

# Determination of CKM angle $\phi_3$ at Belle and Belle II

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**Abstract.** We present the measurement of the angle  $\phi_3$  using a model-independent Dalitz plot analysis of  $B^\pm \rightarrow D(K_S^0 \pi^+ \pi^-) K^\pm$  decays, which currently provides the best sensitivity. The method uses, as input, measurements of the strong phase of the  $D \rightarrow K_S^0 \pi^+ \pi^-$  amplitude from the BESIII collaboration. This is the first measurement using the combined Belle and Belle II data-set of the order of  $1 \text{ ab}^{-1}$ . Here, we describe the extraction strategy developed based on the simulation sample.

**Keywords:**  $\phi_3$ , CKM angle

## 1 Introduction

A more precise determination of the  $CP$ -violating parameter  $\phi_3$  (also called  $\gamma$ ) is a highly promising path to a better understanding of the Standard Model (SM) description of  $CP$  violation and search for contributions from non-SM physics. It can be extracted via tree-level decays, along with non-perturbative strong interaction parameters, which make the method free of theoretical uncertainties to  $\mathcal{O}(10^{-7})$  [1]. The most common channel for  $\phi_3$  extraction is  $B^\pm \rightarrow DK^\pm$ , where  $D$  indicates a  $D^0$  or  $\overline{D^0}$  meson decaying to the same final state  $f$ ; the weak phase  $\phi_3$  appears in the interference between  $b \rightarrow c\bar{u}s$  and  $b \rightarrow u\bar{c}s$  transitions. The  $b \rightarrow u\bar{c}s$  amplitude ( $A_{\text{sup}}$ ) is suppressed relative to the  $b \rightarrow c\bar{u}s$  amplitude ( $A_{\text{fav}}$ ) because of the magnitudes of the CKM matrix elements involved and the requirements of colorless hadrons in the final state. The two amplitudes are related by

$$\frac{A_{\text{sup}}(B^- \rightarrow \overline{D^0} K^-)}{A_{\text{fav}}(B^- \rightarrow D^0 K^-)} = r_B e^{i(\delta_B - \phi_3)}, \quad (1)$$

where  $r_B$  is the magnitude of the ratio of amplitudes and  $\delta_B$  is the strong-phase difference between the favoured and suppressed amplitudes.

### 1.1 BPGGSZ formalism

The Bondar, Poluektov, Giri, Grossman, Soffer and Zupan (BPGGSZ) method [2–4], uses the phase-space distribution of the products of  $D$  decays to multibody

self-conjugate final states, such as  $K_S^0 h^+ h^-$ . In this method, the  $D$  Dalitz space is binned to achieve optimal, and model-independent, sensitivity to  $\phi_3$ . The binning eliminates the model-dependent systematic uncertainty enabling degree-level precision. The signal yield in each bin is given by

$$\Gamma_i^\pm \propto K_i + r_B^2 \bar{K}_i + 2\sqrt{K_i \bar{K}_i} (c_i x_\pm + s_i y_\pm), \quad (2)$$

where  $(x_\pm, y_\pm) = r_B(\cos(\pm\phi_3 + \delta_B), \sin(\pm\phi_3 + \delta_B))$ . Here,  $K_i$  is the number of events in the  $i^{\text{th}}$  bin of a flavour tagged  $D$  decay sample. The parameters  $c_i$  and  $s_i$  are the amplitude-averaged strong-phase difference between  $\bar{D}^0$  and  $D^0$  over the  $i^{\text{th}}$  bin and can be measured using quantum-correlated pairs of  $D$  mesons created at  $e^+e^-$  annihilation experiments operating at the threshold of  $D\bar{D}$  pair production. The  $(x_\pm, y_\pm)$  parameters can be obtained from Eq. 2 using the maximum likelihood method. The values of  $c_i$  and  $s_i$  parameters for  $D^0 \rightarrow K_S^0 \pi^+ \pi^-$  decays, as well as the binning scheme to divide the  $D$  phase space, used in this analysis are reported in Ref. [5].

## 2 Data sample and event selection

The analysis uses  $e^-e^+$  collision data collected at center-of-mass energy corresponding to  $\Upsilon(4S)$  resonance by the Belle [6] and Belle II [7] detectors corresponding to  $771 \text{ fb}^{-1}$  and  $90 \text{ fb}^{-1}$  collected by the year 2020, respectively. Studies on Monte Carlo (MC) samples are performed to optimize the selection criteria, determine the signal efficiencies and identify various sources of background.

We reconstruct  $B^\pm \rightarrow DK^\pm$  and  $B^\pm \rightarrow D\pi^\pm$  decays in which  $D$  decays into  $K_S^0 \pi^- \pi^+$  final states. Charged particle tracks are selected by requiring  $|dr| < 0.2$  cm and  $|dz| < 1$  cm, where  $dr$  and  $dz$  represent the distance of closest approach to the interaction point (IP) in the plane transverse to the beam direction and in the beam direction, respectively. These tracks are then identified as kaons or pions by the particle identification detectors. We reconstruct the  $K_S^0$  candidates from two oppositely charged pion tracks. The dipion candidate mass is required to be within  $\pm 3\sigma$  of the known  $K_S^0$  mass. The  $K_S^0 \pi^+ \pi^-$  mass is restricted to match the known  $D$  mass,  $1.85 < M_{D^0} < 1.88 \text{ GeV}/c^2$ , to reduce combinatorial backgrounds. The  $B$ -meson candidates are reconstructed by combining a  $D$  candidate with a charged kaon or pion. The kinematic variables used for  $B$  reconstruction are the beam-constrained mass ( $M_{\text{bc}}$ ) and the beam-energy difference ( $\Delta E$ ), which are defined as

