MEASUREMENT OF THE CKM ANGLE ϕ_3 AT BELLE II*

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The precise measurement of the CKM angle ϕ_3 is important to further test the Standard Model description of CP violation. The small values of the branching fractions of the decays involved in the measurement limit the precision, hence a larger dataset has to be accumulated to improve the precision. The Belle II experiment at the SuperKEKB asymmetric-energy e^+e^- collider aims to collect 50 ab^{-1} of data, a factor of 50 more than that of its predecessor Belle. The accelerator has been successfully commissioned in 2016 and the first physics collisions were recorded in April 2018. The best sensitivity to ϕ_3 can be achieved by harnessing all possible final states of $B \to D^{(*)}K^{(*)}$ decays. With the full dataset, Belle II is expected to achieve a precision of 1° for the angle ϕ_3. The expected sensitivities and rediscoveries from 2018 data are presented here.

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1. Introduction

The Cabibbo–Kobayashi–Maskawa [1, 2] unitarity triangle angle ϕ_3 is a good probe to test the Standard Model (SM) description of CP violation. Currently, this is limited by the experimental uncertainty on ϕ_3, which is almost a factor 10 worse than the angle ϕ_1 [3]. The CP-violating observables sensitive to ϕ_3 are measured from the interference between the amplitudes of the color-favored $B^- \to D^0K^-$ and color-suppressed $B^- \to \bar{D}^0K^-$ decays, where D indicates a neutral charm meson reconstructed in a final state common to both D^0 and $\bar{D}^0$. These are tree-level decays and the theoretical uncertainty on ϕ_3 is $\mathcal{O}(10^{-7})$ [4].

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The amplitudes for the color-favored and color-suppressed decays are $A_{\rm fav} = A$ and $A_{\rm sup} = Ar_B e^{i(\delta_B - \phi_3)}$, respectively. Here, δ_B is the strong-phase difference between the decay processes, and

$$r_B = \frac{\mid A_{\rm sup} \mid}{\mid A_{\rm fav} \mid} . \tag{1}$$

The statistical uncertainty on ϕ_3 scales with $1/r_B$. The value of r_B is approximately equal to 0.1 for $B \to DK$ decays, whereas for $B \to D\pi$, it is 0.005. Thus, $B \to D\pi$ decays are not very sensitive to ϕ_3, but they serve as an excellent control sample for $B \to DK$ to validate the signal-extraction procedure, due to the similar topology and larger sample size. The remainder of this article is structured as follows: Section 2 describes the different methods of ϕ_3 extraction. The Belle II experiment is described in Sec. 3. The results from the data collected by the initial physics run of Belle II are summarized in Sec. 4. The expected ϕ_3-sensitivity at Belle II is given in Sec. 5, then Sec. 6 provides the summary.

2. Methods for ϕ_3 extraction

There are different methods to determine ϕ_3 according to the D final state under consideration. If the D final state is a CP eigenstate like K^+K^-, $\pi^+\pi^-$ or $K^0_{\rm S}\pi^0$, then the GLW [5] method is followed. For multibody D decays like $\pi^+\pi^-\pi^0$, its CP content is to be used as an external input in the measurement of ϕ_3 [6]. The ADS [7] method is used for doubly Cabibbo-suppressed D decays K^+X^-, where X^- can be $\pi^-, \pi^-\pi^0$ or $\pi^-\pi^-\pi^+$. The D decay parameters r_D and δ_D, which are the ratio of the amplitudes of the suppressed and favored D decays and the D strong phase, respectively, are needed as inputs. For self-conjugate multibody states such as $K^0_{\rm S}\pi^+\pi^-$, $K^0_{\rm S}K^+K^-$, $K^0_{\rm S}\pi^+\pi^-\pi^0$, the GGSZ [8] method is adopted. In this method, the D phase space is divided into independent regions called "bins" and the ϕ_3-sensitive parameters are measured from the partial rate of $B^\pm$ decays in each bin, which is given as

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

where $x_\pm = r_B \cos(\delta_B \pm \phi_3)$; $y_\pm = r_B \sin(\delta_B \pm \phi_3)$. Here, K_i and $\bar{K}_i$ are the fraction of flavour-tagged D^0 and $\bar{D}^0$ events in the $i^{\rm th}$ bin, respectively, which can be estimated from $D^{*\pm} \to D\pi^\pm$ decays with good precision due to their large sample size. The parameters c_i and s_i are the amplitude-weighted average of the cosine and sine of the strong-phase difference between D^0 and $\bar{D}^0$ over the $i^{\rm th}$ bin; these parameters need to be determined at a charm factory experiment like CLEO-c or BESIII, where the quantum-entangled

$D^0\bar{D}^0$ pairs are produced via $e^+e^- \to \psi(3770) \to D^0\bar{D}^0$. This method allows ϕ_3 to be determined from a single decay channel in a model-independent method.

