First results of $B \to DK$ decays at Belle II

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This proceeding reports the first measurement of the observables related to hadronic B decays containing charm mesons using 62.8 fb^{-1} of dataset collected by the Belle II experiment along with the first measurement of the the CKM unitarity triangle angle ϕ_3 from a combining Belle and Belle II datasets that correspond to integrated luminosities of 711 fb^{-1} and 128 fb^{-1}, respectively. The measured value of ϕ_3 is $(78.4 \pm 11.4 \pm 0.5 \pm 1.0)^{\circ}$, where the first uncertainty is statistical, the second is the experimental systematic uncertainty and the third is from the uncertainties on external measurements of the D-decay strong-phase parameters.

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1. Introduction

The Standard Model (SM) is largely successful in explaining the fundamental particles of nature and their interactions. Despite this tremendous success, there are still a few questions unanswered by the SM, such as the matter-antimatter asymmetry, mass and flavor hierarchy of the quarks and leptons and the existence of too many parameters in SM. Many New Physics (NP) scenarios have been proposed to explain such problems. One of the approaches to search for NP is to make measurements of the parameters in the flavor sector to see if they deviate from the SM predictions. Belle II has a unique opportunity to constrain and search for NP at the intensity frontier [1].

The SuperKEKB colliding-beam accelerator provides e^+e^- collisions at an energy corresponding to the mass of the $\Upsilon(4S)$ resonance, with a boost factor $\beta\gamma = 0.28$, which are being recorded by the Belle II detector. It consists of two storage rings, one for the 7 GeV electrons (High Energy Ring, HER) and one for the 4 GeV positrons (Low Energy Ring, LER). The design peak instantaneous luminosity of SuperKEKB is 6×10^{35} cm^{-2}s^{-1}, approximately thirty times higher than that achieved by the KEKB accelerator [2]. So far the Belle II detector has accumulated 216 fb^{-1} of physics data, shown in Fig. 1, and will accumulate a total integrated luminosity of 50 ab^{-1} as soon as possible. With this large dataset, we can perform precision measurements of Cabibbo-Kobayashi-Maskawa (CKM) parameters [3], and search for NP, such as CP violation in charm mesons, lepton-universality violation in $b \to c\tau\nu$ decays, lepton-flavor violations in τ decays, new particles affecting rare flavor-changing neutral current processes and search for light dark matter candidates [1].

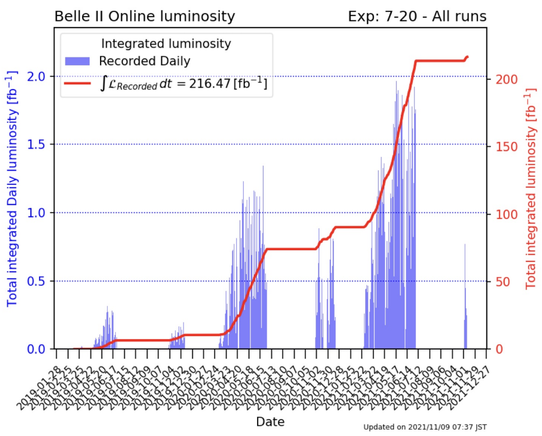

Figure 1: Belle II recorded luminosity until 2021.

In this document, we will discuss the measurement of observables related to $B \to D^{(*)}h$ decays, where h is either π or K, using 62.8 fb^{-1} Belle II dataset, and the results of the first measurement of CKM angle ϕ_3 from a combined analysis of Belle and Belle II datasets corresponding to integrated luminosities of 711 fb^{-1} and 128 fb^{-1}, respectively.

2. Measurement of the ratio $R^{(*)0/+}$

The observable $R^{(*)0/+}$, which is defined as the ratio of $B \to D^{(*)}\pi$ to $B \to D^{(*)}K$ decays, is measured using 62.8 fb^{-1} of Belle II dataset. These observables can test theoretical predictions, particularly of factorization and SU(3) symmetry breaking in quantum chromodynamics [4]. Apart from that, the channels $B \to D^{(*)}\pi$ are important control channels for other fully hadronic B-decay measurements, such as those of time-dependent CP violation and charmless B decays, and the decays $B \to D^{(*)}K$ are sensitive to the CKM unitarity-triangle angle ϕ_3 measurement.

