arXiv:2203.03211v1 [hep-ph] 7 Mar 2022

White Paper for RF01 working group in Snowmass 2021

Charm Physics in the High-Luminosity Super τ-Charm Factory

Hai-Yang Cheng,[a] [1] Xiao-Rui Lyu,[b] [2] Zhi-Zhong Xing[b,c] [3]

[a] Institute of Physics, Academia Sinica, Taiwan 11529, China
[b] University of Chinese Academy of Sciences, Beijing 100049, China
[c] Institute of High Energy Physics, Beijing 100049, China

(on behalf of the STCF working group)

Abstract

This is a white paper on the STCF charm physics contributing to the Snowmass 2021 proceedings in the RF01 working group.

1 Introduction

The discovery of the charm quark in 1974 was a great milestone in the development of particle physics and the establishment of the standard model (SM). A high-luminosity Super τ-Charm Factory (STCF) [1–3], which is capable of producing about $10^9 \sim 10^{10}$ quantum-coherent $D^0\bar{D}^0$ meson pairs and $D^+_{(s)}$ mesons, more than 10^8 Λ_c^+ baryons as well as heavier charmed baryons, will be an important low-background playground to test the standard model (SM) and probe new physics, regarding to the experience at BESIII [4]. In particular, it will serve as a unique tool to determine the Cabbibo-Kobayashi-Maskawa (CKM) matrix elements V_{cd} and V_{cs}, to measure D^0-$\bar{D}^0$ mixing parameters, to probe CP violation in the charm sector, to search for rare and forbidden charmed hadron decays, and to study other fundamental problems associated with the charmed hadron. Many of the golden measurements at STCF will be dominated by systematic uncertainties, which requires a state-of-art detector with excellent performance, especially in identifying the types of different charged particles, detecting low-momentum charged particles and measuring photons [5].

2 Charmed meson

2.1 $D^+_{(s)}$ leptonic decays

Direct determination of the CKM matrix elements $|V_{cd}|$ and $|V_{cs}|$ is one of the most important targets in charm physics. These two quark flavor mixing quantities not only govern the rates of leptonic D^+ and D_s^+ decays, but also play a crucial role in testing the unitarity of the CKM matrix. Precise measurement of $|V_{cd}|$ and $|V_{cs}|$ is a priority of the STCF experiment.

The most precise way to determine $|V_{cd}|$ and $|V_{cs}|$ at STCF is via pure-leptonic decays $D^+_{(s)} \to \ell^+\nu_\ell$ (for $\ell = e, \mu, \tau$), as the semi-leptonic decay suffers from large uncertainties of LQCD calculations of form factors. The product of the decay constant $f_{D^+_{(s)}}$, and $|V_{cd(s)}|$ is

[1] E-mail: phcheng@phys.sinica.edu.tw
[2] E-mail: xiaorui@ucas.ac.cn
[3] E-mail: xingzz@ihep.ac.cn

Table 1: For the studies on $D^+_{(s)} \to \ell^+\nu_\ell$, the obtained precisions at BESIII and projected precisions at STCF and Belle II. Considering that the LQCD uncertainty of $f_{D^+_{(s)}}$ has been updated to be about 0.2% [11], the $|V_{cd}|$ measured at BESIII has been re-calculated, and is marked with *. Preliminary results are marked with †. For Belle II, we assume that the systematic uncertainties can be reduced by a factor of 2 compared to Belle's results.

	BESIII	STCF	Belle II
Luminosity	2.93 fb^{-1} at 3.773 GeV	1 ab^{-1} at 3.773 GeV	50 ab^{-1} at $\Upsilon(nS)$
$\mathcal{B}(D^+ \to \mu^+\nu_\mu)$	$5.1\%_{\rm stat}$ $1.6\%_{\rm syst}$ [6]	$0.28\%_{\rm stat}$	–
f_{D^+} (MeV)	$2.6\%_{\rm stat}$ $0.9\%_{\rm syst}$ [6]	$0.15\%_{\rm stat}$	–
$\|V_{cd}\|$	$2.6\%_{\rm stat}$ $1.0\%^*_{\rm syst}$ [6]	$0.15\%_{\rm stat}$	–
$\mathcal{B}(D^+ \to \tau^+\nu_\tau)$	$20\%_{\rm stat}$ $10\%_{\rm syst}$ [7]	$0.41\%_{\rm stat}$	–
$\frac{\mathcal{B}(D^+ \to \tau^+\nu_\tau)}{\mathcal{B}(D^+ \to \mu^+\nu_\mu)}$	$21\%_{\rm stat}$ $13\%_{\rm syst}$ [7]	$0.50\%_{\rm stat}$	–
Luminosity	3.2 fb^{-1} at 4.178 GeV	1 ab^{-1} at 4.009 GeV	50 ab^{-1} at $\Upsilon(nS)$
$\mathcal{B}(D_s^+ \to \mu^+\nu_\mu)$	$2.8\%_{\rm stat}$ $2.7\%_{\rm syst}$ [8]	$0.30\%_{\rm stat}$	$0.8\%_{\rm stat}$ $1.8\%_{\rm syst}$
$f_{D_s^+}$ (MeV)	$1.5\%_{\rm stat}$ $1.6\%_{\rm syst}$ [8]	$0.15\%_{\rm stat}$	–
$\|V_{cs}\|$	$1.5\%_{\rm stat}$ $1.6\%_{\rm syst}$ [8]	$0.15\%_{\rm stat}$	–
$f_{D_s^+}/f_{D^+}$	$3.0\%_{\rm stat}$ $1.5\%_{\rm syst}$ [8]	$0.21\%_{\rm stat}$	–
$\mathcal{B}(D_s^+ \to \tau^+\nu_\tau)$	$2.2\%_{\rm stat}$ $2.6\%^\dagger_{\rm syst}$	$0.24\%_{\rm stat}$	$0.6\%_{\rm stat}$ $2.7\%_{\rm syst}$
$f_{D_s^+}$ (MeV)	$1.1\%_{\rm stat}$ $1.5\%^\dagger_{\rm syst}$	$0.11\%_{\rm stat}$	–
$\|V_{cs}\|$	$1.1\%_{\rm stat}$ $1.5\%^\dagger_{\rm syst}$	$0.11\%_{\rm stat}$	–
$\overline{f}^{\mu\&\tau}_{D_s^+}$ (MeV)	$0.9\%_{\rm stat}$ $1.0\%^\dagger_{\rm syst}$	$0.09\%_{\rm stat}$	$0.3\%_{\rm stat}$ $1.0\%_{\rm syst}$
$\|\overline{V}^{\mu\&\tau}_{cs}\|$	$0.9\%_{\rm stat}$ $1.0\%_{\rm syst}{}^\dagger$	$0.09\%_{\rm stat}$	–
$\frac{\mathcal{B}(D_s^+ \to \tau^+\nu_\tau)}{\mathcal{B}(D_s^+ \to \mu^+\nu_\mu)}$	$3.6\%_{\rm stat}$ $3.0\%^\dagger_{\rm syst}$	$0.38\%_{\rm stat}$	$0.9\%_{\rm stat}$ $3.2\%_{\rm syst}$

directly accessed by measuring the widths of $D^+_{(s)} \to \ell^+\nu_\ell$. Then with the input of $f_{D^+_{(s)}}$ from LQCD, the value of $|V_{cd(s)}|$ or $f_{D^+_{(s)}}$ can be obtained. Listed in Table 1 are the most precise determinations of $|V_{cs(d)}|$ and $f_{D^+_{(s)}}$ [6–8] at BESIII and the projected precisions at STCF [9,10]. Note that for $\mathcal{B}(D^+ \to \tau^+\nu_\tau)$, several τ^+ decay channels, such as $\tau^+ \to \pi^+\overline{\nu}_\tau$, $e^+\overline{\nu}_\tau\nu_e$, $\mu^+\overline{\nu}_\tau\nu_\mu$, and $\rho^+\overline{\nu}_\tau$, are combined to improve statistical sensitivities.

