Prospects for *CP* and *P* violation in Λ_c^+ decays at Super Tau Charm Facility

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CP violation is an excellent tool for probing flavor dynamics as we learned first with $K_L \to 2\pi$ and later also with the weak decays of beauty mesons. LHCb 2019 data have shown CP violation for the first time in $D^0 \to K^-K^+$ vs $D^0 \to \pi^-\pi^+$. Searching for CP asymmetries is of great interest in the charm quark sector in the Standard Model (SM) or even more beyond it. In charm hadron decays, lots of work had focused on two-body final states, and the measurements of CP asymmetries in three- or four-body final states are rare. Dalitz plots have shown an excellent record for three-body final states, and more results are desired for four-body ones. In this work we study CP asymmetries in the decays $\Lambda_c^+ \to pK^-\pi^+\pi^0/\Lambda\pi^+\pi^+\pi^-/pK_S\pi^+\pi^-$, where the SM gives zero values for the first two channels, while 3.3×10^{-3} is given for the last one due to $K^0 - \bar{K}^0$ oscillation. We performed a fast Monte Carlo simulation study by using electron-positron annihilation data of 1 ab^{-1} at center-of-mass energy $\sqrt{s} = 4.64$ GeV. The data is expected to be available by the next generation Super Tau Charm Facility proposed by China and Russia with one year (or even less) of the data taking operation. The results indicate that a sensitivity at the level of $0.2\sim0.5\%$ is accessible for these processes, which would be enough to measure nonzero CP-violating asymmetries as large as 1%. Furthermore $A_{T\text{-odd}} \neq 0$ can establish parity violation by themselves and likewise for $\bar{A}_{T\text{-odd}} \neq 0$. The SM is based on $W^{+/-}$ being 100% left handed. One can compare decay asymmetry parameters a_P from $\Lambda_c^+ \to \Lambda e^+\nu$ vs $\bar{a}_\mathrm{P}$ from $\bar{\Lambda}_c^- \to \bar{\Lambda}e^-\bar{\nu}$. In the SM one gets $a_\mathrm{P} = 1$ and $\bar{a}_\mathrm{P} = -1$ in the SM, while present data give the following: $(a_\mathrm{P} + \bar{a}_\mathrm{P})/2 = 0.00 \pm 0.04$. Probing these nonleptonic decays of Λ_c^+ would give new lessons about nonperturbative QCD or even indirect impact of new dynamics on parity violation.

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I. INTRODUCTION

Manifestations of charge parity violation (CPV) predicted by the Cabibbo-Kobayashi-Maskawa (CKM) mechanism [1] in the Standard Model (SM) are in impressive agreement with experimental results, especially for the strange and beauty quark sectors [2–4].[1] CPV in the charm quark sector predicted by the SM is at the order of 10^{-3} in singly Cabibbo suppressed decays and much less for doubly Cabibbo suppressed ones [5–7]. The level of 10^{-3} has been near the upper limit of the spread of a substantial range of predictions in the literature, and not really a typical estimate. For the first time CPV has been shown in the weak decays of charm mesons, namely, in $D^0 \to K^-K^+$ vs $D^0 \to \pi^-\pi^+$ in the LHCb 2019 data [8]. Additionally, CPV has never been observed in the decays of baryons, except for the evidence in the $\Lambda_b^0 \to p\pi^-\pi^+\pi^-$ decay [9].

We point out that nonleptonic decays of charmed hadrons mostly occur with many-body final states (FS) (and even more for beauty ones); crucial information is given there about fundamental dynamics, not as a "background" for two-body FS. For three-body FS decays, we have a well-known tool, namely, Dalitz plots with an excellent record. Yet one has to continue to four-body ones since we have to learn much more at least. Furthermore, inspired by evidence for CPV in $\Lambda_b^0 \to p\pi^-\pi^+\pi^-$ from LHCb data [9], it is interesting and meaningful to study CPV by the method of triple-product asymmetries in the charmed *baryon* Λ_c^+ decay.

There is an obvious, but important comment. When discussing CPV in the weak decays of beauty hadrons, one

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[1]However, it is not big enough to account for the matter-antimatter asymmetry which leaves one reason for searching for new physics (NP) beyond SM.

