STCF

Conceptual Design Report

Volume I - Physics

The STCF Study Group

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Abstract

An electron-positron collider, Super $\tau$-Charm factory (STCF), with a center-of-mass energy ranging $12 \sim 7$ GeV and an extra-high luminosity above $0.5 \times 10^{35}$ cm$^{-2}$c$^{-1}$, is of great interest in elementary particle physics. Such a facility with a state-of-the-art 4$\pi$-solid-angle particle detector operating at the transition interval between non-perturbative quantum chromodynamics (QCD) and perturbative QCD, has a very broad physics program covering the exploring QCD and hadron spectroscopy, precisely measurement of electroweak (EW) interactions and flavor physics as well as hunting for the new physics beyond the standard model (SM). Beijing Electron Positron Collider (BEPC) with Beijing Spectrometers (BES), the only collider currently running at the $\tau$-Charm energy region, has significantly advanced our understanding of elementary particle physics. A STCF with an even higher luminosity and a much broad center-of-mass energy, which continues and extends the physics research topics in the relevant energy region, is highly desirable. This document is the conceptual design report presenting the physics potential at STCF.

At STCF, copious $\tau$-leptons, charmed mesons and baryons, and strange hyperons are produced, and therefore provide a broad physics program for these particles. High-statistics of the weak semileptonic decays of hyperons and the fully leptonic decays of tagged $D^\pm$ and $D_s^\pm$ mesons can be used to make independent measurements of the Cabibbo angle precisely, and to test the unitarity of the CKM flavor mixing matrix. High precision studies of CP violation and lepton universality in the $\tau$ system also become possible. Huge samples of strange hyperons produced in quantum-entangled, spin-correlated pairs via charmonium decays would provide a unique platform for searching for the new sources of CP violation in the strange-quark sector with unprecedented sensitivity. Hadronic final states produced in radiative $J/\psi$ decays are ideal for studying spectroscopies of QCD hybrids and glueballs. Searches for anomalous weak decays of the $J/\psi$ would have sensitivities that extend all the way down to the level of SM-model expectations.

In recent years, the new discovered states with peculiar features, the $XYZ$-mesons, provide the opportunities to study QCD dynamics with exotic states beyond usual charmonium states. STCF will be an ideal $XYZ$-meson factory, which will produce multi-million samples of $X$($3872$), $Z_c$($3900$), $Z_c$($4020$) and $Y$($4230$) events with very low background environments, and can be used to explore their properties with high precision and search for their rare decays.

Various quantities, like fragmentation functions, Collins fragmentation function and form factors of baryons, can be studied with high precisions. Especially, nucleon’s form factors can be measured with precisions that match those for the space-like region, which will provide a comprehensive picture of nucleon structure. The puzzling threshold behavior and peculiar oscillation patterns observed in recent low-statistics experiments could be studied in precise detail. Moreover these studies can be performed for other baryons, such as $\Lambda_c$ and strange hyperons, which is a unique feature that is not possible for the space-like region.

The STCF will bring the new opportunities for more precise measurements of SM free parameters related to $SU(3)_C$ of QCD for strong and $SU(2)_L \times U(1)_Y$ for EW interactions, and their dynamics for hadron spectroscopy. With high luminosity, it also provides excellent chances to probe new particles and non-SM interactions. STCF will play a crucial role in leading the high intensity frontier of elementary particle physics worldwide.
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1 Introduction

The Standard Model (SM) of particle physics, comprised of the unified electro-weak (EW) and Quantum Chromodynamics (QCD) theories, successfully explains almost all experimental results related to the micro-world. For example, it successfully predicted: the existence of weak neutral current interactions and the masses, widths and many other properties of the $W^\pm$ and $Z^0$ bosons; large particle-antiparticle differences, so-called CP violations, in specific $B$ meson decay channels that were subsequently confirmed by experiments; and the existence of the Higgs scalar boson that was discovered at CERN in 2012 [1, 2] – 50 years after its existence was predicted – with properties that closely match the model’s expectations. As a result, the SM is currently universally accepted as the theory of elementary particles and their interactions.

However, in spite of its considerable successes, the SM has a number of shortcomings, including:

Many free parameters SM with the minimal particle contents, the gauge particle, the the generations of left-handed quark doublets, the right-handed quark singlet, the left-handed lepton doublets, the right-handed charged leptons, and the Higgs doublet, has 19 free parameters that must be extracted from experimental measurements. These include the quark, lepton and Higgs masses, the mixing angles of the Cabbibo-Kobayashi-Maskawa (CKM) quark-flavor mixing matrix, and the couplings of the electric, weak and QCD color forces (see Fig. 1a). If neutrinos mass problem is also considered, there are even more free parameters.

Baryon asymmetry of the universe The model’s mechanism for CP violation fails to explain our existence in a matter-dominated universe by about ten orders of magnitude. There must be additional CP violating mechanisms in nature that beyond those contained in the SM.

Quark/gluon - hadron disconnect The strongly interacting particles of the SM are quarks and gluons, while the strongly interacting particles that are measured in experiments are hadrons. In principle, QCD accurately describes transitions between quarks/gluons and hadrons. However, at the relevant distance scale of order 1 fermi (see Fig. 1b), QCD is a strongly coupled theory and perturbation theory in not directly applicable. As a result, there is no first-principle connection between the theory and the spectrum and properties of the particles that are actually seen in experiments.

<table>
<thead>
<tr>
<th>Masses</th>
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<th>Value</th>
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Figure 1: a) The free parameters of the Standard Model. Note that here neutrino masses and mixing angles are not included. b) The behavior of the QCD coupling strength $\alpha_s(Q)$ vs. $1/Q$ (bottom axis) and distance (top axis).

Gravity, dark matter, neutrino masses, number of flavors, etc. SM does not contain a quantized theory for gravity. It does not explain the dark matter in the universe; neutrino masses and the number of
particle generations; etc. Because of these shortcomings, SM cannot be taken as a perfect theory.

There is considerable enthusiasm among particle physicists to search for evidence for new, non-SM physics phenomena. In general, this requires evaluating and testing SM predictions with ever-increasing energies and/or levels of precision. For example, at the energy frontier, the ATLAS and CMS experiments at CERN search for new massive particles that are not accounted for in the SM and make precise determinations of Higgs decay coupling strengths to search for deviations from SM predictions. At the intensity frontier, the LHCb experiment at CERN, the recently commissioned BelleII experiment at KEK, and long-baseline neutrino experiments are searching for evidence deviations from SM predictions for processes that are mediated by quantum loops containing massive virtual particles, which could be signs of the influence of non-SM particles that are too heavy to be accessed by experiments at LHC energies. At lower energies region, the tests of the SM include precision measurements of \((g - 2)_\mu\), tests of the unitarity of the CKM matrix, especially the CP triangle, non-SM sources of CP violation in neutrino, searches for lepton flavor violations, consistency between various approaches to determine the value of the Weinberg weak interaction angle \(\theta_W\), etc. These in general require precisely measured values of SM parameters, usually as input from other sources, and independent determinations of the influence of long-distance hadron effects. Thus, a comprehensive challenge to the SM requires a co-ordinated multi-dimensional program that includes careful refinement of theoretical predictions coupled with experimental measurements with state-of-the-art sensitivities.

At low energies, some of the non-perturbative effects of QCD have an important influence on the determination of fundamental parameters. An electron-positron \(e^+e^-\) collider operating at the transition interval between non-perturbative quantum chromodynamics (QCD) and perturbative QCD at a few GeV – a τ-Charm facility – is uniquely well suited to play an important role in the determination of these parameters. Such a facility would address a very broad physics program covering tests of QCD, investigation of hadron spectroscopy, precise tests of electroweak interactions, and searches for new, beyond-the-SM physics. Currently, the only facility operating in this energy region is the Beijing Electron Positron Collider (BEPCII) - BEijing Spectrometer (BESIII) \[3, 4\], which has significantly advanced the progress of elementary particle physics, the comprehensive description for physics program and potential of BESIII can be found in Refs. \[5, 6\]. BESIII has been operated for more than 10 years, and will complete its mission soon. An advanced facility that continues and extends to research topics in the relevant energy region with significantly enhanced sensitivity is definitely necessary to address many of the unsolved problems. A Super τ-Charm facility (STCF), with a factor of two orders higher luminosity, would a natural extension and a viable option. The successful construction and operation of an STCF will play a crucial role in continuing China’s leading role in the world-wide high intensity frontier of elementary particle physics.

### 1.1 The STCF project in China

Starting with the discovery of the charmed quark and the τ lepton during the 1974 “November Revolution” \[7\], results from low energy \(e^+e^-\) collider experiments with center-of-mass energy (CME) of 2 ~ 6 GeV (τ-charm threshold) region have played a key role in elucidating and the properties of these intriguing particles. Historically, there has been several generations of τ-charm facilities (TCF) in the world, including: MARKI–II–III \[8, 9\], DM2 \[10\], CLEO-c \[11\], and BEPC/BES \[12\]; that have produced numerous and critical contributions to the establishment of the SM and for searches for new physics beyond the SM. Of these, the BEPC/BES facility in Beijing, China, is no doubt to be the one of the most prolific TCF that has significantly advanced our understanding of elementary particle physics. This program, which started in the late 1980s, has produced many interesting physics results, such as the precision measurements of τ-lepton mass \[13, 14\] and \(e^+e^-\) annihilation cross sections \[15\], first observations of
purely leptonic charmed meson decays [16], the discovery of the $X(1835)$ candidate for a baryonium state candidate [17, 18, 19, 20], the clear elucidation of the $\sigma (f_0(500))$ [21] and $\kappa (K_0(700))$ [22], the lowest-lying scalar mesons, etc.

The currently operating BEPCII/BESIII [3, 4] complex, which is a major upgrade of BEPC/BESIII [12] that includes separate electron and positron magnet rings as part of the highest ever luminosity TCF, and a completely new, state-of-the-art detector is only facility in the world that confronts the physics opportunities in this interesting energy range. BEPCII/BESIII’s unique capabilities and excellent performance have attracted a large collaboration of researchers from all over the world that has been very successful in producing numerous high-quality, frequently cited physics results. After its ten years of operation, BEPCII operates reliably at its designed luminosity goal of $10^{33} \text{ cm}^{-2}\text{s}^{-1}$ at $\sqrt{s} = 3.77 \text{ GeV}$. It has recently implemented a continuous injection system that increases the integrated luminosity by 30%, and extended its CME upper limit from 4.6 to 4.9 GeV, thereby providing access to charmed baryon thresholds.

In 2019, BESIII achieved one of its main data-taking goals with successful accumulation of 10 billion $J/\psi$ events for studies of light hadron physics. An early pay-off from this unprecedentedly large data sample was the discovery of an isospin-singlet $\eta'$ meson resonance with manifestly exotic $J^{PC} = 1^{-+}$ quantum numbers [23]. This is best explained as a “smoking-gun” candidate for a QCD-hybrid meson comprising a quark-antiquark pair plus a valence gluon, a hadronic sub-structure that was predicted over forty years ago [24] and only recently has started to emerge thanks to the availability of huge data sets like the BESIII 10 billion $J/\psi$ event sample. Other notable light hadron physics results from BESIII include the discoveries of an anomalous in the $X(1835) \rightarrow \pi^+\pi^-\eta'$ line shape at the $p\bar{p}$ mass threshold [20], an anomalously large partial width for isospin violating $\eta(1405) \rightarrow f_0(980)\pi^0$ decay [25], the first observation of $a_0(980) \leftrightarrow f_0(980)$ mixing [26] (another forty-year-old prediction [27] that was eventually confirmed by BESIII) and precise measurements of the $\Lambda$ hyperon decay parameters and tests of $CP$ invariance in $J/\psi \rightarrow \Lambda\bar{\Lambda}$ decays [28].

