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Recent Belle II results on hadronic B decays

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We present recent measurements of hadronic B meson decays produced in electron-positron collisions at the $\Upsilon(4S)$ resonance collected between 2019 and 2022 with the Belle II detector. We show measurements of $B \to D^{(*)} K K^0_S$ decays including the first observation of three modes with different charge combinations in the decay. Furthermore, we report on new results to determine the quark-mixing parameter ϕ_3/γ, performed on a combination of Belle and Belle II data. Measurements of $B \to \rho\rho$ and $B \to \pi\pi$ are presented which serve as input for the determination of ϕ_2/α. Finally, determinations of branching fractions and direct CP-violating asymmetries of $B \to K\pi$ modes are shown to perform a direct test of the Standard Model via the $K\pi$ isospin sum rule.

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1. Introduction

Hadronic B decays are sensitive to all angles of the Cabibbo-Kobayashi-Maskawa (CKM) quark-mixing matrix and provide sensitive probes of physics beyond the Standard Model (SM). To this end, the Belle II experiment [1] targets the measurement of decay products of asymmetric e^+e^- collisions at the $\Upsilon(4S)$ resonance from the SuperKEKB collider [2].
The Belle II detector is a magnetic spectrometer, arranged in a cylindrical configuration surrounding the interaction point, effectively covering nearly the entire solid angle. Its innermost part consists of a silicon based vertex detector, followed by a 56-layer drift chamber. In combination with a 1.5 T magnetic field they reconstruct tracks of charged particles. Particle identification is performed by a time-of-propagation Cherenkov detector in the barrel region and an areogel ring-imaging Cherenkov detector in the forward region. The energy of electrons and photons is reconstructed in a CsI(Tl)-crystal electromagnetic calorimeter. The outermost sub-detector consists of alternating layers of iron plates and active detector elements (plastic scintillators and resistive-plate chambers) to reconstruct muons and K_L^0s.
Owing to the detector's excellent capabilities for reconstruction of neutral particles and the precise knowledge of the initial state opens the door for decays including one or multiple neutral final state particles.
Belle II started data taking in 2019 and has collected an integrated luminosity of 362 fb^{-1}, aiming to collect 50 ab^{-1} in the next decade.
The Belle II hadronic physics program covers a wide range of measurements including the fundamental determinations of branching fractions and CP-violating asymmetries, measurements of all CKM angles and direct tests of the SM via isospin sum rules. The CKM angle $\phi_3 = \arg(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*})$ can be determined via tree-level only B-meson decays and hence exhibits negligible theoretical uncertainties. $\phi_1 = \arg(-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*})$ is the least-well measured CKM angle and can be determined by exploiting isospin relations in $B \to \pi\pi$ and $B \to \rho\rho$ decays. The isospin sum rule in $B \to K\pi$ decays combines branching fractions and CP-violating asymmetries and provides a stringent null test of the SM [3].

Hadronic B-meson decays are typically polluted with large backgrounds coming from $e^+e^- \to q\bar{q}, \quad q \in \{u, d, c, s\}$, so-called "continuum" events. Due to their lower masses, compared to the b-quark, in the center-of-mass frame, their event topology is jet like, while the B-mesons decay isotropically. This can be exploited in binary classifiers based on boosted decision trees that we use to suppress continuum events. The extraction of relevant signal yields is based on observables offering distinguishing power between signal events and remaining backgrounds. We use the difference between the reconstructed energy of the B-meson and the beam-energy, $\Delta E = E_B^* - E_{\mathrm{beam}}^*$, and the the beam constrained mass $M_{\mathrm{bc}} = \sqrt{E_{\mathrm{beam}}^{*2} - |\vec{p}_{B^0}^{\,*}|^2}$, where * indicates that the quantity is evaluated in the center of mass system.

