho^+\rho^-$ measurement on the ϕ_2 determination by performing the ϕ_2 fit using $B \to \rho\rho$ decay modes with or without the Belle II measurement. The ϕ_2 value when the Belle II measurement is included is $(92.6^{+4.5}_{-4.8})^\circ$, compared to $(91.5^{+4.5}_{-5.4})^\circ$ without it. That means that the Belle II data leads in 7% improvement in the ϕ_2 determination. Note, that the current world average value $\phi_2 = 84.1^{+4.5}_{-3.8}$ [4] is slightly lower, mainly due to the contribution from the $B \to \rho\pi$ decays.

4. Conclusions

The Belle II detector is an excellent machine to probe the description of the *CP* violation by the Standard Model. It excels for processes with missing energy, photons or high combinatorial background. We presented several measurements related to the determination of UT angles ϕ_1/β and ϕ_2/α, all of them were based on Run 1 data of integrated luminosity 365 fb^{-1}.

Two examples are the analyses of $B^0 \to J/\psi\pi^0$ and $B^0 \to \pi^0\pi^0$ decay modes, both with the world-leading accuracy. The time-dependent *CP* violation analysis of the $B^0 \to J/\psi\pi^0$ constrains the theoretical uncertainty of $\sin 2\phi_1$ determination originating from the penguin component to the amplitude which will be important when LHCb and Belle II collect more data. The measurement of the branching fraction and *CP* asymmetry in $B^0 \to \pi^0\pi^0$ represents an important input to the global ϕ_2 fit.

All the presented measurements are statistically limited and will improve significantly when Belle II collects more data.

References

[1] Belle collaboration, *Observation of large CP violation in the neutral B meson system*, *Phys. Rev. Lett.* **87** (2001) 091802 [hep-ex/0107061].

[2] BaBar collaboration, *Observation of CP violation in the B^0 meson system*, *Phys. Rev. Lett.* **87** (2001) 091801 [hep-ex/0107013].

[3] M. Kobayashi and T. Maskawa, *CP Violation in the Renormalizable Theory of Weak Interaction*, *Prog. Theor. Phys.* **49** (1973) 652.

[4] Heavy Flavor Averaging Group (HFLAV) collaboration, *Averages of b-hadron, c-hadron, and τ-lepton properties as of 2023*, 2411.18639.

[5] BaBar, Belle collaboration, *The Physics of the B Factories*, *Eur. Phys. J. C* **74** (2014) 3026 [1406.6311].

[6] R. Zlebcik, *CTD2022: The Tracking at Belle II*, June, 2023. 10.5281/zenodo.8119739.

[7] Belle-II collaboration, *New graph-neural-network flavor tagger for Belle II and measurement of* $\sin 2\phi_1$ *in $B^0 \to J/\psi K^0_S$ decays*, *Phys. Rev. D* **110** (2024) 012001 [2402.17260].

[8] LHCb collaboration, *Measurement of CP Violation in $B^0 \to \psi(\to \ell^+\ell^-)K^0_S(\to \pi^+\pi^-)$ Decays*, *Phys. Rev. Lett.* **132** (2024) 021801 [2309.09728].

[9] BaBar collaboration, *Measurement of Time-Dependent CP Asymmetry in $B^0 \to c\bar{c}K^{(*)0}$ Decays*, *Phys. Rev. D* **79** (2009) 072009 [0902.1708].

[10] Belle-II collaboration, *Observation of time-dependent CP violation and measurement of the branching fraction of $B^0 \to J/\psi\pi^0$ decays*, *Phys. Rev. D* **111** (2025) 012011 [2410.08622].

[11] Belle-II collaboration, *Measurement of CP asymmetries in $B^0 \to \eta' K^0_S$ decays at Belle II*, *Phys. Rev. D* **110** (2024) 112002 [2402.03713].

[12] Belle-II collaboration, *Measurement of CP asymmetries in $B^0 \to \phi K^0_S$ decays with Belle II*, *Phys. Rev. D* **108** (2023) 072012 [2307.02802].

[13] M. Gronau and D. London, *Isospin analysis of CP asymmetries in B decays*, *Phys. Rev. Lett.* **65** (1990) 3381.

[14] S. Raiz, “Measurements of hadronic B decay rates at Belle and Belle II.” May, 2024.

[15] Belle collaboration, *Measurement of the branching fraction and CP asymmetry in $B^0 \to \pi^0\pi^0$ decays, and an improved constraint on ϕ_2*, *Phys. Rev. D* **96** (2017) 032007 [1705.02083].

[16] Belle-II collaboration, *Measurement of branching fractions and direct CP asymmetries for $B \to K\pi$ and $B \to \pi\pi$ decays at Belle II*, Phys. Rev. D **109** (2024) 012001 [2310.06381].

[17] Belle-II collaboration, *Measurement of the branching fraction, polarization, and time-dependent CP asymmetry in $B^0 \to \rho^+\rho^-$ decays and constraint on the CKM angle ϕ_2*, 2412.19624.