For studies of charmed mesons and baryons, BESIII has accumulated samples of 1.7 million tagged $D^+D^-$ events and 2.8 million tagged $D^0\bar{D}^0$ events produced via $\psi(3770) \rightarrow D\bar{D}$ decays, 0.30 million tagged $D_s^+D_s^-$ events from $\psi(4160) \rightarrow D_s^+\bar{D}_s^-$ decays and 90 thousand tagged $\Lambda_c^+\bar{\Lambda}_c^-$ events from $e^+e^- \rightarrow \Lambda_c^+\bar{\Lambda}_c^-$ with CME above 4.6 GeV. Measurements of purely leptonic and semileptonic decays of $D$ and $D_s$ mesons produced the world’s best measurements of the $|V_{cs}|$ and $|V_{cd}|$ of CKM matrix elements [29, 30, 31, 32]. Absolute $\Lambda_c$ branching fraction measurements with the tagged $\Lambda_c$ baryon sample [33], including those for a number of previously unseen modes, dominate the Particle Data Group (PDG) 2020 listings for this state. In addition, the large samples of $CP$-tagged $D^0$ meson decays are used to make precise measurements of final-state strong interaction phases decays, which are critical inputs to LHCb and Belle(II) measurements of the $CP$ violating and $\gamma$ angle of the CKM Unitary Triangle [34, 35, 36].

Measurements of $e^+e^-$ annihilations for CME values between 2.0 and 3.0 GeV provided $R$ measurements with unprecedented precision, ~3%, that are critical input to SM calculations $\alpha_{\text{QED}}(m_Z^2)$ [37], that were used in fits to the electroweak sector of the model that provided accurate predictions of the Higgs boson mass that were spectacularly confirmed in 2012 by LHC experiments. BESIII $R$ measurements of the $e^+e^- \rightarrow \pi^+\pi^-$ at CMEs below 1 GeV, extracted from $e^+e^- \rightarrow \gamma_{\text{ISR}}\pi^+\pi^-$ events [38], where $\gamma_{\text{ISR}}$ is an initial-state radiation, significantly improve on the accuracy of previous results and will enable future SM calculations of $(\alpha - 2)_{\mu}$ match the higher precision that is expected for imminent measurements from currently operating experiments at Fermilab [39] and JPARC [40]. In addition, this data sample is being used for numerous low energy QCD studies, including measurements of the proton, neutron and $\Lambda$ time-like form factors with improved precision [41, 42, 43, 44], first measurements of the $\Sigma$, $\Sigma'$, and $\Xi$ form factors.
A data sample of \(\sim 20 \text{ fb}^{-1}\) integrated luminosity accumulated at a variety of CME values between 4.0 and 4.6 GeV support detailed studies of charmonium-like \(XYZ\) mesons, including some of BESIII’s most remarkable results such as the discoveries of the charged charmonium-like states, \(Z_c(3900)\) and \(Z_c(4020)\) [51, 52], the \(Z_{cs}(3985)\), the first example of a charmonium-like state with a non-zero strangeness [53], an anomalous line shape for the \(Y(4260)\) resonance [54] and a large partial decay width for the radiative process \(Y(4260) \to \gamma X(3872)\) [55].

The measurement of the \(\tau\)-lepton mass by the original BES experiment [13] in 1992 yielded a result that was 7 MeV (~2\(\sigma\)) lower than the world average of all previous measurements. It cleared up what was the major discrepancy with the SM at that time [56]. Since then, the BES program has made improved \(\tau\)-mass measurements; the latest BESIII result is in good agreement with the original BES measurement but with an order of magnitude better precision [14].

The primary task of the particle physics community during the next two decades will be to mount a comprehensive challenge to the SM and to develop an understanding of the laws of nature at a more fundamental level. This will require a coordinated multi-dimensional program that includes precise predictions for measurable quantities in the framework of the SM. These predictions, in turn will, have to be confronted with experimental measurements with state-of-the-art sensitivities and well controlled systematic errors. The physics potential of the current BEPCII/BESIII program is limited by its luminosity and CME range. Higher luminosities are crucial for investigations of many of the important key questions that can be uniquely addressed in the \(\tau\)-charm threshold energy region, such as more precise measurements of the SM’s free parameters, a better understanding of internal compositions of exotic hadron states such as the \(XYZ\) and other charmed mesons and baryons and quark-gluon states and their underlying dynamics, measurements of \(CP\) violation in hyperon decays and other systems, \(\tau\) physics and probes for possible new physics beyond the SM. Next-generation studies of charmed baryons, especially the newly discovered double charmed baryon states [57], will require an increased CME range. Because of strict spatial constraints there is not enough space on the IHEP campus at Beijing to accommodate an upgrade of BEPCII that would meet these luminosity and energy goals. As a result, after BEPCII/BESIII completes its mission in near future, there will be a need for a new collider that has two order-of-magnitude higher luminosity and a much broader (a factor 2) energy range in order to continue and extend the scientific opportunities in the \(\tau\)-charm region.

The proposed STCF [58] is an electron-positron collider with separated electron and positron rings and symmetric beam energy in China. It is designed to have a CME spanning between 2 and \(\sim 7\) GeV, with a peak luminosity of at least \(0.5 \times 10^{35} \text{ cm}^{-2}\text{c}^{-1}\) optimized at the CME of 4 GeV. In addition to the boost in luminosity, the extended accessible energy region would provide opportunities to study the recently discovered doubly charmed baryons [57]. The proposed design would leave space for higher luminosity upgrades and for the implementation of a polarized \(e^-\) beam in a future phase-II [59] to the project. To achieve such a high luminosity, several advanced technologies, such as the introduction of a crabbed-waist beam-crossing scheme with a large Piwinski angle interaction region [60], would be implemented in the machine.

Some of the physics a STCF could do, can also be done by the BELLE II [61] and LHCb [62] experiments. A detail description of the physics program of Belle II and LHCb can be found in Refs. [63, 64], respectively. Both of those experiments can produce more \(\tau\)-leptons and charmed hadrons meson than STCF. However, STCF data samples would have distinctly lower backgrounds, near-100% detection efficiencies, better full-event reconstruction rates, well controlled systematic uncertainties, etc. It will also have several unique features that are not available at BELLE II and LHCb, including the direct production of \(1^-\) resonances such as charmonium (\(J/\psi, \psi'\) & \(\psi''\)) and non-standard charmonium-like mesons.
such as $Y(4260)$, $Y(4320)$ and $Y(4660)$, operation near particle-antiparticle thresholds that provides the
capability for fully reconstructing events with final-state neutrinos, neutrons/antineutrons or $K_L$-mesons,
with high efficiency.

To achieve the goals, a sophisticated, machine-compatible detector is required to maximize the
physics potential. The detector is expected to have much improved performance in each sub-system
comparing to the BESIII detector. Currently, STCF detector shown as Fig. 2 by DD4hep[65], is still
under research and development. Several features have to be considered for the detector.

Figure 2: The STCF detector visualized by DD4hep.

The STCF detector features large solid angle coverage, low noise, high detection efficiency and reso-
lation and excellent particle identification capability. It is also required to be of fast trigger, high rate
capability and high levels of radiation tolerance. From the interaction point outwards, the STCF detect-
tor consists of a tracking system, a particle identification (PID) system, an electromagnetic calorimeter
(EMC), a super-conducting solenoid and a muon detector (MUD), where the tracking system is com-
posed of the inner and outer trackers. Among all the sub-detectors, the inner tracker is the closest one to
the interaction point, and hence exposed to the highest level of radiation. To tolerate ultra-high radiation
background, a novel micro-pattern gaseous detector, based on the uRWELL technology and consisted
of three cylindrical layers located at 6, 11 and 16 cm away from the interaction point, is proposed to
be a baseline option for the inner tracker. A thin silicon, e.g. depleted CMOS maps, also is taken as
an option. A large cylindrical drift chamber with ultra-low material, spanning from 200 to 820 mm in
radius, operating with helium-based mixture gas is proposed to be the outer tracker. The momentum
resolution in 1 T magnetic field is expected to be better than 0.5% for charged tracks with a momentum
of 1 GeV/$c$, and the $dE/dx$ resolution is better than 6%, which can be exploited to serve the particle iden-
tification for low momentum charged particles. The PID system uses a Ring Imaging Cherenkov (RICH)
detector in the barrel region and a Detection of Internally Reflected Cherenkov (DIRC) detector in the
endcap regions to achieve a $3\sigma$ separation between kaons and pions with a momentum up to 2 GeV/$c$.
Separation capability between muons and pions of $3\sigma$ is also available with a momentum between 0.2
and 0.6 GeV/$c$ by the PID system. A crystal calorimeter based on pure CsI crystals read out with APD
for energy measurement and SiPM for precise timing, is proposed for the EMC to achieve an excellent
energy resolution (better than 2.5% with an energy 1 GeV) and a good time resolution ($\sim$300 picosec-
onds for photon) in high radiation background. The timing capability of the EMC allows to effectively separate photons from neutrons and $K_L^0$ in the energy region of interest. The size of crystal is optimized to achieve a better spatial resolution to be compatible with the energy resolution. A super-conducting solenoid (SCS) magnet surrounding the EMC provides the tracking system with a magnetic field of 1 T. A hybrid of MRPC (3 inner layers) and plastic scintillator (7 outer layers) detectors is proposed as the baseline option for the MUD, and provide the excellent capability to efficiently separate muons from pions with a mis-identification rate less than 3% or even better.

1.2 Physics Potential at STCF

The SM has 19 free parameters that must be supplied by precision experiments. The discoveries of the charmed mesons, the $\tau$-lepton, and the successful mapping of the charmonium meson spectrum in the 20th century opened a window to the rich physics program that is addressable in the $\tau$-charm region. The original BES experiment’s determination of the $\tau$-lepton mass provided a stringent test of lepton flavor universality in combination with other measurements, such as couplings, and precision measurements of the cross-section for $e^+e^-$ annihilation into hadrons by BESII were crucial input into fits to the electroweak sector of the model that provided an accurate prediction of the Higgs boson mass, prior to its discovery in 2012. BESIII has also made the world’s most precise measurements of the $|V_{cs}|$ and $|V_{cd}|$ elements of the Kobayashi-Maskawa quark-flavor mixing matrix. A deeper understanding of the underlying theory of the fundamental interactions will require even more precise measurements of all of these parameters. A STCF will contribute significantly to this goal.

STCF operating with CME ranging 2~7 GeV would be of great importance to the entire field of elementary particle physics field. It would address a very broad range of physics topics including QCD tests, hadron spectroscopy, precise tests of electroweak sector of the SM, and searches for new physics beyond the SM. The proposed luminosity of STCF is above $0.5 \times 10^{35}$ cm$^{-2}$s$^{-1}$, at this level it is expected to deliver more than 1 ab$^{-1}$ data samples each year. A possible data-taking plan for the STCF along with the expected numbers of conventional events and/or particles is shown in Table 1.

The B-factory and BESIII experiments found a striking failure of the charmonium model to provide an explanation of the spectrum of hidden charm states with masses above $2m_D = 3.63$ GeV, which is a threshold for open charm meson production. In addition to some conventional $c\bar{c}$ charmonium states, a larger number of unexplained charmonium-like meson states, the so-called $XYZ$ mesons with masses in the 3.8~5 GeV mass region, were discovered. These discoveries underline a glaring weakness of the SM: the lack of understanding how QCD, the strong interaction sector of the theory that deals ontly with quarks and gluons, explain experimental data which only invovle hadrons. In addition, after decade of searches, strong candidates for light non-$q\bar{q}$ hadrons such as glueballs and $q\bar{q}$-gluon QCD hybrids with exotic spin-parity quantum numbers $J^{PC} = 1^{-+}$ have been found in large samples of radiative $J/\psi$ decaysadd some references?. Both the $XYZ$ and exotic light hadrons point to entirely new hadron spectroscopies that must be explored and understood. At the moment many of the properties of the $XYZ$ particles are unknown, and there is no clearly identifiable pattern to the $XYZ$ particle spectrum. In certain circumstances it is even unclear if the $XYZ$ resonance signals are partly or totally produced by kinematical singularities. These uncertainties prevent us from obtaining an unambiguous mass spectrum and obscures the insight into the inner structure of the $XYZ$ particles. At STCF, not only large data samples of conventional particles can be collected from Table 1, but also copious $XYZ$ particle event samples will be produced; expected event-numbers of some of the $XYZ$ mesons are given in Table 2. These large data samples would enable detailed studies the $XYZ$ meson properties by precisely studying Argand plots, searching for rare decays, precise measuring mass and width etc, which lead to more conclusive results.

