***CP* Violation Sensitivity at the Belle II Experiment**

Tao Luo* (on behalf of the Belle II Collaboration)

*Key Laboratory of Nuclear Physics
and Ion-beam Application (MOE) and Institute of Modern Physics,
Fudan University, Shanghai, China 200443
luot@fudan.edu.cn*

Published 3 May 2018

The sensitivity on the measurements of the angles of the CKM unitarity triangle, i.e. ϕ_1 , ϕ_2 and ϕ_3 , for Belle II experiment is presented in this letter, the CKM mechanism is expected to be tested at 1% level on Belle II.

Keywords: *CP* Violation; the angles of the CKM unitarity triangle; the Belle II experiment.

1. Introduction

The weak interactions of quarks are described by the Cabibbo-Kobayashi-Maskawa (CKM) ^{1,2} matrix, which needs to meet the unitary condition, so it has four degrees of freedom. If we select proper variables, the CKM matrix can be expressed by three rotation angles and one phase (A, λ, ρ, η). The unitary condition of CKM matrix can be converted to six free triangles in the complex plane, and one of the triangles is related to the B meson decays, which is shown in Fig. 1. In this triangle, the side lengths are related to the amount of branching fractions for the corresponding decays, and also the possible $b\bar{b}$ mixing, while the widths of the three angles are related to the amount of the *CP* Violation (*CPV*) of difference decay processes. These angles are just what we are interested in for the following parts of this letter. Due to history reasons, these three angles have two sets of names, α , β , γ , and ϕ_1 , ϕ_2 , ϕ_3 . They are corresponding to each other like what are shown in Fig. 1. ϕ_1 , ϕ_2 , ϕ_3 are used in this letter.

The values of ϕ_1 ^{3,4,5,6} can be extracted from $b \rightarrow c\bar{c}s$ and $q\bar{q}s$ decay channels, such as: $B^0 \rightarrow J/\psi K_s^0$, $B^0 \rightarrow \phi K_s^0$, and $B^0 \rightarrow \eta' K_s^0$; the effective ϕ_2 can be

*Supported by Fudan University Grant No. JIH5913023, No. IDH5913011/003.

This is an Open Access article published by World Scientific Publishing Company. It is distributed under the terms of the Creative Commons Attribution 4.0 (CC-BY) License. Further distribution of this work is permitted, provided the original work is properly cited.

Fig. 1. The B^0 Unitarity Triangle (UT).

extracted from $B \rightarrow u\bar{u}d$ processes, such as $B \rightarrow \pi\pi$, $\rho\rho$ and $\rho\pi$; the values of ϕ_3 can be extracted from $B \rightarrow c\bar{u}s$ processes, such as the golden mode $B^\pm \rightarrow DK^\pm$. The expected sensitivity of the measurement of these angles from some of these decay modes on Belle II will be introduced one by one in the following parts of this letter.

2. Time dependent measurements

One of the most important tasks on Belle II is to measure the time dependent CP violation of B meson decay, from this measurement, we can extract ϕ_1 . This section just displays how to extract ϕ_1 from B^0 decay. With asymmetric energies, e^+ and e^- collide inside Belle II detector at $\Upsilon(4S)$ energy region, which is shown in Fig. 2. One B meson decays to J/ψ and K_S , which is taken as the signal CP side; the

Fig. 2. Asymmetric B-factories at $\Upsilon(4S)$.

other B meson decays to other final states, which is taken as the flavor-tag side; the distance between this two B meson decay vertices in the boost direction (Δl) can be determined by the detector, and then converted into time difference through the equation:

$$\Delta t \equiv t_{sig} - t_{tag} = \Delta l / \beta \gamma c. \quad (1)$$

The difference of the time-dependent decay rates for the initial B meson, which decays to a CP eigenstate $J/\psi K_S$, can be described by Eq.(2); this CP asymmetry parameter is related to S and C , which represent the indirect and direct CPV . By

fitting to the B meson time dependent CP asymmetry ($\alpha_{f_{CP}}(\Delta t)$) distribution, we can extract S and ϕ_1 from the data.

