First search for direct CP-violating asymmetry in $B^0 \to K^0 \pi^0$ decays at Belle II

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Abstract

We report on the first measurement of the direct CP-violating asymmetry ($A$) in the charmless decay $B^0 \rightarrow K^0 \pi^0$ at Belle II and an updated measurement of its branching fraction ($B$). We use a sample of electron-positron collisions collected in 2019 and 2020 at the $\Upsilon(4S)$ resonance and corresponding to $62.8 \text{ fb}^{-1}$ of integrated luminosity. We reconstruct and select about 50 $B^0 \rightarrow K^0 \pi^0$ candidates, and we measure $A_{K^0 \pi^0} = -0.40^{+0.46}_{-0.44}(\text{stat}) \pm 0.04(\text{syst})$ and $B(B^0 \rightarrow K^0 \pi^0) = [8.5^{+1.7}_{-1.6}(\text{stat}) \pm 1.2(\text{syst})] \times 10^{-6}$. This is the first measurement of CP violation in $B^0 \rightarrow K^0 \pi^0$ decays reported by Belle II. The results agree with previous determinations and show a detector performance comparable with the best Belle results.
1. INTRODUCTION AND MOTIVATION

The study of charmless $B$ decays is a keystone of the worldwide flavor program. Processes mediated by $b \rightarrow sqq$ transitions probe contributions of non-standard-model dynamics in loop decay-amplitudes. However, reliable extraction of weak phases and unambiguous interpretation of measurements involving these amplitudes is spoiled by large hadronic uncertainties, which are rarely tractable in perturbative calculations. Appropriately chosen combinations of measurements from decay modes related by flavor symmetries are used to significantly reduce the impact of such unknowns. An especially fruitful approach consists in combining measurements from decays related by isospin symmetries. This approach has been proposed to address the so-called $K\pi$ puzzle, a long-standing anomaly associated with the significant difference between direct $CP$-violating asymmetries observed in $B^0 \rightarrow K^+\pi^-$ and $B^+ \rightarrow K^+\pi^0$ decays [1]. The asymmetries are expected to be equal at the leading order in the electroweak perturbation theory, as the two decays differ only by the $spectator$ quark. The isospin sum rule

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

properly accounts for subleading amplitudes by combining the branching fractions ($B$) and direct $CP$-violating asymmetries ($A$) of $B$ decays to all four final states $K^+\pi^-, K^0\pi^+, K^+\pi^0$ and $K^0\pi^0$, and the lifetime ($\tau$) ratio between $B^+$ and $B^0$. This rule offers a stringent null test of the standard model (SM), which predicts $I_{K\pi} = 0$ in the limit of isospin symmetry and no electroweak penguin (EWP) contributions, and with an uncertainty much below 1% when including SM EWP amplitudes [2–4]. Belle II has the unique capability of studying jointly, and within a consistent experimental environment, all relevant final states.

The Belle II experiment, complete with its vertex detector, started colliding beam operations in March 2019 and is currently ongoing. The sample of electron-positron collisions used in this work corresponds to an integrated luminosity of $62.8 \text{ fb}^{-1}$ and was collected at the $\Upsilon(4S)$ resonance. This document reports the first Belle II measurement of the direct $CP$-violating asymmetry in $B^0 \rightarrow K^0\pi^0$ decays, which requires flavor tagging of the pair-produced neutral $B$ partner, and an updated measurement of its branching fraction that supersedes the previous Belle II result in Ref. [5].

All analysis procedures are first developed and finalized in simulated data. For the branching fraction measurement, we test the analysis on the data subset used in [5], corresponding to 55% of the total sample, prior to the application to the full data set. A signal selection is applied to suppress the major sources of backgrounds, building on previous work [5]. An initial fit then determines the sample composition in terms of signal; background from $e^+e^- \rightarrow q\bar{q}$ continuum events, where $q$ indicates any quark of the first or second family ($u, d, s,$ and $c$); and background from non-signal $B$ decays. The fit uses

- the energy difference $\Delta E \equiv E_B^s - \sqrt{s}/2$ between the total energy of the reconstructed $B$ candidate and half of the collision energy, both in the $\Upsilon(4S)$ frame, which discriminates misreconstructed from properly reconstructed $B$ decays.

