First look at time-dependent CP violation using early Belle II data

Stefano Lacaprara
on behalf of the Belle II Collaboration
INFN sezione di Padova

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 at the SuperKEKB energy-asymmetric e^+e^- collider is a substantial upgrade of the B factory facility at the Japanese KEK laboratory. The design luminosity of the machine is 8×10^{35} $cm^{-2}s^{-1}$ and the Belle II experiment aims to record 50 ab^{-1} of data, a factor of 50 more than its predecessor. From February to July 2018, the machine has completed a commissioning run, achieved a peak luminosity of 5.5×10^{33} $cm^{-2}s^{-1}$, and Belle II has recorded a data sample of about 0.5 fb^{-1} .

Main operation of SuperKEKB has started in March 2019. This early data set is used to establish the performance of the detector in terms of reconstruction efficiency of final states of interest for the measurement of time dependent CP violation, such as $J/\psi K^0$, $\eta' K^0$, and ϕK^0. A first assessment of the B flavor tagging capabilities of the experiment will be given, along with estimates of the Belle II sensitivity to the CKM angles ϕ_1/β and ϕ_2/α and to potential New Physics contributions in penguin amplitudes dominated decays and in $b \to s\gamma$ transitions.

In this talk we will present estimates of the sensitivity to ϕ_1 in the golden channels $b \to c\bar{c}s$ and in the penguin-dominated modes $B^0 \to \eta' K^0$, ϕK^0, $K^0\pi^0(\gamma)$. A study for the time-dependent analysis of $B^0 \to \pi^0\pi^0$, relevant for the measurement of ϕ_2, and feasible only in the clean environment of an e^+e^- collider, will also be given.

I. INTRODUCTION

The Belle II experiment [1] is currently taking data at SuperKEKB [2] e^+e^- collider at KEK, in Tsukuba, Japan. Its main goal is to search for physics beyond the Standard Model (SM) in B, D, and τ decays, performing precise measurements of quantities for which the SM provide reliable calculation or looking for exotic particles and decays. The SuperKEKB asymmetric collider works at a center of mass energy corresponding (or close to) the $\Upsilon(4S)$ resonance. The target integrated luminosity is 50 ab^{-1} in about five year of operation, with a ultimate instantaneous luminosity of 8×10^{35} $cm^{-2}s^{-1}$, 40 times larger than that of KEKB, its predecessor.

Belle II has collected an integrated luminosity of about 500 pb^{-1} in year 2018 (Phase 2) with an incomplete detector, where only a small fraction of the silicon vertex sub-detector was installed. Starting from march 2019, Belle II is collecting more data at $\Upsilon(4S)$ center of mass energy, with all sub-detectors fully installed and operational.

One of the major goal of the Belle II physics program [3] is to improve the measurement of the CP violating parameter of Cabibbo-Kobayashi-Maskawa (CKM) matrix, via the time-dependent CP violation (TDCPV) technique in the B sector.

In this contribution, we will present the expected sensitivity on CKM Unitary Triangle (UT) angles ϕ_1/β, both in tree- and penguin-mediated transition, and ϕ_2/α. Additionally, searches for New Physics using TDCPV techniques in the $K^0\pi^0(\gamma)$ decay will be described.

II. BELLE II DETECTOR

The Belle II detector is major upgrade of the previous Belle one for almost all subsystem. Particularly relevant for the TDCPV analysis is the new vertex detector, and the particle identifier (PID) ones.

The vertex detector comprises two layers of silicon pixel (PXD), the closest placed at $r = 14$ mm from the beam line, and four layers of silicon strips (SVD). In spite of the reduced boost of the B particle at SuperKEKB with respect to KEKB ($\beta\gamma = 0.28$ vs 0.45), an improvement of secondary vertex precision, and so of Δt of about 30% is expected. The tracking system is completed by a central drift chamber (CDC), installed inside a solenoid providing a 1.5 T magnetic field. The CDC is new, larger than the one used at Belle, with smaller cell size and longer lever arm.

Two new PID detectors have been installed to provide separation between charged hadrons (mostly π and K). In the barrel region, the Imaging Time Of Propagation (iTOP) detector is used, and the Aerogel Cherenkov (ARICH) covers the forward region. Both are based on the Cherenkov effect. The iTOP uses precise determination of time and position of arrival of Cherenkov photons to an array of Micro Channel Plate Photo Multiplier Tube. The photons are produced by charged particle crossing 2 cm of finely polished quartz. The ARICH uses an aerogel radiator with focusing capability, and collect Cherenkov photons via Hybrid Avalanche Photo Detector. The CDC provide additional information on PID measuring the specific ionization energy deposit. The overall performances are expected to provide an efficiency for identification of π (K) greater than 90% with a misidentification rate lower than 10% up to 4 GeV/c for particle momentum.

The improved PID, together with better algorithm based on multivariate selectors, is expected to increase the flavour tagging effective efficiency to $\sim 37\%$, to be compared to $\sim 30\%$ obtained at Belle.

