PoS PROCEEDINGS OF SCIENCE

Measurements of hadronic B decay rates at Belle and Belle II

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The Belle and Belle II experiments have collected a 1.1 ab^{-1} sample of $e^+e^- \to B\bar{B}$ collisions at the $\Upsilon(4S)$. The study of hadronic B decays in these data allow the precise measurement of absolute branching fractions and angular distributions of the decay products. These measurements provide tests of QCD and enable the generation of more realistic simulation samples. We present measurements of the decays $B^- \to D^0\rho^-$, $\bar{B}^0 \to D^+\pi^-\pi^0$, $B \to DK^*K$ and $\bar{B}^0 \to \omega\omega$. In addition, we search for the decays $B \to D^{(*)}\eta\pi$, which can be related to poorly known $B \to X_c\ell\nu$ decays that include an η meson in the final state.

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1. Introduction

Hadronic B decays are a key element in the Belle (II) [1] physics program. These decays often occur through $b \to c, u$ tree or $b \to d, s$ penguin transitions. Although hadronic decays of B-mesons account for around 75% of the total branching fraction, but approximately 50% of this remains largely unknown. At Belle II, PYTHIA [2] is widely used to generate these unmeasured B-decay modes in the simulated data. This leads to larger discrepancy between data and our simulation. Understanding this unknown territory is important and necessary to improve our B physics knowledge.

To account for the decays involving missing energies, we use mainly hadronic B tagging. Effective hadronic B-tagging is essential for a significant portion of Belle II's physics program.In addition to filtering $B\bar{B}$ events with high purity, hadronic B-tagging can provide the direction of the signal B-meson. The tagging algorithm uses Full Event Interpretation (FEI), where $B \to D^{(*)} m\pi^{\pm} n\pi^{0}$ decays are trained in Monte Carlo (MC) simulations using Boosted Decision Trees (BDTs). We observe a large discrepancy between data and MC, which arise from our poor understanding of the B-hadronic sector. Even the decays contributing to the highest branching fractions are measured with large uncertainties, based on old CLEO measurements. Therefore, it is crucial to re-measure these modes to improve hadronic B-tagging.

In this report, we discuss the recent measurements in the B hadronic sector using Belle and Belle II datasets. We cover the decays $B^- \to D^0\rho^-$, $B \to DK^*K$, $\bar{B}^0 \to \omega\omega$, and measurements related to the CKM angle ϕ_3. The Belle II experiment, is the successor to the Belle experiment, located at the asymmetric e^+e^- collider SuperKEKB [1] in Tsukuba, Japan. Utilizing the 387M and 772M $B\bar{B}$ pairs of data collected by the Belle II and Belle experiments respectively, we aim to achieve world-class precise results.

2. $B^+ \to D^0\rho(770)^+$ in Belle II

The current world average branching fraction (BF) for one of the significant modes, $B^+ \to D^0\rho^+$, which heavily contributes to hadronic tagging, is measured with large uncertainty, primarily driven by CLEO [3] measurements. To improve this measurement, we are analyzing this decay using 362 fb^{-1} of data from the Belle II experiment.

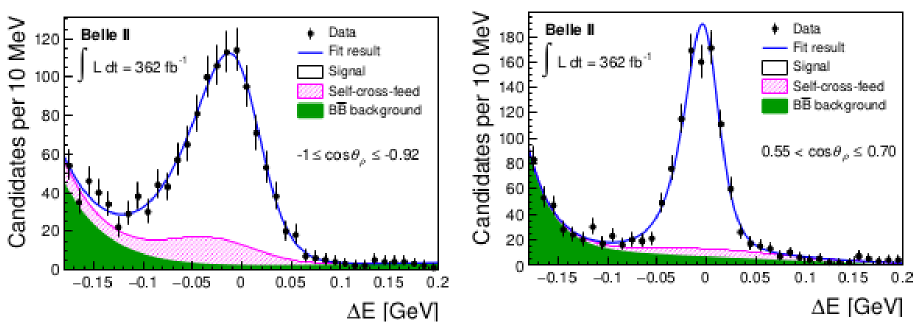

Figure 1: ΔE fit distribution in data for two extreme bins of $\cos\theta_\rho$

A major challenge in this decay involves distinguishing the resonant $B^+ \to D^0\rho^+$ from the non-resonant $B^+ \to D^0\pi^+\pi^0$. This is achieved by fitting in the bins of the cosine of the helicity angle. The helicity angle is defined as the angle between the pion's momentum and the direction opposite to the B momentum in the ρ rest frame.