- the modified beam-energy-constrained mass,

$$M'_{bc} \equiv \sqrt{s/4 - \left( \frac{p^*(\pi^+\pi^-)}{m_{K^0}} + \frac{p^*(\gamma\gamma)}{m_{\gamma\gamma}} \right) \times \sqrt{\left(\sqrt{s}/2 - E^*(\pi^+\pi^-)_{K^0}\right)^2 - m(\gamma\gamma)^2}} \quad \text{(2)}$$
where $\vec{p}^*$ and $E^*$ are the three-momentum and the energy of $K_S^0$ or $\pi^0$ candidates in the CM frame, respectively. This variable is a modification of the standard beam-energy-constrained mass, $M_{bc} \equiv \sqrt{s/(4c^4)} - (p_B^*/c)^2$, where the $B$ energy is replaced by half of the center-of-mass collision energy (which is more precisely known). The variable $M'_{bc}$ compensates for the correlation between $M_{bc}$ and $\Delta E$ introduced by the tails associated with the presence of a final-state $\pi^0$, and discriminates $B$ meson decays from other backgrounds as the standard $M_{bc}$ does.

The analysis focuses only on $\Delta E$ and $M'_{bc}$. For convenience, in the following we refer to the modified mass with the symbol $M_{bc}$ only.

2. THE BELLE II DETECTOR

Belle II is a $4\pi$ particle-physics spectrometer [6, 7], designed to reconstruct the products of electron-positron collisions produced by the SuperKEKB asymmetric-energy collider [8], located at the KEK laboratory in Tsukuba, Japan. Belle II comprises several subdetectors arranged around the interaction space-point in a cylindrical geometry. The innermost subdetector is the vertex detector, which uses position-sensitive silicon layers to sample the trajectories of charged particles (tracks) in the vicinity of the interaction region to extrapolate the decay positions of their long-lived parent particles. The vertex detector includes two inner layers of silicon pixel sensors and four outer layers of silicon microstrip sensors. The second pixel layer is currently incomplete and covers only a small portion of azimuthal angle. Charged-particle momenta and charges are measured by a large-radius, helium-ethane, small-cell central drift chamber, which also offers charged-particle-identification information through a measurement of particles’ energy-loss by specific ionization. A Cherenkov-light angle and time-of-propagation detector surrounding the chamber provides charged-particle identification in the central detector volume, supplemented by proximity-focusing, aerogel, ring-imaging Cherenkov detectors in the forward regions. A CsI(Tl)-crystal electromagnetic calorimeter allows for energy measurements of electrons and photons. A solenoid surrounding the calorimeter generates a uniform axial 1.5 T magnetic field filling its inner volume. Layers of plastic scintillator and resistive-plate chambers, interspersed between the magnetic flux-return iron plates in the barrel, allow for identification of $K_L^0$ and muons. The subdetectors most relevant for this work are the silicon vertex detector, the tracking drift chamber, the particle-identification detectors, and the electromagnetic calorimeter.

3. SELECTION AND RECONSTRUCTION

3.1. Simulated and experimental data

We use generic simulated data to optimize the event selection and compare the distributions observed in experimental data with expectations. We use signal-only simulated data to model relevant signal features for fits and determine selection efficiencies. Generic simulation consists of Monte Carlo samples that include $B^0\bar{B}^0$, $B^+B^-$, $u\bar{u}$, $d\bar{d}$, $s\bar{s}$, and $c\bar{c}$ processes in realistic proportions and corresponding in size to five times the $\Upsilon(4S)$ data. In addition, one million $B^0 \rightarrow K_S^0\pi^0$ signal events are generated. As for experimental data, we use all 2019–2020 $\Upsilon(4S)$ good-quality data collected up to July 1, 2020 and corresponding
to an integrated luminosity of 62.8 fb$^{-1}$. All events are required to satisfy initial loose data-skim selection criteria, based on total energy and charged-particle multiplicity in the event, targeted at reducing sample sizes to a manageable level with negligible impact on signal efficiency. All data are processed using the Belle II analysis software \cite{9}.

