Conceptual Design Report for Super tau-Charm Facility (STCF) at China –Physics Program–

STCF Working Group[1]

[1]*University of Science and Technology of China, Hefei 230026, P.R.C*

[2]*University of Chinese Academy of Sciences, Beijing 100049, P.R.C*

[3]*Institute of High Energy Physics, Beijing 100049, P.R.C*

[4]*Institute of Theoretical Physics, Beijing 100190, P.R.C*

[5]*Peking University, Beijing 100871, P.R.C*

[6]*Shanghai Jiao Tong University, Shanghai 200240, P.R.C*

[7]*Institute of Physics, Academia Sinica, Taipei, Taiwan 115, R.C*

[8]*Nankai University, Tianjin 300071, P.R.C*

[9]*Nanjing University, Nanjing 210093, P.R.C*

[10]*Wuhan University, Wuhan 430072, P.R.C*

[11]*Sun Yat-Sen University, Guangzhou 510275, P.R.C*

[12]*Shandong University, Jinan 250014, P.R.C*

[13]*Fudan University, Shanghai 200443, P.R.C*

[14]*University of South China, Hengyang 421001, P.R.C*

[15]*Beijing Normal University, Beijing 100875, P.R.C*

[16]*State Key Laboratory of Particle Detection and Electronics, Beijing, 100049, Heifei 230026,*

P.R.C

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Abstract

A τ-Charm facility, which is an electron-positron collider operating at the transition interval between non-perturbative quantum chromodynamics (QCD) and perturbative QCD (*i.e.* 2~5 GeV), is of great interested in elementary particle physics field. Due to its several advance features, the τ-Charm facility has very broad physics program and provides an unique platform to study the tau and charm physics, precisely test standard model and hunt the physics beyond. Beijing Electron Positron Collider (BEPCII) and BEijing Spectrometers (BESIII), the only collider running at the τ-Charm energy region, will end its mission in coming 8-10 years. A Super τ-Charm facility (STCF), which is of peak luminosity above 0.5×10^{35} cm^{-2}c^{-1}, and of center-of-mass energy $2 \sim 7$ GeV, is a natural extension and a viable option for the collider physics at the post-BEPCII project in China, and will play crucial role in the high density frontier of elementary particle physics field worldwide. The STCF project in China is under exploring, and the R&D program is underway. This document provides the detailed discussion on the major physics goals on the STCF, which may motivate the R&D programs of accelerator and spectrometer, and is very helpful for us to convince and get the full support for this project from funding agencies and government.

Contents

1 Introduction

The Standard Model (SM) of particle physics, consisting of unified electro-weak (EW) and Quantum Chromodynamics (QCD) theories, has successfully explained almost experimental results of the micro world and precisely predicted a wide variety of phenomena, and is accepted as the remarkable fundamental theory of elementary particle physics to date. The electroweak theory is an unified gauge theory for the weak force and quantum electrodynamics (QED), and has been tested very precisely (in percentage). However, with the deepening of research from theory, more precisely measurements from experiment are desirable. QCD, based on the exact color symmetry SU(3), describes the strong interactions between quarks and gluons, and exhibits two main properties, *i.e.* color confinement and asymptotic freedom. The asymptotic freedom is widely verified by many different experiment at the level of a few percents at short distances, since the perturbative calculation can be implemented theoretically. However, the color confinement, which is dominant at long distances and exhibit non-perturbative feature, is far from being theoretically understood and has been quantitatively test rarely, more efforts from both theory and experiments are expected. Hadrons, which are composite particle made of two or more quarks held by the strong force, its structure, spectroscopy as well as production and decays provide an excellent platform to explore the non-perturbation QCD.

In 2012, the discovery of Higgs particle, the last piece of building block of SM, is the milestone of elementary particle physics. Despite being so successful, there are still leaving several unanswered key scientific questions, and searching for the new physics beyond SM is one of the main tasks in particle physics field. The CP violation (CPV), which can be used to explain the asymmetry between matter and anti-matter in the universe, has been well studied in the bottom and strange sectors, and have recently discovered in the charm sector. However, the current knowledges of CPV are insufficient to explain this key questions, and new CPV sources are desirable. Studying the CPV in leptons and baryon sectors may provide supplementary platform. Nucleon are main constituents of most naturally occurring matter and have been studied extensively. However, the further studies on their internal distribution of charge and current may breakthrough the existing understanding of micro-world.

A tau charm facility (TCF), which is an electron-positron collider operating at the transition energy region between perturbative and non-perturbative QCD, plays a crucial role and is of great interested in elementary particle physics field. A TCF has several advance features in physics, *e.g.* rich production for resonances such as charmonium and charmed hadrons; mass location of the exotic hadrons, gluonic matter and hybrid; pairs production at the energy threshold for the τ and charmed meson *etc*. Comparing to B factory (BELLE II)[5] and hadron collider (LHCb)[6], which also can produce tau lepton and charmed meson copiously, a TCF is of shortage in statistics. However, it has several advantages, *i.e.*, the excellent ratio of signal to background, the perfect detection efficiency, the well controlled systematic uncertainty and the capability of full events reconstruction, the straightforward absolute measurement, *etc*. A TCF covers abundant and broad physics topics, and provides an unique and powerful platform for the physics study including charmonium physics, charmed hadron physics, light hadrons, τ physics, QCD as well as new physics.

1.1 TCF History

Historically, there has lived through several TCF in the world, such as MARKI-III[7, 8, 9], DM2[10] *etc*, which had produced remarkable results in testing SM and searching for beyond SM. Beijing Electron Positron Collider (BEPC) and Beijing Spectrometer (BES)[11], locating at Beijing, China, is one of most remarkable TCFs in the world. BEPC/BES, starting from the end of 1980s, is productive, and have published fruitful physics results, such as the precision measurements of τ-lepton mass and R-value, the discoveries of X(1835), *etc* [12, 13]. BEPCII/BESIII, which is of double ring and the major upgrade of BEPC/BESII experiments, is designed to have center-of-mass energy (CME) between 2.0 and 4.2 GeV, and a peak luminosity, 10^{33} cm^{-2}s^{-1} at $\sqrt{s}$ = 3.77 GeV [14, 15] . BEPCII/BESIII is the only one running and the highest luminosity TCF in the world to date, and is very successful and fruitful.

Despite the success, with the deepening of research and a deeper understanding of the micro world, the physics potential of BEPCII/BESIII is limited by its luminosity and CME. For example, the understanding of international composition of XYZ particles and their underlying dynamics requires more luminosity and extended CME, the study of charmed baryons physics requires extended CME, the researching of charmed mesons and τ physics requires more luminosity. Furthermore, as we know, the Belle II experiment is under commissioning, and is expected to accumulate data 50 ab^{-1} by year 2024 [45]; the LHCb is on the upgrade, and is expected to have much more data in future [23]. Both Belle II and LHCb experiments are challenged to BESIII in part of physics potential, but also required more precise inputs from the TCF, *e.g.*, strong phase of charmed meson decay for the precision measurement of Cabibbo-Kabayashi-Maskawa (CKM) element γ/ϕ_3. Limited by the length of storage ring, BEPCII has not space and potential for the upgrade. BEPCII/BESIII do not has major upgrade plan, and will end her mission in 7∼10 years. Thus, a super tau charm facility (STCF), which is far beyond BEPCII/BESIII experiment, is nature extension and a viable option for China accelerator project in the post BEPCII/BESIII era.

1.2 The proposed STCF project in China

The proposed new generation STCF [24] in China is a electron-positron collider with double ring and symmetry beam energy. It is designed to have CME ranging from 2 ∼ 7 GeV, and have a peaking luminosity above 0.5×10^{35} cm^{-2}c^{-1} at $\sqrt{s}$ =4 GeV. It also leaves space and potential for upgrading to the higher luminosity and implementing the polarized beam at phase II [25]. To achieve such high luminosity, several advanced technologies, such as the solution of crabbed waist and large Piwinski angle collision at interaction region, is implemented in the machine.

STCF project is under the research and development (R&D) stage, a compatibly sophisticated detector is required to maximize the physics potential. With such machine, to competent the high precision and high luminosity, several features are considered for detector during the conceptual design : large solid angle coverage, high detection efficiency and resolution (spatial, momentum, energy and timing), high events rate and fast trigger, high radiation tolerance. A BESIII like detector, consisting of a tracking system, a particle identification (PID) system, an electromagnetic calorimeter (EMC), a super-conducting solenoid and a muon detector from inner to out, is proposed. To achieve high resolution (momentum and spatial) and efficiency of the charged tracks as well as tolerate extremely high radiation close to the interaction point (IP), an inner tracking with radius 15∼20 cm, made of three layers thin silicon (e.g. depleted CMOS maps or depfet) or micron pattern gas detector (e.g. cylindrical GEM, MicroMegas or uRWELL), together with a main draft chamber (MDC) with outer radius 85∼100 cm based on the utra-low material is proposed. A Ring Imaging Cherenkov (RICH) detector in the Barrel region and a Detection of Internally Reflected Cherenkov (DIRC) in the endcap region are suggested for the PID system, to achieve the capability of a 3σ K/π separation up to 2 GeV/c at momentum and π/μ separation at the low momentum region. And the dE/dx information from the MDC system is expected to have more than 3σ K/π separation for the tracks with momentum less than 700 MeV/c. A high granularity EMC based on pure CsI crystal in barrel region and LYSO crystal in the endcap region, combining with APD for the photon detection and SiPM for time measurement with high resolution, is designed to obtain the excellent energy and spatial resolutions for the photon and electron detection as well a good time resolution (a few hundred picoseconds) for the separation of photon from neutron/K$_L$. A super-conducting solenoid magnet with an adjustable magnetic field ranging 0.7∼1.2 Tesla is required to compromise the resolution for the high momentum tracks and the efficiency for the low momentum tracks due to the rather broad range of CME (2∼7 GeV). To achieve a better separation power of muon from pion (a factor 10 generally, except to $>$ 30 refined??) as well as to lower the identification threshold (300 MeV/c at momentum), a muon detector consisting of 2−3 inner layers based on multi-gap resistive plate chamber (MRPC) or plastic scintillator, which are of precise time resolution, as well as ∼6 outer layers with the resistive plat chamber (RPC) or plastic scintillator, is proposed. The designed detector is expected to have much improved performance in each sub-system comparing to the BESIII detector. Currently, the STCF detector shown as Fig. 1 is described by DD4hep[26], and still under research and development.

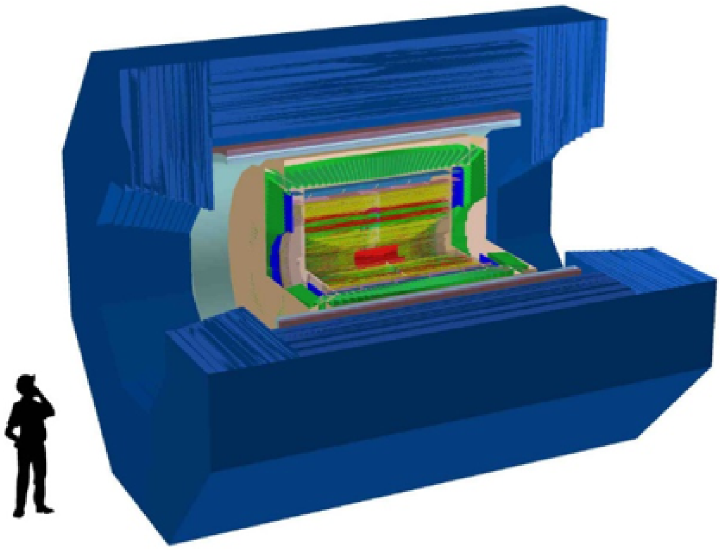

Figure 1: The STCF detector visualized by DD4hep.

1.3 The data samples at STCF

With such high proposed luminosity, above 0.5×10^{35} cm^{-2}c^{-1}, STCF is expected to deliver data more than 1 ab^{-1} per year. Assuming 10 years for the lifetime for STCF, totally 10 ab^{-1} data sample is expected. The possible proposed data taking for the STCF as well as the events number of sample are shown in Table 1.

1.4 The experimental uncertainties

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Table 1: The expected numbers of events per year at different energy points at STCF

CME (GeV)	Lumi (ab^{-1})	samples	σ(nb)	No. of Events	remark
3.097	1	J/ψ	3400	3.4×10^{12}	
3.670	1	$\tau^+\tau^-$	2.4	2.4×10^9	
3.686	1	$\psi(3686)$	640	6.4×10^{11}	
		$\tau^+\tau^-$	2.5	2.5×10^9	
		$\psi(3686) \to \tau^+\tau^-$		2.0×10^9	
3.770	1	$D^0\bar{D}^0$	3.6	3.6×10^9	
		$D^+\bar{D}^-$	2.8	2.8×10^9	
		$D^0\bar{D}^0$		7.9×10^8	Single Tag
		$D^+\bar{D}^-$		5.5×10^8	Single Tag
		$\tau^+\tau^-$	2.9	2.9×10^9	
4.040	1	$\gamma D^0\bar{D}^0$	0.40	4.0×10^6	$\mathrm{CP}_{\mathrm{D^0\bar{D}^0}} = +1$
		$\pi^0 D^0\bar{D}^0$	0.40	4.0×10^6	$\mathrm{CP}_{\mathrm{D^0\bar{D}^0}} = -1$
		$D_s^+ D_s^-$	0.20	2.0×10^8	
		$\tau^+\tau^-$	3.5	3.5×10^9	
4.180	1	$D_s^{+*} D_s^-$+c.c.	0.90	9.0×10^8	
		$D_s^{+*} D_s^-$+c.c.		1.3×10^8	Single Tag
		$\tau^+\tau^-$	3.6	3.6×10^9	
4.230	1	$J/\psi\pi^+\pi^-$	0.085	8.5×10^7	
		$\tau^+\tau^-$	3.6	3.6×10^9	
		$\gamma X(3872)$			
4.360	1	$\psi(3686)\pi^+\pi^-$	0.058	5.8×10^7	
		$\tau^+\tau^-$	3.5	3.5×10^9	
4.420	1	$\psi(3686)\pi^+\pi^-$	0.040	4.0×10^7	
		$\tau^+\tau^-$	3.5	3.5×10^9	
4.630	1	$\psi(3686)\pi^+\pi^-$	0.033	3.3×10^7	
		$\Lambda_c\bar{\Lambda}_c$	0.56	5.6×10^8	
		$\Lambda_c\bar{\Lambda}_c$		6.4×10^7	Single Tag
		$\tau^+\tau^-$	3.4	3.4×10^9	
4.0-7.0	3	300 points scan with 10 MeV step, 1 fb^{-1}/point			
> 5	2-7	several ab^{-1} high energy data, details dependent on scan results			

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2 Charmonium and XYZ Physics

At STCF it is an ideal place to study charmonium states and the exotic states containing a $c\bar{c}$ pair. For these states with the quantum number $J^{PC} = 1^{--}$ they can be copiously produced in their threshold energy regions. For states with other quantum numbers they can be searched in certain decay products. With the design luminosity, large event numbers of the states with the quantum numbers other than 1^{--} can be expected. With the energy regions of STCF, a systematic study of highly excited charmonium states and XYZ-states can be performed with the statistics never reached before. The mass spectrum of charmonia below the $D\bar{D}$ threshold has been successfully described with the quark model with a confining potential between a charm- and an anti-charm quark. However, many excited charmonium states predicted by the model are still missing, or their properties are poolly known. The XYZ states discovered in the last decade can not be predicted by the quark model, or it has difficulties to explain the existence of XYZ states. It is unclear if they are hadronic molecule, tetraquark states, hadro-charmonia and threshold effects. Experimentally, the answers of these questions can be found at STCF combined with studies of theory.

2.1 Charmonium states

Charmonia are dominantly bound states of the charm quark-antiquark pair. Since the discovery of J/ψ in 1974, there are many charmonium states observed, which provide an ideal laboratory to study the strong interaction, especially the the force between a heavy quark and an heavy anti-quark at an energy scale where the nonperturbative QCD interplays with perturbative QCD.