2. $B \to D^{(*)} K K_S^0$ decays

$B \to D^{(*)} K K_S^0$ decays make up a few percent of the overall hadronic branching fraction, however only a small amount of them are well measured. They serve as inputs for simulations and tagging techniques. Hence, improving our knowledge on them will result in improvements of numerous other measurements. We report a preliminary results of the measurement of the $B^- \to D^0 K^- K_S^0$ branching fraction and the first observation of $\overline{B}^0 \to D^+ K^- K_S^0$, $B^- \to D^{*0} K^- K_S^0$ and $\overline{B}^0 \to D^{*+} K^- K_S^0$:

$$\begin{aligned}
\mathcal{B}(B^- \to D^0 K^- K_S^0) &= (1.89 \pm 0.16 \pm 0.10) \times 10^{-4}, \\
\mathcal{B}(\overline{B}^0 \to D^+ K^- K_S^0) &= (0.85 \pm 0.11 \pm 0.05) \times 10^{-4}, \\
\mathcal{B}(B^- \to D^{*0} K^- K_S^0) &= (1.57 \pm 0.27 \pm 0.12) \times 10^{-4}, \\
\mathcal{B}(\overline{B}^0 \to D^{*+} K^- K_S^0) &= (0.96 \pm 0.18 \pm 0.06) \times 10^{-4}
\end{aligned}$$

where the first uncertainties are statistical and the second are systematic [4]. The branching fractions are determined in likelihood fits to the unbinned distributions of the energy difference ΔE. Furthermore, we extract sWeights [5], allowing us to reweight the invariant mass distributions of the $K K_S^0$ system such that they are "background free". In the low-mass region, we observe structures not compatible with a three-body phase space distribution in all four channels. Further studies are being performed to understand their nature.

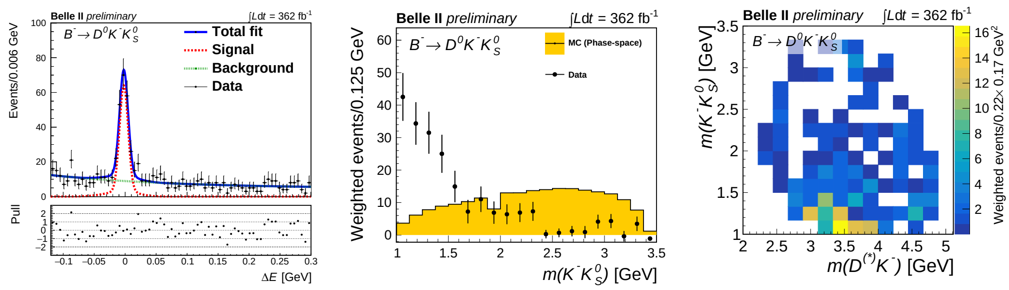

Figure 1: ΔE distribution (left), $m(K^- K_S^0)$ invariant mass distribution (middle) and Dalitz plot (right) of $B^- \to D^0 K^- K_S^0$

3. Measurements of the CKM angle ϕ_3

The CKM angle ϕ_3 describes the weak phase between $b \to c$ and $b \to u$ tree transitions. Its current world average $\phi_3 = 65.9^{+3.3}_{-3.5}$ [6] is dominated by LHCb determinations. Experimentally, ϕ_3 can be measured in the interference of favored $B^- \to D^0 K^-$ and Cabibbo-suppressed $B^- \to \overline{D}^0 K^-$ transitions. Reconstructing the D^0 and $\overline{D}^0$ from a common final state allows the extraction of the weak phase. Different methods are proposed depending on the chosen final states. We present two determinations, using Cabibbo-suppressed modes and CP eigenstates. Both methods extract the relevant signal yields using likelihood fits to the unbinned distributions of ΔE and continuum-suppression classifier output C. Both determinations are statistically limited.

3.1 Cabibbo-suppressed modes

The so-called GLS method uses Cabibbo-suppressed decays of D-mesons, $B^{\pm} \to D[\to K_S^0 K^{\pm}\pi^{\mp}]h^{\pm}$ (with $h \in \{K, \pi\}$), where D is a superposition of D^0 and $\overline{D}^0$ to measure ϕ_3 [7]. The charged kaon originating from the D-meson can either have the same-sign (SS) or the opposite-sign (OS) as the B-meson. The amplitude and strong phase of the D-meson decay are taken as an external input from CLEO [8].

