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Recent time-dependent measurements of *CP* violation at Belle II

Oskar Tittel[a,*] **on behalf of the Belle II collaboration**

[a] *Max-Planck-Institute for Physics, Föhringer Ring 6, 80805 Munich, Germany*

E-mail: otittel@mpp.mpg.de

We report on new time-dependent *CP* violation measurements using the full dataset of Belle II collected between 2019-2022 and on improved analysis software. Hadronic penguin decays, which proceed via a $b \to q\bar{q}s$ transition, are loop dominated, and thus sensitive to new physics. in this class, we measure the time-dependent *CP* violation parameters $C_{CP} = -0.19 \pm 0.08 \pm 0.03$ and $S_{CP} = 0.67 \pm 0.10 \pm 0.04$ in the decay $B^0 \to \eta' K^0_S$. In $b \to \gamma(s, d)$ transitions, radiative penguin decays, the mixing-induced *CP* violation is suppressed by the polarization of the photon. New physics contributions could, however, lead to a sizable mixing-induced term. Here, we measure $C_{CP} = 0.10 \pm 0.13 \pm 0.03$ and $S_{CP} = 0.00 \pm 0.27 \pm 0.04$ in exclusive decays to $B^0 \to K^{*0}\gamma$ and $C_{CP} = -0.06 \pm 0.25 \pm 0.07$ and $S_{CP} = 0.04 \pm 0.45 \pm 0.10$ in inclusive $B^0 \to K^0_S \pi^0 \gamma$ decays excluding a K^{*0} mass-region. These measurements require a flavor tagging algorithm. A flavor tagger based on a graph neural network was developed at Belle II. The increased effective tagging efficiency of $\epsilon_{tag} = (37.40 \pm 0.43 \pm 0.34)\%$ is validated on the channel $B^0 \to J/\psi K^0_S$. The measured values are $C_{CP} = -0.035 \pm 0.026 \pm 0.012$ and $S_{CP} = 0.724 \pm 0.035 \pm 0.014$.

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1. Motivation

In the standard model (SM), *CP* violation is described by the unitary Cabibbo-Kobayashi-Maskawa (CKM) matrix. Since the CKM matrix is a 3×3 matrix, it provides six unitarity conditions which can be visualized as triangles in the complex plane. Any breaking of the unitarity condition, which manifests itself in a non-closed triangle, is a direct hint for new physics (NP). The CKM triangle of the B meson system is of particular interest here, since all sides of the triangle are of the same order of magnitude, which also leads to comparable sizes of the interior angles.

A key element of the Belle II physics program is the measurement of all properties of this triangle. The angle $\phi_1 \equiv \beta$ has been measured by the Belle, BaBar and LHCb collaborations to high precision in the SM $b \to c\bar{c}s$ quark transitions [1]. In this transition, the angle is related to the mixing-induced *CP* violation parameter S_{CP}, given by $S_{CP} = -\eta_{CP} \sin 2\phi_1$, where η_{CP} is the CP eigenvalue of the decay final state. The current world average of $S_{CP} = 0.699 \pm 0.017$ and the, most recent LHCb result of $S_{CP} = 0.717 \pm 0.015$, which is not included in the current average, are in agreement with the SM prediction [1, 2]. Searches for physics beyond the SM expectation can be performed on channels in which the tree amplitude is suppressed. These decays, which allow for a sizable effect of NP, are often difficult to measure due to low branching fractions (BF) and the presence of neutral final state particles. Belle II has the unique opportunity to search for NP here, due to its precise vertex measurements and neutral particle reconstruction capabilities.

2. Measurement of *CP* violation parameters at Belle II

When a neutral B meson decays into a *CP*-eigenstate (f_{CP}), the interference between the neutral $B\overline{B}$ mixing amplitude and the decay amplitude gives rise to mixing-induced *CP* violation. Here, ϕ_1 dominantly contributes to the $B\overline{B}$ mixing phase. The corresponding *CP* violation parameters can be deduced from the measurement of the time-dependent decay rates of a B^0 and a $\overline{B}^0$ to the specific *CP*-eigenstate. The *CP* violation parameters are related to the time-dependent decay rate asymmetry by the following equation:

$$\mathcal{A}_{CP}(\Delta t) = \frac{N(\overline{B}^0 \to f_{CP}) - N(B^0 \to f_{CP})}{N(\overline{B}^0 \to f_{CP}) + N(B^0 \to f_{CP})}(\Delta t) = S_{CP} \sin(\Delta m_d \Delta t) - C_{CP} \cos(\Delta m_d \Delta t). \quad (1)$$

Here, S_{CP} and C_{CP} are the mixing-induced and direct *CP* violation parameters, respectively, while Δm_d describes the mixing frequency of the neutral B meson system. The time difference between the decay of the B meson and an initial state, in which the B flavor is known, is denoted by Δt.