In the charmonium spectroscopy, the spectrum of relatively narrow charmonium states below the open-charm thresholds has been well established experimentally. These states can be assigned to the lowest $n^{2S+1}L_J$ states in the simple $c\bar{c}$ quark model with a confining potential and some sophisticated spin dependent interactions [1]. Using the masses of some observed charmonia as inputs, the masses of higher states can be predicted. The states that can be described by the quark model are usually called conventional charmonia. The charmonium spectrm has also been predicted from the first principle by using Lattice QCD(LQCD) in a model-independent way. To date the results of LQCD for the charmonium spectrum are in good agreement with the experimental data and also consistent with the quark model predictions, especially for the low-lying states. The mass spectrum of conventional charmonia and discovered XYZ-states are illustrated in Fig. [**?**]. The surprisingly good description of charmonium spectrum by the quark model suggests the immediate tasks for experiments to identify the remaining states that are expected, such as $1D$ states, $2P$ states, and other higher-L states and higher radial excitations.

2.1.1 $2P$ charmonia

$2P$ charmonium states are called χ'_{cJ} and h'_c according to the naming rules of hadrons. Quark model studies predict their masses to be around 4.0 GeV. The χ'_{c2} state (named as $\chi_{c2}(3930)$ by PDG2018 [2]) is almost established with $M = 3927.2\pm2.6$ MeV and $\Gamma = 24\pm6$. Belle observes a wide resonance structure of $D\bar{D}$ with $M = 3862^{+26+40}_{-32-13}$ MeV and $\Gamma = 201^{+154+88}_{-67-82}$ MeV in the process $e^+e^- \to J/\psi D\bar{D}$ using the full amplitude analysis [3], which is now tentatively assigned to be $\chi_{c0}(3860)$ by PDG2018. PDG2018 now names $X(3872)$ to be $\chi_{c1}(3872)$, but admit that its properties are different from a conventional $q\bar{q}$ state and can be a candidate for an exotic structure. There is no clear evidence of h'_c yet. Obviously, the masses of these $2P$ states or candidates are a little lower than the quark model prediction. This raises natural questions what on earth their inner dynamics are. On future STCF, $2P$ states can be produced by the radiative transitions from higher vector charmonia. This requires a considerable statistics accumulated

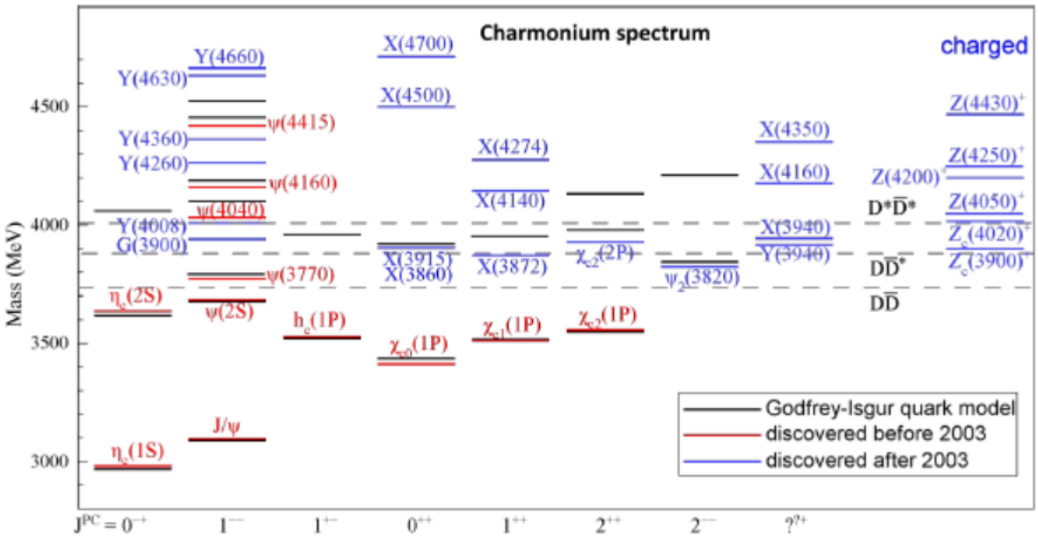

Figure 2: The mass spectrum of charmonia and XYZ states.

at the $\psi(4040)$, $\psi(4160)$ and $\psi(4415)$ energy scales.

2.1.2 $1D$ charmonia η_{c2} and ψ_3

The supermultiplet of $1D$ states includes $1^3D_{1,2,3}$ and 1^1D_2 (named η_{c_2}) with the quantum numbers $(1,2,3)^{--}$ and 2^{-+}, respectively. $1D$ states can be potential objects of physics study of STCF. Apart from the $\psi(3770)$, the Belle [4] and BESIII Collaborations [5] also observe a narrow resonance $X(3823)$ in the $\gamma\chi_{c1}$ system (now named as $\psi_2(3823)$ in PDG2018) with a width less than 20 MeV. Its properties are consistent with the quark model state 1^3D_2, but the quantum numbers need confirmation. Very recently, there is a preliminary information that the 1^3D_3 state (named ψ_3) is likely observed by the LHCb Collaboration. Even if these two states can be confirmed finally, the last $1D$ charmonium state η_{c_2} is still escaping from the experimental search. Lattice QCD studies predict the mass of η_{c2} is around 3.8 GeV [6, 7], which is nearly degenerate to other $1D$ states. Experimentally, η_{c2} can be produced directly from $\psi(4040)$ through the M1 transition. The partial width of $\psi(4040) \to \gamma\eta_{c2}$ is estimated to be a few keV, such that the corresponding branching fraction is at order of $O(10^{-5})$. Therefore, it is difficult for BESIII to observe η_{c2} in this process, since the $\psi(4040)$ event number of BESIII is about 10^6 [8]. However, STCF is expected to have hundreds or even more of the decay events with a 100 times larger luminosity and have hope to search η_{c2}. Since the mass of η_{c2} is right above the $D\bar{D}$ threshold and below the $D\bar{D}^*$ threshold and it cannot decay into $D\bar{D}$, η_{c2} will be very narrow and the hadronic transitions, such as the decay modes $\chi_{c1}\pi\pi$ and $J/\psi\pi^0\pi^-\pi^+$, and the E1 radiative transition $\eta_{c2} \to \gamma h_c$ can be important.

ψ_3 can be search in the processes $e^+e^- \to \pi\pi\psi_3$ with $\psi_3 \to \gamma\chi_{c2}$, similar to the case of $\psi_2(3823) \to \gamma\chi_{c1}$, and also $\psi_3 \to D\bar{D}$. BESIII does not observe ψ_3 in the $e^+e^- \to \pi\pi D\bar{D}$ process [9]. This is understandable since the partial decay width of $\psi_3 \to D\bar{D}(L=3)$ is highly suppressed by the centrifugal potential barrier. Non-relativistic models predict that that both the decay widths of $\psi_3 \to \gamma\chi_{c2}$ and $\psi_2 \to \gamma\chi_{c1}$ are around 280 keV [1], but Belle [4] and BESIII [5] do not observed evidences of a structure around 3.85 GeV in the $\gamma\chi_{c2}$ system. This is an intriguing quenstion and can be clarified by STCF with a much larger statistics.

2.1.3 Charmonium-like hybrids

Besides the conventional charnomia, QCD expects the existence of exotic hadron states (relative to the $q\bar{q}$ mesons and qqq baryons described in the quark model), such as glueballs (bound states of gluons), hybrids (bound states of gluons and quarks), multiquark states. The hybrids of constituent configuration $c\bar{c}g$ are usually called charmonium-like hybrids. Generally speaking, there are theoretical ambiguities in distinguishing the conventional charmonia and hybrid-like charmonia if they have the same quantum number J^{PC}. Therefore, it is more interesting to explore the charmonium-like states with the exotic quantum nubmers $J^{PC} = 1^{-+}, 0^{+-}, 0^{--}, 2^{+-}$, etc., which cannot appear for $q\bar{q}$ mesons.

Extensive lattice QCD studies show that the lowest charmonium-like hybrid is the 1^{-+} state whose mass is around 4.1-4.3 GeV. An interesting observation from lattice QCD is that there seems a supermultiplet including $(0,1,2)^{-+}$ and 1^{--} states with nearly degenerate masses around 4.4 GeV [6]. In addition, these states have a common property that they couple most to the hybrid-like $c\bar{c}g$-type operators. Based on this observation, they can be taken as hybrid candidates with configurations of a color octet $c\bar{c}$ component coupling to a chromo-magnetic gluonic excitation. Obviously, these states, if they do exist, reside in the planned STCF energy region.

- 1^{--} charmonium-like hybrid candidate: $Y(4260)$ is a charmonium-like vector meson and was first observed in the initial-state-radiation process of e^+e^- collisions by Belle. On the other hand, there is a dip at this mass in the e^+e^- inclusive cross section (R-value scan), which is in contrast to the eminent peaks of other vector mesons. It is possible that $Y(4260)$ is an exotic meson state, such as a charmonium-like hybrids [10]. BESIII has made much effort to study the property of $Y(4260)$ in recent years. In each of the processes $e^+e^- \to J/\psi\pi\pi, \chi_{c0}\omega, h_c\pi\pi\psi(3686)\pi\pi$, and $D^0D^{*-}\pi^+$, BESIII observe a structure whose mass parameter is consistently determined to be 4.22-4.23 GeV, but width varies from 30 to 80 MeV (see Ref. [11] for a review). If they are the same resonance $Y(4220)$ corresponding to the afore mentioned $Y(4260)$ a combined analysis of the above processes gives the lower bound of the leptonic decay width of $Y(4220)$ to be $\Gamma_{e^+e^-}(Y(4220)) > 29.1\pm2.5\pm7.0$ eV [12]. This is consitent with leptonic decay width of the hybrid vector charmonium $\Gamma_{e^+e^-} < 40$ eV predicted by a quenched lattice QCD study [13]. However, BESIII also observed a very large cross section of the process $e^+e^- \to D_s^*\bar{D}_s^*$ at energy $\sqrt{s} \sim 4.22$ GeV. If $D_s^*\bar{D}_s^*$ in this process comes from $Y(4220)$, then the leptonic decay width of $Y(4220)$ can be a few times larger. Thus the discussion above must be reconsidered. Anyway, the status assignment of $Y(4220)$ is still premature at present and more experimental and theoretical efforts should be made. In the meantime, the vector charmonium-like state $Y(4360)$ and $Y(4660)$ should be studied jointly with $Y(4220)$. At STCF with a much larger luminosity, the decay modes of $Y(4220)$ can be measured more precisely and other open-charm decay modes can be searched. On the other hand, BESIII studies show that there may be important connections between $Y(4220)$, $X(3872)$ and $Z_c(3900)$, however, a much larger statsitics is desired to unravel them. It is expected that the status of $Y(4220)$ can be finally determined by STCF.

- $(0,1,2)^{-+}$ charmonium-like hybrids: According to lattice QCD study, these hybrids have masses around 4.2-4.4 GeV and can be viewed to be in a spin triplet. On a e^+e^- machine, they can be produced either from the hadronic and radiative transitions of higher charmonia such as $\psi(4S)$ and $\psi(5S)$ (if it exists) or from the final state radiation in the e^+e^- annihilations $e^+e^- \to \gamma X$ with X refering to the $(0,1,2)^{-+}$ hybrids. Obviously their production cross sections in the e^+e^- annihilations are suppressed by $\alpha = 1/134$ in comparison with their 1^{--} counterpart. Given the hybrid assignment of $Y(4220)$, their production cross section can be estimated to be $\sigma(e^+e^- \to \gamma X) \sim O(1\,\text{pb})$ based on the present known largest cross section $e^+e^- \to Y(4220) \to \pi^+D^0D^{*-} \approx$

200 pb at the peak position observed by BESIII [11]. STCF will work in the energy range 2-7 GeV and is expected to deliver roughly 1 ab^{-1} data per year, therefore the number of hybrid events can be as large as 10^4 if the integrated luminosity is 10 fb^{-1} at the resonance energy. A "color-halo" picture proposed by a quenched lattice QCD study implies the hidden charm decay modes (a charmonium plus light hadrons) can be important for the decays of charmonium-like hybrids. This is compatible with the observed $Y(4220)$ decay properties. Accordingly $(0,1,2)^{-+}$ hybrids can be searched in $J/\psi(\omega,\phi)$ and $\chi_{cJ}\eta$ final states, which are expected to have $O(10)$ or $O(100)$ events near the peak position at STCF. In this sense, STCF has a good opportunity on the study of charmonium-like hybrids.

2.1.4 Radiative tansitions and decays of charmonia

Apart from the spectroscopy, the understanding of the known charmonium states can be greatly improved through more precise measurements of transitions involving these states, including both radiative and hadronic ones [8]. In the following the two types of decays will be discussed.

For the radiative transitions, at STCF one will be able to measure rare electric-dipole transitions $\eta_c(2S) \to h_c\gamma$, $\psi(3770) \to \chi_{c0}\gamma$ and magnetic-dipole transitions $\psi(2S) \to \eta_c(2S)\gamma$, $\eta_c(2S) \to J/\psi\gamma$, $h_c \to \chi_{c0}\gamma$. One will be also able to measure the total and leptonic or two-photon widths with high precision. These transitions and decay widths can be calculated both in the quark model and lattice QCD. The comparison between the experimental data and the theoretical predictions can help us to understand more clearly the inner structure of charmonia. On the other hand, the radiative transition can be a discovery ground for novel charmonium-like states. E.g., given a mass of $\sim$ 4.2 GeV predicted by lattice QCD [6], 1^{-+} exotic charmonium can be produced from $\psi(4415)$ through M1 radiative transition and be detected by the E1 transition into $h_c\gamma$ and M1 transition into J/ψ and ψ'. There are also radiative transitions between J^{PC}-exotic states such as 1^{-+}, 0^{+-}, and 2^{+-}. $Y(4260)$ is sometimes thought as an hybrid charmonium, which can be tested experimentally by the measurement of the M1 transition $Y \to \eta_c\gamma$, etc. Recently BESIII reported the first observation of $e^+e^- \to X(3872)\gamma$ around the energy $\sqrt{s}$ = 4.26 GeV [14] which hints the possible transition $Y \to X\gamma$. This type of transitions can be measured more precisely in the future experiments.

A systematic study of the decays of all low-lying charmonium states is also one of the tasks at STCF. These states are below the threshold of D-meson production and decay dominantly into hadrons consisting of light u, d and s quarks through the annihilation of $c\bar{c}$ or lower mass charmonium. However, information about their decays is incomplete at present. For the best-studied J/ψ meson only about 40% of its hadronic decays have been measured. For other states the situation is even worse. At STCF precision measurement of hadronic transitions between charmonium states, decays into photons like $h_c \to 3\gamma$ and $\eta_c, \chi_{c0}, \chi_{c1} \to 2\gamma$ can be done.

The photon spectrum in the inclusive decay $\psi \to \gamma X$ can be well measured to test pertubative QCD. Special attention should be paid to the radiative decays of J/ψ. Glueballs have searched by experiments for a long time. The radiative decay of J/ψ is the best hunting ground. LQCD has predicted the glueball spectrum [15] and the production rates of lowest-lying glueballs in the J/ψ radiative decays [16, 17] in the quenched approximation. However, this information is not enough for the identification of glueballs in experiments. The key question is the mixing of glueballs with regular two-quark mesons or even four-quark mesons. In order to distinguish a glueball from regular mesons or determine the gluebll-meson mixing pattern, more measurements of J/ψ radiative decays should be made, such that a systematic data analysis can be carried out.

