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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 performed using e^+e^- collision data recorded at the $\Upsilon(4S)$ resonance with the Belle II detector at the SuperKEKB collider. These include a test of the standard model using isospin sum rule, an investigation of localized *CP* asymmetries in the Dalitz plot, and an expected improvement on the precision of the CKM unitarity angle ϕ_2/α. All the results agree with the previous determinations and contribute important information to an early assessment of Belle II performance.

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1. Introduction

The study of charmless B decays is a keystone of the worldwide flavor physics program to test the standard model (SM) and its extension. These decays mediated by Cabbibo-suppressed $b \to u$ tree and $b \to d, s$ loop transitions are sensitive to non-SM contributions. They also provide the access to the three CKM unitarity angles. Furthermore, we can test the prediction of an isospin sum rule [1], given by

$$\mathcal{A}_{+-} + \mathcal{A}_{00}\frac{\mathcal{B}(K^0\pi^+)}{\mathcal{B}(K^+\pi^-)}\frac{\tau_0}{\tau_+} - 2\mathcal{A}_{+0}\frac{\mathcal{B}(K^+\pi^0)}{\mathcal{B}(K^+\pi^-)}\frac{\tau_0}{\tau_+} - 2\mathcal{A}_{00}\frac{\mathcal{B}(K^0\pi^0)}{\mathcal{B}(K^+\pi^-)} = 0, \qquad (1)$$

that combines the branching fraction ($\mathcal{B}$) and direct CP asymmetry ($\mathcal{A}_{CP}$) values measured in B decays to four possible $K\pi$ final states: $K^+\pi^-$, $K^0\pi^+$, $K^+\pi^0$, and $K^0\pi^0$. Belle II has a unique capability of studying jointly, and within a consistent experimental environment for, all the relevant final states towards a consistency test of the SM.

2. The Belle II detector

Belle II [2] is a magnetic spectrometer having almost 4π 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. The energies of the positron and electron beams are 4 and 7 GeV, respectively. Belle II comprises a number of subdetectors surrounding the interaction point (IP) in a cylindrical geometry. The innermost one is the vertex detector, which uses position-sensitive silicon layers to sample the trajectories of charged particles ('tracks') in the vicinity of the IP to determine the decay positions of their long-lived parent particles. Charged-particle momenta and charges are measured by a large-radius, helium-ethane, small-cell drift chamber, which also offers charged-particle-identification information via a measurement of specific ionization. A Cherenkov-light angle and time-of-propagation detector surrounding the drift chamber provides charged-particle identification in the central detector volume, supplemented by proximity-focusing, aerogel, ring-imaging Cherenkov detector in the forward region with respect to the electron beam. A CsI(Tl)-crystal electromagnetic calorimeter provides electron-energy measurements and photon reconstruction. Layers of plastic scintillators and resistive-plate chambers, interspersed between the magnetic flux-return iron plates, allow for the identification of K^0_L and muons.

3. Analysis overview

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. We then apply optimized continuum suppression and particle identification criteria. Signal reconstruction efficiencies are calculated from simulation and validated on data themselves. For the signal extraction, we develop fit model from simulation, later adjusted according to high-statistics control channels. To determine the systematic uncertainties, pseudo-experiment and control channel studies are performed. For the validation purpose, we

perform full analysis on control channel. We then inspect the most interesting region (or, signal region) on data to measure the physics observables.

4. Challenges

The key challenge in reconstructing significant charmless signal is the large contamination from $e^+e^- \to q\overline{q}$ ($q = u, d, s, c$) 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 ΔE and $M_{\rm bc}$ is below $\pm 5\%$ to reduce possible bias in the signal yield determination. The latter two are the energy difference $\Delta E = E^* - \sqrt{s}/2$ 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 $M_{\rm bc} = \sqrt{s/(4c^4) - (p^*/c)^2}$, 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, the background from $B^+ \to \overline{D}^0(\to K^+\pi^-)\pi^+$ decays is suppressed by vetoing candidates with a kaon-pion mass in the range $[1.84, 1.89]\,\mathrm{GeV}/c^2$.

