Measurement of CKM angle ϕ_3 at Belle II

Niharika Rout
(On behalf of Belle II Collaboration)
Indian Institute of Technology Madras, Chennai, India, 600036

The CKM angle ϕ_3 is the only angle of the unitarity triangle that is accessible with tree-level decays in a theoretically clean way. The Belle II experiment is a substantial upgrade of the Belle detector and will operate at the SuperKEKB energy-asymmetric e^+e^- collider. The accelerator has already successfully completed the first phase of commissioning, with the first e^+e^- collisions recorded in 2018. The design luminosity of SuperKEKB is 8×10^{35} cm^{-2}s^{-1} and the Belle II experiment aims to record 50 ab^{-1} of data, a factor of 50 more than the Belle experiment. The key method to measure ϕ_3 is through the interference between $B^+ \to D^0 K^+$ and $B^+ \to \overline{D}^0 K^+$ decays, which occurs if the final state of the charm-meson decay is accessible to both the D^0 and $\overline{D}^0$ mesons. To achieve the best sensitivity, a large variety of D and B decay modes are required, which is possible at the Belle II experiment as almost any final state can be reconstructed, including those with photons. 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.

arXiv:1906.11792v1 [hep-ex] 27 Jun 2019

I. INTRODUCTION

The 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-standard model 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]. Figure 1 shows the two interfering diagrams for the most commonly used decay channel $B^\pm \to DK^\pm$, 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 ($A_{\rm sup}$) is suppressed relative to the $b \to u\bar{c}s$ amplitude ($A_{\rm fav}$) 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

$$\frac{A_{\rm sup}}{A_{\rm fav}} = r_B e^{i(\delta_B - \phi_3)}, \tag{1}$$

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. The current world average value of r_B is 0.103 ± 0.005 [2].

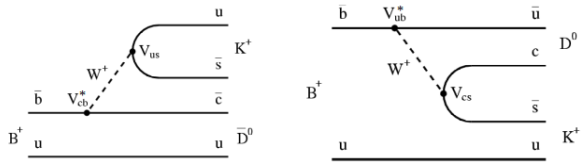

FIG. 1: Leading order quark flow diagrams for the decay channel $B^+ \to DK^+$.

II. PRIMARY METHODS TO EXTRACT ϕ_3

A. GLW method

In 1991, Gronau, London and Wyler (GLW) were the first to propose a method for measuring ϕ_3 using $B^\pm \to DK^\pm$ decay, where the D decays to a CP eigenstate with eigenvalue ±1 [3]. For the extraction of ϕ_3, the following observables are used in the GLW method

$$R_{CP^\pm} = 1 + r_B^2 \pm 2r_B \cos(\delta_B)\cos(\phi_3), \tag{2}$$

$$A_{CP^\pm} = \pm 2r_B \sin(\delta_B)\sin(\phi_3)/R_{CP^\pm}. \tag{3}$$

CP eigenstates such as $D \to K^+K^-$, $\pi^+\pi^-$ and $K_{\rm S}\pi^0$ are used to extract ϕ_3 via this method.

B. ADS method

This method was proposed by Atwood, Dunietz and Soni (ADS) in 1997 [4]. The main idea was to pick a final state for which $D^0 \to f$ is suppressed relative to $\overline{D^0} \to f$. For example, $B^- \to [K^+\pi^-]K^-$ can be reached via doubly Cabibbo-suppressed decay mode $D^0 \to K^+\pi^-$ or via Cabibbo-favored decay mode $\overline{D^0} \to K^+\pi^-$. The observables used are

$$R_{ADS} = r_B^2 + r_D^2 + 2r_B r_D \cos(\delta_B + \delta_D)\cos(\phi_3), \tag{4}$$

$$A_{ADS} = 2r_B r_D \sin(\delta_B + \delta_D)\sin(\phi_3)/R_{ADS}. \tag{5}$$

Here, r_D and δ_D are the amplitude ratio of the suppressed and favored D decays and the strong-phase difference between them, respectively.

C. GGSZ method

This method was proposed by Giri, Grossman, Soffer and Zupan in 2003 [5]. The method uses self-conjugate multi-body D final states, such as $K^0_S\pi^+\pi^-$ and $K^0_S K^+K^-$. 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 [6]. Figure 2 shows an optimal binning used for a GGSZ analysis [6]. The signal yield in each bin is given by

$$\Gamma_i^{\pm} \propto K_i + r_B^2\overline{K}_i + 2\sqrt{K_i\overline{K}_i}(c_i x_{\pm} + s_i y_{\pm}), \qquad (6)$$

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; these parameters are obtained with high precision using a large statistics sample of $D^{*\pm} \to D\pi^{\pm}$ decays. The parameters c_i and s_i are the amplitude-averaged strong phase difference between $\overline{D}^0$ and D^0 over 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 [7]. The $(x_{\pm}, y_{\pm})$ parameters can be obtained from equation (6) using maximum likelihood method.

