PROCEEDINGS OF SCIENCE

Time-dependent *CP* violation measurements at Belle II

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We report the measurements of time-dependent *CP* violation at Belle II. The benchmark measurements of B^0 lifetime (τ_{B^0}) and mixing frequency (Δm_d) and time-dependent *CP* asymmetries in $B^0 \to J/\psi K_S^0$ have been performed using $190\,\mathrm{fb}^{-1}$. These measurements are statistically limited and show excellent detector performance and readiness for analysis setup. We also present the *CP* asymmetries in $b \to q\overline{q}s$ transitions using $362\,\mathrm{fb}^{-1}$ which are very crucial to probe the effective value of $\sin 2\phi_1$ and sensitive for new physics appearing through loops. All results agree with previous determinations and some of them are already competitive with the world's best measurement.

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1. Introduction

Measurement of Cabbibo-Kobayashi-Maskawa (CKM) [1, 2] angles (ϕ_1, ϕ_2, ϕ_3) is very important in flavor physics program to test Standard Model (SM) and its extensions. Measurement of B^0 lifetime (τ_{B^0}) and mixing frequency (Δm_d) is important element to constrain the CKM matrix. Measurement of time-dependent *CP* violation in the $b \to q\bar{q}s$ transition is very sensitive to new physics as they proceed through flavor-changing-neutral-current loop transitions. These decays are also very important to probe the effective value of $\sin 2\phi_1$ [3]. There are several challenges to performing these types of decay such as low branching fractions ($\approx 10^{-5}$), neutral particles in the final state (π^0, K_S^0), B flavor tagging, and poor decay time resolution. Belle II has the unique environment to improve this measurement using excellent flavor tagging, vertex resolution, and neutral particle reconstruction.

Belle II, as described in [4], is a magnetic spectrometer that offers nearly full 4π solid-angle coverage. Its primary purpose is to accurately reconstruct the particles produced in e^+e^- collisions, which occur at the SuperKEKB collider [5], situated at the KEK laboratory in Tsukuba, Japan. Belle II has decreased the boost ($\beta\gamma$) from 0.43 to 0.29 compared to the original Belle experiment. To compensate for the reduced boost, two layers of pixel detector are installed just outside the interaction region. The data collection for the Belle II experiment started in March 2019. Due to the asymmetric energy beams, produced $B\overline{B}$ from $\Upsilon(4S)$ have some separation which is measured using a vertex detector. The proper decay time difference between the two B-meson (Δt) is measured using the separation between two B-meson vertex divided by the Lorentz boost factor ($\beta\gamma$). Belle II has achieved an enhanced Δt resolution thanks to its outstanding vertex precision, coupled with the utilization of the beam-constraint profile offered by the nano-beam scheme. In this proceeding, we will focus on the dataset corresponding to a total integrated luminosity of $362\,\text{fb}^{-1}$, which was collected during operations at the $\Upsilon(4S)$ resonance. Currently, SuperKEKB has the world-record maximum instantaneous luminosity of $4.7 \times 10^{34}\ \text{cm}^{-2}\text{s}^{-1}$.

2. Measurement of B^0 lifetime (τ_{B^0}), mixing frequency (Δm_d) and $\sin 2\phi_1$

When one of the B mesons goes to *CP* eigenstate (f_{CP}) and another one goes to flavor-specific tag-side final state (f_{tag}), the time-dependent decay rate is given by

$$\mathcal{P}(\Delta t, q) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}} \Big\{ 1 + q\,[S \sin(\Delta m_d \Delta t) - C \cos(\Delta m_d \Delta t)] \Big\}, \quad (1)$$