2.1.5 Summary

The physical goals of STCF in the study of charmonium-like states can be summarized as follows:

- The $(0, 1, 2)^{-+}$ charmonium-like hybrids can be searched for at STCF, among which the most important object is the 1^{-+} state. Their production can be through the radiative transition of $\psi(4S)$ and $\psi(5S)$ (if possible) or the direct production of $e^+e^- \rightarrow \gamma X((0, 1, 2)^{-+})$. Given the hybrid assignment of $Y(4220)$, the resonance cross section of is estimated to be $O(1)$ pb based on $\sigma(e^+e^- \rightarrow Y(4220) \rightarrow \pi^+ D^0 D^{*-}) \approx 200$ pb. The $J\psi\omega(\phi)$ and $\chi_{cJ}\eta$ can be important decay modes of $X((0, 1, 2)^{-+})$ and the experimental yields of this modes at STCF are roughly $O(10) - O(100)$ events at the peak position.

- STCF can play an important role in the search of $1D$ charmonia η_{c2} and ψ_3.

- At STCF with a much larger luminosity, the decay modes of $Y(4220)$ can be measured more precisely and other open-charm decay modes can be searched. On the other hand, BESIII studies show that there may be important connections between $Y(4220)$, $X(3872)$ and $Z_c(3900)$, however, a much larger statsitics is desired to unravel them. It is expected that the status of $Y(4220)$ can be finally determined by STCF.

2.2 XYZ states

Charmonium states being bound states of a charm and an anticharm quark were supposed to be well described by nonrelativistic potential quark models. This was indeed the case before 2003. Since the discovery of the $X(3872)$ by Belle in 2003, there have been a large number of new resonance(-like) structures observed in the charmonium mass region by various high energy experiments, including BESIII, BaBar, Belle, CDF, D0, ATLAS, CMS and LHCb (see e.g. Refs. [18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 11, 45, 29, 2] for recent reviews), as shown in Fig. 2 in comparison with the predictions of the Godfrey–Isgur quark model [50]. Most of them have peculiar features that deviate from quark model expectations:

- Masses are a few tens of MeV away from the quark model predictions for charmonia with the same quark numbers, and cannot be easily accommodated in quark model spectra. Examples include the $X(3872)$, $Y(4260)$, $Y(4360)$, see Fig. 2.

- All of the XYZ states are above or at least in the vicinity of open-charm thresholds. For those above thresholds, one would expect them to dominantly decay into open-charm channels because of the OZI rule. However, many of them have only been seen as peaks in final states of a charmonium and light mesons/photon. For instance, four resonant structures were observed in the $J/\psi\phi$ final states, which are $X(4140), X(4274), X(4500)$ and $X(4700)$, and no signal of them was reported in open charm channels.

- Charged structures were observed, including $Z_c(3900)$, $Z_c(4020)$, $Z_c(4050)$, $Z_c(4250)$, $Z_c(4200)$ and $Z_c(4430)$. Were they hadron resonances, they must contain at least four quarks, making explicitly exotic multiquark states beyond the conventional quark model.

Because of these features, they are thus excellent candidates of exotic hadrons which have been searched for decades.

In Table 2, most of the XYZ reported so far are listed together with their observed production processes and decay modes. One sees that there are basically four types of production processes: B decays

Table 2: Some of the XYZ states in the charmonium mass region as well as the observed production processes and decay modes. For the complete list and more detailed information, we refer to the latest version of the Review of Particle Physics (RPP) [2].

XYZ	$I^G(J^{PC})$	Production processes	Decay modes
$X(3872)$	$0^+(1^{++})$	$B \to KX/K\pi X, e^+e^- \to \gamma X$, $pp/p\bar{p}$ inclusive	$\pi^+\pi^- J/\psi, \omega J/\psi, D^{*0}\bar{D}^0, \gamma J/\psi, \gamma\psi(2S)$
$X(3915)$	$0^+(0 \text{ or } 2^{++})$	$B \to KX$, $\gamma\gamma \to X$	$\omega J/\psi$
$X(4140)$	$0^+(1^{++})$	$B \to KX$, $p\bar{p}$ inclusive	$\phi J/\psi$
$X(4274)$	$0^+(1^{++})$	$B \to KX$	
$X(4500)$	$0^+(0^{++})$		
$X(4700)$	$0^+(0^{++})$		
$X(3940)$	$?^?(?^{??})$	$e^+e^- \to J/\psi + X$	$D\bar{D}^*$
$X(4160)$	$?^?(?^{??})$		$D^*\bar{D}^*$
$X(4350)$	$0^+(?^{?+})$	$\gamma\gamma \to X$	$\phi J/\psi$
$Y(4008)$	$0^-(1^{--})$	$e^+e^- \to Y$	$\pi\pi J/\psi$
$Y(4260)$	$0^-(1^{--})$	$e^+e^- \to Y$	$\pi\pi J/\psi, D\bar{D}^*\pi, \chi_{c0}\omega, h_c\pi\pi$
$Y(4360)$	$0^-(1^{--})$	$e^+e^- \to Y$	$\pi\pi\psi(2S)$
$Y(4660)$	$0^-(1^{--})$		$\pi\pi\psi(2S), \Lambda_c\bar{\Lambda}_c$
$Z_c(3900)$	$1^+(1^{+-})$	$e^+e^- \to \pi Z_c$, inclusive b-hadron decays	$\pi J/\psi, D\bar{D}^*$
$Z_c(4020)$	$1^+(?^{?-})$	$e^+e^- \to \pi Z_c$	$\pi h_c, D^*\bar{D}^*$
$Z_1(4050)$	$1^-(?^{?+})$	$B \to KZ_c$	$\pi^\pm\chi_{c1}$
$Z_2(4250)$	$1^-(?^{?+})$		
$Z_c(4200)$	$1^+(1^{+-})$	$B \to KZ_c$	$\pi^\pm J/\psi$
$Z_c(4430)$	$1^+(1^{+-})$		$\pi^\pm J/\psi, \pi^\pm\psi(2S)$

with a kaon in the final state; e^+e^- collisions, including the direct production and the initial state radiation (ISR) processes; pp or $p\bar{p}$ collisions; photon-photon fusion. In particular, the first two are the main ones because they have cleaner background compared to the hadron collisions and larger rates compared to the photon-photon fusion processes. However, their following aspects need to be improved upon:

- $B \to KX$: The maximal mass of the X or Z_c states that can be found via this type of reactions is about 4.8 GeV, the mass difference between the B meson and the kaon. So far the heaviest charmonium-like state that has been observed is the $X(4700)$. One more complexity comes from the fact that these charmonium-like states were all observed as invariant-mass-distrbution peaks in final states with two or more hadrons. As a consequence, there are further complexities in analyzing the data: 1) resonances from cross channels; 2) possible triangle singularities. Thus, the structures observed in the B decays need to be confirmed further in other reactions, such as the e^+e^- collisions.

- e^+e^- collisions: Charmonia and charmonium-like states with vector quantum numbers can be easily produced directly or via ISR processes. As a result, the $Y(4260)$ has been studied with unprecedented precision at the BES-III. The heaviest among the vector Y states is the $Y(4660)$ above the $\Lambda_c\bar{\Lambda}_c$ threshold, which is beyond the current energy range of BES-III. Charmonium-like states with other quantum numbers can only be produced from the decays of heavier vector states with the emission of pions or a photon. Thus, BES-III observed only the $X(3872)$, $Z_c(3900)$ and $Z_c(4020)$ among the many non-vector states.

So far no clear pattern emerges for the messy XYZ spectrum. In order to establish a pattern such that the XYZ states can be classified, more measurements are absolutely necessary, including searching for new charmonium-like structures. There are a few guidelines for possible measurements: 1) No matter what kind of internal structure the states have, there should be partners in the same heavy quark spin multiplet [31], which need to be searched for. There are complications coming from the mixing of them and their partners with spin multiplets of other structures (such as $c\bar{c}$) with the same quantum numbers can only be sorted out with observations, which can only be sorted out with enough measurements. For instance, the $(0^{++}, 1^{++}, 2^{++}, 1^{+-})$ states are the J^{PC} quantum numbers of P-wave $c\bar{c}$. Thus, the states with these quantum numbers having masses around 3.9 GeV need to be studied systematically in as many final states as possible. 2) It is important to disentangle the contribution from kinematical singularities from resonances in order to establish a correct mass spectrum, and thus energy dependence of structures like the Z_c needs to be measured. 3) Some of the structures that have been reported have similar masses, and might have the same origin. In order to check this, it is important to search for them in other channels and to measure their properties more precisely. 4) It is worthwhile to pay special attention to energies around S-wave open-charm thresholds.

Let us list opportunities at the STCF regarding the physics of hidden-charm XYZ states:

- With a luminosity of 10^{35} cm^{-2}s^{-1}, two orders of magnitude higher than that of the BEPC-II, the vector charmonium-like states that are being investigated at BES-III can be studied in much more detail, as well as the intriguing $Z_c(3900)$ and $Z_c(4020)$ through $e^+e^- \to \pi^\pm Z_c^\mp$ at various c.m. energies. The dependence of the Z_c line shapes and production rates on the c.m. energy is crucial to have kinematical effects from triangle singularities under control.

- Among all the $PC = ++$ XYZ states, only the $X(3872)$ has been observed in e^+e^- collisions, associated with a photon, and all the others were only seen in B decays. This is because of the low production rates of the radiative processes, and the $X(3872)$ production receives an enhancement due to its large coupling to the $D\bar{D}^*$ pair. At STCF with $E_{\rm cm} \gtrsim 4.7$ GeV, the J^{++} states, $X(3915)$, $\chi_{c0}(3860)$ and $\chi_{c2}(3930)$, can be produced via $e^+e^- \to \omega X$ which should have much larger rates than the radiative ones.

- At STCF with $E_{\rm cm} \gtrsim 5$ GeV, the J^{++} states observed in the $\phi J/\psi$ invariant mass distributions can be investigated via $e^+e^- \to \phi X$. Searching for these states and others mentioned in the above item is crucial in establishing the spectrum of in the highly excited charmonium mass region, and thus important in understanding the effects of hadron thresholds on the spectrum and confinement.

- The lowest charm baryon-antibaryon threshold, $\Lambda_c\bar{\Lambda}_c$, is at 4.57 GeV. With $E_{\rm cm} \gtrsim 5$ GeV, the STCF can reveal the expected rich phenomena due to the charmed baryon-antibaryon channels as well as those of excited charmed mesons.

- With $E_{\rm cm} \gtrsim 5$ GeV, hidden-charm pentaquark states can also be studied in processes such as $e^+e^- \to J/\psi p\bar{p}$ and $e^+e^- \to \Lambda_c\bar{D}\bar{p}$. Similar to the XYZ states above the $D\bar{D}$ threshold, there should be rich phenomena above the $\Lambda_c\bar{D}$ threshold. The cross section for $e^+e^- \to J/\psi p\bar{p}$ between 5 to 7 GeV may be estimated as $\sigma(e^+e^- \to J/\psi p\bar{p}) = O(4\ \text{fb})$ [preliminary, in preparation]. With an integrated luminosity of 2 ab^{-1}/year, $O(8\times 10^3)$ $J/\psi p\bar{p}$ events can be produced per year. A similar amount is expected for $J/\psi n\bar{n}$, and this process can be studied at STCF but impossible for LHCb. The open-charm final sates are expected to have larger cross sections. Furthermore, the hidden-charm pentaquarks are expected to decay much more easily into $\Lambda_c\bar{D}^{(*)}$ than into $J/\psi N$ [32], and the $\Sigma_c^{(*)}\bar{D}^{(*)}$ hadronic molecules, proposed by many authors to explain the LHCb P_c states, couple strongly to $\Sigma_c^{(*)}\bar{D}^{(*)}$. Therefore, promising channels for the search of hidden-charm pentaquarks at STCF include $e^+e^- \to \Lambda_c\bar{D}^{(*)}\bar{p}$ and $\Sigma_c^{(*)}\bar{D}^{(*)}\bar{p}$. Thus, the STCF has a good opportunity to search for hidden-charm P_c pentaquarks as well.

- Unique physics opportunity with $E_{\rm cm} \in [6, 7]$ GeV: In addition to the double-charmonium production can be studied (Prof. K.-T. Chao can add more), the energy range is ideal for the search of fully-charm tetraquark states, which are expected to have a mass of above 6 GeV (see Refs. [33, 34, 35, 36]). While whether the ground state $cc\bar{c}\bar{c}$ is below the double-J/ψ or double-η_c threshold is uncertain, the low-lying $cc\bar{c}\bar{c}$ states are expected to decay dominantly into final states containing a pair of charm and anti-charm hadrons via annihilating a $c\bar{c}$ pair into a gluon, and the widths are of the order of 100 MeV [33, 37]. Excited states with a mass well above 6.2 GeV threshold can also easily decay into $J/\psi J/\psi$. Searching for such fully-charm tetraquarks is difficult at hadron colliders due to the huge background, and the STCF is rather unique.

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3 Charmed hadron physics

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), which is capable of producing about $10^9 \sim 10^{10}$ quantum-coherent $D^0\bar{D}^0$ meson pairs, D^+ or D_s^+ mesons, and Λ_c^+ baryons, will be an important low-background playground to test the SM and probe possible new physics beyond the SM. 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.

3.1 Charmed meson

3.1.1 $D_{(s)}$ leptonic decays and LFU test

A 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. A determination of $|V_{cd}|$ and $|V_{cs}|$ to a much better degree of accuracy is therefore desirable at STCF.

In charmed meson decays in STCF, the most precise way to determine $|V_{cd}|$ and $|V_{cs}|$ 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. By measuring the widths of $D^+_{(s)} \to \ell^+\nu_\ell$, the product of the decay constant $f_{D^+_{(s)}}$, and $|V_{cd(s)}|$ is directly accessed to. 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 3 are the world-best precisions of $|V_{cs(d)}|$ and $f_{D^+_{(s)}}$ [6, 7, 8] at BESIII and the projected precisions at STCF. Note that for $\mathcal{B}(D^+ \to \tau^+\nu_\tau)$, more τ^+ decay channels, such as $\tau^+ \to \pi^+\bar{\nu}_\tau$, $e^+\bar{\nu}_\tau\nu_e$, $\mu^+\bar{\nu}_\tau\nu_\mu$, and $\rho^+\bar{\nu}_\tau$, are combined to improve statistical sensitivities.

For STCF, the systematic uncertainties are required to be optimized to a subleading level, as the statistical uncertainties are expected be less than 0.5%. To reduce 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% [9], 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 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%. On the other hand, the precise measurements of the semi-leptonic branching fractions for $D_{(s)} \to h\ell^+\nu_\ell$ will facilitate to calibrate LQCD calculations of the involved form factors, by introducing the $|V_{cd(s)}|$ from global CKM fits (such as CKMfitter [2, 3] and UTfit [4, 5]).

Lepton flavor universality (LFU) can 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 [10]. 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

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

With the world average values of the masses of lepton and $D^+_{(s)}$ [9], one obtains $R_{D^+} = 2.67 \pm 0.01$ and $R_{D_s^+} = 9.74 \pm 0.03$. The preliminary measured value of $R_{D^+_{(s)}}$ reported by BESIII is 3.21 ± 0.64 [11]

Table 3: 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% [9], 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	2.92 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]	$0.15\%_{\rm stat.}$	–
$\mathcal{B}(D^+ \to \tau^+\nu_\tau)$	$20\%_{\rm stat.}\ 10\%^\dagger_{\rm syst.}$ [7]	$0.41\%_{\rm stat.}$	–
$\frac{\mathcal{B}(D^+ \to \tau^+\nu_\tau)}{\mathcal{B}(D^+ \to \mu^+\nu_\mu)}$	$21\%_{\rm stat.}\ 10\%^\dagger_{\rm syst.}$ [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)	$0.9\%_{\rm stat.}\ 1.0\%^\dagger_{\rm syst.}$	$0.09\%_{\rm stat.}$	$0.3\%_{\rm stat.}\ 1.0\%_{\rm syst.}$
$\|\overline{V}^{\mu\&\tau}_{cs}\|$	$0.9\%_{\rm stat.}\ 1.0\%^\dagger_{\rm syst.}$	$0.09\%_{\rm stat.}$	–
$\frac{\mathcal{B}(D^+_s \to \tau^+\nu_\tau)}{\mathcal{B}(D^+_s \to \mu^+\nu_\mu)}$	$3.6\%_{\rm stat.}\ 3.0\%^\dagger_{\rm syst.}$	$0.38\%_{\rm stat.}$	$0.9\%_{\rm stat.}\ 3.2\%_{\rm syst.}$

(10.2 ± 0.5), which agrees with the SM predicted values. However, these measurements are statistically limited. At STCF, as listed in Table 3, the statistical precision on $R_{D^+_{(s)}}$ will be comparable to the SM precisions. Hence, it will provide meaningful test on LFU via these channels.