### 3.2. Reconstruction and baseline selection

We form final-state particle candidates by applying loose baseline selection criteria and then combine candidates in kinematic fits consistent with the topologies of decays to reconstruct intermediate states and $B$ candidates. We reconstruct neutral-pion candidates by combining pairs of photons with energies greater than about 20 MeV. We restrict the diphoton mass and excluding extreme helicity-angle values to suppress combinatorial background from collinear soft photons. The mass of the $\pi^0$ candidates is constrained to its known value \cite{10} in subsequent kinematic fits. For $K_{S}^0$ reconstruction, we use pairs of oppositely charged particles that originate from a common space-point and have dipion mass consistent with a $K_{S}^0$. To reduce combinatorial background, we apply additional requirements, dependent on $K_{S}^0$ momentum, on the distance between trajectories of the two charged-pion candidates, the $K_{S}^0$ flight distance, and the angle between the pion-pair momentum and the direction of the $K_{S}^0$ flight. The resulting $\pi^0$ and $K_{S}^0$ candidates are combined in a simultaneous kinematic fit of the whole decay chain with a constraint on the position of the interaction region to form our target signal channel.

### 3.3. Continuum suppression

The main challenge in reconstructing charmless $B$ decay signals is the large contamination from continuum background. We use a binary boosted decision-tree classifier that combines nonlinearly 39 variables known to provide statistical discrimination between $B$-meson signals and continuum background and to be loosely correlated with $\Delta E$ and $M_{bc}$. The variables are quantities associated to event topology (global and signal-only angular configurations). We train the classifier to identify statistically significant signal and background features using unbiased simulated samples.

We validate the input and output distributions of the classifier by comparing control sample data with simulation. Fig. 1 shows the distribution of the output for $B^+ \to \bar{D}^0(\to K^+\pi^-)\pi^+$ candidates reconstructed in data and simulation. No inconsistency is observed.

### 4. OPTIMIZATION OF THE SIGNAL SELECTION

We vary the requirements on photon energy (independently for end-cap and barrel photons), its helicity angle, the diphoton mass range, dipion mass range, and the continuum-suppression output, to maximize $S/\sqrt{S+B}$ using simulated data, where $S$ and $B$ are signal and background yields, respectively. The optimal requirements select energy larger than about 220 (80) MeV for endcap (barrel) photons; absolute cosine values of the photon helicity angles smaller than 0.953, and diphoton and dipion mass ranges 119–150 MeV and 482–513 MeV, respectively. The optimal continuum-suppression requirement suppresses more than 98% of continuum background while retaining about 50% signal efficiency.
FIG. 1. Data-simulation comparison of the output of the boosted decision-tree classifier on (left) side-band and (right) side-band-subtracted $B^+ \to \bar{D}^0 (\to K^+\pi^-)\pi^+$ candidates in the signal region.

5. DETERMINATION OF SIGNAL YIELDS

More than one candidate per event populates the selected sample, with average multiplicities of approximately 1.01. We restrict to one candidate per event by selecting the $\pi^0$ candidate with the highest $p$-value of the mass-constrained diphoton fit. If multiple candidates still remain, the $K_s^0$ with the best vertex fit $p$-value is used. Signal yields are determined with maximum likelihood fits of the unbinned two-dimensional $M_{bc}$-$\Delta E$ distributions of candidates within the analysis range $M_{bc} > 5.24$ GeV/$c^2$ and $-0.3 < \Delta E < 0.3$ GeV. Plots in this document are projected into the signal region, defined as $M_{bc} > 5.27$ GeV/$c^2$ for the $\Delta E$ projection or $-0.16 < \Delta E < 0.08$ GeV for the $M_{bc}$ projection, to clearly display the signal.

