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Prospects for CP violation in inclusive and exclusive B decays at Belle II

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A review of the prospects for inclusive and exclusive study of CP violation is presented, including projections for sensitivity on the measurements of the angles of the CKM unitarity triangle, i.e. ϕ_1 and ϕ_2, for Belle II experiment. The CKM mechanism is expected to be tested at 1% level on Belle II.

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1. Introduction

Weak interactions violate charge-conjugation invariance C, spatial reflection P and, at a much lower level, their product CP. This symmetry is broken in any theory containing an irreducible phase in the Lagrangian. The necessary condition for CP asymmetry to occur in any given process is interference between amplitudes with non-zero relative phase which has opposite signs for the CP-conjugated modes. In the Standard Model the only source of CP violation is the phase in the CKM matrix (Kobayashi-Maskawa mechanism) [1, 2] and the theory offers well defined constraints on CP violation in weak decays.

The great advantage of B mesons is a big variety of channels in which CP violation can be studied. The basic observables in these studies are asymmetries between partial decay rates:

$$A_{CP} = \frac{\Gamma(\bar{B} \to \bar{f}) - \Gamma(B \to f)}{\Gamma(\bar{B} \to \bar{f}) + \Gamma(B \to f)} \tag{1.1}$$

2. Time-dependant evolution

Electrons and positrons are accelerated such that the center of mass energy is equal to the mass of the $\Upsilon(4S)$ resonance. This resonance decays almost exclusively to $B\bar{B}$ pair. At the KEKB accelerator, the energies were 3.5 GeV for positrons and 8.0 GeV for electrons. At SuperKEKB, this asymmetry is somewhat smaller, with positron energy at 4.0 GeV and electron at 7.0 GeV. The beam energy asymmetry is important to obtain a boosted frame for the outgoing particles. The induced Lorentz boost is $\beta\gamma$=0.28.

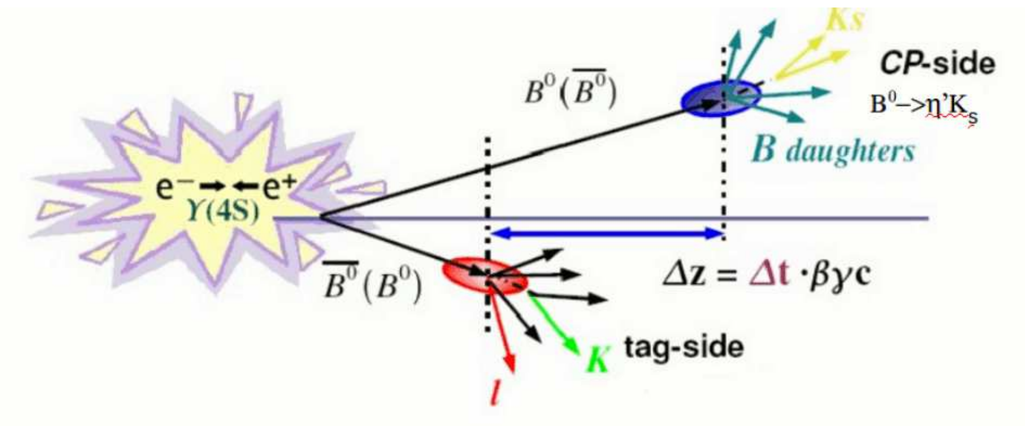

Figure 1: Diagram of the time dependant evolution in the $e^+e^- \to \Upsilon(4S) \to \bar{B}B$ process.

An illustration of a B-meson pair decaying in the laboratory frame of reference is given on fig. 1. On the left hand side of the figure, the initial e^+e^- pair collides producing a $\Upsilon(4S)$ resonance. This subsequently decays into two B mesons, one decaying into a B_{tag} final state and the other into a B_{CP} final state. Once the first B meson decays, the remaining one oscillates with the characteristic frequency before finally decaying. The spacial distance Δz between the decay vertices of the B_{tag} and B_{CP} as measured in the laboratory frame of reference is related to the proper time difference Δt between the decays of these particles in the center of mass reference frame (for Belle II $\Delta z = 130\mu m$). The time-dependant asymmetry is given by formula:

$$A_{f_{CP}}(\Delta t) \equiv \frac{\Gamma[\bar{B}(\Delta t)] - \Gamma(B[\Delta t])}{\Gamma[\bar{B}(\Delta t)] + \Gamma(B[\Delta t])} = C\cos(\Delta M \Delta t) - S\sin(\Delta M \Delta t), \tag{2.1}$$

where C is corresponding to the direct CPV and S to the mixing induced CPV.

The purpose of flavour tagging is to classify the B_{tag} either as B or $\bar{B}$. The performance of the flavour tagging algorithm determines how well the values of S and C can be extracted from data.

3. SuperKEKB

The upgrade of the KEKB to the SuperKEKB is being followed by the update of the Belle detector to the Belle II detector. Two of the most important upgrades for the accelerator are: doubling the beam current and reduction in the beam size by 1/20 at the IP of that used for KEKB. The total peaking luminosity of SuperKEKB will achieve 40 times of that for KEKB, reaching up 8×10^{35} cm^{-2}s^{-1} [3]. The main improvement on Belle II is in two areas:

- new tracking detector: Central Drift Chamber and new vertex determination detector
- two new charged particle identification detectors.

