HADRONIC B DECAYS AT BELLE II*

Sebastiano Raiz

on behalf of the Belle II Collaboration

University of Trieste and INFN, sezione di Trieste, Italy
sebastiano.raiz@ts.infn.it

Received 30 September 2022, accepted 2 January 2023, published online 15 February 2023

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

DOI:10.5506/APhysPolBSupp.16.3-A11

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 μm. 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 for 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

* Presented at the XIV International Conference on *Beauty, Charm and Hyperon Hadrons*, Kraków, Poland, 5–10 June, 2022.

energy of electrons and photons, with 1.6%–4% resolution. Layers of plastic scintillators and resistive-plate chambers alternated with iron plates provide muon and $K^0_{\rm L}$ reconstruction. Belle II started collecting physics data in March 2019, aiming to accumulate about 50 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 fb^{-1} [2].

2. Combined Belle and Belle II measurement of the angle γ

Since it can be extracted using tree-level decays, where no non-SM physics is anticipated, the direct measurement of the CKM parameter $\gamma = \arg(-V_{ud}V^*_{ub}/V_{cd}V^*_{cb})$ provides a powerful SM gauge when compared to indirect determinations based on other Unitarity Triangle parameters. We present the measurement of γ from $B^\pm \to DK^\pm$ decays, where D indicates D^0 or $\bar{D}^0$ mesons decaying to the same final states f; the weak phase γ is measured through the interference of favored and suppressed decay amplitudes via $\frac{A(B^- \to \bar{D}^0 K^-)}{A(B^- \to D^0 K^-)} = r_B \exp^{i(\delta_B - \gamma)}$, where r_B and δ_B are the magnitude of the ratio and strong-phase difference between suppressed and favored amplitudes [3]. We reconstruct the $B^- \to D\left(\to K^0_{\rm S} h^+ h^-\right) h^-$ decays, where h is either a pion or a kaon. $D \to K^0_{\rm S} h^+ h^-$ decays 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 γ that reduces model-dependent systematic uncertainties. The signal yield in each bin depends on r_B, δ_B, γ, and strong-phase differences between D^0 and $\bar{D}^0$ decays, that are measured precisely by the charm factories CLEO and BESIII experiments [6–8]. Charged pions and kaons are identified from good-quality tracks and by using PID information. The K and π candidates are then combined to form $K^0_{\rm S}$ and D candidates with proper quality and kinematic requirements. The B candidates are selected further using the kinematic variables $M_{\rm bc} = \sqrt{(\sqrt{s}/2)^2 - (\Sigma \vec{p}^{\,*}_i)^2}$ 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 $e^+e^- \to q\bar{q}$ $(q = u, d, s, c)$ events, called "continuum". We suppress it by 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 $e^+e^- \to \Upsilon(4S) \to B\bar{B}$ events have a more spherical shape. We extract the PID efficiency and misidentification rate parameters from data by fitting simultaneously the $B \to D\pi$ and $B \to DK$ samples with an extended maximum-likelihood fit of the ΔE 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 the PID 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 the Belle II data set only corresponds to about 20% of the Belle one. The precision is still limited by the statistical uncertainty.

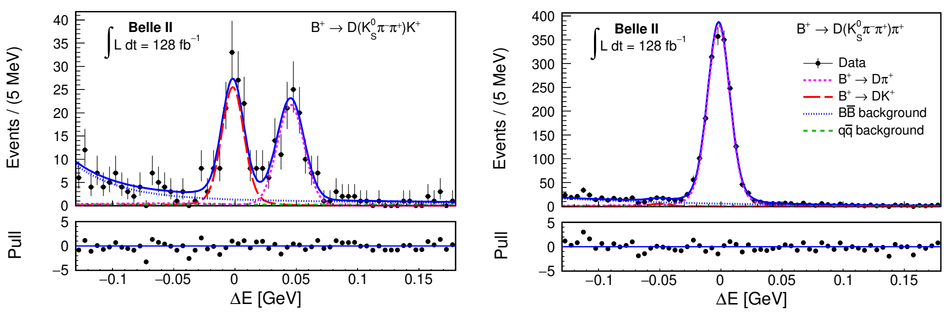

Fig. 1. ΔE distributions of (left) $B^- \to D\left(\to K^0_S\pi^+\pi^-\right)K^-$ and (right) $B^- \to D\left(\to K^0_S\pi^+\pi^-\right)\pi^-$ candidates reconstructed in Belle II data, with fit projections overlaid.

3. $B^+ \to \rho^+\rho^0$ towards the determination of α

Belle II has a unique capability of studying within the same experimental environment isospin partner decays $B \to \rho\rho$, $\rho\pi$, $\pi\pi$, thus enjoying promising opportunities for determining the CKM parameter $\alpha = \arg(-V_{td}V^*_{tb}/V_{ud}V^*_{ub})$ by combining branching fractions and CP-violating asymmetries [10].