III. MEASUREMENT OF ϕ_1/β

The most precise determination of $\sin 2\beta$ is obtained from TDCPV analysis of tree mediated $\mathrm{b} \to \mathrm{c}$ processes, dominated by the decay $\mathrm{B}^0 \to \mathrm{J}/\psi \mathrm{K}^0$. An improved measurement might indicate New Physics in case of incompatibility with other measurement of the UT parameters. The measurement of $\sin 2\beta$ in $\mathrm{B}^0 \to \mathrm{c\bar{c}K}^0$ decays will be soon dominated by systematics uncertainties, thanks to the large dataset expected at Belle II. Dominant irreducible systematics come from alignment of vertex detector, Δt resolution, and tag-side interference.

Independent determination of time dependent CP asymmetry S will come from penguin dominated $\mathrm{b} \to \mathrm{s}q\bar{q}$ ($q = \mathrm{s,d,u}$). These decays are suppressed with respect to $\mathrm{b} \to \mathrm{c}$, due to the presence of loop amplitudes, but New Physics can introduce new phases in the loop, and shift the value of S as measured in the tree-dominated diagram. A significant difference would be a clear indication of New Physics, as shown in Fig. 1.

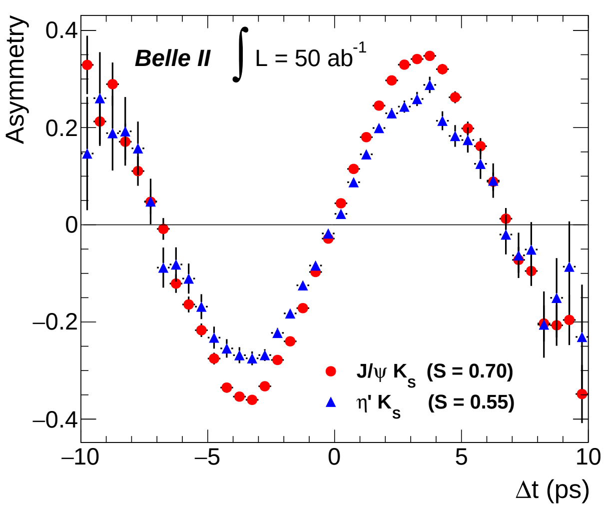

FIG. 1: Simulated time dependent CP asymmetry in the $\mathrm{J}/\psi\mathrm{K}^0$ (red dots) and $\eta'\mathrm{K}^0$ (blue triangles) expected with an integrated luminosity of $50\,\mathrm{ab}^{-1}$, using $S = 0.70(0.55)$ for the former (latter) channel, respectively.

The expected sentitivity for several final states have been studied: the most interesting are $\mathrm{B}^0 \to \eta'\mathrm{K}^0$ and $\phi\mathrm{K}^0$. The former has many different final states, from the η' decay, all including neutrals. The latter have final states with K and π, and the PID performances will be critical. These two channels are also the cleaner from the thoerotical point of view, so the comparison of S to that of tree-dominated diagram is more sensitive.

Given the suppressed amplitudes, the precision of S in most of the decay channels is expected to be dominated by statistical uncertainties. A notable exception is the decay $\mathrm{B}^0 \to \eta'\mathrm{K}^0$, where the systematics uncertainties are expected to be similar to the statistical one around $10 - 20\,\mathrm{ab}^{-1}$.

To probe for New Physics, it is also interesting to look for TDCPV when none is expected in the SM. An example is the decay channel $\mathrm{B}^0 \to \mathrm{K}^0_\mathrm{S}\pi^0\gamma$, which includes many neutrals in the final states, making very hard, if possible at all, for LHCb. The decay $\mathrm{b} \to \mathrm{s}\gamma_R$ is helicity suppressed with respect to the analogous with γ_L, but New Physics can enhance the $b \to s\gamma_R$ decay rate. The interference between $\mathrm{B}^0 \to f_{CP}\gamma_R$ and $\mathrm{B}^0 \to \overline{\mathrm{B}}^0 \to f_{CP}\gamma_R$ happens only for helicity suppressed decay, and a measurement of time dependent asymmetry S in this channel larger than SM prediction (few % [4]) would be an evidence of New Physics.

A summary of expected precision on time dependent (S) and direct (A) CP violation parameters is presented in Table I.

TABLE I: Expected uncertainties on time dependent (S) and direct (A) CP violation parameters for integrated luminosity of 5 and $50\,\mathrm{ab}^{-1}$. Current World Average (WA) uncertainties are also reported [5]

	WA		**5 ab^{-1}**		**50 ab^{-1}**	
Channel	$\sigma(S)$	$\sigma(A)$	$\sigma(S)$	$\sigma(A)$	$\sigma(S)$	$\sigma(A)$
$J/\psi K^0$	0.22	0.21	0.012	0.011	0.0052	0.0090
$\eta' K^0$	0.06	0.04	0.032	0.020	0.015	0.008
ϕK^0	0.12	0.14	0.048	0.035	0.020	0.011
ωK^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	0.010	0.09	0.06	0.028	0.018