mostly looks at CKM suppressed transition processes. What about CKM favored ones? Indirect CPV has been established in the decay $B^0 \to J/\psi K_S$; the CKM favored amplitude of $b \to c\bar{c}s$ gives $|V_{cb}V_{cs}^*| \sim \mathcal{O}(\lambda^2) \simeq 0.05 \ll 1$. However, the situation is very different for charm hadrons, where the leading source is described by $|V_{cs}V_{ud}^*| \simeq 1 - \lambda^2 \simeq 0.95$. Furthermore charm baryons can produce direct CPV only. Thus, the SM cannot explain sizeable CPV asymmetries for $V_{cs}V_{ud}^*$ amplitudes in general, and in particular for $\Lambda_c^+ \to pK^-\pi^+\pi^0/\Lambda\pi^+\pi^+\pi^-$. Yet there is a special case, the SM predicts CPV for $\Lambda_c^+ \to pK_S\pi^+\pi^-$ at "around" 3.3×10^{-3} due to CPV in $K^0 - \bar{K}^0$ oscillation [6], although it is not due to $\Delta C \neq 0$. This similar prediction for CPV has been tested for $D^\pm \to K_S\pi^\pm$ with some success: $A_{CP}(D^+ \to K_S\pi^+) = (-0.41 \pm 0.09)$ %; yet the "landscape" is more complex for Λ_c^+. It would be close to a miracle, if NP could produce nonzero CPV for $\Lambda_c^+ \to pK^-\pi^+\pi^0/\Lambda\pi^+\pi^+\pi^-$ or sizably above 3.3×10^{-3} for $\Lambda_c^+ \to pK_S\pi^+\pi^-$, but it is possible. Thus, experimenters cannot ignore that. With more data and refined analyses in the future, one can use much better tools to calibrate favored decays, when one goes for accuracy. One has to be open minded about this project. Our community has successful experience with triple-product asymmetries $A_{T\text{-odd}}$ and $\bar{A}_{T\text{-odd}}$ (see also Sec. II B below). In the weak decays of charm baryons one goes after parity violation (PV) and direct CPV measurements in somewhat different ways.

$A_{T\text{-odd}} \neq 0$ establish PV by itself and likewise for $\bar{A}_{T\text{-odd}}$:

$$a_{\mathrm{P}} \equiv A_{T\text{-odd}} \neq 0, \qquad \bar{a}_{\mathrm{P}} \equiv \bar{A}_{T\text{-odd}} \neq 0; \tag{1}$$

in practice one can test experimental uncertainties by comparing $A_{T\text{-odd}}$ vs $\bar{A}_{T\text{-odd}}$. In the literature, e.g., in [9], PV is also defined as $(a_{\mathrm{P}} + \bar{a}_{\mathrm{P}})/2$. The SM produces large PV; we will return to that below. As we had said above, the landscape of $\Delta C \neq 0$ is close to CP invariance; thus one can connect CV (charged conjugation violation) with PV: $a_{\mathrm{P}} + a_{\mathrm{C}} \simeq 0$. Using different words to describe the same situations we know that these CP asymmetries are very small at best:

$$\delta_{CP} \equiv \frac{1}{2}(A_{T\text{-odd}} - \bar{A}_{T\text{-odd}}) \ll 1. \tag{2}$$

Strong final-state interactions (FSI) are not the source of CPV. That has to come from new dynamics with weak phases—yet FSI should show their impact. One has to be realistic, very likely we will not find CPV in these weak decays of Λ_c^+. Yet it is *not* a waste of time, and those channels are worth exploring in experiments due to the following points:

(i) It is not a miracle to find CPV in Cabibbo suppressed decays of Λ_c^+; one can use those mentioned channels to calibrate singly Cabibbo suppressed decays to probe *regional* CP asymmetries in $\Lambda_c^+ \to p\pi^-\pi^+\pi^0/pK^-K^+\pi^0/\Lambda K^+\pi^+\pi^-$ with accuracy in the future.

(ii) One expects sizable PV in the weak decays of Λ_c^+.

(iii) At least, one can get novel lessons about the impact of strong forces close to thresholds, namely, about nonperturbative QCD.

We will consider three decay processes: $\Lambda_c^+ \to \Lambda\pi^+\pi^+\pi^-$, $\Lambda_c^+ \to pK^-\pi^+\pi^0$, and $\Lambda_c^+ \to pK_S\pi^+\pi^-$ due to their large branching fractions (BR) [10][2]:

$$\begin{aligned} &\mathrm{BR}(\Lambda_c^+ \to pK^-\pi^+\pi^0) \simeq 4.4\%, \\ &\mathrm{BR}(\Lambda_c^+ \to \Lambda\pi^+\pi^+\pi^-) \simeq 3.6\%, \\ &\mathrm{BR}(\Lambda_c^+ \to pK_S\pi^+\pi^-) \simeq 1.6\%. \end{aligned} \tag{3}$$

The current paper is mainly dedicated to the study of physics sensitivities that can be achieved at a future Super Tau Charm Facility (STCF), where the central values for PV and CPV quantities of charmed baryon decays are surely measurable.