Another LFU test would be via the SL decay modes, where as 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 $\mathcal{B}(D^0 \to \pi^-\mu^+\nu_\mu)/\mathcal{B}(D^0 \to \pi^-e^+\nu_e) = 0.922\pm0.030\pm0.022$ and $\mathcal{B}(D^+ \to \pi^0\mu^+\nu_\mu)/\mathcal{B}(D^+ \to \pi^0e^+\nu_e) = 0.964\pm0.037\pm0.026$ [12]. These results are consistent with the SM predictions, within 1.7σ and 0.5σ [12], respectively. These measurements are currently statistically limited [13, 12], and will be significantly improved with 1 ab^{-1} of data at 3.773 GeV at STCF.

3.1.2 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. At STCF, will be an ideal place for the study of D^0-$\bar{D}^0$ mixing. By convention the mass states of two neutral D mesons are written as

$$\begin{aligned} |D_1\rangle &= p|D^0\rangle + q|\bar{D}^0\rangle , \\ |D_2\rangle &= p|D^0\rangle - q|\bar{D}^0\rangle , \end{aligned} \tag{1}$$

where $|p|^2 + |q|^2 = 1$ holds. 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 mass and width of $D_{1,2}$, $\Gamma \equiv (\Gamma_1 + \Gamma_2)/2$ 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 be calculated in the SM, as there involve large long-distance uncertainties in this nonperturbative regime. One expects $x \sim y \sim \sin^2\theta_C \times [\mathrm{SU}(3)\ \text{breaking}]^2$ 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 $10^{-3} < |x| < 10^{-2}$ [16]. A global fit to the world measurements of x and y, carried out by the Heavy Flavor Averaging Group [17, 18], gives $0.4 \times 10^{-3} \lesssim x \lesssim 6.2 \times 10^{-3}$ and $5.0 \times 10^{-3} \lesssim y \lesssim 8.0 \times 10^{-3}$ at the 95% confidence-level intervals [9]. 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 [19].

The charm sector is a sensitive playground to explore possible CP-violating new physics, because the SM-induced CP violation effects in D-meson decays are typically in the range from 10^{-4} to 10^{-3} in the SM [20] and very challenging to be detected in experiment. The CP-violating asymmetries in the singly Cabibbo-suppressed D-meson decays are usually much larger than those in the Cabibbo-favored and doubly Cabibbo-suppressed decays [19]. There are in general four different types of CP-violating effects in neutral and charged D-meson decays [21]: 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; 4) CP violation in the *CP*-forbidden decay of coherent D^0 and $\bar{D}^0$ mesons. Besides these four 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_S or K_L in their final states. Its magnitude is typically $2\mathrm{Re}(\epsilon_K) \simeq 3.3 \times 10^{-3}$, which may be comparable with or even larger than the *charmed* CP-violating effects [22, 23]. 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

$$\begin{aligned} \Delta a_{CP} &= \frac{\Gamma(D \to K^+K^-) - \Gamma(\bar{D} \to K^+K^-)}{\Gamma(D \to K^+K^-) + \Gamma(\bar{D} \to K^+K^-)} - \frac{\Gamma(D \to \pi^+\pi^-) - \Gamma(\bar{D} \to \pi^+\pi^-)}{\Gamma(D \to \pi^+\pi^-) + \Gamma(\bar{D} \to \pi^+\pi^-)} \\ &= (-0.154 \pm 0.029)\%, \end{aligned} \tag{2}$$

where $D(\bar{D})$ is a $D^0(\bar{D}^0)$ at time t=0 [21], and it mainly arises from direct CP violation in the charm-quark decay. This result is consistent with some theoretical estimates within the SM (see, e.g., Refs. [26, 27, 28, 29, 30, 31, 32, 33]), 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 [34]. 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 [35], 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 on the $\psi(3770)$, $\psi(4040)$ or $\psi(4140)$ resonance. In fact, a $D^0\bar{D}^0$ pair can be coherently produced through $\psi(3770) \to (D^0\bar{D}^0)_{\mathrm{CP}=-}$ or $\psi(4140) \to D^0\bar{D}^{*0} \to \pi^0(D^0\bar{D}^0)_{\mathrm{CP}=-}$ or $\gamma(D^0\bar{D}^0)_{\mathrm{CP}=+}$ decays. 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 [21]. 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 4.040 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 4.040 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 [36]. Another case is that the decay mode $\left(D^0\bar{D}^0\right)_{\mathrm{CP}=\pm} \to \left(f_1 f_2\right)_{\mathrm{CP}=\mp}$, 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

$$\Gamma^{++}_{D^0\bar{D}^0} = \left[\left(x^2 + y^2\right)\left(\cosh^2 a_m - \cos^2\phi\right)\right]\Gamma^2(D \to f_+), \tag{3}$$

where $\phi = \arg(p/q)$, $R_m = |p/q|$, and $a_m = \log R_m$ [37].

CPT is conserved in all the 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 [38]. 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 [39].

3.1.3 Strong phase difference in D^0 hadronic decays

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. 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) [17].

The measurements of the CKM unitary triangle (UT) angles α, β, and γ in B decays are important to test 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 measurement of γ is from LHCb: $\gamma = (74.0^{+5.0}_{-5.8})^\circ$ [40]. 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 [41, 42, 43]. In the future, the statistical uncertainties of these measurements 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 ~0.4° for the γ measurement. 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.

3.1.4 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 $D \to \nu\bar{\nu}X$, 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 [46], but they can be significantly enhanced by new physics [47]. Current experimental bounds on these two typical FCNC channels are $\mathcal{B}(D^0 \to \gamma\gamma) < 8.5 \times 10^{-7}$ and $\mathcal{B}(D^0 \to \mu^+\mu^-) < 6.2 \times 10^{-9}$ [9]. However, the following 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} [9]. This shows non-trivial contributions from complicated long-distance effects. At STCF, it is more optimal to study the di-electron modes $D \to e^+e^- X$ [48], which provide sensitivities of $10^{-8} \sim 10^{-9}$ for $m_{e^+e^-}$ in the range less polluted by the long-range resonance contributions. Furthermore, STCF has advantage to best constrain the upper limit of BF for D rare decays with neutrinos, such as $D \to \pi^0\nu\bar{\nu}$ and $D \to \gamma\nu\bar{\nu}$.

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 $\mathcal{B}(D^0 \to \mu^\pm e^\mp) < 1.3 \times 10^{-8}$) [9]. 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.

3.1.5 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 [49]. 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. It has been agreed 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.

In 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 6.0 GeV. Then, the higher excited open-charm states can be studied through their hadronic or radiative decays [54] 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.

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

3.2 Charmed baryon

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.

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 the Λ_c^+. BESIII has played an essential role in these new developments. Motivated by the experimental progresses, there exist growing theoretical activities in the study of hadronic weak decays of singly charm baryons.

3.2.1 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 [55], but its spin-parity assignment is quite diverse (see Ref. [56] for a review). The constraints on its spin and parity were recently found to be $J^P = \frac{3}{2}^-$ by LHCb [57]. However, it was suggested in Ref. [58] that the quantum number of the $\Lambda_c(2940)^+$ is most likely $\frac{1}{2}^-(2P)$ based on the Regge analysis. 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 $\Omega_c(3119)$ [59]. Except the $\Omega_c(3119)$, the first four states were also confirmed by Belle later [60]. This has triggered a flood of interest in attempting to identify their spin-parity quantum numbers.

For STCF, its total energy is designed in the range of 2–7 GeV. It is thus 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 5–7 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.

Table 5: The measured branching fractions of the Cabibbo-allowed two-body decays of the Λ_c^+ (in units of %) taken from PDG [9]. We have included the new BESIII measurements of $\Lambda_c^+ \to \Sigma^+\eta, \Sigma^{*+}\eta, \Sigma^+\eta'$ [61, 62].

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	$\Lambda_c^+ \to \Sigma^{*+}\eta'$	
$\Lambda_c^+ \to \Xi^0K^+$	0.55±0.07	$\Lambda_c^+ \to \Xi^0K^{*+}$		$\Lambda_c^+ \to \Xi^{*0}K^+$	0.43±0.09
$\Lambda_c^+ \to pK_S$	1.59±0.08	$\Lambda_c^+ \to p\bar{K}^{*0}$	1.96±0.27	$\Lambda_c^+ \to \Delta^+\bar{K}^0$	

3.2.2 Hadronic weak decays

- Nonleptonic decays of singly charmed baryons

  <u>Λ_c decays</u>

  The branching fractions of the Cabibbo-allowed two-body decays of Λ_c^+ are listed in Table 5. 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 [63] and BESIII [64] 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 PDG [9].

  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 rates by most of the models except current algebra are below experimental measurements. Moreover, 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 [65]. In contrast, current algebra always leads to a negative decay asymmetry for aforementioned two modes: -0.49 in Ref. [66], -0.31 in Ref. [67], -0.76 in Ref. [68] and -0.47 in Ref. [69]. The issue with the sign of $\alpha_{\Sigma^+\pi^0}$ was finally resolved by BESIII. The decay asymmetry parameters of $\Lambda_c^+ \to \Lambda\pi^+, \Sigma^0\pi^+, \Sigma^+\pi^0$ and pK_S were recently measured by BESIII [70], 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 nicely confirmed by BESIII. For $\Lambda_c^+ \to \Xi^{(*)0}K^+$ decays, BESIII [71] found $\alpha_{\Xi K} = 0.77 \pm 0.78$ and $\alpha_{\Xi^* K} = -1.00 \pm 0.34$ where the statistical uncertainties are dominant.

  <u>Ξ_c and Ω_c decays</u>

  The absolute branching fractions of $\Xi_c^0 \to \Xi^-\pi^+$ and $\Xi_c^+ \to \Xi^-\pi^+\pi^+$ were recently measured by Belle [72, 73] to be $\mathcal{B}(\Xi_c^0 \to \Xi^-\pi^+) = (1.80 \pm 0.50 \pm 0.14)\%$ and $\mathcal{B}(\Xi_c^+ \to \Xi^-\pi^+\pi^+) = (2.86 \pm 1.21 \pm 0.38)\%$. 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. The hadronic weak decays of the Ω_c^0 were recently studied in great detail in Ref. [74], 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 the Λ_c^+ and $\Xi_c^{+,0}$ can be measured by 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 [75]. 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 $10^{-3} \sim 10^{-4}$ and should be readily accessible in the near future. It appears that Belle may have seen a possible signal of the charm-flavor-conserving decay $\Xi_c^0 \to \Lambda_c^+\pi^-$. Belle has measured the masses of the $\Sigma_c(2455)$ and $\Sigma_c(2520)$ baryons [76] and found that a fit to the mass difference $M(pK^-\pi^+\pi^-) - M(pK^-\pi^+)$ exhibits a peak near 185 MeV, corresponding to the decay $\Xi_c^0 \to \Lambda_c^+\pi^- \to pK^-\pi^+\pi^-$. STCF should be able to check this and search for c-flavor-conserving weak decays.

3.2.3 Semileptonic decays

Exclusive semileptonic decays of charmed baryons: $\Lambda_c^+ \to \Lambda e^+(\mu^+)\nu_e$, $\Xi_c^+ \to \Xi^0 e^+\nu_e$ 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

$$\begin{aligned}\langle \mathcal{B}_f(p_f)|V_\mu - A_\mu|\mathcal{B}_c(p_i)\rangle &= \bar{u}_f(p_f)[f_1(q^2)\gamma_\mu + if_2(q^2)\sigma_{\mu\nu}q^\nu + f_3(q^2)q_\mu \\ &\quad -(g_1(q^2)\gamma_\mu + ig_2(q^2)\sigma_{\mu\nu}q^\nu + g_3(q^2)q_\mu)\gamma_5]u_i(p_i). \qquad (4)\end{aligned}$$

These form factors have been evaluated using the non-relativistic quark model, MIT bag model, relativistic quark model, light-front quark model, QCD sum rules and LQCD. Many of the early predictions of $\mathcal{B}(\Lambda_c^+ \to \Lambda e^+\nu)$ are smaller than the first measurement of the absolute branching fraction of $(3.6 \pm 0.4)\%$ by BESIII [77]. LQCD calculations in Ref. [78] yield good agreement with experiment for both $\Lambda_c^+ \to \Lambda e^+\nu$ and $\Lambda_c^+ \to \Lambda\mu^+\nu$. Needless to say, the semileptonic decays of the Λ_c^+ (including the yet-to-be-observed $\Lambda_c^+ \to ne^+\nu_e$), $\Xi_c^{+,0}$ and Ω_c^0 will be thoroughly studied at STCF, which can be used to discriminate between different form-factor models.

3.2.4 Electromagnetic decays

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

The calculated results in Refs. [79, 80], [81] and [82] denoted by (i), (ii) and (iii), respectively, in Table 6 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

Table 6: Electromagnetic decay rates (in units of keV) of s-wave charmed baryons in heavy hadron chiral perturbation theory to (i) LO [79, 80], (ii) NLO [81] and (iii) NNLO [82].

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

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.

3.2.5 CP Violation

The CKM matrix contains a phase which implies the existence of CP violation, but at a very small level in the decays of charmed baryons. The search for CP violation in charmed baryon decays has taken on new momentum with the large samples of Λ_c obtained by BESIII and LHCb. For example, 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 $\Delta A_{CP} = (0.30 \pm 0.91 \pm 0.61)\%$ [83], to be compared with a generic SM prediction of a fraction of 0.1% [84]. In order to probe the SM level, one has to multiply 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 may provide a great platform for this kind of study. A fast Monte Carlo simulation in Ref. [85] by using the e^+e^- annihilation data of 1 ab^{-1} 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%.

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 the T-odd observables, such as $C_{\hat{T}} = \vec{p}_p \cdot (\vec{p}_{h_1} \times \vec{p}_{h_2})$, where $h_1 = K^-$ and $h_2 = \pi^+$ for $\Lambda_c^+ \to pK^-\pi^+\pi^0$, for example. The asymmetries are defined as

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

where N and $\bar{N}$ are the numbers of Λ_c^+ and $\bar{\Lambda}_c^-$ decays, respectively. The CP asymmetry is given by

$$a_{CP}^{\hat{T}-\mathrm{odd}} = \frac{1}{2}(A_{\hat{T}} - \bar{A}_{\hat{T}}). \tag{6}$$

For a detailed study of the CP-violating quantity $a_{CP}^{\hat{T}-\mathrm{odd}}$ at STCF, see Ref. [85].

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4 Tau Physics

At STCF, the $\tau^+\tau^-$ pair event number can be as large as 7.0×10^9 per year at $\sqrt{s} = 4.26$ GeV, which is about 3 orders of magnitude higher than currently accumulated events at the BES III. At the threshold the event number can also be as large as 10^8 per year. Near the threshold one can use data just below the threshold to understand the background to have a better control of systematic errors compared with BES III [1]. In this regard STCF has advantages over τ physics studies at the LHCb and Belle II. In the energy range covered by the STCF, one can also have a good control of polarizations of the e^+ and e^- beams to extract new information about τ. The STCF will tremendously increase the statistical significance for τ-related physics studies and will reach a precision level which has never been achieved before.

The τ lepton assumes a unique place in the SM. Being the heaviest charged lepton, it has much more decay channels than the next heaviest charged lepton, the muon μ. With an unprecedented large number of τ produced not far from the threshold and possible polarization information at the STCF, one can know more precisely not only the properties of the τ itself but also how it interacts with other particles, so that one can determine more precisely the SM parameters, probe possible new interactions and may also shed light on some of the related anomalies in particle physics. In the following we describe some of the interesting subjects in τ physics which can be addressed at the STCF.

