First measurements from charmless $B$ decays at Belle II

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We report on first measurements of branching fractions, $CP$-violating charge-asymmetries, and polarizations in various charmless $B$ decays at Belle II. We use a sample of electron-positron collisions collected in 2019–2020 at the $\Upsilon(4S)$ resonance from the SuperKEKB collider corresponding to an integrated luminosity of 34.6 fb$^{-1}$. All results are consistent with known values and provide extensive validations of the detector performances and analysis strategies.
1. Introduction

Charmless $B$ decays are important to search for non-standard-model (non-SM) physics in the flavor sector. Many decay channels are governed by ‘penguin’ amplitudes, which are sensitive to non-SM contributions to the loop. Studying them in detail is an important goal of the Belle II experiment. With the largest sample of $e^+e^-$ collisions expected in the next decade, Belle II is expected to improve significantly important measurements such as the determination of the CKM phase $\alpha/\phi_2$ [1, 2], the precision test of of $K\pi$ isospin sum rule [1, 3], and the study of CP-violating asymmetries localized in the three-body $B$ decays’ phase space [1]. In addition, the measurement of decay-time dependent $CP$ violation in the penguin-dominated $B^0 \rightarrow \phi K^0$ mode, compared with corresponding results from $B^0 \rightarrow J/\psi K^0$ decays, offers a sharp probe of non-SM physics. Measurements of the longitudinal polarization fractions ($f_L$) of decays of $B$ mesons into pairs of vector mesons also probe non-SM dynamics. Previous measurements of $f_L$ in $B^0 \rightarrow J/\psi K^0$ showed a sizable contribution from transverse polarization, while most predictions expect the longitudinal component to dominate.

SuperKEKB [6] is an asymmetric $e^+e^+$ collider, that started collision operations with the Belle II detector [7] in March 2019. We use a data sample of 34.6 fb$^{-1}$, which was collected at the $\Upsilon$(4S) resonance up to May 2020. This report presents the first measurements of branching fractions ($\mathcal{B}$), $CP$-violating charge-asymmetries ($\mathcal{A}(CP)$), and longitudinal polarization fractions ($f_L$) based on the following $B$ decays reconstructed in Belle II data: $B^0 \rightarrow K^+\pi^-$, $B^0 \rightarrow \pi^+\pi^-$, $B^+ \rightarrow K^+\pi^0$, $B^+ \rightarrow \pi^+\pi^0$, $B^+ \rightarrow K^0\pi^+$, $B^+ \rightarrow K^+K^-\pi^+$, $B^+ \rightarrow K^0\pi^+$, $B^0 \rightarrow \phi K^0$, $B^+ \rightarrow \phi K^+$, $B^0 \rightarrow \phi K^0$, and $B^{*-} \rightarrow \phi K^{*+}$ [8, 9].

The $B$ reconstruction, event selection criteria, and background suppression strategy are studied with various simulated signal and background samples. Charged-particle trajectories (tracks) are identified with inner vertex detectors and a central drift chamber with requirements on the displacement from the interaction point to reduce beam-background-induced tracks. The identification of charged particles uses the information from two particle-identification (PID) devices, a time-of-propagation counter in the barrel region and a proximity-focusing aerogel ring-image Cherenkov counter in the forward endcap region. Decays of $\pi^0$ candidates are reconstructed by using two isolated clusters in the electromagnetic calorimeter, with requirements on the helicity angle and kinematic fit to constrain $\pi^0$ mass. Decays of $K^0_S$ candidates are reconstructed from two opposite-charge pion candidates from a common vertex, restricted to meet additional requirements on their kinematic variables, e.g. momentum, flight distance, distance between pion trajectories, etc, to further reduce the combinatorial background. Decays of $\phi$ candidates are reconstructed from two opposite-charge kaon candidates. Decays of $K^{*0}$ candidates are reconstructed from one $K^+$ and one $\pi^-$, and decays of $K^{*+}$ candidates are reconstructed from one $K^0_S$ and one $\pi^+$. In three-body decays, we suppress the relevant peaking backgrounds from charmed or charmonium intermediate states by excluding the corresponding two-body mass ranges.

We use the following two major variables to distinguish the signal $B$ events from other backgrounds: the energy difference $\Delta E \equiv E_B - \sqrt{s}/2$ between the reconstructed $B$ candidate and half of the collision energy in the $\Upsilon$(4S) frame, and beam-energy-constrained mass $M_{bc} \equiv \sqrt{s}/(4e^2) - (p_B/c)^2$. 

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Yun-Tsung Lai
2. Continuum background suppression

One of the main challenges of the charmless $B$ decays’ reconstruction is the large combinatorial background with the same final state from the $e^+e^- \rightarrow q\bar{q}$ ($q = u,d,s,c$) processes. Signal rates $10^5$ times smaller than continuum background and the lack of distinctive final-state features (leptons or intermediate resonances) make the reconstruction of signal hard. A binary boosted decision-tree (BDT) classifier is used to combine more than 30 variables nonlinearly. The input variables to the BDT include event topology variables, flavor-tagging information, vertex-fitting information, and kinematic-fit information. All of them are required to be loosely or not correlated to $\Delta E$ and $M_{bc}$.

