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Charm and time-dependent CPV in B decays at Belle II*

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Abstract

The Belle II measurements relying on the precise determination of the positions of displaced vertices are presented. It is the analysis of the $B^0 - \bar{B}^0$ mixing and CP violation based on the early Belle II data and the D^0 and D^+ lifetime measurement, where the world-leading accuracy was achieved already with the analysed data set. Lifetime measurements of other charm mesons are in the pipeline.

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1. INTRODUCTION

Excellent performance of the Belle II tracking system [1] allows for precise measurement of the position of the displaced vertices, i.e. vertices not corresponding to the primary e^+e^- interaction. Reconstruction of these vertices is essential for the lifetime measurements, measurement of the B^0–$\bar{B}^0$ oscillations as well as for the CP violation parameters measured in the time-dependent analysis of the B meson decays [2].

Compared to the LHCb, at Belle II the momenta of the produced particles are typically smaller and so are the flight distances. On the other hand, at the e^+e^- B-factories the event topology is much clearer and the event reconstruction profits from the knowledge of the energies of the beams, in contrast to the pp collisions, where partons entering the hard interaction carries only (unknown) fraction of the proton's momentum.

In this text a prompt measurement of the B^0 meson oscillation frequency Δm_d is presented, this analysis was recently superseded by [3] with 6times higher luminosity. Measuring the oscillation frequency paves a highway toward high-precision measurements of the CKM angle $\sin 2\phi_1$ related to the CP violation, where Belle has achieved the world-leading accuracy of 3% [4] and the full Belle II data set should improve it to 1% precision [5]. In this text, the $\sin 2\phi_1$ measurement on the early Belle II data is shown as a demonstration of Belle II capabilities. Measurement on data with higher statistics will follow.

The Belle II is not only a B-factory as the $e^+e^- \to c\bar{c}$ process has a similar cross section. Especially, it allowed measuring the D^+ and D^0 lifetimes with world-leading accuracy already with the current data set.

2. BELLE II EXPERIMENT

The Belle II experiment [6] is a B meson factory located in Tsukuba, Japan based on the SuperKEKB accelerator complex. Electrons and positrons are collided at a centre-of-mass (CM) energy at or near the mass of the $\Upsilon(4S)$ resonance, i.e. 10.58 GeV. The $\Upsilon(4S)$ decays almost instantly into a $B\bar{B}$ pair. Belle II is an upgrade of its predecessor Belle [7], with a target integrated luminosity of $50\,\mathrm{ab}^{-1}$ which is 50times the size of the Belle data set. Data taking at Belle II has started in March 2019 and in April 2022 a total integrated luminosity of $314\,\mathrm{fb}^{-1}$ has been reached. The data taking will continue until Summer 2022 when a shut-down is planned.

3. $B^0 - \bar{B}^0$ MIXING AND THE CP VIOLATION MEASUREMENT

Precise measurement of the B^0–$\bar{B}^0$ mixing frequency Δm_d and/or the B^0-meson lifetime is essential to validate the tools and techniques used for the time-dependent studies of the $B^0\bar{B}^0$ system. In particular, proving that Belle II detector can measure these quantities accurately ensures that it can also be used to perform a precise measurement of the CKM angle ϕ_1 in the near future. The ϕ_1 measurement uses very similar experimental techniques but with a data set approximately 10times smaller [8] than the one used for the Δm_d determination. Therefore, the presented analysis allows probing the framework which a much higher level of scrutiny.

In contrast to the ϕ_1 where Belle I and LHCb achieved similar accuracy, the world average Δm_d value, $\Delta m_d = 0.5065 \pm 0.0019\,\mathrm{ps}^{-1}$ is dominated by LHCb [9] measurement.

