Determination of the CP violation parameters at Belle II

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Determination of the CP violation parameters at Belle II

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Abstract. This paper briefly describes some prospects for new physics searches related to CP violation studies in $B$ decays with the Belle II experiment. With a design luminosity of $8 \cdot 10^{35}$ cm$^{-2}$ s$^{-1}$, and an integrated luminosity above 50 ab$^{-1}$, the new B-factory SuperKEKB will exceed the record instantaneous luminosity of its predecessor KEKB by a factor of 40. The new Belle II detector with most subsystems upgraded will allow to measure the parameters of CP violation even more precisely in spite of increased backgrounds and radiation loads. The CKM mechanism is expected to be tested at 1% level at Belle II.

1. Introduction

Up to now the Standard Model (SM) of the particle physics remains one of the best experimentally verified theories. For almost 50 years since its establishment the SM has managed to overcome all experimental tests and has precisely described all processes in a wide energy range up to the scale probed at the LHC energy frontier experiments. Moreover, the SM predicted the existence of new processes not only in particle physics but also in cosmology and astrophysics. The observation by ATLAS and CMS of the Higgs boson [1], the last SM fundamental particle, that escaped the detection for decades, marked a triumph of that theory. Furthermore, the properties of Higgs boson measured so far by LHC are consistent with the SM expectations.

However, the SM remains an incomplete theory with a number of inner contradictions and unresolved problems. The quark sector of the SM is especially rich in the SM puzzles and the largest contributor in terms of the number of free parameters. This sector can potentially reveal New Physics (NP) effects, as it can feel them in the loops. The measurement of the quark mixing parameters provides a major test of this sector of the SM, in particular of the Cabibbo-Kobayashi-Maskawa (CKM) description of flavor-changing currents [2] and CP violation. On the other side, although CKM mixing does provide a sole source for CP violation – one of the Sakharov’s conditions for the evolution of a matter-dominated universe [3], its magnitude is not sufficient for baryogenesis [4]. This implies that some hidden mechanism resulting in larger CP violation exists at a higher energy scale. Flavor physics is a promising tool for NP searches through quantum-loop effects: rare decays, neutral meson-antimeson mixing and CP violation are potentially subject to NP virtual corrections even if the NP scale is above those accessible at the present energy-frontier experiments.
2. Measurement of the angles of Unitarity Triangle

The CKM matrix unitary conditions can be illustrated by six triangles in the complex plane; one of them, related to the $B$ decays, has side lengths of the same order of magnitude (while the four other triangles are almost degenerate). In this Unitarity Triangle (UT) the angles are related to the amount of the CP violation in different $B$ decay processes. The measurement of the UT angles provides an important test of consistency of the UT geometry and thus of the CKM mechanism on the whole.

The time-dependent rate of CP asymmetry is given by

$$A_{CP} = \frac{\Gamma(B \to f_{CP}) - \Gamma(\bar{B} \to \bar{f}_{CP})}{\Gamma(B \to f_{CP}) + \Gamma(\bar{B} \to \bar{f}_{CP})} = S \times \sin(\Delta m_d \Delta t) - C \times \cos(\Delta m_d \Delta t),$$

where $\Delta t$ is the interval between the time at which the flavor of the $B$ meson is known and the time when it decays into the CP eigenstate, $C$ is a coefficient that measure the amount of direct CP violation and $S$ is a parameter of indirect CP violation, directly related to a particular combination of UT angles for a given final state. If there is only one amplitude contributing to the decay, the $C$-term vanishes.

The asymmetric energy $e^+e^-$ B-factories are the ideal environment to perform measurements of CP violation parameters. Indeed, the quantum correlation of the $B^0\bar{B}^0$ pairs produced in the decay of the $\Upsilon(4S)$ resonance allows to determine $\Delta t$ as the time between the decays of two $B$ mesons in the event: the first decaying into a flavor-specific decay and providing the flavor tag for the second, accompanying $B$ meson, that decays into the CP eigenstate. The asymmetric initial kinematics in the laboratory frame makes possible to measure with the present vertex detectors the spatial separation $\Delta z$ between the two $B$ mesons decay vertices, from which $\Delta t$ is computed through the known boost factor.

2.1. UT angle $\phi_1$

The UT angle $\phi_1$ has been already measured with high precision (better than $1^\circ$) in the $b \to c\bar{c}s$ transitions by Belle and BaBar [5]. While the precision of the $S$ parameter is still dominated by the statistical uncertainty, determination of the $C$ parameter in $B^0 \to J/\psi K^0$ is already limited by systematics. At Belle II $\phi_1$ will be measured with the unprecedented statistical accuracy of $0.3^\circ$ [6]. The systematic errors are expected to be also improved at Belle II; the most critical systematic uncertainty due to vertexing performances is assumed to improve due to the better vertexing algorithms, that allows to better exclude tracks from charm decays smearing the vertex position.