4.1 Precision Measurement of the τ Properties

To test the SM and search for new physics in the τ sector, it is important that its properties are known to great precision. Here we list a few of such measurements at the STCF which can improve our understanding.

4.1.1 τ mass and lifetime

Many of the tests for the SM and beyond involve the τ mass m_τ and lifetime. At STCF there is not much handling on the lifetime because the τs produced have a small kinetic energy and do not leave tracks in the detector for lifetime measurement. However, the measurement for the mass can be much improved. The mass has been measured at a 70 ppm level with a world average [2] $m_\tau = 1776.86 \pm 0.12$ MeV. In charged-current induced leptonic decays, $\tau \to \nu_\tau l \bar{\nu}_l$ ($l = e, \mu$), the decay widths are proportional the fifth power of m_τ. A small error in the mass can cause significant deviations in the test of the SM universality and in the search of new physics. At the STCF, the number of τ can be one to three orders of magnitude more which will greatly enhance the statistical significance compared to that achieved at the BES III. With improvements further in particle ID and energy measurement, the sensitivity can increase the accuracy by 7 times to reach a level better than 10 ppm. This improved τ mass measurement will consolidate the base for any further τ physics studies.

4.1.2 Measurement of $a_\tau = (g-2)_\tau/2$

The quantity $a_\tau = (g_\tau - 2)/2$ of the anomalous magnetic dipole moment of the τ lepton is another property of fundamental importance. The values a_l for the electron and muon have been measured to great precision. There are some deviations from the SM predictions, with $\Delta a_e = a_e^{\text{exp}} - a_e^{\text{SM}} = -78(36) \times 10^{-14}$ [3] at about 2σ level and $\Delta a_\mu = 268(63)(43) \times 10^{-11}$[2] at about a 4σ significance. The latter is the longstanding muon magnetic dipole moment anomaly. As this may be an indication of new physics, it has generated extensive theoretical studies within the SM and beyond to understand possible causes. It is therefore important to test whether there is also a deviation in a_τ.

The measurement of a_τ is, however, drastically different from that of $a_{e,\mu}$ due to the short lifetime of τ. The SM prediction for a_τ is $1177.21(5) \times 10^{-6}$ [4]. Currently a_τ is measured from the production cross section of the τ pair together with the spin or angular distributions of the τ decays; for instance, the current bound $-0.052 \le a_\tau \le 0.013$ (95% C.L.) was obtained by the DELPHI collaboration [?] from the cross section for the process $e^+e^- \to e^+e^-\tau^+\tau^-$ under the assumption that the SM tree level result is only modified by the anomalous magnetic moment. These measurements are still far from making a precision test for the SM. The conventional measurements through similar processes may not reach that precision. The Belle II can do a much better job than STCF. New methods are needed to achieve the required precision. To this end, it has been shown that in $e^+e^- \to \tau^+\tau^-$ with a polarized electron beam it is plausible to achieve this goal by measuring the transverse and longitudinal polarizations of the τ lepton [5]. Since the background can be well controlled near the threshold, a precision level of 10^{-6} can be reached. This will provide an important test for the SM and hopefully shed light on anomalies in magnetic dipole moments of the other leptons.

4.2 The Determination of the SM Parameters

The τ lepton has well defined interactions with other particles in the SM. Experimental measurements are consistent with the SM predictions [7]. With a large number of τ samples, many of the interaction parameters in the SM can be determined to great precision. Here we discuss some of the most important tests: the universality properties, the Michel parameters, the strong coupling constant α_s, and the V_{us} element in the Cabibbo-Kobayashi-Maskawa (CKM) mixing matrix.

4.2.1 The universality test

The charged current interaction of the left-handed leptons with the W boson is given by

$$\mathcal{L} = -\frac{g_i}{\sqrt{2}}\bar{l}_i\gamma^\mu P_L \nu_i W^-_\mu + \text{H.C.}, \tag{7}$$

where $P_L = (1-\gamma_5)/2$. The charged lepton universality refers to the fact that $g_e = g_\mu = g_\tau$. This is indeed the case in the SM but not necessarily so in models beyond the SM. Therefore, the measurement of these quantities can test the SM. One obtains [6] using very good approximation $B(\mu \to e\bar{\nu}_e\nu_\mu(\gamma)) \approx 1$:

$$\begin{aligned}
\frac{g_\tau}{g_e} &= \sqrt{B(\tau^- \to \mu^-\bar{\nu}_\mu\nu_\tau(\gamma))\frac{\tau_\mu}{\tau_\tau}\frac{m_\mu^5}{m_\tau^5}\frac{F_{\text{corr}}(m_\mu, m_e)}{F_{\text{corr}}(m_\tau, m_\mu)}}\,, \\
\frac{g_\tau}{g_\mu} &= \sqrt{B(\tau^- \to e^-\bar{\nu}_e\nu_\tau(\gamma))\frac{\tau_\mu}{\tau_\tau}\frac{m_\mu^5}{m_\tau^5}\frac{F_{\text{corr}}(m_\mu, m_e)}{F_{\text{corr}}(m_\tau, m_e)}}\,,
\end{aligned} \tag{8}$$

where $F_{\text{corr}}(m_i, m_j)$ includes radiative corrections and corrections due to different charged lepton masses.

The current data $g_\tau/g_e = 1.0029 \pm 0.0015$, $g_\mu/g_e = 1.0019 \pm 0.0014$, and $g_\tau/g_\mu = 1.0010 \pm 0.0015$ [6] are consistent with the universality prediction. As discussed earlier, with the value of m_τ improved to achieve a level better than 10 ppm, this implies that the universality prediction can be tested at a better than 3 times level to constrain the allowed room for new physics.

4.2.2 The Michel parameters

The decays $\tau \to l\bar{\nu}_l\nu_\tau$ provide sensitive constraints to other forms of interactions due to new physics. The most general form of new physics is parameterized by the Michel parameters ρ, η, ξ, and δ [2],

$$\frac{d^2\Gamma(\tau \to l\bar{\nu}_l\nu_\tau)}{x^2 dx d\cos\theta}\frac{96\pi^3}{G_F^2 m_\tau^5} \\ = 3(1-x) + \rho_l\Big(\frac{8}{3}x - 2\Big) + 6\eta_l \frac{m_l}{m_\tau}\frac{(1-x)}{x} - P_\tau \xi_l \cos\theta\Big[(1-x) + \delta\Big(\frac{8}{3}x - 2\Big)\Big], \tag{9}$$

where P_τ is the degree of τ polarization, $x = E_l/E_l^{\max}$, and θ is the angle between the τ spin and the l momentum direction. In the SM the Michel parameters are

$$\rho_l = \frac{3}{4}\,, \quad \eta_l = 0\,, \quad \xi_l = 1\,, \quad \xi_l\delta_l = \frac{3}{4}\,. \tag{10}$$

Experimentally, the values are [2]

$$\rho_e = 0.747 \pm 0.010,\ \rho_\mu = 0.763 \pm 0.020,\ \ \xi_e = 0.994 \pm 0.040,\ \ \xi_\mu = 1.030 \pm 0.059, \tag{11}$$
$$\eta_e = 0.013 \pm 0.020,\ \ \eta_\mu = 0.094 \pm 0.073,\ \ (\xi\delta)_e = 0.734 \pm 0.028,\ \ (\xi\delta)_\mu = 0.778 \pm 0.037.$$

Again experimental measurements are consistent with the SM predictions.

With a larger number of τ produced and improved sensitivities, the STCF will be capable of reducing the error bars by at least a factor of 2. This will help to limit new physics beyond SM.

4.2.3 The strong coupling α_s extraction

It is well-known that the strong coupling constant α_s can be extracted from the ratio [8]:

$$R_\tau = \frac{\Gamma(\tau^- \to \nu_\tau \text{hadrons})}{\Gamma(\tau^- \to \nu_\tau e^- \bar{\nu}_e)}. \tag{12}$$

The theoretical predictions of the ratio have been carefully examined in [9, 10]. According to the structure of weak interactions, the ratio can be decomposed as:

$$R_\tau = R_{V,ud} + R_{A,ud} + R_{\tau,s}. \tag{13}$$

$R_{\tau,s}$ is the contribution from the final states containing an s-quark. Each part contains perturbative and nonperturbative contributions. The perturbative contributions are now determined at the 5-loop level while the nonperturbative contributions are estimated with QCD sum rules. Because of the large quark mass m_s, large power-correction exists in $R_{\tau,s}$ whose theoretical estimation therefore cannot reach the precision level of $R_{V,ud}$ and $R_{A,ud}$. The analysis in [7] gives the value

$$\alpha_s(m_\tau) = 0.331 \pm 0.013, \tag{14}$$

with one set of parameterizations of nonperturbative contributions. To improve the determination, the experimental study at STCF will be important. Especially, a precise measurement of $R_{\tau,s}$ and the spectral function containing the strange quark will help to understand nonperturbative contributions and to precisely extract the CKM matrix element V_{us}.

4.2.4 The CKM element V_{us} extraction

The experimental study of hadronic decays of τ has provided one of the most precise measurements of V_{us}. There are two main methods to determine this parameter. One is by measuring the ratio of $\tau^- \to \pi^-\nu_\tau$ and $\tau^- \to K^-\nu_\tau$ and the other by measuring the ratio $R_\tau = R_{V,ud} + R_{A,ud} + R_{\tau,s}$ discussed earlier. Theoretically

$$\frac{B(\tau \to K^-\nu_\tau)}{B(\tau^- \to \pi^-\nu_\tau)} = \frac{f_K^2}{f_\pi^2}\frac{|V_{us}|^2}{|V_{ud}|}\frac{(m_\tau^2 - m_K^2)^2}{(m_\tau^2 - m_\pi^2)^2}\frac{1+\delta R_{\tau/K}}{1+\delta R_{\tau/\pi}}(1+\delta R_{K/\pi}) ,$$
$$|V_{us}|^2 = \frac{R_{\tau,s}}{[(R_{V,ud} + R_{A,us})/|V_{ud}|^2 - \delta R_{\text{theory}}]} . \tag{15}$$

With known values from theory calculations and experimental measurements [6]: $f_K/f_\pi = 1.1930 \pm 0.0030$, $V_{ud} = 0.97417 \pm 0.00021$, $1 + \delta R_{\tau/K} = 1 + (0.90 \pm 0.22)\%$, $1 + \delta R_{\tau/\pi} = 1 + (0.16 \pm 0.14)\%$, $1 + \delta R_{K/\pi} = 1 + (-1.13 \pm 0.23)\%$, and $\delta R_{\text{theory}} = 0.242 \pm 0.032$, one obtains respectively from the above two ways

$$|V_{us}|_{\tau K/\pi} = 0.2236 \pm 0.0018 , \quad |V_{us}|_{\tau s} = 0.2186 \pm 0.0021 . \tag{16}$$

The first value is 1.1 σ away from the value determined by the unitarity relation $|V_{us}|_{\text{uni}} \approx \sqrt{1 - |V_{ud}|^2} = 0.2258 \pm 0.0009$. The second is 3.1 σ away from $|V_{us}|_{\text{uni}}$. These deviations need to be further checked with better precision before claiming new physics beyond the SM.

The STCF can measure the values of R_i and may therefore confirm or nullify the deviation.

4.3 CP Symmetry Tests

How CP symmetry is broken may hold the key to the question of why our universe has more matter than anti-matter. Violation of CP symmetry is one of the required conditions to understand this. CP violation in the SM is, however, not enough to explain this fundamental question affecting our very existence in the Universe, and therefore new CP violating sources are demanded. The search for new CP violating effects is one of the most active areas in particle physics. Physical processes involving the τ lepton are a potential place at which new CP violating effects may show up.

4.3.1 CP violation in $\tau^- \to K_S^0\pi^-\nu_\tau$

In the SM, because of CP violation in the $K^0 - \bar{K}^0$ mixing, a detectable CP violating effect is predicted for this process to be [?]

$$A_Q = \frac{B(\tau^+ \to K_S^0\pi^+\bar{\nu}_\tau) - B(\tau^- \to K_S^0\pi^-\nu_\tau)}{B(\tau^+ \to K_S^0\pi^+\bar{\nu}_\tau) + B(\tau^- \to K_S^0\pi^-\nu_\tau)} = (+0.36 \pm 0.01)\% . \tag{17}$$

However, the experimental measurement at the BABAR B-factory gives a value, $A_Q = (-0.36 \pm 0.23 \pm 0.11)\%$ [?], which is 2.8σ away from the SM prediction.

The above deviation poses a challenge for the SM. Theoretical efforts have been made to reconcile the difference. Even with beyond SM effects included, it is not so easy to obtain the central value of the BABAR data. The SCTF can provide a crucial check with a large number of the $\tau^+\tau^-$ pair at not too far away from the threshold where the background can be well controlled.

4.3.2 Measurement of the electric dipole moment of τ

The initial state of the e^+e^- pair in the center of mass system is a CP eigenstate. Therefore, the CP test at any e^+e^- collider can be conveniently performed. By measuring the decay products from τ-decays, the CP test can be done with the process $e^+e^- \to \tau^+\tau^-$, as suggested in [13]. By measuring CP-odd observables, one can determine the electric and weak dipole moments of τ. In the SM these moments are predicted to be extremely small (for example the electric dipole moment is expected to be of order 10^{-34} e cm). If any of the two moments is nonzero at a level much larger than the SM predictions, it will be a clear signal for new physics beyond the SM. The two moments have been studied at the LEP and B-factories. Because the energy reach is low, the effects of the weak dipole moment are suppressed, while the electric dipole moment d_τ^γ can be probed. The newest result for the electric dipole moment obtained from the Belle experiment [14] is, in units of 10^{-16} *e cm*,

$$-0.22 < \mathrm{Re}(d_\tau^\gamma) < 0.45, \quad -0.25 < \mathrm{Im}(d_\tau^\gamma) < 0.08. \tag{18}$$

These bounds can be tightened by 2 or 3 orders of magnitude with the experiments at the STCF.

4.3.3 CPV with polarized beam

With polarized e^+ and/or e^- beams, one can produce highly polarized $\tau^\pm$s. Their polarizations normal (N) to their production plane can be measured by studying the semileptonic decays $\tau^\pm \to \pi^\pm/\rho^\pm\bar{\nu}_\tau(\nu_\tau)$. One then constructs the asymmetry observables with respect to the left- (L) and right-hand (R) sides of the plane, which are directly related to the electric dipole moment, d_τ^γ, of $\tau^\pm$ [11],

$$A_N^\pm = \frac{\sigma_L^\pm - \sigma_R^\pm}{\sigma} = \alpha_\pm \frac{3\pi\beta}{8a(3-\beta^2)} \frac{2m_\tau}{e} \mathrm{Re}(d_\tau^\gamma) \,, \tag{19}$$

where σ is the cross section, $a = 2m_\tau/\sqrt{s}$, and $\beta = \sqrt{1-a^2}$. $\alpha^\pm$ is the polarization analyzer in the decays $\tau^\pm \to \pi^\pm/\rho^\pm\bar{\nu}_\tau(\nu_\tau)$. Belle II can reach a sensitivity of 3×10^{-19} *e cm* with a 50 ab^{-1} integrated luminosity. At the STCF the sensitivity can be improved by about 30 times reaching 10^{-20} *e cm*.

With polarized e^+ and e^- beams, one can also construct new T-odd observables to measure CP violating effects. An interesting observable is the triple product $P_z^{\tau^\pm}\hat{z}\cdot(\vec{p}_{\pi^\pm}\times\vec{p}_{\pi^0})$ from measuring the two pion momenta in the decays $\tau^\pm \to \pi^\pm\pi^0\bar{\nu}_\tau(\nu_\tau)$ [12]. Here $P_z^\tau = [(w_{e^-}+w_{e^+})/(1+w_{e^+}w_{e^-})][(1+2a)/(2+a^2)]$ is the component of the polarization vector of the τ upon averaging over its momentum direction and $w_{e^\pm}$ the components of the polarization vectors of the $e^\pm$, all in the e^- beam direction $\hat{z}$. If the difference of triple products for τ^+ and τ^- are nonzero, it is a signal of CP violation. Since the SM predicts very small triple products, measurements of nonzero triplet already signal new physics beyond SM. This can be measured at the STCF to provide new information about CP violation sources. Similar measurements can be done by replacing $\pi^\pm$ by $K^\pm$.

