

# Hadronic $B$ decays at Belle and Belle II

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**Abstract.** The Belle and Belle II B-factories have collectively gathered an extensive  $1.1 \text{ ab}^{-1}$  dataset of  $e^+e^-$  collisions at the  $\Upsilon(4S)$  resonance, resulting in the production of numerous  $B\bar{B}$  pairs. This allows for precise measurements of hadronic  $B$  decays, essential to test Quantum Chromodynamics (QCD) and refine theoretical models. This also helps improve simulation accuracy. We present results for the  $B$  to hadronic decays such as  $B^- \rightarrow D^0\rho^-$ ,  $B \rightarrow DK^*K_{(s)}^{(*)0}$  and the first Belle and Belle II combined  $\phi_3$  measurement.

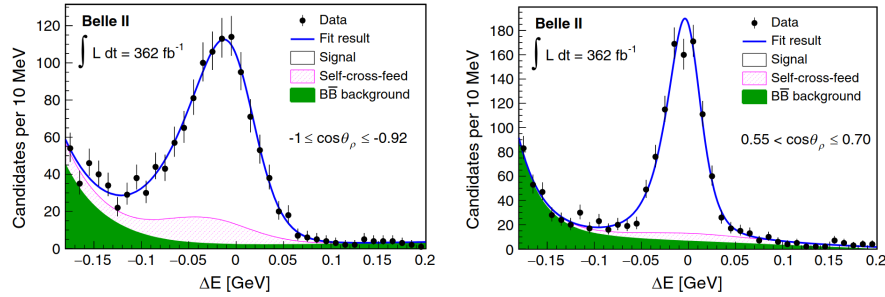
**Keywords:** Hadronic, CKM, Belle II

## 1 Introduction

Hadronic  $B$  decays make up about 75% of all  $B$  meson decays, yet nearly half remain unmeasured. To estimate the unmeasured decays, Belle II [1] relies on the PYTHIA [2] fragmentation model, which doesn't accurately represent  $B$  decays. Belle II also offers a unique opportunity to study decays involving missing energy through a  $B$ -tagging technique. Here, one of the two  $B$  mesons produced in a collision is fully reconstructed. Hadronic  $B$ -tagging provides high precision in determining the  $B$  meson's momentum and direction. Belle II uses a specialized algorithm for this called Full Event Interpretation (FEI) [3], which employs machine learning classifiers trained on Belle II's Monte Carlo (MC) simulations. However, mismatches between the simulation and data can affect the FEI's efficiency, reducing its performance and limiting the experiment's potential. By making more measurements of hadronic  $B$  decays, we can improve the FEI's efficiency and background rejection, leading to better  $B$  meson studies and a deeper understanding of  $B$  decay models.

## 2 $B^- \rightarrow D^0\rho^-$

$B^- \rightarrow D^0\rho^-$  (with charge conjugation implied) is crucial in hadronic tagging for Belle II. However, the tagging efficiency for this decay is hindered by a significant discrepancy between data and Monte Carlo (MC) simulations, highlighting the need of re-evaluation. An effort is being made to improve the measurement using  $365 \text{ fb}^{-1}$  of data in Belle II [4]. To extract the signal, an unbinned maximum



**Fig. 1.** Fitted  $\Delta E$  distribution for  $B^- \rightarrow D^0\rho^-$  in the lowest(left) and highest(right)  $\cos\theta_\rho$  interval [4].

