

# Hadronic $B$ decays at Belle II\*

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We report on recent measurements of hadronic  $B$  decays using the data set collected from 2019 to 2021 by the Belle II experiment and corresponding to an integrated luminosity of  $189.8 \text{ fb}^{-1}$ . We present the measurement of the CKM angle  $\gamma$ , performed combining Belle II data with the full Belle data set, and measurements of  $B^0 - \bar{B}^0$  mixing frequency and  $B^0$  lifetime, branching fractions and  $CP$ -violating asymmetries of  $B^+ \rightarrow \rho^+ \rho^0$  and  $B^0 \rightarrow K_S^0 \pi^0$  decays.

## 1. Introduction

The physics of beauty meson decays is fundamental in the Belle II physics program, with results expected to improve the precision of several sensitive tests of the Standard Model (SM) in the flavor sector. Belle II is a particle detector designed to study 7-on-4 GeV  $e^+e^-$  collisions at the energy of the  $\Upsilon(4S)$  resonance, produced at very high luminosity by the SuperKEKB collider located at the KEK laboratory in Japan [1]. The  $\Upsilon(4S)$  decays almost exclusively into  $B\bar{B}$  pairs, resulting in low backgrounds. Belle II consists of several subdetectors, arranged hermetically in a cylindrical geometry around the interaction point. The innermost detector is a silicon tracker with a decay position (vertex) resolution of about  $25 \mu\text{m}$ . A large-radius wire drift chamber measures charged-particle charges, momenta with 0.4% resolution, and  $dE/dx$  with about 7% resolution. A time-of-propagation Cherenkov detector and an aerogel ring-imaging Cherenkov detector surround the drift chamber and provide charged-particle identification (PID) information, allowing a separation of kaons from pions of up to 4 GeV/ $c$  momentum, with typical 90% efficiency and 5% misidentification rate. A CsI(Tl)-crystal electromagnetic calorimeter measures the energy of electrons and photons, with 1.6%–4% resolution. Layers of plastic scintillators and resistive-plate chambers alternated with iron plates provide muon

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and  $K_L^0$  reconstruction. Belle II started collecting physics data in March 2019, aiming to accumulate about  $50 \text{ ab}^{-1}$  in the next decade. The results shown in this document are based on a data set corresponding to an integrated luminosity of  $189.9 \text{ fb}^{-1}$  [2].

## 2. Combined Belle and Belle II measurement of the angle $\gamma$

Since it can be extracted using tree-level decays, where no non-SM physics is anticipated, the direct measurement of the CKM angle  $\gamma = \arg(-V_{ud}V_{ub}^*/V_{cd}V_{cb}^*)$  provides a powerful SM gauge when compared to indirect determinations based on other Unitarity Triangle parameters. We present the measurement of  $\gamma$  from  $B^\pm \rightarrow DK^\pm$  decays, where  $D$  indicates  $D^0$  or  $\bar{D}^0$  mesons decaying to the same final states  $f$ ; the weak phase  $\gamma$  enters through the interference of the favored and suppressed transitions via  $\frac{A(B^- \rightarrow \bar{D}^0 K^-)}{A(B^- \rightarrow D^0 K^-)} = r_B \exp^{i(\delta_B - \gamma)}$ , where  $r_B$  and  $\delta_B$  are the magnitude of the ratio and strong-phase difference between favored and suppressed amplitudes [3]. We reconstruct the decays  $B^- \rightarrow D (\rightarrow K_S^0 h^+ h^-) h^-$ , where  $h$  is either a pion or a kaon. Decays  $D \rightarrow K_S^0 h^+ h^-$  proceed through various intermediate resonances, resulting in the variation of the  $CP$ -asymmetry over the  $D$  phase space. Following the BPGGSZ method [4, 5], the  $D$  Dalitz space is binned to achieve a model-independent determination of  $\gamma$  that reduces model-dependent systematic uncertainties. The signal yield in each bin depends on  $r_B$ ,  $\delta_B$ ,  $\gamma$ , and strong-phase differences between  $D^0$  and  $\bar{D}^0$  decays, that are measured precisely by the charm factories CLEO and BESIII experiments [6, 7, 8]. Charged pions and kaons are identified from good-quality tracks and using PID information. The  $K$  and  $\pi$  candidates are then combined to form  $K_S^0$  and  $D$  candidates, with proper quality and kinematic requirements. The  $B$  candidates are selected further using the kinematic variables  $M_{bc} = \sqrt{(\sqrt{s}/2)^2 - (\Sigma \vec{p}_i^*)^2}$  and  $\Delta E = E_B^* - (\sqrt{s}/2)$ , where  $\sqrt{s}$  is the collision energy,  $\vec{p}_i^*$  are the momenta of the reconstructed  $B$  daughters and  $E_B^*$  is the reconstructed energy of the  $B$  meson, all in the center of mass frame. The dominant background comes from  $e^+e^- \rightarrow q\bar{q}$  ( $q = u, d, s, c$ ) events, called ‘‘continuum’’. We suppress it combining information on the event geometry in a binary classifier based on boosted decision trees. This exploits the fact that continuum background events produce particles collimated into back-to-back jets, while  $e^+e^- \rightarrow \Upsilon(4S) \rightarrow B\bar{B}$  events have a more spherical shape. We extract the PID efficiency and misidentification rate parameters from data by fitting simultaneously the  $B \rightarrow D\pi$  and  $B \rightarrow DK$  samples with an extended maximum-likelihood fit of the  $\Delta E$  and continuum-suppression output,  $\mathcal{C}$ , distributions, obtaining about 310 (1660) signal candidates in the Belle II (Belle) data set.