3. Signal extraction and measurement results

We use unbinned maximum likelihood fits to extract signal yields from the data to calculate various physics observables. In the $B \rightarrow hh$ and $B \rightarrow hhh$ ($h = K$ or $\pi$) analysis, only $\Delta E$ is fit for events restricted to $M_{bc} > 5.27$ GeV/c$^2$. The fits to the two $B \rightarrow \phi K$ modes use five variables including $\Delta E$, $M_{bc}$, output of the continuum suppression BDT discriminator ($C_{\text{out}}$), $K^+K^-$ candidate mass ($m_{K^+K^-}$), and $\phi$ candidate’s cosine of the helicity angle ($\cos\theta_{H,\phi}$). The fits to the two $B \rightarrow \phi K^*$ modes use seven variables: $K^*\pi^-$ candidate mass ($m_{K^*\pi}$) and $K^+$ candidate’s cosine of the helicity angle ($\cos\theta_{H,K^+}$) in addition to the ones used in $B \rightarrow \phi K$ modes. By fitting data, we determine the following quantities:

- Branching fractions: $B = \frac{N}{N_{\text{tot}}}$, where $N$ is the signal yield, $\epsilon$ is the signal reconstruction efficiency determined from simulation and validated with control samples, and $N_{BB}$ is the number of $B\bar{B}$ events (19.7M for $B^+B^-$ and 18.7M for $B^0\bar{B}^0$). $N_{BB}$ is obtained from the measured integrated luminosity, the exclusive $e^+e^-\rightarrow\Upsilon(4S)$ cross section, and $B(\Upsilon(4S)\rightarrow B^0\bar{B}^0)$ [10].

- $CP$ asymmetries: The raw asymmetries are obtained as $C = \frac{N(b) - N(\bar{b})}{N(b) + N(\bar{b})}$, where $N(b)$ and $N(\bar{b})$ are the yields of the final-state meson containing $b$ and $\bar{b}$ flavors, respectively. The $CP$ asymmetry is obtained by considering the instrumental effect $C = C_{\text{inst}} + C_{\text{det}}$. $C_{\text{det}}(K^+\pi^-) = -0.010 \pm 0.003$ and $C_{\text{det}}(K^0\pi^+) = -0.007 \pm 0.022$, which are measured on large samples of $D^0 \rightarrow K^+\pi^-$ and $D^+ \rightarrow K^0_S\pi^+$ decays with negligible $CP$ violation. Then, $C_{\text{det}}(K^+) = -0.015 \pm 0.022$ is obtained from $C_{\text{det}}(K^+) = C_{\text{det}}(K^+\pi^-) - C_{\text{det}}(K^0_S\pi^+) + C_{\text{det}}(K^0_S)$ [11].

- Longitudinal polarization fractions: $f_L = \frac{N_{(L)}}{N_{U} + N_{D}}$, where $N_{L(T)}$ and $\epsilon_{L(T)}$ are the signal yield and signal reconstruction efficiency with longitudinal (transverse) polarization, respectively. The distinctive helicity-angle distributions allow for separating the two signal components.

Figures 1–8 show the $\Delta E$ distributions in data for $B^0 \rightarrow K^+\pi^-$, $B^0 \rightarrow \pi^+\pi^-$, $B^+ \rightarrow K^0\pi^+$, $B^0 \rightarrow K^0\pi^0$, $B^+ \rightarrow K^+K^-$, and $B^+ \rightarrow K^+\pi^+\pi^-$ decays, with fit projections overlaid. Figure 9 shows the $\Delta E$, $M_{bc}$, $C_{\text{out}}$, $m_{K^+K^-}$, and $\cos\theta_{H,\phi}$ distributions in data for $B^+ \rightarrow \phi K^*$ and $B^0 \rightarrow \phi K^0$ decays, with fit projections overlaid. Figure 10 shows the $\Delta E$, $M_{bc}$, $C_{\text{out}}$, $m_{K^+K^-}$, $\cos\theta_{H,\phi}$, $m_{K\pi}$, and $\cos\theta_{H,K^*}$ distributions in data for $B^+ \rightarrow \phi K^{*+}$ and $B^0 \rightarrow \phi K^{*0}$.
decays, with fit projections overlaid. The major systematic uncertainties come from tracking, PID, and fit modelling. All the measurement results are summarized in Table 1.

Figure 1: Distribution of $\Delta E$ for $B^0 \to K^+ \pi^-$ (left) and $B^0 \to K^- \pi^+$ (right) decays with fit projections overlaid.