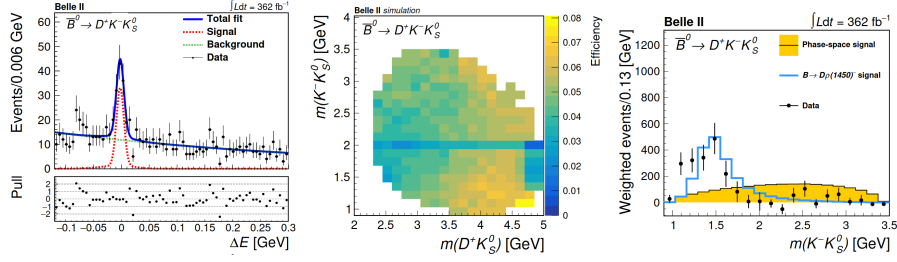
likelihood fit to the  $\Delta E$  (difference between expected and observed B meson energy) distribution shown in Fig. 1 is performed. The major challenge is the contribution from the non-resonant  $B^- \rightarrow D\pi^-\pi^0$  as the  $\Delta E$  distribution is indistinguishable from that of  $B^- \rightarrow D^-\rho$ . This is addressed by fitting  $\Delta E$  in nine bins of the cosine of  $\rho$  helicity angle ( $\cos\theta_\rho$ ). A  $(1.9 \pm 1.8)\%$  fraction of  $B^- \rightarrow D\pi^-\pi^0$  contribution is found in  $B^- \rightarrow D^-\rho$  decays. The background-subtracted  $\pi^-\pi^0$  invariant mass distribution overlaid is compared with simulated data using the fractions of  $B^- \rightarrow D\pi^-\pi^0$  and  $B^- \rightarrow D\rho^-$  decays resulting from the fit.

The simulation matches the data distribution well. The BF measured is  $(0.939 \pm 0.021(stat) \pm 0.050(syst))\%$ , which is, to date, the most precise measurement.

### 3 $B \rightarrow D^*KK_{(s)}^{(*)0}$ and $B \rightarrow DD_s$

$B \rightarrow D^*KK_{(s)}^{(*)0}$  decays make up a few percent of the overall hadronic branching fraction. But only a few of these decays are well measured. Since these decays serve as inputs for simulations and tagging techniques, they must be well-measured.

These decays proceed via a tree-level diagram with external  $W$  emission, but there is also the possibility of  $B \rightarrow DX^-(\rightarrow KK^-)$ , with an intermediate resonance  $X^-$ . This study reports a more precise measurement of eight  $B \rightarrow DK^-K$  absolute branching fractions and observation of the three unobserved  $B \rightarrow DK^-K_S^0$  channels using a data sample of  $365\text{fb}^{-1}$  collected at Belle II [5]. The intermediate states are also studied by Dalitz analysis, and more precise BFs for four  $B \rightarrow DD_s$  are obtained. The signal yields are extracted using likelihood fits to the unbinned  $\Delta E$  distribution. The BF is obtained by the efficiency-corrected integral of the  $m(KK^-), m(DK)$  distribution for the three body decays. The  $\Delta E$ , Dalitz plot and  $M(KK_S^0)$  distributions for one of the first observed decay  $B^0 \rightarrow D^+K^-K_S^0$  is shown in Fig. 2. The table with all the measured BFs and their significance is shown in Fig.3



**Fig. 2.**  $\Delta E$ (left), Dalitz(middle) and  $m(KK_S^0)$ (right) distribution of  $\bar{B}^0 \rightarrow D^+ K^- K_S^0$  [5].

Channel	Yield	Average $\varepsilon$	$\mathcal{B}$ [ $10^{-4}$ ]	Stat. significance [ $\sigma$ ]
$B^- \rightarrow D^0 K^- K_S^0$	$209 \pm 17$	0.098	$1.82 \pm 0.16 \pm 0.08$	$> 10$
$\bar{B}^0 \rightarrow D^+ K^- K_S^0$	$105 \pm 14$	0.048	$0.82 \pm 0.12 \pm 0.05$	10
$B^- \rightarrow D^{*0} K^- K_S^0$	$51 \pm 9$	0.044	$1.47 \pm 0.27 \pm 0.10$	8
$\bar{B}^0 \rightarrow D^{*+} K^- K_S^0$	$36 \pm 7$	0.046	$0.91 \pm 0.19 \pm 0.05$	9
$B^- \rightarrow D^0 K^- K^{*0}$	$325 \pm 19$	0.043	$7.19 \pm 0.45 \pm 0.33$	$> 10$
$\bar{B}^0 \rightarrow D^+ K^- K^{*0}$	$385 \pm 22$	0.021	$7.56 \pm 0.45 \pm 0.38$	$> 10$
$B^- \rightarrow D^{*0} K^- K^{*0}$	$160 \pm 15$	0.019	$11.93 \pm 1.14 \pm 0.93$	$> 10$
$\bar{B}^0 \rightarrow D^{*+} K^- K^{*0}$	$193 \pm 14$	0.020	$13.12 \pm 1.21 \pm 0.71$	$> 10$
$B^- \rightarrow D^0 D_s^-$	$144 \pm 12 / 153 \pm 13$	$0.09 / 0.04$	$95 \pm 6 \pm 5$	$> 10 / > 10$
$\bar{B}^0 \rightarrow D^+ D_s^-$	$145 \pm 12 / 159 \pm 13$	$0.05 / 0.02$	$89 \pm 5 \pm 5$	$> 10 / > 10$
$B^- \rightarrow D^{*0} D_s^-$	$30 \pm 6 / 29 \pm 7$	$0.04 / 0.02$	$65 \pm 10 \pm 6$	7 / 8
$\bar{B}^0 \rightarrow D^{*+} D_s^-$	$43 \pm 7 / 37 \pm 7$	$0.04 / 0.02$	$83 \pm 10 \pm 6$	$> 10 / > 10$