The new generation STCF is an electron-positron collider which operates at the τ-charm energy region, with peak luminosity above $0.5 \times 10^{35}\ \mathrm{cm^{-2}\,s^{-1}}$ at a center-of-mass energy (CME) of $\sqrt{s} \sim 4\ \mathrm{GeV}/c^2$ [11–13]. The facility is discussed strongly and proposed by the Chinese and Russian high energy physics communities in last few years, and is expected to be realized in the coming ten years. With such high luminosity, the proposed STCF can deliver electron-position collisions to accumulate more than $1\ \mathrm{ab^{-1}}$ of integrated luminosity per year, thus providing an excellent opportunity to study charm physics, notably including CPV with charmed meson and baryon decays.

In the electron-positron annihilation process, the Λ_c baryon can be produced via the process $e^+e^- \to \Lambda_c^+\bar{\Lambda}_c^-$ abundantly. The Belle experiment has measured the production cross section of $e^+e^- \to \Lambda_c^+\bar{\Lambda}_c^-$ by the initial state radiation (ISR) process, where a peak is depicted as the measured Born cross section with the value of $\sigma \sim 470$ pb at CME of $\sqrt{s} = 4.63\ \mathrm{GeV}/c^2$, and is assigned to originate from the charmoniumlike state $Y(4630)$ decay [14]. The BESIII experiment has collected data at CME of $\sqrt{s} = 4.6\ \mathrm{GeV}/c^2$ with an integrated luminosity of $567\ \mathrm{pb^{-1}}$, as well as other three data sets at lower CME but above the $\Lambda_c^+\bar{\Lambda}_c^-$ mass threshold ($\sqrt{s} = 4.575$, 4.580, and 4.590 GeV) with more than 1 order smaller luminosity (47.7, 8.54, and $8.16\ \mathrm{pb^{-1}}$, respectively). With these data sets, BESIII is very productive, and has published several interesting results, such as the production cross section of $e^+e^- \to \Lambda_c^+\bar{\Lambda}_c^-$, the absolute decay branching fractions of $\Lambda_c^+ \to pK^-\pi^+$ as well as other eleven Cabibbo favored (CF) hadronic modes, the branching fractions of singly Cabibbo suppressed decays, the decay with neutron included, semileptonic decay, and inclusive decays, etc. [15–20]. In proton-proton collisions, such as at the LHCb experiment, the Λ_c^+ baryon is abundantly produced directly from proton-proton collision or via beauty baryon decays [21–23]. Comparing to the Belle II and

[2]Maybe one can measure also BR $(\Lambda_c^+ \to pK_L\pi^+\pi^-) \sim 1.6\%$.

LHCb experiments, the STCF is short on statistics. However, STCF has several advantages, such as the excellent ratio of signal to background, the perfect detection efficiency, the well-controlled systematic uncertainty and the capability of full event reconstruction, etc. By implementing the double tag method, STCF can perform systematic researches of Λ_c^+ decays, including the absolute measurements of semileptonic decays and the decays with a neutron, K_L or invisible particles included in final state [24]. Besides studying Λ_c^+ physics, STCF will play a crucial role in the study of how the $Y(4630)$ state enters $e^+e^- \to \Lambda_c^+\bar{\Lambda}_c^-$ production [25], the mixing of axial-vector mesons [26], the proton form factors [27,28], etc.

In what follows, we will perform a careful investigation for the sensitivities on *CPV* and *PV* in the decays $\Lambda_c^+ \to \Lambda\pi^+\pi^+\pi^-$, $\Lambda_c^+ \to pK^-\pi^+\pi^0$, and $\Lambda_c^+ \to pK_S\pi^+\pi^-$ at the future STCF. There is a rich landscape of strong and weak forces. One needs more refined analyses—but we have the tools for that; all we need is more data.

II. OBSERVABLES

The situations between *PV* and *CPV* are very different as said above; thus, the goals are also different. The first example is the following: with more data one should find nonzero values of *PV* in these nonleptonic transitions.

A. Parity asymmetries

It had been realized that it is a crucial test of the SM: charged $W^\pm$ bosons are left handed, as we had learned from $\pi^+/K^+ \to \mu^+\nu$ vs $\pi^+/K^+ \to e^+\nu$; so far, we have not seen a right-handed one. 2018 PDG data [10] have shown *PV* in $\Lambda_c^+ \to \Lambda l^+\nu$ that are consistent with the SM predictions, although with sizable uncertainties:

$$(a_P + \bar{a}_P)/2 = 0.00 \pm 0.04. \tag{4}$$

On the other hand, this situation is not well tested in nonleptonic decays. Probing these nonleptonic decays of Λ_c^+ would give new lessons about nonperturbative QCD or even the indirect impact of new dynamics on PV. In these nonleptonic decays of Λ_c^+ *T*-odd moments should produce sizable *PV* with different values; see Eq. (1). We have added these analyses of *PV* below. Indeed, one gets a nontrivial test of this experiment.