The systematic uncertainties at STCF are to be optimized to a subleading level, as the statistical uncertainties are expected be less than 0.5%. To reduce the systematic uncertainty due to background and fitting, it becomes optimal for STCF to study $D_s^+ \to \ell^+\nu_\ell$ using $e^+e^- \to D_s^+D_s^-$ at 4.009 GeV. So far, $f_{D^+_{(s)}}$ are calculated by LQCD with precisions of about 0.2% [11], which are given as $f_D^+ = 212.7\pm0.6$ MeV, $f_{D_s}^+ = 249.9\pm0.4$ MeV and $f_{D_s}^+/f_D^+ = 1.1749\pm0.0016$. At the time of STCF, their precisions are expected to be below 0.1%. This means that the sizes of systematic uncertainties at STCF are crucial and necessary to be improved to the level of 0.1%. Among them, the efficiencies of muon and electron identifications will be the critical issues, which is required to be optimized in order to constrain the total uncertainty to the level of 0.1%.

On the other hand, the precise measurements of the semi-leptonic branching fractions for $D_{(s)} \to h\ell^+\nu_\ell$, where h is a charmless hadron, will be used to calibrate LQCD calculations of the involved form factors, by introducing the $|V_{cd(s)}|$ from global CKM fits (such as CKMfitter [12,13] and UTfit [14,15]). For the case of $D_{(s)} \to V(h_1h_2)\ell^+\nu_\ell$ (V denotes a vector meson, decaying into hadrons h_1 and h_2), a time reversal (T) invariance can be tested in high precision by constructing triple product T-odd observables [16]. This will serve as a sensitive probe of CP violation mechanisms beyond standard model and new physics [17], such as those with multi-Higgs doublets or leptoquarks. Ref. [18] proposes combined measurements of $D \to K_1(1270)\ell^+\nu_\ell$ and $B \to K_1(1270)\gamma$ to unambiguously determine the photon polarization in $b \to s\gamma$ in a clean way to probe right-handed couplings in new physics. A feasibility study shows that a statistical sensitivity of 1.5×10^{-2} for the ratio of up-down asymmetry can be reached based on about 60 thousands signals of $D^0 \to K_1(1270)^-e^+\nu$ with 1 ab^{-1} of data at 3.773 GeV at STCF [19].

Lepton flavor universality (LFU) can also be tested in charmed meson leptonic decays. LFU violation may happen in $c \to s$ transitions due to an amplitude that includes a charged Higgs boson, that arises in a two-Higgs-doublet model, interfering with the SM amplitude involving a $W^\pm$ boson [20]. In the SM, the ratio of the partial widths of $D^+_{(s)} \to \tau^+\nu_\tau$ and $D^+_{(s)} \to \mu^+\nu_\mu$ is predicted to be

$$R_{D^+_{(s)}} = \frac{\Gamma(D^+_{(s)} \to \tau^+\nu_\tau)}{\Gamma(D^+_{(s)} \to \mu^+\nu_\mu)} = \frac{m^2_{\tau^+}\left(1-\frac{m^2_{\tau^+}}{m^2_{D^+_{(s)}}}\right)^2}{m^2_{\mu^+}\left(1-\frac{m^2_{\mu^+}}{m^2_{D^+_{(s)}}}\right)^2}. \quad (1)$$

Using the world average values of the masses of leptons and $D^+_{(s)}$ [21], one obtains $R_{D^+} = 2.67 \pm 0.01$ and $R_{D_s^+} = 9.75 \pm 0.01$. The preliminary measured value of $R_{D^+_{(s)}}$ reported by BESIII is 3.21 ± 0.64 (10.2 ± 0.5), which agrees with the SM predicted values. However, these measurements are currently statistically limited. At STCF, as listed in Table 1, the statistical precision on $R_{D^+_{(s)}}$ will be comparable to the uncertainties of the predictions in the SM. Hence, it will provide meaningful test on LFU via these channels [9,10].

Another LFU test would be via the semi-leptonic decay modes, where the semi-tauonic decay is kinematically forbidden or suppressed. Measurements of the ratios of the partial widths of $D^{0(+)} \to h\mu^+\nu_\mu$ over those of $D^{0(+)} \to he^+\nu_e$ in different q^2 intervals constitute a complementary test of LFU to those using tauonic decays. BESIII reported precise measurements of the ratios $\mathcal{B}(D^0 \to \pi^-\mu^+\nu_\mu)/\mathcal{B}(D^0 \to \pi^-e^+\nu_e) = 0.922 \pm 0.030 \pm 0.022$ and $\mathcal{B}(D^+ \to \pi^0\mu^+\nu_\mu)/\mathcal{B}(D^+ \to \pi^0e^+\nu_e) = 0.964 \pm 0.037 \pm 0.026$ [22]. These results are consistent with the SM predictions, within 1.7σ and 0.5σ [22], respectively. These measurements are cur-

rently statistically limited [22,23], and will be significantly improved with 1 ab^{-1} of data taken at 3.773 GeV at STCF.

2.2 D^0-$\bar{D}^0$ mixing and CP violation

The phenomenon of meson-antimeson mixing has been of great interest in the long history of particle physics. Contrary to B-meson and Kaon systems, CP-violation in mixing of D-mesons has not been observed. STCF will be an ideal place for the study of D^0-$\bar{D}^0$ mixing and CP-violation. By convention the mass states of two neutral D mesons are written as

$$\begin{aligned} |D_1\rangle &= p|D^0\rangle + q|\bar{D}^0\rangle \,, \\ |D_2\rangle &= p|D^0\rangle - q|\bar{D}^0\rangle \,, \end{aligned} \tag{2}$$

where $|p|^2 + |q|^2 = 1$. The D^0-$\bar{D}^0$ mixing parameters are defined by $x \equiv (M_2 - M_1)/\Gamma$ and $y \equiv (\Gamma_2 - \Gamma_1)/(2\Gamma)$, where $M_{1,2}$ and $\Gamma_{1,2}$ are the masses and widths of $D_{1,2}$, respectively. Also $\Gamma \equiv (\Gamma_1 + \Gamma_2)/2$ and $M \equiv (M_1 + M_2)/2$. This system is unique because it is the only meson-antimeson system whose mixing (or oscillation) takes place via the intermediate states with down-type quarks. It is also the only meson-antimeson system whose mixing parameters x and y are notoriously hard to calculate in the SM, as those involve large long-distance uncertainties in this nonperturbative regime. One expects $x \sim y \sim \sin^2\theta_{\rm C} \times [\text{SU(3) breaking}]^2$ as the second-order effect of the flavor SU(3) symmetry breaking. A more careful analysis yields the order-of-magnitude estimates $x \lesssim y$ and $10^{-3} < |x| < 10^{-2}$ [24]. A global fit to the world measurements of x and y, carried out by the Heavy Flavor Averaging Group [25,26], gives $1.6 \times 10^{-3} \lesssim x \lesssim 6.1 \times 10^{-3}$ and $5.2 \times 10^{-3} \lesssim y \lesssim 7.9 \times 10^{-3}$ at the 95% confidence-level intervals [25,26]. We see that the allowed region of x and y are essentially consistent with the theoretical estimates (i.e., $x \lesssim y \sim 7 \times 10^{-3}$). Much more precise measurements of these two D^0-$\bar{D}^0$ mixing parameters can be achieved at STCF. While their accurate values might not help much to clarify the long-distance effects in D^0-$\bar{D}^0$ mixing, they will help a lot to probe the presumably small effects of CP violation in neutral D-meson decays and mixing [28].