Fit models are determined from Monte Carlo simulation, with the only additional flexibility of a $\Delta E$ peak position shift determined from $B^0 \to K^0\pi^0$ data to account for a negative O(10) MeV bias in the $\pi^0$ energy calibration. For the signal component, we use the sum of a single or a double Gaussian and a Crystal Ball model \[11\] for the $M_{bc}$ and $\Delta E$ distributions, respectively. For the continuum background, the $M_{bc}$ distribution is modelled by an Argus function \[12\], and that of $\Delta E$ is modelled by a linear function. A small fraction of non-signal $B$ decays survive the selection, dominated by the decays $B^+ \to \rho^+ K^0$ and $B^+ \to K^*(892)^+\pi^0$ and totaling $12.7 \pm 1.1$ decays as estimated from simulation. These are lumped together into a single “$B$-decay background” component peaking under the signal in $M_{bc}$ and shifted toward lower $\Delta E$ values, which is modelled by a two-dimensional kernel distribution. The yield of this component is Gaussian-constrained to its estimated value in the fit to data. The $M_{bc}$-$\Delta E$ distributions of $B^0 \to K_s^0\pi^0$ data are shown in Fig. 2 with the fit curve overlaid.

5.1. Efficiencies and determination of branching fractions

The signal efficiency determined from simulation is around 16% after all selections. For those efficiency factors for which simulation may not accurately model data, we perform dedicated checks on control samples of data and assess systematic uncertainties in Sec. \[7\]
FIG. 2. Distribution of $M_{bc}$ and $\Delta E$ for $B^0 \to K_S^0\pi^0$ candidates reconstructed in 2019–2020 Belle II data selected through the baseline criteria with an optimized continuum-suppression, and projected onto the signal region (left panel: $-0.16 < \Delta E < 0.08$ GeV, right panel: $M_{bc} > 5.27$ GeV/$c^2$). The projection of the unbinned maximum likelihood fit is overlaid.

We determine the branching fraction as

$$B = \frac{N_{\text{sig}}}{\varepsilon \cdot B_s \cdot 2 \cdot N_{B\bar{B}}}$$

(3)

where $N_{\text{sig}}$ is the signal yield obtained from the fit, $\varepsilon$ is the signal efficiency, and $N_{B\bar{B}}$ is the number of produced $B\bar{B}$ pairs, corresponding to 33.9 million $B^0\bar{B}^0$ pairs. We obtain the number of $B^0\bar{B}^0$ pairs from the measured integrated luminosity, the $e^+e^-\to \Upsilon(4S)$ cross section (1.110 ± 0.008) nb [13] (assuming that the $\Upsilon(4S)$ decays exclusively to $B\bar{B}$ pairs), and the $\Upsilon(4S)\to B^0\bar{B}^0$ branching fraction $f^{00} = 0.487 \pm 0.010 \pm 0.008$ [14]. The symbol $B_s$ accounts for the 50% probability to have a $K_S^0$ meson from a $K^0$.

TABLE I. Summary of signal efficiency $\varepsilon$, probability of a $K^0$ decays into a $K_S^0$ meson $B_s = f(K^0 \to K_S^0)$, signal yield in 2019–2020 Belle II data, and the resulting branching fraction. Only the statistical contributions to the uncertainties are given here.

| Decay     | $\varepsilon$ [%] | $B_s$ [%] | Yield $B \times 10^{-6}$ |
|-----------|-------------------|-----------|--------------------------|
| $B^0 \to K^0\pi^0$ | 15.6              | 50        | $45_{-8}^{+9}$          |
| $B^+ \to K^+\pi^0$ | $8.5_{-1.6}^{+1.7}$ |           |                          |

6. DECAY-TIME-INTEGRATED DIRECT $\mathcal{A}_{K^0\pi^0}$

Unlike $B^0 \to K^+\pi^−$ or $B^+ \to K^+\pi^0$, the kaon charge does not tag the $B$ flavor and therefore the $b$-quark flavor must be determined from the inclusive properties of the rest of the event ("flavor tagging"). We measure the $CP$-violating asymmetry of the $CP$-eigenstate $B^0 \to K^0\pi^0$ with the signal-side quark flavor $q$, using the flavor content of the other $B$ meson ($B_{\text{tag}}$) provided by the category-based flavor tagger [15]. On an event-by-event basis, the tagging algorithm provides the flavor and associated dilution ($r$), which is the complement to twice the mistag probability $w$ and measures the dilution of the asymmetry amplitude due to an incorrect tag ("wrong tag") assignment. Events are categorized in 7 $r$-bin intervals. For
each $r$-bin interval, the wrong tag fractions ($w_r$) and tagging efficiencies ($\epsilon_r$) are determined in control samples reconstructed in 2019 Belle II data [16] and constrained using Gaussian likelihoods in our fit. Systematic uncertainties are associated by varying the parameters from the control decay mode in the fit to the signal decay. The asymmetry $A_{K^0 \pi^0}$ is determined from a simultaneous maximum-likelihood fit to the unbinned $M_{bc}$-$\Delta E$-$q$ distributions with signal-to-background fractions constrained by the yield fit of Sec. 5. The signal probability density function (PDF) of $q$ is the integral of the known $B^0 \rightarrow K^0 \pi^0$ decay-time evolution [17]