IV. MEASUREMENT OF ϕ_2/α

The second UT angle ϕ_2/α can be measured using the decay $\mathrm{B}^0 \to \pi\pi$ as well as $\rho\rho$, using an isospin analysis [6], due to the fact that there are two amplitudes of comparable size but different weak phase. The isospin techniques requires to determine the magnitude and phases of $\mathrm{B}^0 \to \pi^+\pi^-$ as well as $\mathrm{B}^0 \to \pi^0\pi^0$. Previous B-factories measurements include both for $\mathrm{B}^0 \to \pi\pi$, but the phase of $\mathrm{B}^0 \to \pi^0\pi^0$ has not been measured, resulting in a eightfold ambiguity in the determination of ϕ_2. By measuring the phase, namely the time dependent asymmetry of

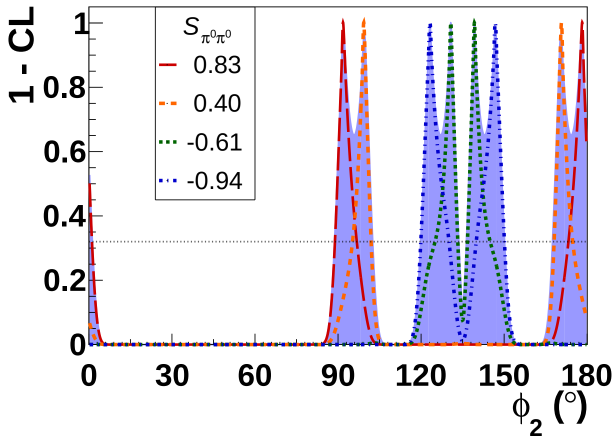

FIG. 2: Expected CL-1 for ϕ_2, using isospin analysis for $B^0 \to \pi\pi$ final state, only with improvement on current measurement (blue area) and including also the determination of $S_{\pi^0\pi^0}$ values (colored lines) for four different central value of S.

$B^0 \to \pi^0\pi^0$, the ambiguity can be reduced by a factor of two or four. Given the neutral final state, this decay channel is very difficult to study at LHCb.

At Belle II, the high integrated luminosity allows to study TDCPV for $B^0 \to \pi^0\pi^0$ using the Dalitz decays $\pi^0 \to \gamma e^+e^-$ and the $\gamma \to e^+e^-$ conversion on beam pipe and first layers of vertex detector. The B^0 decay vertex can be reconstructed from the B^0 flight direction and that of e^+e^-, with a vertex resolution only 50% worse than that obtained with charged final state, such as $J/\psi K^0$. With the full integrated luminosity of $50\,\mathrm{ab}^{-1}$, Belle II expects to reconstruct ~ 270 $B^0 \to \pi^0\pi^0$ signal events with Dalitz decay, and ~ 50 with a γ conversion. The foreseen precision on S would be ~ 0.28, and the impact on reducing the ambiguity on ϕ_2 is shown in Fig. 2 for four different possible values of $S_{\pi^0\pi^0}$.

The $B^0 \to \pi\pi$ will provide a resolution on ϕ_2 around $2°$: combining with the similar isospin analysis of $\rho\rho$ final state, the ultimate precision will be $0.6°$, using the full statistics.

V. CONCLUSION AND OUTLOOK

The Belle II experiment is taking data at SuperKEKB in Tsukuba, Japan. In the physics program of the experiment, the study of time dependent CP violation will play a major role. The ultimate precision on ϕ_1 and ϕ_2 is expected to go below $\sim 1°$, with interesting prospect in term of New Physics searches.

Looking at B-factory (Belle and BaBar) past history, with an integrated luminosity around $10\,\mathrm{fb}^{-1}$, Belle II could re-discover TDCPV in the $B^0 \to J/\psi K^0_S$ final state, as well the decay into $\eta' K^0_S$. Larger dataset, around $40\,\mathrm{fb}^{-1}$ would be required for TDCPV in the latter channel as well as in the $B^0 \to \pi^+\pi^-$ one. Even larger $\sim 100\,\mathrm{fb}^{-1}$ were needed for TDCPV in ϕK^0_S. For channel $B^0 \to K^0_S\pi^0\gamma$, Belle II can provide interesting improvement with few ab^{-1}, while the full dataset of $50\,\mathrm{ab}^{-1}$ will be needed for the challenging $B^0 \to \pi^0\pi^0$.

More information about the Belle II physics program can be found on [3].

[1] T. Abe et al. (Belle-II) (2010), 1011.0352.
[2] Y. Ohnishi et al., PTEP **2013** (2013), ISSN 2050-3911.
[3] E. Kou et al. (Belle-II) (2018), 1808.10567.
[4] P. Ball, G. W. Jones, and R. Zwicky, Phys. Rev. D **75**, 054004 (2007), URL `https://link.aps.org/doi/10.1103/PhysRevD.75.054004`.
[5] Y. Amhis et al. (HFLAV), Eur. Phys. J. **C77**, 895 (2017), 1612.07233.
[6] M. Gronau and D. London, Phys. Rev. Lett. **65**, 3381 (1990), URL `https://link.aps.org/doi/10.1103/PhysRevLett.65.3381`.