The charm sector is a precision laboratory to explore possible CP-violating new physics, because the SM-induced CP-violating asymmetries in D-meson decays are typically in the range from 10^{-4} to 10^{-3} [27] and are very challenging to be detected in experiment. The CP-violating asymmetries in the singly Cabibbo-suppressed D-meson decays are now expected to be much larger than those in the Cabibbo-favored and doubly Cabibbo-suppressed decays [28], where such asymmetries vanish. There are in general three different types of CP-violating effects in neutral and charged D-meson decays [29]: 1) CP violation in D^0-$\bar{D}^0$ mixing; 2) CP violation in the direct decay; 3) CP violation from the interplay of decay and mixing. Besides these three types of CP-violating effects in D-meson decays, one may expect the effect of CP violation induced by K^0-$\bar{K}^0$ mixing in some decay modes with $K_{\rm S}$ or $K_{\rm L}$ in their final states. Its magnitude is typically $2{\rm Re}(\epsilon_K) \simeq 3.3 \times 10^{-3}$, which may be comparable with or even larger than the *charmed* CP-violating effects [30,31]. So far a lot of effort has been put into searching for CP violation in D-meson decays. The LHCb Collaboration has recently discovered CP violation in combined $D^0 \to \pi^+\pi^-$ and $D^0 \to K^+K^-$ decays with the significance of 5.3σ. The time-integrated CP-violating asymmetry is given as

$$\begin{aligned} \Delta a_{CP} &= \frac{\Gamma(D \to K^+K^-) - \Gamma(\bar{D} \to K^+K^-)}{\Gamma(D \to K^+K^-) + \Gamma(\bar{D} \to K^+K^-)} - \frac{\Gamma(D \to \pi^+\pi^-) - \Gamma(\bar{D} \to \pi^+\pi^-)}{\Gamma(D \to \pi^+\pi^-) + \Gamma(\bar{D} \to \pi^+\pi^-)} \\ &= (-0.154 \pm 0.029)\%, \end{aligned} \tag{3}$$

where $D(\bar{D})$ is a $D^0(\bar{D}^0)$ at time t=0 [32], and it mainly arises from direct CP violation in the charm-quark decay [33]. This result is consistent with some theoretical estimates within the SM (see, e.g., Refs. [34–41]), but the latter involve quite large uncertainties. STCF will have a 10^{-4} level of sensitivity on systematically searching for CP violation in different types of charm meson decays. Especially, advantages of kinematical constraints to the initial four-momenta of e^+e^-

collisions will make STCF competitive in studies of CP-violating asymmetries in multi-body D-decays [42], such as 4-body hadronic decays and therein CP asymmetries in local Dalitz region. As the CKM mechanism of CP violation in the SM fails to explain the puzzle of the observed matter-antimatter asymmetry in the Universe by more than 10 orders of magnitude [43], it is well motivated to search for new (heretofore undiscovered) sources of CP violation associated with both quark and lepton flavors. In this connection the charm-quark sector is certainly a promising playground.

Note that STCF will be a unique place for the study of D^0-$\bar{D}^0$ mixing and CP violation by means of quantum coherence of D^0 and $\bar{D}^0$ mesons produced at the energy points near threshold. In fact, a $D^0\bar{D}^0$ pair can be coherently produced through reactions $e^+e^- \to (D^0\bar{D}^0)_{\rm CP=-}$ at 3.773 GeV and $e^+e^- \to D^0\bar{D}^{*0} \to \pi^0(D^0\bar{D}^0)_{\rm CP=-}$ or $\gamma(D^0\bar{D}^0)_{\rm CP=+}$ at 4.009 GeV. One may therefore obtain useful constraints on D^0-$\bar{D}^0$ mixing and CP-violating parameters in the respective decays of correlated D^0 and $\bar{D}^0$ events [29]. For example, the D^0-$\bar{D}^0$ mixing rate $R_M = (x^2+y^2)/2$ can be accessed via the same charged final states $(K^\pm\pi^\mp)(K^\pm\pi^\mp)$ or $(K^\pm\ell^\mp\nu)(K^\pm\ell^\mp\nu)$ with a sensitivity of 10^{-5} with 1 ab^{-1} data at 3.773 GeV. Considering $e^+e^- \to \gamma D^0\bar{D}^0$ at 4.009 GeV, $D^0\bar{D}^0$ pairs are in C-even states and charm mixing contribution is doubled as compared with the time-dependent (un-correlated) case. With 1 ab^{-1} data at 4.009 GeV, it is expected that the measurement sensitivities of the mixing parameters (x, y) will reach a level of 0.05%, and those of $|q/p|$ and $\arg(q/p)$ will be 1.5% and 1.4°, respectively [44]. These sensitivities are complementary to the future precision measurements foreseen at Belle II and the LHCb upgrades. Another case is that the decay mode $\left(D^0\bar{D}^0\right)_{\rm CP=\pm} \to (f_1f_2)_{\rm CP=\mp}$, where f_1 and f_2 are proper CP eigenstates (e.g., $\pi^+\pi^-$, K^+K^- and $K_S\pi^0$), is a CP-forbidden process and can only occur due to CP violation. The rate of a pair of CP-even final states f_+ (such as $f_+ = \pi^+\pi^-$) can be expressed as

$$\Gamma^{++}_{D^0\bar{D}^0} = \left[\left(x^2+y^2\right)\left(\cosh^2 a_m - \cos^2\phi\right)\right]\Gamma^2(D\to f_+), \tag{4}$$

where $\phi = \arg(p/q)$, $R_M = |p/q|$, and $a_m = \log R_M$ [45].

CPT is conserved in all local Lorentz-invariant theories, which includes the SM and its all commonly-discussed extensions. When CPT is conserved, CP violation implies time reversal (T) symmetry violation. Yet, CPT violation might arise in string theory or some extra-dimensional models with Lorentz-symmetry violation in four dimensions. Hence, direct observation of T violation without the presumption of CPT conservation is very important [46]. Experimental studies of the time evolution of CP-correlated D^0-$\bar{D}^0$ states at STCF could be complementary to CPT-violation studies at the super-B factories and the LHCb experiments [47]. However, this becomes very challenging with symmetric e^+e^- collisions, as the produced D mesons have very low momentum in the laboratory frame, and hence have too small flight distances to be detected. Only asymmetric e^+e^- collision mode can be feasible for this topic.

The quantum correlation of the $D^0\bar{D}^0$ meson pair has a unique feature to probe the amplitudes of the D^0 decays and determine the strong-phase difference between their Cabibbo-favored and doubly Cabibbo-suppressed amplitudes [48]. Measurements of the strong-phase difference are well motivated in several aspects: understanding the non-perturbative QCD effects in the charm sector; serving as essential inputs to extract the angle γ of the CKM unitarity triangle (UT), and relating the measured mixing parameters in hadronic decay (x', y') to the mass and width difference parameters (x, y) [25].

The measurements of the CKM unitary triangle (UT) angles α, β, and γ in B decays are important tests of the CKM unitarity and search for possible CP violation beyond the SM. Any discrepancy in the measurements of the UT involving tree- and loop-dominated processes would indicate the existence of heavy new degrees of freedom contributing to the loops. Among the three CKM angles, γ is of particular importance because it is the only CP-violating observable that can be determined using tree-level decays. Currently the world-best single measurement of γ is from LHCb: $\gamma = (69 \pm 5)^\circ$ [49]. The precision measurement of γ will be one of the top priorities for the LHCb upgrade(s) and Belle II experiments.

The most precise method to measure γ is based upon the interference between $B^+ \to \bar{D}^0K^+$ and $B^+ \to D^0K^+$ decays [50–52]. In the future, the statistical uncertainties of these measure-

ments will be greatly reduced by using the large B meson samples recorded by LHCb and Belle II. Hence, limited knowledge of the strong phases of the D decays will systematically restrict the overall sensitivity. A 20 fb^{-1} of data set at 3.773 GeV at BESIII would lead to a systematic uncertainty of $\sim$0.4° for the γ measurement [53]. Hence, to match the future statistical uncertainty of less than 0.4° in the future LHCb upgrade II, STCF would provide important constraints to reduce the systematic uncertainty from D strong-phase to be less than 0.1° and allow detailed comparisons of the γ results from different decay modes.

2.3 Rare and forbidden decays

With high luminosity, clean collision environment and excellent detector performance, STCF has great potential to perform searches for rare and forbidden D-meson decays, which may serve as a useful tool for probing new physics beyond the SM. They can be classified into three categories: (1) decays via the flavor-changing neutral current (FCNC), such as $D^{0(+)} \to \gamma V^{0(+)}$, $D^0 \to \gamma\gamma$, $D^0 \to \ell^+\ell^-$, $D \to \ell^+\ell^- X$ channels (for $\ell = e, \mu$), and $D \to \nu\overline{\nu}X$, which provide a SM-allowed transition between c and u quarks; (2) decays with lepton flavor violation (LFV), such as $D^0 \to \ell^+\ell'^-$ and $D \to \ell^+\ell'^- X$ channels (for $\ell \neq \ell'$), which are forbidden in the SM; (3) decays with lepton number violation (LNV), such as $D^+ \to \ell^+\ell'^+ X^-$ and $D_s^+ \to \ell^+\ell'^+ X^-$ channels (for either $\ell = \ell'$ or $\ell \neq \ell'$), which are also forbidden in the SM. The discoveries of neutrino oscillations have confirmed LFV in the lepton sector, and LNV is possible if massive neutrinos are the Majorana particles. It is therefore meaningful to search for the LFV and LNV phenomena in the charm-quark sector.