where $\Delta t = t_{CP} - t_{\text{tag}}$ is the proper decay time difference between two B-meson, τ_{B^0} is the B^0 lifetime, q is the flavor of the tag-side B meson (+1 for B^0 and -1 for $\bar{B}^0$), Δm_d is the $B^0 - \bar{B}^0$ mixing frequency, and C (the parameter C is also denoted as $-A$ in the literature) and S are the direct and mixing induced *CP* asymmetries. The flavor of the tag-side B-meson is determined using category-based flavor tagger algorithm [6] which uses inclusive properties of tracks that are not associated with *CP*-side particles. Measurement of τ_{B^0} and Δm_d is important to test both the QCD theory of strong interaction at low energy [7] and the CKM theory of weak interaction. In the SM, expected values of C and S in $B^0 \to J/\psi K_S^0$ decay are 0 and $\sin 2\phi_1$, respectively. We reconstruct 33000 signal $B^0 \to D^{(*)-}\pi^+$ decay [8] and 2755 signal $B^0 \to J/\psi K_S^0$ decay in a data sample corresponding to $190\,\text{fb}^{-1}$. Both analyses employ a similar methodology for fitting the energy difference between B meson and beam energy (ΔE) to identify signal events, followed by fitting the background-subtracted Δt distribution to assess the observables. To determine the *CP* asymmetries in the $B^0 \to J/\psi K_S^0$ decay, we use fixed values for the flavor tagger and resolution function parameters, which were previously determined for $B^0 \to D^{(*)-}\pi^+$. The background-substracted [9] Δt distribution for both the analyses is shown in Fig. 1. Measurement of lifetime, mixing frequency, and *CP* asymmetries are listed in Tab. 1 together with the world average values [10]. For the lifetime and mixing measurement, the major contributors to systematic uncertainty arise from the resolution function parameters set based on simulation and potential detector misalignment. For the $B^0 \to J/\psi K_S^0$ measurement, the major contribution to systematic uncertainty arises from the limited $B^0 \to D^{(*)-}\pi^+$ sample size which is used to determine flavor tagger and resolution function parameters. These results are statistically limited and do not reach the level of precision of world-leading measurement and exhibit systematic uncertainties on par with those seen in earlier-generation B-factories.

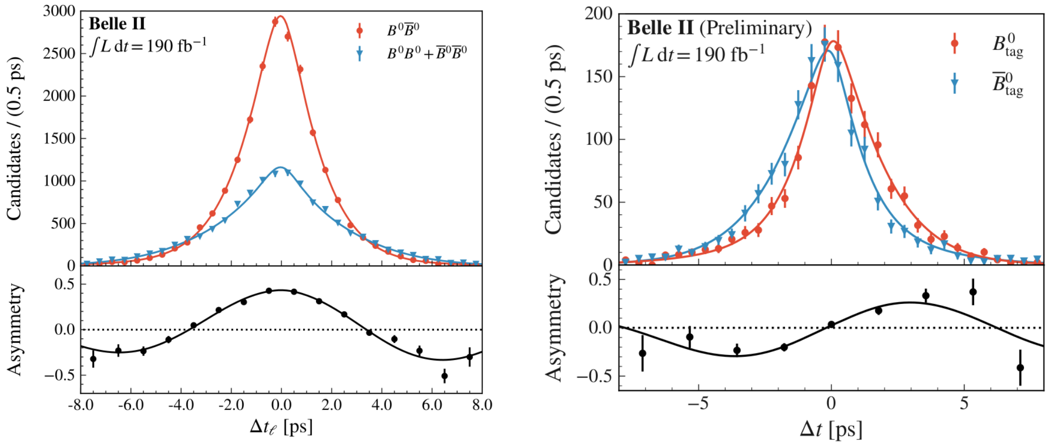

Figure 1: Background-substracted Δt distribution of $B^0 \to D^{(*)-}\pi^+$ (left) and $B^0 \to J/\psi K_S^0$ (right). Points with error bars represent data. For the left plot, same-flavor and opposite-flavor B-meson pairs are shown as blue and red curves, respectively and their asymmetry expressed as $[N(\mathrm{OF}) - \mathrm{N(SF)}]/[\mathrm{N(OF)} + \mathrm{N(SF)}]$, is shown below together with the fit projection. For the right plot, the fit projections corresponding to $q = +1$ and $q = -1$ tagged distributions are shown as red and blue curves, respectively and their asymmetry, expressed as $[N(B^0_{\mathrm{tag}}) - N(\bar{B}^0_{\mathrm{tag}})]/[N(B^0_{\mathrm{tag}}) + N(\bar{B}^0_{\mathrm{tag}})]$, is shown below together with the fit projection.

Table 1: Comparison between Belle II results (where the first uncertainties are statistical and the second are systematic) and world average value of B^0 lifetime, mixing frequency and *CP* asymmetries in $B^0 \to J/\psi K_S^0$ decay.