At Belle II the Δm_d or $\sin 2\phi_1$ are determined using the $e^+e^- \to \Upsilon(4S) \to B^0\bar{B}^0$ events. As the e^+ and e^- beam energies are different, the $\Upsilon(4S)$ is produced with a Lorentz boost $\beta\gamma \approx 0.288$. The B^0 mesons are produced almost at the rest in the $\Upsilon(4S)$ reference frame. One B^0 meson, B^0_{sig} is fully reconstructed either as the flavor specific final state (mixing analysis) or as the CP symmetric final state (ϕ_1 analysis). The other B^0 meson, B^0_{tag}, is reconstructed by combining all other tracks in the event not used for the B^0_{sig} reconstruction. The flavor of the B^0_{tag} meson is determined using the category-based flavor tagging algorithm [10]. Neglecting the detector effects on the decay time measurement, the time evolution of the B^0_{sig} B^0_{tag} system is for the mixing measurement described as:

$$f^{\text{mixing}}_{\text{phys}}(\Delta t) = \frac{e^{-|\Delta t|\tau_{B^0}}}{4\tau_{B^0}}(1 + q\cos\Delta m_d \Delta t), \tag{1}$$

where $q = 1$ (-1) for events where B^0_{sig} and B^0_{tag} have opposite (same) flavor at their respective decay time. For B^0_{sig} corresponding to the CP eigen-state, the expression is similar:

$$f^{\text{CP}}_{\text{phys}}(\Delta t) = \frac{e^{-|\Delta t|\tau_{B^0}}}{4\tau_{B^0}}(1 + qS\sin\Delta m_d \Delta t), \tag{2}$$

where $S = \sin 2\phi_1$ is related to the time-dependent CP asymmetry, whereas the direct CP asymmetry is assumed to be zero. Flavor of B^0_{tag} is described by q, $q = 1$ ($q = -1$) corresponds to particle (anti-particle).

The proper-time difference between the B^0_{sig} and B^0_{tag} decays, Δt, is reconstructed from the difference between the two B meson vertex position vectors projected into the direction of $\Upsilon(4S)$ momentum Δl, i.e. $\Delta t' = \Delta l/(\beta\gamma c)$.

The reconstructed $\Delta t'$ differs from the truth Δt due to the detector resolution effects, the efficiency of the flavor tagger, as well as the residual movement of the B-mesons in the $\Upsilon(4S)$ reference frame. They are described by the detector resolution function which is the probability density of the difference between the truth and the reconstructed Δt. A perfect understanding of the Δt resolution is essential for precise measurement of the CKM angle ϕ_1. The Δt resolution is dominated by the reconstruction of the B^0_{tag} vertex, while the fully reconstructed signal B^0 vertex is determined with higher precision. The resolution function obtained from the mixing analysis is also of use in the CPV measurement.

In the analysis of the prompt 2020 Belle II data [11] with integrated luminosity $34.6\,\text{fb}^{-1}$, the parameters of the resolution function are kept identical for both mixing and CPV measurement. The flavor specific B-meson decay is reconstructed in $B^0 \to D^-(K^+\pi^-\pi^-)\pi^+$ and the B-meson in CP eigen-state is reconstructed via $B^0_{\text{CP}} \to J/\psi(ll)K_s(\pi^+\pi^-)$ decay. The measured spectra of the Δt together with the fitted curve are shown in Figure 1. Several selection criteria are applied to suppress the background, for example on the beam-constrained invariant mass of the B^0_{sig} meson or on the reduced Fox-Wolfram moment R_2 to suppress the continuum background which typically has jet-like topology.

The obtained values $\Delta m_d = 0.531 \pm 0.046 \pm 0.013\,\text{ps}^{-1}$ and $\sin 2\phi_1 = 0.55 \pm 0.21 \pm 0.04$ are in agreement with the world average values and their precision is driven by the statistical uncertainty. It is also consistent with recent Belle II measurement [3], $\Delta m_d = 0.516 \pm 0.008 \pm 0.005\,\text{ps}^{-1}$, based on data with $L_{\text{int}} = 190\,\text{fb}^{-1}$. It demonstrates that the employed analysis workflow can be used for the state-of-the-art ϕ_1 measurement with emerging full Belle II data set.