We present measurements of $R^{(*)0/+}$ for four decay modes: (1) $B^- \to D^0 h^-, D^0 \to K^-\pi^+$ or $D^0 \to K_S^0\pi^-\pi^+$; (2) $B^- \to D^{*0}h^-, D^{*0} \to D^0\pi^0, D^0 \to K^-\pi^+$; (3) $\bar{B}^0 \to D^+h^-, D^+ \to K^-\pi^+\pi^+$; and (4) $\bar{B}^0 \to D^{*+}h^-, D^{*+} \to D^0\pi^+, D^0 \to K^-\pi^+$. The selection has been designed to be largely common among the modes studied, and is described in Ref. [5]. The signal extraction is done by fitting the beam-energy difference (ΔE) variable, defined as $\Sigma E_i - E_{\rm beam}$, where $E_{\rm beam}$ and E_i are the beam energy and energy of B daughter particles in the center-of-mass frame, respectively. In general, the signal distribution of ΔE peaks at zero. The fit is performed simultaneously in $B \to D\pi$ and $B \to DK$ samples for all the modes [5]. The values of $R^{(*)0/+}$ are directly extracted from the fit to data. These are summarized in Tables 1 and 2, and are compared to the values obtained by the LHCb experiment [6]. Various sources of systematic uncertainties are also considered for these measurements as reported in Ref. [5]. The results are compatible with the world-average values reported in Ref. [7].

Table 1: $R^+(\times10^{-2})$ and $R^0(\times10^{-2})$ results compared to those reported by the LHCb Collaboration [6].

	$B^- \to D^0(K^-\pi^+)h^-$	$B^- \to D^0(K_S^0\pi^-\pi^+)h^-$	$\bar{B}^0 \to D^+(K^-\pi^+\pi^+)h^-$
Belle II	$7.66 \pm 0.55\,^{+0.11}_{-0.08}$	$6.32 \pm 0.81^{+0.09}_{-0.11}$	$9.22 \pm 0.58 \pm 0.09$
LHCb	$7.77 \pm 0.04 \pm 0.07$	$7.77 \pm 0.04 \pm 0.07$	$8.22 \pm 0.11 \pm 0.25$

Table 2: $R^{*+}(\times10^{-2})$ and $R^{*0}(\times10^{-2})$ results compared to those reported by the LHCb Collaboration [6].

	$B^- \to D^{*0}h^-$	$\bar{B}^0 \to D^{*+}h^-$
Belle II	$6.80 \pm 1.01 \pm 0.07$	$5.99 \pm 0.82\,^{+0.17}_{-0.08}$
LHCb	$7.93 \pm 0.11 \pm 0.56$	$7.76 \pm 0.34 \pm 0.26$

3. Measurement of the CKM angle ϕ_3

Among the three CKM angles, ϕ_3 is the only angle that is accessible at tree-level decays. Therefore, assuming the absence of new physics at tree level, the measurement of ϕ_3 provides a test of the SM when compared to indirect determinations. The latter are derived from independent measurements of the sides and other angles of the unitarity triangle, which can be influenced by beyond-the-SM particles via loop amplitudes. The world-average value of direct measurements of ϕ_3 is $\left(66.2^{+3.4}_{-3.2}\right)^\circ$ [8]. The indirect determination of ϕ_3 has a precision of $(63.4 \pm 0.9)^\circ$ [9]. Therefore, improvement in the direct determination of ϕ_3 is required to better constrain possible NP contributions to CP violation. We have used the decay mode $B^- \to D\left(K_S^0 h^+h^-\right)h^-$, where D is either a D^0 or $\bar{D}^0$ and h is a pion or kaon, for this precision measurement. The $D \to K_S^0 h^+h^-$ decays proceed via several intermediate resonances, which results in a variation of the *CP* asymmetry over phase space such that ϕ_3, as well as other parameters related to the B-decay amplitude, can be determined from a single decay.