Observable	Belle II (190 fb^{-1})	World Average
τ_{B^0}	$1.499 \pm 0.013 \pm 0.008$ ps	1.519 ± 0.004 ps
Δm_d	$0.516 \pm 0.008 \pm 0.005$ ps^{-1}	0.5065 ± 0.0019 ps^{-1}
$C\ (B^0 \to J/\psi K_S^0)$	$-0.094 \pm 0.044^{+0.017}_{-0.042}$	-0.005 ± 0.015
$S\ (B^0 \to J/\psi K_S^0)$	$0.720 \pm 0.062 \pm 0.016$	0.699 ± 0.017

3. Measurement of $\sin 2\phi_1$ in $b \to q\bar{q}s$ transitions

$B^0 \to \phi K^0_S$, $B^0 \to K^0_S\pi^0$ and $B^0 \to K^0_S K^0_S K^0_S$ decays proceed through $b \to q\bar{q}s$ gluonic penguin transitions and are very sensitive to non-SM particles that appear through the loops. In addition, these decays provide excellent probes to the effective value of $\sin 2\phi_1$. We have reported the measurements of three decays using the Belle II data set corresponding to 362 fb^{-1}. These three analyses use a similar methodology to separate signal from background events. A multidimensional fit is performed using signal-determination variables; beam-energy constraint mass (M_{bc}), energy difference (ΔE), decay-time difference Δt, and transformed continuum suppression output (C_{out}). Flavor tagging parameters are fixed to the values determined from $B^0 \to D^{(*)-}\pi^+$ decay. Background-substracted Δt distribution is shown in Fig. 2. Measured *CP* asymmetries are listed in Tab. 2.

3.1 $B^0 \to \phi K^0_S$

The decay $B^0 \to \phi K^0_S$ has a similar resolution compared to the $B^0 \to J/\psi K^0_S$ decay as the decay vertex is well reconstructed from two prompt charged tracks of the $\phi \to K^+K^-$ decays. One of the challenges in the analysis is the contribution of non-resonant backgrounds from $B^0 \to K^+K^-K^0_S$ decays with a similar final state but opposite *CP* eigen state which eventually dilutes the *CP* asymmetry measurement. The non-resonant background is separated by including the cosine helicity angle in the multi-dimensional fit of M_{bc}, ΔE, C_{out}. The reconstructed signal and non-resonant yield are 162 ± 17 and 21 ± 12, respectively [11]. The full analysis procedure is validated with a control sample of $B^+ \to \phi K^+$ which features similar background, vertexing, and *CP* asymmetries. The sensitivity on C has a similar value compared to Belle [12] and BABAR [13] despite using a smaller data set. A similar quasi-two-body approach yields a 10% to 20% enhancement in S compared to the analysis performed with Belle [12] and BABAR [13]. The major contributors to systematic uncertainty arise from the fit model used to separate background from signal events.

3.2 $B^0 \to K^0_S\pi^0$

One of the challenges of this analysis is the absence of primary charged tracks, which leads to poor decay time resolution. We also need good performance of the neutral particle reconstruction. We divided the data set based on good and poor decay time resolution. While events with poor decay time resolution won't enhance the precision of S, they will contribute to improved precision for C. We combine the time-dependent and time-integrated measurements to improve the precision on C. The complete analysis procedure is validated by applying it to the $B^0 \to J/\psi K^0_S$ decay, in which no tracking information from the J/ψ is employed for vertexing the B meson. The number of reconstructed signal events is 415^{+26}_{-25} [14]. The precision achieved for parameter S is better (similar) to that obtained at Belle [16] (BABAR [15]) despite using the smaller data sample. The greater acceptance of the vertex detector, which enables better K^0_S reconstruction, along with improved continuum suppression, are key factors contributing to these competitive measurements. The major contributors to systematic uncertainty arise from possible *CP* asymmetry from $B\bar{B}$ background and resolution function parameters. We obtain an overall isospin test [17] of $I_{K\pi} = -0.03 \pm 0.13 \pm 0.04$ [18], where the first uncertainty is statistical and the second one is systematic. This result is consistent with SM prediction and comparable with the world's best measurement (-0.13 ± 0.11) despite using the smaller data set.