$$p_{\text{sig}}(q) = \frac{1}{2}(1 + q \cdot (1 - 2w_r) \cdot (1 - 2\chi_d)A_{K^0 \pi^0})$$

with the time-integrated mixing parameter $\chi_d$ set to its known value $\chi_d = 0.1858 \pm 0.0011$ [10]. We assume the background from charmless $B$ decays to be flavor symmetric as well as the continuum sample. The resulting asymmetry is $A_{K^0 \pi^0} = -0.40^{+0.46}_{-0.44}$, where the uncertainty includes only the statistical contribution. In Fig. 3, the results of the fit on well-tagged events are displayed separately in $M_{bc}$ and $\Delta E$ projections.

**FIG. 3.** Flavor-specific ($M_{bc}$, $\Delta E$) projections on 2019-2020 Belle II data. The top panel shows candidates where $B_{\text{tag}}$ is tagged as a $\bar{B}^0$ (signal-side: $B^0$) and the bottom panel for candidates where $B_{\text{tag}}$ is tagged as a $B^0$ (signal-side: $\bar{B}^0$). The distribution and fit are integrated over $r$-bin in the good tag region $0.25 \leq r \leq 1$ and in the signal region (left panel: $-0.16 < \Delta E < 0.08$ GeV, right panel: $M_{bc} > 5.27$ GeV/$c^2$).
7. SYSTEMATIC UNCERTAINTIES

We consider several sources of systematic uncertainties. We assume the sources to be independent and add in quadrature the corresponding uncertainties. Summaries of systematic uncertainties are reported in Tables II and III for the measurement of the branching fraction and \( CP \) asymmetry, respectively. Each contribution is described in detail below.

7.1. Systematic uncertainties for branching fraction measurement

Tracking efficiency

We assess a systematic uncertainty associated with possible data-simulation discrepancies in the reconstruction of charged particles [18]. The tracking efficiency in data agrees with the value observed in simulation within a 0.91% uncertainty, which we (linearly) add as a systematic uncertainty for each final-state charged particle.

\( K_S^0 \) reconstruction efficiency

A small decrease, approximately linear with flight length, in the \( K_S^0 \) reconstruction efficiency was observed in early Belle II data with respect to simulation. We assess a systematic uncertainty based on dedicated studies performed for the \( B \to \phi K^{(*)} \) analysis [19]. We apply an uncertainty of 0.31% for each centimeter of average flight length of the \( K_S^0 \) candidate, with an additional 15% uncertainty accounting for the data and simulation mismatch between the second and third layer of the vertex detector, resulting in a 3.82% total systematic uncertainty.

\( \pi^0 \) reconstruction efficiency

We assess a systematic uncertainty associated with possible data-simulation discrepancies in the \( \pi^0 \) reconstruction and selection using the decays \( B^0 \to D^{*-} (\to D^0 (\to K^+ \pi^- \pi^0) \pi^-) \pi^+ \) and \( B^0 \to D^{*+} (\to D^0 (\to K^+ \pi^-) \pi^-) \pi^+ \) where the selection of charged particles is identical and all distributions are weighted so as the \( \pi^0 \) momentum matches the \( \pi^0 \) momentum in charmless channels. We compare the yields obtained from fits to the \( \Delta E \) distribution of reconstructed \( B \) candidates and obtain the \( \pi^0 \) reconstruction efficiency in data and simulation. The efficiency ratio \( \varepsilon_{MC}(\pi^0)/\varepsilon_{data}(\pi^0) \) is close to 1, and the 13.0% uncertainty of the efficiency ratio is quoted as the systematic uncertainty.

