PROCEEDINGS OF SCIENCE

# Prospects on time-integrated CPV measurements at Belle II

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Charge-conjugation-partiy (CP) violation in charm decays can be searched using the time integrated decay rates of charm hadrons into various final states. This proceeding analyzes some of the current results in time-integrated CP violation in charm decays and discusses the future projections of these results at Belle II. Besides, new flavor tagging techniques to be employed at Belle II to increase the statistics of the sample available for such studies is also described.

*9th International Workshop on the CKM Unitarity Triangle*
*28 November - 3 December 2016*
*Tata Institute for Fundamental Research (TIFR), Mumbai, India*

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## 1. Introduction

Charm physics encompasses the study of composite particles containing charm quarks which provide unique opportunities for probing the strong and weak interactions in the Standard Model (SM) and beyond. Being the up-type quark of the second of the three generations, the charm quark is the third-heaviest of the six quarks. The first evidence for mixing of neutral charm mesons was reported by BaBar [1] and Belle [2] in 2007. Although mixing in charm sector is now well established, there is no clear evidence of direct charge-conjugation-parity violation (CPV) and no hints of indirect CPV in the charm sector yet [3]. Presently, lot of work in experimental searches for CP violation in charm sector is ongoing and considerable progress has been made in the theoretical calculations as well.

## 2. Present Status of time-integrated CPV studies

CP violation in charm decays can be searched for by examining the time integrated decay rates of the charm hadrons into various final states. The CP asymmetry in a two-body $D^0 \to f$ is defined as:

$$A^{f}_{CP} = \frac{\Gamma(D^0 \to f) - \Gamma(\bar{D}^0 \to \bar{f})}{\Gamma(D^0 \to f) + \Gamma(\bar{D}^0 \to \bar{f})} \tag{2.1}$$

In the SM, indirect CPV is expected to be very small, of the order of $10^{-3}$, and is universal for $CP$ eigenstates. Direct CPV is predicted to be small as well. In the SM, it is expected to be negligible in Cabibbo-favored modes and in SCS modes; it is plausible up to $\mathcal{O}(10^{-3})$ [4]. Hence, observation of large direct $A_{CP}$ would indicate hint of new physics. Belle, LHCb and BES III have already published interesting results in this area. The future upgrade of Belle, Belle II and LHCb are two complementary experiments, with the former having advantage in luminosity sector and the latter in intensity sector.

## 3. Belle II projections for time-integrated CPV studies

B-factory experiments namely the Belle experiment at the KEKB collider in KEK and the BaBar experiment at the PEPII collider in SLAC, using $e^+ - e^-$ asymmetric colliders, have collected 1.5 ab$^{-1}$ of integrated luminosity on $\Upsilon$ (4S) resonances, mainly decaying to $B\bar{B}$ meson pairs, in long term operation. To improve statistics, upgrades of both the KEKB collider and the Belle detector to the SuperKEKB [5] collider and the Belle II [6] detector are in progress in order to achieve 50 ab$^{-1}$ of luminosity to search for physics beyond the Standard Model with more precise checks of the predictions of the Standard Model.

The Belle II projections are discussed in a Belle II Internal note [7]. The systematic uncertainties can be primarily grouped as reducible and irreducible. The reducible errors can be reduced with increase in statistics whereas the irreducible errors can not be reduced with higher statistics.

### 3.1 $D^0 \to hh$

To illustrate the sensitivity of such measurements at Belle II, we estimate the expected accuracy of $A^{h^+h^-}_{CP}$, where $h = K, \pi$ most recently measured by Belle using 976 fb$^{-1}$ of data [8]. The

$D^0$ mesons are required to originate from the decay $D^{*+} \to D^0\pi^+$ in order to provide a tag on the $D$ flavor as well as to suppress combinatorial background. The pion originating from $D^{*+}$ is a low pion. Systematic uncertainties due to slow pion correction and $A_{CP}$ extraction are reducible and that due to signal counting is an irreducible uncertainty.

$$\begin{aligned}\sigma_{total}^{A_{CP}^{K^+K^-}} &= \sqrt{(0.220+0.0662^2)\times 0.976\ ab^{-1}/\mathscr{L}_{int}+0.0552^2}\times 10^{-2}\\ \sigma_{total}^{A_{CP}^{\pi^+\pi^-}} &= \sqrt{(0.220+0.0662^2)\times 0.976\ ab^{-1}/\mathscr{L}_{int}+0.0552^2}\times 10^{-2}\end{aligned} \tag{3.1}$$

### 3.2 $D^0 \to \phi\gamma$

$$\sigma_{total}^{A_{CP}^{\phi\gamma}} = \sqrt{(19.9^2)\times 0.078\ ab^{-1}/\mathscr{L}_{int}+0.06^2}\times 10^{-2} \tag{3.2}$$

Reducible errors include Tracking, PID, $\Delta M$, $M_\phi$, efficiency correction and MC statistics [9], [10]. Since we have limited knowledge about the branching fraction $(\mathscr{B}) of \mathrm{D}^0 \to K^+K^-$ and $D^0 \to V\gamma$ modes, the error due to the $\mathscr{B}$ is an irreducible uncertainty.