3.3 $B^0 \to K_S^0 K_S^0 K_S^0$

Similar to $B^0 \to K_S^0 \pi^0$, this decay mode presents a challenge since there are no primary charged tracks available for vertex reconstruction. The vertex is reconstructed by projecting the K_S^0 trajectory to the interaction region which is described by a three-dimensional Gaussian. Similar to $B^0 \to K_S^0 \pi^0$, the data set is divided into two categories to improve the precision on C. Furthermore, the parameters of the resolution function obtained through simulation are adjusted in the data by incorporating the $B^+ \to K_S^0 K_S^0 K^+$ control channel into the combined fit. The number of reconstructed signal events for good and poor decay time resolution are 158^{+14}_{-13} and 62 ± 9, respectively [19]. The major contributors to systematic uncertainty arise from bias related to the fit model and calibration of flavor tagging parameters.

4. Summary

In summary, the measurement of B^0 lifetime, mixing frequency, and *CP* asymmetries play an important role in sharpening the flavor picture. Belle II has unique access to the channel that offers a key test of SM. We reported measurement of B^0 lifetime and mixing frequency and $\sin 2\phi_1$ measurement in $B^0 \to J/\psi K_S^0$ decays using 190 fb^{-1} data set. Furthermore, we reported measurement of *CP* asymmetry in $b \to q\bar{q}s$ transitions using 362 fb^{-1} data set. Some measurements are already competitive with the world's best measurements despite having a smaller data set. Due to its exceptional vertex resolution and efficient reconstruction of neutral particles, Belle II is uniquely positioned to advance our current experimental knowledge of these decay modes.

Table 2: Comparison between Belle II results (where the first uncertainties are statistical and the second are systematic) and world average value of *CP* asymmetries in $b \to q\bar{q}s$ transitions.

Observable		Belle II (362 fb^{-1})	World Average
$B^0 \to \phi K_S^0$	C	$-0.31 \pm 0.20 \pm 0.05$	$+0.01 \pm 0.14$
	S	$+0.54 \pm 0.26^{+0.08}_{-0.06}$	$+0.74^{+0.13}_{-0.11}$
$B^0 \to K_S^0 \pi^0$	C	$-0.04^{+0.14}_{-0.15} \pm 0.05$	$+0.01 \pm 0.10$
	S	$+0.75^{+0.20}_{-0.23} \pm 0.04$	$+0.57 \pm 0.17$
$B^0 \to K_S^0 K_S^0 K_S^0$	C	$-0.07^{+0.20}_{-0.15} \pm 0.02$	$+0.15 \pm 0.12$
	S	$-1.37^{+0.35}_{-0.45} \pm 0.03$	-0.83 ± 0.17

References

[1] N. Cabibbo, Phys. Rev. Lett. **10**, 531 (1963).

[2] M. Kobayashi and T. Maskawa, Prog. Theo. Phys. **49**, 652 (1973).

[3] D. London and A. Soni, Phys. Lett. B **407**, 61 (1997).

