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CP Violation sensitivity at the Belle II Experiment

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The measurement of the time-dependent CP violation parameters for B-meson decays is crucial for tightening the constraints on the unitarity triangle and for the search of new physics beyond the Standard Model. A clean environment for the study of B decay channels is provided by B-factories. With a design luminosity of $8 \cdot 10^{35}\ cm^{-2}\ s^{-1}$, leading ultimately to an integrated luminosity beyond 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 will exploit the expected high statistics data sample thanks to a major upgrade of the tracking system, including a novel pixel vertex detector in its innermost part. Additionally, the detector capabilities will be complemented by substantial improvements in the reconstruction software. A strategy for CP violation analysis is being developed in order to maximally exploit the new data set and to characterize the sensitivity of Belle II for various benchmark B decay channels.

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1. Time dependent CP violation in B meson system at the Belle II experiment

Two of the three angle of the Unitarity Triangle (UT), describing the CP violation in the Standard Model, depend on the coupling between the b and t quarks. For that reason they can be measured through processes involving $B^0 - \bar{B}^0$ oscillations. In particular they enter the expression for the time dependent rate asymmetry of neutral B mesons decaying into CP eigenstates:

$$a_{f_{CP}}(\Delta t) \equiv \frac{\Gamma[B(\Delta t)] - \Gamma[\bar{B}(\Delta t)]}{\Gamma[B(\Delta t)] + \Gamma[\bar{B}(\Delta t)]} = C\cos(\Delta m \Delta t) - S\sin(\Delta m \Delta t) \tag{1.1}$$

being Δt the interval between the time t_0 at which the flavor of the B meson is known and the time where it decays into the CP eigenstate. The C coefficient quantifies the amount of "*direct*" CP violation in the decay, while the S coefficient quantifies the so-called "*mixing induced*" CP violation, and is directly related to particular combinations ϕ_i^{eff} of the angles of the UT through $S \equiv \sin(2\phi_i^{eff})$.

The asymmetric e^+e^- B-factories are the ideal environment to perform such measurements. Indeed the entanglement of the $B^0 - \bar{B}^0$ pairs produced in the decay of the $\Upsilon(4S)$ resonance allows to define the time t_0 as the one where one of the two mesons (hereafter referred as the *tag* meson) undergoes a flavor specific decay providing the flavor tag for the companion B meson undergoing the decay into the CP invariant final state, and referred as *signal*. The asymmetric topology in the laboratory frame makes possible to measure with the currently available vertex detectors the spatial separation Δz between the tag and the signal B mesons decay vertexes, from which the time interval Δt can be computed through the boost factor $\beta\gamma$ as

$$\Delta t \simeq \frac{\Delta z}{\beta\gamma c} \quad . \tag{1.2}$$

SuperKEKB, the upgrade of the KEKB accelerator system, will deliver an instantaneous luminosity of $8 \cdot 10^{35}\ cm^{-2}\ s^{-1}$, a factor ~ 40 larger than at KEKB. This increase in the luminosity will allow to collect, at the end of the data taking period, a dataset of ~ 50 ab^{-1} integrated luminosity, thus allowing to reduce the statistical and all those systematic uncertainties that scale with luminosity. The main properties of the SuperKEKB accelerator system and the KEKB corresponding values are reported in Table 1.

	KEKB	SuperKEKB
$\mathscr{L}$ $(10^{34} s^{-1} \cdot cm^{-2})$	2.11	80
$\int \mathscr{L}$dt (ab^{-1})	0.8	50
e^+ energy (GeV)	8	7
e^- energy (GeV)	3.5	4
$\beta\gamma$	0.45	0.28
$< \Delta z >$	$\sim 200\ \mu$m	$\sim 130\ \mu$m

Table 1: SuperKEKB main features and the corresponding of its predecessor KEKB accelerator system.