### 3.3 $D^+ \to K_sK^+$

The systematic uncertainty owing to the detector induced asymmetries due to the differences in the reconstruction efficiencies between $K^+$ and $K^-$ $(A_\varepsilon^K)$ and the effect of binning in some kinematic variables are reducible errors [[11], [12], [13]]. Due to the presence of neutral kaons in the final state one needs to consider the difference in nuclear interactions of kaons and anti-kaons in the detector material. The systematic error due to this effect, fitting and systematic errors of $A_{CP}$ of $D_s \to \phi\gamma$ and $D^0 \to K^-\pi^+$ are irreducible sources.

$$\sigma_{total}^{A_{CP}^{K_sK^+}} = \sqrt{(0.275^2+0.124^2+\rho 0.053^2\times 0.976\ ab^{-1}/\mathscr{L}_{int}+(1-\rho)0.053^2}\times 10^{-2} \tag{3.3}$$

### 3.4 $D^0 \to \pi^0\pi^0$

Belle II will measure the $A_{CP}$ in $D^0 \to \pi^0\pi^0$ decay with good precision owing to the high efficiency at BELLE II to detect neutral final states [14]. The dominant error in the current Belle measurement of $A_{CP}$ in $D^0 \to \pi^0\pi^0$ decay is statistical. The systematic error is $\pm 0.10\times 10^{-2}$. We expect similar sources of systematic errors at Belle II as well. However, a large fraction of the systematic uncertainty $\pm 0.07\times 10^{-2}$ will be reduced with a larger data set, since it arises from the corrections of positive and negative slow pion reconstruction efficiencies, using a dedicated sample of tagged and un-tagged $D^0 \to K\pi$ decay.

$$\sigma_{total}^{A_{CP}^{\pi^0\pi^0}} = \sqrt{(0.64^2+0.10^2)\times 0.996\ ab^{-1}/\mathscr{L}_{int}+0.01^2}\times 10^{-2} \tag{3.4}$$

### 3.5 $D^0 \to K_s\pi^0$

The systematic uncertainties for $D^0 \to K_s\pi^0$ are similar to $D^0 \to \pi^0\pi^0$ [14]. The only difference is an additional irreducible systematic uncertainty due to the neutral kaon interactions in the material.

$$\sigma_{total}^{A_{CP}^{K_S\pi^0}} = \sqrt{(0.16^2+0.09^2)\times 0.996\ ab^{-1}/\mathscr{L}_{int}+0.01^2}\times 10^{-2} \tag{3.5}$$

### 3.6 $D^0 \to K_s K_s$

The $D^0 \to K_S^0 K_S^0$ decay is Single Cabibbo Suppressed channel [15]. The most recent SM-based analysis obtained a 95% confidence level upper limit of 1.1% for direct *CP* violation in this decay [16]. The analysis is based on a data sample that corresponds to an integrated luminosity of 921 fb$^{-1}$ collected with the Belle detector [17] at the KEKB asymmetric-energy $e^+e^-$ collider [18] operating at the $\Upsilon$(4S) resonance, $\Upsilon$(4S) off-resonance, and $\Upsilon$(5S) resonance with integrated luminosities 710.5 fb$^{-1}$, 89.2 fb$^{-1}$, and 121.4 fb$^{-1}$, respectively.

Recently, Belle has measured the time-integrated *CP*-violating asymmetry $A_{CP}$ in the $D^0 \to K_S^0 K_S^0$ decay to be

$$A_{CP} = (-0.02 \pm 1.53 \pm 0.02)\%$$

using a data sample of 921 fb$^{-1}$ integrated luminosity [19], where, the first uncertainty is statistical and the second is systematic. The result is consistent with Standard Model expectations and is a significant improvement compared to the previous measurements of CLEO [20] and LHCb Collaborations [21], already probing the region of interest.

The dominant error in $A_{CP}$ measurement in the $D^0 \to K_S^0 K_S^0$ is statistical. Hence, Belle II can greatly improve precision; we expect a precision of 0.2% with similar systematic errors as at Belle. The dominant systematic uncertainty in the current Belle analysis comes from the $A_{CP}$ error of the normalization channel, $D^0 \to K_S^0 \pi^0$. Errors on the measurements performed in the normalization channel will also reduce with increased statistics at Belle II.