At Belle II, the asymmetric-energy collision of electrons and positrons, tuned to the $\Upsilon(4S)$ resonance, produce pairs of $B\overline{B}$ mesons almost at rest in the center-of-mass system. The created B mesons are initially quantum entangled with each other. Thus, determining the flavor of one of the B mesons (B_{tag}) from its decay also identifies (or tags) the other B meson (B_{sig}) flavor to be opposite at that moment. This process is called 'flavor tagging'. The proper decay time difference of the two

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mesons is calculated from the boost of the asymmetric-energy collision and the difference of the vertex positions of the two B mesons along the boost direction. Hence, a high effective flavor tagging efficiency (currently $\epsilon_{tag} = (31.7 \pm 0.4)\%$) and good spatial resolution (currently $\Delta z < 30\,\mu\text{m}$) are vital for precise time-dependent *CP* violation measurements at Belle II. The current Belle II full data, collected between 2019 and 2022, has approximately 362fb^{-1} of integrated luminosity. [3, 4]

3. Hadronic Penguin Decays

One class of decays, which are sensitive to NP contributions, is decays via the $b \to q\overline{q}s$ transition. These so called 'hadronic penguin decays' are dominated by a loop diagram, which allows for additional contributions of NP particles [5]. In the following, the analysis of one decay channel from this class is presented.

$B^0 \to \eta' K_S^0$:

The channel $B^0 \to \eta' K_S^0$ has a high BF with respect to other penguin-mediated decays to *CP*-eigenstates. In addition, there is a clean SM prediction in which the relation $S_{CP} = -\eta_{CP} \sin 2\phi_1$ holds within 1% [5]. In this analysis, the signal candidates are reconstructed using the sub-decay channels ($\eta' \to \eta[\to \gamma\gamma]\pi^+\pi^-$) and ($\eta' \to \rho[\to \pi^+\pi^-]\gamma$). Random combinations of tracks from $e^+e^- \to q\overline{q}$ ($q = u, d, c, s$) events (continuum background) are the dominating source of background. These are suppressed by a specifically trained BDT based on event-shape variables. The fit is performed in two steps. First, a multidimensional fit, excluding Δt, is performed with most parameters of the signal and continuum background shape, including yields, floating. From the full Belle II dataset, 829 ± 35 total signal events for the two sub-channels are extracted in this step. In the second step, solely the parameters S_{CP} and C_{CP} are extracted from a multidimensional fit including Δt in the signal region. The fit procedure is validated using the control channel $B^\pm \to \eta' K^\pm$. Here, the value of $S_{CP} = -0.083 \pm 0.059$, in which the error is purely statistical, is in agreement with the expectation of no *CP* violation. The resulting values for $B^0 \to \eta' K_S^0$ and the corresponding plot of the decay time distributions, including background, are shown in Table 1 and Figure 1, respectively.

Table 1: Belle II measurement on 362fb^{-1} of integrated luminosity and world average of the *CP* violation parameters for the channel $B^0 \to \eta' K_S^0$.

Observable		Belle II (362fb^{-1})	World Average [1]
$B^0 \to \eta' K_S^0$	C_{CP}	$-0.19 \pm 0.08 \pm 0.03$	-0.05 ± 0.04
	S_{CP}	$0.67 \pm 0.10 \pm 0.04$	0.63 ± 0.06

This channel is uniquely available to Belle II due to the neutral particles in the final state and high background rates. The results are in agreement with the current world average and the SM expectation.