Continuum-suppression efficiency

We evaluate possible data-simulation discrepancies in the continuum-suppression distributions using the control channel \( B^+ \to D^0 (\to K^+ \pi^- \pi^0) \pi^+ \). The selection efficiency obtained in data and simulation agrees well, hence the statistical uncertainty on data efficiency is assigned as the systematic uncertainty.
Number of $B\bar{B}$ pairs

We assign a 1.4% systematic uncertainty on the number of $B\bar{B}$ pairs, which includes the uncertainty on cross section, integrated luminosity [20], and potential shifts from the peak center-of-mass energy during the run periods.

Fit modelling

Because we used empirical fit models for signal, we assess a systematic uncertainty associated with the choice of model. We consider the effect by performing independent variations on the $M_{bc}$ and $\Delta E$ shapes of signal PDF modeling. The uncertainty due to signal modeling is given by changing the nominal fit configuration to an alternate configuration, with the difference quoted as the systematic uncertainty. For both variations on $M_{bc}$ and $\Delta E$, around a 0.01% uncertainty is obtained. We perform a variation of the continuum background modelling, allowing for more degrees of freedom in the PDF. The resulting systematic uncertainty is about 1%.

7.2. Systematic uncertainties for direct $CP$ asymmetry measurement

Flavor tagging modelling

A potential bias exists in flavor parameters between $B^0 \rightarrow K^0_S \pi^0$ and the control sample used in determining the flavor parameters. The uncertainty is assessed from the shift observed in the value of $A_{K^0 \pi^0}$ when fitting simulated data using flavor tagging parameters determined either from the signal decay or from the control decay.

$B^0$ mixing parameter $\chi_d$

In the nominal fit, the value of the mixing parameter $\chi_d$ is fixed. Two alternative fits, where the fixed value of $\chi_d$ is increased and decreased by its uncertainty, are performed. The largest variation of $A_{K^0 \pi^0}$ from its known value is quoted as the systematic uncertainty.

$B$-decay background asymmetry

In the nominal fit, the peaking backgrounds from charmless $B$ decays are assumed to be $CP$ symmetric. Since several decays with poorly known $CP$-violating asymmetries may contribute, we perform two alternative fits, where the asymmetry of this background is fixed to $\pm 1$. We then assign as a systematic the resulting largest shift observed in $A_{K^0 \pi^0}$.

Continuum background asymmetry

In addition, the continuum background is assumed to be symmetric in the nominal fit. We allow for an asymmetry of this component in an alternative fit, and found that its value
is consistent with zero with a 7% uncertainty. We assign as a systematic uncertainty the observed shift on $A_{K^0\pi^0}$ from this alternative fit.

TABLE II. Summary of the (fractional) systematic uncertainties of the branching fraction measurement.

| Source                                      | $\delta B(\%)$ |
|---------------------------------------------|----------------|
| Tracking efficiency                         | 1.8            |
| $K_S^0$ reconstruction efficiency           | 3.8            |
| $\pi^0$ reconstruction efficiency           | 13.0           |
| Continuum-suppression efficiency            | 2.4            |
| $N(B\bar{B})$ (as written in Eq. 3)         | 1.4            |
| Signal model                                | <0.1           |
| Continuum background model                  | 1.4            |
| Total                                       | 14.0           |

TABLE III. Summary of (absolute) systematic uncertainties in the $A_{K^0\pi^0}$ measurement.

| Source                                      | $\delta A_{K^0\pi^0}$ |
|---------------------------------------------|------------------------|
| Flavor tagging modelling                    | 0.03                   |
| $B^0$ mixing parameter $\chi_d$             | <0.01                  |
| $B$-decay background asymmetry              | 0.03                   |
| Continuum background asymmetry              | 0.01                   |
| Total                                       | 0.04                   |