We determine the sample composition with a maximum likelihood fit to the unbinned distribution of ΔE. The ΔE fit is performed in nine independent intervals of $\cos\theta_\rho$ to reconstruct the background-subtracted distribution of this variable and separate the resonant and non-resonant components. We observe a flat distribution for the resonant decay in the bins of $\cos\theta_\rho$ compared to the non-resonant component, which contributes less than 2%.

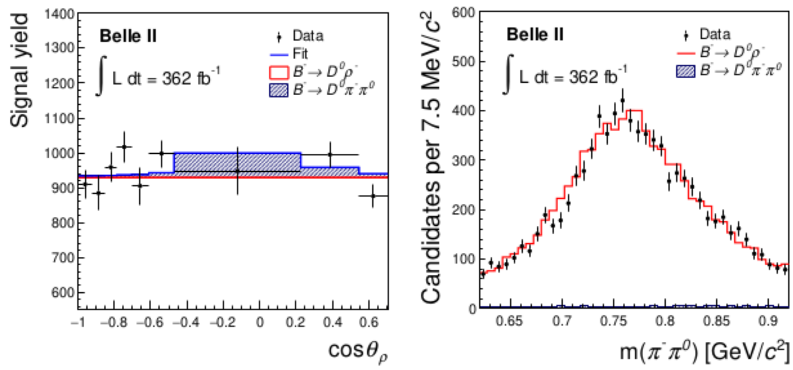

Figure 2: Left:background-subtracted $\cos\theta_\rho$ distribution with fit projection overlaid. Right:background-subtracted distribution of the $\pi^-\pi^0$ invariant mass, with overlaid simulated data reflecting the $B^+ \to D^0\rho^+$ and $B^+ \to D^0\pi^+\pi^0$ proportions from the $\cos\theta_\rho$ fit

We measure the branching fraction of the $B^- \to D^0\rho^-$ decay using e^+e^--collision data collected by the Belle II detector at the $\Upsilon(4S)$ resonance, containing 387 million $B\bar{B}$ meson pairs. The result is $(0.939 \pm 0.021\,(\text{stat}) \pm 0.050\,(\text{syst}))\%$ [4], in agreement with previous determinations. Our measurement improves the fractional precision of the world average by more than a factor of two and will significantly enhance the calibration factor of the Belle II hadronic-tagging algorithm.

3. $B \to D^{(*)}K^-K^{(*)0}$ in Belle II

Hadronic B sector is largely unexplored with more than 40% of decay width unknown. Among the unknown, $B \to DKK$ sector contributes to few percentage of the branching fraction, yet its largely unexplored. Only around 0.3% of these decays are measured so far. Knowing the BF of these decays surely help in the hadronic B tagging. We report twelve of $B \to DDK$ decays in which 3 are first observation and 6 are with world's best precision and 3 $B \to DDs$ decays compatible with world avearge using the full Belle II data sample of 362 fb^{-1}. The BFs are extracted using likelihood fits to the unbinned distributions of the energy difference ΔE, where the first uncertainties are statistical and the second are systematic. The invariant mass $m(KK_S^0)$ of the two kaons is also investigated.

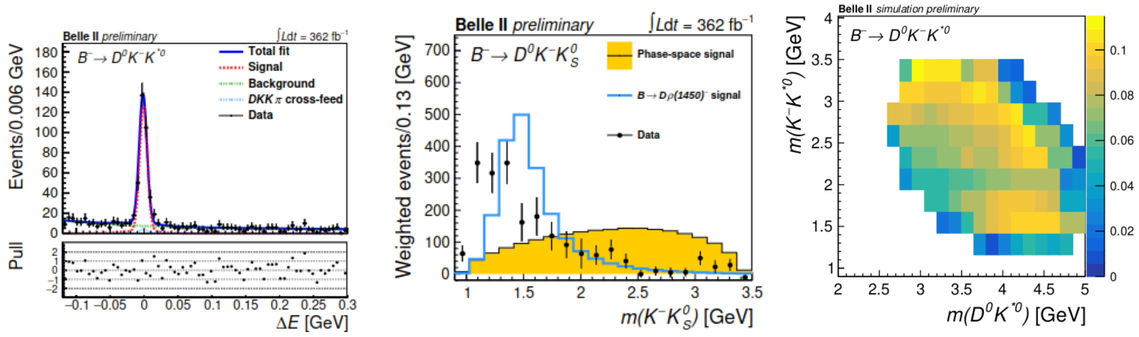

Figure 3: ΔE (left), $m(KK_S^0)$ (middle), and Dalitz (right) distributions of of $B^- \to D^0K^-K_S^0$ decay.