**Fig. 3.** Table listing the branching fractions and significance of all the decay channels studied [5].

#### 4 $\phi_3$ measurement with Belle + Belle II data

The CKM angle  $\phi_3(\gamma)$ , defined as  $\phi_3 = \arg(V_{ud}V_{ub}^*/V_{cd}V_{cb}^*)$  can be measured directly by exploiting the interference between tree-level quark-transition amplitudes that involve  $\bar{b} \rightarrow \bar{u}c\bar{s}$  and  $\bar{b} \rightarrow \bar{c}u\bar{s}$ . Assuming contribution from only the standard model, the measurement of  $\phi_3$  provides a good test against indirect determinations from global unitarity fits. Here,  $\phi_3$  is measured using results from samples of up to  $711 \text{ fb}^{-1}$  from the Belle experiment and up to  $362 \text{ fb}^{-1}$  from the Belle II [6]. experiment. This study combines results from analyses of  $B^+ \rightarrow DK^+$ ,  $B^+ \rightarrow D\pi^+$ , and  $B^+ \rightarrow D^*K^+$  decays, where  $D$  is an admixture of  $D^0$  and  $\bar{D}^0$  mesons. Several methods and different final states are used in the study to obtain  $\phi_3$ . Fig. 4 shows the 1-CL distribution as a function of  $\phi_3$ . The  $\phi_3$  measured is  $(75.2 \pm 7.6)^\circ$ , which agrees with the current world average.

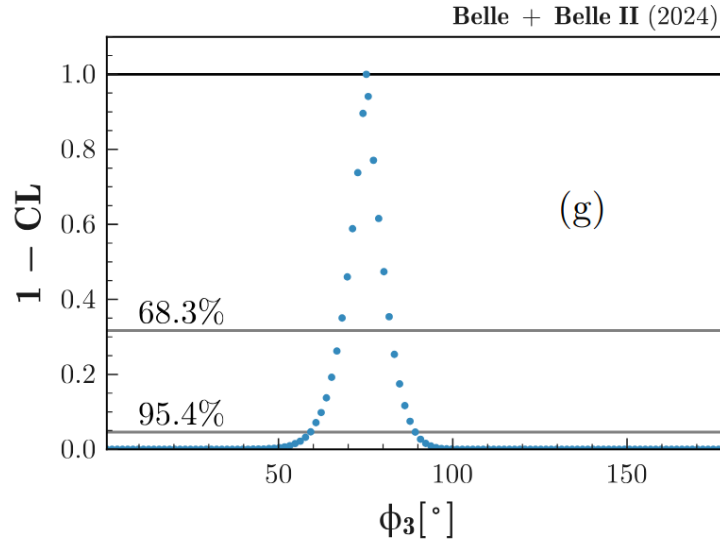


Fig. 4. 1-CL distributions as functions of  $\phi_3$  [6].

## 5 Conclusion

We discuss precise measurements of hadronic  $B$  decays in the Belle and Belle II experiment. The decays  $B^- \rightarrow D\rho^-$  and  $B \rightarrow DD_s$  are measured more precisely. There are new observations for  $B \rightarrow DKK_S^0$ . We also present the first combined Belle+Belle II result on  $\phi_3$ , which agrees with the world average.

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