Although the FCNC decays of D mesons are allowed in the SM, they can only occur via the loop diagrams and hence are strongly suppressed. The long-distance dynamics is expected to dominate the SM contributions to such decays, but their branching fractions are still tiny. For instance, $\mathcal{B}(D^0 \to \gamma\gamma) \sim 1 \times 10^{-8}$ and $\mathcal{B}(D^0 \to \mu^+\mu^-) \sim 3 \times 10^{-13}$ in the SM [54], but they can be significantly enhanced by new physics [55]. Current experimental bounds on these two typical FCNC channels are $\mathcal{B}(D^0 \to \gamma\gamma) < 8.5 \times 10^{-7}$ and $\mathcal{B}(D^0 \to \mu^+\mu^-) < 6.2 \times 10^{-9}$ [21]. However, the following semi-leptonic decays of $D^0 \to \pi^+\pi^-\mu^+\mu^-$, $K^+K^-\mu^+\mu^-$ and $K^-\pi^+\mu^+\mu^-$ have been observed at LHCb with the BF level of 10^{-7} [21]. Besides the removal of helicity suppression as dominates the highly suppressed BF for $D^0 \to \mu^+\mu^-$, the observed BFs for the semi-leptonic decays indicate non-trivial contributions from complicated long-distance effects. At STCF, it is more optimal to study the di-electron modes $D \to e^+e^- X$ [56], which provide sensitivities of $10^{-8} \sim 10^{-9}$ for $m_{e^+e^-}$ in the range less polluted by the long-range resonance contributions. Compared to Belle II and LHCb, STCF has competitive sensitivities in the channels which contains neutral final states, such as photon and π^0, because of clean backgrounds. Furthermore, STCF has advantage to best constrain the upper limit of BF for D rare decays with neutrinos, such as $D^0 \to \pi^0\nu\overline{\nu}$ and $D^0 \to \gamma\nu\overline{\nu}$.

No evidence has been found for the forbidden $D_{(s)}$-meson decays with either LFV or LNV, or both of them. The present experimental bounds on the LFV decays are generally set at the level of 10^{-6} to 10^{-5} (with an exception of $\mathcal{B}(D^0 \to \mu^\pm e^\mp) < 1.3 \times 10^{-8}$) [21]. A STCF will provide more stringent limits on such interesting LFV and LNV decay modes, with a sensitivity of 10^{-8} to 10^{-9} or smaller, taking advantage of its clean environment and accurate charge discrimination.

2.4 Charmed meson spectroscopy

STCF will also act as a good playground to study the production of charmed mesons and explore the charmed meson spectroscopy. So far, all the $1S$ and $1P$ $D_{(s)}$ states have been found in experiment [57]. However, for other quantum states, almost all other predicted excited states in QCD-derived effective models are missing. Furthermore, there are many excited open-charm states reported in experiment, which are still controversial in understanding their natures. Some of them are candidates of exotic mesons. For instance, the narrow $D_{sJ}^*(2632)$ state is observed by SELEX, but CLEO, BaBar and FOCUS all reported negative search results. The unexpected

low masses of the $D_{s0}^*(2317)$ and $D_{s1}(2460)$ bring in various exotic explanations, such as $D^{(*)}K$ molecule state [58]. It has been claimed that the strong S-wave $D^{(*)}K$ scattering contributes to the mass drop. More systematic researches on the open-charm meson spectroscopy are highly desired.

At STCF, excited charmed meson states D^{**} can be produced via direct e^+e^- production processes, such as $e^+e^- \to D^{**}\bar{D}^{(*)}(\pi)$, in the energy rang from 4.1 to 7.0 GeV. Then, the higher excited open-charm states can be studied through their hadronic or radiative decays [59] to lower open-charm states. Systematical studies at STCF on the open-charm meson spectra provide important data to explore the non-perturbative QCD dynamics in the charm regime and test various theoretical models.

3 Charmed baryon

Theoretical interest in hadronic weak decays of charmed baryons peaked around the early 1990s and then faded away. Nevertheless, there are two major breakthroughs in recent charmed-baryon experiments in regard to hadronic weak decays of Λ_c^+. BESIII has played an essential role in these new developments [4]. LHCb made significant progress on re-ordering the lifetime hierarchy of charmed baryon lifetimes from $\tau_{\Xi_c^+} > \tau_{\Lambda_c^+} > \tau_{\Xi_c^0} > \tau_{\Omega_c^0}$ to $\tau_{\Xi_c^+} > \tau_{\Omega_c^0} > \tau_{\Lambda_c^+} > \tau_{\Xi_c^0}$ [62–65]. Motivated by these experimental progresses, there exist growing theoretical activities in the study of hadronic weak decays of singly charm baryons.

Charm baryon spectroscopy provides an excellent ground for studying the dynamics of light quarks in the environment of a heavy quark. In the past decade, many new excited charmed baryon states have been discovered by BaBar, Belle, CLEO and LHCb. B decays and the $e^+e^- \to c\bar{c}$ continuum are both very rich sources of charmed baryons. Many efforts have been made to identify the quantum numbers of these new states and understand their properties.

3.1 Hadronic weak decays

- Nonleptonic decays of singly charmed baryons

  Λ_c decays

  The branching fractions of the Cabibbo-favored two-body decays of Λ_c^+ are listed in Table 2. Many of them such as $\Sigma^+\phi$, $\Xi^{(*)}K^{(*)+}$ and $\Delta^{++}K^-$ can proceed only through W-exchange. Experimental measurement of them implies the importance of W-exchange, which is not subject to color suppression in charmed baryon decays. Both Belle [66] and BESIII [67] have measured the absolute branching fraction of the decay $\Lambda_c^+ \to pK^-\pi^+$. A new average of $(6.28 \pm 0.32)\%$ for this benchmark mode is quoted by the Particle Data Group (PDG) [21]. Doubly Cabibbo-suppressed decay $\Lambda_c^+ \to pK^+\pi^-$ has been observed by Belle [68] and LHCb [69]. It is thus important to search for the two-body modes which are doubly Cabibbo-suppressed: $pK^{0(*)}$ and $nK^{+(*)}$.

  Various theoretical approaches to weak decays of heavy baryons have been investigated, including the current algebra approach, factorization scheme, pole model, relativistic quark model, quark diagram scheme and SU(3) flavor symmetry. In general, the predicted decay rates by most of the models except current algebra are below experimental measurements. Moreover, the decay asymmetries of the two-body hadronic weak decays of charmed baryons can be investigated, which are defined as $\alpha \equiv \frac{2\mathrm{Re}(s^*p)}{|s|^2+|p|^2}$. Here s and p stand for the parity-violating s-wave and parity-conserving p-wave amplitudes in the decay, respectively. The pole model, the covariant quark model and its variant all predict a positive decay asymmetry α for both $\Lambda_c^+ \to \Sigma^+\pi^0$ and $\Sigma^0\pi^+$, while it is measured to be $-0.45 \pm 0.31 \pm 0.06$ for $\Sigma^+\pi^0$ by CLEO [70]. In contrast, current algebra always leads to a negative decay asymmetry for aforementioned two modes: -0.49 in Ref. [71], -0.31 in Ref. [72], -0.76 in Ref. [73] and -0.47 in Ref. [74]. The issue with the sign of $\alpha_{\Sigma^+\pi^0}$ was finally resolved by BESIII. The decay asymmetry parameters of $\Lambda_c^+ \to \Lambda\pi^+, \Sigma^0\pi^+, \Sigma^+\pi^0$

Table 2: The measured branching fractions of the Cabibbo-favored two-body decays of Λ_c^+ (in units of %) taken from 2020 Particle Data Group [21]. BESIII measurements of $\Lambda_c^+ \to \Sigma^+\eta, \Sigma^{*+}\eta, \Sigma^+\eta'$ are included. [60, 61].