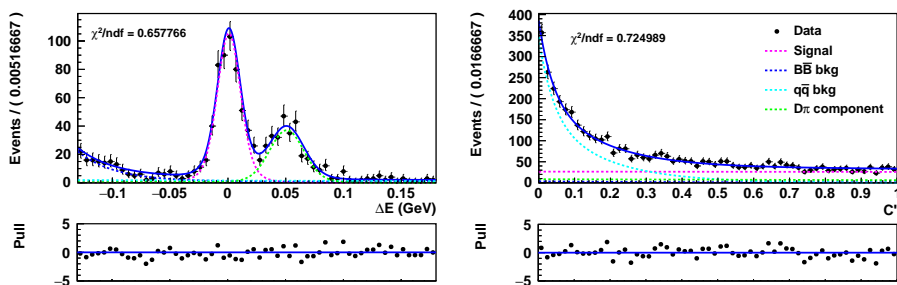
$$M_{\text{bc}} = \sqrt{E_{\text{beam}}^2 - (\Sigma \vec{p}_i^\perp)^2}, \quad \Delta E = \Sigma E_i - E_{\text{beam}}, \quad (3)$$

where  $E_{\text{beam}}$  is the beam energy in the center-of-mass frame and  $E_i$  and  $\vec{p}_i^\perp$  are the energy and momenta of  $B$  daughter particles in the center-of-mass frame. The selection criteria chosen are  $-0.13 < \Delta E < 0.18 \text{ GeV}$  and  $M_{\text{bc}} > 5.27 \text{ GeV}/c^2$ . A kinematic constraint is applied so that the  $B$  daughters come from a common vertex. In events with more than one candidate, the candidate with the smallest  $\chi^2$  value, constructed from the  $M_{\text{bc}}$  and  $M_D$  pulls, is retained.

The main source of background in our analysis are events coming from the  $e^+e^- \rightarrow q\bar{q}$  ( $q = u, d, s$  or  $c$ ) continuum process. These backgrounds are suppressed by utilizing the event topology, which is different from that of  $B\bar{B}$  events, with a binary classifier based on boosted decision trees that combines nonlinearly seven inputs into a scalar output discriminator. Continuum events preferentially produce particles collimated into back-to-back jets, whereas the  $e^+e^- \rightarrow \Upsilon(4S) \rightarrow B\bar{B}$  are distributed uniformly over the  $4\pi$  solid angle. The overall selection efficiency is 17.77% and 19.85% for  $B^\pm \rightarrow DK^\pm$  at Belle and Belle II, respectively.

### 3 Fit procedure and $(x_\pm, y_\pm)$ parameters extraction

The signal yield in each  $D$  phase-space bin is determined from a two-dimensional extended maximum-likelihood fit to  $\Delta E$  and transformed FBDT output ( $C'$ ) simultaneously in  $B \rightarrow D\pi$  and  $B \rightarrow DK$ . We use a combined fit with a common likelihood in all the 16 bins. Figure. 1 represents the signal-enhanced fit projections of  $\Delta E$  and  $C'$  of the channel  $B^\pm \rightarrow DK^\pm$  in a simulated sample equivalent to the Belle sample. The fit strategy is the same for Belle II.



**Fig. 1.** Signal enhanced fit projections of  $\Delta E$  and  $C'$  of the channel  $B^\pm \rightarrow DK^\pm$  in a simulated sample equivalent to the Belle sample. The signal region is defined as  $|\Delta E| < 0.05$  GeV and  $0.65 < C' < 1$ .

We have adopted the new strategy, for  $(x_\pm, y_\pm)$  parameters extraction, recently used by LHCb [8]. We use the control sample  $B \rightarrow D\pi$  to determine the  $K_i$  and  $K_{-i}$  fractions in the simultaneous fit itself as these events will have the same relative acceptance over phase space as of  $B \rightarrow DK$  if a common selection is applied. An alternate parameterisation is introduced, to make the fit stable at low  $r_B$  value, which utilises the fact that  $\phi_3$  is a common parameter, and that the  $CP$  violation in  $B \rightarrow D\pi$  decays can therefore be described by the addition of a single complex variable [9], which is function of  $x_\pm^{D\pi}, y_\pm^{D\pi}$ .

The obtained values of physics parameters of interest  $x_\pm^{DK}, y_\pm^{DK}$  in simulation are shown in Table. 1. As there is no  $CP$  violation present in the simulation, the

expected values of these parameters are zero. In data, the asymmetry between the signal yields of  $B^+$  and  $B^-$  will drive the extraction of hadronic parameters  $r_B, \delta_B$  and  $\phi_3$ .

**Table 1.** Results on a simulated sample equivalent to the Belle data set

Parameter	Value
$x_+^{DK}$	$-0.04 \pm 0.04$
$x_-^{DK}$	$0.01 \pm 0.03$
$y_+^{DK}$	$-0.10 \pm 0.06$
$y_-^{DK}$	$-0.01 \pm 0.03$

## 4 Summary

The precise measurement of the angle  $\phi_3$  will give us a SM benchmark to which other measurements of the CKM parameters can be compared to, both within the SM and beyond. Here, we outlined the analysis overview of the decays  $B^\pm \rightarrow D(K_S^0 \pi^+ \pi^-)K^\pm$  for  $\phi_3$  extraction. This is our first attempt to obtain sensitivity from a combined data-set of Belle and Belle II. The signal extraction procedure is established in an MC sample and we will look at data soon. With the ultimate Belle II data sample of  $50 \text{ ab}^{-1}$ , a determination of  $\phi_3$  with a precision of  $1^\circ$  or better is foreseen [7].

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