8. RESULT AND FUTURE IMPACT

We report a measurement of the direct $CP$ asymmetry of the $B^0 \rightarrow K^0\pi^0$ decay and an update of its branching fraction that supersedes the value measured in Ref. [5]. We use data collected by Belle II experiment in 2019 and 2020, corresponding to 62.8 fb$^{-1}$ of integrated luminosity, collected at the $\Upsilon(4S)$ resonance. We used simulation to devise and optimize the candidate selection. We reconstruct and select $45^{+9}_{-8}$ signal candidates, from which we determine the $CP$ asymmetry and the branching fraction to be

$$A_{K^0\pi^0} = -0.40^{+0.46}_{-0.44}(\text{stat}) \pm 0.04(\text{syst}),$$

and

$$\mathcal{B}(B^0 \rightarrow K^0\pi^0) = [8.5^{+1.7}_{-1.6}(\text{stat}) \pm 1.2(\text{syst})] \times 10^{-6}.$$  

The value of the branching fraction is in agreement with known determinations. The direct $CP$ asymmetry $A_{K^0\pi^0}$ is measured for the first time at Belle II, paving the way for a precise test of the isospin sum rule with larger Belle II datasets.

Belle II plays a crucial role in updating the isospin sum rule results, as it is the only running experiment that reports measurements of branching fraction and $CP$-violating asymmetries of $B^0 \rightarrow K^0\pi^0$ decays. We investigate the impact that these and future measurements
will have on the testing power of the isospin sum rule. As a figure of merit, we use the expected resolution on $I_{K\pi}$ (sensitivity) determined by extrapolating the current measurements under certain assumptions and approximations. The statistical uncertainties in the inputs for $I_{K\pi}$ are assumed to scale as $1/\sqrt{\int L dt}$ and the corresponding systematics are assumed to be less than or equal to the statistical uncertainties. For simplicity, we symmetrize asymmetric uncertainties and treat each measurement as an independent input, when incorporating it into the calculation of the $I_{K\pi}$. In the calculation, we adopt a simple weighted average for the combination of new Belle II inputs with the current world average [10].

Fig. [4] shows a projection of the $I_{K\pi}$ sensitivity in the next decade according to the current luminosity plans from LHCb [21] and the Belle II experiment. For measurements of $A_{K^+\pi^-}, A_{K^+\pi^0}, A_{K^0\pi^0}$, we average previous Belle and BaBar results with projected inputs from LHCb, which are anticipated to dominate the precision on these quantities and are scaled with expected sample size. We compare the sensitivity on $I_{K\pi}$ in the scenarios with and without Belle II contributions. As expected, the sensitivity to $I_{K\pi}$ is mostly determined by the $K^0\pi^0$ inputs, which makes Belle II’s $K^0\pi^0$ measurements essential. We provide an estimation for the future sensitivity of Belle II’s $A_{K^0\pi^0}$ measurement in Fig. [5].

The projection based on current inputs is conservative. We expect a gain in the signal efficiency and the overall sensitivity by relaxing the continuum suppression requirement and including the continuum suppression variable in the fit. A measurement using a time-dependent $CP$ violation method with a specific optimization on the vertex quality (resolution) requirement can also bring additional benefits.

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FIG. 4. The projected uncertainty on $I_{K\pi}$ with and without Belle II inputs. The inputs for $I_{K\pi}$ are averages of the estimated updates from ongoing LHCb and Belle II experiments with current world averages [10]. The red curve shows a projection when updates on the complete set of $K\pi$ measurements are considered, and the grey curve is the case if only $A_{K^{+}\pi^{-}}, A_{K^{+}\pi^{0}}, A_{K^{0}\pi^{+}}$ are updated by LHCb. The projection corresponds to the luminosity plans from LHCb and Belle II.
FIG. 5. The projected uncertainty on $A_{K^0\pi^0}$ measurement. The inset panel shows the comparison of (red marker) the measurement reported here with (green band) the world average value, and (blue band) the indirect determination from Eq. 1 assuming $I_{K\pi} = 0$ and world average values for the other inputs. The red curve in the main panel is Belle II’s expected uncertainty on the $A_{K^0\pi^0}$ measurement as a function of the integrated luminosity, while the green and blue dashed lines are the uncertainties of the world average value and of the indirect determination, respectively.

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