4.4 New Flavor Violating τ Decays

Flavor changing neutral current (FCNC) interactions of τ are suppressed in the SM that incorporates neutrino mass and mixing. When going beyond, larger FCNC effects may show up in some decays, such as τ decays into $3l$, $l\gamma$, and also to hadron(s) plus charged leptons. With increased τ events at the STCF, these decays can be searched for to test the SM and beyond.

4.4.1 The decay $\tau^- \to 3l$

The decay $\tau^- \to 3l$ is one of the most sensitive probes of FCNC interactions. The current upper bound is about a few times 10^{-8}. At the Belle II upon accumulating 50 ab^{-1} integrated luminosity, the sensitivity can reach 4×10^{-10}. Running STCF at the peak energy ($\sqrt{s}$ = 4.26 GeV) of the $\tau^+\tau^-$ production, 7×10^9 τ pairs can be produced each year which can be used to push the branching ratio down to a level better than 7×10^{-10}. With 4-year running data, the sensitivity will reach a level better than the Belle II can do.

4.4.2 The decays $\tau^- \to l\gamma$

Equally interesting are the decays $\tau \to l\gamma$ with $l = e,\ \mu$. The current limits are a few times 10^{-8}. Again, at the STCF one expects to achieve a sensitivity of a few times 10^{-10} with one-year running.

4.4.3 The decays $\tau^- \to lM_1M_2$

The decays $\tau^\pm \to l^\pm M_1M_2$ with $M_i = \pi,\ K$ have been previously searched for with a sensitivity of order 10^{-8}. Similar to these decays are the lepton-number-violating ones $\tau^\pm \to l^\mp M_1^\pm M_2^\pm$ whose current bounds are also order 10^{-8}. At the STCF, the sensitivity of these decays can be increased by two orders of magnitude to a few times 10^{-10}.

As mentioned earlier FCNC interactions are highly suppressed in the SM. In some new physics models FCNC interactions can be generated at the tree level and may therefore induce some of the above processes at a level close to their current bounds. In this circumstance the STCF will be capable of providing very useful information on those models.

4.5 Summary

With a large number of τ pairs produced near the threshold possibly with polarized e^- and e^+ beams, the STCF has a great potential for τ physics research. It will enhance statistical significance of many measurements of the τ properties and its interactions with other particles, and help to determine more precisely the SM parameters. It has the capability of probing new sources of CP violation and new FCNC interactions, and may also shed light on some of the related anomalies in particle physics.

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5 Light Hadron Physics

5.1 Spectroscopy

The spectrum of light hadrons serves as an excellent probe of nonperturbative QCD [1, 2, 3, 4, 5, 6] . The complexity of strong QCD manifests itself in hadrons, their properties and internal structures. The quark model suggests mesons are made of a constituent quark and an antiquark and baryons consist of three such quarks. QCD predicts a richer spectrum of mesons that takes into account not only the quark degrees of freedom but also the gluonic degrees of freedom. Excited hadronic states are sensitive to the details of quark confinement, which is only poorly understood within QCD. It is one of the key issues in hadronic physics to identify the effective degrees of freedom and how they relate to strong coupling QCD. Lattice-QCD calculations of both the baryon and the meson spectra have made tremendous progress and have now reached a maturity so that they can provide some guidance in the experimental efforts.

The mass spectrum of hadrons is clearly organized according to flavor content, spin, and parity. For intermediate and long-distance phenomena such as hadron properties, the full complexity of QCD emerges, which makes it is difficult to understand hadronic phenomena at a fundamental level. However, many states are not well established and evidence remains vague, particularly in the baryon sector. Based on quark model expectations, the experimental meson spectrum appears to be overpopulated, which has inspired speculations about states beyond the $q\bar{q}$ picture, whereas fewer states have been observed in the baryon spectrum, which has led to the problem of the so-called missing baryon resonances. Even for several well-established baryons, the spin and parity have never been measured and are merely quark model assignments, in particular for resonances containing strange quarks.

The goal of hadron spectroscopy is not only to assemble hadron states, but also to determine their resonance parameters (pole properties), and their couplings to all the channels in which they appear, and from these to learn about the composition of these states.

Simplified quark models of the proton based on three quark degrees of freedom have historically been most useful in predicting the spectrum of excited states. Models in which the three quarks are independent of each other predict a richer spectrum of states than has been observed, which is known as the issue of "missing baryons". While models in which two of the quarks are coupled together (quark-diquark models) explain the existing spectrum better, but are in disagreement with other observations on the structure of the proton. High statistics data samples of J/ψ and $\psi(3686)$ decays provide an unprecedented opportunity to obtain a better understanding of the properties of excited baryons.

In the meson sector, nearly all the observed states can be explained as simple $q\bar{q}$ systems. Within QCD, one of the perplexing issues has been the existence of gluonic excitations. A long-standing goal of hadronic physics has been to understand whats the role of gluonic excitation and how does it connect to the confinement. How might the gluon-gluon interaction give rise to physical states with gluonic excitations (glueballs or hybrids)? The primary goal of the experimental efforts is to conduct a definitive mapping of states in the light-meson sector, with an emphasis on searching for glueballs and hybrids. The radiative decays of the J/ψ meson provide a gluon-rich environment and are therefore regarded as one of the most promising hunting grounds for glueballs. Isoscalar hybrids is also expected to be largely produced in the J/ψ radiative decays.

As discussed in the physics program of BESIII [7] , BESIII remains unique for studying and searching for QCD exotics and new excited baryons, as its high-statistics data sets of charmonia provide a gluon rich environment with clearly defined initial and final state properties. Recent progress and future plan of light hadron physics at BESIII has been reviewed in [8]. With ultimately high statistics of charmonia at a super tau charm factory, there're great opportunities to further map out light mesons and baryons as complete, as precise as possible. The production property suggests the prominent glueball nature of $f_0(1710)$ and the flavor octet structure of $f_0(1500)$ [8]. However, the scalar meson sector is the most complex one and the interpretation of the states nature and nonet assignments are still very controversial. There is no question that more states than can be accommodated by a single meson nonet have been found. However, the nature of all of these states is still open for discussion. Measurements of electromagnetic couplings to glueball candidates would be extremely useful for the clarification of the nature of these states. The radiative transition rates of a relatively pure glueball would be anomalous relative to the expectations for a conventional $q\bar{q}$ state. A glueball should have suppressed couplings to $\gamma\gamma$, which can be measured at BelleII or a super tau-charm factory. The dilepton decay modes of the light unflavored mesons give a deeper insight into meson structure, allowing to measure transition form factors at the time-like region. In the baryon sector, the first step is still to establish the spectrum of nucleons and hyperons. The fundamental symmetries could be addressed with the accumulation of more data. New probes with high precison measurement will be enabled, such as radiative transitions, form factors, which will provide critical information of the internal structure of baryon excitations.

5.2 Precision tests with light hadrons

5.2.1 η/η' decays

As the neutral members of the ground state pseudoscalar nonet, both η and η' play an important role in understanding low energy Quantum Chromodynamics (QCD). Decays of the η/η' probe a wide variety of physics issues *e.g.* $\pi^0-\eta$ mixing, light quark masses and pion-pion scattering. In particular the η' meson, much heavier than the Goldstone bosons of broken chiral symmetry, plays a special role as predominantly the singlet state arising from the strong axial $U(1)$ anomaly. In addition, being the eigenstates of the C, P and CP operators, the decays of η/η' offer a unique opportunity for testing these fundamental discrete symmetries.

Although η/η' can not be produced directly from e^+e^- collisions, their high production rate in J/ψ decays provide an efficiency source of a great number of η/η' mesons. The STCF is designed to have a luminosity of $10^{35}\ cm^{-2}s^{-1}$ and the goal is to have at least 10^{12} J/ψ events produced per year. In this case, the expected η/η' decays could reach about 10^9, as listed in Table. 7, which makes it possible to gain more precise knowledge of various rare decay modes of the η/η' mesons, and the searches for CP violation are particularly challenging. In this sense, the STCF is also a factory of light meson productions. It is then proposed to high precision measurements of η/η' decays. In particular, investigations of symmetry breaking in the decays of η/η' are very promising.

Table 7: The expected η/η' events calculated with the 1×10^{12} J/ψ events produced at STCF per year.

Decay Mode	$\mathcal{B}$ ($\times10^{-4}$) [9]	η/η' events
$J/\psi\to\gamma\eta'$	52.1 ± 1.7	5.21×10^9
$J/\psi\to\gamma\eta$	11.08 ± 0.27	1.1×10^9
$J/\psi\to\phi\eta'$	7.4 ± 0.8	7.4×10^8
$J/\psi\to\phi\eta$	4.6 ± 0.5	4.6×10^8

Both η and η' decays are important tools for studies of strong interactions in non-perturbative region and for determination of some SM parameters. All this makes the η/η' unique particles for investigating the range of applicability of Chiral Perturbation Theory (ChPT) as well as different effective-Lagrangian models for exploring QCD in the vast non-perturbative region. The main decays of the η/η' meson are hadronic and radiative processes. Alternatively one can divide the decays into two following classes. The

Table 8: The sensitivity of η' rare and forbidden decays. The expected sensitivities are estimated by considering the detector efficiencies for different decay mode at STCF. We assume no background dilution and the observed number of signal events is zero. The STCF limit refers to a 90% confidence level.

Decay mode	Best upper limits 90% CL	STCF limit (1×10^{12} J/ψ events)	Theoretical predictions	Physics
$\eta' \to e^+e^-$	5.6×10^{-9}	5×10^{-10}	1.1×10^{-10}	leptonquark
$\eta' \to \mu^+\mu^-$	–	5×10^{-10}	1.1×10^{-7}	leptonquark
$\eta' \to e^+e^-e^+e^-$	–	8×10^{-10}	1×10^{-4}	$\gamma^*\gamma^*$
$\eta' \to \mu^+\mu^-\mu^+\mu^-$	–	8×10^{-10}	4×10^{-7}	$\gamma^*\gamma^*$
$\eta' \to \pi^+\pi^-\mu^+\mu^-$	2.9×10^{-5}	8×10^{-10}	2.2×10^{-5}	VMD, TFF
$\eta' \to \pi^0\mu^+\mu^-$	6.0×10^{-5}	8×10^{-10}		C violation
$\eta' \to \pi^0e^+e^-$	1.4×10^{-3}	8×10^{-10}		C violation
$\eta' \to \pi^0\gamma$	–	7×10^{-10}		angular momentum
$\eta' \to \pi^0\pi^0$	9.0×10^{-4}	1×10^{-9}		CP violation
$\eta' \to \pi^+\pi^-$	2.9×10^{-3}	5×10^{-10}		CP violation
$\eta' \to \mu^+e^- + \mu^-e^+$	4.7×10^{-4}	5×10^{-10}		LPV
$\eta' \to$ invisible	5.3×10^{-4}	1×10^{-7}		Dark matters
$\eta' \to \eta e^+e^-$	2.4×10^{-3}	2×10^{-9}		C violation
$\eta' \to \eta\mu^+\mu^-$	1.5×10^{-5}	2×10^{-9}		C violation

first class consists of hadronic decays into three pseudoscalar mesons, such as $\eta' \to \eta\pi\pi$. Those processes are already included in the lowest order, $O(p^2)$, of chiral perturbation theory (ChPT) [10]. The second class includes anomalous processes involving odd number of pseudoscalar mesons, such as $\eta' \to \rho^0\gamma$ and $\eta' \to \pi^+\pi^-\pi^+\pi^-$. They are driven by the Wess-Zumino-Witten (WZW) term [11, 12] which enters at $O(p^4)$ order [13]. Dynamics of η decays remains a subject of extensive studies aiming at precision tests of ChPT in $SU_L(3)\times SU_R(3)$ sector (*i.e.* involving s quark). Model-dependent approaches for describing low energy meson interactions, such as Vector Meson Dominance (VMD) [14, 15], and the large number of colors, N_C, extensions of ChPT [16] together with dispersive methods could be extensively tested in η' decays.

In addition they provide an indirect way to probe physics beyond the standard model. In particular the η and η' decay program at STCF, where the data collected at J/ψ peak is used for wealth of other studies, represents smart and resource efficient research strategy. Both η and η' mesons are very well suited for tests of the SM. As the eigenstates of the C, P and CP operators, both η/η' decays provide an ideal laboratory to explore these fundamental symmetries. Searches for C or CP violating decays such as $\eta/\eta' \to \gamma\gamma\gamma$, $\eta/\eta' \to \pi\pi$, $\eta/\eta' \to \pi^0e^+e^-$, $\eta' \to \eta e^+e^-$ and for effects beyond the SM in $\eta \to e^+e^-$ are challenging research topics. The new experimental facility STCF will allow detailed investigations of the η/η' rare decays at a level of 10^{-9}.

Precise information about the $\eta \to \pi^0\gamma\gamma$ and $\eta \to \pi^0e^+e^-$ are very important. The η meson has a positive eigenvalue for its charge conjugation operator. Therefore it follows that decays into an odd number of photons are forbidden since the photon has a negative C eigenvalue. Thus also the very rare $\eta \to \pi^0e^+e^-$ decay is forbidden by C if the electron-positron pair comes from a virtual intermediate photon, i.e. $\eta \to \pi^0\gamma^*$. Provided sufficient statistics can be obtained, it will be possible to test CP and CPT by exploring not only the value for branching ratio but also various differential decay distributions. The decays $\pi^0\pi^0$ or $\pi^+\pi^-$ of the η/η' are forbidden by P and CP because of the negative eigenvalues of P for these pseudoscalar mesons.

Many other decays of the η meson are useful for tests of the SM. The decays $\eta \to \mu^+\mu^-$ and $\eta \to$

e^+e^- are of interest when searching for non-standard physics. They cannot proceed via a single-photon intermediate state due to angular momentum conservation since the spins of an η and a photon differ by one unit. Within the framework of the SM, the decays are dominated by a two-photon intermediate state. The decay $\eta \to e^+e^-$ is strongly suppressed according to conventional mechanisms and should be sensitive to non-standard physics such as leptoquark exchange between the quark-antiquark constituents or an exotic heavy propagator between the initial η meson and the final lepton-antilepton pair. In weak interactions, P violation is accompanied by C violation. For this reason, only an observation of the C-odd effects with a strength considerably large would be an evidence for a new interaction, conserving strangeness and parity, but violating C invariance. The decays of η mesons are particularly suited for this purpose. The reason being that the decays of η meson into strongly interacting particles are suppressed by G-parity, and therefore new C-violating interactions, if they exist, get a better change to manifest themselves. The C-parities of η meson and 3γ system are opposite. Therefore, an observation of such decay would imply C violation.

The η/η' meson and the neutral system of two pions have opposite P and CP parity and consequently the decays $\eta(\eta') \to 2\pi$ violate CP invariance [17], which could be induced by (a) the CP violating phase Kobayashi-Maskawa, (b) by the θ term of QCD Lagrangian and (c) by additional phases appearing the electroweak models with extended Higgs sectors. In SM, the CP violating phase appears in flavor-changing quark transitions. But η meson and 2π system are flavorless. Therefore, to induce $\eta \to 2\pi$ transition, the flavour must be changed twice. And the rates of $\eta(\eta') \to 2\pi$ decays are expected to be hopelessly small, at a level of $10^{-27}(\eta)$ and $10^{-29}(\eta')$. In case of the strong interactions violate CP invariance through the θ term, the rate of the decay $\eta \to 2\pi$ is estimated to be $\eta \to 2\pi < 3 \times 10^{-17}$. Finally, CP violation in the extended Higgs sector of the electroweak could generate the decay $\eta \to 2\pi$ with the rate $\eta \to \pi^+\pi^- < 1.2 \times 10^{-15}$. which is again very small. Therefore, an observation of the decay $\eta \to 2\pi$, with a rate considerably larger than quoted above would imply new sources of CP violation beyond those considered here.

