# Time-dependent $CP$ violation measurements at Belle II

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Time dependent CP-violation phenomena are a powerful tool to precisely measure fundamental parameters of the Standard Model and search for New Physics. The Belle II experiment is a substantial upgrade of the Belle detector and will operate at the SuperKEKB energy-asymmetric $e^+e^-$ collider. The design luminosity of SuperKEKB is $8 \times 10^{35}$ cm$^{-2}$s$^{-1}$ and the Belle II experiment aims to record 50 ab$^{-1}$ of data, a factor of 50 more than the Belle experiment. This dataset will greatly improve the present knowledge, particularly on the CKM angles $\phi_1/\beta$ and $\phi_2/\alpha$ by measuring a wide spectrum of B-meson decays, including many with neutral particles in the final state. A study for the time-dependent analysis of $B^0 \to \pi^0\pi^0$, relevant for the measurement of $\phi_2/\alpha$, and feasible only in the clean environment of an $e^+e^-$ collider, will also be given.

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The Belle II Experiment [1] at the SuperKEKB $e^+e^-$ Collider [2] is devoted to the search for evidence of physics beyond the Standard Model (SM) by studying the decays of $B$ and $D$ mesons and of $\tau$ leptons, by searching for the production of exotic particles, and in general by looking for any significant discrepancy between measurements and predictions in observables for which the theory can provide a reliable calculation. SuperKEKB operates at a center of mass energy corresponding (or close to) the mass of the $\Upsilon(4S)$ resonance, and its target instantaneous luminosity is $8 \times 10^{35}$ cm$^{-2}$s$^{-1}$, which will allow the experiment to collect an integrated luminosity of 50 ab$^{-1}$ in about five years of operation. At the time of presenting this contribution, the accelerator has begun delivering collisions in the so-called Phase2 of the commissioning program, and the experiment has accumulated an integrated luminosity of $\sim$400 pb$^{-1}$.

One of the most important areas of the Belle II physics programme is the precise measurement of the parameters of the Cabibbo-Kobayashi-Maskawa quark mixing matrix through the measurement of time-dependent $CP$ violation phenomena in the decays of $B$ mesons. In this contribution, an estimate of the sensitivity achievable on the CKM Unitarity Triangle angles $\phi_1/\beta$ and $\phi_2/\alpha$, along with other searches of New Physics in time dependent $CP$ violation in $B$ decays will be given. Unless otherwise stated, the sensitivity estimates presented here are taken from [3].



## 1. Features of Belle II

The Belle II detector is an extensive upgrade of the previous Belle experiment. The areas in which the upgrade has been more significant are the silicon vertex trackers and the Particle Identification (PID) detectors.

Concerning the former, the position of the particle decay vertices will be measured by a combination of a two-layer silicon Pixel detector (PXD) and a four-layer silicon Strip detector (SVD). Thanks to the fact that the first layer of the PXD will be placed at a radius $r = 14$mm from the beam line and to the reduced amount of material, we expect (despite the lower boost) an improvement by $\sim 30\%$ compared to Belle on the $\Delta t$ resolution in $B$ decays.

Two novel detectors provide PID information (mostly for the separation of charged hadrons): the Time Of Propagation (TOP) detector instruments the barrel region of the detector, while the Aerogel Cherenkov (ARICH) detector provides information in the forward endcap region. Together with the measurement of the specific ionization energy provided by the tracking devices, we expect to have a $K$ ($\pi$) identification efficiency $> 90\%$ with a corresponding $\pi$ ($K$) mis-identification rate $< 10\%$ for momenta as high as 4 GeV/$c$.

PID is a crucial ingredient for the B flavor tagging capabilities of the experiment. The improvements in the PID performance, combined with a more efficient algorithm based on multivariate selectors will increase the effective flavor tagging efficiency from the typical value of $\sim 30\%$ of Belle, to the expected $\sim 37\%$.

## 2. Measurements of $\phi_1/\beta$

Belle II will measure the quantity $\sin(2\phi_1)$ both from tree level dominated $b \to c$ transitions and from penguin dominated $b \to sq\bar{q}$ ($q = s, d, u$) processes. The former (dominated by the $B^0 \to J/\psi K^0$ decays) provide a very precise input to the CKM Unitarity Triangle fit, which might reveal the presence of New Physics from any irreconcilable inconsistency among the different inputs. The latter, being suppressed by the fact that they dominantly proceed through loop amplitudes, might be influenced by New Physics amplitudes which could carry different phases and thus shift the measured value of the time dependent *CP* asymmetry $S$ from the value that is measured in the $b \to c$ transitions. Any significant difference in the measured values of $S$ of tree- and penguin-dominated processes (see e.g. left part of Fig. 1) would be a clear evidence of New Physics (this is especially true for the theoretically cleaner $B^0 \to \eta' K^0$ and $B^0 \to \phi K^0$).

The measurements of $S$ for the favored $B^0 \to c\bar{c}K^0$ decays will quickly become limited by the systematic uncertainties, so it is mandatory to devise strategies to keep those under control. The dominant irreducible systematics are those related to the alignment of the vertex detectors, and those arising from doubly Cabibbo suppressed decays on the tag side. On the other hand, the precision of almost all the decays proceeding from loop diagrams will be dominated by the statistical uncertainties until the end of data taking at Belle II.

On a related topic, Belle II will measure also time dependent *CP* asymmetries in decays where the SM does not expect any significant asymmetry (so any evidence of the contrary would signal New Physics). One example is $B^0 \to \pi^0 K^0_S \gamma$, where the polarization of the photon can separate $B^0$'s from $\overline{B}^0$'s decays (thus destroying the interference between mixing and decay).