4. $\sin(2\phi_1)$ in the $b \to c\bar{c}s$ transitions

The decays to CP eigenstated via $b \to c\bar{c}s$ transition include B^0 to charmonium ($c\bar{c}$) and K_S^0 or K_L^0. These modes have experimentally clean signals and large signal yields due to relatively large branching fractions (they are CKM favored, though color suppressed). These decays are also thoretically very clean for ϕ_1 determination. The deviation due to the contribution of penguin diagrams with different CKM phase should be $\leqslant 1\%$. As a result the $B^0 \to J/\psi K_S^0$ decays is called a "Golden mode".

For the final state $J/\psi K_S^0$ the B decay is dominated by a tree $b \to c\bar{c}s$ amplitude followed by $K^0 - \bar{K}^0$ mixing. As a result C- component is expected to be almost zero and $S \sim \sin 2\phi_1$. The current precision on the world-average values for S from the $J/\psi K_S^0$ final state is dominated by the statistical uncertainty [4].

To understand the penguin amplitudes contribution one can group tree and penguin according to their CKM factors. Penguin amplitudes phase has suppressed magnitude, therefore, the effect of this amplitude on ϕ_1 is expected to be very small.

The comparison between S-parameter Belle results and Belle II predictions for 50 ab^{-1} [5] are given in table 1.

PRL 108 171802	Value	Stat (10^{-3})	Syst (10^{-3})	stat. Belle II	syst.reduc.	syst1	syst2
$J/\psi K_S^0$ (S)	+0.67	29	13	3.5	1.2	8.2	4.4
$c\bar{c}s$ (S)	+0.667	23	12	2.7	2.6	7.0	3.6

Table 1: Belle II expected sensitivity on the CP parameters for the $J/\psi K_S^0$ decay mode.

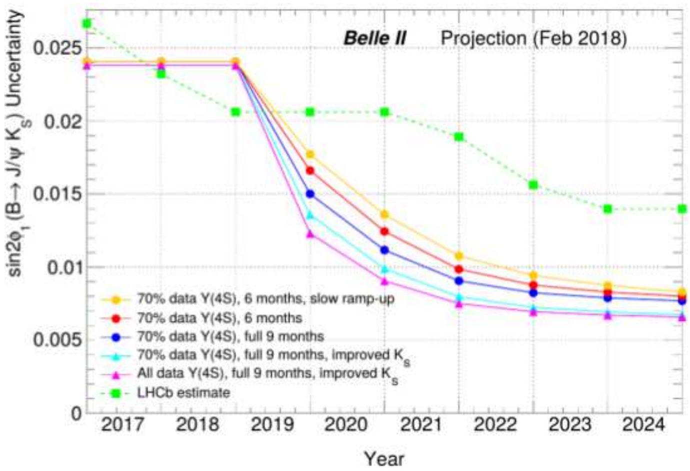

Figure 2: Sensitivity study for $\sin 2\phi_1 (B \to J/\psi K_S)$ as a function of the integrated luminosity [6].

5. ϕ_1 from the $b \to q\bar{q}s$ transitions

Two more channels of particular interest: $B^0 \to \phi K_S^0$ and $B^0 \to \eta' K_S^0$ are the cleanest among penguin loop processes with non-negligible uncertainties. They are also used for the $\sin 2\phi_1$ measurements in the Standard Model [7,8]. The dominant penguin contribution has the same phase as that in $b \to c\bar{c}s$ tree diagram, and the sub-dominant term is suppressed. Any deviation of S from the $b \to c\bar{c}s$ decay is a clear indication of the effect of New Physics.

The decays proceeding via $b \to s\bar{s}s$ penguin diagrams such as $B^0 \to \phi K^0$, $K_S^0 K_S^0 K_S^0$ and $\eta' K^0$ have a small thoretical unceirtainty on S due to the lack of a tree amplitude contribution. These decays are particularly promising for new physics searches on Belle II. Tables 2 and 3 lists the expected sensitivity estimated for an integrated luminosity of 5 ab^{-1}.

Channel	ε_{reco}	Yield	$\sigma(S_{\phi K^0})$	$\sigma(A_{\phi K^0})$
$\phi(K^+K^-)K_S^0(\pi^+\pi^-)$	35%	2280	0.078	0.055
$\phi(K^+K^-)K_S^0(\pi^0\pi^0)$	25%	765	0.132	0.096
$\phi(\pi^+\pi^-\pi^0)K_S^0(\pi^+\pi^-)$	28%	545	0.151	0.113
K_S^0 modes combination			0.060	0.044
$K_S^0 + K_L^0$ modes combination			0.048	0.035

Table 2: Sensitivity estimated for $S_{\phi K^0}$ and $A_{\phi K^0}$ parameters, the expected yield and the reconstruction efficiency for an integrated luminosity of 5 ab^{-1} in the $B^0 \to \phi K^0$ decay mode.

