Charmless $B$ Decay Measurements at Belle II

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We report the measurements of $CP$ asymmetry and branching fraction of various charmless $B$ decays at the Belle II experiment. We use a sample of electron-positron collisions at the $\Upsilon(4S)$ resonance delivered by the SuperKEKB collider that corresponds to $62.8 \text{ fb}^{-1}$ of integrated luminosity. All the results agree with the previous determinations and contribute important information to an early assessment of Belle II performance.
1. Introduction

The study of charmless $B$ decays is a keystone of the flavor physics program to test the standard model (SM) and its extension. These decays mediated by Cabibbo-suppressed $b \rightarrow u$ tree and $b \rightarrow d, s$ loop transitions are sensitive to non-SM contributions. The CKM angle $\theta_{13}$ can be measured directly only by an analysis of charmless $B \rightarrow \pi \pi, \rho \rho$ decays related by isospin symmetry. Isospin symmetry can be used also the make sum-rules, i.e. linear combination of $B$ and $C\bar{P}$ asymmetries of charmless decays, that can provide test of the standard model with precision generally better than 1%. Belle II has a unique capability of studying jointly, and within a consistent experimental environment for, all relevant final states of isospin-related $B$ decays to improve the knowledge of alpha and put stringent bound on sum-rule tests.

Belle II [2] is a magnetic spectrometer having almost $4\pi$ solid-angle coverage, designed to reconstruct final-state particles of $e^+e^-$ collisions delivered by the SuperKEKB asymmetric-energy collider [3], located at the KEK laboratory in Tsukuba, Japan. Belle II experiment started collecting data from March 2019. In this proceeding, we will focus on the result based on $62.8 \text{ fb}^{-1}$ dataset which was collected at $\Upsilon(4S)$ resonance. With this dataset, charmless $B$ decay mainly focus the early assessment of detector performance and advance analysis techniques capabilities.

2. Analysis overview and Challenges

We form final-state particle candidate by applying loose baseline selection criteria and then combine them in kinematic fits consistent with the topologies of the desired decays to reconstruct intermediate states and $B$ candidates. The key challenge in reconstructing significant charmless signal is the large contamination from $e^+e^- \rightarrow q\bar{q}$ ($q = u,d,s,c$) continuum background coupled with low signal branching fraction. We use a binary-decision-tree classifier that combines a number of mostly topological variables having some discrimination between $B$-meson signal and continuum background. We pick up those variables whose correlation with $\Delta E$ and $M_{bc}$ is below $\pm 5\%$ to reduce possible bias in the signal yield determination. The latter two are the energy difference $\Delta E = E_{B} - \sqrt{s}/2$ between the energy of the reconstructed $B$ candidate and half of the collision energy, both in the $\Upsilon(4S)$ frame, and the beam-energy-constrained mass $M_{bc} = \sqrt{s}/(4c^2) - (p_B/c)^2$, which is the invariant mass of the $B$ candidate with its energy being replaced by the half of the center-of-mass collision energy. Another challenge is to separate $B$ background events that peak in the signal region. To deal with this peaking background, we either kinematically veto it from the sample or include a separate component in the fit model. For example, in the analysis of $B \rightarrow K\pi\pi$ decays the background from $B^* \rightarrow \bar{D}^{0}(\rightarrow K^{*}\pi\pi)\pi$ decays is suppressed by vetoing candidates with a kaon-pion mass in the range $[1.84, 1.89]$ GeV/c$^2$. We then apply optimized continuum suppression and particle identification criteria. For the signal reconstruction efficiencies calculation and fit model development, we use simulation and correct/validate with control data. To determine the systematic uncertainties, pseudo-experiment and control channel studies are performed. We then inspect the most interesting region (or, signal region) on data to measure the physics observables.
3. Isospin sum-rule

The isospin sum-rule relation for the $B \rightarrow K\pi$ system given in Eq. (1) provides a stringent test of the SM.

$$I_{K\pi} = A_{K^+\pi^-} + A_{K^0\pi^0} \frac{B(K^0\pi^0)}{B(K^+\pi^-)} \tau_{B^0} - 2A_{K^+\pi^0} \frac{B(K^0\pi^0)}{B(K^+\pi^-)} \tau_{B^+} - 2A_{K^0\pi^0} \frac{B(K^0\pi^0)}{B(K^+\pi^-)} = 0. \quad (1)$$