5. Results

5.1 Isospin sum-rule

The isospin sum-rule relation for the $B \to K\pi$ system given in Eq. (1) provides a stringent test of the SM. In all the four $K\pi$ channels, signal yields are determined with unbinned extended maximum-likelihood fits of the ΔE and $M_{\rm bc}$ distributions. The $B^0 \to K^0\pi^0$ channel is most challenging one as it requires the reconstruction of two neutral particles, namely K^0 and π^0. We measure the time-integrated asymmetry of the CP-eigenstate $B^0 \to K^0\pi^0$ 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 $\mathcal{A}_{K^0\pi^0}$ is determined from a simultaneous maximum-likelihood fit to the unbinned $M_{\rm bc}-\Delta E$–q distributions. The signal probability density function (PDF) is given by

$$\mathcal{P}_{\rm sig} = \frac{1}{2}[1 + q(1 - 2w_A) \cdot (1 - 2\chi_3)\mathcal{A}_{K^0\pi^0}], \tag{2}$$

where χ_3 is the B^0–$\overline{B}^0$ mixing frequency, w_A is the wrong tag fraction in each dilution (r) interval. Figures 1 and 2 show the ΔE distribution of all the four $K\pi$ system. We obtain the following branching fractions,

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

and *CP*-violating rate asymmetries

$$\begin{aligned}
\mathcal{A}_{CP}(B^0 \to K^+\pi^-) &= -0.16 \pm 0.05(\text{stat}) \pm 0.01(\text{syst}),\\
\mathcal{A}_{CP}(B^+ \to K^+\pi^0) &= -0.09 \pm 0.09(\text{stat}) \pm 0.03(\text{syst}),\\
\mathcal{A}_{CP}(B^+ \to K^0\pi^+) &= -0.01 \pm 0.08(\text{stat}) \pm 0.05(\text{syst}),\\
\mathcal{A}_{CP}(B^0 \to K^0\pi^0) &= -0.40^{+0.46}_{-0.44}(\text{stat}) \pm 0.04(\text{syst}).
\end{aligned}$$

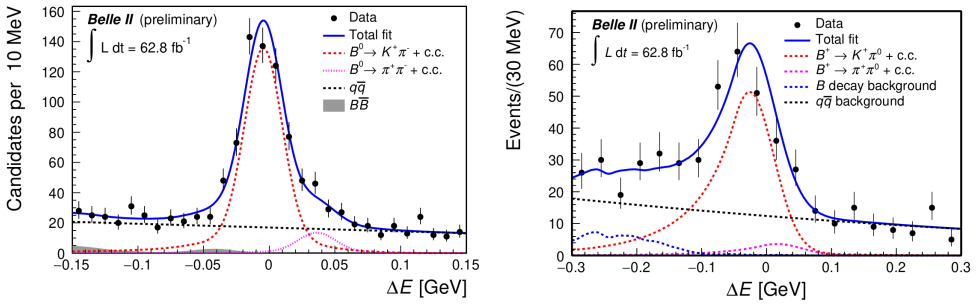

Figure 1: Signal-enhanced E distributions of $B^0 \to K^+\pi^-$ (left) and $B^+ \to K^+\pi^0$ (right).

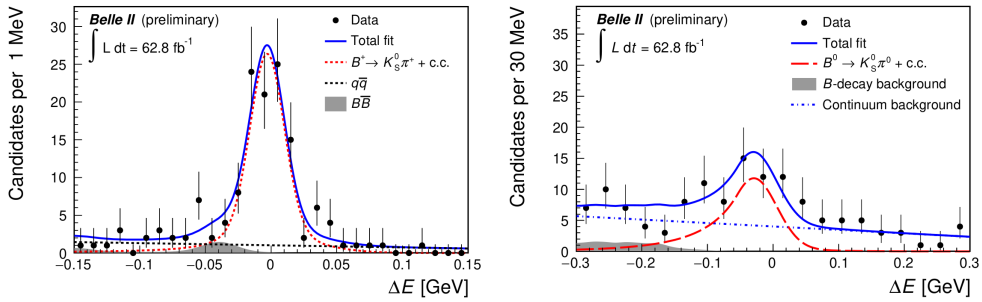

Figure 2: Signal-enhanced E distributions of $B^+ \to K^0\pi^+$ (left) and $B^0 \to K^0\pi^0$ (right).