We measure four CP-violating asymmetries and three ratios of branching fractions [9] in the full phase space of the D meson decay and in the $K^*(892)$ region of the $m(KK_S^0)$ invariant mass, where a large strong phase difference enhances the sensitivity on ϕ_3. The measurement is performed on a combined Belle (711 fb^{-1}) and Belle II (362 fb^{-1}) dataset and is consistent, although less precise, with LHCb results [10]. The results constrain the value of ϕ_3 by combining them with other measurements.

	Full D phase space	K^* region
$\mathcal{A}_{SS}^{DK}$	$-0.089 \pm 0.091 \pm 0.011$	$0.055 \pm 0.119 \pm 0.020$
$\mathcal{A}_{OS}^{DK}$	$0.109 \pm 0.133 \pm 0.013$	$0.231 \pm 0.184 \pm 0.014$
$\mathcal{A}_{SS}^{D\pi}$	$0.018 \pm 0.026 \pm 0.009$	$0.046 \pm 0.029 \pm 0.016$
$\mathcal{A}_{OS}^{D\pi}$	$-0.028 \pm 0.031 \pm 0.009$	$0.009 \pm 0.046 \pm 0.009$
$\mathcal{R}_{SS}^{DK/D\pi}$	$0.122 \pm 0.012 \pm 0.004$	$0.093 \pm 0.012 \pm 0.005$
$\mathcal{R}_{OS}^{DK/D\pi}$	$0.093 \pm 0.013 \pm 0.003$	$0.103 \pm 0.020 \pm 0.006$
$\mathcal{R}_{SS/OS}^{D\pi}$	$1.428 \pm 0.057 \pm 0.002$	$2.412 \pm 0.132 \pm 0.019$

Table 1: CP-violating charge asymmetries ($\mathcal{A}$) and ratios of branching fractions ($\mathcal{R}$) of $B^{\pm} \to D[\to K_S^0 K^{\pm}\pi^{\mp}]h^{\pm}$ decays. The results are extracted from a combined Belle (711 fb^{-1}) and Belle II (362 fb^{-1}) dataset in the full D phase space and in the K^* region. The first uncertainties are statistical and the second are systematic.

3.2 CP eigenstates

The GLW method uses D-meson decays to CP eigenstates to extract ϕ_3 [11, 12]. We are reconstructing the D-meson from the CP-even final state K^+K^- and the CP-odd final state $K_S^0\pi^0$, where the latter is uniquely accessible to Belle II due to its neutral final state particles. The measurement is performed on a combined Belle (711 fb^{-1}) and Belle II (362 fb^{-1}) dataset and is consistent but not competitive with results from BaBar [13] and LHCb [14]. We report two ratios of branching fractions ($\mathcal{R}_{CP^{\pm}}$) and two CP-violating asymmetries $\mathcal{A}_{CP^{\pm}}$

$$\mathcal{R}_{CP^+} = 1.164 \pm 0.081 \pm 0.036,$$
$$\mathcal{R}_{CP^-} = 1.151 \pm 0.074 \pm 0.019,$$
$$\mathcal{A}_{CP^+} = 0.125 \pm 0.058 \pm 0.014,$$
$$\mathcal{A}_{CP^-} = -0.167 \pm 0.057 \pm 0.060,$$

where the first uncertainties are statistical and the second are systematic [15]. We observe evidence for different sign of $\mathcal{A}_{CP^+}$ and $\mathcal{A}_{CP^-}$. The results constrain ϕ_3 in combination with other measurements.

4. Towards the CKM angle ϕ_2

In the absence of loop contributions the time-dependent CP-violation amplitude in $b \to u\bar{u}d$ transitions is proportional to $sin(2\phi_2)$. However, non-negligible loop contributions introduce a large non-trivial shift. The tree and loop contributions can be disentangled exploiting isospin relations in $B \to \pi\pi$ and $B \to \rho\rho$. Belle II has the unique capability to measure all modes in a consistent way.