$$\alpha_{f_{CP}}(\Delta t) \equiv \frac{\Gamma_{\bar{B} \rightarrow f_{CP}}(\Delta t) - \Gamma_{B \rightarrow f_{CP}}(\Delta t)}{\Gamma_{\bar{B} \rightarrow f_{CP}}(\Delta t) + \Gamma_{B \rightarrow f_{CP}}(\Delta t)} = S \sin(\Delta M \Delta t) - C \cos(\Delta M \Delta t), \quad (2)$$

where

$$S = -\xi_f \sin 2\phi_1, C \approx 0. \quad (3)$$

3. Belle II Detector on SuperKEKB

KEKB has been upgraded to SuperKEKB, accordingly, the Belle detector has been upgraded to Belle II ⁷. Two of the most important upgrades for the accelerator are: the beam size has been reduced to $\frac{1}{20}$ of that used for KEKB, and reaches nano meter level; the beam currents have been doubled. So totally the peaking luminosity of SuperKEKB will achieve 40 time of that for KEKB, reaching up to $8 \times 10^{35} \text{ cm}^2\text{s}^{-1}$. The Belle II experiment expects to accumulate 50 ab^{-1} data ¹² by 2024. There are many upgrades needed for the Belle II detector in order to increase the performance and cope with much more severe background conditions. The main improvement on Belle II is in two aspects: 1. new tracking detector: Central Drift Chamber and new vertex determination detector; 2. two new charged particle identification detectors ⁷.

3.1. Vertex fit performance

Kinematic vertex fits are usually used to identify particle decay vertex. We use benchmark for testing the Belle II vertexing performance, while the decay vertex of J/ψ coming from the $B^0 \rightarrow J/\psi K^0$ decay mode. The top left plot in Fig. 3 shows the fit residuals of the z component of the J/ψ vertex fit. A resolution of $22 \mu\text{m}$ is obtained from this fit.

The same vertex fit performed using Belle Monte Carlo returns a resolution of $43 \mu\text{m}$, which is two times of the one expected by Belle II, and is compatible with the expected improvement in the impact resolution due to the Belle II Pixel Vertex Detector.

From Eq. 1, the most important contribution to the Δt resolution comes from the tagging B vertex fit. For the tag side vertex fit of correctly reconstructed B mesons, a resolution of $52 \mu\text{m}$ ¹² is obtained, which is independent of the signal B decay mode. The top right plot in Fig. 3 shows the residuals of the B-tag vertex fit of fully reconstructed $B^0 \rightarrow [J/\psi \rightarrow \mu^+ \mu^-][K_s^0 \rightarrow \pi^+ \pi^-]$.

In order to improve resolution of the tag side vertex fit, RAVE adaptive vertex fit algorithm has been adapted. We required that all of the tracks inputted to the vertex fit needs to have one hit on the PXD, and they are not from the signal side B , also and not from K_s . We constrain the fit to a region defined by an ellipsoid around the boost direction (bottom right plot in Fig. 3), where the B has an higher

Fig. 3. Vertex fit performance of the Belle II detector.

probability to decay than a possible D meson. This method helps a lot in the vertex fit.

The sensitivity to the time-dependent CP violating parameters of equation 2 strongly depends on the detector resolution of the Δt distribution, which is relying on the resolution of the distance of the decay vertices of the two exclusively produced B mesons (see Eq. 1). Thanks to the Belle II Pixel Vertex Detector and the new vertexing algorithms, Belle II provides an improvement, compared to Belle of the vertex resolution of both B mesons. The distance measurement (Δl) translates to Δt with a resolution of 0.77 ps¹², which provides a better separation capability compared to Belle. The bottom left plot in Fig. 3 shows the Δt residuals of fully reconstructed $B^0 \rightarrow [J/\psi \rightarrow \mu^+\mu^-][K_s^0 \rightarrow \pi^+\pi^-]$ from the Belle II simulation study.

