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Prospects on time-integrated CPV measurements at Belle II

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

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1. Introduction

Charm physics encompasses the studies of composite particles containing charm quarks which provide unique opportunities for probing the strong and weak interactions in the Standard Model (SM) and beyond. In addition to being the up-type member of the second generation, the charm quark is the third heaviest among 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 the charm sector is now well established, there is no clear signature of direct or indirect charge-parity violation (CPV) in the charm sector yet [3]. Presently, lot of work in experimental searches for CPV in this sector is ongoing and considerable progress has been made in the theoretical calculations as well.

2. Present Status of time-integrated CPV studies

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

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

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 particular, it is expected to be negligible in Cabibbo-favored and Singly Cabibbo-suppressed modes, it is plausible up to $\mathcal{O}(10^{-3})$ [4]. Hence, observation of large direct A_{CP} would provide hint of new physics. Belle, BaBar, LHCb and BESIII 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 reconstruction of the modes involving neutrals and missing energy.

3. Belle II projections for time-integrated CPV studies

B-factory experiments namely Belle at the KEKB collider in KEK and BaBar at the PEPII collider in SLAC, using e^+e^- asymmetric colliders, have collected over 1.5 ab^{-1} data at the Υ (4S) resonance, which mainly decays to $B\bar{B}$ meson pairs. Upgrades of the KEKB collider and the Belle detector to SuperKEKB [5] and Belle II [6], respectively, are in progress in order to achieve 50 ab^{-1} of luminosity to search for physics beyond the SM with more precise checks of the SM predictions.

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 first category can be reduced with increase in statistics whereas the latter 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 $A_{CP}^{h^+h^-}$, 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 identify ('tag') on the D flavor as well as to suppress combinatorial background. The pion originating from D^{*+} is a low momentum or slow one. Systematic uncertainties due to the slow pion correction and A_{CP} extraction are reducible while those due to signal counting is an irreducible uncertainty.

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

Here, $\mathscr{L}_{int}$ stands for the total integrated luminosity.

3.2 $D^+ \to K_s K^+$

The systematic uncertainty owing to the detector induced asymmetries because of the differences in the reconstruction efficiencies between K^+ and K^- (A_{ε}^{K}), and the effect of binning in some kinematic variables are reducible errors [11]-[13]. On the other hand, the systematic error due to the difference in nuclear interactions of kaons and anti-kaons in the detector material, fitting and systematic errors of A_{CP} of $K_s \to K^+$ are irreducible sources.

$$\sigma_{total}^{A_{CP}^{K_sK^+}} = \sqrt{(0.275^2+0.124^2+\rho 0.053^2\times 0.976\ \text{ab}^{-1}/\mathscr{L}_{int}+(1-\rho)0.053^2}\times 10^{-2} \tag{3.2}$$

Here, ρ is a parameter to determine the scalability of the irreducible uncertainties, where $\rho = 1(0)$ means complete scalability (inscalability).

3.3 $D^0 \to \pi^0\pi^0$

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

$$\sigma_{total}^{A_{CP}^{\pi^0\pi^0}} = \sqrt{(0.64^2+0.10^2)\times 0.996\ \text{ab}^{-1}/\mathscr{L}_{int}+0.01^2}\times 10^{-2} \tag{3.3}$$

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

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 detector material.

$$\sigma_{total}^{A_{CP}^{K_s\pi^0}} = \sqrt{(0.16^2+0.09^2)\times 0.996\ \text{ab}^{-1}/\mathscr{L}_{int}+0.01^2}\times 10^{-2} \tag{3.4}$$

3.5 $D^0 \to K_s K_s$

The $D^0 \to K^0_S K^0_S$ decay is a singly Cabibbo-suppressed channel [15]. The most recent SM-based analysis obtained a 95% confidence-level upper limit of 1.1% for direct CPV in this decay [16].