Decay	$\mathcal{B}$	Decay	$\mathcal{B}$	Decay	$\mathcal{B}$
$\Lambda_c^+ \to \Lambda\pi^+$	1.30±0.07	$\Lambda_c^+ \to \Lambda\rho^+$	< 6	$\Lambda_c^+ \to \Delta^{++}K^-$	1.08 ± 0.25
$\Lambda_c^+ \to \Sigma^0\pi^+$	1.29±0.07	$\Lambda_c^+ \to \Sigma^0\rho^+$		$\Lambda_c^+ \to \Sigma^{*0}\pi^+$	
$\Lambda_c^+ \to \Sigma^+\pi^0$	1.25±0.10	$\Lambda_c^+ \to \Sigma^+\rho^0$	< 1.7	$\Lambda_c^+ \to \Sigma^{*+}\pi^0$	
$\Lambda_c^+ \to \Sigma^+\eta$	0.53±0.15	$\Lambda_c^+ \to \Sigma^+\omega$	1.70±0.21	$\Lambda_c^+ \to \Sigma^{*+}\eta$	0.96 ± 0.17
$\Lambda_c^+ \to \Sigma^+\eta'$	1.34±0.57	$\Lambda_c^+ \to \Sigma^+\phi$	0.38±0.06	$\Lambda_c^+ \to \Sigma^{*+}\eta'$	
$\Lambda_c^+ \to \Xi^0 K^+$	0.55±0.07	$\Lambda_c^+ \to \Xi^0 K^{*+}$		$\Lambda_c^+ \to \Xi^{*0}K^+$	0.43±0.09
$\Lambda_c^+ \to pK_S$	1.59±0.08	$\Lambda_c^+ \to p\bar{K}^{*0}$	1.96±0.27	$\Lambda_c^+ \to \Delta^+\bar{K}^0$	

and pK_S were recently measured by BESIII [75], for example, $\alpha_{\Sigma^+\pi^0} = -0.57 \pm 0.12$ was obtained. Hence, the negative sign of $\alpha_{\Sigma^+\pi^0}$ measured by CLEO is confirmed by BESIII.

Ξ_c and Ω_c decays

The absolute branching fractions of $\Xi_c^0 \to \Xi^-\pi^+$ and $\Xi_c^+ \to \Xi^-\pi^+\pi^+$ were recently measured by Belle [76, 77] to be

$$\mathcal{B}(\Xi_c^0 \to \Xi^-\pi^+) = (1.80 \pm 0.50 \pm 0.14)\%, \quad \mathcal{B}(\Xi_c^+ \to \Xi^-\pi^+\pi^+) = (2.86 \pm 1.21 \pm 0.38)\%. \quad (5)$$

With these measurements, branching fractions of other Ξ_c^0 and Ξ_c^+ decays can be inferred. No absolute branching fractions have been measured for the Ω_c^0. The hadronic weak decays of the Ω_c^0 were recently studied in great detail in Ref. [78], where most of the decay channels in Ω_c^0 decays were found to proceed only through the W-exchange diagram.

It is conceivable that nonleptonic decay modes of Λ_c^+ and $\Xi_c^{+,0}$ can be measured at STCF with significantly improved precision. Priority will be ascribed to the decay asymmetries α in various charm baryon decays and the absolute branching fractions of Ω_c^0 decays.

- Charm-flavor-conserving nonleptonic decays

  There is a special class of weak decays of charmed baryons that can be studied reliably, namely, heavy-flavor-conserving nonleptonic decays. Some examples are the singly Cabibbo-suppressed decays $\Xi_c \to \Lambda_c\pi$ and $\Omega_c \to \Xi_c'\pi$. In these decays, only the light quarks inside the heavy baryon will participate in weak interactions, while the heavy quark behaves as a "spectator". The synthesis of the heavy quark and chiral symmetries provides a natural setting for investigating these reactions [79]. The predicted branching fractions for the charm-flavor-conserving decays $\Xi_c^0 \to \Lambda_c^+\pi^-$ and $\Xi_c^+ \to \Lambda_c^+\pi^0$ are of the order of $10^{-3} \sim 10^{-4}$ [79]. Very recently, the first measurement of the charm-flavor-conserving decay $\Xi_c^0 \to \Lambda_c^+\pi^-$ has been achieved by the LHCb with the branching fraction $(0.55\pm0.02\pm0.18)\%$ [80], which is in general larger than the theoretical predictions. STCF should be able to cross-check this and search for another c-flavor-conserving weak decay, namely, $\Xi_c^+ \to \Lambda_c^+\pi^0$.

- Semileptonic decays

  Exclusive semileptonic decays of charmed baryons: $\Lambda_c^+ \to \Lambda e^+(\mu^+)\nu_{e(\mu)}$, $\Xi_c^+ \to \Xi^0 e^+\nu_e$ and $\Xi_c^0 \to \Xi^- e^+\nu_e$ have been observed experimentally. Their rates depend on the $\mathcal{B}_c \to \mathcal{B}$ form factors $f_i(q^2)$ and $g_i(q^2)$ $(i = 1, 2, 3)$ defined as

$$\begin{aligned} \langle \mathcal{B}_f(p_f)|V_\mu|\mathcal{B}_c(p_i)\rangle &= \bar{u}_f(p_f)[f_1(q^2)\gamma_\mu + if_2(q^2)\sigma_{\mu\nu}q^\nu + f_3(q^2)q_\mu]u_i(p_i), \\ \langle \mathcal{B}_f(p_f)|A_\mu|\mathcal{B}_c(p_i)\rangle &= \bar{u}_f(p_f)[g_1(q^2)\gamma_\mu + ig_2(q^2)\sigma_{\mu\nu}q^\nu + g_3(q^2)q_\mu]\gamma_5 u_i(p_i). \end{aligned} \quad (6)$$

Table 3: Electromagnetic decay rates (in units of keV) of s-wave charmed baryons in heavy hadron chiral perturbation theory to (i) LO [95, 96], (ii) NLO [97] and (iii) NNLO [98].

	$\Sigma_c^+ \to \Lambda_c^+\gamma$	$\Sigma_c^{*+} \to \Lambda_c^+\gamma$	$\Sigma_c^{*++} \to \Lambda_c^{++}\gamma$	$\Sigma_c^{*0} \to \Sigma_c^0\gamma$	$\Xi_c^{\prime+} \to \Xi_c^+\gamma$
(i)	91.5	150.3	1.3	1.2	19.7
(ii)	164.2	893.0	11.6	2.9	54.3
(iii)	65.6	161.8	1.2	0.49	5.4
	$\Xi_c^{*+} \to \Xi_c^+\gamma$	$\Xi_c^{*0} \to \Xi_c^0\gamma$	$\Xi_c^{\prime0} \to \Xi_c^0\gamma$	$\Omega_c^{*0} \to \Omega_c^0\gamma$	
(i)	63.5	0.4	1.0	0.9	
(ii)	502.1	0.02	3.8	4.8	
(iii)	21.6	0.46	0.42	0.32	

These form factors have been evaluated using the non-relativistic quark model [81–84], MIT bag model [81], relativistic quark model [85–87], light-front quark model [88], QCD sum rules [89–91] and lattice QCD [92, 93]. Many of the early predictions of $\mathcal{B}(\Lambda_c^+ \to \Lambda e^+\nu_e)$ are smaller than the first measurement of the absolute branching fraction of $(3.6 \pm 0.4)\%$ by BESIII [94]. Lattice QCD calculations in [92] yield good agreement with experiment for both $\Lambda_c^+ \to \Lambda e^+\nu_e$ and $\Lambda_c^+ \to \Lambda\mu^+\nu_\mu$. Needless to say, the semileptonic decays of Λ_c^+ (including the yet-to-be-observed $\Lambda_c^+ \to n e^+\nu_e$), $\Xi_c^{+,0}$ and Ω_c^0 will be thoroughly studied at STCF, which can be used to discriminate between different form-factor models.

3.2 Electromagnetic and weak radiative decays

The electromagnetic decays of interest in the charmed baryon sector are: (i) $\Sigma_c \to \Lambda_c + \gamma, \Xi_c^\prime \to \Xi_c + \gamma$, (ii) $\Sigma_c^* \to \Lambda_c + \gamma, \Xi_c^* \to \Xi_c + \gamma$, (iii) $\Sigma_c^* \to \Sigma_c + \gamma, \Xi_c^* \to \Xi_c^\prime + \gamma, \Omega_c^* \to \Omega_c + \gamma$, and (iv) $\Lambda_c(2595, 2625) \to \Lambda_c + \gamma$, $\Xi_c(2790, 2815) \to \Xi_c + \gamma$. Among them, the decay modes $\Xi_c^{\prime0} \to \Xi_c^0\gamma$, $\Xi_c^{\prime+} \to \Xi_c^+\gamma$ and $\Omega_c^{*0} \to \Omega_c^0\gamma$ have been seen experimentally.