In all the four $K\pi$ channels, signal yields are determined with unbinned extended maximum-likelihood fits of the $\Delta E$ and $M_{bc}$ distributions. The key challenge in $B^0 \rightarrow K^0\pi^0$ analysis arises due to the absence of primary charged final-state particles at the $B$ decay vertex. The position of the $B$ vertex reconstructed from the intersection of the $K^0_d$ trajectory with the interaction region. We measure the time-integrated asymmetry of the $CP$-eigenstate $B^0 \rightarrow K^0\pi^0$ with the signal-side quark flavor $q$ obtained using the flavor content of the other $B$-meson, provided by the category-based flavor tagger [4]. The asymmetry $A_{K^0\pi^0}$ is determined from a simultaneous maximum-likelihood fit to the unbinned $M_{bc}$-$\Delta E-q \cdot r$ distributions, where $r$ is the dilution factor of flavor tagger output. The signal probability density function (PDF) is given by

$$P_{\text{sig}} = \frac{1}{2} [1 + q(1 - 2w_r) \cdot (1 - 2\chi_d)A_{K^0\pi^0}], \quad (2)$$

where $\chi_d$ is the $B^0\overline{B}^0$ mixing frequency, $w_r$ is the wrong tag fraction in each dilution ($r$) interval. Figures 1 and 2 show the $\Delta E$ distribution of all the four $K\pi$ system. We obtain the following branching fractions,

- $B(B^0 \rightarrow K^+\pi^-) = [18.0 \pm 0.9(\text{stat}) \pm 0.9(\text{syst})] \times 10^{-6}$,
- $B(B^+ \rightarrow K^+\pi^0) = [11.9^{+1.1}_{-1.0}(\text{stat}) \pm 1.6(\text{syst})] \times 10^{-6}$,
- $B(B^+ \rightarrow K^0\pi^+)$ = $[21.4^{+2.3}_{-2.2}(\text{stat}) \pm 1.6(\text{syst})] \times 10^{-6}$,
- $B(B^0 \rightarrow K^0\pi^0) = [8.5^{+1.7}_{-1.6}(\text{stat}) \pm 1.2(\text{syst})] \times 10^{-6}$

and $CP$-violating rate asymmetries

- $A_{CP}(B^0 \rightarrow K^+\pi^-) = -0.16 \pm 0.05(\text{stat}) \pm 0.01(\text{syst})$,
- $A_{CP}(B^+ \rightarrow K^+\pi^0) = -0.09 \pm 0.09(\text{stat}) \pm 0.03(\text{syst})$,
- $A_{CP}(B^+ \rightarrow K^0\pi^+)$ = $-0.01 \pm 0.08(\text{stat}) \pm 0.05(\text{syst})$,
- $A_{CP}(B^0 \rightarrow K^0\pi^0) = -0.40^{+0.46}_{-0.44}(\text{stat}) \pm 0.04(\text{syst})$.

The dominant contribution in the systematic uncertainties comes from $\pi^0$ and $K^0_s$ reconstruction efficiency, it will be reduced with more data.

4. $CP$ violation in multibody decays

The study of multibody [5] charmless $B$ decays has recently attracted significant attention in the flavor program. The contribution between weak- and strong-interaction dynamics in $B^+ \rightarrow K^+K^-K^+$, $B^+ \rightarrow K^+\pi^-\pi^+$ and $B^0 \rightarrow K^+\pi^-\pi^0$ decays are enriched by the amplitude structure
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Figure 1: Signal-enhanced $\Delta E$ distributions of $B^0 \to K^*\pi^-$ (left) and $B^+ \to K^*\pi^0$ (right).

Figure 2: Signal-enhanced $\Delta E$ distributions of $B^+ \to K^0\pi^+$ (left) and $B^0 \to K^0\pi^0$ (right).

accessible via their Dalitz plot. In Fig. 3 we show the $\Delta E$ distributions for two of these multibody systems. We obtain the following branching fractions,

$$\mathcal{B}(B^+ \to K^+K^-K^+) = [35.8 \pm 1.6(\text{stat}) \pm 1.4(\text{syst})] \times 10^{-6},$$

$$\mathcal{B}(B^+ \to K^+\pi^-\pi^+) = [67.0 \pm 3.3(\text{stat}) \pm 2.3(\text{syst})] \times 10^{-6},$$

$$\mathcal{B}(B^0 \to K^+\pi^-\pi^0) = [38.1 \pm 3.5(\text{stat}) \pm 3.9(\text{syst})] \times 10^{-6}$$

and CP-violating rate asymmetries

$$\mathcal{A}_{CP}(B^+ \to K^+K^-K^+) = -0.103 \pm 0.042(\text{stat}) \pm 0.020(\text{syst}),$$

$$\mathcal{A}_{CP}(B^+ \to K^+\pi^-\pi^+) = -0.010 \pm 0.050(\text{stat}) \pm 0.021(\text{syst}),$$

$$\mathcal{A}_{CP}(B^0 \to K^+\pi^-\pi^0) = +0.207 \pm 0.088(\text{stat}) \pm 0.011(\text{syst}).$$

The dominant contribution in the systematic uncertainties comes from $\pi^0$ reconstruction and tracking efficiency, it will be reduced with more data.