4. Radiative Penguin Decays

The second class of interesting decays are radiative penguin decays. Here, a photon is radiated in the loop of a $b \to \gamma(s, d)$ transition. Since the weak force is left-handed, the polarization of the

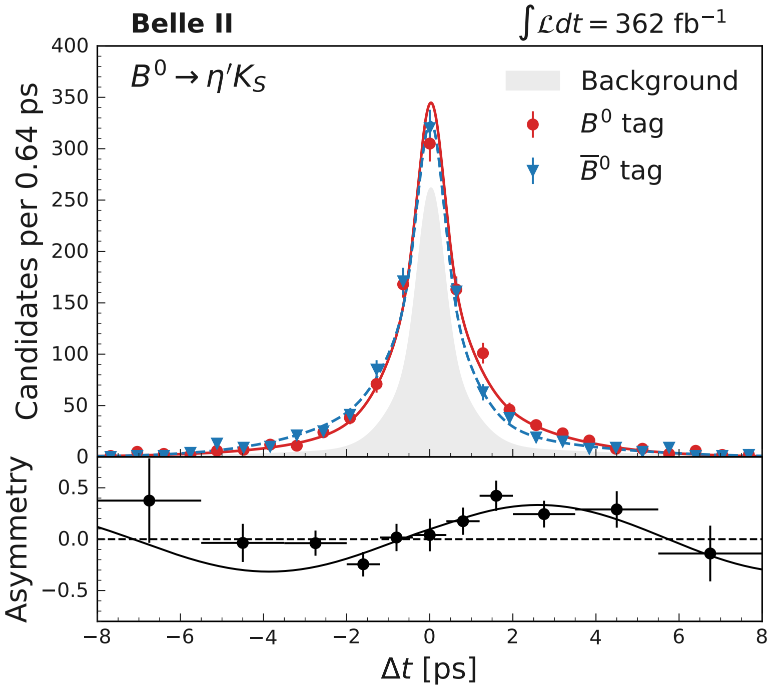

Figure 1: Distributions of the proper decay-time difference for B^0 and $\bar{B}^0$ tag cases including continuum background (above) and the resulting asymmetry after background subtraction (below).

photon strongly constrains the flavor of the initial state. Thus, the final state is not a *CP*-eigenstate and S_{CP} is suppressed by the helicity of the photon. However, possible NP contributions could lead to a significant mixing-induced *CP* violation.

$B^0 \to K_S^0 \pi^0 \gamma$:

In the case of $B^0 \to K_S^0 \pi^0 \gamma$, the expected value of S_{CP} within the SM is -0.035 ± 0.017 [6]. Since the average flight length of the K_S^0 before its decay is of the order of cm, there is no track in this decay coming directly from the signal decay vertex. This makes this analysis uniquely available to Belle II. The vertex reconstruction of the signal B meson is done by combining the reconstructed K_S^0 momentum with a constraint constructed from the position of the interaction point and the B_{sig} trajectory. Candidates with a poor vertex reconstruction are used for the extraction of C_{CP}, but are excluded for the time-dependent measurement. The main background here comes from fake photons from energetic π^0 and η decays which combine with a K_S^0 and a π^0 to form a signal candidate. A dedicated multi-variate algorithm has been trained to suppress this background. The exclusive B^0 decay $K^{*0}[\to K_S^0\pi^0]\gamma$ is considered separately to the inclusive decay to $K_S^0\pi^0\gamma$. The two cases are separated by the $K_S^0\pi^0$ mass: we select K^{*0} with $M_{K_S^0\pi^0} \in]0.8, 1.0[$ GeV/c^2 and the inclusive decay with $M_{K_S^0\pi^0} \in [0.6, 0.8]$ GeV/$c^2 \cup [1.0, 1.8]$ GeV/c^2. The measured results for both mass ranges with symmetric errors are presented in Table 2. The corresponding decay-time distributions are shown in Figure 2.

