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Charmless B Decay Measurements at Belle II

Sagar Hazra

Tata Institute of Fundamental Research,
Mumbai 400 005, India

E-mail: sagar.hazra@tifr.res.in

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.

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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 Cabbibo-suppressed $b \to u$ tree and $b \to d, s$ loop transitions are sensitive to non-SM contributions. The CKM angle α/ϕ_2 can be measured directly only by an analysis of charmless $B \to \pi\pi, \rho\rho$ decays related by isospin symmetry. Isospin symmetry can be used also the make sum-rules, i.e. linear combination of $\mathcal{B}$ and CP 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 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. Belle II experiment started collecting data from March 2019. In this proceeding, we will focus on the result based on 62.8 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 $e^+e^- \to q\overline{q}$ ($q = u, d, s, c$) 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 E and M_{bc} is below ±5% to reduce possible bias in the signal yield determination. The latter two are the energy difference $E = E^* - \sqrt{s}/2$ 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 $M_{\text{bc}} = \sqrt{s/(4c^4) - (p^*/c)^2}$, 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, in the analysis of $B \to K\pi\pi$ decays 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] 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 $B \to K\pi$ system given in Eq. (1) provides a stringent test of the SM.

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

In all the four $K\pi$ channels, signal yields are determined with unbinned extended maximum-likelihood fits of the $\ E$ and $M_{\rm bc}$ distributions. The key challenge in $B^0 \to K^0\pi^0$ 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 $K^0_($ trajectory with the interaction region. 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 $\mathcal{A}_{\ 0c^0}$ is determined from a simultaneous maximum-likelihood fit to the unbinned $M_{\rm bc}$– $\ E$–$q \cdot r$ distributions, where r is the dilution factor of flavor tagger output. The signal probability density function (PDF) is given by

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

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

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

and CP-violating rate asymmetries

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

The dominant contribution in the systematic uncertainties comes from π^0 and $K^0_($ 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 $B^+ \to K^+K^-K^+$, $B^+ \to K^+\pi^-\pi^+$ and $B^0 \to K^+\pi^-\pi^0$ decays are enriched by the amplitude structure

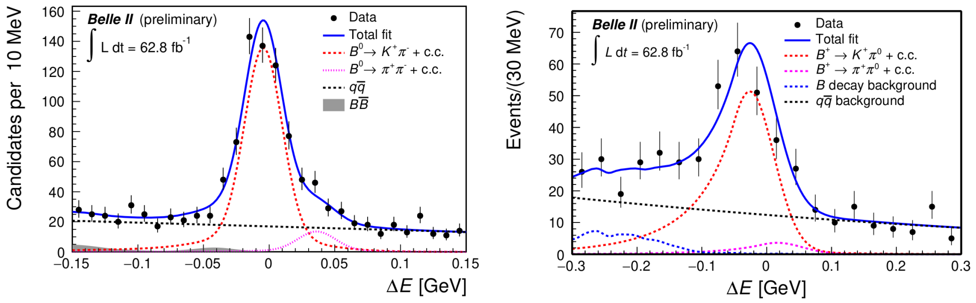

Figure 1: Signal-enhanced E distributions of $B^0 \to K^+\pi^-$ (left) and $B^+ \to K^+\pi^0$ (right).

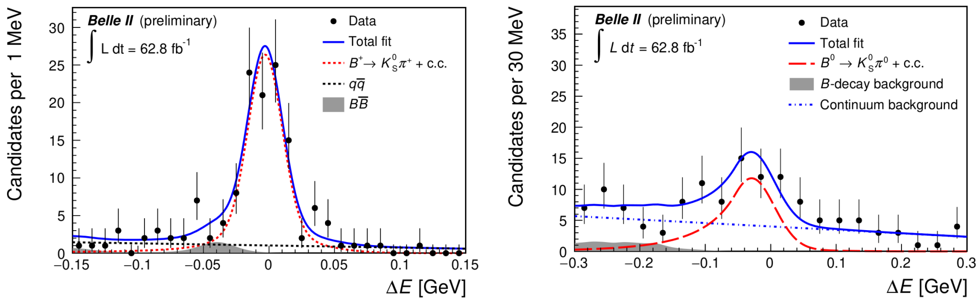

Figure 2: Signal-enhanced E distributions of $B^+ \to K^0\pi^+$ (left) and $B^0 \to K^0\pi^0$ (right).