5.2.2 Hyperon polarization

The ongoing experimental studies of the combined charge conjugation parity (CP) symmetry violation in particle decays aim to find effects that are not expected in the Standard Model (SM), such that new dynamics is revealed. The existence of CP violation in kaon and beauty meson decays is well established [18, 19, 20]. The first observation of the CP violation for charm mesons was reported this year by the LHCb experiment [21] and in the bottom baryon sector evidence is mounting [22]. All the observations are consistent with the SM expectation. However, no signal is detected in decays of baryons with strange quark(s) (hyperons). Hyperon decays offer promising possibilities for such searches as they are sensitive to sources of CP violation that neutral kaon decays are not [23]. A signal of CP violation can be a difference in decay distributions between the charge conjugated decay modes. The main decay modes of the ground state hyperons are weak transitions into a baryon and a pseudoscalar meson like $\Lambda \to p\pi^-$, branching fraction $\mathcal{B} \approx 64$ %, and $\Xi^- \to \Lambda\pi^-$, $\mathcal{B} \approx 100$ % [9]. They involve two amplitudes: parity conserving to the relative p state, and parity violating to the s state. The angular distribution and the polarization of the daughter baryon are described by two decay parameters: the decay asymmetry $\alpha = 2\mathrm{Re}(s^*p)/(|p|^2 + |s|^2)$ and the relative phase $\phi = \arg(s/p)$. Here, we denote decay asymmetries for $\Lambda \to p\pi^-$ and $\Xi^- \to \Lambda\pi^-$ as α_Λ and α_Ξ, respectively. In the CP symmetry conserving limit the parameters α and ϕ for the charge conjugated decay mode have the same absolute values but opposite signs e.g. $\alpha_\Lambda = -\alpha_{\bar{\Lambda}}$. The best limit for CP violation in the strange baryon sector was obtained by comparing the Ξ^- and $\bar{\Xi}^+$ decay chains of unpolarized Ξ baryons at the HyperCP (E871) experiment [24] by determining the asymmetry $A_{\Xi\Lambda} = (\alpha_\Lambda\alpha_\Xi - \alpha_{\bar{\Lambda}}\alpha_{\bar{\Xi}})/(\alpha_\Lambda\alpha_\Xi + \alpha_{\bar{\Lambda}}\alpha_{\bar{\Xi}})$. The result, $A_{\Xi\Lambda} = (0.0 \pm 5.1 \pm 4.7) \times 10^{-4}$, is consistent

Decay mode	$\mathcal{B}$(units 10^{-4})	Angular distribution parameter α_ψ	Detection efficiency	No. events expected at STCF
$J/\psi \to \Lambda\bar{\Lambda}$	$19.43 \pm 0.03 \pm 0.33$	0.469 ± 0.026	40%	1100×10^6
$\psi(2S) \to \Lambda\bar{\Lambda}$	$3.97 \pm 0.02 \pm 0.12$	0.824 ± 0.074	40%	130×10^6
$J/\psi \to \Xi^0\bar{\Xi}^0$	11.65 ± 0.04	0.66 ± 0.03	14%	230×10^6
$\psi(2S) \to \Xi^0\bar{\Xi}^0$	2.73 ± 0.03	0.65 ± 0.09	14%	32×10^6
$J/\psi \to \Xi^-\bar{\Xi}^+$	10.40 ± 0.06	0.58 ± 0.04	19%	270×10^6
$\psi(2S) \to \Xi^-\bar{\Xi}^+$	2.78 ± 0.05	0.91 ± 0.13	19%	42×10^6

Table 9: Branching fractions for some $J/\psi, \psi' \to B\bar{B}$ decays and the estimated sizes of the data samples from the full data set of 3.4×10^{12} J/ψ and 3.2×10^9 ψ' to be collected by STCF. The approximate detection efficiencies for the final states reconstructed using $\Lambda \to p\pi^-$ and $\Xi \to \Lambda\pi$ decay modes are based on the published BESIII analyses using partial data sets [27, 28, 29].

	A_Ξ	A_Λ	$A_{\Xi\Lambda}$	$\langle\phi_\Xi\rangle$	B_Ξ
$J/\psi \to \Lambda\bar{\Lambda}$	–	1.7×10^{-4}	–	–	–
$J/\psi \to \Xi^-\bar{\Xi}^+$ ($\Delta\Phi = 0$)	2.2×10^{-4}	2.1×10^{-4}	2.5×10^{-4}	2.5×10^{-4}	7×10^{-3}

Table 10: Standard errors for the asymmetry parameters extracted using STCF data samples. The input values of the parameters are from Table 9 and Ref [33].

with the SM predictions: $|A_{\Xi\Lambda}| \leq 5 \times 10^{-5}$ [25]. However, a preliminary HyperCP result presented at the BEACH 2008 Conference suggests a large value of the asymmetry $A_{\Xi\Lambda} = (-6.0 \pm 2.1 \pm 2.0) \times 10^{-4}$ [26].

With a well-defined initial state charmonium decay into a strange baryon-antibaryon pair offers an ideal system to test fundamental symmetries. Vector charmonia J/ψ and ψ' can be directly produced in an electron-positron collider with large yields and have relatively large branching fractions into a hyperon-antihyperon pair, see Table 9. The potential impact of such measurements was shown in the recent BESIII analysis using a data set of 4.2×10^5 $e^+e^- \to J/\psi \to \Lambda\bar{\Lambda}$ events reconstructed via $\Lambda \to p\pi^-$ + c.c. decay chain [30]. The determination of the asymmetry parameters was possible due to the transverse polarization and the spin correlations of the Λ and $\bar{\Lambda}$. In the analysis the complete multi-dimensional information of the final state particles was used in an unbinned maximum log likelihood fit to the fully differential angular expressions from Ref. [31]. The method allows for a direct comparison of the decay parameters of the charge conjugate decay modes and a test of the CP symmetry.

In Ref. [32] the formalism was extended to describe processes which include decay chains of multi-strange hyperons like the $e^+e^- \to \Xi\bar{\Xi}$ reaction with the $\Xi \to \Lambda\pi$, $\Lambda \to p\pi^-$ + c.c. decay sequences. The expressions are much more complicated than the single step weak decays in $e^+e^- \to \Lambda\bar{\Lambda}$. The joint distributions for $e^+e^- \to \Xi\bar{\Xi}$ allows to determine all decay parameters simultaneously and the statistical uncertainties are independent on the size of the transverse polarization in the production process. The uncertainties of the various possible CP odd asymmetries which can be extracted from the exclusive analysis was estimeted in Ref. [33]. To study the angular distribution for the $e^+e^- \to \Xi^-\bar{\Xi}^+$ reaction we fix the decay parameters of the Λ and Ξ^- to the central values from PDG **??**. For the production process the unknown parameter is the phase $\Delta\Phi$ but the result nearly does not depend on it and we set $\Delta\Phi = 0$. In Table 10 we report the statistical uncertainties in the $J/\psi \to \Xi^-\bar{\Xi}^+$ decay.

An exclusive experiment allows to determine both the average values and differences of the decay parameters for the charge conjugated modes, which e.g. for the ϕ_D parameter are defined as:

$$\langle \phi_D \rangle \equiv \frac{\phi_D - \phi_{\bar{D}}}{2} \text{ and } \Delta\phi_D \equiv \frac{\phi_D + \phi_{\bar{D}}}{2}. \tag{20}$$

The CP asymmetry A_D is defined as:

$$A_D \equiv \frac{\alpha_D + \alpha_{\bar{D}}}{\alpha_D - \alpha_{\bar{D}}} \tag{21}$$

and $B_\Xi \approx \Delta\phi_\Xi / \langle \phi_\Xi \rangle$. The sensitivities for the A_Ξ, A_Λ, $A_{\Xi\Lambda}$ and B_Ξ asymmetries are given in Table 10. The statistical uncertainty for the $A_{\Xi\Lambda}$ asymmetry from the dedicated HyperCP experiment will be surpassed at STCF in a run at the J/ψ c.m. energy. The SM predictions for the A_Ξ and A_Λ asymmetries are $-3 \times 10^{-5} \leq A_\Lambda \leq 4 \times 10^{-5}$ and $-2 \times 10^{-5} \leq A_\Xi \leq 1 \times 10^{-5}$ [25].

A prerequisite for a complementary CP test using B_Ξ asymmetry, advocated in Ref. [23] as the most sensitive probe, is $\langle \phi_\Xi \rangle \neq 0$. Assuming $\langle \phi_\Xi \rangle = 0.037$, according to the Table **??** value for Ξ^-, the five sigma significance requires 3.1×10^5 exclusive $\Xi^-\bar{\Xi}^+$ events. To reach the statistical uncertainty of 0.011, as in the HyperCP experiment [**?**] requires 1.4×10^5 $J/\psi \to \Xi^-\bar{\Xi}^+$ events, while the single cascade HyperCP result is based on 114×10^6 events. The present PDG precision of ϕ_{Ξ^0} can be achieved with just 3×10^2 $\Xi^0\bar{\Xi}^0$ events. The SM estimate for B_Ξ is 8.4×10^{-4}, an order of magnitude larger compared to the A asymmetries [23, **?**], while the sensitivities for B_Ξ in Table 10 are $20 - 30$ times worse. However, it should be stressed that the SM predictions for all asymmetries need to be updated in view of the recent and forthcoming BESIII results on hyperon decay parameters using collected 10^{10} J/ψ. A wide range of CP precision tests can be conducted in a single measurement. Thus, the spin entangled cascade-anticascade system is a promising probe for testing fundamental symmetries in the strange baryon sector. At Super Tau Charm Factories (STCF) in with data samples of more than 10^{12} J/ψ events, such asymmetries can be measured with the precision close to the SM predictions.

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6 QCD Physics

The formation from QCD partons to observed hadrons is still not understood. Experimentally, an e^+e- collider is a suitable place to study the hadronization because of its initial states. The study at a hadron collider will suffer the uncertainties from initial hadrons. At STCF, such a study can be performed by measuring R-value for totally inclusive cross-section, and by measuring the inclusive production of one- or two hadrons. The later will provide important information about various parton fragmentation functions. Besides inclusive processes, exclusive processes should be also studied at STCF. There are interesting phenomena near the threshold in the threshold in $e^+e^- \to B\bar{B}$ with B as a Baryon. Because STCF will run at c.m.s. energy up to 7 GeV, it is possible to exclusively produce two charmiona. It is also interesting to study inclusive production of single charmonium.

6.1 R-value

The R value is defined as

$$R(s) = \frac{\sigma_{\rm tot}(e^+e^- \to \gamma^* \to \text{hadrons})}{\sigma(e^+e^- \to \gamma^* \to \mu^+\mu^-)}, \tag{22}$$

which is a function of s. This quantity plays an important role in determining the running of electroweak coupling and in the study of precision tests of SM. This can be seen in a recent study of global SM-fit[1]. $R(s)$ is also important for $g-2$ experiment. At STCF it is definitely that more precise results about R-value will be obtained.

6.2 Inclusive Production of Single Hadron

For large enough $\sqrt{s}$ the inclusive production of single hadron in $e^+e^- \to h + X$ can be predicted from QCD with QCD factorization theorem[2]:

$$\begin{aligned} \frac{d\sigma(e^+e^- \to h + X)}{dz} &= \sum_{a=q,\bar{q},g} \int \frac{d\xi}{\xi} H_a(\frac{z}{\xi}, Q^2, \mu^2) D_{a\to h}(\xi, \mu^2) \\ &= \sum_q \sigma(e^+e^- \to q\bar{q}) \Big(D_{q\to h}(z) + D_{\bar{q}\to h}(z) \Big) + O(\alpha_s), \end{aligned} \tag{23}$$

where z is the fraction of the energy carried by the observed hadron h. $H_a(a = q, \bar{q}, g)$ are functions which can be calculated with perturbation theory. $D_{a\to h}$'s are parton fragmentation functions describing hadronization of a parton a to h. Eg.(23) is the statement from QCD collinear factorization. The fragmentation functions are universal for any process where the QCD factorization is applicable. Extracting fragmentation functions at rather lower energy like the energy region of STCF around 4-5GeV is specially important besides the information about hadronization, because from the extracted fragmentation functions one can test their energy evolution from rather low energy scale to high energy scales.

6.3 Collins Effect in Inclusive Production of two hadrons

If two hadrons in the final state are observed in the kinematic region where two hadrons are almost back-to-back, the collinear factorization fails. But, there is another factorization, called Transverse-Momentum-Dependent(TMD) factorization, which holds in this region. The angular distributions in this kinematical region are determined by TMD quark fragmentation functions. The general from of angular distributions can be found in [3]. The study of the production in this region will provide many interesting results for TMD parton fragmentation functions. Among them one, called Collins function, is of particular interesting. This function describes how a transversely polarized quark fragments into a hadron[4]. It is zero if there is no T-odd effect. Belle at $\sqrt{s} = 10.6$GeV has performed a study of Collins function[5]. It will be interesting to see that one can measure Collins functions at STCF. Theoretical predictions about Collins effect at the energy region $\sqrt{s} \sim 4$GeV have been made in [6]. In general, through studying the angular correlations of the two produced hadrons in the kinematical region one can extract various TMD quark fragmentation functions. These functions contain more information how quarks are hadronized into a hadron. The study of TMD parton fragmentation functions is not only important for understanding hadronization, but also crucial for exploring the inner structure of hadrons in semi inclusive DIS, where one needs to know TMD parton fragmentation functions for extracting TMD parton distribution functions.

6.4 Form Factors near Threshold

With measurements of the production rate of $e^+e^- \to B\bar{B}$ one can extract form factors of the baryon in the time-like region. Because the energy region of STCF the extracted form factors may not be at the energy scale at which perturbative QCD of exclusive processes works. However, the behavior near the threshold is important for extracting information about the interaction between a baryon and anti baryon. In the decay $J/\psi \to \gamma p\bar{p}$ the enhancement has been observed by BES[7] near the threshold of the $p\bar{p}$ system. Babar has reported the enhancement in the process $e^+e^- \to p\bar{p}, \Lambda\bar{\Lambda}, \Sigma^0\bar{\Sigma}^0$[8], respectively. Likely, such an enhancement is a common phenomenon near threshold. At STCF one can study this enhancement more precisely, and can extend the study to the system of $\Lambda_c\bar{\Lambda}_c$ to see if the enhancement happens in heavy baryon and anti heavy baryon system.

6.5 Production of Charmonia

Inclusive production of a charmonium has been observed at Belle. The ratio has been measured as[9] :

$$R_{c\bar{c}} = \frac{\sigma(e^+e^- \to J/\psi + c + \bar{c} + X)}{\sigma(e^+e^- \to J/\psi + X)} \approx 0.63. \tag{24}$$

This has been in conflict with theoretical expectations. Progresses in theory have been made to explain this result by including various higher-order corrections. Although the experimental result can be explained by adding one-loop corrections[10, 11], it may be not consistent. If one includes the so-called color-octet contributions estimated from hadroproduction of J/ψ, there is still conflict between experiment and theory(See also [12]). Belle has also observed the exclusive production of double charmonia $e^+ + e^- \to J/\psi + \eta_c$[13]. Theoretically, the measured cross-section is still not well-explained even including two-loop predictions in theory[14].

With STCF running at $\sqrt{s}$ larger than 6GeV, the production processes can be studied more precisely in experiment. This will be helpful to understand the production.

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7 New light particles beyond SM

In this report, we briefly describe the BSM motivations for STCF. Since the Higgs boson was discovered, for the first time, one has the complete theory to describe the electro-weak and strong interactions. A draw-back for the success of the SM is that one loses the future direction. Under such circumstance, one has to scrutinize all possibilities, like STCF, super-B, LHC and other facilities to find the clues to proceed. We listed three categories motivations in terms of BSM: (1) Forbidden and rare decays; (2) CP violation; and (3) New weakly interacting light particle search. We should point out that BSM is more extensive than those listed here and other new topics can also be investigated.