2.2. UT angle $\phi_2$

The measurement of $\phi_2$ is complicated by the necessity to control the penguin contribution in $B$ decays via $b \to u\bar{d}t$ transitions. In spite of the significant penguin pollution, $\phi_2$ measurement in these modes is possible by exploiting isospin relations [7]. Up to now the isospin analysis in $B \to \pi\pi$ is based on the measured six branching fractions and CP asymmetry in $B^0 \to \pi^+\pi^-$ but without a value of indirect CP violation in $B^0 \to \pi^0\pi^0$. Ignorance of the latter parameter results to an eight-fold ambiguity on the $\phi_2$ value (Figure 1). Belle II will provide an important breakthrough exploiting converted photons from $\pi^0$ and $\pi^0$ Dalitz decays to reconstruct the $B^0$ decay vertex to perform the time-dependent CP violation analysis in $B^0 \to \pi^0\pi^0$. The simulation shows that about 9% of the generated events contain at least one photon that undergoes conversion within the vertex detectors (either pixel or strip) volume.

The isospin analysis will also be performed in the $B \to \rho\rho$ and $B \to \rho\pi$ decay modes. The expected improvement in the determination of $\phi_2$ using the 50 ab$^{-1}$ data set is shown in Figure 1, the expected statistical uncertainty is $\sim 0.6^\circ$. 

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2.3. UT angle $\phi_3$

The UT angle $\phi_3$ relies on the measurement of direct CP violation in $B^+ \rightarrow D^0 K^+$ decays caused by interference between the two contributing amplitudes with different CKM phases (Figure 3), if both $D^0$ and $\bar{D}^0$ mesons decay to a common final state. The method is theoretically clean due to the absence of loop contributions, however the color-suppressed amplitude (Figure 3, right) is almost an order of magnitude smaller, hence resulting in a small CP asymmetry, which makes difficult to extract $\phi_3$. There are basically three methods for this measurement: the GLW method [8] uses the $D^0$ decays in CP-even and CP-odd final states like $K^+K^-$ or $K^0\pi^0$; the ADS method [9] is based on doubly-Cabibbo suppressed decays like $D^0 \rightarrow K^+\pi^-$; the GGSZ method [10] is based on a Dalitz plot analysis of the three body decays of $D^0$ decays such as $D^0 \rightarrow K^0\pi^+\pi^-$. 

While for the moment the Dalitz method provides the highest statistical power for measuring $\phi_3$, it turns out to be subjected to the model uncertainty due to the Dalitz plot parameterization. In future, this model uncertainties will become critical. An attempt to remove this limitation of the method was performed by Belle [11]. Instead of using a parameterized function, Belle substituted the Dalitz plot distribution taken directly from the data obtained by CLEO [12] from the decays of quantum-correlated $D^0\bar{D}^0$ pairs produced in the $\psi(3770)$ decay. In contrast
to the previous method, the model-independent approach has to utilize a binned Dalitz plot. Compared to the results of the model-dependent method, the last measurement has slightly poorer statistical precision. However, the large model uncertainty for the model-dependent study (i.e. \(8.9^\circ\)) was replaced by a purely statistical uncertainty due to the limited size of the CLEO data sample (i.e. \(4.3^\circ\)), which in future can be reduced with the BESIII or Super Charm-Tau factory data. The model-independent approach therefore offers a perspective course for studies at Belle II.

A simulation study indicates a statistical uncertainty of \(3.0^\circ\) is maybe achievable with a Belle II sample of \(50\,\text{ab}^{-1}\) [6]. The anticipated precision based on the combination of all Belle results, including GLW and ADS as well, is expected to be \(1.6^\circ\).

### 2.4. UT summary

Besides the measurement of the UT angles, many further analyses will be performed at Belle II to constrain the sides of the UT. The overall consistency of the angles and sides of UT will provide a precision test of the CKM mechanism and will allow to constrain the NP parameter space.

It is worth mentioning that thanks to BaBar and Belle the allowed area for the position of the UT upper apex is squeezed by two orders of magnitudes compared to the pre-B factory era. Belle II will further reduce the region size by almost two orders of magnitudes.

### 3. CP violation in penguin-dominated modes

It is widely believed that \(B\) penguin decays can serve as one of the most sensitive probes for NP due to a possible non-SM contribution (e.g. from SUSY particles) in the loop diagram. In particular, manifestations of NP contribution in the penguin-dominated modes can be revealed as deviations of CP violation parameters from the SM expectations. In \(b \rightarrow sqq\) hadronic decays, the SM weak phase is the same as in the \(b \rightarrow c\bar{c}s\) transition. Therefore, the main task is to check whether the penguin parameter \(\sin 2\phi_{\text{eff}}\) is equal to \(\sin 2\phi_1\), and the direct CP violation is absent (\(A = 0\)). However, there are some SM corrections to these relations coming from the Cabibbo-suppressed tree diagram, final state interaction effects, etc. Theoretical calculations predict uncertainties of the order of 1\% for \(b \rightarrow s\bar{s}s\), and up to 10\% for other \(b \rightarrow sqq\) modes [6].