5. Towards the determination of $\alpha/\phi_2$

The study of charmless decays at Belle II can provide improved measurements of the CKM unitarity angle $\alpha/\phi_2 = \arg\left(-\frac{V_{td}V_{cb}^*}{V_{ud}V_{ub}^*}\right)$, where $V_{ij}$ are elements of the quark-mixing matrix. In particular, the combined analysis of branching fractions and CP violating asymmetries of the complete set of $B \to \pi\pi, \rho\rho$ isospin partners enables a determination of $\alpha$ [6]. We are now focusing
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Figure 3: Signal-enhanced ΔE distributions of $B^+ \to K^+K^-K^+$ (left) and $B^0 \to K^+\pi^-\pi^0$ (right).

On $B^0 \to \pi^0\pi^0$, $B^+ \to \pi^+\pi^0$, $B^0 \to \pi^+\pi^-$ and $B^+ \to \rho^+\pi^0$ decays. The $B^0 \to \pi^0\pi^0$ channel is particularly challenging as it requires two $\pi^0$ reconstruction. A dedicated boosted decision-trees classifier used to suppress background photons by combining 20 calorimetric variables. Signal yields are determined with an extended maximum-likelihood fit of the $\Delta E$, $M_{bc}$ and transformed continuum suppression variable. Figure 4 shows the $\Delta E$ distribution of two $\pi\pi$ channels. We obtain the following branching fractions,

$$B(B^0 \to \pi^+\pi^-) = \left[5.8 \pm 0.7\text{ (stat)} \pm 0.7\text{ (syst)}\right] \times 10^{-6},$$

$$B(B^+ \to \pi^+\pi^0) = \left[5.5^{+1.0}_{-0.5}\text{ (stat)} \pm 0.7\text{ (syst)}\right] \times 10^{-6},$$

$$B(B^0 \to \pi^0\pi^0) = \left[0.98^{+0.48}_{-0.39}\text{ (stat)} \pm 0.27\text{ (syst)}\right] \times 10^{-6}$$

and $CP$ asymmetry of $\mathcal{A}_{CP}(B^+ \to \pi^+\pi^0) = -0.04 \pm 0.17\text{ (stat)} \pm 0.06\text{ (syst)}$. The $B^+ \to \rho^+\rho^0$ decay involves pion-only final state, where the large width of the $\rho$ mesons offers reduced distinctive features against dominant continuum background. Isolating a low-background signal is therefore the main challenge of the analysis. Signal yields are determined with an unbinned maximum-likelihood fits of $\Delta E$, continuum-suppression decision-tree output, the dipion masses and cosines of helicity angles of the $\rho$ candidates. Figure 5 shows the $\Delta E$ and log transform continuum-suppression output of $B^+ \to \rho^+\rho^0$ candidates. We obtain the branching fraction $B = [20.6 \pm 3.2\text{ (stat)} \pm 4.0\text{ (syst)}] \times 10^{-6}$ and longitudinal polarization fraction $f_L = 0.936^{+0.049}_{-0.047}\text{ (stat)} \pm 0.021\text{ (syst)}$. The dominant contribution in the systematic uncertainties comes from $\pi^0$ reconstruction and tracking efficiency, it will be reduced with more data.

Figure 4: Signal-enhanced $\Delta E$ distributions of $B^+ \to \pi^+\pi^0$ (left) and $B^0 \to \pi^0\pi^0$ (right).
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Figure 5: Distributions of $\Delta E$ (left) and log transform continuum-suppression output (right) for $B^+ \rightarrow \rho^+ \rho^0$ candidates.

6. Summary

Charmless $B$ decays play an important role in sharpening flavor picture. Belle II is getting ready to play a lead role in testing isospin sum rule, the study of local $CP$ violation, and the determination of $\alpha$. We discuss herein the preliminary measurements of charmless decays performed using 63 fb$^{-1}$ of early data. First Belle II measurement of $B^0 \rightarrow K^0 \pi^0$ completes the ingredients for the isospin sum rule; $B \rightarrow \rho \rho$ and $\pi \pi$ analysis show performance better than early Belle result. All results agree with known values within uncertainties and are mostly dominated by small sample size.

References