3. Belle II experiment

The Belle II [9] detector is located at the interaction point of SuperKEKB [10] asymmetric-energy e^+e^- collider in Tsukuba, Japan. Belle II is expected to accumulate a dataset corresponding to an integrated luminosity of 50 ab^{-1}, a factor of 50 larger than its predecessor Belle. The accelerator has been upgraded to ultimately provide a peak instantaneous luminosity 40 times more than KEKB. The Belle II detector design has also incorporated significant improvements compared to Belle. The reconstruction efficiency of K^0_S mesons is expected to improve with the larger coverage of the vertex detector. The new particle identification system is capable of providing better separation between kaons and pions. The phase I of Belle II happened in 2016, when accelerator commissioning took place. In 2018, the Belle II detector, without the full vertex subsystem, was integrated at the interaction point of SuperKEKB. The collisions were recorded between April 25 and July 17, 2018 and this period is known as phase II of Belle II. A total of 472 pb^{-1} of data were collected during phase II.

4. Results from phase II data

The data from the phase II run is helpful in assessing the performances of the accelerator and detector. A number of D^* and B decay modes have been rediscovered. These include various D final states: $K^0_\mathrm{S}\pi^0$, which is a CP-odd eigenstate, K^+K^-, which is a CP-even as well as a singly Cabibbo-suppressed mode, and multibody self-conjugate states $K^0_\mathrm{S}\pi^+\pi^-$ and $K^0_\mathrm{S}\pi^+\pi^-\pi^0$. The observable ΔM, the difference between M_{D^*} and M_D, and M_D distributions of $K^0_\mathrm{S}\pi^0$ and $K^0_\mathrm{S}\pi^+\pi^-$ candidates are shown in Figs. 1 and 2, respectively. The resolution is comparable to the expected values from Belle II Monte Carlo simulations. These analyses indicate the capability of Belle II to reconstruct a variety of final-state particles, including the neutral ones.

The B mesons are analyzed by defining two kinematic variables the energy difference ΔE and the beam-constrained mass M_bc as $\Delta E = E_B - E_\mathrm{beam}$ and $M_\mathrm{bc} = c^{-2}\sqrt{E^2_\mathrm{beam} - |\vec{\boldsymbol{p}}_B|^2c^2}$, where E_B ($\vec{\boldsymbol{p}}_B$) is the energy (momentum) of the B candidate and E_beam is the beam energy in the centre-of-mass frame. There are around 245 B candidates observed in the phase II data from different final states and their ΔE and M_bc distributions are shown in Fig. 3.

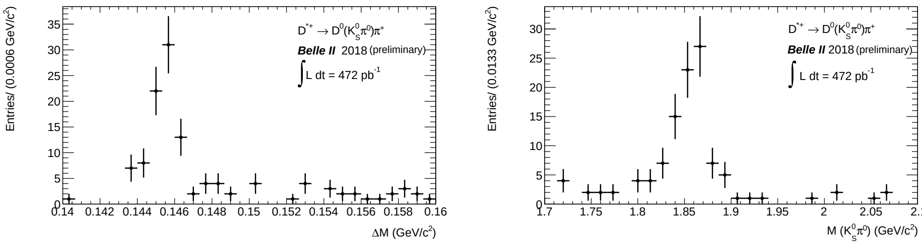

Fig. 1. Distributions of the difference in the invariant masses of D^* and D mesons denoted as ΔM (left) and the invariant mass of D meson denoted as M_D (right) for $D^{*\pm} \to D(K^0_S\pi^0)\pi^{\pm}_{\rm slow}$ decays.

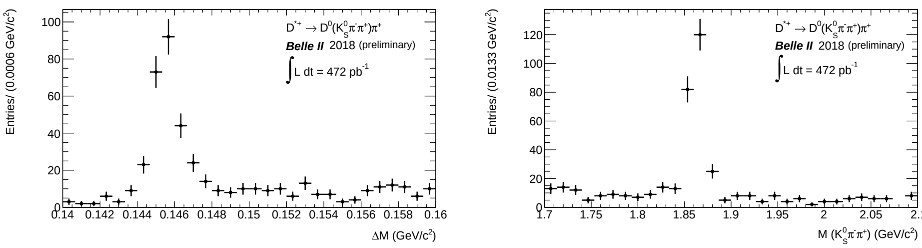

Fig. 2. Distributions of the difference in the invariant masses of D^* and D mesons denoted as ΔM (left) and the invariant mass of D meson denoted as M_D (right) for $D^{*\pm} \to D(K^0_S\pi^+\pi^-)\pi^{\pm}_{\rm slow}$ decays.

