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CP violation in tree and loop processes at SuperB

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Simone Stracka for the SuperB Collaboration.[*]
Università degli Studi di Milano and INFN-Milano, Italy
E-mail: `simone.stracka@mi.infn.it`

As we are entering the LHC era, two *B* factories upgrade projects, SuperKEKB/Belle-II in Japan and SuperB in Italy, have been proposed to probe the theory of Cabibbo, Kobayashi and Maskawa to an unprecedented level of precision and to search for New Physics at the loop level. We present the prospect for extracting the angles of the Unitarity Triangle from *CP* violating observables in tree and loop processes at SuperB.

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[*] Speaker.

1. Introduction

The study of CP violation observables in rare B decays is a key ingredient to meet two of the primary goals of the proposed B-factories upgrades [1, 2]: assessing the validity of the Cabibbo-Kobayashi-Maskawa (CKM) picture of CP-violation [3] by precisely measuring the elements of the Unitarity Triangle (UT), and searching for hints of New Physics (NP), or otherwise constraining NP scenarios, in processes which are suppressed in the Standard Model (SM).

In loop processes, in particular, NP at some higher energy scale may manifest itself in the low energy effective theory as new couplings, such as those introduced by new very massive virtual particles in the loop. The comparison between the direct measurement of a parameter of the UT with the indirect determination of the same quantity, obtained from a global SM fit to all the other available constraints [4], might therefore reveal new physics phenomena. At the present level of precision in the determination of the UT apex [5]

$$(\bar{\rho}, \bar{\eta}) = (0.132^{+0.022}_{-0.014}, 0.341 \pm 0.013),$$

a remarkable agreement is observed between direct measurements and SM predictions. The SuperB project [1] will be able to improve the precision of measurements of the UT elements to the 1% level. This will be crucial in restricting the parameter space for physics beyond the Standard Model, guiding direct searches at high energies, or even providing evidence for New Physics. The achieved precision may also be beneficial to other NP searches with flavor, e.g., in the kaon sector.

In the following we report on the SuperB prospects for the measurement of the UT angles in CP violating tree and loop processes. The extrapolation to SuperB is based on five years operating at the $\Upsilon(4S)$, corresponding to $50-75\,\mathrm{ab}^{-1}$ integrated luminosity at a center of mass energy of $10.58\,\mathrm{GeV}$. Performances similar to those of the BaBar detector are assumed, and we furthermore foresee a realistic reduction of systematic and theoretical uncertainties.

2. Measurements of $\sin 2\beta$ in penguin-mediated decays

An important class of measurements is related to the CKM angle β. This angle is accessible experimentally through the interference between the direct decay of the B meson to a CP eigenstate and decay after $B^0\overline{B}^0$ mixing, which affects the time evolution of the decay. In the time-dependent analyses of the B decays, one of the two B mesons produced in $e^+e^- \to \Upsilon(4S)$ events is fully reconstructed according to the final state f of interest. The flavor and the decay vertex position for the other B in the event (B_{tag}) are identified from its decay products. The proper time difference between the two B mesons is:

$$f(\Delta t) = \frac{e^{-|\Delta t|/\tau}}{4\tau}\left\{1+q\left[-\eta_f S_f \sin(\Delta m_d \Delta t) - C_f \cos(\Delta m_d \Delta t)\right]\right\}, \tag{2.1}$$

where η_f is the CP eigenvalue of the final state f, $q=+1(-1)$ if the B_{tag} decays as a B^0 ($\overline{B}^0$), $\tau = (1.525 \pm 0.009)\,\mathrm{ps}$ [5] is the mean B lifetime, and $\Delta m_d = (0.507 \pm 0.005)\,\mathrm{ps}^{-1}$ is the $B^0 - \overline{B}^0$ mixing frequency [5].

At SuperB, a precision on Δt similar to the one achieved in BaBar ($\sim 0.6\,\mathrm{ps}$) is expected. The preferred choice for the beam-energy asymmetry, compatible with the machine design, results in

Mode	Current Precision			Predicted Precision ($75\,\mathrm{ab}^{-1}$)		
	Stat.	Syst.	ΔS_f (Th.)	Stat.	Syst.	ΔS_f (Th.)
$J/\psi K_S$	0.022	0.010	0 ± 0.01	0.002	0.005	0 ± 0.001
$\eta' K_S$	0.08	0.02	0.015 ± 0.015	0.006	0.005	0.015 ± 0.015
ϕK_S	0.26	0.03	0.03 ± 0.02	0.020	0.005	0.03 ± 0.02
$K_S K_S K_S$	0.19	0.03	0.02 ± 0.01	0.015	0.020	0.02 ± 0.01

Table 1: Current experimental precision of S_f, and that expected at a SuperB experiment with $75\,\mathrm{ab}^{-1}$ of data, reproduced from Ref. [11].

a lower boost $\beta\gamma = 0.28$ with respect to BaBar ($\beta\gamma = 0.56$), which is compensated by a reduced beamspot size, the addition of an innermost layer (Layer0, to reduce the SVT inner radius), and a lower material budget for the beampipe [6]. The larger tracking coverage and improved particle identification devices, as well as better vertexing performances are expected to result in improved tagging performances with respect to BaBar.