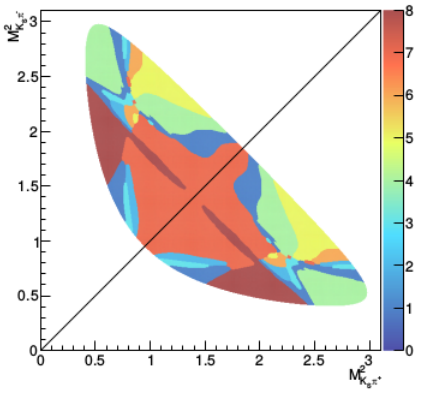

FIG. 2: Optimal binning of $D \to K^0_S\pi\pi$ Dalitz plot.

The average value of ϕ_3 obtained when combining all measurements from the Belle collaboration is $(73^{+13}_{-15})^{\circ}$, which is dominated by the GGSZ final states. The current world average value of ϕ_3 is $(73.5^{+4.2}_{-5.1})^{\circ}$, where the precision is dominated by the results from LHCb experiment.

III. SUPERKEKB AND BELLE II DETECTOR

The SuperKEKB colliding-beam accelerator provides e^+e^- collisions at an energy corresponding to the mass of the $\Upsilon(4S)$ resonance, which are being recorded by the Belle II detector. SuperKEKB consists of two storage rings of 3.012 km length each, one for the 7 GeV electrons and one for the 4 GeV positrons. The design peak instantaneous luminosity of SuperKEKB is 8×10^{35} cm^{-2}s^{-1}, approximately forty times higher than what was achieved by the KEKB accelerator. This will allow a data sample to be accumulated that corresponds to an integrated luminosity of 50 ab^{-1}.

Belle II is the upgraded version of the Belle detector. It can tolerate the much higher level of beam-related background that arises from the increase in instantaneous luminosity. The different subdetectors are shown in the Fig. 3. In terms of performance, it has good tracking, vertexing, K-π separation and good neutral reconstruction efficiency.

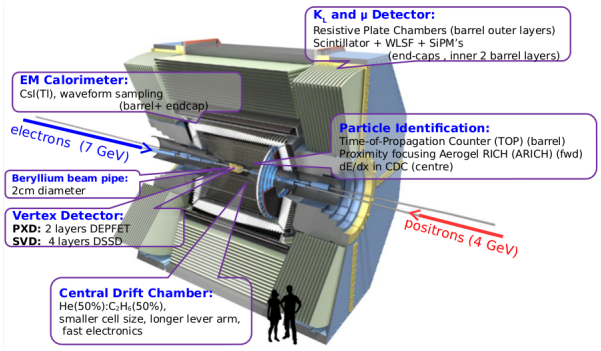

FIG. 3: Belle II detector.

IV. GLIMPSE OF THE PHASE II DATA COLLECTED BY BELLE II

The accelerator commissioning of the Belle II experiment, also known as Phase I, was completed in 2016. The detector entered its second commissioning period (Phase II) in February 2018, with the first collisions taking place on the 25$^{\text{th}}$ April, 2018. A data sample was collected corresponding to an integrated luminosity of 0.5 fb^{-1}. Only one ladder of each layer of the vertex detector was present during the data taking, which corresponds to $\frac{1}{8}$ of the full detector.

We observed various charm decay modes, including the CP eiganestates, like $K^0_S\pi^0$ and multi-body final states like $K^0_S\pi^+\pi^-$, validating the potential for charm physics at Belle II. The invariant mass distributions for $D^0 \to K^0_S\pi^0$ and $D^0 \to K^0_S\pi^-\pi^+$ are shown in Figs. 4 and 5, respectively. Possible charged and neu-

tral B meson candidates are reconstructed from different charmed mesons and a total of 245 signal events are obtained, which is consistent with the yields from the data samples of the ARGUS/CLEO experiment [9]. The signal enhanced ΔE distribution is shown in Fig. 6, which is defined as

$$\Delta E = \Sigma E_i - E_{\rm beam}, \tag{7}$$

where $E_{\rm beam}$ is the beam energy in the center-of-mass frame and E_i is the energy of the B daughter particles in the center-of-mass frame.