In addition to mesons containing a charmed-anticharmed quark pair, new heavy baryons containing
Table 1: The expected numbers of events per year at different STCF energy points.

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<td>3.670</td>
<td>1</td>
<td>(\tau^+\tau^-)</td>
<td>2.4</td>
<td>(2.4 \times 10^{9})</td>
<td></td>
</tr>
<tr>
<td>3.686</td>
<td>1</td>
<td>(\psi(3686)) (\rightarrow \tau^+\tau^-)</td>
<td>640</td>
<td>(6.4 \times 10^{11})</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2.5</td>
<td>(2.5 \times 10^{9})</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(2.0 \times 10^{9})</td>
<td></td>
</tr>
<tr>
<td>3.770</td>
<td>1</td>
<td>(D^0\bar{D}^0)</td>
<td>3.6</td>
<td>(3.6 \times 10^{9})</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>(D^+\bar{D}^-)</td>
<td>2.8</td>
<td>(2.8 \times 10^{9})</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>(D_y^0\bar{D}^0)</td>
<td>7.9 \times 10^8</td>
<td>(2.9 \times 10^{9})</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>(D_y^+\bar{D}^-)</td>
<td>5.5 \times 10^8</td>
<td>(2.9 \times 10^{9})</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>(\tau^+\tau^-)</td>
<td>2.9</td>
<td>(2.9 \times 10^{9})</td>
<td></td>
</tr>
<tr>
<td>4.040</td>
<td>1</td>
<td>(\gamma D^0\bar{D}^0)</td>
<td>0.40</td>
<td>(4.0 \times 10^6)</td>
<td>(\text{Single Tag}) (\text{Single Tag})</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(\pi^0 D^0\bar{D}^0)</td>
<td>0.40</td>
<td>(4.0 \times 10^6)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>(D_s^+D_s^-)</td>
<td>2.0 \times 10^8</td>
<td>(2.0 \times 10^8)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>(\tau^+\tau^-)</td>
<td>3.5</td>
<td>(3.5 \times 10^9)</td>
<td></td>
</tr>
<tr>
<td>4.180</td>
<td>1</td>
<td>(J/\psi\pi^+\pi^-) (\rightarrow \tau^+\tau^-)</td>
<td>0.90</td>
<td>(9.0 \times 10^8)</td>
<td>(\text{Single Tag})</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(\gamma X(3872))</td>
<td>3.6</td>
<td>(1.3 \times 10^8)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(3.6 \times 10^9)</td>
<td></td>
</tr>
<tr>
<td>4.230</td>
<td>1</td>
<td>(\psi(3686)\pi^+\pi^-) (\rightarrow \tau^+\tau^-)</td>
<td>0.085</td>
<td>(8.5 \times 10^7)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>(\gamma X(3872))</td>
<td>3.6</td>
<td>(3.6 \times 10^9)</td>
<td></td>
</tr>
<tr>
<td>4.360</td>
<td>1</td>
<td>(\psi(3686)\pi^+\pi^-) (\rightarrow \tau^+\tau^-)</td>
<td>0.058</td>
<td>(5.8 \times 10^7)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>(\gamma X(3872))</td>
<td>3.5</td>
<td>(3.5 \times 10^9)</td>
<td></td>
</tr>
<tr>
<td>4.420</td>
<td>1</td>
<td>(\psi(3686)\pi^+\pi^-) (\rightarrow \tau^+\tau^-)</td>
<td>0.040</td>
<td>(4.0 \times 10^7)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>(\gamma X(3872))</td>
<td>3.5</td>
<td>(3.5 \times 10^9)</td>
<td></td>
</tr>
<tr>
<td>4.630</td>
<td>1</td>
<td>(\psi(3686)\pi^+\pi^-) (\rightarrow \Lambda_c\bar{\Lambda_c})</td>
<td>0.033</td>
<td>(3.3 \times 10^7)</td>
<td>(\text{Single Tag})</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(\Lambda_c\bar{\Lambda_c})</td>
<td>0.56</td>
<td>(5.6 \times 10^8)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>(\tau^+\tau^-)</td>
<td>3.4</td>
<td>(6.4 \times 10^7)</td>
<td></td>
</tr>
<tr>
<td>4.0-7.0</td>
<td>3</td>
<td>(\text{300 points scan with 10 MeV step, 1 fb}^{-1}/\text{point})</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>&gt; 5</td>
<td>2-7</td>
<td>(\text{several ab}^{-1} \text{ high energy data, details dependent on scan results})</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 2: The expected event-numbers of XYZ-particles per year at STCF

<table>
<thead>
<tr>
<th>XYZ</th>
<th>(Y(4260))</th>
<th>(Z_c(3900))</th>
<th>(Z_c(4020))</th>
<th>(X(3872))</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of events</td>
<td>(10^{10})</td>
<td>(10^9)</td>
<td>(10^9)</td>
<td>(5 \times 10^6)</td>
</tr>
</tbody>
</table>
a charmed quark and doubly charmed baryons have been discovered and these open new territories for QCD spectroscopic studies. A comprehensive portfolio of high precision and comprehensive measurements of these spectra could challenge and calibrate predictions from LQCD, which is rapidly emerging as a powerful theoretical tool for doing precision first-principle QCD calculations for long-distance phenomena. The STCF’s high luminosity will help us complete the task of developing a comprehensive and precise spectrum of these hadrons. The extension of the STCF’s high energy coverage to around 7 GeV is motivated by the need to understand the dynamics of these doubly charmed heavy baryons.

With the large data samples as indicated in Table 1, STCF would provide an ideal facility for studies of the physics of charmed hadron decays. A large $D$-meson production rate will support rigorous tests of the SM. For example, purely leptonic decays of tagged $D^+$ and $D_s^+$ mesons produced in large numbers at the $\psi(3770)$ and $\psi(4040)$ (or $\psi(4160)$) resonances would provide precise measurements of the $|V_{cd}|$ and $|V_{cs}|$ matrix elements to test the second-row unitarity of the CKM matrix and uniquely address the Cabibbo angle anomaly, i.e., a ~4σ discrepancy in $\theta_c$ values measured in different processes [66]. In addition, $D^0 - \bar{D}^0$ mixing parameters could be measured with significantly improved precision. Measurements of and searches for rare- and forbidden decays with up to two orders-of-magnitude improvements in sensitivity could be realized as part of a search for new physics.

The $\tau$, as the heaviest charged lepton, occupies a unique place in the SM. It has more decay channels than muon, which could supply unique access to new physics beyond the SM. At the STCF, the number of accumulated $\tau^+\tau^-$ pair events would be about three orders of magnitude higher than the currently accumulated number of such events at BES III. As many as a few billion of $\tau$ pairs could be obtained in a one-year run at the CME=2$m_\tau$ threshold. Operation near threshold would provide STCF with unique advantages over BelleII [63] and LHCb [64], even though they would have larger $\tau$-pair event samples. For example, these events, together with well controlled background studies using data accumulated just below the threshold, would be uniquely well suited for a high-sensitivity study of the anomalous (∼3σ) sign of $CP$ violation in $\tau \rightarrow K_S \pi\nu_\tau$ decays that was reported by BaBar [67]. Another unique advantage of $\tau$-pairs that are produced near-threshold $\tau$ pairs, is that they are primarily produced in an $S$-wave and, thus, if the electron beam is polarized, this polarization translates nearly 100% into a well understood polarization of the two final-state $\tau$ leptons [68]. Thus, STCF operation with a polarized electron beam just above the $\tau$-pair threshold would enable a high-sensitivity search for $CP$ violating asymmetries in $\tau^+ \rightarrow \pi^+\pi^0\nu_\tau$ decays [68]. The same data sample would also provide better determinations of the SM $\tau$-lepton parameters, stringent tests of lepton-flavor universality of weak interactions, and may reveal possible clues to understand and the study of $g - 2$ of $\tau$ may shed light on the anomaly in $g - 2$ of muon.

The large matter-antimatter asymmetries in the $b$-quark sector that were observed by the $B$-factory experiments confirmed the CKM ansatz as the SM mechanism for $CP$ violation. This model can also explain the $CP$ violations that were first observed in neutral Kaon mixing and Kaon decays into two and three pions. However, this mechanism fails to explain the baryon asymmetry of the universe by about ten orders of magnitude, which strongly suggests the presence of additional, non-SM $CP$-violating interactions. Promising channels for searching for new sources of $CP$ violation are weak decays of the $\Lambda$ and $\Xi$ hyperons, where SM-CPV effects are small but effects of new, beyond SM interactions could be large [64]. These measurements are elegantly done with high statistics samples quantum-entangled hyperon-antihyperon pair events that are produced via $J/\psi \rightarrow \Lambda\bar{\Lambda}$ and $\Xi\bar{\Xi}$ decays. A one-year STCF run at the $J/\psi$ resonance, would produce data samples of 160 M (60 M) fully reconstructed $J/\psi \rightarrow \Lambda\bar{\Lambda}$ ($\Xi\bar{\Xi}$) events and more than an order of magnitude improvement of the BESIII $CP$ sensitivity. With ~80% electron beam polarization, this sensitivity would be improved by an additional factor of four.

BESIII measurements are demonstrating that hadronic final states produced in radiative $J/\psi$ decays are replete with QCD hybrids and glueballs and ideally well suited for studying the spectroscopies of
these mostly unexplored systems. Searches for anomalous weak decays of the $J/\psi$ at STCF would have
sensitivities that extend all the way down to the level of SM-model expectations some references?. With
STCF data runs at a variety of energies, interesting $Q^2$-dependent quantities can be studied with high
precisions. These include time-like nucleon form-factors that could be measured for $Q^2$ values as high
as 50 GeV$^2$ with precisions that match the existing measurements in the space-like region. The puzzling
threshold behavior and peculiar oscillation patterns observed in recent low-statistics experiments could
be studied in precise detail. Moreover, unlike space-like form-factor measurements, which are only possi-
ble for the proton & neutron, the time-like form-factor studies could be repeated for the $\Lambda$, $\Sigma$, $\Xi$ & $\Omega$−
strange hyperons, a unique new window on baryon structure. With this very high luminosity, high-
sensitivity searches for light new particles and new interactions that are predicted by a number of beyond
the SM theories could be performed using decays of all of the weakly & electromagnetically decaying
particle systems that are accessible in the STCF energy range.

In short, STCF will undoubtedly cover a very broad physics program, and would support a multi-
dimensional program of experimental measurements with state-of-the-art sensitivities and address many
of the challenges of the SM. In the following chapters, more details for some of the highlighted physics
topics that could be addressed at STCF are provided. These materials include discussions of research
opportunities for particles ranging from the high-mass $XYZ$ states to low mass systems such as hyper-
ons, glueball/hybrid states, and possible new, beyond-the-SM light particles. Some studies to extract
important SM information for non-resonance energies will also be presented. Studies of the decays and
interactions can provide essential information to both flesh out the SM and search for clues for new
physics beyond SM. In addition to spectroscopic issues, the precision of strong- and weak-interaction
parameter determinations, sensitivities of measurements of rare & searches for forbidden decays and $CP$
violating asymmetries, and how new particles and new, beyond the SM interactions might show up are
discussed.