B factories have determined the angle β very accurately and with small theoretical uncertainties from the analysis of the decay rate asymmetries in $b \to c\bar{c}s$ decays. The current average, $S_{cc} \equiv -\eta_f \sin 2\beta = 0.67 \pm 0.02$ [7], is limited by systematic uncertainties, the main contribution being due to the Δt resolution model. Reduction of systematics on S could be possible thanks to the higher statistics, as it allows the use of cleaner tagging strategies (e.g., relying exclusively on leptons) and because some of the systematic uncertainties, related to the characterization of background, are statistical in origin.

A parameter $S_{qq} = -\eta_f \sin 2\beta_{\mathrm{eff}}$ (where β_{eff} denotes an effective value of β) can also be extracted from penguin (loop) dominated $b \to q\bar{q}s$ decays. These decays could receive contributions from NP effects (e.g., new quanta in the loops) that could lead to measurable differences $\Delta S \equiv S_{qq} - S_{cc}$. In some NP scenario, deviations can be $\approx O(1)$ [8].

A limiting factor to the ΔS measurements as a tool for NP searches is represented by SM contributions that may also introduce shifts in the parameter S, such as CKM suppressed $b \to q\bar{q}s$ tree amplitudes. The SM effect is predicted in most models to be a positive shift in ΔS [9]. The size of this shift is related to the ratio of tree to penguin amplitudes, which depends on the decay mode. Theoretical estimates for this ratio are affected by large uncertainties for most decay modes, with the exception of the $K_S K_S K^0$ and ϕK^0 modes (in which tree amplitudes don't contribute), and $\eta' K^0$ (in which the gluon penguin amplitude is enhanced) [10]. These measurements are statistically limited at *B*-factories. The reach of SuperB for the study of these transitions is summarized in Table 1, along with the theoretical errors due to SM neglected effects.

3. Measuring α to 1°

The measurement of the CKM angle α from the analysis of time-dependent *CP* violating asymmetries in tree-dominated $b \to u\bar{u}d$ decays ($B^0 \to \pi^+\pi^-, \rho^+\rho^-, \rho^\pm\pi^\mp, a_1^\pm\pi^\mp$) is limited at the present-day *B* factories by the determination of the penguin pollution. The effect of penguin amplitudes is to shift the value of the phase extracted from the time distribution of the *B* decays by an amount $\Delta\alpha$, which has to be determined from auxiliary measurements, under the assumption of SU(2) or SU(3) flavor symmetries.

For the $\rho\pi$ final state, a SU(2)-based analysis of the time-dependent $\pi^+\pi^-\pi^0$ Dalitz plot [12] will allow to extract α with no ambiguities in the $[0,180]^\circ$ range, with an expected precision of 2° at $75\,\mathrm{ab}^{-1}$ [1]. As a matter of comparison, the expected statistical error at LHCb for $2\,\mathrm{fb}^{-1}$ is about 10° [13]. For the $a_1\pi$ final state (not a CP-eigenstate), the penguin-induced shift $\Delta\alpha$ is estimated from the rates of $B\to K_{1A}\pi$ and $B\to a_1K$ decays, assuming the approximate SU(3) flavor symmetry [14]. The complexity of this analysis doesn't allow a straightforward extrapolation to SuperB luminosities. The analyses of B decays to $\pi^+\pi^-$ and $\rho^+\rho^-$ (which is measured to be an almost pure CP eigenstate) rely instead on an isospin analysis to constrain penguin pollution [15] and extract α with an eightfold ambiguity.

As neutral pions appear in the final states that are partner under SU(2) of $\pi^+\pi^-$ and $\rho^+\rho^-$, the analysis of these systems will be very challenging for LHCb, where the main contribution is expected to be represented by the improvement of the measurement of the $B^0\to\rho^0\rho^0$ decay mode, that will allow a reduction of the degeneracy between the mirror solutions in the $B\to\rho\rho$ analysis. Similarly, a time-dependent study of the $B^0\to\pi^0\pi^0$ decays could be used to relieve the degeneracies in the extraction of α from the $B\to\pi\pi$ analysis. While not accessible at current B factories, at SuperB this measurement could be performed by reconstructing the B decay vertex from converted photons [16].

The study of the $\rho\rho$ system currently provides the most sensitive determination of α, with a precision of $\sim 6^\circ$ [17]. At SuperB, where all channels entering the isospin analysis are accessible, an error of about 0.75° is within the experimental reach. At this level of precision, the analysis becomes sensitive to theoretical limitations of the analysis (at the $O(1^\circ)$ level) such as SU(2)-breaking effects (e.g., $u-d$ quark mass difference, $\pi^0-\eta-\eta'$ mixing), neglected $\Delta I=5/2$ transitions that can break the isospin triangle relations, electroweak penguin contributions to $B^\pm\to\rho^\pm\rho^0$, and the possible breakdown of Bose statistics resulting from the finite widths of the ρ mesons. The extraction of α is therefore expected to be ultimately limited by the size of theoretical uncertainties, estimated around $1-2^\circ$ [1, 11].

