Determination of CKM angle ϕ_3 at Belle and Belle II

Niharika Rout
(On behalf of Belle and Belle II collaboration)

Indian Institute of Technology Madras, Chennai 600036, India,
niharikarout@physics.iitm.ac.in

Abstract. We present the measurement of the angle ϕ_3 using a model-independent Dalitz plot analysis of $B^{\pm} \to DK^{\pm}, D \to K_S^0\pi^+\pi^-$ decays, which currently provides the best sensitivity. The method uses, as input, measurements of the strong phase of the $D \to K_S^0\pi^+\pi^-$ amplitude from the BESIII collaboration. This is the first measurement using the combined Belle and Belle II data-set of the order of 1 ab^{-1}. With the ultimate Belle II data sample of 50 ab^{-1}, a determination of ϕ_3 with a precision of 1° or better is foreseen.

Keywords: ϕ_3, CKM angle

1 Introduction

A more precise determination of the CP-violating parameter ϕ_3 (also called γ) is the most 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 makes the method free of theoretical uncertainties to $\mathcal{O}\left(10^{-7}\right)$ [1]. The most commonly used decay channel for ϕ_3 extraction is $B^{\pm} \to DK^{\pm}$, where D indicates a D^0 or $\overline{D^0}$ meson decaying to the same final state f; the weak phase ϕ_3 appears in the interference between $b \to c\bar{u}s$ and $b \to u\bar{c}s$ transitions. The $b \to u\bar{c}s$ amplitude (A_{sup}) is suppressed relative to the $b \to c\bar{u}s$ amplitude (A_{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

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

where r_B is the magnitude of the ratio of amplitudes and δ_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 distribution over phase space of the products of D decays to multi-body self-conjugate final states, such as $K_S^0h^+h^-$. In this method, the D Dalitz space is binned in a way that gives the maximum sensitivity to ϕ_3 in a model-independent manner. The binning eliminates the model-dependent systematic uncertainty in the measurement and can give degree-level precision. The signal yield in each bin is given by:

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

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^{th} bin of a flavour tagged D decay sample. The parameters c_i and s_i are the amplitude-averaged strong-phase difference between $\overline{D^0}$ and D^0 over the i^{th} bin and can be measured using quantum-correlated pairs of D mesons created at e^+e^- annihilation experiments operating at the threshold of $D\overline{D}$ 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 Υ(4S) resonance by the Belle [6] and Belle II [7] detectors corresponding to 771 fb^{-1} and 90 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 to $K_S^0\pi^-\pi^+$. The good charged tracks are defined 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 $x - y$ plane and along the z-axis, respectively. These tracks are then identified as kaons or pions with the help of the particle identification detectors. We reconstruct the K_S^0 candidates from two oppositely charged pion tracks. The invariant mass of these pion candidates is required to be within $\pm 3\sigma$ of the nominal K_S^0 mass. The invariant mass D is required to be in the range $1.85 < M_{D^0} < 1.88$ GeV/c^2 to reduce combinatorial backgrounds. The B-meson candidates are reconstructed by combining a D candidate with a charged kaon or pion track. The kinematic variables used for B reconstruction are the beam-constrained mass (M_{bc}) and the beam-energy difference (ΔE), which are defined as

$$M_{\text{bc}} = \sqrt{E_{\text{beam}}^2 - (\Sigma \overrightarrow{p_i})^2},\ \Delta E = \Sigma E_i - E_{\text{beam}}, \tag{3}$$

where E_{beam} is the beam energy in the center-of-mass frame and E_i and $\overrightarrow{p_i}$ are the energy and momenta of B daughter particles in the center-of-mass frame. The selection criteria chosen are $-0.13 < \Delta E < 0.18$ GeV and $M_{\text{bc}} > 5.27$ 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 χ^2 value, constructed from the M_{bc} and M_D pulls, is retained.

The main source of background in our analysis are events coming from the $e^+e^- \to q\bar{q}$ ($q = u, d, s$ or c) continuum process. These backgrounds are suppressed by utilizing the event topology, which are different to that of $B\bar{B}$ events, via a multivariate technique (Fast Boosted Decision Tree). Continuum events have particles collimated into back-to-back jets, whereas the $e^+e^- \to \Upsilon(4S) \to B\overline{B}$ are distributed uniformly over the 4π solid angle. We apply a cut on FBDT output > 0.2 which rejects 67% continuum backgrounds by retaining 96% signal. The overall selection efficiency is 17.77% and 19.85% for $B^\pm \to DK^\pm$ 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 ΔE and transformed FBDT output (C') simultaneously in $B \to D\pi$ and $B \to DK$. We use a combined fit with a common likelihood in all the 16 bins. Figure. 1 represents the signal-enhanced fit projections of ΔE and C' of the channel $B^\pm \to DK^\pm$ in MC simulation sample of luminosity equivalent to data sample collected by Belle. The fit strategy is the same for Belle II.

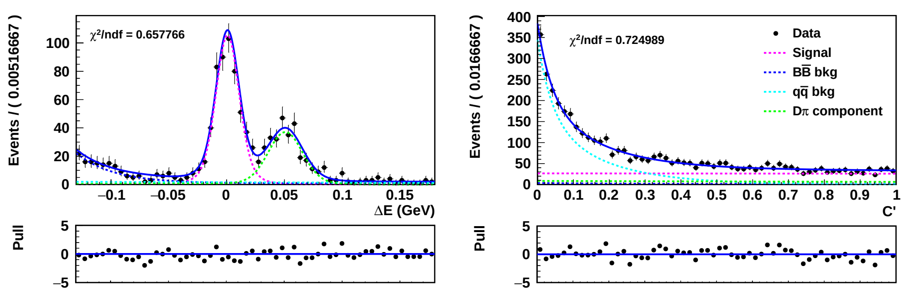

Fig. 1. Signal enhanced fit projections of ΔE and C' of the channel $B^\pm \to DK^\pm$ in MC simulation sample of luminosity equivalent to data sample collected by Belle. The signal region is defined as $|\Delta E| < 0.05$ GeV and $0.65 < C' < 1$.

We have adopted the new strategy, for $(x_\pm, y_\pm)$ parameters extraction, recently used by LHCb [8]. We are using the control sample $B \to D\pi$ 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 $B \to DK$ 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 ϕ_3 is a common parameter, and that the CP violation in $B \to D\pi$ 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 MC sample 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, δ_B and ϕ_3.

Table 1. Obtained values of the parameters $x_{\pm}^{DK}, y_{\pm}^{DK}$ in an MC simulation sample of luminosity equivalent to data sample collected by Belle.

Parameter	Value
x_+^{DK}	-0.04 ± 0.04
x_-^{DK}	0.01 ± 0.03
y_+^{DK}	-0.10 ± 0.06
y_-^{DK}	-0.01 ± 0.03

4 Summary

The precise measurement of the angle ϕ_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 explained the analysis overview of the decays $B^{\pm} \rightarrow D(K_S^0\pi^+\pi^-)K^{\pm}$ for ϕ_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 are hoping to look at data soon. With the ultimate Belle II data sample of 50 ab^{-1}, a determination of ϕ_3 with a precision of 1° or better is foreseen [7].

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