A projection of this fit on Belle II data is shown in Fig. 1. Once these parameters are fixed, the same fit is performed simultaneously in all the Dalitz plot bins to measure the  $CP$  asymmetry parameters. The result is  $\gamma = (78.4 \pm 11.4(\text{stat}) \pm 0.5(\text{syst}) \pm 1.0(\text{ext}))^\circ$ , where the third uncertainty is due to the uncertainty of the external inputs. The result is compatible with and more precise than the previous Belle result [9]. The net improvement is equivalent to doubling the sample size, even if Belle II data set only corresponds to about 20% of the Belle one. The precision is still limited by the statistical uncertainty.

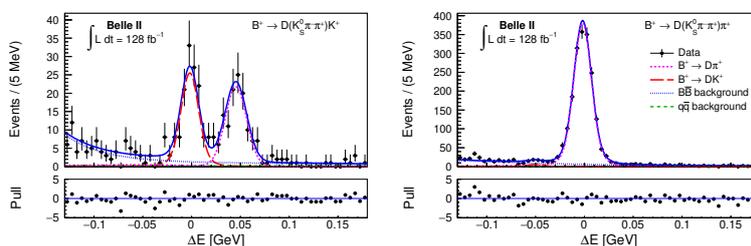


Fig. 1.  $\Delta E$  distributions of (left)  $B^- \rightarrow D(\rightarrow K_S^0 \pi^+ \pi^-) K^-$  and (right)  $B^- \rightarrow D(\rightarrow K_S^0 \pi^+ \pi^-) \pi^-$  candidates reconstructed in Belle II data, with fit projections overlaid.

### 3. $B^+ \rightarrow \rho^+ \rho^0$ towards the determination of $\alpha$

Belle II has the unique capability of studying within the same experimental environment isospin partner decays  $B \rightarrow \rho\rho$ ,  $\rho\pi$ ,  $\pi\pi$ , thus enjoying promising opportunities for determining the CKM angle  $\alpha$  by combining branching fractions and  $CP$  violating asymmetries [10].

We report here the measurement of the branching fraction  $\mathcal{B}$ , the  $CP$ -violating asymmetry  $A_{CP}$ , and fraction of longitudinal polarized decays  $f_L$  of  $B^+ \rightarrow \rho^+ \rho^0$  decays reconstructed in  $190 \text{ fb}^{-1}$  of Belle II data [11]. These decays involve pion-only final states where the large width of  $m(\rho)$  suffers from reduced distinctive features against dominant continuum background: isolating a low-background signal is the main challenge of the analysis. Signal yields are determined with an unbinned maximum-likelihood fit of  $\Delta E$ ,  $\mathcal{C}$ , two dipion masses and the two cosines of helicity angles of the  $\rho$  candidates. Specific difficulty is to model all the dependencies between these variables. Figure 2 shows the  $\Delta E$  and cosine of the  $\rho^+$  helicity angle distributions of  $B^+ \rightarrow \rho^+ \rho^0$  candidates. We observe about 350 signal candidates, and obtain  $\mathcal{B} = [23.2_{-2.1}^{+2.2}(\text{stat}) \pm 2.7(\text{syst})] \times 10^{-6}$ ,  $A_{CP} = -0.069 \pm 0.069(\text{stat}) \pm 0.060(\text{syst})$ , and  $f_L = 0.943_{-0.033}^{+0.035}(\text{stat}) \pm 0.027(\text{syst})$ , in agreement with previous determinations.