In section II, the charmonium and $XYZ$ meson systems are discussed with emphasis on opportunities
for solving the $XYZ$ puzzle and the discovery of other higher charmonium states. In sections III and
IV, charmed meson & baryon physics, and tau physics are discussed, including the determination of
SM parameters, searches for rare and forbidden decays, and $CP$ violations. In section V, several topics
related for QCD such as $R$-value and Collins effect measurements, the $Q^2$ behavior of baryon form
factors, precision tests of rare/forbidden decays & $CP$ violation in $\eta/\eta'$ and hyperon decays, and studies
of glueballs and hybrids are discussed. In Section VI, the discovery potentials for new, beyond the SM
light particles are provided. Section VII is a summary.

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2 Charmonium and XYZ Physics

2.1 The XYZ puzzles

STCF is an ideal place to study charmonium states and the exotic states containing a $c\bar{c}$ pair. 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 thought to be 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 experiments, including BESIII, BaBar, Belle, CDF, D0, ATLAS, CMS and LHCb (see e.g. Refs. [1, 2, 3, 4, 5, 6, 50, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17] for recent reviews), as shown in Fig. 3 in comparison with the predictions of the Godfrey–Isgur quark model [18]. 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. 3.

- 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, XYZ particles are thus excellent candidates of exotic hadrons, which include hadronic molecules, tetraquarks, hadro-charmonia and hybrids in this context and have been searched for decades.

Within the energy region of STCF and designed luminosity, a huge amount of states with the quantum number $J^{PC} = 1^{−−}$ can be produced. The states with other quantum numbers can be searched in certain decay products. A systematic study of the intriguing XYZ states and related highly excited charmonium states can be performed with the statistics never reached before. With collaborative inputs from theory and lattice QCD, answers to the XYZ puzzles and a deeper understanding of how color confinement organizes the QCD spectrum are foreseen.

2.2 Limitations of current experiments

Most of the XYZ states reported so far, together with their observed production processes and decay modes, are listed in Table 3. There are basically four types of production processes: $e^+e^−$ collisions, including the direct production and the initial state radiation (ISR) processes; $B$ decays with a kaon in the final state; $pp$ 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 have larger rates compared to the photon-photon fusion processes. However, their following aspects need to be improved upon:

- $B \to KX$: The maximum 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
Figure 3: The mass spectrum of charmonia and $XYZ$ states in comparison with the predictions from the Godfrey-Isgur quark model [18].

Charmonium-like state that has been observed is the $X(4700)$. Similarly, the $P_c$ states can hardly be studied in $B$ decays. Additional complexity comes from the fact that these charmonium-like states were all observed as invariant-mass-distribution peaks in final states with two or more hadrons. As a consequence, there are further complications in analyzing the data coming from: 1) resonances from cross channels; 2) possible triangle singularities (see Ref. [17] for a review). 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. 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.
Table 3: 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) [14].

<table>
<thead>
<tr>
<th>XYZ</th>
<th>$J^P(C^P)$</th>
<th>Production processes</th>
<th>Decay modes</th>
</tr>
</thead>
<tbody>
<tr>
<td>X(3872)</td>
<td>0+(1++)</td>
<td>$B \rightarrow KX/K\pi X, e^+e^- \rightarrow \gamma X, p\bar{p}/p\bar{p}$ inclusive</td>
<td>$\pi^+\pi^-J/\psi, \omega J/\psi, D^{\ast0}D^0, J/\psi, \gamma J/\psi(2S)$</td>
</tr>
<tr>
<td>X(3915)</td>
<td>0+(2++ or 2++)</td>
<td>$B \rightarrow KX, \gamma\gamma \rightarrow X$</td>
<td>$\omega J/\psi$</td>
</tr>
<tr>
<td>X(4140)</td>
<td>0+(1++)</td>
<td>$B \rightarrow KX, p\bar{p}$ inclusive</td>
<td>$\phi J/\psi$</td>
</tr>
<tr>
<td>X(4274)</td>
<td>0+(1++)</td>
<td>$B \rightarrow KX$ inclusive</td>
<td>$\phi J/\psi$</td>
</tr>
<tr>
<td>X(4500)</td>
<td>0+(0++)</td>
<td>$B \rightarrow KX$ inclusive</td>
<td>$\phi J/\psi$</td>
</tr>
<tr>
<td>X(3940)</td>
<td>0+(??)</td>
<td>$e^+e^- \rightarrow J/\psi + X$</td>
<td>$DD^*$</td>
</tr>
<tr>
<td>X(4160)</td>
<td>0+(??)</td>
<td>$\gamma\gamma \rightarrow X$</td>
<td>$D^<em>\bar{D}^</em>$</td>
</tr>
<tr>
<td>Y(4008)</td>
<td>0+(?)</td>
<td>$e^+e^- \rightarrow Y$</td>
<td>$\pi\pi J/\psi$</td>
</tr>
<tr>
<td>Y(4260)</td>
<td>0+(?)</td>
<td>$e^+e^- \rightarrow Y$</td>
<td>$\pi\pi J/\psi, D^\ast D^*, \pi, \chi, h, \pi\pi$</td>
</tr>
<tr>
<td>Y(4360)</td>
<td>0+(?)</td>
<td>$e^+e^- \rightarrow Y$</td>
<td>$\pi\pi\psi(2S)$</td>
</tr>
<tr>
<td>Y(4660)</td>
<td>0+(?)</td>
<td>$e^+e^- \rightarrow Y$</td>
<td>$\pi\pi\psi(2S), \Lambda_c \bar{\Lambda}_c$</td>
</tr>
<tr>
<td>Z_0(3900)</td>
<td>1+(1++)</td>
<td>$e^+e^- \rightarrow \pi Z_c$, inclusive b-hadron decays</td>
<td>$\pi J/\psi, DD^*$</td>
</tr>
<tr>
<td>Z_0(4020)</td>
<td>1+(?)</td>
<td>$e^+e^- \rightarrow \pi Z_c$</td>
<td>$\pi h_c, D^<em>\bar{D}^</em>$</td>
</tr>
<tr>
<td>Z_1(4050)</td>
<td>1+(?)</td>
<td>$B \rightarrow KZ_c$</td>
<td>$\pi^\pm\chi_{c1}$</td>
</tr>
<tr>
<td>Z_2(4250)</td>
<td>1+(?)</td>
<td>$B \rightarrow KZ_c$</td>
<td>$\pi^\pm J/\psi, \pi^\pm\psi(2S)$</td>
</tr>
<tr>
<td>Z_0(4200)</td>
<td>1+(1++)</td>
<td>$B \rightarrow KZ_c$</td>
<td>$\pi^\pm J/\psi, \pi^\pm\psi(2S)$</td>
</tr>
<tr>
<td>Z_0(4430)</td>
<td>1+(1++)</td>
<td>$B \rightarrow KZ_c$</td>
<td>$\pi^\pm J/\psi, \pi^\pm\psi(2S)$</td>
</tr>
</tbody>
</table>

2.3 Opportunities in solving the XYZ puzzles

So far no clear pattern emerges for the complicated spectrum of XYZ states. In order to establish a pattern such that the XYZ states can be classified, more measurements are absolutely necessary, including searches 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 [19], 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. These can only be sorted out with observations, which can only be done with enough measurements. For instance, the (0\^{++}, 1\^{++}, 2\^{++}, 1\^{++}) states have 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 decays to 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 the opportunities at the STCF regarding the physics of hidden-charm XYZ states:

- With a luminosity of $0.5 \times 10^{35}$ cm$^{-2}$s$^{-1}$, optimized at $\sqrt{s} = 4$ GeV, 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 $Z_0(3900)$ and $Z_0(4020)$ through...
$e^+e^- \rightarrow \pi^+Z_c^+$ at various c.m. energies. The dependence of the $Z_c$ line shapes and production rates on the c.m. energy is crucial to keep kinematic 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 $E_{cm} \gtrsim 4.7$ GeV, the $J^{++}$ states, $X(3915)$, $\chi_{c0}(3860)$ and $\chi_{c2}(3930)$, can be produced via $e^+e^- \rightarrow \omega X$ transitions which should have much larger rates than the radiative ones.

- At STCF with $E_{cm} \gtrsim 5$ GeV, the $J^{++}$ states observed in the $\phi J/\psi$ invariant mass distributions can be investigated via $e^+e^- \rightarrow \phi X$. 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. In addition to the above mentioned transitions, the processes such as $e^+e^- \rightarrow \eta X$ and so on should also be studied.

- Higher energy of STCF than 5 GeV will be useful for searches of the hadronic transitions to the spin partners of the $Z_c(3900)$ and $Z_c(4020)$ exotic states, named as $W_c$, as well as of conventional but not yet observed charmonium states. The spin partners of the $Z_c$ are similar to those of the $Z_b$ proposed in Ref. [20]. They are isospin vector states with $J^{PC} = 0^{++}$, $1^{++}$ and $2^{++}$, where the $C$ parity is for the charge-neutral state. The neutral ones can decay into $J/\psi \pi^+\pi^-$. The $W_c$ can be studied in $e^+e^- \rightarrow pX$ transitions.

- The lowest charm baryon-antibaryon threshold, $\Lambda_c\bar{\Lambda}_c$, is at 4.57 GeV. The BESIII measurement of the $e^+e^- \rightarrow \Lambda_c\bar{\Lambda}_c$ near-threshold production cross section indicates a state below the $\Lambda_c\bar{\Lambda}_c$ threshold [21, 22], which is the lowest among a wealth of charmed baryon-antibaryon molecules recently predicted [22]; see Fig. 4. With $E_{cm} \gtrsim 5$ 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 $E_{cm} \gtrsim 5$ GeV, hidden-charm pentaquark states can also be studied in processes such as $e^+e^- \rightarrow J/\psi p\bar{p}$ and $e^+e^- \rightarrow \Lambda_c\bar{D}\bar{p}$. 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 $e^+e^- \rightarrow J/\psi p\bar{p}$ between 5 to 7 GeV may be estimated as $\sigma(e^+e^- \rightarrow J/\psi p\bar{p}) = O(4 \text{ fb})$ based on the result of the $e^+e^- \rightarrow J/\psi gg$ cross section estimated using the nonrelativistic QCD (NRQCD) [23]. 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 states 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 $J/\psi N$ [24], 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 $e^+e^- \rightarrow \Lambda_c\bar{D}^(*)\bar{p}$ and $\Sigma_c^*\bar{D}^(*)\bar{p}$. The STCF has a good opportunity to search for hidden-charm $P_c$ pentaquarks.

- For the interpretation of the nature of well-established highly excited charmonium states, detailed measurements of the production rates of the open-charm final states like $D^*(\bar{D}^*)^0$, $D^{\ast\ast}_s\bar{D}_s^{(*)}$, and $D^{(*)}\bar{D}^{(*)}\pi(\pi)$ in the whole energy range of the STCF are necessary. To measure the cross sections of the three independent $D^*\bar{D}^*$ processes, namely, the $P$ wave with total spin $S = 0$, the $P$ wave
Figure 4: The spectrum of hadronic molecules consisting of a pair of charmed-anticharmed hadrons with negative parity and (isospin, strangeness) = (0, 0) predicted in Ref. [22]. The colored rectangle, green for a bound state and orange for a virtual state, covers the uncertainty of the predicted mass. Thresholds are marked by dotted horizontal lines. The rectangle closest to, but below, the threshold corresponds to the hadronic molecule in that system. When the masses of two hadronic molecules overlap, small rectangles are used with the left (right) one for the system with the higher (lower) threshold. The blue line (band) represents the center value (error) of the mass of the \( \psi(4230) \) [14].
with $S = 2$, and the $F$ wave with $S = 2$, studies of angular correlations of the $D^*$ decay products have to be performed.