4.1 $B \to \rho\rho$ decays

Since the ρ-meson is a vector-meson the analysis requires an angular analysis to extract the polarization states. The fit is six-dimensional in $M_{\rm bc}$, ΔE, the dipion masses and the helicity angles of the ρ candidates. We report preliminary Belle II results of $B^0 \to \rho^+\rho^-$ and $B^+ \to \rho^+\rho^0$ based on 189 fb^{-1} of data [16, 17]. The measurements are on par with previous Belle [18, 19] and BaBar [20, 21] determinations. The results are shown in Table 2.

4.2 $B \to \pi\pi$ decays

We present a measurement of $B^0 \to \pi^0\pi^0$ using 189 fb^{-1} of Belle II data [22]. The final state, consisting of four photons only, as well as the CKM- and colour-suppressed nature of this decay poses experimental challenges. The fit to $M_{\rm bc}$, ΔE and C achieves a similar precision as Belle, despite using a four times smaller dataset, due to improved π^0 and continuum-suppression selection criteria.
Furthermore, we report measurements of $B^0 \to \pi^+\pi^-$ and $B^+ \to \pi^+\pi^0$ using 362 fb^{-1} of Belle II data [23]. The obtained branching ratio of $B^0 \to \pi^+\pi^-$ represents the world's most precise determination. The results are shown in Table 2.

	$\mathcal{B}$ [10^{-6}]	$\mathcal{A}_{CP}$	f_L
$B^0 \to \rho^+\rho^-$	$26.7 \pm 2.8 \pm 2.8$	-	$0.956 \pm 0.035 \pm 0.033$
$B^+ \to \rho^+\rho^0$	$23.2^{+2.2}_{-2.1} \pm 2.7$	$-0.069 \pm 0.068 \pm 0.060$	$0.943^{+0.035}_{-0.033} \pm 0.027$
$B^0 \to \pi^0\pi^0$	$5.83 \pm 0.22 \pm 0.17$	-	-
$B^0 \to \pi^+\pi^-$	$5.02 \pm 0.28 \pm 0.31$	$-0.082 \pm 0.054 \pm 0.008$	-
$B^+ \to \pi^+\pi^0$	$1.38 \pm 0.27 \pm 0.22$	$0.14 \pm 0.46 \pm 0.07$	-

Table 2: $B \to \rho\rho$ and $B \to \pi\pi$ results for the branching ratios ($\mathcal{B}$), the direct CP violation ($\mathcal{A}$) and the longitudinal polarization fraction (f_L). The first uncertainties are statistical and the second are systematic.

5. $K\pi$ isospin sum rule

The $K\pi$ isospin sum rule combines the branching fractions and direct CP violation parameters of the four isospin related $B \to K\pi$ modes and is defined as

$$I_{K\pi} = \mathcal{A}_{CP}^{K^+\pi^-} + \mathcal{A}_{CP}^{K^0\pi^+}\frac{\mathcal{B}_{K^0\pi^+}}{\mathcal{B}_{K^+\pi^-}}\frac{\tau_{B^0}}{\tau_{B^+}} - 2\mathcal{A}_{CP}^{K^+\pi^0}\frac{\mathcal{B}_{K^+\pi^0}}{\mathcal{B}_{K^+\pi^-}}\frac{\tau_{B^0}}{\tau_{B^+}} - 2\mathcal{A}_{CP}^{K^0\pi^0}\frac{\mathcal{B}_{K^0\pi^0}}{\mathcal{B}_{K^+\pi^-}},$$

where τ_{B^0} and τ_{B^+} are the lifetimes of the neutral and charged B-mesons. $I_{K\pi}$ is predicted to be zero within an uncertainty of 1% in the SM [24]. Large deviations from the SM prediction could

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indicate anomalously enhanced amplitudes or non-SM physics. The current experimental precision is about 11% and is limited by $\mathcal{A}_{CP}^{K^0\pi^0}$ with an uncertainty of 13% [25].
We report measurements of all involved branching fractions and CP violation parameters using Belle II data of 362 fb^{-1}. Belle II has the unique capability to measure all involved final states in a consistent way allowing for the cancellation of related systematic uncertainties. The relevant signal yields are extracted in fits to the unbinned ΔE and C distributions. Fit projections in ΔE are shown in Figure 2. The results are summarized in Table 3. They are in agreement and competitive with