We report on the measurement of the branching fraction $\mathcal{B}$, the CP-violating asymmetry A_{CP}, and the fraction of longitudinal polarized decays f_{L} of $B^+ \to \rho^+\rho^0$ decays reconstructed in 190 fb^{-1} of Belle II data [11]. These decays involve pion-only final states where the large width of $m(\rho)$ reduces signal discrimination against the 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 ΔE, $\mathcal{C}$, two dipion masses, and the two cosines of helicity angles of the ρ candidates. The specific difficulty is to model all the dependencies between these variables. Figure 2 shows the ΔE and cosine of the ρ^+ helicity angle distributions of $B^+ \to \rho^+\rho^0$ candidates. We observe about 350 signal candidates, and obtain $\mathcal{B} = [23.2^{+2.2}_{-2.1}(\text{stat.}) \pm 2.7(\text{syst.})] \times 10^{-6}$, $A_{\text{CP}} = -0.069 \pm 0.069(\text{stat.}) \pm 0.060(\text{syst.})$, and $\text{f}_{\text{L}} = 0.943^{+0.035}_{-0.033}(\text{stat.}) \pm 0.027(\text{syst.})$ in agreement with previous determinations.

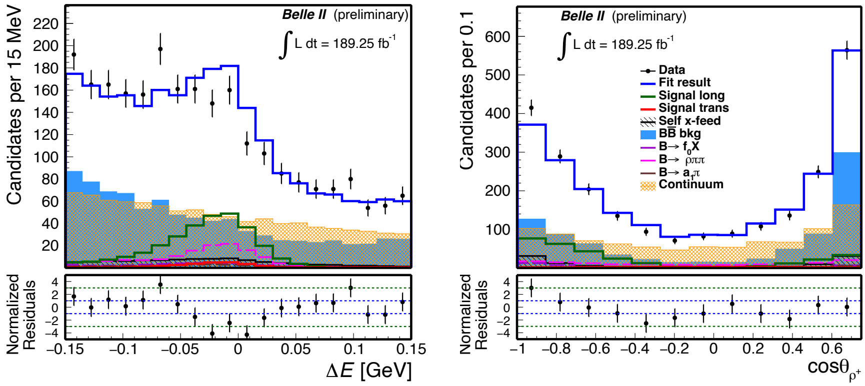

Fig. 2. Distributions of ΔE (left) and cosine of helicity angle of the ρ^+ candidates (right) for $B^+ \to \rho^+\rho^0$ candidates reconstructed in Belle II data, with fit projections overlaid.

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

Measurement of the B^0-meson lifetime and B^0–$\bar{B}^0$ mixing frequency 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 parameter $\beta = \arg(-V_{cd}V_{cb}^*/V_{td}V_{tb}^*)$. Neutral B undergo flavor oscillations with frequency Δm_d before decaying; the probability of a B^0 initially being in a particular flavor state and decaying after time Δt is

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

where $q = +1$ (-1) is the unchanged (changed) flavor of the B^0 when it decays, τ_{B^0} is the B^0-meson lifetime, and Δm_d is the B^0–$\bar{B}^0$ mixing frequency. We use $e^+e^- \to \Upsilon(4S) \to B\bar{B}$ events, where one B, $B_{\rm sig}$, is the signal-side B meson, and the other B, $B_{\rm tag}$, is the partner B meson. The variable Δt is the proper time between their decays. In each event, we reconstruct $B_{\rm sig}$ via $B^0 \to D^-h^+$ (with $D^- \to K^+\pi^-\pi^-$) and $B^0 \to D^{*-}h^+$ (with $D^{*-} \to \bar{D}^0\pi_s^-$ and $\bar{D}^0 \to K^+\pi^-$, $\bar{D}^0 \to K^+\pi^-\pi^0$, or $\bar{D}^0 \to K^+\pi^-\pi^+\pi^-$), where $h^+ = \pi^+$ or K^+, and identify its decay flavor via the charge of h. We fit to the ΔE and $\mathcal{C}$ distributions of $B_{\rm sig}$ 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 the Δt distribution for τ_{B^0} and Δm_d. We derive Δt from the distance between the decay vertices of the B mesons, reconstructed from positions and momenta of the charged particles coming from their decays. We obtain q from the flavor of $B_{\rm sig}$ and $B_{\rm tag}$ at the time of their respective decays. The latter is determined by the flavor tagger algorithm described in Ref. [12], with a tagging efficiency of $30.0 \pm 1.3\%$. We fit Δt using a resolution function that accounts for relevant detector effects and effects from $B_{\rm tag}$ secondary tracks. We define the asymmetry of the two types of $B\bar{B}$ pairs as the number of opposite-flavor pairs ($B^0\bar{B}^0$, $q = +1$) minus the number of same-flavor pairs (B^0B^0 or $\bar{B}^0\bar{B}^0$, $q = -1$), divided by their sum. Figure 3 (left) shows the distributions of the opposite- and same-flavor candidate pairs in data, the results of the fit, and the asymmetry as a function of Δt. The results, with associated statistical and systematic uncertainties, are $\tau_{B^0} = (1.499 \pm 0.013(\text{stat.}) \pm 0.008(\text{syst.}))$ ps and $\Delta m_d = (0.516 \pm 0.008(\text{stat.}) \pm 0.005(\text{syst.}))\ \text{ps}^{-1}$. 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.