The Bondar, Poluektov, Giri, Grossman, Soffer and Zupan (BPGGSZ) method [11–13], which uses the phase-space distribution of the products of D decays to multibody self-conjugate final states, such as $K^0_S h^+ h^-$, has been used. In this method, the D Dalitz space is binned to achieve optimal, and model-independent, sensitivity to ϕ_3. The binning eliminates the model-dependent systematic uncertainty enabling degree-level precision with a large enough dataset. The signal yield in each bin is given by

$$\Gamma_i^{\pm} \propto F_i + r_B^2 \overline{F}_i + 2\sqrt{F_i \overline{F}_i}(c_i x_{\pm} + s_i y_{\pm}), \tag{1}$$

where $(x_{\pm}, y_{\pm}) = r_B(\cos(\pm\phi_3 + \delta_B),\ \sin(\pm\phi_3 + \delta_B))$. Here, F_i is the number of events in the i^{th} bin of a flavor-tagged D decay sample. The parameters c_i and s_i are the amplitude-averaged strong-phase difference between $\overline{D^0}$ and D^0 over the i^{th} bin and can be measured using quantum-correlated pairs of D mesons created at e^+e^- annihilation experiments operating at the threshold of $D\overline{D}$ pair production. The $(x_{\pm}, y_{\pm})$ parameters are obtained from Eq. 1 using the maximum likelihood method. The control sample $B \to D\pi$ is used to determine the F_i and F_{-i} fractions in the likelihood method itself as these events have the same relative acceptance over phase space as of $B \to DK$ if a common selection is applied. An alternate parameterisation is introduced, to make the fit stable at low r_B value, which utilises the fact that ϕ_3 is a common parameter, and that the *CP* violation in $B \to D\pi$ decays can therefore be described by the addition of a single complex variable [14], $\xi^{D\pi}$, which is function of the parameters $x_{\pm}^{D\pi}, y_{\pm}^{D\pi}$. The values of c_i and s_i parameters for $D^0 \to K^0_S h^+ h^-$ decays, as well as the binning scheme to divide the D phase space, used in this analysis are reported in Ref. [15, 16].

The decays $B \to DK$ and $B \to D\pi$ are reconstructed, where D decays into $K^0_S h^- h^+$ final states. Charged particle tracks are selected by requiring $|dr| < 0.2$ cm and $|dz| < 1$ cm, where dr and dz represent the distance of closest approach to the interaction point (IP) in the plane transverse to the beam direction and in the beam direction, respectively. These tracks are then identified as kaons or pions by the particle identification detectors. The K^0_S candidates are reconstructed from two oppositely charged pion tracks. The dipion candidate mass is required to be within $\pm 3\sigma$ of the known K^0_S mass. The $K^0_S h^+ h^-$ mass is restricted to match the known D mass, $1.85 < M_{D^0} < 1.88$ GeV/c^2, to reduce combinatorial backgrounds. The B-meson candidates are reconstructed by combining a D candidate with a charged kaon or pion. The kinematic variables used for B reconstruction are the beam-constrained mass (M_{bc}), defined as $\sqrt{E^2_{\text{beam}} - (\Sigma\overrightarrow{p_i})^2}$, where $\overrightarrow{p_i}$ are the momenta of B daughter particles in the center-of-mass frame, and the ΔE. The selection criteria chosen are $-0.13 < \Delta E < 0.18$ GeV and $M_{\text{bc}} > 5.27$ GeV/c^2. A kinematic constraint is applied so that the B daughters come from a common vertex. In events with more than one candidate, the candidate with the smallest χ^2 value, constructed from the M_{bc} and M_D pulls, is retained.

The main source of background is $e^+e^- \to q\overline{q}$ ($q = u, d, s$ or c) continuum events. These backgrounds are suppressed by utilizing the event topology, which is different from that of $B\bar{B}$ events, with a binary classifier based on boosted decision trees (BDT) that combines eight inputs into a scalar output discriminator. Continuum events preferentially produce particles collimated into back-to-back jets, whereas the $e^+e^- \to \Upsilon(4S) \to B\overline{B}$ are distributed uniformly over the 4π