- Unique physics opportunity with $E_{cm}$ [6, 7] GeV: This energy range offers a unique opportunity to study physics related to the production of two pairs of $c\bar{c}$. The production cross sections for $e^+e^- \rightarrow J/\psi \eta_c$ and $e^+e^- \rightarrow J/\psi c\bar{c}$ from based on the NRQCD calculations in Refs. [25, 26] are at the order of tens of fb, see also Section 5.1.5. In addition to the double-charmonium production which is of its own interest, 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. [27, 28, 29, 30]). While whether the ground state $cc\bar{c}\bar{c}$ is below the double-$J/\psi$ or double-$\eta_c$ 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 [27, 31]. Excited states with a mass well above 6.2 GeV threshold can also easily decay into $J/\psi J/\psi$. The LHCb measurement of the double-$J/\psi$ invariant mass spectrum in semi-inclusive processes of $pp$ collisions shows clear evidence for the existence of such states [32]. Searching for fully-charm tetraquarks in final states other than charged leptons is difficult at hadron colliders due to the huge background, and the STCF is rather unique.

- The charmonium-like hybrid candidates are also important objects to be search for at STCF, among which the most intriguing one is the lowest $1^{--}$ state since the quantum numbers are prohibited for quark-antiquark states and it is expected to be the lowest charmonium-like hybrid from extensive lattice studies. The mass is around 4.1-4.3 GeV. In addition, one expects a hybrid supermultiplet including $(0,1,2)^{++}$ and $1^{---}$ states with nearly degenerate masses around 4.4 GeV [33]. At STCF with $E_{cm}$ $\gtrsim$ 4.5 GeV, the $(0,1,2)^{++}$ states can be produced either from the hadronic and radiative transitions from highly excited charmonia such as $\psi(4S)$ and higher excitations or from the final state radiations in the $e^+e^-$ annihilations. The $Y(4220)$ has a possible assignment of $1^{---}$ charmonium-like hybrid [34], but more experimental and theoretical efforts should be made in order to unravel its nature. At STCF with a much larger luminosity than BEPCII/BESIII, the decay properties of $Y(4220)$ can be measured more precisely and other open-charm decay modes can be searched along with the possible connections between $Y(4220)$, $X(3872)$ and $Z_c(3900)$. It is expected that the status of $Y(4220)$ can be finally determined by STCF.

### 2.4 Opportunities in higher charmonium states

Closely related to the XYZ puzzles, there are also predictions of states from quark model [18] and lattice QCD [33] that have not been identified. Some of them, such as the $2P$ states, certainly intertwine with the $X$ states with the same quantum numbers. There are still missing states that are believed to be relatively clean such as the $1D$ state $\eta_{c2}$ and other higher-$L$ excitations.

The supermultiplet of $1D$ states includes $^{13}D_{1,2,3}$ and $^{11}D_2$ (named $\eta_{c2}$) with the quantum numbers $(1,2,3)^{--}$ and $2^{--}$, respectively. Apart from the well-know $\psi(3770)$, the $2^{--}$ state has been likely observed by Belle [36] and BESIII [37] and is labelled as $\psi_2(3823)$ by PDG2018. Very recently, LHCb reported a candidate for the $^{13}D_3$ state (named $\psi_3$). However, the the spin singlet $1D$ state $\eta_{c2}$ is still escaping from the experimental search. Lattice QCD studies predict the mass of $\eta_{c2}$ is around 3.8 GeV [33, 38], which is nearly degenerate to other $1D$ states. Experimentally, $\eta_{c2}$ can be produced directly from $\psi(4040)$ through the $M1$ transition. If the partial width of $\psi(4040) \rightarrow \gamma \eta_{c2}$ is a few keV, then the corresponding branching fraction is $O(10^{-5})$. Therefore, it is difficult for BESIII to observe $\eta_{c2}$ in this process (the $\psi(4040)$ events at BESIII is $O(10^6)$ [39]). However, STCF with a 100 times larger luminosity has the
possibility to search $\eta_{c2}$. Since it has no open-charm decay modes, the hadronic transitions, such as the
decay modes $\chi_{c1}\pi\pi$ and $J/\psi\pi^0\pi^+\pi^-$, and the E1 radiative transition $\eta_{c2} \rightarrow \gamma h_c$ can be important.

Apart from the spectroscopy, the understanding of the known charmonium states can be greatly improved through more precise measurements of their radiative and hadronic ones [39]. 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
$\eta_c(2S) \rightarrow h_c\gamma$, $\psi(3770) \rightarrow \chi_{c0}\gamma$ and magnetic-dipole transitions $\psi(2S) \rightarrow \eta_c(2S)\gamma$, $\eta_c(2S) \rightarrow J/\psi\gamma$, $h_c \rightarrow \chi_{c0}\gamma$. 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.

A more systematic and comprehensive study of the decays of low-lying charmonia can be performed 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. However, information about their decays is incomplete at present. For the best-studied $J/\psi$ meson only about 40% of its hadronic decays have been measured. For other states the situation is even worse. The high luminosity of STCF will facilitate us to make more precise measurements of the properties of light hadrons from low-lying charmonium decays, and subsequently to acquire a more complete scenario of the low-energy strong interaction.

References

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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 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 $\Lambda_c^+$ baryons, will be an important low-background playground to test the SM and probe new physics. In particular, it will serve as a unique tool to determine the Cabbibo-Kobayashi-Maskawa (CKM) matrix elements $V_{cd}$ and $V_{cs}$, to measure $D^0\bar{D}^0$ mixing parameters, to probe CP violation in the charm sector, to search for rare and forbidden charmed hadron decays, and to study other fundamental problems associated with the charmed hadron. Many of the golden measurements at STCF will be dominated by systematic uncertainties, which requires a state-of-art detector with excellent performance, especially in identifying the types of different charged particles, detecting low-momentum charged particles and measuring photons.

3.1 Charmed meson

3.1.1 $D_{s(0)}^+$ leptonic decays

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

Table 4: For the studies on $D_{s(0)}^+ \to \ell^+\nu\ell$, the obtained precisions at BESIII and projected precisions at STCF and Belle II. Considering that the LQCD uncertainty of $f_{D_s^+}$ has been updated to be about 0.2% [11], the $|V_{cd}|$ measured at BESIII has been re-calculated, and is marked with †. Preliminary results are marked with †. For Belle II, we assume that the systematic uncertainties can be reduced by a factor of 2 compared to Belle’s results.

<table>
<thead>
<tr>
<th></th>
<th>BESIII</th>
<th>STCF</th>
<th>Belle II</th>
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<tbody>
<tr>
<td>Luminosity</td>
<td></td>
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<tr>
<td>$B(D^+ \to \mu^+\nu)$</td>
<td>2.93 fb$^{-1}$ at 3.773 GeV</td>
<td>1 ab$^{-1}$ at 3.773 GeV</td>
<td>50 ab$^{-1}$ at $\Upsilon(nS)$</td>
</tr>
<tr>
<td>$f_{D^+}$ (MeV)</td>
<td>5.1%stat 1.6%syst [8]</td>
<td>0.28%stat</td>
<td>–</td>
</tr>
<tr>
<td>$</td>
<td>V_{cd}</td>
<td>$</td>
<td>2.6%stat 0.9%syst [8]</td>
</tr>
<tr>
<td>$B(D^+ \to \tau^+\nu\tau)$</td>
<td>20%stat 10%syst [9]</td>
<td>0.41%stat</td>
<td>–</td>
</tr>
<tr>
<td>$B(D^+ \to \mu^+\nu)$</td>
<td>21%stat 13%syst [9]</td>
<td>0.50%stat</td>
<td>–</td>
</tr>
</tbody>
</table>

|                        |        |      |          |
| $B(D_{s}^+ \to \mu^+\nu\mu)$ | 3.2 fb$^{-1}$ at 4.178 GeV | 1 ab$^{-1}$ at 4.009 GeV | 50 ab$^{-1}$ at $\Upsilon(nS)$ |
| $f_{D_s^+}$ (MeV)        | 2.8%stat 2.7%syst [10] | 0.30%stat | 0.8%stat 1.8%syst |
| $|V_{cs}|$              | 1.5%stat 1.6%syst [10] | 0.15%stat | – |
| $f_{D_s^+}/f_{D^+}$      | 1.5%stat 1.6%syst [10] | 0.15%stat | – |
| $B(D_s^+ \to \tau^+\nu\tau)$ | 2.2%stat 2.6%m[†yst | 0.24%stat | 0.6%stat 2.7%syst |
| $f_{D_s^+}$ (MeV)        | 1.1%stat 1.5%m[†yst | 0.11%stat | – |
| $|V_{cs}|$              | 1.1%stat 1.5%m[†yst | 0.11%stat | – |
| $f_{D_s^{(s)\tau}}$ (MeV) | 0.9%stat 1.0%m[†yst | 0.09%stat | 0.3%stat 1.0%syst |
| $|\tau_{c\bar{s}}^{D_s^{(s)\tau}}|$ | 0.9%stat 1.0%m[†yst | 0.09%stat | – |
| $B(D_s^+ \to \tau^+\nu\tau)$ | 3.6%stat 3.0%m[†yst | 0.38%stat | 0.9%stat 3.2%syst |

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The most precise way to determine $|V_{cd}|$ and $|V_{cd}|$ at STCF is via pure-leptonic decays $D_{(s)}^+ \to \ell^+ \nu_\ell$ (for $\ell = e, \mu, \tau$), as the semi-leptonic decay suffers from large uncertainties of LQCD calculations of form factors. The product of the decay constant $f_{D_{(s)}^+}$ and $|V_{cd(s)}|$ is directly accessed by measuring the widths of $D_{(s)}^+ \to \ell^+ \nu_\ell$. Then with the input of $f_{D_{(s)}^+}$ from LQCD, the value of $|V_{cd(s)}|$ or $f_{D_{(s)}^+}$ can be obtained. Listed in Table 4 are the most precise determinations of $|V_{cd(s)}|$ and $f_{D_{(s)}^+}$ [8, 9, 10] at BESIII and the projected precisions at STCF. Note that for $B(D^+ \to \tau^+ \nu_\tau)$, several $\tau^+$ decay channels, such as $\tau^+ \to \pi^+ \nu_\tau, e^+ \nu_\tau \nu_e, \mu^+ \nu_\tau \nu_\mu$, and $\rho^+ \nu_\tau$, are combined to improve statistical sensitivities.

The systematic uncertainties at STCF are to be optimized to a subleading level, as the statistical uncertainties are expected to be less than 0.5%. To reduce the systematic uncertainty due to background and fitting, it becomes optimal for STCF to study $D_{(s)}^+ \to \ell^+ \nu_\ell$ using $e^+e^- \to D_{(s)}^+D_{(s)}^-$ at 4.009 GeV. So far, $f_{D_{(s)}^+}$ are calculated by LQCD with precisions of about 0.2% [11], which are given as $f_{D_{(s)}^+} = 212.7 \pm 0.6$ MeV, $f_{D_{(s)}^+} = 249.9 \pm 0.4$ MeV and $f_{D_{(s)}^+}/f_{D_{(s)}^+} = 1.1749 \pm 0.0016$. At the time of STCF, their precisions are expected to be below 0.1%. This means that the sizes of systematic uncertainties at STCF are crucial and necessary to be improved to the level of 0.1%. Among them, the efficiencies of muon and electron identifications will be the critical issues, which is required to be optimized in order to constrain the total uncertainty to the level of 0.1%.