5.1.1 *CP* violation in multibody decays

The study of multibody charmless B decays has recently attracted significant attention in the worldwide flavor program. The contribution between weak- and strong-interaction dynamics in $B^+ \to K^+K^-K^+$, $B^+ \to K^+\pi^-\pi^+$ and $B^0 \to K^+\pi^-\pi^0$ decays are enriched by the amplitude structure accessible via their Dalitz plot. Belle II has the unique capability of studying jointly all these final states within a consistent experimental environment. In Fig. 3 we show the E distributions for two of these multibody systems. We obtain the following branching fractions,

$$\begin{aligned}
\mathcal{B}(B^+ \to K^+K^-K^+) &= [35.8 \pm 1.6(\text{stat}) \pm 1.4(\text{syst})] \times 10^{-6},\\
\mathcal{B}(B^+ \to K^+\pi^-\pi^+) &= [67.0 \pm 3.3(\text{stat}) \pm 2.3(\text{syst})] \times 10^{-6},\\
\mathcal{B}(B^0 \to K^+\pi^-\pi^0) &= [38.1 \pm 3.5(\text{stat}) \pm 3.9(\text{syst})] \times 10^{-6}
\end{aligned}$$

and CP-violating rate asymmetries

$$\begin{aligned}
\mathcal{A}_{CP}(B^+ \to K^+K^-K^+) &= -0.103 \pm 0.042(\text{stat}) \pm 0.020(\text{syst}),\\
\mathcal{A}_{CP}(B^+ \to K^+\pi^-\pi^+) &= -0.010 \pm 0.050(\text{stat}) \pm 0.021(\text{syst}),\\
\mathcal{A}_{CP}(B^0 \to K^+\pi^-\pi^0) &= +0.207 \pm 0.088(\text{stat}) \pm 0.011(\text{syst}).
\end{aligned}$$

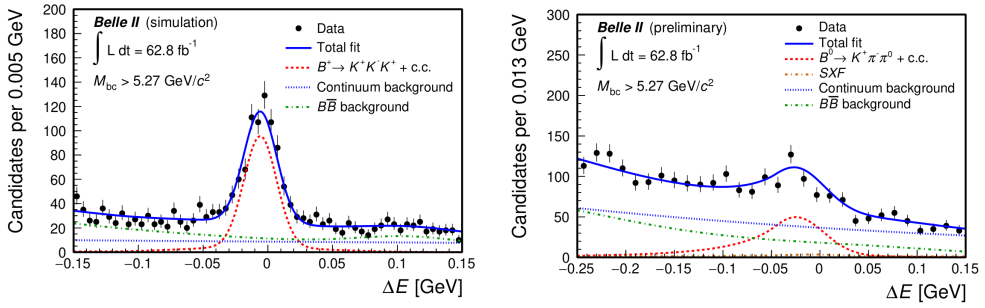

Figure 3: Signal-enhanced E distributions of $B^+ \to K^+K^-K^+$ (left) and $B^0 \to K^+\pi^-\pi^0$ (right).

5.1.2 Determination of α/ϕ_2

The study of charmless decays at Belle II can provide improved measurements of the CKM unitarity angle $\alpha/\phi_2 = \arg\left(-\frac{V_{tb}V_{td}^*}{V_{ub}V_{ud}^*}\right)$, where $V_{qq'}$ 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 α [5]. The $B^0 \to \pi^0\pi^0$ channel is particularly challenging as it requires two π^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 E, M_{bc} and transformed continuum suppression variable. Figure 4 shows the E distribution of two $\pi\pi$ channels. We obtain the following branching fractions,

$$\begin{aligned}
\mathcal{B}(B^0 \to \pi^+\pi^-) &= [5.8 \pm 0.7(\text{stat}) \pm 0.7(\text{syst})] \times 10^{-6},\\
\mathcal{B}(B^+ \to \pi^+\pi^0) &= [5.5^{+1.0}_{-0.9}(\text{stat}) \pm 0.7(\text{syst})] \times 10^{-6},\\
\mathcal{B}(B^0 \to \pi^0\pi^0) &= [0.98^{+0.48}_{-0.39}(\text{stat}) \pm 0.27(\text{syst})] \times 10^{-6}
\end{aligned}$$

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 ρ 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 E, continuum-suppression decision-tree output, the dipion masses and cosines of helicity angles of the ρ candidates. Figure 5 shows the E and log transform continuum-suppression output of $B^+ \to \rho^+\rho^0$ candidates. We obtain the branching fraction $\mathcal{B} = [20.6 \pm 3.2(\text{stat}) \pm 4.0(\text{syst})] \times 10^{-6}$ and longitudinal polarization fraction $f_L = 0.936^{+0.049}_{-0.041}(\text{stat}) \pm 0.021(\text{syst})$.