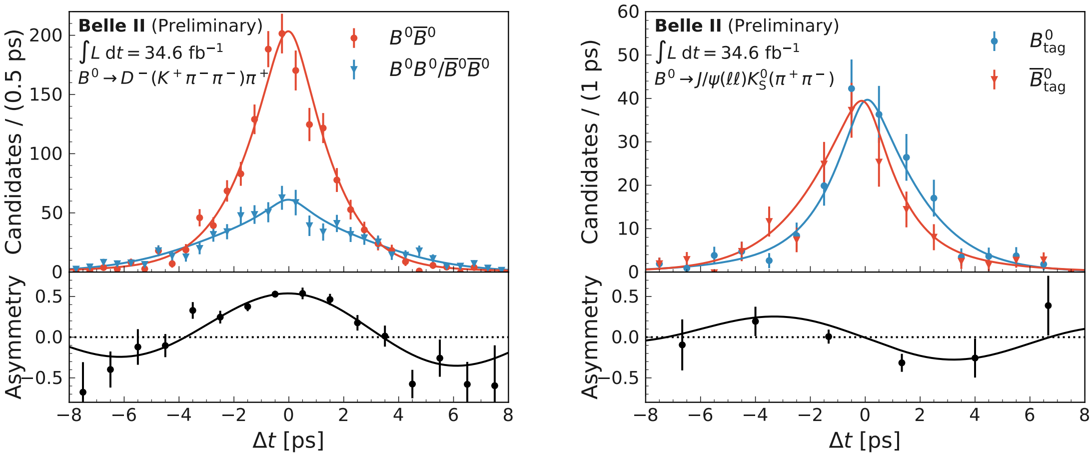

FIG. 1: The Δt distribution for the $B^0 \to D^-(K^+\pi^-\pi^-)\pi^+$ flavor-specific state (left) and for $B^0 \to J/\psi(ll)K_s(\pi^+\pi^-)$ CP eigen-state (right) [11]. The data points and the fitted curves are plotted for both flavor states of the B^0_{tag}.

4. *D* LIFETIME MEASUREMENT

Accurate predictions of lifetimes of weakly decaying charmed and bottom hadrons are challenging because they involve strong-interaction theory at low energy. Predictions must resort to effective models, such as the heavy-quark expansion [12]. Precise lifetime measurements provide excellent tests of such effective models whose precision is still far behind the precision of the experiment.

Up to now, the most precise estimates of the D^+ and D^0 lifetimes are from the FOCUS experiment [13], where D mesons where produced in $\gamma(180\,\text{GeV})+\text{BeO}$ interactions. There is no estimate of these lifetimes from Belle, BaBar or LHCb. However, the LHCb collaboration precisely measured the lifetimes of the D_s^+ [14] mesons and several charmed baryons, e.g. [15], relative to that of the D^+ meson. Such relative measurements minimise systematic uncertainties due to decay-time-biasing event-selection criteria that are particularly severe at hadron colliders. For these LHCb lifetime estimates the external uncertainty coming from the D^+ lifetime is one of the dominant systematic sources.

By contrast, experiments at e^+e^- colliders, owing to the reconstruction of large charmed hadron yields without decay-time-biasing selections, have a great potential for absolute lifetime measurements. The high precision Belle II measurement of the D^0 and D^+ lifetimes is based on $D^{*+} \to D^0(\to K^-\pi^+)\pi^+$ and $D^{*+} \to D^+(\to K^-\pi^+\pi^+)\pi^0$ decay modes [16]. The analysed data correspond to the integrated luminosity of 72 fb^{-1}. At Belle II the D^* meson is produced in the $e^+e^- \to c\bar{c}$ interactions and the decay vertex of D^* is identical to the primary vertex due to the short D^* lifetime. The flight lengths of D^0 and D^+ are $\approx$200 μm and $\approx$500 μm, respectively, which is higher than for B^0-mesons ($\approx$130μm) due to the higher boost of produced D mesons. The decay time t is reconstructed as $t = m_D \vec{L} \cdot \vec{p}/|\vec{p}|^2$, where $\vec{p}$ is the momentum of the D meson and $\vec{L}$ is the vector pointing from the reconstructed D meson production vertex to its decay vertex. The production vertex is estimated with a help of the known beam spot, i.e. the probability distribution of the primary vertexes. At