### 3.7 $D^0 \to V\gamma$

The study of radiative decays $D^0 \to V\gamma$, where $V$ is a vector meson could be sensitive to New Physics (NP) via CP asymmetry ($A_{CP}$ ). Theoretical studies [[22], [23]] predict that in Standard Model (SM) extensions with chromomagnetic dipole operators, $A_{CP}$ can rise to several percent for $V = \phi$ , $\rho^0$, compared to the $\mathscr{O}(10^{-3})$ SM expectation. However, there has been no study of CP violation in $D^0 \to V\gamma$ decays conducted up to this point.

Recently, Belle published the measurement of the branching fractions and CP asymmetries in decays $D^0 \to V\gamma$, where $V = \phi, \bar{K}^{*0}, \rho^0$ [24]. This is the first observation of the decay $D^0 \to \rho^0\gamma$. The analysis is based on 943 fb$^{-1}$ of data collected by the Belle detector, operating at the asymmetric KEKB $e^+$-$e^-$ collider.

The preliminary branching fractions are:

$\mathscr{B}(D^0 \to \phi\gamma)$ = (2.76 ± 0.19 ± 0.10 ×10$^{-5}$,

$\mathscr{B}(D^0 \to \bar{K}^{*0}\gamma)$ = (4.66 ± 0.21± 0.21 ×10$^{-4}$,

$\mathscr{B}(D^0 \to \rho^0\gamma)$ = (1.77 ± 0.30 ± 0.07)×10$^{-5}$,

where the first uncertainty is statistical and the second systematic. The result of the $\phi$ mode is improved compared to the previous Belle result and is consistent with the world average value [25]. For the $\rho^0$ mode, this analysis reports the first observation of the decay. The significance of the observation is greater than $5\sigma$, including systematic uncertainties.We also report the first-ever measurement of $A_{CP}$ in the decays $D^0 \to V\gamma$. The preliminary values are:

$A_{CP}(D^0 \to \phi\gamma)$= $-0.094 \pm 0.066 \pm 0.001$
$A_{CP}(D^0 \to \bar{K}^{*0}\gamma)$ = $-0.003 \pm 0.020 \pm 0.000$
$A_{CP}(D^0 \to \rho^0\gamma)$ = $+\ 0.056 \pm 0.152 \pm 0.006$
Results are consistent with no CP asymmetry in any of the $D^0 \to V\gamma$ decay modes.

The dominant error in $A_{CP}$ and $\mathscr{B}$ measurements in the $D^0 \to V\gamma$ is statistical. Hence, Belle II can greatly improve precision, as shown in Table 1.

| Mode | 1 ab$^{-1}$ | 5 ab$^{-1}$ | 15 ab$^{-1}$ | 50 ab$^{-1}$ |
|---|---|---|---|---|
| $A_{CP}(D^0 \to \phi\gamma)$ | 0.020 | 0.01 | 0.005 | 0.003 |
| $A_{CP}(D^0 \to \bar{K}^{*0}\gamma)$ | 0.066 | 0.03 | 0.02 | 0.01 |
| $A_{CP}(D^0 \to \rho^0\gamma)$ | 0.152 | 0.07 | 0.04 | 0.02 |

**Table 1:** Projected statistical errors for the $D^0 \to V\gamma$ modes with increased statistics

## 4. New flavor tagging techniques at Belle II

In order to measure CPV in charm decays, it is crucial to determine the flavour of the $D^0$ at production. The $D^{*+}$ mesons mostly originate from the $e^+e^- \to c\bar{c}$ process via hadronization, where the inclusive yield has a large uncertainty of 12.5% [25]. The $D^0$ meson is required to originate from the decay $D^{*+} \to D^0\pi_s^+$ in order to identify the $D$ flavor and to suppress the combinatorial background, where $\pi_s^+$ is a slow pion. This is the usual flavor tagging technique employed at B-factories.

We discuss a new method called the rest of the events (ROE) method [26]. Since three-fourth of the $D^0$ candidates in $c\bar{c}$ events at the B-Factories are not produced from $D^+$ decays, we developed a new flavour tagging method in order to recover a fraction of these $D^0$ for analysis in which is fundamental to determine the flavour of the neutral mesons at the production moment. This method is called the ROE method. Since the Cabibbo-favored transition for a charm quark is $c \to s(\bar{c} \to \bar{s})$, we expect to have at least one strange meson in the ROE, such as $K^+$ or $K^0$. The flavour tagging is performed selecting the events with only one K in the ROE and using the charge of the kaon to determine the flavour of the $D^0$ at the time of its production.