The reduced boost factor $\beta\gamma$ in SuperKEKB will end up in a smaller average separation of the tag and signal B mesons decay vertexes. This, together with the increased background level from beam interactions, requires an improvement in the vertexing performances of the Belle II

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detector. This will be achieved thorough the use of DEPFET technology [2] for the construction of the PXD pixel detector, the innermost tracking system whose first layer distance with respect to the interaction point is 14 mm. The limitations on the vertexing performances are one of the most important sources of systematic uncertainty (not scaling with luminosity) on the measured values of the UT angles. The expected systematic uncertainties in the CP violation sensitivity studies [1] have been computed within two scenarios: a first one assumes (very unlikely) that no improvement at all will be achieved with the Belle II detector with respect to the performances of its predecessor; the second one, more realistic, assumes that an improvement of a factor 2 on the error on the reconstructed Δz will be attained thanks also to the improvement in the vertexing algorithms.

Last but not least relevant ingredient in the time dependent CP violation analysis is the tagging efficiencies ε_{tag}, namely the fraction of events for which it is possible to determine the flavor of the signal B meson. In Belle II ε_{tag} has been computed on simulated events being $\sim 35.8\%$, which represents a relative improvement of $\sim 20\%$ if compared to the performances achieved by Belle, for which $\varepsilon_{tag} \sim 30\%$.

2. Sensitivity on ϕ_1

The UT angle ϕ_1 is the most precisely measured nowadays ($\phi_1^{WA}|_{1\sigma} = (21.85^{+0.68}_{-0.67})^\circ$) [3]. It can be measured in processes where the decay of the B meson into the CP eigenstate originates either from a tree dominated interaction (such as $B^0 \to J/\psi K_S^0$) or through penguin dominated quark transitions (such as $B^0 \to \phi K_S^0$ or $B^0 \to \eta' K_s^0$).

The current values for the C and S parameters in $b \to c\bar{c}s$ tree dominated modes measured by the Belle Collaboration are reported in Table 2. While the precision of the S parameter is still dominated by the statistical uncertainty, the determination of the C parameter in $B^0 \to J/\psi K_S^0$ is already systematically limited. Systematic uncertainties can be classified into two categories: those which are computed on control samples and that scale with the integrated luminosity (such as the value of the wrong-tag fraction, biases in the fit, uncertainty in the determination of the signal fraction, error on τ_B, and Δm_d, and mismodeling of the Δt distribution for background); and those arising from the vertex resolution and tag-side interference [5] which do not scale with the integrated luminosity. The expected uncertainties with the full 50 ab^{-1} Belle II dataset are reported in Table 3 which shows that a precision better than 1% is expected on ϕ_1 when combining all the $b \to c\bar{c}s$ modes. The combination of the $b \to c\bar{c}s$ modes allows to reduce the systematic uncertainty on the measured values thanks to the cancellation of the tag-side interference systematic uncertainties between final states with K_S^0 and K_L^0 because of their opposite CP properties.

The determination of the ϕ_1 angle through those modes dominated by penguin $b \to q\bar{q}s$ transitions represents an interesting complementary measurement of this CKM angle, being much more sensitive to the presence of new heavy degrees of freedom that may appear as off-shell states inside the loops.

The current value of the S parameter measured by the BaBar collaboration [6] is still dominated by the statistical uncertainty. Three benchmark final states for the ϕK^0 system have been considered for the sensitivity studies: $\phi(K^+K^-)K^0(\pi^+\pi^-)$, $\phi(K^+K^-)K^0(\pi^0\pi^0)$, and $\phi(\pi^+\pi^-\pi^0)K^0(\pi^+\pi^-)$. At present the effects of the beam induced background have been neglected. In these conditions

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

Table 2: Values for the C and S parameters as measured by the Belle Collaboration in the $J/\psi K_S^0$ decay and through a combination of all the tree dominated $b \to c\bar{c}s$ modes [4].

Expected errors (10^{-3}) @ **50 ab**$^{-1}$		stat	syst reducible	Syst 1	Syst 2
$J/\psi K_S^0$	S	3.5	1.2	8.2	4.4
	$\mathscr{A} \equiv -C$	2.5	0.7	+43,-22	+42, - 11
$c\bar{c}s$	S	2.7	2.6	7.0	3.6
	$\mathscr{A} \equiv -C$	1.9	1.4	10.6	8.7

Table 3: Expected uncertainties on the measured values of S and C with the full 50 ab^{-1} Belle II dataset. Systematically uncertainties have been separated into the reducible (which scale with the integrated luminosity) and irreducible. These have been estimated in the two benchmark scenarios of no improvement (syst 1) and a factor 2 improvement in vertexing capabilities (syst 2) with respect to Belle.

the expected statistical uncertainty on the C and S parameters for these benchmark channels, and the extrapolation to the modes with K_L^0 (using the yields from Belle and BaBar experiments, and the expected Δt resolution in Belle II), is the one reported in Table 4.