The calculated results of [95,96], [97] and [98] denoted by (i), (ii) and (iii), respectively, in Table 3 can be regarded as the predictions of heavy hadron chiral perturbation theory (HHChPT) to the leading order (LO), next-to-leading order (NLO) and next-to-next-to-leading order (NNLO), respectively. It is not clear why the predictions of HHChPT to NLO are quite different from that to LO and NNLO for the following three modes: $\Sigma_c^{*+} \to \Lambda_c^+\gamma$, $\Sigma_c^{*++} \to \Sigma_c^{++}\gamma$ and $\Xi_c^{*+} \to \Xi_c^+\gamma$. It is naively expected that all HHChPT approaches should agree with each other to the lowest order of chiral expansion provided that the coefficients are inferred from the nonrelativistic quark model. This issue can be clarified by STCF through the measurement of these decay rates.

Very recently, Belle has observed the electromagnetic decays of orbitally excited charmed baryons $\Xi_c(2790)$ and $\Xi_c(2815)$ for the first time [99]. The partial widths of $\Xi_c(2815)^0 \to \Xi_c^0\gamma$ and $\Xi_c(2790)^0 \to \Xi_c^0\gamma$ are measured to be $320 \pm 45^{+45}_{-80}$ keV and ~ 800 keV, respectively. However, no signal was found for the analogous decays of $\Xi_c(2815)^+$ and $\Xi_c(2790)^+$.

Weak radiative decays such as $\Lambda_c^+ \to \Sigma^+\gamma$ and $\Lambda_c^+ \to p\gamma$ can proceed through the bremsstrahlung processes $cd \to us\gamma$ (Cabibbo-favored) and $cd \to ud\gamma$ (Cabibbo-suppressed), respectively. The branching fraction of the former was estimated to be of order 10^{-4} [100].

3.3 CP violation

The CKM matrix contains a phase which implies the existence of CP violation. This means CP-violation can be studied with baryons as well. The predicted CP-violating asymmetries are, however, small for charmed baryons. The search for CP violation in charmed baryon decays has

Table 4: Antitriplet and sextet states of charmed baryons. Mass differences $\Delta m_{\Xi_c\Lambda_c} \equiv m_{\Xi_c} - m_{\Lambda_c}$, $\Delta m_{\Xi_c'\Sigma_c} \equiv m_{\Xi_c'} - m_{\Sigma_c}$, $\Delta m_{\Omega_c\Xi_c'} \equiv m_{\Omega_c} - m_{\Xi_c'}$ are all in units of MeV.

	$J^P(nL)$	States	Mass difference
$\bar{\mathbf{3}}$	$\frac{1}{2}^+(1S)$	$\Lambda_c(2287)^+$, $\Xi_c(2470)^+, \Xi_c(2470)^0$	$\Delta m_{\Xi_c\Lambda_c} = 183$
	$\frac{1}{2}^-(1P)$	$\Lambda_c(2595)^+$, $\Xi_c(2790)^+, \Xi_c(2790)^0$	$\Delta m_{\Xi_c\Lambda_c} = 198$
	$\frac{3}{2}^-(1P)$	$\Lambda_c(2625)^+$, $\Xi_c(2815)^+, \Xi_c(2815)^0$	$\Delta m_{\Xi_c\Lambda_c} = 190$
	$\frac{3}{2}^+(1D)$	$\Lambda_c(2860)^+$, $\Xi_c(3055)^+, \Xi_c(3055)^0$	$\Delta m_{\Xi_c\Lambda_c} = 201$
	$\frac{5}{2}^+(1D)$	$\Lambda_c(2880)^+$, $\Xi_c(3080)^+, \Xi_c(3080)^0$	$\Delta m_{\Xi_c\Lambda_c} = 196$
$\mathbf{6}$	$\frac{1}{2}^+(1S)$	$\Omega_c(2695)^0$, $\Xi_c'(2575)^{+,0}, \Sigma_c(2455)^{++,+,0}$	$\Delta m_{\Omega_c\Xi_c'} = 119$, $\Delta m_{\Xi_c'\Sigma_c} = 124$
	$\frac{3}{2}^+(1S)$	$\Omega_c(2770)^0$, $\Xi_c'(2645)^{+,0}, \Sigma_c(2520)^{++,+,0}$	$\Delta m_{\Omega_c\Xi_c'} = 120$, $\Delta m_{\Xi_c'\Sigma_c} = 128$

taken on new momentum with the large samples of Λ_c obtained by BESIII and LHCb. For two-body decays of the Λ_c^+, CP violation can be explored through the measurement of CP-violating asymmetry, $\mathcal{A} = (\alpha+\bar{\alpha})/(\alpha-\bar{\alpha})$, which corresponds to the asymmetry of α for the Λ_c^+ decays and $\bar{\alpha}$ for $\bar{\Lambda}_c^-$ decays. For example, $\mathcal{A}$ in $\Lambda_c^+ \to \Lambda\pi^+$ and $\bar{\Lambda}_c^- \to \bar{\Lambda}\pi^-$ was measured by FOCUS to be $-0.07\pm0.19\pm0.24$ [101]. In STCF, much more sensitive searches for CP violation will be carried out by combining the single tag Λ_c^+ data [102] and double tag $\Lambda_c^+\bar{\Lambda}_c^-$ data, where the pairs of $\Lambda_c^+\bar{\Lambda}_c^-$ are quantum-correlated regarding to their spins aligned to the initial spins of the virtual photons. Especially, with polarized beams [103], unique advantage of enhanced sensitivities on the decay asymmetries and the CP violations can be achieved with prior knowledge of the spin direction of the produced Λ_c^+. As for three-body decays, LHCb has measured ΔA_{CP} as the difference between CP asymmetries in $\Lambda_c^+ \to pK^+K^-$ and $\Lambda_c^+ \to p\pi^+\pi^-$ decay channels. The result is $\Delta A_{CP} = (0.30 \pm 0.91 \pm 0.61)\%$ [104], to be compared with a generic SM prediction of a fraction of 0.1% [105]. In order to probe the SM contribution to such asymmetries, one has to increase the available statistics by at least a factor of 100.

For multi-hadrons in the final state of Λ_c^+ decays such as $\Lambda_c^+ \to pK^-\pi^+\pi^0$, $\Lambda_c^+ \to \Lambda\pi^+\pi^+\pi^-$ and $\Lambda_c^+ \to pK_S\pi^+\pi^-$, CP violation can be exploited through several T-odd observables. Owing to its characters of high luminosity, broad center-of-mass energy acceptance, abundant production and clean environment, STCF will provide a great platform for this kind of study. A fast Monte Carlo simulation [106] of 1 ab^{-1} e^+e^- annihilation data at $\sqrt{s} = 4.64$ GeV, which are expected to be available at the future STCF, indicates that a sensitivity at the level of (0.25-0.5)% is accessible for the above-mentioned three decay modes. This will be enough to measure non-zero CP-violating asymmetries as large as 1%.

3.4 Spectroscopy

The observed antitriplet and sextet states of charmed baryons are listed in Table 4. By now, the $J^P = \frac{1}{2}^+, \frac{1}{2}^-, \frac{3}{2}^+, \frac{3}{2}^-$ and $\frac{5}{2}^+$ antitriplet states Λ_c, Ξ_c and $J^P = \frac{1}{2}^+, \frac{3}{2}^+$ sextet states $\Omega_c, \Xi_c', \Sigma_c$ are established. The highest state $\Lambda_c(2940)^+$ in the Λ_c family was first discovered by BaBar in the D^0p decay mode [107] but its spin-parity assignment is quite diverse (see [108] for a review). The constraints on its spin and parity were recently found to be $J^P = \frac{3}{2}^-$ by LHCb [109]. It was suggested in [110] that the quantum numbers of $\Lambda_c(2940)^+$ are most likely $\frac{1}{2}^-(2P)$ based on the Regge analysis. However, it was argued in [111] that $\Lambda_c(2940)^+$ is a $\frac{3}{2}^-(2P)$ state and there is a state $\frac{1}{2}^-(2P)$ higher than the $\Lambda_c(2P, 3/2^-)$. This issue can be clarified by STCF.