Channel	Yield	Average ε	$\mathcal{B}$ $[10^{-4}]$
$B^- \to D^0K^-K_S^0$	209 ± 17	0.098	$1.82 \pm 0.16 \pm 0.08$
$\overline{B}^0 \to D^+K^-K_S^0$	105 ± 14	0.048	$0.82 \pm 0.12 \pm 0.05$
$B^- \to D^{*0}K^-K_S^0$	51 ± 9	0.044	$1.47 \pm 0.27 \pm 0.10$
$\overline{B}^0 \to D^{*+}K^-K_S^0$	36 ± 7	0.046	$0.91 \pm 0.19 \pm 0.05$
$B^- \to D^0K^-K^{*0}$	325 ± 19	0.043	$7.19 \pm 0.45 \pm 0.33$
$\overline{B}^0 \to D^+K^-K^{*0}$	385 ± 22	0.021	$7.56 \pm 0.45 \pm 0.38$
$B^- \to D^{*0}K^-K^{*0}$	160 ± 15	0.019	$11.93 \pm 1.14 \pm 0.93$
$\overline{B}^0 \to D^{*+}K^-K^{*0}$	193 ± 14	0.020	$13.12 \pm 1.21 \pm 0.71$
$B^- \to D^0D_s^-$	144 ± 12 / 153 ± 13	0.09 / 0.04	$95 \pm 6 \pm 5$
$\overline{B}^0 \to D^+D_s^-$	145 ± 12 / 159 ± 13	0.05 / 0.02	$89 \pm 5 \pm 5$
$B^- \to D^{*0}D_s^-$	30 ± 6 / 29 ± 7	0.04 / 0.02	$65 \pm 10 \pm 6$
$\overline{B}^0 \to D^{*+}D_s^-$	43 ± 7 / 37 ± 7	0.04 / 0.02	$83 \pm 10 \pm 6$

Figure 4: Complete branching fraction results of twelve of the decay channel studied [5]

4. $B^0 \to \omega\omega$ in Belle

In the Standard Model (SM), the decay $B^0 \to \omega\omega$ proceeds via a $b \to u$ spectator amplitude and a $b \to d$ loop ("penguin") amplitude. Interference between these amplitudes, which have different weak and strong phases, and possible interference with amplitudes arising from beyond-the-SM physics, gives rise to direct CP violation. In addition, the fraction of longitudinal polarization (f_L) for this vector-vector (VV) final state can also be affected by physics beyond the SM.

We report measurements of the decay $B^0 \to \omega\omega$ using 772×10^6 $B\bar{B}$ pairs produced at the Belle experiment. In this study, the signal extraction is performed using a 7-dimensional fit to the following variables: ΔE, M_{bc}, continuum suppression, ω invariant masses, and the cosine of the helicity angles of both ω mesons. The branching fraction, fraction of longitudinal polarization, and time-integrated CP asymmetry are measured to be:

$$B = (1.48 \pm 0.28 \pm 0.15) \times 10^{-6}$$
$$f_L = 0.87 \pm 0.13 \pm 0.13$$
$$A_{CP} = -0.44 \pm 0.43 \pm 0.11 \text{ [6]}$$

where the first uncertainties are statistical and the second are systematic. This represents the first observation of the decay with a significance of 7.9σ. Additionally, there is no significant CP asymmetry (A_{CP}).