One should expect large values of *PV* in those nonleptonic transitions. A small/tiny value of *PV* would be a signal of NP. However, one cannot predict future results of *PV* even within the SM. It means our community would learn new lessons about the impact of strong forces. So far, no true predictions can be given due to nonperturbative QCD with many resonances in the region of 0.5–2 GeV, including broad ones like $f_0(500)$, $K_0^*(700)$, etc. Our main point is that we describe the route to use when our community has the future data to get the information about the underlying dynamics.

B. *CP* asymmetries

The SM predicts tiny *CPV* in charm baryon decays; therefore, large statistics are required. Obviously one goes after direct *CPV*. The landscape of data is very "flat" for *CP* asymmetries: it is expected to be very unlikely that any evidence for *CPV* in CF transitions is found, e.g., $\Lambda_c^+ \to \Lambda\pi^+$ [29] or $\Lambda_c^+ \to \Lambda e^+\nu$ [30], where *CPV* was investigated by measuring the decay asymmetry parameters. There are also recent theoretical papers about the decay asymmetry parameters [31–33], and especially in Ref. [33], the model calculations are done for the singly Cabibbo-suppressed decays. We also notice that BESIII has measured the absolute branching fraction of $\Lambda_c^+ \to \Lambda l^+\nu$ with fewer uncertainties [18]. We exploit triple-product asymmetries composed by four-momenta without repeating the information of polarization as has been done in Refs. [34,35].

The CF decays of Λ_c^+ baryons with multihadrons in the final state, such as $\Lambda_c^+ \to pK^-\pi^+\pi^0$, $\Lambda_c^+ \to \Lambda\pi^+\pi^+\pi^-$, and $\Lambda_c^+ \to pK_S\pi^+\pi^-$, depict a very "complex" landscape [10,20], which is believed to give us much more information about the underlying dynamics than that of $\Lambda_c^+ \to \Lambda\pi^+$ and $\Lambda_c^+ \to \Lambda e^+\nu$, but both need more data and refined analyses. To describe the four-body weak decays of Λ_c^+ one has one baryon in the FS, p or Λ, plus three pseudoscalar mesons–kaons or pions. In the rest frame of the charm baryon, we have two observables of spin-1/2 ($\mathbf{s}_{\Lambda_c}$ and $\mathbf{s}_{p/\Lambda}$) and the momenta of the four particles $\mathbf{p}_{p/\Lambda}$ plus the momenta of the three mesons. One can describe *T*-odd moments in different ways, which give us the same information about the underlying dynamics; however, with finite data and lack of perfect control of QCD, some are better than others. We exploit the scalar triple products to construct *CPV* observables; see the Refs. [35–46]. These papers came mostly from theorists who had focused on singly Cabibbo transitions. This method has been widely applied in several experiments; see recent ones in Refs. [9,47–49]. Some early ones can be found in Refs. [50–52].

For these Λ_c^+ decays, the scalar triple products $C_{\hat{T}} = \mathbf{p}_{p/\Lambda}\cdot(\mathbf{p}_{h_1}\times\mathbf{p}_{h_2})$ and the conjugate, $\bar{C}_{\hat{T}} = \mathbf{p}_{\bar{p}/\bar{\Lambda}}\cdot(\mathbf{p}_{\bar{h}_1}\times\mathbf{p}_{\bar{h}_2})$, with pseudoscalar mesons h_i, are defined to study *CPV*. The momenta $\mathbf{p}$ are measured in the rest frame of the Λ_c^+ baryon. When two π^+ (or two π^-) mesons are present, the one with the larger momentum is selected. The asymmetries are then defined as

$$A_{\hat{T}}(C_{\hat{T}}) = \frac{N(C_{\hat{T}} > 0) - N(C_{\hat{T}} < 0)}{N(C_{\hat{T}} > 0) + N(C_{\hat{T}} < 0)},$$
$$\bar{A}_{\hat{T}}(\bar{C}_{\hat{T}}) = \frac{\bar{N}(-\bar{C}_{\hat{T}} > 0) - \bar{N}(-\bar{C}_{\hat{T}} < 0)}{\bar{N}(-\bar{C}_{\hat{T}} > 0) + \bar{N}(-\bar{C}_{\hat{T}} < 0)}. \tag{5}$$