accessible via their Dalitz plot. 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

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

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

5. Towards the determination of α/ϕ_2

The study of charmless decays at Belle II can provide improved measurements of the CKM unitarity angle $\alpha/\phi_2 = \arg\left(-\frac{+_{C3}+^{*}_{21}}{+_{D3}+^{*}_{D1}}\right)$, where V_{89} 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 [6]. We are now focusing

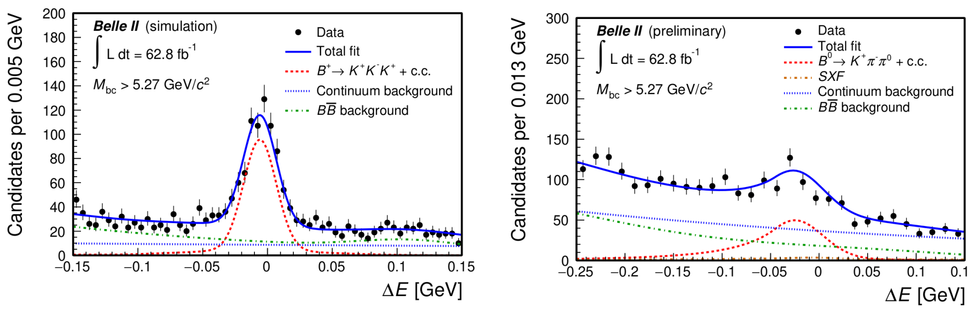

Figure 3: Signal-enhanced E distributions of $B^+ \to K^+K^-K^+$ (left) and $B^0 \to K^+\pi^-\pi^0$ (right).

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 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, $M_{\rm bc}$ and transformed continuum suppression variable. Figure 4 shows the E distribution of two $\pi\pi$ channels. We obtain the following branching fractions,

$$\begin{aligned}
\mathcal{B}(B^0 \to \pi^+\pi^-) &= [5.8 \pm 0.7(\text{stat}) \pm 0.7(\text{syst})] \times 10^{-6}, \\
\mathcal{B}(B^+ \to \pi^+\pi^0) &= [5.5\,^{+1\cdot0}_{-0\cdot9}(\text{stat}) \pm 0.7(\text{syst})] \times 10^{-6}, \\
\mathcal{B}(B^0 \to \pi^0\pi^0) &= [0.98\,^{+0\cdot48}_{-0\cdot39}(\text{stat}) \pm 0.27(\text{syst})] \times 10^{-6}
\end{aligned}$$

and CP asymmetry of $\mathcal{A}_{\%}(B^+ \to \pi^+\pi^0) = -0.04 \pm 0.17(\text{stat}) \pm 0.06(\text{syst})$. 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 $f_{!} = 0.936\,^{+0\cdot049}_{-0\cdot041}(\text{stat}) \pm 0.021(\text{syst})$. The dominant

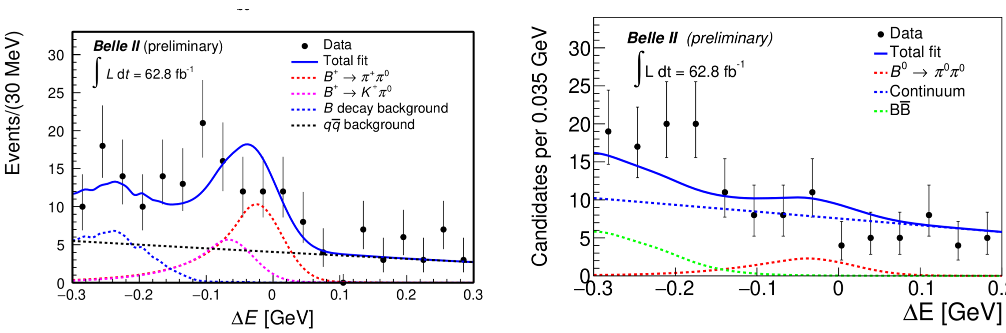

Figure 4: Signal-enhanced E distributions of $B^+ \to \pi^+\pi^0$ (left) and $B^0 \to \pi^0\pi^0$ (right).

contribution in the systematic uncertainties comes from π^0 reconstruction and tracking efficiency, it will be reduced with more data.