4. Time integrated γ measurements

The presence of New Physics might affect the result of the UT analysis, by changing the functional dependencies of the experimental quantities upon $\bar{\rho}$ and $\bar{\eta}$. However, there exist two constraints now available, that are almost unchanged by the presence of NP: $|V_{ub}/V_{cb}|$ as determined from semileptonic B decays, and the UT angle γ measured from the time integrated analysis of B meson decays to final states containing charm mesons.

The most popular approaches to extract γ at B factories rely on the interference of two paths, proceeding through the color favored $b\to c$ transition $B^-\to D^{(*)0}K^{(*)-}$ and the color and CKM suppressed $b\to u$ transition $B^-\to\overline{D}^{(*)0}K^{(*)-}$, which occurs when the $D^{(*)0}$ and $\overline{D}^{(*)0}$ mesons in the event decay to the same final state f_D. The amount of interference, and hence the sensitivity to γ, depend on the magnitude $r_B^{(*)}$ of the $b\to u$ amplitude relative to the $b\to c$ amplitude. Hadronic effects in the amplitude are parameterized as a strong phase δ_B between the B decay amplitudes. Several methods have been devised to put constraints on the cartesian coordinates defined as $x_\pm \equiv r_B \cos(\delta_B \pm \gamma)$ and $y_\pm \equiv r_B \sin(\delta_B \pm \gamma)$, each method being characterized by the choice of a particular class of final states f_D for the D meson decay.

The GLW [18] and ADS [19] methods are based on the analysis of the Cabibbo suppressed D decays to CP eigenstates, either CP-odd ($K_S\pi^0$, $K_S\phi$) or CP-even (K^+K^-, $\pi^+\pi^-$), and of doubly Cabibbo suppressed D decays to flavor eigenstates (e.g., $K^+\pi^-$), respectively. For each decay channel, two experimental observables are extracted, associated to the branching fraction and B^+/B^- asymmetry for the Cabibbo suppressed decay. Several methods and several channels must therefore be combined in order to constrain the system of unknowns, which consists of a minimum of three unknowns (γ, r_B, δ_B). In this respect, SuperB offers better prospects than hadron colliders, as more final states, and in particular those involving D^{*0} [20], are available and result in a better control over model uncertainties.

Another approach is represented by the GGSZ method [21], where γ is extracted from the interference pattern over D-Dalitz plots from charged B decays, where the D meson is reconstructed in the $K_S\pi^+\pi^-$ and $K_SK^+K^-$ channels. This method allows to extract γ with a two-fold ambiguity in the range $[-180, 180]^\circ$, yielding $\gamma = (68^{+15}_{-14} \pm 4 \pm 3)^\circ$ [22] and $\gamma = (78^{+11}_{-12} \pm 4 \pm 9)^\circ$ [23] at BaBar and Belle, respectively, where the first error is statistical, the second is the experimental systematic uncertainty and the third reflects the uncertainty in the description of the neutral D decay amplitudes.

The γ precision is mainly dominated by Dalitz analyses, and the error associated to the D-Dalitz model is the limiting factor at very high statistics. A way to circumvent this limitation is to derive the decay amplitude description, and in particular the missing information about the strong phase in D^0 decays, from quantum-correlated $D\overline{D}$ decays at the $\psi(3770)$ resonance [24], such as those currently available at the CLEO-c experiment with $818\,\mathrm{pb}^{-1}$ [25]. Input from CLEO would reduce the model uncertainty to about 1.7° [26].

At LHCb with $10\,\mathrm{fb}^{-1}$, the expected combined sensitivity to γ from time-integrated analyses, for $\delta_B = 135^\circ$, is 3.2° (4.8°) with (without) CLEO-c constraints on the D decay amplitudes [26]. For a similar choice of the parameters ($r_B \approx 0.1$, $\gamma \approx 70^\circ$, $\delta_B = 110^\circ$) the SuperB can eventually reach sub-degree precision with the combination of the analyses of charged B modes ($D^{(*)0}K^*$), a combination of methods (GGSZ, GLW, ADS) and the use of correlated charm data resulting from about three months ($\sim 500\,\mathrm{fb}^{-1}$) of data-taking at the $\psi(3770)$ resonance [11, 27]. The expected sensitivity for the GGSZ method is 0.79° (2.8°) with (without) the input coming from the $\psi(3770)$ running, while the sensitivity from the combination of the different methods is 0.72° (1.7°).

5. Conclusions

At SuperB, a rich program will be devoted to measuring the angles of the Unitarity Triangle to an even higher degree of precision than the one reached at BaBar and Belle. A $O(1\%)$ precision on the nontrivial apex of the Unitarity Triangle is expected after five years of operations.

SuperB will probe flavor observables complementary to hadron collider experiments; where there is overlap, the strength of SuperB lies in its ability to use multiple approaches, therefore allowing for a better control on theoretical uncertainties. This is particularly relevant for the measurement of the angle α, where model uncertainties at the $O(1^\circ)$ level are the limiting factor.

Another important design feature of the SuperB is its ability to run at the threshold for open charm production, that would be instrumental to achieving a sub-degree precision on the weak phase γ from tree processes.

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