Another mode that will be studied in Belle II is the $B^0 \to \eta' K^0$ decay. The current value of the S parameter measured by the Belle collaboration is $S_{\eta' K_S^0} = +0.68 \pm 0.07(syst) \pm 0.03(stat)$ [7]. For this mode the $\eta'(\eta(\gamma\gamma)\pi^+\pi^-)K_S^0(\pi^+\pi^-)$ and the $\eta'(\eta(\pi^+\pi^-\pi^0)\pi^+\pi^-)K_S^0(\pi^+\pi^-)$ benchmark channels have been considered. The crucial aspect of these modes is related with the reconstruction of final state neutral particles, such as π^0 and η^0, and will benefit of the particularly clean environment of the e^+e^- machine; nevertheless, the non negligible amount of the beam induced background will give rise to a large fraction of mis-reconstructed signal candidates that has to be properly treated in the analysis, and with strategies which depend on the particular final state under investigation [1]. For that reason the effects of the beam background have been taken into account in the simulated samples used for the sensitivity studies. The expected uncertainty on the C and S parameters for the two benchmark modes with a 5 ab^{-1} dataset, along with the extrapolation to the K_L^0 modes are reported in Table 4. Remarkably this mode will be the first one among the penguin induced $b \to s\bar{q}q$ transitions being dominated by the systematic uncertainty, already at an integrated luminosity of 10 ab^{-1} in the scenario where a factor 2 improvement on vertexing capabilities is achieved in Belle II.

3. Sensitivity on ϕ_2

The measurement of ϕ_2 features some peculiar aspects related to the control of the penguin contribution in the B decays into the CP eigenstate $(\pi^{\pm,0}, \pi^{\mp,0})$ or $(\rho^{\pm,0}, \rho^{\mp,0})$. Indeed the non

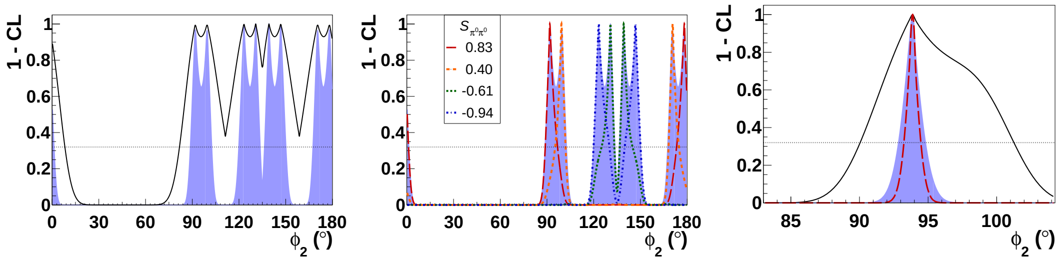
Channel $B^0 \to \phi K^0$	$\sigma(S)$	$\sigma(C)$	Channel $B^0 \to \eta' K^0$	$\sigma(S)$	$\sigma(C)$
$\phi(K^+K^-)K^0_S(\pi^+\pi^-)$	0.078	0.055	$\eta'(\eta_{\gamma\gamma}\pi^+\pi^-)K^0_S(\pi^+\pi^-)$	0.06	0.04
$\phi(K^+K^-)K^0_S(\pi^0\pi^0)$	0.132	0.096	$\eta'(\eta_{3\pi}\pi^+\pi^-)K^0_S(\pi^+\pi^-)$	0.11	0.08
$\phi(\pi^+\pi^-\pi^0)K^0_S(\pi^+\pi^-)$	0.151	0.113	K^0_S modes	0.028	0.021
K^0_S modes	0.060	0.044	$K^0_S + K^0_L$ modes	0.027	0.020
$K^0_S + K^0_L$ modes	0.048	0.035	Syst	0.021 (0.017)	

Table 4: Expected statistical uncertainty in on the S and C parameters in $B^0 \to \phi K^0$ (left) and $B^0 \to \eta' K^0$ (right) with a 5 ab^{-1} dataset. The systematic uncertainty reported for the $B^0 \to \phi K^0$ are computed in the two hypothesis of no (a factor 2) improvement in vertexing performances.

negligible contribution of the penguin processes must be controlled by exploiting isospin relations between the decay amplitudes $(\pi^{\pm,0}, \pi^{\mp,0})$ or $(\rho^{\pm,0}, \rho^{\mp,0})$ as explained in [8].