These correspond to $A_{T\text{-odd}}$ $\bar{A}_{T\text{-odd}}$ moments. *CPV* observables are δ_{CP}; see Eq. (2). Any significant deviation from zero indicates *CPV*; in particular, one also looks for the number N of events for the *direct CPV* asymmetries:

$$A_{CP}^{(K)} = \frac{N(\Lambda_c^+ \to pK^-\pi^+\pi^0) - N(\bar{\Lambda}_c^- \to \bar{p}K^+\pi^-\pi^0)}{N(\Lambda_c^+ \to pK^-\pi^+\pi^0) + N(\bar{\Lambda}_c^- \to \bar{p}K^+\pi^-\pi^0)},$$
$$A_{CP}^{(\pi)} = \frac{N(\Lambda_c^+ \to \Lambda\pi^+\pi^+\pi^-) - N(\bar{\Lambda}_c^- \to \bar{\Lambda}\pi^+\pi^-\pi^-)}{N(\Lambda_c^+ \to \Lambda\pi^+\pi^+\pi^-) + N(\bar{\Lambda}_c^- \to \bar{\Lambda}\pi^+\pi^-\pi^-)},$$
$$A_{CP}^{(K_S^0)} = \frac{N(\Lambda_c^+ \to pK_S^0\pi^+\pi^-) - N(\bar{\Lambda}_c^- \to \bar{p}K_S^0\pi^-\pi^-)}{N(\Lambda_c^+ \to pK_S^0\pi^+\pi^-) + N(\bar{\Lambda}_c^- \to \bar{p}K_S^0\pi^-\pi^-)}. \quad (6)$$

One can expect sizable values of $A_{\hat{T}}$ and $\bar{A}_{\hat{T}}$ due to FSI effects [6,40]. It is also possible to find nonzero *CPV*. In Ref. [36], the authors show that large *CPV* can indeed happen in NP with the two-Higgs doublet model as an example. The *CP* violation $\sim 0.18 \sin\phi$ with ϕ denoting the new-physics *CP*-violating phase. Then it can reach 18% if $\sin\phi$ is close to 1.

The measurements may vary over the phase space due to resonant contributions or their interference effects, which may be canceled if integrating over the whole phase space. For the decays $\Lambda_c^+ \to pK^-\pi^+\pi^0$, $\Lambda_c^+ \to \Lambda\pi^+\pi^+\pi^-$, and $\Lambda_c^+ \to pK_S^0\pi^+\pi^-$, the semiregional *CPV* is measured with respect to several bins separated by the dihedral angle, and the Monte Carlo (MC) simulation is also exploited to study this case. We stress again that no *CP* asymmetry has been found yet in the transitions of charm baryons. Therefore, one has to probe *CPV* with more data and tools, although this is not trivial.

III. MEASUREMENT PROCEDURE

The STCF project is in the research and development stage. To maximize the physics potential, a BESIII-like detector but with much improved performance for each subsystem is proposed. From inside to outside, the STCF detector consists of a tracking system, a particle identification (PID) system, a high granularity electromagnetic calorimeter, and a muon detector with high μ/π separation capability. To be competitive on high precision measurements, and to cope with high event rate and radiation dose, several advanced technologies are proposed to be the STCF subdetectors, such as a thin silicon detector or a micropattern gas detector for the inner tracking system, a Cherenkov based PID system, crystal LYSO or a pure CsI based electromagnetic calorimeter, etc. To investigate the physics potential capability and optimize the detector design, a fast simulation tool dedicated to the STCF detector has been developed, where the detection efficiency and measurement resolution of each subdetector are parametrized according to an empirical formula and the BESIII detector performance, and the parameters are adjustable flexibly. The event generators for both signal and background processes are migrated from the BESIII experiment. The tool has been validated by the BESIII full simulation package [53] using Geant4, and provides a perfect platform to perform physics studies with huge statistics. A note dedicated to this tool is under preparation.

To study the sensitivities of *CPV* and *PV* in the decays $\Lambda_c^+ \to \Lambda\pi^+\pi^+\pi^-$, $\Lambda_c^+ \to pK^-\pi^+\pi^0$, and $\Lambda_c^+ \to pK_S\pi^+\pi^-$, both signals and inclusive MC samples are generated based on the STCF fast simulation tool, where the parameters for each subdetector are from BESIII. In this study, the Λ_c^+ signal is originated from the process $e^+e^- \to \Lambda_c^+\Lambda_c^-$ at the CME of $\sqrt{s} = 4.64$ GeV, where the peak of the production cross section lies. The study is performed based on the integrated luminosity of 1 ab^{-1}, which is expected to be achieved at STCF within one year (or even less) of data taking. In the simulation, e^+e^- collisions are simulated by the KKMC generator [54], which takes into account the beam energy spread and the ISR correction, where the beam energy spread is assigned to be same value as that of BEPCII. To study the potential background and optimize event selection, an inclusive MC sample, which includes $\Lambda_c^+\bar{\Lambda}_c^-$ pair production, l^+l^- $(l = e, \mu, \tau)$ events, open charm processes, ISR-produced low-mass ψ states, and the continuum process $e^+e^- \to q\bar{q}$ with $q = u, d, s$ quarks [55] are generated with the integrated luminosity of 1 ab^{-1}, where the decays of intermediate states, such as Λ_c^+ baryons, charmed mesons, charmonium state, and light hadrons, is performed according to the branching fractions quoted from PDG. To study the signal shape and detection efficiency, the signal MC samples of $\Lambda_c^+ \to pK^-\pi^+\pi^0$, $\Lambda_c^+ \to \Lambda\pi^+\pi^+\pi^-$, and $\Lambda_c^+ \to pK_S\pi^+\pi^-$ are generated with uniform distribution in phase space; no intermediate state in the two or three bodies is considered. The real data will show the impact of intermediate states, such as ρ, K^*, Δ, etc.