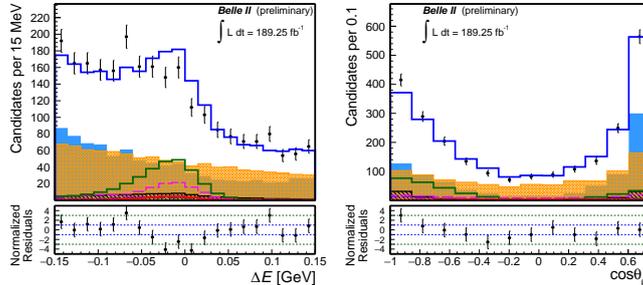


Fig. 2. Distributions of  $\Delta E$  (left) and cosine of helicity angle of the  $\rho^+$  candidates (right) for  $B^+ \rightarrow \rho^+\rho^0$  candidates reconstructed in Belle II data, with fit projections overlaid.

#### 4. $B^0 - \bar{B}^0$ mixing and $B^0$ lifetime

Measurement of the  $B^0 - \bar{B}^0$  mixing frequency  $\Delta m_d$  and  $B^0$ -meson lifetime  $\tau_{B^0}$  is essential to validate the tools and techniques used for the decay-time-dependent studies of the  $B^0 - \bar{B}^0$  system, and in particular for the measurement of the CKM angle  $\beta$ . Neutral  $B$  undergo flavor oscillations with frequency  $\Delta m_d \hbar/c^2$  before decaying; the probability of a  $B^0$  initially being in a particular flavor state and decaying after time  $\Delta t$  is

$$\mathcal{P}(\Delta t, q | \tau_{B^0}, \Delta m_d) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{\tau_{B^0}} (1 \pm q \cos \Delta m_d \Delta t \frac{\hbar}{c^2}),$$

where  $q = +1$  ( $-1$ ) is the unchanged (changed) flavor of the  $B^0$  when it decays. By measuring this time dependence, we determine  $\tau_{B^0}$  and  $\Delta m_d$ . We measure the flavor of the  $B$  meson by reconstructing the partner  $B$  produced in the  $e^+e^- \rightarrow \Upsilon(4S) \rightarrow B\bar{B}$  event in a flavor-specific decay, where  $\Delta t$  is the proper time between decays. In each event, we fully reconstruct one  $B$ ,  $B_{\text{sig}}^0$ , via  $B^0 \rightarrow D^- h^+$  (with  $D^- \rightarrow K^+ \pi^- \pi^-$ ) and  $\bar{B}^0 \rightarrow D^{*-} h^+$  (with  $D^{*-} \rightarrow \bar{D}^0 K_S^0$  and  $\bar{D}^0 \rightarrow K^+ \pi^-$ ,  $\bar{D}^0 \rightarrow K^+ \pi^- \pi^0$ , or  $\bar{D}^0 \rightarrow K^+ \pi^- \pi^+ \pi^-$ ), where  $h^+ = \pi^+$  or  $K^+$ , and identify its decay flavor via the charge of  $h$ . We partially reconstruct the other  $B$  meson,  $B_{\text{tag}}^0$ , from the charged particles not used to reconstruct  $B_{\text{sig}}^0$ . We use the so-called flavor tagger algorithm described in Ref. [12] to determine its flavor, with a tagging efficiency of  $30.0 \pm 1.3\%$ . We fit to the  $\Delta E$  and  $\mathcal{C}$  distributions of  $B_{\text{sig}}^0$  candidates to determine the numbers of signal and background candidates, obtaining about 33000 signal candidates. We use results to subtract the background contribution when fitting for  $\tau_{B^0}$  and  $\Delta m_d$  the  $\Delta t$  distribution (obtained from the distance between the decay vertices of the  $B$  mesons). We fit  $\Delta t$  using a resolution function that accounts for relevant detector effects. We define the asymmetry of the two types of  $B\bar{B}$  pairs as the number

of opposite-flavor pairs minus the number of same-flavor pairs, divided by their sum. Figure 3 (left) shows the distributions of opposite- and same-flavor candidate pairs in data, the results of the fit, and the asymmetry as a function of  $\Delta t$ . The results, with associated statistical and system-