Channel	$\sigma(S_{\eta' K^0_S})$	$\sigma(A_{\eta' K_S})$
$\eta'(\eta(\gamma\gamma)\pi^+\pi^-)K^0_S(\pi^+\pi^-)$	0.06	0.04
$\eta'(\eta(\pi^+\pi^-\pi^0)\pi^+\pi^-)K^0_S(\pi^+\pi^-)$	0.11	0.08
K^0_S modes	0.028	0.021
$K^0_S + K^0_L$ modes	0.027	0.020

Table 3: Sensitivity estimated for $S_{\eta' K^0_S}$ and $A_{\eta' K_S}$ parameters for an integrated luminosity of 5 ab^{-1} in the $B^0 \to \eta' K^0$ decay.

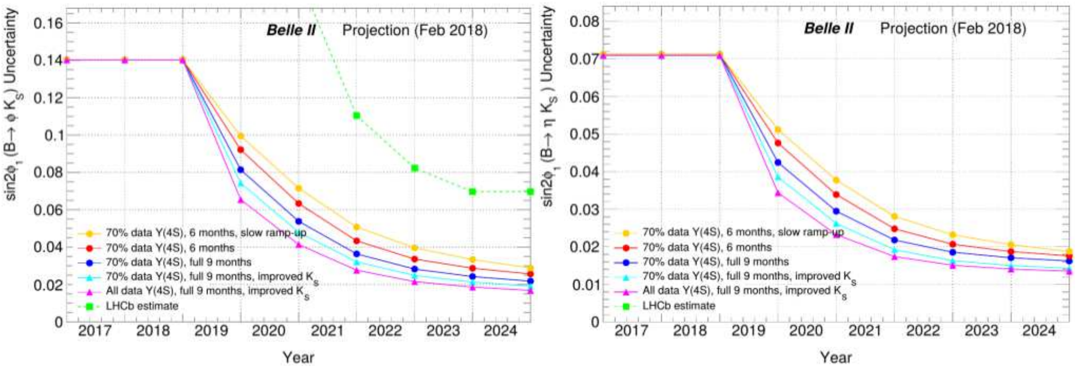

Figure 3: Sensitivity study for $\sin 2\phi_1(B \to \phi K_S)$ (left) and $\sin 2\phi_1(B \to \eta K_S)$ (right) [6].

Fig. 3 shows the expected precision of some of the $b \to s\bar{q}q$ transitions as a function of the integrated luminosity at Belle II. With a 50 ab^{-1} data sample, Belle II is expected to improve measurement precision by one order of magnitude.

6. ϕ_2 measurement in $B \to \pi\pi; \rho\rho$

The CP asymmetry in $B^0 \to \pi^+\pi^-$ depends on ϕ_2, however because of the two contributing amplitudes (tree and penguin) in the SM one expects direct CP violation to be manifest in $B^0 \to \pi^+\pi^-$ if either of the asymmetry parameters are non-zero ($C \neq 0$). The all charged modes $B \to \pi\pi; \rho\rho$ are dominated by the external tree and gluonic penguin amplitudes, while the all neutral modes $B^0 \to \pi^0\pi^0; \rho^0\rho^0$ are very sensitive to the penguin contribution since the internal tree diagram is color suppressed.

Experimentally the complete isospin analysis of the $B \to \pi\pi$ system is complicated by the need to measure time-dependant CP asymmetry of the all-neutral final state decays of B^0 meson to $\pi^0\pi^0$. It was impossible on previous flavour factories, but Belle II will be able to constrain the decay vertex of the $B^0 \to \pi^0\pi^0$ candidates using Dalitz decays of one or both π^0 mesons.

7. Inclusive B mesons decays

In contrast to the exclusive rare B decay modes, the inclusive ones are theoretically clean observables, because no specific model in needed to describe the hadronic final states. For instance the decay width $\Gamma(B \to X_s \gamma)$ is well approximated by the partonic decay rate $\Gamma(b \to X_s^{parton} \gamma)$ [9]. The direct normalized CP asymmetry fo the inclusive decay modes is given by:

$$\alpha_{CP}(B \to X_{s/d}\gamma) = \frac{\Gamma(\bar{B} \to X_{s/d}\gamma) - \Gamma(B \to X_{\bar{s}/\bar{d}}\gamma)}{\Gamma(\bar{B} \to X_{s/d}\gamma) + \Gamma(B \to X_{\bar{s}/\bar{d}}\gamma)} \tag{7.1}$$

In the SM predictions for the difference of branching ratios based on model and on a sum rule calculation of the form factors $A = 0$. Any significant deviation from the SM prediction would be a direct hint to non-CKM contributions to CP violation.

8. Conclusions

Belle II provides a large dataset together with improved detector and physics software (Flavor tagging and Vertex reconstruction). It gives the unique possibilities for modes with final states with neutral particles. CP violation can be measured in B decays exclusively and inclusively. Exclusive approach gives up to now the most stringent test of SM. In contrast, the inclusive ones are theoretically clean, usually zero in SM. CKM mechanism is expected to be tested at 1% level on Belle II.

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