In this analysis, the single tag method is implemented to improve the statistics. Candidate events are selected with the similar criteria (including charged tracks, π^0 and K_S candidates selection, PID, etc.) as in Ref. [19] according to the final state of signal. The signal yields are determined by performing a binned maximum likelihood fit to the distribution of the beam constrained mass M_{BC}, which is defined as $M_{BC} \equiv \sqrt{E_{\rm beam}^2/c^4 - p_{\Lambda_c}^2/c^2}$, with $E_{\rm beam}$ denoting the energy of the electron-positron beam and p_{Λ_c} the three-momentum of the Λ_c^+ candidate calculated from the momenta of the final-state particles in the initial e^+e^- center-of-mass system. Figure 1 shows the M_{BC} distributions for $\Lambda_c^+ \to pK^-\pi^+\pi^0$, $\Lambda_c^+ \to \Lambda\pi^+\pi^+\pi^-$, and $\Lambda_c^+ \to pK_s\pi^+\pi^-$ decays corresponding to 1 ab^{-1} of an inclusive MC sample, where ΔE, defined as $\Delta E = E_{\rm beam} - E_{\Lambda_c}$ with E_{Λ_c} denoting the energy of Λ_c candidate summing over the energy of the corresponding final-state particles, is required to be within 3 times its resolution. Clear Λ_c^+ signals with low background are observed. Detailed studies by the inclusive MC sample indicate that there is no peaking background in the M_{BC} distributions. Thus, in the fit to

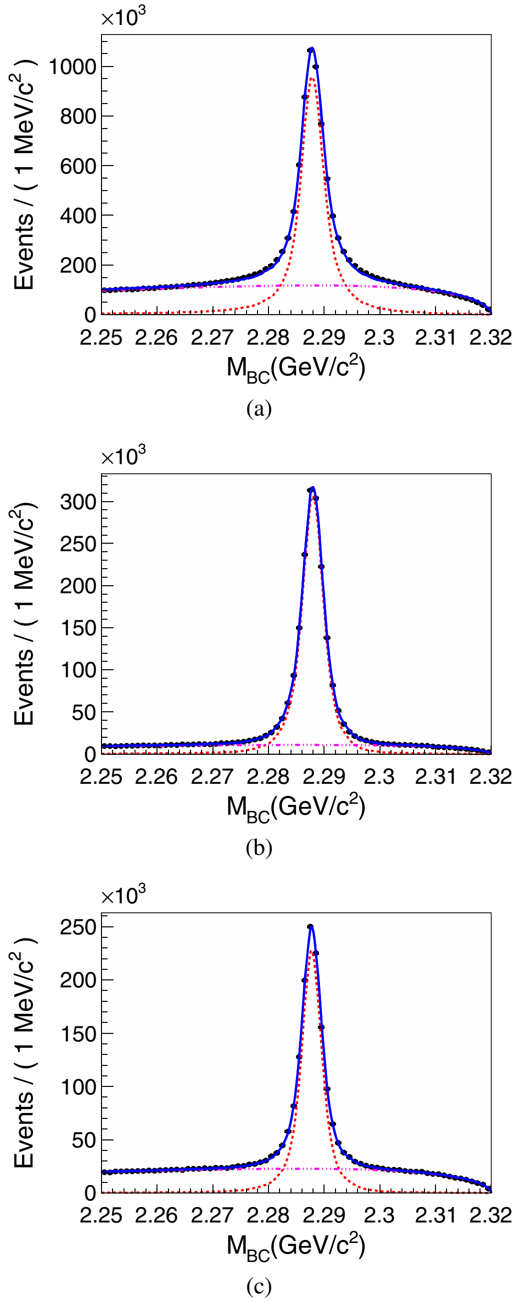

FIG. 1. M_{BC} distribution for (a) $\Lambda_c^+ \to pK^-\pi^+\pi^0$, (b) $\Lambda_c^+ \to \Lambda\pi^+\pi^+\pi^-$, and (c) $\Lambda_c^+ \to pK_S^0\pi^+\pi^-$ decays. The dots correspond to the MC simulation. The blue solid curves are the fit functions, while the pink dotted (red dashed) lines represent the backgrounds (signals).

determine the signal yields, the shape of background is described by an ARGUS function [56] with fixed high-end truncation, and those of signal are obtained from the signal MC samples.