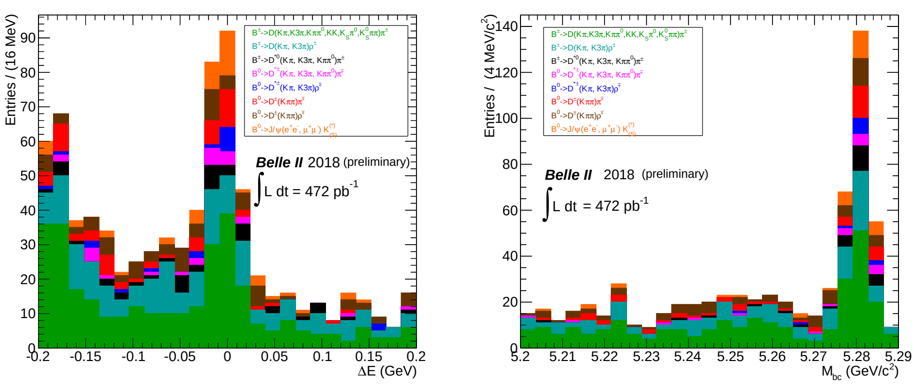

Fig. 3. Distributions of energy difference ΔE (left) and beam-constrained mass $M_{\rm bc}$ (right) for various B decay modes with phase II Belle II data.

5. ϕ_3-sensitivity at Belle II

The decay $B^\pm \to D(K_S^0\pi^+\pi^-)K^\pm$ is considered the golden mode to measure ϕ_3 at Belle II. The model-independent GGSZ method has been successful in determining ϕ_3 precisely from this decay mode. Belle II simulations show that the uncertainty of this ϕ_3 measurement can be brought down up to 3°, provided the D strong-phase difference parameters c_i and s_i are measured from the 10 fb^{-1} of data from BESIII [11]. The sensitivity of $B^\pm \to D(K_S^0\pi^+\pi^-\pi^0)K^\pm$ has been estimated by assuming that the product of reconstruction efficiency and branching fraction is similar to that of $B^\pm \to D(K_S^0\pi^+\pi^-)K^\pm$. This decay mode is expected to provide a sensitivity of 4.4° on ϕ_3 [12]. The GLW mode $B \to D^{(*)}K$ also has significant impact on the projected uncertainty. The expected ϕ_3-sensitivity at Belle II as a function of data-taking time is shown in Fig. 4.

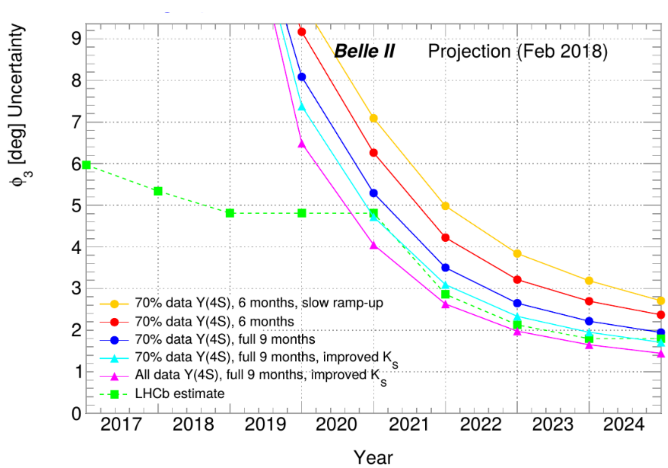

Fig. 4. Projected sensitivity of ϕ_3 at Belle II [11].

6. Summary

The precise measurement of ϕ_3 is important to make precision tests of the Standard Model description of CP violation. It is important to add more D final states to reduce the statistical uncertainty on the measurement of ϕ_3. A combined sensitivity of 1.6° is expected with the full 50 ab^{-1} of data from Belle II [11]. The D decay inputs from BESIII become imperative for achieving this precision. The rediscoveries in the first data from Belle II show good prospects for the decay modes involved in CKM measurements.

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