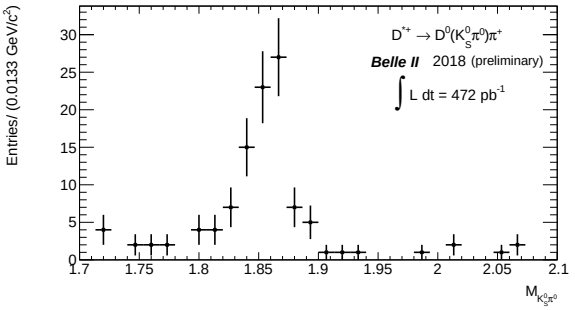

FIG. 4: $M(K^0_S\pi^0)$ for the mode $D^{*\pm} \to D^0(K^0_S\pi^0)\pi^\pm$.

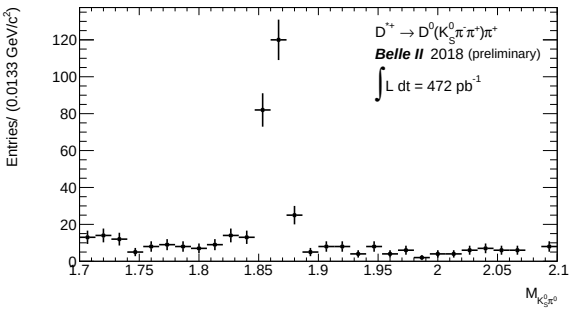

FIG. 5: $M(K^0_S\pi^-\pi^+)$ for the mode $D^{*\pm} \to D^0(K^0_S\pi^-\pi^+)\pi^\pm$.

V. $B \to DK$ DECAYS AT BELLE II

The current level of precision of the measurements of ϕ_3 is dominated by the statistical uncertainty from the limited number of B decays. The 50 ab^{-1} data set of Belle II will improve the uncertainty significantly. The first ϕ_3 sensitivity study at Belle II was performed using the mode $B^+ \to D(K^0_S\pi^-\pi^+)K^+$ with the GGSZ formalism. Based on these studies a 3° precision is expected from the 50 ab^{-1} data set using this mode alone [6]. However, the anticipated precision is 1.6° when all Belle results, including GLW and ADS as well, are extrapolated to the 50 ab^{-1} data-set.

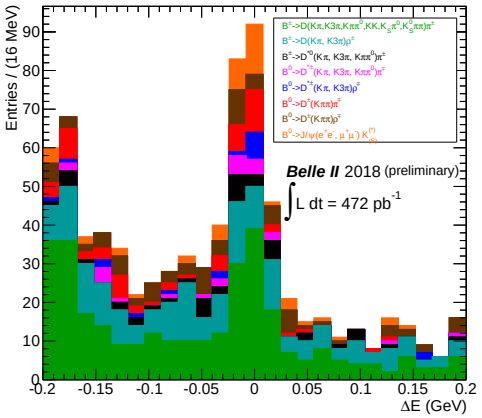

FIG. 6: ΔE distribution for the B candidates selected in the Phase II data.

At Belle II, the dominant background comes from $e^+e^- \to q\bar{q}$, where $q = u, d, s, c$, also known as continuum events. So, continuum suppression plays an important role in identifying the signal from the huge background. Figure 7 demonstrates the outcome of continuum suppression algorithm at Belle II for the mode $B^+ \to D(K^0_S\pi^-\pi^+)K^+$ using Belle II Monte Carlo (MC) sample.

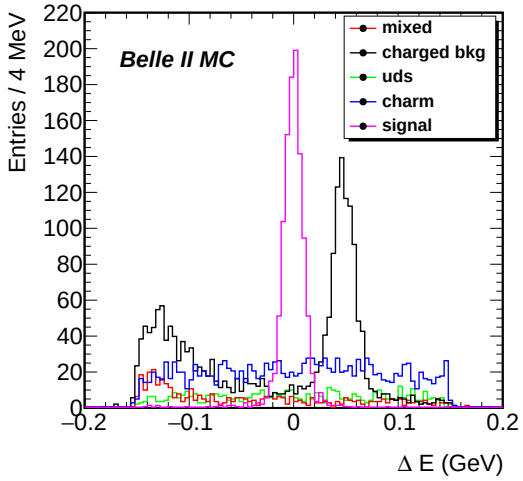

FIG. 7: ΔE distribution using MC after continuum suppression at Belle II. The peak at 40 MeV is from the topologically identical $B^+ \to D\pi^+$ events in which a π has been misidentified as kaon.

We are currently analyzing the following decay modes at Belle II.

- $B^+ \to D(K^0_S\pi^-\pi^+)K^+$,
- $B^+ \to D(K^0_S\pi^0)K^+$ and

- $B^+ \to D(\pi^-\pi^+, K^+K^-)K^+$.