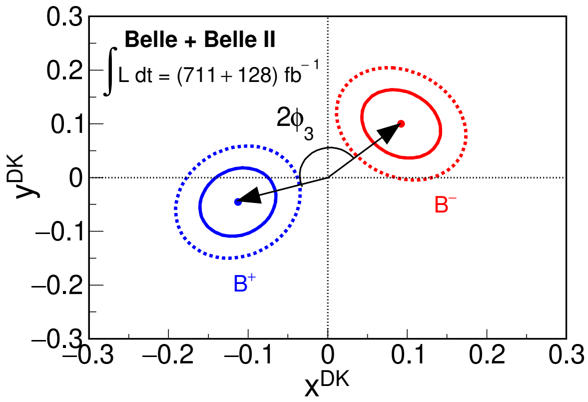

Figure 2: Statistical confidence levels at 68.2% and 95.5% probability for (x_+^{DK}, y_+^{DK}) (blue) and (x_-^{DK}, y_-^{DK}) (red) as measured in $B \to DK$ decays from a profile likelihood scan. The dots represent central values.

solid angle. The overall selection efficiencies for all the decay modes used in this analysis are summarized in the Ref. [10].

We determine the $(x_\pm^{DK}, y_\pm^{DK}, x_\xi^{D\pi}$ and $y_\xi^{D\pi})$ parameters using a two-dimensional extended maximum-likelihood fit to the variables ΔE and transformed BDT output (C') [10], fitted simultaneously in $B \to D\pi$ and $B \to DK$ samples using the combined Belle and Belle II datasets. The obtained values of these parameters along with their two-dimensional confidence regions are demonstrated in Fig. 2. The CP-asymmetry in each Dalitz plot bin i is extracted using the bin-yield N_i as $\left(N_{-i}^- - N_{+i}^+\right) / \left(N_{-i}^- + N_{+i}^+\right)$; considering only the statistical uncertainties the obtained CPV has a significance of 5.8 standard deviations. Various sources of the systematic uncertainties are also considered in this analysis, which are described in the Ref. [10].

The parameters $\phi_3, r_B^{DK}, \delta_B^{DK}, r_B^{D\pi}$ and $\delta_B^{D\pi}$ are determined from $x_\pm^{DK}, y_\pm^{DK}, x_\xi^{D\pi}$ and $y_\xi^{D\pi}$ using a frequentist package described in the Ref. [14]. Generally, there is a two-fold ambiguity in the results of these physics parameters as Eqs. (1) are invariant under the simultaneous substitutions of $\phi_3 = \phi_3 + 180^\circ$ and $\delta_B^{Dh} = \delta_B^{Dh} + 180^\circ$. We choose the solution in the range $0^\circ < \phi_3 < 180^\circ$, which is favoured by other measurements [8]. The results are

$$\begin{aligned}
\phi_3 &= (78.4 \pm 11.4 \pm 0.5 \pm 1.0)^\circ\,, \\
r_B^{DK} &= 0.129 \pm 0.024 \pm 0.001 \pm 0.002, \\
\delta_B^{DK} &= (124.8 \pm 12.9 \pm 0.5 \pm 1.7)^\circ\,, \\
r_B^{D\pi} &= 0.017 \pm 0.006 \pm 0.001 \pm 0.001, \\
\delta_B^{D\pi} &= (341.0 \pm 17.0 \pm 1.2 \pm 2.6)^\circ\,.
\end{aligned} \tag{2}$$

The ϕ_3 result is consistent with the previous Belle results [17] but the statistical precision on ϕ_3 is improved from 15° due to improved K_S^0 selection and background suppression. The uncertainty related to strong-phase inputs has also decreased from 4° because of the new measurements reported by the BESIII collaboration [15, 16]. Furthermore, the experimental systematic uncertainty is decreased from 4° primarily from the improved background suppression and the use of the $B \to D\pi$ sample to determine the acceptance.

4. Conclusion

The measurement of the decay rate ratio between $B \to D^{(*)}K$ and $B \to D^{(*)}\pi$ decays are reported using 62.8 fb^{-1} Belle II dataset. The results are compatible with the world-average values.

The results of the first Belle and Belle II combined model-independent measurement of the CKM unitarity triangle angle ϕ_3 using $B^- \to D^0(K^0_S h^- h^+)h^-$ decays reconstructed from a combined sample of 711 fb^{-1} of Belle data and 128 fb^{-1} of Belle II data are presented. The measured precision is limited by the size of the data sample, so a future analysis with a Belle II data set corresponding to 10 ab^{-1} will provide measurements with a precision of approximately 4° from the $B^- \to D^0\left(K^0_S\pi^+\pi^-\right)h^-$ mode alone.

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