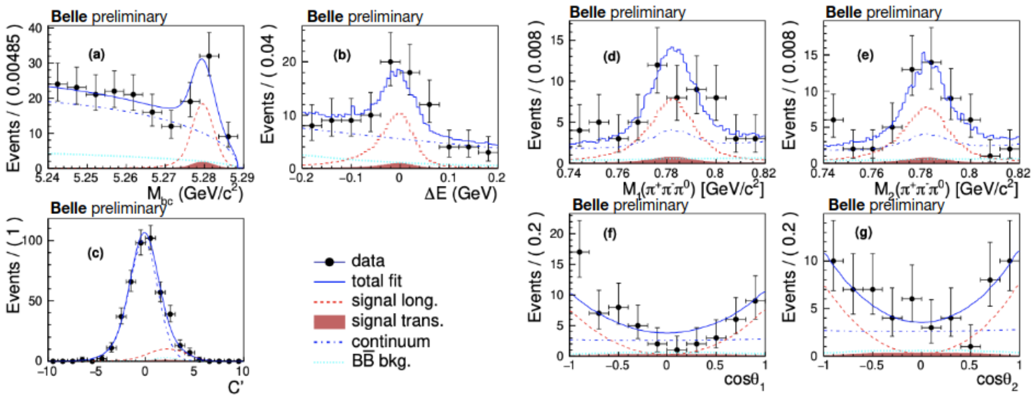

Figure 5: 7D fit distributions

5. First Belle+Belle II combination of Φ_3 measurements

The angle ϕ_3 is investigated through the interference between the transition amplitudes of $b \to c\bar{u}s$ and $b \to u\bar{c}s$ in tree-level B hadronic decays. The current global average value, $\phi_3 = \left(65.9^{+3.3}_{-3.5}\right)^\circ$, is primarily influenced by measurements from LHCb [7, 8]. This angle is determined using various methods, each involving different D meson final states resulting from B decays into charmed final states. The most accurate result from Belle II is obtained using D meson decays into self-conjugate final states $K^0_S h^+ h^-$, where h can be K or π, involving several intermediate resonances in D decays, leading to variations in the CP-violating asymmetry across the phase space [9]. Additionally, two other methods have been explored: one involving Cabibbo-suppressed D decays and another where the D meson decays into two-body CP eigenstates. However, the precision in these methods is constrained by the limited sample size.

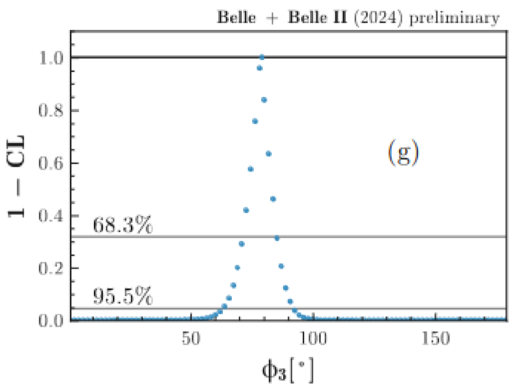

Figure 6: 1-CL distribution as a function of ϕ_3

Parameters	$\phi_3(^\circ)$	r_B^{DK}	$\delta_B^{DK}(^\circ)$	$r_B^{D\pi}$	$\delta_B^{D\pi}(^\circ)$	$r_B^{D^*K}$	$\delta_B^{D^*K}(^\circ)$
Best fit value	78.6	0.117	138.4	0.0165	347.0	0.234	341
68.3% interval	[71.4, 85.4]	[0.105, 0.130]	[129.1, 146.5]	[0.0109, 0.0220]	[337.4, 355.7]	[0.165, 0.303]	[327,355]
95.5% interval	[63, 92]	[0.092, 0.141]	[118, 154]	[0.006, 0.027]	[322, 366]	[0.10, 0.37]	[307, 369]

Figure 7: Combination results: best-fit values and 68.3% and 95.5% confidence intervals.

The first combination of Belle+Belle II measurement, ϕ_3 obtained as $\phi_3 = \left(78.6^{+7.2}_{-7.3}\right)^{\circ}$ [10].

6. Conclusion

We report on precise measurements of hadronic B decays at the Belle and Belle II experiment. We obtained the world's best branching fraction measurements with 2 times improved precision for $B \to D\rho$ decays. We present the first observation of three new $B \to D^{(*)}KK^0_S$ decays along with $B \to \omega\omega$ decay. We present the Belle+Belle II combined measurement of the CKM angle ϕ_3 with the GLS [11] and GLW [12] methods, with precision significantly improved with respect to the previous Belle [13] measurements.

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