Table 1 summarizes the expected sensitivity on the time dependent and direct *CP* asymmetries on the most important channels for Belle II.

**Table 1:** Expected uncertainties on the time dependent ($S$) and direct ($A$) *CP* asymmetries for the main channels sensitive to $\sin 2\phi_1$ for an integrated luminosity of 5 and 50 ab$^{-1}$. The current World Average [4] errors are also reported.

| | WA [4] | | 5 ab$^{-1}$ | | 50 ab$^{-1}$ | |
|---|---|---|---|---|---|---|
| Channel | $\sigma(S)$ | $\sigma(A)$ | $\sigma(S)$ | $\sigma(A)$ | $\sigma(S)$ | $\sigma(A)$ |
| $J/\psi K^0$ | 0.022 | 0.021 | 0.012 | 0.011 | 0.0052 | 0.0090 |
| $\phi K^0$ | 0.12 | 0.14 | 0.048 | 0.035 | 0.020 | 0.011 |
| $\eta' K^0$ | 0.06 | 0.04 | 0.032 | 0.020 | 0.015 | 0.008 |
| $\omega K^0_S$ | 0.21 | 0.14 | 0.08 | 0.06 | 0.024 | 0.020 |
| $K^0_S \pi^0 \gamma$ | 0.20 | 0.12 | 0.10 | 0.07 | 0.031 | 0.021 |
| $K^0_S \pi^0$ | 0.17 | 0.10 | 0.09 | 0.06 | 0.028 | 0.018 |

## 3. Measurements of $\phi_2/\alpha$

The CKM angle $\phi_2/\alpha$ can be measured in several ways. One of the best known is the derivation from an isospin analysis of the $B \to \pi\pi$ or the $B \to \rho\rho$ decays. Since most of the decay channels contain at least one $\pi^0$ in the final state (which are difficult to reconstruct at the LHCb experiment), Belle II will dominate the World Average for most of the relevant measurements. Due to the ambiguities in the isospin method, each analysis can determine the angle $\phi_2$ only within an 8-fold ambiguity.

A reduction by a factor of 2 or 4 of the ambiguities can be obtained by adding the value of the time dependent *CP* violation on the channel $B^0 \to \pi^0\pi^0$. This measurement has never been done at

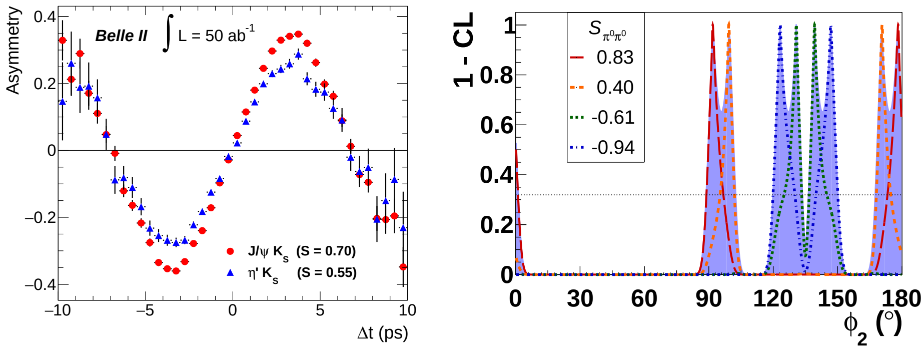


**Figure 1:** Left plot: simulated time-dependent *CP* asymmetries for the final states $J/\psi K_S^0$ (red dots) and $\eta' K_S^0$ (blue triangles), using $S_{J/\psi K_S^0} = 0.70$ and $S_{\eta' K_S^0} = 0.55$ as inputs to the Monte Carlo (corresponding to an integrated luminosity of 50 ab$^{-1}$). Right plot: Scan of the CL-1 for $\phi_2$ performing isospin analysis of the $B \to \pi\pi$ system. The shaded areas show the result without including the time dependent CP asymmetry of $B^0 \to \pi^0\pi^0$, while the colored lines show the impact of $S_{\pi^0\pi^0}$ for different hypotheses on its value.

the previous experiments, due to the fact that most of the times the $\pi^0$'s in the final state decay to pairs of photons, which cannot be used to precisely determine the decay vertex. Thanks to the much higher statistics that will be available at Belle II, the Dalitz decays $\pi^0 \to \gamma e^+ e^-$ and the $\gamma \to e^+ e^-$ conversions on the beampipe and first layers of the vertex detectors can be exploited to determine the $B^0$ decay vertex. Studies on the simulation show that, with 50 ab$^{-1}$ of integrated luminosity, $\sim 270$ $B^0 \to \pi^0\pi^0$ signal events can be reconstructed, with a vertex resolution only $\sim 50\%$ worse of what can be obtained in $B^0 \to J/\psi K^0$ events. The precision on the time dependent *CP* asymmetry $S_{\pi^0\pi^0}$ would be $\sim 0.28$. Fig. 1 (right) shows the impact of such measurement on reducing the ambiguities on the determination of $\phi_2$ from the isospin analysis of the $B \to \pi\pi$ system.

Combined with an isospin analysis of the $B \to \rho\rho$ system, a precision of $0.6^\circ$ can be obtained, using the full statistics.

## 4. Conclusions

The Belle II experiment is approaching the beginning of its first physics run. Time dependent *CP* violation is a major part of the physics programme and leading or very competitive results on the determination of the CKM angles $\phi_1$ and $\phi_2$ will be obtained.

## References

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