Here we mainly focus on new light particles in the hidden sector which has weak coupling with the SM sector. The new light particles include dark photon, new light scalars, and millicharged particles.

7.1 Particles in dark sector

The existence of a dark sector which weakly couples to the SM sector is well motivated by many theories. Some new particles in the new physics may be at the TeV scale or above, and can be only probed at high energy colliders. However, the messengers connecting the dark sector to the SM sector may be at low energies, such as the GeV scale. These messengers can be scalars, pseudo-scalars, and gauge bosons, which interact with the SM particles through some "portals" [1]. Because the new light sector interacts with SM particles very weakly in order to escape constraints from current experiments, it is generally dubbed "dark sector".

A particular motivation for such a scenario is from the observations of anomalous cosmic-ray positrons. In 2008, the PAMELA collaboration reported excess positrons above ~ 10 GeV [2], which have been confirmed by many other experiments, such as ATIC [3], Fermi-LAT [4] and AMS02 [5]. In a class of dark matter models, dark matter particles with masses of $\sim \mathcal{O}(\mathrm{TeV})$ annihilate into a pair of light bosons with masses of $\sim \mathcal{O}(\mathrm{GeV})$, which decay into charged leptons [6, 7]. The exchange of light bosons increases the dark matter annihilation cross section so that the observations of anomalous cosmic-ray positrons can be explained. Moreover, if the mediator is light enough, no extra anti-proton will be produced due to the kinematics. This feature is consistent with the PAMELA anti-proton data.

The light boson may be a massive dark photon in the models with an extra U(1) gauge symmetry. Dark photons couple to photons through the kinetic mixing $\frac{\epsilon}{2}F^{\mu\nu}F'_{\mu\nu}$. Since the QED is a well-tested model, the mixing strength ϵ should be small. In the theory, ϵ can be zero at the tree level, and can be generated by high-order effects [8]. Therefore, ϵ is naturally $\sim 10^{-2} - 10^{-3}$ or smaller. The dark photon can acquire a mass through the spontaneous symmetry breaking mechanism. Some models could predict that the mass of dark photon is at the $\sim \mathcal{O}(\mathrm{MeV}) - \mathcal{O}(\mathrm{GeV})$ scale [8, 9]. That suggests the structure of the dark sector can be complicated. There would be a class of light particles including scalars, pseudo-scalars, gauge bosons and fermions at the GeV scale.

Since the interaction between the dark sector and the SM sector is very weak, it is well-motivated to search for the light dark photon (or other light particles) in the intensity frontier. In the phenomenology, the most important parameters are the mass of the dark photon $m_{A'}$ and the mixing strength ϵ. Fig. 3 shows the constraints on ϵ and m'_A from the measurements of electron and muon anomalous magnetic moments, low energy e^+e^- colliders, beam dump experiments and fixed target experiments [1]. Due to the high luminosity and the low center-of-mass energy which is close to the mass of dark photon, electron-positron colliders are also suitable for probing dark photons through either the direct production or rare decays of mesons.

Electron-positron collisions could directly produce dark photons, which subsequently decay into charged leptons, via $e^+e^- \to \gamma + A'(\to l^+l^-)$ [10, 11, 12, 13, 14]. In comparison with the irreducible

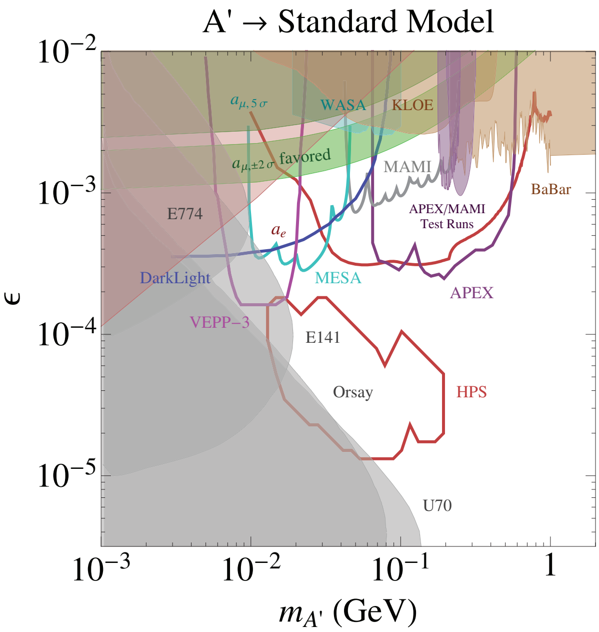

Figure 3: Constraints on the mixing strength ϵ with the dark photon mass $m_{A'} > 1$ MeV from the measurements of electron and muon anomalous magnetic moments, low energy e^+e^- colliders, beam dump experiments and fixed target experiments. For details, see Ref. [1]. Reproduced from Ref. [1].

QED background $e^+e^- \to \gamma l^+l^-$, the dark photon production is suppressed by a factor of ϵ^2. To reduce the background, a precious reconstruction of the dark photon mass and a high luminosity are important. Such researches for $\Upsilon \to \gamma + A'(\to \mu^+\mu^-)$ have been done by interpreting results from the *BABAR* experiment [15, 16, 12]. Since there is no new peak found in the data, the mixing strength ϵ is constrained to be smaller than $\sim 2 \times 10^{-3}$ for the dark photon with the mass ~ 1 GeV, and can be limited down to 5×10^{-4} at SuperB [17]. Fig. 4 shows the reach of ϵ at BESIII for $e^+e^- \to \gamma + A'(\to l^+l^-)$ [18]. 20 fb^{-1} of data collected at $\psi(3770)$ is assumed in Ref. [18]; ϵ can be limited down to 2×10^{-3} with $m_{A'} \sim 1$ GeV. A similar analysis can be performed at STC; the sensitivity to ϵ will be $O(10^{-4})$ for $m_{A'} \sim 0.6 - 3.7$ GeV with $O(\text{ab}^{-1})$ of data.

If there is also a light Higgs h', which provides the mass of dark photon, with a mass of $\sim O(\text{MeV}) - O(\text{GeV})$ in the dark sector, some new processes can be used to investigate the dark sector at electron-positron colliders [19, 20]. If $m_{h'} > 2m_{A'}$, the signal process $e^+e^- \to A' + h'(\to 2A') \to 3l^+l^-$ will be very clean for the dark research due to the several resonances in lepton pairs. If $m_{h'} < m_{A'}$, h' can only decay into lepton pairs via loop processes. In this case, the lifetime of h' will be long; possible signals are displaced vertices or even missing energies in the detector. Note that there may also exist other light bosons, such as gauge bosons under an extra non-Abelian symmetry, in the dark sector [19]. The final states of the direct production can contain more lepton pairs. In this case, it is easier to extract the signals from large QED backgrounds via the reconstruction of resonances.

In general, if mesons have decay channels into photons, they could also decay into dark photons with branching ratios $\sim \epsilon^2 \times \text{BR}(\text{meson} \to \gamma)$ [12, 18]. Since low energy electron-positron colliders produce numerous mesons, such as π, ρ, K, ϕ, and J/ψ, it is possible to investigate dark photons in the rare decays of mesons. For instance, one can search for a resonance in the processes $\phi \to \eta + A'$ and $\pi/\eta \to \gamma + A'$ with $A' \to l^+l^-$. At STC where a large sample of charm mesons are produced, charmonium decay channels, such as $J/\psi \to e^+e^- + A'$ [10] and $\psi(2S) \to \chi_{c1,2} + A'$ can be used to probe dark photons.

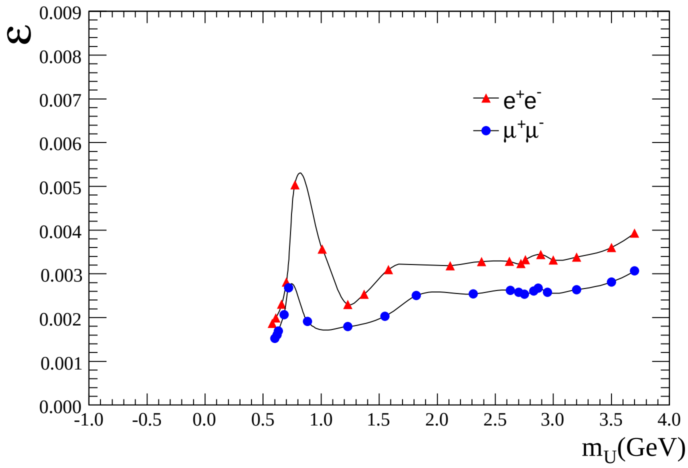

Figure 4: The reach of the mixing strength ϵ at BESIII for $e^+e^- \to \gamma + A'(\to l^+l^-)$ with 20 fb^{-1} of data. Reproduced from Ref. [18].

7.2 Millicharged particles

Particles with an electric charge that is significantly smaller than electron are often referred to as millicharged particles (MCPs). A variety of BSM models predicts MCPs; for example, millicharged fermions in the hidden sector can naturally arise via kinetic mixing [21, 22, 23] or Stueckelberg mass mixing [24, 25, 26]. MCPs have been searched for previously at various mass scales either at terrestrial laboratories or via astrophysical processes (see e.g. [27] for the review). Electron colliders operated at the GeV scale can probe the previously allowed MCP parameter space for mass in the MeV-GeV range [28, 29]. At the MeV-GeV energy scale, the existing laboratory constraints on MCPs include the collider constraints [30], the SLAC electron beam dump experiment [31], and the neutrino experiments [32].

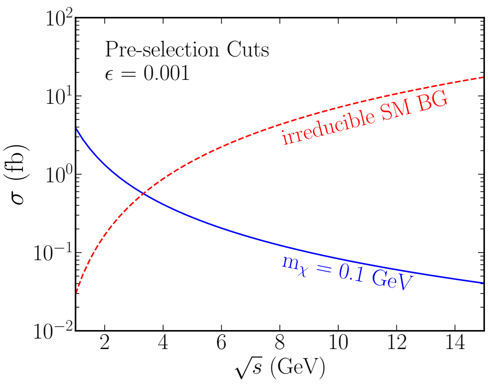

Figure 5: The monophoton cross section for MCP (solid) and for SM irreducible BG (dashed) versus colliding energy $\sqrt{s}$. The cross section is computed with the pre-selection detector cuts: $E_\gamma > 25$ MeV for $\cos\theta_\gamma < 0.8$, and $E_\gamma > 50$ MeV for $0.86 < \cos\theta_\gamma < 0.92$. The model parameters $\epsilon = 0.001$ and $m_\chi = 0.1$ GeV are used for the MCP model. Taken from Ref. [29].

A small fraction of the dark matter (DM) can be millicharged. Recently, EDGES experiment detected an anomalous absorption signal in the global 21 cm at the cosmic dawn [33]. Millicharged dark matter models have been invoked to provide sufficient cooling to the cosmic hydrogens [34, 35, 36]; because the interaction cross section between millicharged DM and baryons increases as the universe cools, constraints from early universe can be somewhat alleviated.

MCPs can be searched for at the electron colliders via the monophoton final state [28, 29]. This is because the ionization signals from MCPs is so weak that typical detectors in particle colliders are unable to detect MCPs directly. Searches for MCPs via monophoton at STCF can be easily extended to a variety of invisible particles in the hidden sector. In MCP models, the monophoton events can be produced via $e^+e^- \to \bar{\chi}\chi\gamma$ where χ is the MCP. The irreducible monophoton background processes are $e^+e^- \to \bar{\nu}\nu\gamma$, where ν is neutrino. There are also reducible monophoton backgrounds due to the limited coverage of the detectors. There are two types of reducible backgrounds: the "bBG" background which occurs when all other visible final state particles emitted along the beam directions, and the "gBG" background which is due to visible particles escaping the detectors via the gaps [29].

Fig. (5) shows the monophoton cross section for MCPs and for the SM irreducible background, where the analytic differential cross sections for these processes are taken from Ref. [28]. The monophoton cross section for MCPs increases when the colliding energy decreases, as shown in Fig. (5). However, the monophoton irreducible backgorund grows with the colliding energy. Thus, the electron collider with a smaller colliding energy has a better sensitivity to kinematically accessible MCPs.

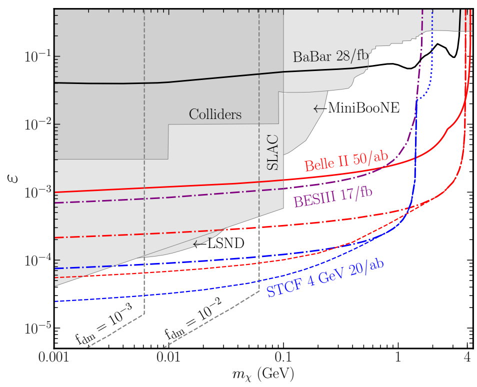

Figure 6: The expected 95% C.L. upper bound on MCPs from STCF, as well as from Belle-II, BESIII, and BaBar. The dot-dashed curves are obtained with the bBG cut for STCF, BESIII, and Belle-II where gBG is neglected [29]. Taken from Ref. [29].

To analyze the sensitivity of the proposed STCF experiment to millicharge, the STCF detector are assumed to have the same acceptance as the BESIII detector. The STCF sensitivity on MCPs in the MeV-GeV mass range is shown in Fig. (6), assuming 20 ab^{-1} data collected at $\sqrt{s}$ = 4 GeV. STCF can probe a large parameter space below the SLAC electron beam dump experiment for MCPs from ~4 MeV to 0.1 GeV. MCPs with $\epsilon \lesssim (0.8-3)\times 10^{-4}$ and mass from ~4 MeV to 1 GeV can be probed by STCF with 20 ab^{-1} data at $\sqrt{s}$ = 4 GeV. This also eliminates a significant portion of the parameter space in which the 21 cm anomaly observed by the EDGES experiment can be explained [34]. The expected constraints on MCPs from STCF analyzed with 20 ab^{-1} data at $\sqrt{s}$ = 4 GeV are better than Belle-II with 50 ab^{-1} data for MCPs from 1 MeV to 1 GeV. The increase in sensitivity is largely due to the fact that the colliding energy of the STCF is lower than Belle-II, which is ∼ 10.6 GeV. Thus, STCF has the unprecedented sensitivity to millicharge parameter space for MeV-GeV mass that has not been explored by current experiments.

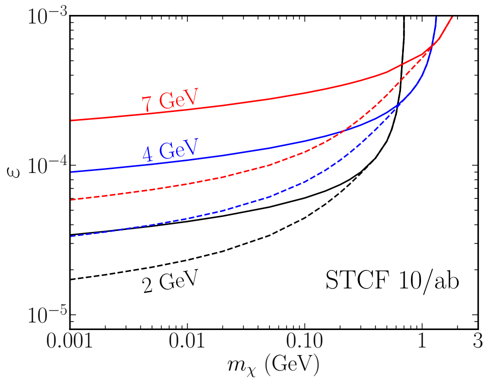

Figure 7: The expected 95% C.L. upper bound on millicharge with 10 ab^{-1} data assumed for each of the three STCF $\sqrt{s}$. The solid curves are analyzed with the bBG cut. Taken from Ref. [29].

For simplicity, a single colliding energy $\sqrt{s} = 4$ GeV with 20 ab^{-1} is assumed for obtaining the limits in Fig. (6). However, because STCF is going to be operated at various energy points, as shown in Table 1, the actual limit should be analyzed taking into account various colliding energies and detailed detector simulations. The STCF sensitivity on millicharge at three different colliding energies are compared in Fig. (7), where 10 ab^{-1} data is assumed for each colliding energy. Although the low energy mode loses sensitivity to heavy MCPs, it has better sensitivity than the high energy mode in probing light MCPs. For example, 10 ab^{-1} data with $\sqrt{s} = 2$ GeV can probe millicharge down to $\sim 4 \times 10^{-5}$ for 10 MeV mass, as shown in Fig. (7), which outperforms the $\sqrt{s} = 7$ GeV mode by a factor of ~ 5.

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8 Summary

9 Acknowledgement