3.2. The flavor tagging efficiency and the PID performance

Another two key aspects of the detector performance for the CPV measurement are the flavor tagging efficiency and the PID performance. Multivariate combiner is used to improve the global performance of the flavor tagger. The FBDT combiner achieves a total effective efficiency of 35.8%, the effective efficiency here reflects the fraction of real tagged events over the total events. A maximization of the effective

Fig. 4. Charged particle identification selection efficiency for various pairs of particle types as a function of momentum in release-00-07-00¹². The black markers show the selection efficiency as determined from an inclusive MC sample without beam backgrounds, while the red markers show the fake rate. Only tracks that fall within the acceptance of at least one of the PID detectors or the CDC are considered.

efficiency results in a minimization of the statistical uncertainty for the final physical results.

Because of the new charged PID detectors, the Belle II is very powerful in the charged particle separations, especially in the low momentum region. The selection efficiency for various pairs of particle types are given in Fig.4¹².

4. ϕ_1 determination from $b \rightarrow c\bar{c}s$ decay channels

As mentioned in previous section, $B^0 \rightarrow J/\psi K^0$ is the golden mode for extracting ϕ_1 for two reasons^{3,4}: 1. The expected theoretical uncertainty is small; 2. The experimental signature is clean. This process happens mainly through the tree diagram process, but there is also penguin pollution. One good thing is that the theoretical estimates on penguin pollution have been significantly improved. Table 1 shows the

Table 1. Current status of ϕ_1 determination from Belle ⁸.

PRL108 171802	-	Value	stat. (10^{-3})	syst. (10^{-3})
$J/\psi K^0$	S	+0.67	29	13
	$\mathcal{A} \equiv -C$	-0.015	21	+45 -23
$c\bar{c}s$	S	+0.667	23	12
	$\mathcal{A} \equiv -C$	-0.006	16	12

Table 2. Belle2 expected uncertainties on ϕ_1 determination @ 50 ab^{-1} . Case1: irreducible syst. same as Belle; Case2: irreducible syst. (vertexing)reduced by a factor 2 due to the new Pixel Vertex detector and improved tracking and alignment algorithms ¹²

Expected errors (10^{-3})	-	stat.	syst. reducible	syst.(case 1)	syst.(case 2)
$J/\psi K^0$	S	3.5	1.2	8.2	4.4
	$\mathcal{A} \equiv -C$	2.5	0.7	+43 -22	+42 -11
$c\bar{c}s$	S	2.7	2.6	7.0	3.6
	$\mathcal{A} \equiv -C$	1.9	1.4	10.6	8.7

current status of this angle determination from Belle. For S measurement, it is statistical uncertainty dominated. Table 2 shows the expected uncertainties on Belle II at 50 ab^{-1} data, which will give results with precision better than 1% comparing to the current 5%. The results will become systematic uncertainty dominated in the SuperKEKB era.

Fig. 5 shows the time dependent CP asymmetry distributions that can be measured at Belle II in the $B^0 \rightarrow J/\psi K_s^0$ and $\eta' K_s^0$ channels with an integrated luminosity of 50 ab^{-1} . As inputs to the simulations, we set $S_{J/\psi K_s^0} = 0.70$ and $S_{\eta' K_s^0} = 0.55$

Fig. 5. Time dependent CP asymmetries for the final states $J/\psi K_s^0$ (red dots) and $\eta' K_s^0$ (blue triangles), using $S_{J/\psi K_s^0} = 0.70$ and $S_{\eta' K_s^0} = 0.55$ as inputs to the Monte Carlo. With the full integrated luminosity of 50 ab^{-1} ; the two values would be unambiguously distinguishable, signifying the existence of New Physics.

(see Eq. 3). Such a difference between $S_{J/\psi K_s^0}$ and $S_{\eta' K_s^0}$ would be an unambiguous sign of New Physics and would be easily detectable by the Belle II experiment.