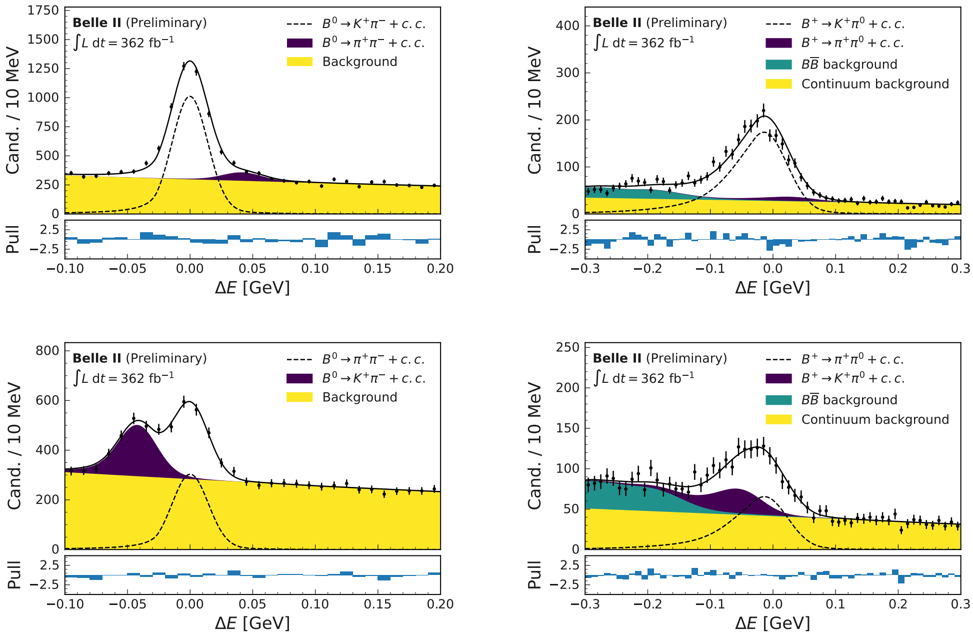

Figure 2: ΔE distributions of $B \to K^+\pi^-$ (top left), $B \to K^+\pi^0$ (top right), $B \to K_S^0\pi^+$ (bottom left) and $B \to K_S^0\pi^0$ (bottom right) candidates reconstructed in Belle II data. The fit projections are overlaid as solid black line.

world averages [25]. By combing the reported time-integrated measurement of $B^0 \to K_S^0\pi^0$ with

	$\mathcal{B}$ [10^{-6}]	$\mathcal{A}_{CP}$
$B^0 \to K^+\pi^-$	$20.67 \pm 0.37 \pm 0.62$	$-0.072 \pm 0.019 \pm 0.007$
$B^+ \to K^+\pi^0$	$13.93 \pm 0.38 \pm 0.71$	$0.013 \pm 0.027 \pm 0.005$
$B^+ \to K^0\pi^+$	$24.37 \pm 0.71 \pm 0.86$	$0.046 \pm 0.029 \pm 0.007$
$B^0 \to K^0\pi^0$	$10.40 \pm 0.66 \pm 0.60$	$-0.06 \pm 0.15 \pm 0.04$
$I_{K\pi}$	$-0.03 \pm 0.13 \pm 0.04$	

Table 3: $B \to K\pi$ results using 362 fb^{-1} of Belle II data. The first uncertainties are statistical and the second are systematic.

a second, time-dependent measurement [26], we achieve the worlds most precise determination of $\mathcal{A}_{K^0\pi^0}$.

6. Summary

We present several new measurements of hadronic B decays at Belle II. We observe three $B \to D^{(*)} K K_S^0$ modes for the first time. The CKM angle ϕ_3 is measured via the GLS and GLW methods on a combined Belle and Belle II dataset. We measure $B \to \rho\rho$ and $B \to \pi\pi$ modes needed for the determination of ϕ_2. Finally, we report a measurement of the $K\pi$ isospin sum rule on par with the worlds best result.

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