Belle II the beam spot is described by 3D Gaussian distribution and its parameters, which are heavily time-dependent, are continuously monitored using $e^+e^- \to \mu^+\mu^-$ events. The measured spectra of the reconstructed D meson mass and the decay times t are shown in Figure 2. The tail towards negative t values is related to the resolution which is about 70 fs

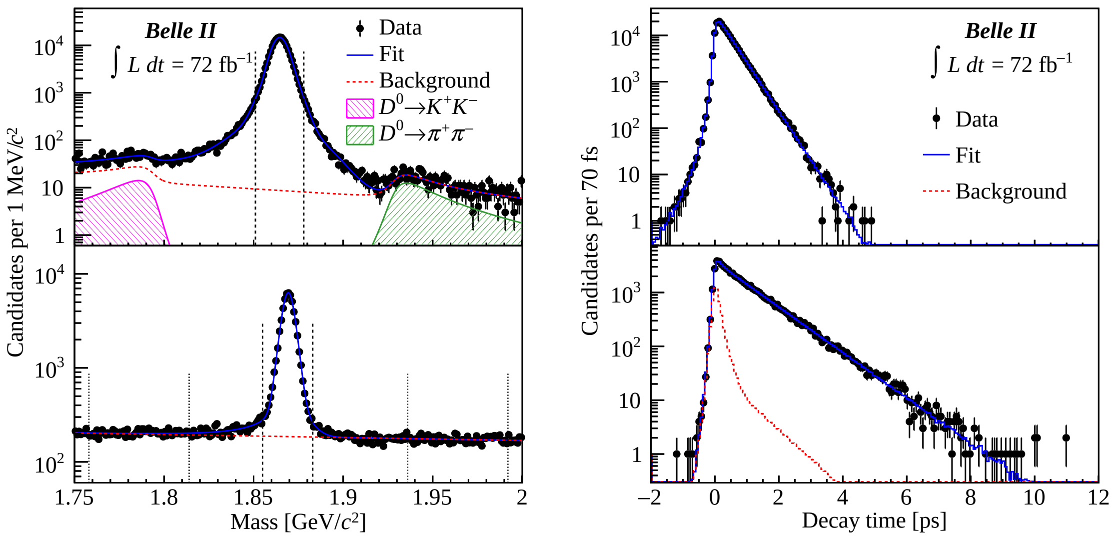

FIG. 2: Mass and decay time distribution of the D^0 (top) and D^+ (bottom) candidates [16]. Vertical lines depict borders of signal and side-band regions.

for D^0 and 60 fs for D^+, respectively.

The unbinned maximum likelihood fits of t performed simultaneously for the signal and side-band D mass regions result in $\tau(D^0) = 410.5 \pm 1.1 \pm 0.8$ fs and $\tau(D^+) = 1030.4 \pm 4.7 \pm 3.1$ fs. For both D meson charges the obtained values are consistent with the world average but have higher precision. The analysis is statistically limited, the dominant systematic uncertainty originates from the background modelling for D^+ and from detector alignment for D^0.

5. CONCLUSIONS

The Belle II detector is an excellent machine to study the time-dependent CP violation in the $B^0 - \bar{B}^0$ and the lifetimes of the heavy-flavor hadrons. For the D^+ and D^0 mesons, the measured lifetimes have world-leading accuracy. In the case of the parameters related to the CP violation, like $\sin 2\phi_1$, higher integrated luminosity is needed for the competitive results.

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