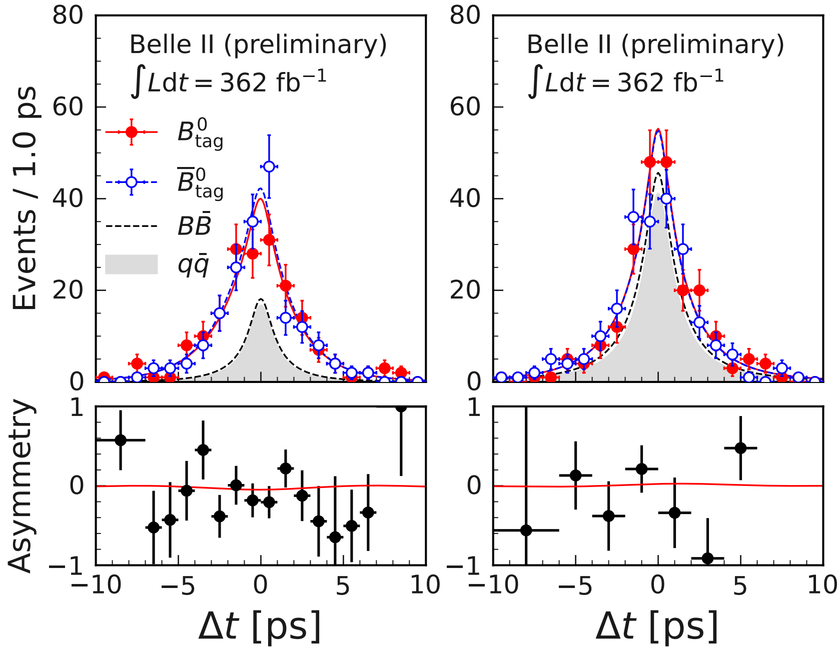

Figure 2: Distributions of the proper decay-time difference for B^0 and $\bar{B}^0$ tag cases including $q\bar{q}$ and $B\bar{B}$ background (above) and the resulting asymmetry after background subtraction (below). The plot for the exclusive decay via $B^0 \to K^{*0}\gamma$ is shown on the left, while the inclusive decay is shown on the right.

Table 2: Belle II measurements for 362fb^{-1} of integrated luminosity and world averages of the *CP* violation parameters for the channel $B^0 \to K^0_S\pi^0\gamma$, split up into the exclusive decay via $B^0 \to K^{*0}\gamma$ (above) and the inclusive decay (below).

Observable		Belle II (362fb^{-1})	World Average [1]
$B^0 \to K^{*0}\gamma$	C_{CP}	$0.10 \pm 0.13 \pm 0.03$	-0.04 ± 0.14
	S_{CP}	$0.00 \pm 0.27 \pm 0.04$	-0.16 ± 0.22
$B^0 \to K^0_S\pi^0\gamma$	C_{CP}	$-0.06 \pm 0.25 \pm 0.07$	
	S_{CP}	$0.04 \pm 0.45 \pm 0.10$	

The results are in agreement with the SM expectation and the current world averages. The Belle II results are the most precise results to-date.

5. Graph-Neural-Network Flavor Tagger

In order to achieve more world leading results, analysis technipues are constantly improved at Belle II. One recent improvement is the development of a new flavor tagger (GFlaT) based on a graph neural network. In contrast to the previous algorithm, the GFlaT uses inter-relational information between particles in the $B_{\rm tag}$ decay. Using this new approach, the effective tagging efficiency ϵ_{tag} has been improved from $\epsilon_{tag} = (31.68 \pm 0.45 \pm 0.41)\%$ to $\epsilon_{tag} = (37.40 \pm 0.43 \pm 0.34)\%$. This is an 18% increase in effective tagging efficiency.

$B^0 \to J/\psi K_S^0$:

To test the behavior of the new flavor tagger, the *CP* violation parameters of $B^0 \to J/\psi K_S^0$ have been measured. This channel is dominated by the $b \to c\bar{c}s$ transition, has a large BF, and a clean experimental signature. Thus, it serves as an optimal testing ground for GFlaT. The statistical uncertainty is reduced by about 8% compared to the same result with the conventional flavor tagger. The measured results agree with the expected values from the previous measurements.

Table 3: Belle II measurement from 362fb^{-1} of integrated luminosity, and world averages of the *CP* violation parameters of the channel $B^0 \to J/\psi K_S^0$.

Observable		Belle II (362fb^{-1})	World Average [1]
$B^0 \to J/\psi K_S^0$	C_{CP}	$-0.035 \pm 0.026 \pm 0.012$	0.000 ± 0.020
	S_{CP}	$0.724 \pm 0.035 \pm 0.014$	0.695 ± 0.019

6. Conclusion

Time-dependent *CP* violation is an active field of research in Belle II. Searches for new physics in several classes of decays as well as analysis technique improvements are performed. Three new results in these fields have been presented. Many channels of the covered decay classes are uniquely available to Belle II, due to the clean collision environment. In addition, several of the recent Belle II results are on par with the best measurements to date, or even world leading. As data taking restarts early 2024, and both software and hardware improvements have been achieved on the experiment, there are improved results to be expected from Belle II in the near future.

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