For semiregional *CPV*, one may discretize the dihedral angle and/or the invariant mass into different bins, as in Ref. [9]. In the intermediate state regions, strong phases are enhanced and thus can provide opportunity for large *CP* asymmetries due to large interference. Since the components of intermediate states are unknown due to the lack of experimental data, in this study, we split the phase space into different bins along the dihedral angle Φ distribution only, and the binning along the invariant mass distribution is not considered. Here, Φ is the angle between the decay planes formed by the $p\pi^0$ and $K^-\pi^+$ ($p\pi^-$ and $K_S^0\pi^+$, $\Lambda\pi^+_{\rm fast}$ and $\pi^+_{\rm slow}\pi^-$) for the process $\Lambda_c^+ \to pK^-\pi^+\pi^0$ ($\Lambda_c^+ \to pK_S^0\pi^+\pi^-$, $\Lambda_c^+ \to \Lambda\pi^+\pi^+\pi^-$). In the future, once collecting huge data at STCF, we can have a better understanding of the underlying dynamics of the Λ_c^+ decay, including the impact of broad intermediate states, such as $K_0^*(700)/\kappa$ and $f_0(500)/\sigma$, etc., and the analyses of semiregional *CPV* can be refined.[3]

IV. RESULTS AND DISCUSSIONS

Following the approaches described in Sec. III, we report in Table I the physics sensitivities for direct *CPV*, as defined in Eq. (6), as well as for *PV* and *CPV* observables constructed from the *T*-odd moments elaborated in Eqs. (1) and (2). The physics sensitivities include the statistical uncertainties only; systematic uncertainties are expected to be well under control.[4] By error propagation, according to Eqs. (6), (1), and (2), if we ignore the impact of the statistical uncertainty from background contamination, and assume $N_{\Lambda_c^+} = N_{\bar{\Lambda}_c^-} = N$ and $N(C_{\hat{T}} > 0) = N(C_{\hat{T}} < 0) = \bar{N}(\bar{C}_{\hat{T}} > 0) = \bar{N}(\bar{C}_{\hat{T}} < 0) = N/2$, the statistical uncertainties for A_{CP}, $(a_{\rm P} + \bar{a}_{\rm P})/2$ and δ_{CP} are $1/\sqrt{2N}$, where $N_{\Lambda_c^+}$ and $N_{\bar{\Lambda}_c^-}$ are the numbers of Λ_c^+ and $\bar{\Lambda}_c^-$ candidate events, and $N(C_{\hat{T}} > 0)$ ($\bar{N}(\bar{C}_{\hat{T}} > 0)$) and $N(C_{\hat{T}} < 0)$ ($\bar{N}(\bar{C}_{\hat{T}} < 0)$) are the numbers of candidate events with $C_{\hat{T}} > 0$ and $C_{\hat{T}} < 0$ for the Λ_c^+ ($\bar{\Lambda}_c^-$) candidates, respectively. Thus, as shown in Table I, the three measured variables have the same sensitivities, mostly due to the small impact from the background, and provide complementary and more comprehensive information to search for *PV* and *CPV* in Λ_c^+ hadronic decays. With an $e^+e^- \to \Lambda_c^+\bar{\Lambda}_c^-$ data sample of 1 ab^{-1} integrated luminosity at $\sqrt{s} = 4.64$ GeV collected by STCF, the physics sensitivities to search for *PV* and *CPV* are at the few per mille level for three interesting decay modes, individually, which are at the level of potential *CPV* in charm sector and unambiguous *PV* if observed.

As discussed previously, the sensitivity on *CPV* may be enlarged in some regions of phase space due to the enhancement of the strong phase and interference. This kind of *CPV* is called semiregional *CPV* or localized *CPV*, and is of great interest for both theorists and experimentalists. In this study, we also perform a sensitivity study for

[3] We also note that the knowledge of the two-photon couplings to the scalars [57] is helpful to understand their structures.

[4] Only the systematic uncertainty related with the asymmetry between positive and negative charged tracking will have to be taken into account.