On the other hand, the precise measurements of the semi-leptonic branching fractions for $D_{(s)}^+ \to h\ell^+ \nu_\ell$, where $h$ is a charmless hadron, will be used to calibrate LQCD calculations of the involved form factors, by introducing the $\{V_{cd(s)}\}$ from global CKM fits (such as CKMfitter [2, 3] and UTfit [4, 5]). For the case of $D_{(s)}^+ \to V(h_1h_2)e^+\nu_\ell$ ($V$ denotes a vector meson, decaying into hadrons $h_1$ and $h_2$), a time reversal (T) invariance can be tested in high precision by constructing triple product T-odd observables [6]. This will serve as a sensitive probe of CP violation mechanisms beyond standard model and new physics [7], such as those with multi-Higgs doublets or leptoquarks.

Lepton flavor universality (LFU) can also be tested in charged meson 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 [12]. 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

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

Using the world average values of the masses of leptons and $D_{(s)}^+$ [1], one obtains $R_{D^+} = 2.67 \pm 0.01$ and $R_{D^+} = 9.75 \pm 0.01$. The preliminary measured value of $R_{D^+}$ reported by BESIII is $3.21 \pm 0.64$ (10.2 \pm 0.5), which agrees with the SM predicted values. However, these measurements are currently statistically limited. At STCF, as listed in Table 4, the statistical precision on $R_{D^+}$ will be comparable to the uncertainties of the predictions in the SM. Hence, it will provide meaningful test on LFU via these channels.

Another LFU test would be via the semi-leptonic decay modes, where the semi-tauonic decay is kinematically forbidden or suppressed. Measurements of the ratios of the partial widths of $D_{(s)}^{0(k)} \to h\mu^+ \nu_\mu$ over those of $D_{(s)}^{0(k)} \to h\nu_\ell$ in different $q^2$ intervals constitute a complementary test of LFU to those using tauonic decays. BESIII reported precise measurements of the ratios $B(D^0 \to \pi^0 \mu^+ \nu_\mu)/B(D^0 \to \pi^- e^+ \nu_e) = 0.922 \pm 0.030 \pm 0.022$ and $B(D^+ \to \pi^0 \mu^+ \nu_\mu)/B(D^+ \to \pi^0 e^+ \nu_e) = 0.964 \pm 0.037 \pm 0.026$ [13]. These results are consistent with the SM predictions, within $1.7\sigma$ and $0.5\sigma$ [13], respectively. These measurements are currently statistically limited [14, 13], and will be significantly improved with 1 $ab^{-1}$

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of data taken at the center-of-mass energy of 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. Contrary to B-meson and Kaon systems, CP-violation in mixing of $D$-mesons has not been observed. STCF will be an ideal place for the study of $D^0$-$\bar{D}^0$ mixing and CP-violation. By convention the mass states of two neutral $D$ mesons are written as

$$|D_1\rangle = p|D^0\rangle + q|\bar{D}^0\rangle,$$

$$|D_2\rangle = p|\bar{D}^0\rangle - q|D^0\rangle,$$

where $|p|^2 + |q|^2 = 1$. The $D^0$-$\bar{D}^0$ mixing parameters are defined by $x \equiv (M_2 - M_1)/\Gamma$ and $y \equiv (\Gamma_2 - \Gamma_1)/(2\Gamma)$, where $M_{1,2}$ and $\Gamma_{1,2}$ are the masses and widths of $D_{1,2}$, respectively. Also $\Gamma \equiv (\Gamma_1 + \Gamma_2)/2$ and $M \equiv (M_1 + M_2)/2$. This system is unique because it is the only meson-antimeson system whose mixing (or oscillation) takes place via the intermediate states with down-type quarks. It is also the only meson-antimeson system whose mixing parameters $x$ and $y$ are notoriously hard to calculate in the SM, as those involve large long-distance uncertainties in this nonperturbative regime. One expects $x \sim y \sim \sin^2 \theta_C \times [SU(3)\text{ breaking}]^2$ 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 $10^{-3} < |x| < 10^{-2}$ [17]. A global fit to the world measurements of $x$ and $y$, carried out by the Heavy Flavor Averaging Group [18, 19], gives $1.6 \times 10^{-3} \lesssim x \lesssim 6.1 \times 10^{-3}$ and $5.2 \times 10^{-3} \lesssim y \lesssim 7.9 \times 10^{-3}$ at the 95% confidence-level intervals [18, 19]. We see that the allowed region of $x$ and $y$ are essentially consistent with the theoretical estimates (i.e., $x \lesssim y \sim 7 \times 10^{-3}$). Much more precise measurements of these two $D^0$-$\bar{D}^0$ mixing parameters can be achieved at STCF. While their accurate values might not help much to clarify the long-distance effects in $D^0$-$\bar{D}^0$ mixing, they will help a lot to probe the presumably small effects of CP violation in neutral $D$-meson decays and mixing [20].

The charm sector is a precision laboratory to explore possible CP-violating new physics, because the SM-induced CP violating asymmetries in $D$-meson decays are typically in the range from $10^{-4}$ to $10^{-3}$ [21] and are very challenging to be detected in experiment. The CP-violating asymmetries in the singly Cabibbo-suppressed $D$-meson decays are now expected to be much larger than those in the Cabibbo-favored and doubly Cabibbo-suppressed decays [20], where such asymmetries vanish. There are in general three different types of CP-violating effects in neutral and charged $D$-meson decays [22]: 1) CP violation in $D^0$-$\bar{D}^0$ mixing; 2) CP violation in the direct decay; 3) CP violation from the interplay of decay and mixing. Besides these three types of CP-violating effects in $D$-meson decays, one may expect the effect of CP violation induced by $K^0$-$\bar{K}^0$ mixing in some decay modes with $K_S$ or $K_L$ in their final states. Its magnitude is typically $2\text{Re}(\epsilon_K) \approx 3.3 \times 10^{-3}$, which may be comparable with or even larger than the charmed CP-violating effects [23, 24]. 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 5.3$\sigma$. The time-integrated CP-violating asymmetry is given as

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

where $D(\bar{D})$ is a $D^0(\bar{D}^0)$ at time $t=0$ [52], and it mainly arises from direct CP violation in the charm-quark decay [26]. This result is consistent with some theoretical estimates within the SM (see, e.g., April 12, 2021 – 11:51 26}
Refs. [27, 28, 29, 30, 31, 32, 33, 34]), 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 [35], such as 4-body hadronic decays and therein CP asymmetries in local Dalitz region. As the CKM mechanism of CP violation in the SM fails to explain the puzzle of the observed matter-antimatter asymmetry in the Universe by more than 10 orders of magnitude [36], it is well motivated to search for new (heretofore undiscovered) sources of CP violation associated with both quark and lepton flavors. In this connection the charm-quark sector is certainly a promising playground.

Note that STCF will be a unique place for the study of D^0-\bar{D}^0 mixing and CP violation by means of quantum coherence of D^0 and \bar{D}^0 mesons produced at the energy points near threshold. In fact, a D^0-\bar{D}^0 pair can be coherently produced through reactions e^+e^- \rightarrow (D^0\bar{D}^0)_{CP=-} at 3.773 GeV and e^+e^- \rightarrow D^0\bar{D}^{*0} \rightarrow \pi^0(D^0\bar{D}^0)_{CP=-} or \gamma(D^0\bar{D}^0)_{CP=+} at 4.009 GeV. One may therefore obtain useful constraints on D^0-\bar{D}^0 mixing and CP-violating parameters in the respective decays of correlated D^0 and \bar{D}^0 events [22]. 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^+\pi^-)(K^+\pi^-) or (K^0\bar{\pi}^0)(K^0\bar{\pi}^0) with a sensitivity of 10^{-5} with 1 ab^{-1} data at 3.773 GeV. Considering e^+e^- \rightarrow \gamma D^0\bar{D}^0 at 4.009 GeV, D^0\bar{D}^0 pairs are in C-even states and charm mixing contribution is doubled as compared with the time-dependent (un-correlated) case. With 1 ab^{-1} data at 4.009 GeV, it is expected that the measurement sensitivities of the mixing parameters (x, y) will reach a level of 0.05%, and those of |q/p| and arg(q/p) will be 1.5% and 1.4°, respectively [37]. Another case is that the decay mode (D^0\bar{D}^0)_{CP=\pm} \rightarrow (f_1f_2)_{CP=\mp}, where f_1 and f_2 are proper CP eigenstates (e.g., π^+π^-, K^+K^- and K_Sπ^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_+ = π^+π^-) can be expressed as

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

where \phi = \arg(p/q), R_M = |p/q|, and a_m = \log R_M [38].

CPT is conserved in all local Lorentz-invariant theories, which includes the SM and its all commonly-discussed extensions. 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 [39]. 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 [40]. However, this becomes very challenging with symmetric e^+e^- collisions, as the produced D mesons have very low momentum in the laboratory frame, and hence have too small flight distances to be detected. Only asymmetric e^+e^- collision mode can be feasible for this topic.

The quantum correlation of the D^0-\bar{D}^0 meson pair has a unique feature to probe the amplitudes of the D^0 decays and determine the strong-phase difference between their Cabibbo-favored and doubly Cabibbo-suppressed amplitudes. 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 \gamma 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) [18].

The measurements of the CKM unitary triangle (UT) angles \alpha, \beta, and \gamma in B decays are important tests of the CKM unitarity and search for possible CP violation beyond the SM. Any discrepancy in the measurements of the UT involving tree- and loop-dominated processes would indicate the existence of heavy new degrees of freedom contributing to the loops. Among the three CKM angles, \gamma is of particular importance because it is the only CP-violating observable that can be determined using tree-level decays.

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Currently the world-best single measurement of $\gamma$ is from LHCb: $\gamma = (69 \pm 5)\degree$ [41]. The precision measurement of $\gamma$ will be one of the top priorities for the LHCb upgrade(s) and Belle II experiments.

The most precise method to measure $\gamma$ is based upon the interference between $B^+ \to \bar{B}^0 K^+$ and $B^+ \to D^0 K^+$ decays [42, 43, 44]. 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 $\sim 0.4\degree$ for the $\gamma$ measurement [45]. 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 $\gamma$ results from different decay modes.

### 3.1.3 Rare and forbidden decays

With high luminosity, clean collision environment and excellent detector performance, STCF has great potential to perform searches for rare and forbidden $D$-meson decays, which may serve as a useful tool for probing new physics beyond the SM. They can be classified into three categories: (1) decays via the flavor-changing neutral current (FCNC), such as $D^{(*)} \to \gamma V_{0\ell\ell}$, $D^0 \to \gamma\gamma$, $D^0 \to \ell^+\ell^-$, $D \to \ell^+\ell^-X$ 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 $\mathcal{B}(D^0 \to \mu^+\mu^-) < 6.2 \times 10^{-9}$ [1]. However, the following semi-leptonic decays of $D^0 \to \pi^\pm\pi^0\mu^+\mu^-$, $K^+K^-\mu^+\mu^-$ and $K^-\pi^+\mu^+\mu^-$ have been observed at LHCb with the BF level of $10^{-5}$ [1]. Besides the removal of helicity suppression as dominates the highly suppressed BF for $D^0 \to \mu^+\mu^-$, the observed BFs for the semi-leptonic decays indicate non-trivial contributions from complicated long-distance effects. At STCF, it is more optimal to study the di-electron modes $D \to e^+e^-X$ [48], which provide sensitivities of $10^{-8} \sim 10^{-9}$ for $m_{\nu\ell}c$ in the range less polluted by the long-range resonance contributions. Compared to Belle II and LHCb, STCF has competitive sensitivities in the channels which contains neutral final states, such as photon and $\pi^0$, because of clean backgrounds. Furthermore, STCF has advantage to best constrain the upper limit of BF for $D$ rare decays with neutrinos, such as $D^0 \to \pi^0\nu\bar{\nu}$ and $D^0 \to \gamma\gamma\bar{\nu}$.