A correctly tagging $K$ is produced by a Cabibbo-favored (CF) decay of a charmed meson or a charmed baryon. However, there are some sources of mis-tagging, the main source of mis-tagging being $c\bar{c}s\bar{s}$ events, in which a pair of $s\bar{s}$ quarks is created jointly with the pair of $c\bar{c}$ quarks. The other minor sources of mis-tagging are if the K in the ROE is produced by a doubly Cabibbo-suppressed (DCS) decay of a charmed meson or a charmed baryon or if the K in the ROE is produced by a CF decay of a $D^0(\bar{D}^0)$ that has oscillated in a $\bar{D}^0(D^0)$. The tagging efficiency ($\varepsilon$) is 41.2 % and mis-tagging level (w) $= 7.2\%$. In order to reduce the mistagging level due to the dominant source of mistagging, a veto on the presence of neutral kaons $K_L$ and $K_S$ in the ROE is applied, which yields $\varepsilon$ = 30 % and mis-tagging level (w) $< 1\%$.

For this method, the selection of tagging charged kaon is most important and is performed using a multivariate classification, which is a boosted decision tree (FastBDT), labelled as "Criteria a". The selection of tagging charged kaon is a two-step selection based on a boosted decision tree

(BDT) with a first loose cut to reject most of the background, and a second tighter cut to reject fake kaons. The "Criteria b" is referred to events in which the "Criteria a" has been applied and a cut on the angle between the momenta in the CM frame of the $D^0$ candidate and the charged K in the ROE and a veto on the reconstructed $K_S$ in the ROE is applied. The "Criteria b" is referred to events in which the "Criteria b" has been applied and a veto on the reconstructed $K_L$ in the ROE is also applied.

The tagging efficiency ($\varepsilon$) = 15 %, mis-tagging level (w) $<$ 5%, after vetoing then presence of neutral kaons $K_L$ and $K_S$ in the ROE [from MC truth]. BaBar reached a ratio of 1.4 between the purity of the untagged $D^0$ sample and the purity of the tagged (with $D^*$) sample [27]. In the best case, assuming the value 1.4 for Belle II, we can expect a reduction of $\approx 15\%$ of the statistical error on a $A_{CP}$ measurement. Figure. 1 shows the ratio between the statistical error on a $A_{CP}$ measurement using the two different flavour tagging methods, namely, $D^*$ and ROE, given by $\sigma^X_{A_0}$ and $\sigma^0_{A_0}$ as a function of the purity of $D^0$ samples and the ratio between the combined statistical error ($\sigma^C_{A_0}$) and the statistical error from the $D^*$ method [28]. The second plot illustrate how much Belle II can improve the statistical error on a $A_{CP}$ measurement adding the ROE flavour tagging method.

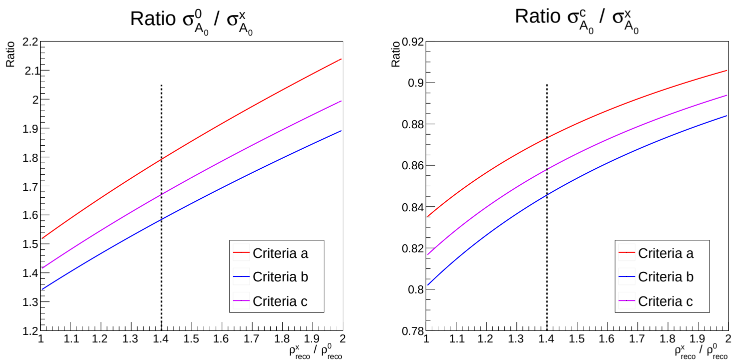


**Figure 1:** The left (right) plot shows the ratio between the statistical error on a $A_{CP}$ measurement using the two different flavour tagging methods, namely, $D^*$ and ROE, given by $\sigma^X$ and $\sigma^0$ as a function of the purity of $D^0$ samples (the ratio between the combined statistical error ($\sigma^C$) and the statistical error from the $D^*$ method).

## 5. Conclusions

Precision measurements of CP asymmetry in charm sector will be pursued by the Belle II collaboration. The future projections of the CP asymmetry at Belle II looks promising. Belle II will use novel flavor-tagging techniques in order to increase statistics of the analysis sample. In short, Belle II envisions to be one of the prime players in the search for CP violation in the charm sector.

## 6. Acknowledgements

I would like to convey my gratitude to the organizers of the 9th International Workshop on the

CKM Unitarity Triangle workshop for giving me an opportunity to deliver a talk on behalf of the Belle collaboration. I would also like to thank Giulia Casarosa, Giacomo De Pietro, Alan Schwartz, Phillip Urquijo and Christoph Schwanda for their valuable comments and suggestions.

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