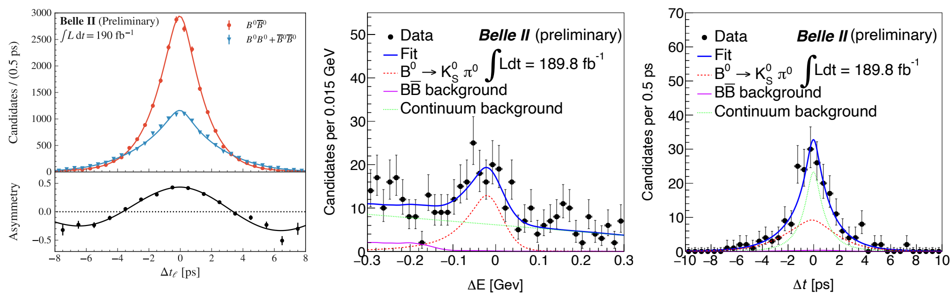

Fig. 3. Left: Distribution of Δt_ℓ in data (points) with fit overlaid (lines) for the opposite-flavor candidate pairs (red) and same-flavor pairs (blue), and their asymmetry (black). Center and right: $B^0 \to K^0_S\pi^0$ analysis: distributions of ΔE and Δt for $B^0 \to K^0_S\pi^0$ candidates reconstructed in Belle II data, with fit projections overlaid.

5. Time evolution of $B^0 \to K^0_S\pi^0$ 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 $B \to K\pi$ 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 $B^0 \to K^0_S\pi^0$ decays. Therefore, its precise measurement is crucial for this test, and 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 $B^0 \to K^0_S\pi^0$ decays. We do that by projecting the K^0_S flight direction back to the interaction region. Only K^0_S that decay inside the vertex detector are used to have enough resolution on the vertex determination. Signal yields are determined with an unbinned maximum-likelihood fit of ΔE, $\mathcal{C}$, $M_{\rm bc}$, and Δt. Figure 3 (center and right) shows the ΔE and Δt distributions of $B^0 \to K^0_{\rm S}\pi^0$ 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 $A_{\rm CP} = -0.041^{+0.30}_{-0.32}(\text{stat.}) \pm 0.09(\text{syst.})$. This is the first measurement of $A_{\rm CP}$ in $B^0 \to K^0_{\rm S}\pi^0$ 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 the first Belle–Belle II combined measurement of the CKM angle γ. The uncertainties are dominated by the sample size, and the precision is significantly improved with respect to the previous Belle measurement, showing a good understanding of the detector and the analysis procedure. We present measurements of the B^0 lifetime and B^0–$\bar{B}^0$ mixing frequency, branching fractions, and CP-violating asymmetries of $B^+ \to \rho^+\rho^0$ and $B^0 \to K^0_{\rm S}\pi^0$ decays. All results agree with previous determinations, proving excellent early detector performance.

REFERENCES

[1] SuperKEKB Accelerator Team (K. Akai *et al.*), *Nucl. Instrum. Methods Phys. Res. A* **907**, 188 (2018).
[2] Belle II Collaboration (F. Abudinén *et al.*), *Chinese Phys. C* **44**, 021001 (2020).
[3] Belle II Collaboration (F. Abudinén *et al.*), *J. High Energy Phys.* **2022**, 63 (2022).
[4] A. Giri, Y. Grossman, A. Soffer, J. Zupan, *Phys. Rev. D* **68**, 054018 (2003).
[5] Belle Collaboration (A. Poluektov *et al.*), *Phys. Rev. D* **70**, 072003 (2004).
[6] CLEO Collaboration (J. Libby *et al.*), *Phys. Rev. D* **82**, 112006 (2010).
[7] BESIII Collaboration (M. Ablikim *et al.*), *Phys. Rev. D* **101**, 112002 (2020).
[8] BESIII Collaboration (M. Ablikim *et al.*), *Phys. Rev. D* **102**, 052008 (2020).
[9] Belle Collaboration (H. Aihara *et al.*), *Phys. Rev. D* **85**, 112014 (2012).
[10] M. Gronau, D. London, *Phys. Rev. Lett.* **65**, 3381 (1990).
[11] Belle II Collaboration (F. Abudinén *et al.*), arXiv:2206.12362 [hep-ex].
[12] Belle II Collaboration (F. Abudinén *et al.*), *Eur. Phys. J. C* **82**, 4 (2022).
[13] M. Gronau, *Phys. Lett. B* **627**, 82 (2005).
[14] Belle II Collaboration (F. Abudinén *et al.*), arXiv:2206.07453 [hep-ex].