No evidence has been found for the forbidden $D_{s(s)}$-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 $\mathcal{B}(D^0 \to \mu^+e^-) < 1.3 \times 10^{-8}$) [1]. 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.
3.1.4 Charmed meson spectroscopy

STCF will also act as a good playground to study the production of charmed mesons and explore the charmed meson spectroscopy. So far, all the 1S and 1P $D_{s1}$ 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 $D^{s*}(2632)$ state is observed by SELEX, but CLEO, BaBar and FOCUS all reported negative search results. The unexpected low masses of the $D^{s_0}(2317)$ and $D^{s_1}(2460)$ bring in various exotic explanations, such as $D^{(*)}K$ molecule state [50]. It has been claimed that the strong $S$-wave $D^{(*)}K$ scattering contributes to the mass drop. More systematic researches on the open-charm meson spectroscopy are highly desired.

At STCF, excited charmed meson states $D^{++}$ can be produced via direct $e^+e^-$ production processes, such as $e^+e^- \rightarrow D^{(*)}D^{(*)}(\pi)$, in the energy range from 4.1 to 7.0 GeV. Then, the higher excited open-charm states can be studied through their hadronic or radiative decays [55] to lower open-charm states. Systematical studies at STCF on the open-charm meson spectra provide important data to explore the non-perturbative QCD dynamics in the charm regime and test various theoretical models.

3.2 Charmed baryon

Theoretical interest in hadronic weak decays of charmed baryons peaked around the early 1990s and then faded away. Nevertheless, there are two major breakthroughs in recent charmed-baryon experiments in regard to hadronic weak decays of $\Lambda_c^+$. 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.

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 $e^+e^- \rightarrow c\bar{c}$ continuum are both very rich sources of charmed baryons. Many efforts have been made to identify the quantum numbers of these new states and understand their properties.

3.2.1 Hadronic weak decays

- Nonleptonic decays of singly charmed baryons

$\Lambda_c$ decays

The branching fractions of the Cabibbo-allowed two-body decays of $\Lambda_c^+$ 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 [58] and BESIII [59] have measured the absolute branching fraction of the decay $\Lambda_c^+ \rightarrow pK^-\pi^+$. A new average of $(6.28 \pm 0.32)\%$ for this benchmark mode is quoted by the PDG [1]. Doubly Cabibbo-suppressed decay $\Lambda_c^+ \rightarrow pK^+\pi^-$ has been observed by Belle [60] and LHCb [61]. It is thus important to search for the two-body modes which are doubly Cabibbo-suppressed: $pK^{(*)}$ and $nK^{(*)}$.

Various theoretical approaches to weak decays of heavy baryons have been investigated, including the current algebra approach, factorization scheme, pole model, relativistic quark model, quark diagram scheme and SU(3) flavor symmetry. In general, the predicted decay rates by most of the
Table 5: The measured branching fractions of the Cabibbo-allowed two-body decays of $\Lambda_c^+$ (in units of %) taken from 2020 Particle Data Group [1]. We have included the new BESIII measurements of $\Lambda_c^+ \to \Sigma^+\eta, \Sigma^+\eta, \Sigma^+\eta$ [56, 57].

<table>
<thead>
<tr>
<th>Decay</th>
<th>$B$</th>
<th>Decay</th>
<th>$B$</th>
<th>Decay</th>
<th>$B$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Lambda_c^+ \to \Lambda\pi^+$</td>
<td>1.30±0.07</td>
<td>$\Lambda_c^+ \to \Lambda\rho^+$</td>
<td>&lt; 6</td>
<td>$\Lambda_c^+ \to \Delta^{++}\bar{K}^-$</td>
<td>1.08 ± 0.25</td>
</tr>
<tr>
<td>$\Lambda_c^+ \to \Sigma^0\pi^+$</td>
<td>1.29±0.07</td>
<td>$\Lambda_c^+ \to \Sigma^0\rho^+$</td>
<td></td>
<td>$\Lambda_c^+ \to \Sigma^0\pi^0$</td>
<td></td>
</tr>
<tr>
<td>$\Lambda_c^+ \to \Sigma^+\pi^0$</td>
<td>1.25±0.10</td>
<td>$\Lambda_c^+ \to \Sigma^+\rho^0$</td>
<td>&lt; 1.7</td>
<td>$\Lambda_c^+ \to \Sigma^+\pi^0$</td>
<td></td>
</tr>
<tr>
<td>$\Lambda_c^+ \to \Sigma^0\eta'$</td>
<td>0.53±0.15</td>
<td>$\Lambda_c^+ \to \Sigma^0\omega$</td>
<td>1.70±0.21</td>
<td>$\Lambda_c^+ \to \Sigma^0\eta$</td>
<td>0.96 ± 0.17</td>
</tr>
<tr>
<td>$\Lambda_c^+ \to \Sigma^+\eta'$</td>
<td>1.34±0.57</td>
<td>$\Lambda_c^+ \to \Sigma^+\phi$</td>
<td>0.38±0.06</td>
<td>$\Lambda_c^+ \to \Sigma^+\eta'$</td>
<td></td>
</tr>
<tr>
<td>$\Lambda_c^+ \to \Xi^0K^+$</td>
<td>0.55±0.07</td>
<td>$\Lambda_c^+ \to \Xi^0K^{++}$</td>
<td></td>
<td>$\Lambda_c^+ \to \Xi^0K^+$</td>
<td>0.43±0.09</td>
</tr>
<tr>
<td>$\Lambda_c^+ \to pK_S$</td>
<td>1.59±0.08</td>
<td>$\Lambda_c^+ \to pK_S$</td>
<td>1.96±0.27</td>
<td>$\Lambda_c^+ \to \Delta^+K^0$</td>
<td></td>
</tr>
</tbody>
</table>

models except current algebra are below experimental measurements. Moreover, the decay asymmetries of the two-body hadronic weak decays of charmed baryons can be investigated, which are defined as $\alpha \equiv \frac{2\text{Re}(s'p)}{|s|^2+|p|^2}$. Here $s$ and $p$ stand for the parity-violating $s$-wave and parity-conserving $p$-wave amplitudes in the decay, respectively. The pole model, the covariant quark model and its variant all predict a positive decay asymmetry $\alpha$ 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 $\Sigma^0\pi^0$ by CLEO [62]. In contrast, current algebra always leads to a negative decay asymmetry for aforementioned two modes: $-0.49$ in [63], $-0.31$ in [64], $-0.76$ in [65] and $-0.47$ in [66]. The issue with the sign of $\alpha_{\Sigma^+,\pi^0}$ was finally resolved by BESIII. The decay asymmetry parameters of $\Lambda_c^+ \to \Lambda\pi^+, \Sigma^0\pi^+, \Sigma^0\pi^0$ and $pK_S$ were recently measured by BESIII [67], for example, $\alpha_{\Sigma^+,\pi^0} = -0.57 \pm 0.12$ was obtained. Hence, the negative sign of $\alpha_{\Sigma^+,\pi^0}$ measured by CLEO is confirmed by BESIII.

$\Xi_c$ and $\Omega_c$ decays

The absolute branching fractions of $\Xi_c^0 \to \Xi^0\pi^+$ and $\Xi_c^+ \to \Xi^+\pi^+\pi^+$ were recently measured by Belle [68, 69] to be

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

With these measurements, branching fractions of other $\Xi_c^0$ and $\Xi_c^+$ decays can be inferred. No absolute branching fractions have been measured for the $\Omega_c^0$. The hadronic weak decays of the $\Omega_c^0$ were recently studied in great detail in [70], where most of the decay channels in $\Omega_c^0$ decays were found to proceed only through the $W$-exchange diagram.

It is conceivable that nonleptonic decay modes of $\Lambda_c^+$ and $\Xi_c^{+,0}$ can be measured at STCF with significantly improved precision. Priority will be ascribed to the decay asymmetries $\alpha$ in various charm baryon decays and the absolute branching fractions of $\Omega_c^0$ 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 $\Xi_c \to \Lambda\pi$ and $\Omega_c \to \Xi^0\pi$. 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.
The electromagnetic decays of interest in the charmed baryon sector are: (i) $\Sigma^0 \to \Lambda^+_c\pi^-$ and $\Xi^+_c \to \Lambda^+_c\pi^0$ are of the order of $10^{-3} \sim 10^{-4}$ [71]. Very recently, the first measurement of the charm-flavor-conserving decay $\Xi^0 \to \Lambda^+_c\pi^-$ has been achieved by the LHCb with the branching fraction $(0.55 \pm 0.02 \pm 0.18)\%$ [72], which is in general larger than the theoretical predictions.

STCF should be able to cross-check this and search for another c-flavor-conserving weak decay, namely, $\Xi^+_c \to \Lambda^+_c\pi^0$.

- Semileptonic decays

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

$$
\langle B_i(p_f)|V_{\mu\nu}|B_c(p_i)\rangle = \bar{u}_f(p_f)[f_1(q^2)\gamma_\mu + if_2(q^2)\sigma_{\mu\nu}q^\nu + f_3(q^2)q_\mu]u_i(p_i),
$$

$$
\langle B_f(p_f)|A_\mu|B_c(p_i)\rangle = \bar{u}_f(p_f)g_1(q^2)\gamma_\mu + ig_2(q^2)\sigma_{\mu\nu}q^\nu + g_3(q^2)q_\mu\gamma_5u_i(p_i).
$$

These form factors have been evaluated using the non-relativistic quark model [73, 74, 75, 76], MIT bag model [73], relativistic quark model [77, 78, 79], light-front quark model [80], QCD sum rules [81, 82, 83] and lattice QCD [84, 85]. Many of the early predictions of $B(\Lambda^+_c \to \Lambda e^+\nu_e)$ are smaller than the first measurement of the absolute branching fraction of $(3.6 \pm 0.4)\%$ by BESIII [86]. Lattice QCD calculations in [84] yield good agreement with experiment for both $\Lambda^+_c \to \Lambda e^+\nu_e$ and $\Lambda^+_c \to \Lambda\mu^+\nu_\mu$. Needless to say, the semileptonic decays of $\Lambda^+_c$ (including the yet-to-be-observed $\Lambda^+_c \to n e^+\nu_e$), $\Xi^+_{c,0}$ and $\Omega^0_{c,0}$ will be thoroughly studied at STCF, which can be used to discriminate between different form-factor models.

### 3.2.2 Electromagnetic and weak radiative decays

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

The calculated results of [87, 88], [89] and [90] 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 that all HHChPT approaches should agree with each other to the lowest order of chiral expansion provided that the coefficients are inferred from the nonrelativistic quark model. This issue can be clarified by STCF through the measurement of these decay rates.
Very recently, Belle has observed the electromagnetic decays of orbitally excited charmed baryons \( \Xi_c(2790) \) and \( \Xi_c(2815) \) for the first time [91]. The partial widths of \( \Xi_c(2815)^0 \rightarrow \Xi_c^0\gamma \) and \( \Xi_c(2790)^0 \rightarrow \Xi_c^0\gamma \) are measured to be \( 320 \pm 45^{+45}_{-80} \) keV and \( \sim 800 \) keV, respectively. However, no signal was found for the analogous decays of \( \Xi_c(2815)^+ \) and \( \Xi_c(2790)^+ \).

Weak radiative decays such as \( \Lambda_c^+ \rightarrow \Sigma^0\gamma \) and \( \Lambda_c^+ \rightarrow p\gamma \) can proceed through the bremsstrahlung processes \( cd \rightarrow usy \) (Cabibbo-allowed) and \( cd \rightarrow udy \) (Cabibbo-suppressed), respectively. The branching fraction of the former was estimated to be of order \( 10^{-4} \) [92].