5. ϕ_2 determination on Belle II

The values of ϕ_2 angle are determined mainly through $b \rightarrow u\bar{u}d$ processes, such as $B \rightarrow \pi\pi$, $\rho\rho$, and $\rho\pi$. Because of the existence of non-negligible strong phase, we can not extract ϕ_2 directly but determine the effective ϕ_2 like Eq. 4. C is no longer equal to 0, which means that there will be direct CP violation.

$$S = \sin(2\phi_2^{\text{eff}}), \phi_2^{\text{eff}} = \phi_2 + \Delta\phi_2; C \neq 0 \quad (4)$$

As an example, Table. 3 shows the expected sensitivity of ϕ_2 determination from $B \rightarrow \pi\pi$ channels at 50 ab^{-1} Belle II data from the isospin analysis of MC simulation. Belle II will make big contributions on the research of these channels, especially on the branch fraction measurements.

Table 3. Branching fractions and CP asymmetry parameters entering in the isospin analysis of the $B \rightarrow \pi\pi$ system: Belle measurements at 0.8 ab^{-1} together with the expected Belle II sensitivity at 50 ab^{-1} .¹²

	Value	0.8 ab^{-1}	50 ab^{-1}
$\mathcal{B}_{\pi^+\pi^-} [10^{-6}]$	5.04	$\pm 0.21 \pm 0.18^{10}$	$\pm 0.03 \pm 0.08$
$\mathcal{B}_{\pi^+\pi'^-} [10^{-6}]$	1.31	$\pm 0.19 \pm 0.18^9$	$\pm 0.04 \pm 0.04$
$\mathcal{B}_{\pi^+\pi'^0} [10^{-6}]$	5.86	$\pm 0.26 \pm 0.38^{10}$	$\pm 0.03 \pm 0.09$
$C_{\pi^+\pi^-}$	-0.33	$\pm 0.06 \pm 0.03^{11}$	$\pm 0.01 \pm 0.03$
$S_{\pi^+\pi^-}$	-0.64	$\pm 0.08 \pm 0.03^{11}$	$\pm 0.01 \pm 0.01$
$C_{\pi^0\pi^0}$	-0.14	$\pm 0.36 \pm 0.12^9$	$\pm 0.03 \pm 0.01$
$S_{\pi^0\pi^0}$	-	-	$\pm 0.29 \pm 0.03$

6. Summary

Belle has been a successful B factory, especially for the research on CPV . Major upgrades of KEKB and Belle have been made to build SuperKEKB and Belle II. CKM mechanism will be tested at 1% level¹² on Belle II. Some flavor variables are still to be measured precisely, therefore a lot of room for discoveries at Belle II are expected!

References

1. N. Cabibbo, Phys. Rev. Lett. **10**, 531 (1963).
2. M. Kobayashi and T. Maskawa, Prog. Th. Phys. **49** 652 (1973).
3. K. Abe et al. (Belle Collaboration) Phys. Rev. Lett. **87**, 091802 (2001).
4. B. Aubert et al. (BABAR Collaboration) Phys. Rev. Lett. **87**, 241801 (2001).
5. K. Abe et al. (Belle Collaboration) Phys. Rev. D **66**, 071102 (2002).
6. B. Aubert et al. (BABAR Collaboration) Phys. Rev. Lett. **89**, 201802 (2002).
7. T. Abe, Belle II Collaboration (2010), arXiv:1011.0352.

8. C. Patrignani et al. (Particle Data Group), *Chin. Phys. C*, **40**, 100001 (2016) and 2017 update (2017).
9. arXiv:1705.02083.
10. Y.-T. Duh et al. (Belle Collaboration) *Phys. Rev. D* **87**, 031103 (2013).
11. J. Dalseno et al. (Belle Collaboration) *Phys. Rev. D* **88**, 092003 (2013).
12. The Belle II collaboration and B2TiP theory community, *The Belle II Physics Book*, to be published.