In 2017 LHCb has explored the charmed baryon sector of the Ω_c and observed five narrow excited Ω_c states decaying into $\Xi_c^+K^-$: $\Omega_c(3000)$, $\Omega_c(3050)$, $\Omega_c(3066)$, $\Omega_c(3090)$ and $\Omega_c(3119)$

[112]. Except $\Omega_c(3119)$, the first four states were also confirmed by Belle later [113]. This has triggered a lot of interest in possible identification of their spin-parity quantum numbers.

Within the energy region of STCF up to 7 GeV, it is suitable to study the spectroscopy of singly charmed baryon states Λ_c, Σ_c, $\Xi_c^{(\prime)}$, Ω_c and their excited states in the energy range of $5 \sim 7$ GeV. It is important for SCTF to explore their possible structure and spin-parity quantum number assignments, especially for the five new and narrow Ω_c resonances. If the energy region is extended to above 7.4 GeV, the production of the double charmed baryon Ξ_{cc}^{++} is allowed. This will also enable the study of some more detailed of the recently discovered double charmed baryons.

4 Summary

To summarize, STCF will be an ideal facility to study charm physics using the unique pair production of the charmed hadrons near threshold. In particular, the charm mixing and CP-violating parameters, as well as the strong phase of the neutral D mesons, can be precisely determined utilizing the quantum correlation of the $D^0\bar{D}^0$ pair system. With 1 ab^{-1} data at 4.009 GeV, it is expected that the measurement sensitivities of the mixing parameters (x, y) will reach a level of 0.05%, and those of $|q/p|$ and $\arg(q/p)$ will be 1.7% and 1.3°, respectively. D strong-phase measurement at STCF will be necessary to constrain the uncertainty of the CP-violating phase γ being less than 0.1° and allow detailed comparisons of the γ results from different analysis channels in the future LHCb upgrade II. These measurements are complementary to those studies at LHCb and Belle II, and provide crucial information to understand the mechanism of CP violation. In addition, the leptonic decays of the charmed mesons and baryons will be systematically explored in world-best precisions, which serves for overconstraint of the CKM matrix, clean probe of the dynamics of strong force, stringent test of LFU and search for new physics.

Furthermore, in the energy region above the charmed baryon threshold, studies of production and decay properties of the (excited) charmed baryons can be extensively carried out, which are still lacking of experimental data. The absolute measurements of the semi-leptonic and nonleptonic decays of the Λ_c^+, $\Xi_c^{+,0}$ and Ω_c^0 baryons will be significantly improved at STCF. Priority will be ascribed to the decay asymmetries α in various charm baryon decays, which can be further used to search for CP violation effects, and the absolute branching fractions of Ω_c^0 decays. Moreover, measurements of and searches for rare- and forbidden decays of charmed hadrons with up to two orders-of-magnitude improvements in sensitivity could be realized as part of a search for new physics.

Many of these measurements at STCF will benefit from the clean reaction environment, strictly constrained kinematics and well-controlled systematic uncertainties, which necessitates a detector with excellent performance, especially in identifying the types of different charged particles, detecting low-momentum charged particles and measuring photons. The unprecedented precisions obtained with high statistics charm data will enable us to have a much more in-depth understanding of the challenges facing the SM and hopefully will provide some clues/solutions to them. Hence, it will play a crucial role in leading the high intensity frontier of elementary particle physics worldwide.

References

[1] H. P. Peng, Y. H. Zheng and X. R. Zhou, Physics **49**, 513-524 (2020).

[2] B. Wang, X. R. Lyu and Y. H. Zheng, Journal of University of Chinese Academy of Sciences **38**, 433 (2021).

[3] X. R. Lyu (STCF Working Group), PoS **BEAUTY2020**, 060 (2021).

[4] H. B. Li and X. R. Lyu, Natl. Sci. Rev. **8**, nwab181 (2021).

[5] X. D. Shi, X. R. Zhou, X. S. Qin and H. P. Peng, JINST **16**, P03029 (2021).

[6] M. Ablikim *et al.* (BESIII Collaboration), Phys. Rev. D **89**, 051104 (2014).
[7] M. Ablikim *et al.* (BESIII Collaboration), Phys. Rev. Lett. **123**, 211802 (2019).
[8] M. Ablikim *et al.* (BESIII Collaboration), Phys. Rev. Lett. **122**, 071802 (2019).
[9] J. Liu, X. Shi, H. Li, X. Zhou and B. Zheng, [arXiv:2109.14969 [hep-ex]].
[10] H. Li, T. Luo, X. Shi and X. Zhou, [arXiv:2110.08864 [hep-ex]].
[11] A. Bazavov *et al.*, Phys. Rev. D **98**, 074512 (2018).
[12] J. Charles *et al.* (CKMfitter Group), Eur. Phys. J. C **41**, 1 (2005).
[13] CKMfitter Group, http://ckmfitter.in2p3.fr.
[14] M. Bona *et al.* (UTfit Collaboration), JHEP **0507**, 028 (2005).
[15] UTfit Collaboration, http://utfit.org/UTfit/WebHome.
[16] G. Belanger and C. Q. Geng, Phys. Rev. D **44**, 2789 (1991).
[17] Y. Grossman, Int. J. Mod. Phys. A **19**, 907 (2004)
[18] W. Wang, F. S. Yu and Z. X. Zhao, Phys. Rev. Lett. **125**, 051802 (2020).
[19] Y. L. Fan, X. D. Shi, X. R. Zhou and L. Sun, Eur. Phys. J. C **81**, 1068 (2021).
[20] S. Fajfer, I. Nisandzic, and U. Rojec, Phys. Rev. D **91**, 094009 (2015).
[21] P. A. Zyla *et al.* (Particle Data Group), Prog. Theor. Exp. Phys. **2020**, 083C01 (2020).
[22] M. Ablikim *et al.* (BESIII Collaboration), Phys. Rev. Lett. 121, 171803 (2018).
[23] M. Ablikim *et al.* (BESIII Collaboration), Phys. Rev. Lett. **122**, 011804 (2019).
[24] A. Falk, Y. Grossman, Z. Ligeti, Y. Nir, and A. Petrov, Phys. Rev. D **69**, 114021 (2004).
[25] Y. S. Amhis *et al.* (HFLAV Collaboration), arXiv:1909.12524 [hep-ex].
[26] HFLAV Collaboration, https://hflav.web.cern.ch.
[27] Z. Z. Xing, Chin. Phys. C **32** 483 (2008).
[28] D. M. Asner *et al.*, Int. J. Mod. Phys. A **24**, S1 (2009); B. O'Leary *et al.* (SuperB Collaboration), arXiv:1008.1541 [hep-ex].
[29] Z. Z. Xing, Phys. Rev. D **55**, 196 (1997).
[30] Z. Z. Xing, Phys. Lett. B **353**, 313 (1995) Erratum: [Phys. Lett. B **363**, 266 (1995)].
[31] F. S. Yu, D. Wang and H. N. Li, Phys. Rev. Lett. **119**, 181802 (2017).
[32] R. Aaij *et al.* (LHCb Collaboration), Phys. Rev. Lett. **122**, 211803 (2019).
[33] M. Saur and F. S. Yu, Sci. Bull. **65**, 1428 (2020).
[34] H. Y. Cheng and C. W. Chiang, Phys. Rev. D **85**, 034036 (2012); Phys. Rev. D **86**, 014014 (2012).
[35] H. N. Li, C. D. Lü and F. S. Yu, Phys. Rev. D **86**, 036012 (2012).
[36] D. Pirtskhalava and P. Uttayarat, Phys. Lett. B **712**, 81 (2012).
[37] M. Gronau, Phys. Lett. B **730**, 221 (2014); Addendum: [Phys. Lett. B **735**, 282 (2014)].
[38] F. Buccella, M. Lusignoli, G. Miele, A. Pugliese, and P. Santorelli, Phys. Rev. D **88**, 074011 (2013).
[39] F. Buccella, A. Paul and P. Santorelli, Phys. Rev. D **99**, 113001 (2019)
[40] H. N. Li, C. D. Lü and F. S. Yu, arXiv:1903.10638 [hep-ph].
[41] Y. Grossman and S. Schacht, JHEP **1907**, 020 (2019).
[42] I. I. Bigi and A. Paul, JHEP **03**, 021 (2012).
[43] D. E. Morrissey and M. J. Ramsey-Musolf, New J. Phys. **14**, 125003 (2012).
[44] A. Bondar, A. Poluektov and V. Vorobiev, Phys. Rev. D **82**, 034033 (2010).