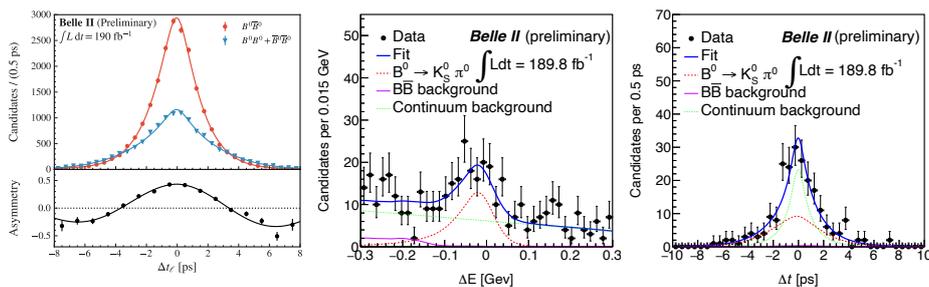


Fig. 3. (Left) Distribution of  $\Delta t_\ell$  in data (points) with fit overlaid (lines) for opposite-flavor candidate pairs (red) and same-flavor pairs (blue) and their asymmetry (black). (Center and right)  $B^0 \rightarrow K_S^0 \pi^0$  analysis: distributions of  $\Delta E$  and  $\Delta t$  for  $B^0 \rightarrow K_S^0 \pi^0$  candidates reconstructed in Belle II data, with fit projections overlaid.

atical uncertainties, are  $\tau_{B^0} = (1.499 \pm 0.013(\text{stat}) \pm 0.008(\text{syst}))$  ps and  $\Delta m_d = (0.516 \pm 0.008(\text{stat}) \pm 0.005(\text{syst}))$   $\text{ps}^{-1} \hbar/c^2$ . These results have lower statistical precision than previous measurements, with which they agree, but better systematic precision than the results from the Belle and BaBar collaborations.

## 5. Time evolution of $B^0 \rightarrow K_S^0 \pi^0$ decays

One sensitive consistency test of the SM is provided by the  $K\pi$ -sum rule, a combination of decay widths and direct  $CP$  asymmetries of four  $B \rightarrow K\pi$  decays related by isospin symmetry that is expected to hold with an uncertainty below 1% [13]. The dominant contribution to the sum-rule uncertainty comes from the  $CP$ -violating asymmetry of  $B^0 \rightarrow K_S^0 \pi^0$  decays. Therefore, its precise measurement is crucial for this test, as Belle II is the only experiment capable of achieving it. The key challenge of this analysis [14] is the determination of the decay vertex position of the  $B^0 \rightarrow K_S^0 \pi^0$  decays. We do that by projecting the  $K_S^0$  flight direction back to the interaction region and requiring the  $K_S^0$  to decay inside the vertex detector. Signal yields are determined with an unbinned maximum-likelihood fit of  $\Delta E$ ,  $\mathcal{C}$ ,  $M_{bc}$ , and  $\Delta t$ . Figure 3 (center and right) shows the  $\Delta E$  and  $\Delta t$  distributions of  $B^0 \rightarrow K_S^0 \pi^0$  candidates reconstructed in Belle II data. We find 135 signal candidates, and obtain  $\mathcal{B} = [11.0 \pm 1.2(\text{stat}) \pm 1.0(\text{syst})] \times 10^{-6}$  and  $A_{CP} = -0.041_{-0.32}^{+0.30}(\text{stat}) \pm 0.09(\text{syst})$ . This is the first measurement

of  $A_{CP}$  in  $B^0 \rightarrow K_S^0 \pi^0$  decays performed at Belle II using a decay-time-dependent analysis, and the results agree with previous determinations.

## 6. Summary

We report on precise measurements of hadronic  $B$  decays at the Belle II experiment. We present first combined measurement of the CKM angle  $\gamma$ . The uncertainties are dominated by the sample size, and the precision is significantly improved with respect to the previous Belle measurement, showing good understanding of the detector and of the analysis procedure. We present measurements of the  $B^0 - \bar{B}^0$  mixing frequency and  $B^0$  lifetime, branching fractions and  $CP$ -violating asymmetries of  $B^+ \rightarrow \rho^+ \rho^0$  and  $B^0 \rightarrow K_S^0 \pi^0$  decays. All results agree with previous determinations, proving excellent early detector performance.

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