Among the input quantities for the isospin analysis in $B^0 \to \pi\pi$ the value of the S parameter in the $B^0 \to \pi^0\pi^0$ decay has not yet been measured, leaving an eight-fold ambiguity on the value of ϕ_2. One of the main focus of Belle II will be on the analysis of the $B^0 \to \pi^0\pi^0$ mode exploiting the following final states $B^0 \to \pi^0_{\gamma\gamma}(\to \gamma\gamma)\ \pi^0_{\gamma\gamma}(\to \gamma\gamma)$, $B^0 \to \pi^0_{\rm dal}(\to e^+e^-\gamma)\ \pi^0_{\gamma\gamma}(\to \gamma\gamma)$ and $B^0 \to \pi^0_{\gamma_c\gamma}(\to \gamma_c(\to e^+e^-)\gamma)\ \pi^0_{\gamma\gamma}(\to \gamma\gamma)$. In particular the last two modes, featuring a pair electron-positron originating from the same point, allow to approximately reconstruct the B decay vertex and can be used to perform the time-dependent CP violation analysis aiming to measure $S_{\pi^0\pi^0}$. The expected statistical uncertainty on the value of S has been estimated using simulated data to be ~ 0.29. In addition to the measured value of $S_{\pi^0\pi^0}$, the isospin analysis for the measurement of ϕ_2 will also benefit of reduced errors on the currently used input observables.

The isospin analysis will also be performed in the $B^0 \to \rho\rho$ decay mode and combined with the $B \to \pi\pi$ one. The expected improvement in the determination of ϕ_2 using the 50 ab^{-1} dataset is shown in Figure 1, from which can be seen that a statistical uncertainty at 1σ is $\sim 0.6^\circ$ can be reached.



(a) (b) (c)

Figure 1: Impact of the improved isospin analysis inputs in the determination of the ϕ_2 angle with an integrated luminosity of 50 ab^{-1}. (a) shows the improvement with respect to the present determination of ϕ_2 (black line) in $B \to \pi\pi$ (inputs from [9]) when using only the currently available input with a reduced uncertainty; (b) shows the benefit from including the $S_{\pi^0\pi^0}$ input: the eight-fold ambiguity reduces to a two-fold one, with values depending on the measured $S_{\pi^0\pi^0}$; (c) improvement in the $B \to \pi\pi$ and $B \to \rho\rho$ combined analysis with respect the current status (black line) (inputs from [9] and [10]) when using the current (blue shadow region) and after adding the $S_{\pi^0\pi^0}$ inputs (red dashed line) with the reduced uncertainty.

4. Conclusions

The Belle II program for the measurement of UT angles ϕ_1 and ϕ_2 will benefit of the large dataset ($\sim$ 50 ab^{-1}) collected at the end of the SuperKEKB operations, together of the improvement of the Belle II detector and the physics software performances improving crucial aspects such as Flavor tagging and vertex reconstruction. In particular the Belle II detector offers unique possibilities for the study of modes with final state with neutral particles.

$\sin(2\phi_1)$ will remain the most precise measurement on the UT parameters, reaching a precision level of $\sim 1\%$ which is of the same order of the penguin pollution and will require phenomenological efforts to control it; on the other side the measurement of $\sin(2\phi_2)$ will benefit of reduced errors and new isospin analysis inputs such as $S_{\pi^0\pi^0}$

In addition, thanks to the expected improvement in the neutral and photons reconstruction performances, other time dependent CP violation analysis will be feasible at Belle II, such as the measurement of the photon polarization in $B^0 \to K^\star(\to \pi^0 K^0_S)\gamma$ [1].

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