[45] D. Atwood and A. A. Petrov, Phys. Rev. D **71**, 054032 (2005).

[46] Y. Shi and J. Yang, Phys. Rev. D **98**, 075019 (2018).

[47] V. A. Kostelecky, Phys. Rev. D **64**, 076001 (2001).

[48] G. Wilkinson, Sci. Bull. **66**, 2251 (2021).

[49] R. Aaij *et al.* (LHCb collaboration), LHCb-CONF-2020-001.

[50] M. Gronau and D. London, Phys. Lett. B **253**, 483 (1991); M. Gronau and D. Wyler, Phys. Lett. B **265**, 172 (1991).

[51] D. Atwood, I. Dunietz, and A. Soni, Phys. Rev. Lett **78**, 3257 (1997); Phys. Rev **D 63**, 036005 (2001).

[52] A. Giri, Y. Grossman, A. Soffer, and J. Zupan, Phys. Rev. D **68** (2003).

[53] M. Ablikim *et al.* (BESIII Collaboration), Chin. Phys. C **44**, 040001 (2020).

[54] G. Burdman and I. Shipsey, Ann. Rev. Nucl. Part. Sci. **53**, 431 (2003).

[55] E. Golowich, J. Hewett, S. Pakvasa, and A. Petrov, Phys. Rev. D **79**, 114030 (2009).

[56] M. Ablikim *et al.* (BESIII Collaboration), Phys. Rev. D **97**, 072015 (2018).

[57] H. X. Chen, W. Chen, X. Liu, Y. R. Liu and S. L. Zhu, Rept. Prog. Phys. **80**, 076201 (2017).

[58] F. K. Guo, C. Hanhart, U. G. Meißner, Q. Wang, Q. Zhao and B. S. Zou, Rev. Mod. Phys. **90**, 015004 (2018).

[59] Y. Kato and T. Iijima, Prog. Part. Nucl. Phys. **105**, 61 (2019).

[60] M. Ablikim *et al.* (BESIII Collaboration), Chin. Phys. C **43**, 083002 (2019).

[61] M. Ablikim *et al.* (BESIII Collaboration), Phys. Rev. D **99**, 032010 (2019).

[62] R. Aaij *et al.* (LHCb Collaboration), Phys. Rev. Lett. **121**, no.9, 092003 (2018).

[63] R. Aaij *et al.* (LHCb Collaboration), Phys. Rev. D **100**, 032001 (2019).

[64] R. Aaij *et al.* (LHCb Collaboration), [arXiv:2109.01334 [hep-ex]].

[65] H. Y. Cheng, [arXiv:2111.09566 [hep-ph]].

[66] A. Zupanc *et al.* (Belle Collaboration), Phys. Rev. Lett. **113**, 042002 (2014).

[67] M. Ablikim *et al.* (BESIII Collaboration), Phys. Rev. Lett. **116**, 052001 (2016).

[68] S. B. Yang *et al.* (Belle Collaboration), Phys. Rev. Lett. **117**, 011801 (2016).

[69] R. Aaij *et al.* (LHCb Collaboration), JHEP **1803**, 043 (2018).

[70] M. Bishai *et al.* (CLEO Collaboration), Phys. Lett. B **350**, 256 (1995).

[71] H. Y. Cheng and B. Tseng, Phys. Rev. D **48**, 4188 (1993).

[72] K.K. Sharma and R.C. Verma, Eur. Phys. J. C **7**, 217 (1999).

[73] P. Żenczykowski, Phys. Rev. D **50**, 402 (1994).

[74] A. Datta, arXiv:hep-ph/9504428 [hep-ph].

[75] M. Ablikim *et al.* (BESIII Collaboration), Phys. Rev. D **100**, 072004 (2019).

[76] Y. B. Li *et al.* (Belle Collaboration), Phys. Rev. Lett. **122**, 082001 (2019).

[77] Y. B. Li *et al.* (Belle Collaboration), Phys. Rev. D **100**, 031101 (2019).

[78] R. Dhir and C. S. Kim, Phys. Rev. D **91**, 114008 (2015).

[79] H. Y. Cheng, C. Y. Cheung, G. L. Lin, Y. C. Lin, T. M. Yan and H. L. Yu, Phys. Rev. D **46**, 5060 (1992).

[80] R. Aaij *et al.* (LHCb Collaboration), [arXiv:2007.12096 [hep-ex]].

[81] R. Pérez-Marcial, R. Huerta, A. Garcia, and M. Avila-Aoki, Phys. Rev. D **40**, 2955 (1989); ibid. D **44**, 2203(E) (1991).

[82] R. Singleton, Phys. Rev. D **43**, 2939 (1991).

[83] H.Y. Cheng and B. Tseng, Phys. Rev. D **53**, 1457 (1996); Phys. Rev. D **55**, 1697(E) (1997).

[84] M. Pervin, W. Roberts and S. Capstick, Phys. Rev. C **72**, 035201 (2005).

[85] M. A. Ivanov, V. E. Lyubovitskij, J. G. Körner and P. Kroll, Phys. Rev. D **56**, 348 (1997).

[86] T. Gutsche, M. A. Ivanov, J. G. Körner, V. E. Lyubovitskij and P. Santorelli, Phys. Rev. D **90**, 114033 (2014).

[87] R. N. Faustov and V. O. Galkin, Eur. Phys. J. C **76**, 628 (2016).

[88] C.W. Luo, Eur. Phys. J. C **1**, 235 (1998).

[89] R.S. Marques de Carvalho *et al.,* Phys. Rev. D **60**, 034009 (1999).

[90] M. Q. Huang and D. W. Wang, hep-ph/0608170.

[91] K. Azizi, Y. Sarac and H. Sundu, Eur. Phys. J. A **48**, 2 (2012).

[92] S. Meinel, Phys. Rev. Lett. **118**, 082001 (2017).

[93] S. Meinel, Phys. Rev. D **97**, 034511 (2018).

[94] M. Ablikim *et al.* (BESIII Collaboration), Phys. Rev. Lett. **115**, 221805 (2015).

[95] H. Y. Cheng, Phys. Lett. B **399**, 281 (1997).

[96] H. Y. Cheng, C. Y. Cheung, G. L. Lin, Y. C. Lin, T. M. Yan and H. L. Yu, Phys. Rev. D **47**, 1030 (1993).

[97] N. Jiang, X. L. Chen and S. L. Zhu, Phys. Rev. D **92**, 054017 (2015).

[98] G. J. Wang, L. Meng and S. L. Zhu, Phys. Rev. D **99**, 034021 (2019).

[99] J. Yelton *et al.* (Belle Collaboration), arXiv:2009.03951 [hep-ex].

[100] H. Y. Cheng, C. Y. Cheung, G. L. Lin, Y. C. Lin, T. M. Yan and H. L. Yu, Phys. Rev. D **51**, 1199 (1995).

[101] J. M. Link *et al.* (FOCUS Collaboration), Phys. Lett. B **634**, 165 (2006).

[102] M. Ablikim *et al.* (BESIII Collaboration), Phys. Rev. D **100**, 072004 (2019).

[103] A. Bondar, A. Grabovsky, A. Reznichenko, A. Rudenko and V. Vorobyev, JHEP **03**, 076 (2020).

[104] R. Aaij *et al.* (LHCb Collaboration), JHEP **1803**, 182 (2018).

[105] I. I. Bigi, arXiv:1206.4554 [hep-ph].

[106] X. D. Shi, X. W. Kang, I. Bigi, W. P. Wang and H. P. Peng, Phys. Rev. D **100**, 113002 (2019).

[107] B. Aubert *et al.* (BaBar Collaboration), Phys. Rev. Lett. **98**, 012001 (2007).

[108] H. Y. Cheng, Front. Phys. **10**, 101406 (2015).

[109] R. Aaij *et al.* (LHCb Collaboration), JHEP **1705**, 030 (2017).

[110] H. Y. Cheng and C. W. Chiang, Phys. Rev. D **95**, 094018 (2017).

[111] S. Q. Luo, B. Chen, Z. W. Liu and X. Liu, Eur. Phys. J. C **80**, 301 (2020).

[112] R. Aaij *et al.* (LHCb Collaboration), Phys. Rev. Lett. **118**, 182001 (2017).

[113] J. Yelton *et al.* (Belle Collaboration), Phys. Rev. D **97**, 051102 (2018).