TABLE I. The physics sensitivities for direct CPV as well as $(a_{\rm P} + \bar{a}_{\rm P})/2$ (PV) and δ_{CP} (CPV) constructed from the T-odd moments for $\Lambda_c^+ \to pK^-\pi^+\pi^0$, $\Lambda_c^+ \to \Lambda\pi^+\pi^+\pi^-$, and $\Lambda_c^+ \to pK_S^0\pi^+\pi^-$ processes with 1 ab^{-1} of data at $\sqrt{s} = 4.64$ GeV at STCF. The results for $(a_{\rm P} + \bar{a}_{\rm P})/2$ and δ_{CP} are the same.

Channel	Direct CPV	$(a_{\rm P} + \bar{a}_{\rm P})/2$, δ_{CP}
$\Lambda_c^+ \to pK^-\pi^+\pi^0$	0.0025	0.0026
$\Lambda_c^+ \to \Lambda\pi^+\pi^+\pi^-$	0.0052	0.0052
$\Lambda_c^+ \to pK_S^0\pi^+\pi^-$	0.0040	0.0041

TABLE II. The sensitivities for semiregional CPV (δ_{CP}) in $\Lambda_c^+ \to pK^-\pi^+\pi^0$, $\Lambda_c^+ \to \Lambda\pi^+\pi^+\pi^-$, and $\Lambda_c^+ \to pK_S^0\pi^+\pi^-$ decays with ten bins, for 1 ab^{-1} at $\sqrt{s} = 4.64$ GeV at STCF.

Φ	$pK^-\pi^+\pi^0$	$\Lambda\pi^+\pi^+\pi^-$	$pK_S^0\pi^+\pi^-$
(0, 0.1π)	0.0078	0.016	0.013
(0.1π, 0.2π)	0.0080	0.016	0.013
(0.2π, 0.3π)	0.0081	0.017	0.013
(0.3π, 0.4π)	0.0082	0.017	0.013
(0.4π, 0.5π)	0.0083	0.017	0.013
(0.5π, 0.6π)	0.0083	0.017	0.013
(0.6π, 0.7π)	0.0083	0.017	0.013
(0.7π, 0.8π)	0.0080	0.016	0.013
(0.8π, 0.9π)	0.0079	0.016	0.013
(0.9π, π)	0.0077	0.016	0.013

semiregional CPV for the three Λ_c^+ decay models, individually. Because of the lack of information on the intermediate states, the studies are performed only by binning the dihedral angle Φ, as defined in Sec. III, based on MC samples generated with a phase-space model. The measurements with real data are expected to be of better sensitivity due to the contribution from intermediate states. In this study, we discretize the dihedral angle Φ into ten bins with equal steps from 0 to π, and measure the T-odd moments CPV in each bin. As shown in Table II, the sensitivities for $\Lambda_c^+ \to pK^-\pi^+\pi^0$, $\Lambda\pi^+\pi^+\pi^-$, and $pK_S^0\pi^+\pi^-$ in each bin are around 0.0080, 0.016, and 0.013, respectively, which are smaller by a factor $1/\sqrt{10}$ relative to global CPV values, since the statistics is reduced by a factor 10 in each bin.

V. CONCLUSIONS AND PROSPECTS

Searching for CPV and PV in charmed baryon decays certainly provide complementary and comprehensive information to understand the underlaying dynamics of charmed hadrons and test the SM, and is of great interest both for theorists and experimentalists. The future STCF proposed by Chinese and Russian scientists may provide a great platform for these kinds of studies due to its characters of high luminosity, broad center-of-mass energy acceptance, abundant production, clean environment, etc. In this work, we propose to study direct CPV by measuring the asymmetries of decay branching fractions between charge conjugate modes as well as PV and CPV by constructing T-odd moments in Λ_c^+ decays to multihadron final states. We study the physics sensitivities for CPV and PV in the decays $\Lambda_c^+ \to pK^-\pi^+\pi^0$, $\Lambda_c^+ \to \Lambda\pi^+\pi^+\pi^-$, and $\Lambda^+ \to pK_S\pi^+\pi^-$ by performing a fast simulation, where the Λ_c^+ is assumed to be from the e^+e^- annihilation to the $\Lambda_c^+\bar{\Lambda}_c^-$ pair at the center-of-mass energy of $\sqrt{s} = 4.64$ GeV with 1 ab^{-1} e^+e^- integrated luminosity, i.e., it is expected to be available in one year (or even less) operating at a future STCF. The results indicate that the physics sensitivities are around $0.25 \sim 0.5\%$ for the three decay modes, individually, which is at the level of potential CPV in the charm hadron sector or for an unambiguous PV observation. We also discuss how semiregional CPV may be enlarged due to the enhancement of the strong phase and interference, and perform the sensitivity study for the same decay modes by binning the dihedral angle distribution. Simulations cannot give predictions, in particular, for many-body final states. In the future, with huge real data collected at STCF, we can also study the intermediate states and their impact. Many exciting results are expected at STCF, providing excellent information for nonperturbative QCD studies.

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