Figure 2: Distribution of $\Delta E$ for $B^0 \to \pi^+ \pi^-$ decays with fit projections overlaid.
Figure 3: Distribution of $\Delta E$ for $B^+ \rightarrow K^+ \pi^0$ (left) and $B^- \rightarrow K^- \pi^0$ (right) decays with fit projections overlaid.

Figure 4: Distribution of $\Delta E$ for $B^+ \rightarrow \pi^+ \pi^0$ (left) and $B^- \rightarrow \pi^- \pi^0$ (right) decays with fit projections overlaid.

Figure 5: Distribution of $\Delta E$ for $B^+ \rightarrow K_3^0 \pi^+$ (left) and $B^- \rightarrow K_3^0 \pi^-$ (right) decays with fit projections overlaid.
Figure 6: Distribution of $\Delta E$ for $B^0 \rightarrow K_0^0 \pi^0$ decays with fit projections overlaid.

Figure 7: Distribution of $\Delta E$ for $B^+ \rightarrow K^+ K^- K^+$ (left) and $B^- \rightarrow K^- K^+ K^-$ (right) decays with fit projections overlaid.

Figure 8: Distribution of $\Delta E$ for $B^+ \rightarrow K^+ \pi^- \pi^+$ (left) and $B^- \rightarrow K^- \pi^+ \pi^-$ (right) decays with fit projections overlaid.
Figure 9: Distribution of $\Delta E$, $M_{bc}$, $C'_\text{out}$, $m_{K^+K^-}$, and $\cos\theta_{H,\phi}$ for $B^+ \rightarrow \phi K^+$ and $B^0 \rightarrow \phi K^0$ decays with fit projections overlaid.
Figure 10: Distribution of $\Delta E$, $M_{bc}$, $C_{out}$, $m_{K^-K^+}$, $\cos\theta_{H,\phi}$, $m_{K\pi}$, and $\cos\theta_{H,K^*}$ for $B^+ \rightarrow \phi K^{*+}$ and $B^0 \rightarrow \phi K^{*0}$ decays with fit projections overlaid.
Table 1: Summary of measurement results. The first uncertainties are statistical and the second ones are systematic.

<table>
<thead>
<tr>
<th>Mode</th>
<th>$\mathcal{B}$ ($10^{-6}$)</th>
<th>$\mathcal{A}_CP$</th>
<th>$f_L$</th>
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<tr>
<td>$B^0 \rightarrow K^+\pi^-$</td>
<td>$18.9\pm1.4\pm1.0$</td>
<td>$0.030\pm0.064\pm0.008$</td>
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<td>$B^0 \rightarrow \pi^+\pi^-$</td>
<td>$5.6^{+1.0}_{-0.9}\pm0.3$</td>
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<td>$B^+ \rightarrow K^+\pi^0$</td>
<td>$12.7^{+2.2}_{-2.1}\pm1.1$</td>
<td>$0.052^{+0.121}_{-0.119}\pm0.022$</td>
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<tr>
<td>$B^+ \rightarrow \pi^+\pi^0$</td>
<td>$5.7\pm2.3\pm0.5$</td>
<td>$-0.268^{+0.249}_{-0.322}\pm0.123$</td>
<td>-</td>
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<tr>
<td>$B^+ \rightarrow K^0\pi^+$</td>
<td>$21.8^{+3.3}_{-3.0}\pm2.9$</td>
<td>$-0.072^{+0.109}_{-0.114}\pm0.024$</td>
<td>-</td>
</tr>
<tr>
<td>$B^0 \rightarrow K^0\pi^0$</td>
<td>$10.9^{+2.9}_{-2.6}\pm1.6$</td>
<td>-</td>
<td>-</td>
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<tr>
<td>$B^+ \rightarrow K^+K^-K^+$</td>
<td>$32.0\pm2.2\pm1.4$</td>
<td>$-0.049\pm0.063\pm0.022$</td>
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<tr>
<td>$B^+ \rightarrow K^+\pi^-\pi^+$</td>
<td>$48.0\pm3.8\pm3.3$</td>
<td>$-0.063\pm0.081\pm0.023$</td>
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<td>$B^0 \rightarrow \phi K^0$</td>
<td>$5.9\pm1.8\pm0.7$</td>
<td>-</td>
<td>-</td>
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<tr>
<td>$B^+ \rightarrow \phi K^+$</td>
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<td>$B^0 \rightarrow \phi K^0$</td>
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<td>$0.57\pm0.20\pm0.04$</td>
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<td>$B^+ \rightarrow \phi K^{*0}$</td>
<td>$21.7\pm4.6\pm1.9$</td>
<td>-</td>
<td>$0.58\pm0.23\pm0.02$</td>
</tr>
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</table>
4. Summary

Belle II reports first measurements in charmless $B$ decays with a data sample corresponding to $34.6 \text{ fb}^{-1}$. The measurements include branching fractions, $CP$ asymmetries, and longitudinal polarization fractions. All the results are in agreement with the known values, and offer good validations on the detector performance and analysis strategies.

References