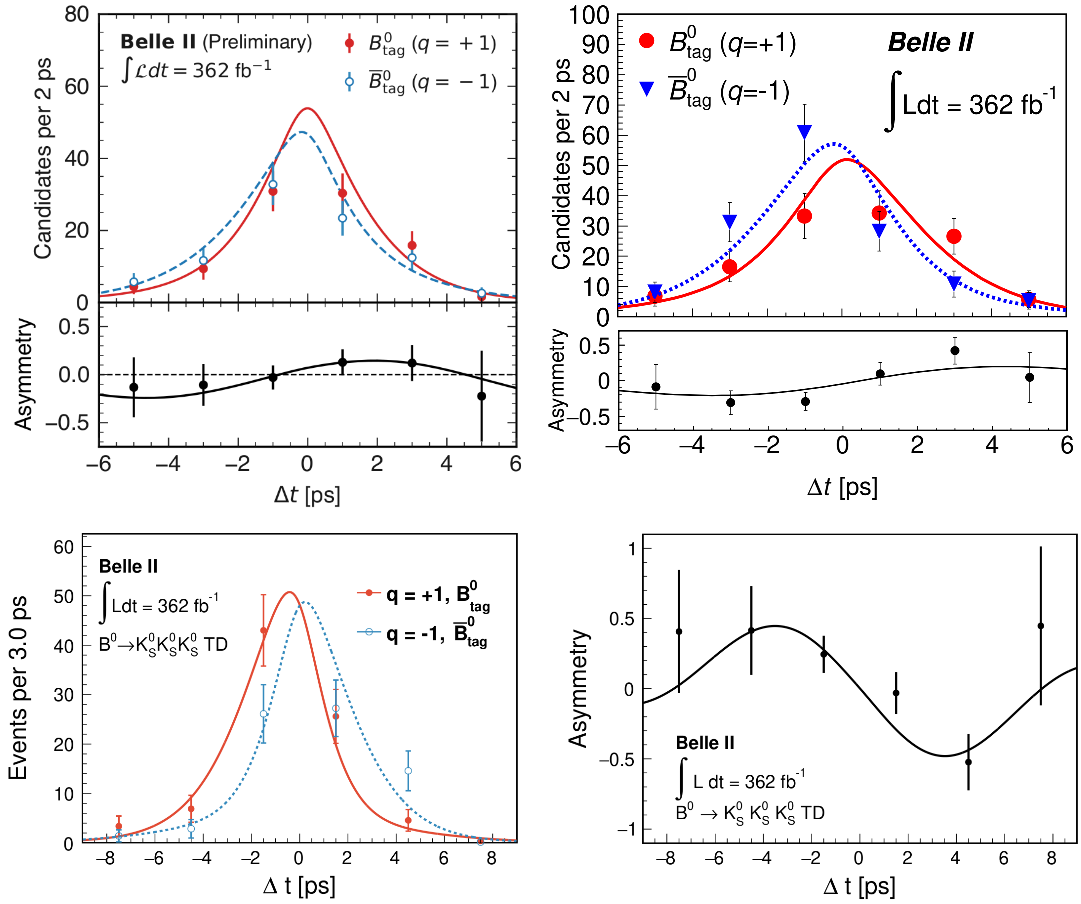

Figure 2: Background-substracted Δt distribution and *CP* asymmetries of $B^0 \to J/\psi K^0_S$ (top left), $B^0 \to K^0_S\pi^0$ (top right) and $B^0 \to K^0_S K^0_S K^0_S$ (bottom). Points with error bars represent data. The fit projections corresponding to $q = +1$ and $q = -1$ tagged distributions are shown as solid and dashed curves, respectively. The asymmetry, expressed as $[N(B^0_{\rm tag}) - N(\bar{B}^0_{\rm tag})]/[N(B^0_{\rm tag}) + N(\bar{B}^0_{\rm tag})]$, is shown below together with the fit projection.

[4] T. Abe *et al*. (Belle II Collaboration), arXiv:1011.0352.

[5] K. Akai *et al*. (SuperKEKB Group), Nucl. Instrum. Meth. A **907**, 188 (2018).

[6] F. Abudinén *et al*. (Belle II Collaboration), Eur. Phys. J. C **82**, 283 (2022).

[7] A. Lenz, Int. J. Mod. Phys. A **30**, 1543005 (2015).

[8] F. Abudinén *et al*. (Belle II Collaboration), Phys. Rev. D **107**, L091102 (2023).

[9] M. Pivk and F. R. Le Diberder, Nucl. Instrum. Meth. A **555**, 356 (2005).

[10] Y. Amhis *et al*. (Heavy Flavor Averaging Group), Phys. Rev. D **107**, 052008 (2023).

[11] I. Adachi *et al*. (Belle II Collaboration), Phys. Rev. D **108**, 072012 (2023).

[12] Y. Nakahama *et al*. (Belle Collaboration), Phys. Rev. D **82**, 073011 (2010).

[13] J. P. Lees *et al*. (*BABAR* Collaboration), Phys. Rev. D **85**, 112010 (2012).

[14] I. Adachi *et al*. (Belle II collaboration), Phys. Rev. Lett. **131**, 111803 (2023).

[15] B. Aubert *et al*. (*BABAR* Collaboration), Phys. Rev. D **79**, 052003 (2009).

[16] M. Fujikawa *et al*. (Belle Collaboration), Phys. Rev. D **81**, 011101(R) (2010).

[17] M. Gronau, Phys. Lett. B **627**, 82 (2005).

[18] I. Adachi *et al*. (Belle II Collaboration), arXiv:2310.06381.

[19] I. Adachi *et al*. (Belle II collaboration), Phys. Rev. D **109**, 112020 (2024).