To illustrate how NP can manifest itself, Figure 2 shows the time-dependent CP asymmetry distributions that can be measured at Belle II in the \(B^0 \rightarrow J/\psi K^0_s\) and \(\eta K_S^0\) channels with an integrated luminosity of \(50\,\text{ab}^{-1}\). As inputs to the simulations, \(S_{J/\psi K^0_S} = 0.70\) and \(S_{\eta K_S^0} = 0.55\) (e.g. the present values) were set. Such a difference between \(S_{J/\psi K^0_S}\) and \(S_{\eta K_S^0}\) would be easily detectable by the Belle II experiment and would be an unambiguous sign of NP.

### 4. Time-dependent CP violation in radiative penguin decays

Radiative loop \(b \rightarrow s\) processes have been extensively studied as a probe of NP at Belle and BaBar. The branching fractions of the inclusive and exclusive radiative decays have been measured with high precision and gave an important constraints on NP parameters. A new and interesting study at Belle II is the measurement of indirect CP violation in \(B \rightarrow f_{CP}\gamma\) modes. Since in the SM the \(B(\bar{B})\)-meson decays predominantly into a photon with right(left)-handed helicity, no interference between \(B \rightarrow f_{CP}\gamma\) and \(B \rightarrow \bar{B} \rightarrow f_{CP}\gamma\) emerges. In the SM the time-dependent asymmetry is thus generated by QCD corrections only, which are strongly suppressed by a factor of \(\mathcal{O}(m_s/m_b)\). NP can induce a much larger contribution to the “wrong” helicity amplitudes inducing a larger time-dependent CP asymmetry. The most promising channel is \(B^0 \rightarrow K^{*0}\gamma \rightarrow K^0_S\pi^0\gamma\). For an integrated luminosity of \(50\,\text{ab}^{-1}\) the expected uncertainties on the \(S\) and \(C\) CP violation parameters for this channel are 0.031 and 0.021, respectively [6], which
are a factor of $5 - 7$ better than the present accuracy. In addition, other time-dependent CP violation analyses in radiation penguin decays will be feasible at Belle II, e.g. $B^0 \rightarrow K^0_S \pi^+ \pi^- \gamma$.

5. Summary
CP violation studies in $B$ decays pioneered by Belle and BaBar demonstrated that the CKM mechanism of quark mixing is a true model and is a dominant contribution to neutral meson mixing and CP violation. Major upgrades of KEKB and Belle have been made to build SuperKEKB and Belle II. Already at the beginning of 2019 Belle II will take data for CP violation studies with improved vertex detectors. At the SuperKEKB collider and the Belle II detector, we expect about 40 times higher luminosity and improved detection in several aspects. Thanks to the new experiment and accelerator, the CKM mechanism will be tested at 1% level. Some flavor variables are still to be measured precisely, therefore there is a lot of room for discoveries at Belle II!

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References
[1] Aad G et al. (ATLAS Collaboration) 2012 Phys. Lett. B 716 1–29; Chatrchyan S et al. (CMS Collaboration) 2012 Phys. Lett. B 716 30–61
[2] Cabibbo N 1963 Phys. Rev. Lett. 10 531–33; Kobayashi M and Maskawa T 1973 Prog. Theor. Phys. 49 652–57
[3] Sakharov A D 1967 Pisma Zh. Eksp. Teor. Fiz. 5 32–35
[4] Gavela M B, Hernandez P, Orloff J and Pene O 1994 Mod. Phys. Lett. A 9 795–810
[5] Aubert B et al. (BaBar Collaboration) 2009 Phys. Rev. D 79 072009-1–13; Adachi I et al. (Belle Collaboration) 2012 Phys. Rev. Lett. 108 171802-1–7; Adachi I et al. (BaBar and Belle Collaborations) arXiv:1804.06153
[6] Kou E et al. arXiv:1808.10567
[7] Gronau M and London D 1990 Phys. Rev. Lett. 65 3381–84
[8] Gronau M and London D 1991 Phys. Lett. B 253 483–88; Gronau M and Wyler D 1991 Phys. Lett. B 265 172–76
[9] Atwood D, Dunietz I and Soni A 1997 Phys. Rev. Lett. 78, 3257–60; 2001 Phys. Rev. D 63 036005
[10] Bondar A 2002 Proceedings of BNP Special Analysis Meeting on Dalitz Analysis; Giri A, Grossman Y, Soffer A and Zupan J 2003, Phys. Rev. D 68 054018
[11] Aihara H et al. (Belle Collaboration) 2012 Phys. Rev. D 85 112014
[12] Briere R A et al. (CLEO Collaboration) 2009 Phys. Rev. D 80 032002