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

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

using a data sample of 921 fb^{-1} integrated luminosity [17], where the first uncertainty is statistical and the second is systematic. The result is consistent with SM expectations and is a significant improvement compared to the previous measurements of CLEO [18] and LHCb Collaborations [19], already probing the region of interest. At Belle II, we expect a precision of 0.2% with similar systematic errors as at Belle. As discussed in Section 3.4, errors on the measurements performed in the normalization channel, $D^0 \to K^0_S \pi^0$ will also reduce with increased statistics at Belle II.

3.6 $D^0 \to V\gamma$

The study of radiative decays $D^0 \to V\gamma$, where V is a vector meson, could be sensitive to new physics (NP) via significantly non-zero A_{CP} [20], [21]. Recently, Belle published the measurement of the branching fractions and CP asymmetries in decays $D^0 \to V\gamma$, where $V = \phi$, $\bar{K}^{*0}$, ρ^0 [22]. This constitutes 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 measured A_{CP} values for $D^0 \to \phi\gamma$, $D^0 \to \bar{K}^{*0}\gamma$ and $D^0 \to \rho^0\gamma$ are $-0.094 \pm 0.066 \pm 0.001$, $-0.003 \pm 0.020 \pm 0.000$ and $+0.056 \pm 0.152 \pm 0.006$, respectively. 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 $D^0 \to V\gamma$ is statistical. Hence, Belle II can greatly improve precision, as shown in Table 1.

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

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

4. A new flavor tagging technique 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% [23]. 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 suppress the combinatorial background, where π^+_s is a slow pion. This is the standard flavor tagging technique employed so far at B-factories.

Since three-fourth of the D^0 candidates in $c\bar{c}$ events at the B-Factories are not produced from D^{*+} decays, we have developed a new flavour tagging method, called the rest of the events (ROE) method [24]. As 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.

For this method, the selection of tagging charged kaon is crucial and is performed using a multivariate classifier, which is a boosted decision tree, labelled as "Criteria a". The "Criteria b" is referred to events in which the "Criteria a" along with a cut on the angle between the momenta in the center-of-mass frame of the D^0 candidate and the charged kaon in the ROE and a veto on the reconstructed K_S. The "Criteria c" 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 (ε) is 15% with a mis-tagging rate (w) below 5%, after vetoing the presence of neutral kaons K_L and K_S in the ROE [from Monte-Carlo (MC) truth]. BaBar achieved a ratio of 1.4 between the purity of the untagged D^0 sample and that of the tagged (with D^*) sample [25]. 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 an A_{CP} measurement. Figure 1 illustrates the ratio between the statistical error on an 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 alone [26]. The second plot illustrates how much Belle II can improve the statistical error on an A_{CP} measurement adding the ROE flavour tagging method.

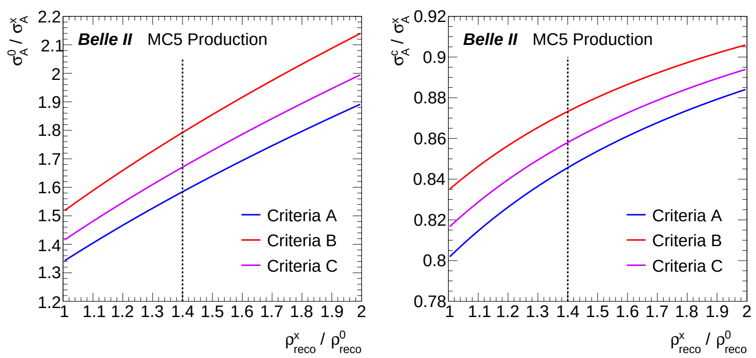

Figure 1: The left (right) plot shows the ratio between the statistical error on an A_{CP} measurement using the two different flavour tagging methods, namely, D^* and ROE, given by σ^X and σ^0 as a function of the purity of D^0 samples (the ratio between the combined statistical error (σ^C) and the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

5. Conclusions

Precision measurements of CP asymmetry in charm sector will be pursued by the Belle II Collaboration. The future projections of CP asymmetry at Belle II look promising. It will use a novel flavor-tagging technique 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.

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