The improved particle identification, good neutral and K^0_S reconstruction, better tracking efficiency and improved continuum suppression algorithms at Belle II will all benefit the selection of these modes. In addition to these modes, D^0 hadronic parameters measured at external charm factories like *BESIII* will play a vital role.

VI. FUTURE PROSPECTS

The phase III run of Belle II has already started. We expect Belle II and LHCb upgrade to match each others performance. Due to the unbiased trigger, Belle II will give excellent performance for Dalitz plot analyses. In addition, sensitivity to the neutral particles will allow the inclusion of more D modes, though LHCb will clearly have more precise results in final states consisting solely of charged tracks. Figure 8 shows the precision of ϕ_3 with the data sets that will be collected from 9 months run of Belle II experiment. So, we clearly expect the uncertainty to be less than 2^o by 2027.

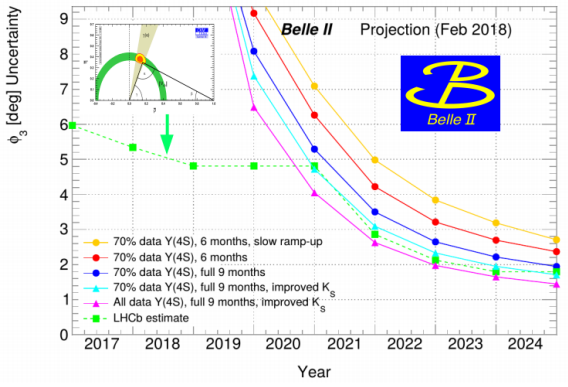

FIG. 8: Belle II projection of expected uncertainty on ϕ_3 by 2027 as per the new luminosity projection of SuperKEKB [11].

VII. 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 referred to, both within the SM and beyond. The current uncertainty on ϕ_3 is $\sim 5^o$. Combined sensitivity of 1.6^o is expected when all Belle results are extrapolated to 50 ab^{-1} data-set. Accounting for recent results of new physics in tree-level amplitudes, a shift of up to 4^o on the SM value of ϕ_3 is possible [10]. This is one of the strongest motivations for the 1^o precision being pursued by Belle II. Figure 9 shows the precision on ϕ_3 in CKM triangle when the fit extrapolated to 50 ab^{-1} for a SM-like scenario [6].

The phase II run of Belle II was successful despite of the very small data sample collected. Phase III run is in full swing and Belle II is ready to realize its potential for flavor physics.

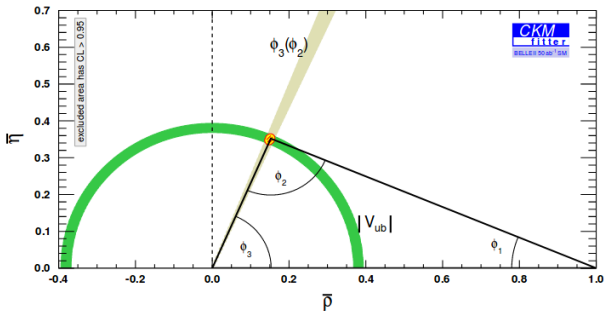

FIG. 9: Fit extrapolated to the 50 ab^{-1} for an SM-like scenario.

[1] J. Brod and J. Zupan, J. High. Energ. Phys. **051**, 1401 (2014).
[2] HFLAV16, Y. Amhis *et al.* (Heavy Flavor Averaging Group), Eur. Phys. J. C **77**, 895 (2017).
[3] M. Gronau and D. London, Phys. Lett. B **253**, 483 (1991); M. Gronau and D. Wyler, Phys. Lett. B **265**, 172 (1991).
[4] D. Atwood, I. Dunietz and A. Soni. Phys. Rev. Lett. **78**, 3257 (2001).
[5] A. Giri, Yu. Grossman, A. Soffer, J. Zupan, Phys. Rev. D **68**, 054018 (2003).
[6] E. Kou (ed.), P. Urquijo (ed.), arXiv:1808.10567 [hep-ex].
[7] Libby, J. *et al.* (CLEO Collaboration), Phys. Rev. D.**82**, 112006 (2010).
[8] The LHCb Collaboration, LHCb-CONF-2017-004
[9] H. Albrecht *et al.* (ARGUS), Phys. Lett. B **192**, 245 (1987).
[10] J. Brod, A. Lenz, G. Tetlalmatzi-Xolocotzi and M. Wiebusch, Phys. Rev. D **92**, 033002 (2015).
[11] http://www-superkekb.kek.jp/