### 3.2.3 CP violation

The CKM matrix contains a phase which implies the existence of CP violation. This means CP-violation can be studied with baryons as well. The predicted CP-violating asymmetries are, however, small for charmed baryons. The search for CP violation in charmed baryon decays has taken on new momentum with the large samples of \( \Lambda_c \) obtained by BESIII and LHCb. For two-body decays of the \( \Lambda_c^+ \), CP violation can be explored through the measurement of CP-violating asymmetry, \( A = (a + \bar{a})/(a - \bar{a}) \), which corresponds to the asymmetry of \( a \) for the \( \Lambda_c^+ \) decays and \( \bar{a} \) for \( \bar{\Lambda}_c^- \) decays. For example, \( A \) in \( \Lambda_c^+ \rightarrow \Lambda\pi^+ \) and \( \bar{\Lambda}_c^- \rightarrow \bar{\Lambda}\pi^- \) was measured by FOCUS to be \( -0.07 \pm 0.19 \pm 0.24 \) [93]. In STCF, much more sensitive searches for CP violation will be carried out by combining the single tag \( \Lambda_c^+ \) data [94] and double tag \( \Lambda_c^+\bar{\Lambda}_c^- \) data, where the pairs of \( \Lambda_c^+\bar{\Lambda}_c^- \) are quantum-correlated regarding to their spins aligned to the initial spins of the virtual photons. Especially, with polarized beams [95], unique advantage of enhanced sensitivities on the decay asymmetries and the CP violations can be achieved with prior knowledge of the spin direction of the produced \( \Lambda_c^+ \). As for three-body decays, LHCb has measured \( \Delta A_{\text{CP}} \) as the difference between CP asymmetries in \( \Lambda_c^+ \rightarrow pK^+K^- \) and \( \Lambda_c^+ \rightarrow p\pi^+\pi^- \) decay channels. The result is \( \Delta A_{\text{CP}} = (0.30 \pm 0.91 \pm 0.61)\% \) [96], to be compared with a generic SM prediction of a fraction of \( 0.1\% \) [97]. In order to probe the SM contribution to such asymmetries, one has to increase the available statistics by at least a factor of 100.

For multi-hadrons in the final state of \( \Lambda_c^+ \) decays such as \( \Lambda_c^+ \rightarrow pK^+\pi^0 \), \( \Lambda_c^+ \rightarrow \Lambda\pi^+\pi^- \) and \( \Lambda_c^+ \rightarrow pK_S\pi^+\pi^- \), CP violation can be exploited through several T-odd observables. Owing to its characters of high luminosity, broad center-of-mass energy acceptance, abundant production and clean environment, STCF will provide a great platform for this kind of study. A fast Monte Carlo simulation [98] of 1 ab\(^{-1}\) \( e^+e^- \) annihilation data at \( \sqrt{s} = 4.64 \) GeV, which are expected to be available at the future STCF, indicates that a sensitivity at the level of \( (0.25-0.5)\% \) is accessible for the above-mentioned three decay modes. This will be enough to measure non-zero CP-violating asymmetries as large as \( 1\% \).

### 3.2.4 Spectroscopy

The observed antitriplet and sextet states of charmed baryons are listed in Table 7. By now, the \( J^P = \frac{1}{2}^+, \frac{1}{2}^-, \frac{3}{2}^+ \) and \( \frac{3}{2}^+ \) antitriplet states \( \Lambda_c, \Xi_c \) and \( J^P = \frac{1}{2}^+, \frac{3}{2}^+ \) sextet states \( \Omega_c, \bar{\Xi}_c, \bar{\Sigma}_c \) are established. The highest state \( \Lambda_c(2940)^+ \) in the \( \Lambda_c \) family was first discovered by BaBar in the \( D^0\bar{p} \) decay mode [99] but its spin-parity assignment is quite diverse (see [100] for a review). The constraints on its spin and parity were recently found to be \( J^P = \frac{3}{2}^+ \) by LHCb [101]. It was suggested in [102] that the quantum numbers of \( \Lambda_c(2940)^+ \) are most likely \( \frac{1}{2}^+ (2P) \) based on the Regge analysis. However, it was argued in [105] that \( \Lambda_c(2940)^+ \) is a \( \frac{3}{2}^- (2P) \) state and there is a state \( \frac{1}{2}^- (2P) \) higher than the \( \Lambda_c(2P, 3/2^-) \). This issue can be clarified by STCF.

In 2017 LHCb has explored the charmed baryon sector of the \( \Omega_c \) and observed five narrow excited \( \Omega_c \) states decaying into \( \Xi_c^0 K^- \): \( \Omega_c(3000), \Omega_c(3050), \Omega_c(3066), \Omega_c(3090) \) and \( \Omega_c(3119) \) [103]. Except
Table 7: Antitriplet and sextet states of charmed baryons. Mass differences $\Delta m_{\Xi_c,\Lambda_c} \equiv m_{\Xi_c} - m_{\Lambda_c}$, $\Delta m_{\Omega_c,\Sigma_c} \equiv m_{\Omega_c} - m_{\Sigma_c}$ are all in units of MeV.

<table>
<thead>
<tr>
<th>$J^P(nL)$</th>
<th>States</th>
<th>Mass difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>$\Lambda_c(2287)^+, \Xi_c(2470)^+, \Xi_c(2470)^0$</td>
<td>$\Delta m_{\Xi_c,\Lambda_c} = 183$</td>
</tr>
<tr>
<td></td>
<td>$\Lambda_c(2595)^+, \Xi_c(2790)^+, \Xi_c(2790)^0$</td>
<td>$\Delta m_{\Xi_c,\Lambda_c} = 198$</td>
</tr>
<tr>
<td></td>
<td>$\Lambda_c(2625)^+, \Xi_c(2815)^+, \Xi_c(2815)^0$</td>
<td>$\Delta m_{\Xi_c,\Lambda_c} = 190$</td>
</tr>
<tr>
<td></td>
<td>$\Lambda_c(2860)^+, \Xi_c(3055)^+, \Xi_c(3055)^0$</td>
<td>$\Delta m_{\Xi_c,\Lambda_c} = 201$</td>
</tr>
<tr>
<td></td>
<td>$\Lambda_c(2880)^+, \Xi_c(3080)^+, \Xi_c(3080)^0$</td>
<td>$\Delta m_{\Xi_c,\Lambda_c} = 196$</td>
</tr>
<tr>
<td>6</td>
<td>$\Omega_c(2695)^0, \Xi_c(2575)^{++}, \Sigma_c(2520)^{++}$</td>
<td>$\Delta m_{\Omega_c,\Xi_c} = 119, \Delta m_{\Xi_c,\Sigma_c} = 124$</td>
</tr>
<tr>
<td></td>
<td>$\Omega_c(2770)^0, \Xi_c(2645)^{+}, \Sigma_c(2520)^{++}$</td>
<td>$\Delta m_{\Omega_c,\Xi_c} = 120, \Delta m_{\Xi_c,\Sigma_c} = 128$</td>
</tr>
</tbody>
</table>

$\Omega_c(3119)$, the first four states were also confirmed by Belle later [104]. This has triggered a lot of interest in possible identification of their spin-parity quantum numbers.

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

References

4 Tau Physics

At STCF, as many as $7.0 \times 10^9$ per year at $\sqrt{s} = 4.26$ GeV $\tau^+\tau^-$ pairs can be produced, which is about 3 orders of magnitude higher than currently accumulated $\tau^+\tau^-$ events at BES III. At the production threshold there could be as many as $10^8 \tau^+\tau^-$ events 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 LHCb and Belle II $\tau$ physics studies. In the energy range covered by STCF, one can also have a good control of polarizations of the $e^+$ and $e^-$ beams to extract new information about $\tau$. STCF will tremendously increase the statistical significance for $\tau$-related physics studies and will reach a precision level which has never been achieved before.

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

4.1 Precision Measurement of the $\tau$ Properties

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

4.1.1 $\tau$ mass and lifetime

Many of the tests for the SM and beyond involve precise measurements of the $\tau$ mass $m_\tau$ and lifetime. While at the threshold of $\tau^+\tau^-$ pair the measurement of $\tau$ lifetime is difficult, at the high energy ($5 \sim 7$ GeV) end of STCF it could be possible to measure it by reconstructing the $\tau^+\tau^-$ vertex. With a high statistics, there is a chance to improve the measurement of $\tau$ lifetime, for which a more dedicated study is called for. On the other hand, the measurement for the mass can be 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, $\tau \to \nu_\ell l \bar{l}$ ($l = e, \mu$), the decay widths are proportional to the fifth power of $m_\tau$. 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 STCF, the number of $\tau$ produced 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 $\tau$ mass measurement will consolidate the base for any further $\tau$ physics studies.

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

The quantity $a_\tau$ of the anomalous magnetic dipole moment of the $\tau$ lepton is another property of the fundamental importance. The values $a_l$ for the electron and muon have been measured to a great precision. There are some deviations from the SM predictions, with $\Delta a_\tau = a_\tau^{\text{exp}} - a_\tau^{\text{SM}} = -78(36) \times 10^{-14}$ [3] at about 2$\sigma$ level and $\Delta a_\mu = 268(63)(43) \times 10^{-11}$ [2] at about 4$\sigma$ significance. The latter is the longstanding muon magnetic dipole moment anomaly, and $a_\mu$ is currently being measured at the Fermilab and J-PARC. 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 $a_{\tau}$. This is especially important for testing models of new physics which include states whose couplings are proportional to mass.

The measurement of $a_{\tau}$ is, however, drastically different from that of $a_{e,\mu}$ due to the short lifetime of $\tau$. The SM prediction for $a_{\tau}$ is $1177.21(5) \times 10^{-6}$ [4]. Currently $a_{\tau}$ is measured from the production cross section of the $\tau$ pair together with the spin or angular distributions of the $\tau$ decays; for instance, the current bound $-0.052 \leq a_{\tau} \leq 0.013$ (95\% C.L.) was obtained by the DELPHI collaboration [5] 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. To this end, a new method has recently been proposed in Ref. [6] which finds it feasible to reach a precision level of $10^{-5}$ at the Belle II before considering systematics. In addition, it was shown some time ago that in $e^+e^- \to \tau^+\tau^-$ with a polarized electron beam it would be plausible to achieve this precision goal at STCF by measuring the transverse and longitudinal polarizations of the $\tau$ lepton [7]. It has been argued that if $\tau^+\tau^-$ are produced on the top of the narrow $\Upsilon(1S, 2S, 3S)$ resonances, with very well controlled background near the threshold, a precision even better than Belle II can be expected. It has been pointed out, however, in Ref [8] that an energy spread with $e^+e^-$ beams of order a few MeV which is likely to happen, would invalidate the practicality because resonant contributions are contaminating non-resonant ones of at least similar size which would have to be subtracted to extract the dipole moment. In addition, the momentum transfer is too large to be related directly to dipole moments. The authors in Ref [8] proposed another method to measure dipole moments, i.e., by radiative decays $\tau^- \to \ell^-\nu_\ell\gamma$. They estimated the sensitivity to $a_{\tau}$ is about 0.085 (0.012) using full data of Belle (Belle II), which is to be compared with 0.017 at DELPHI, and the sensitivity to $d_\ell^T$ cannot be improved either. More critical studies are needed.

4.2 The Determination of the SM Parameters

The $\tau$ lepton has well defined interactions with other particles in the SM. Experimental measurements are consistent with the SM predictions [9]. With a large sample of $\tau$'s, 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 $\alpha_s$, and the $V_{tb}$ 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

$$\mathcal{L} = -\frac{g_\mu}{\sqrt{2}} \bar{\ell}\gamma^\mu P_L \nu_l W^-_\mu + \text{H.C.},$$

(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 [10] using very good approximation $B(\mu \to e\bar{\nu}_e\nu_\mu(\gamma)) \approx 1$:

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

$$\frac{g_\tau}{g_\mu} = \sqrt{\frac{B(\tau^- \to \mu^-\bar{\nu}_\mu\nu_\tau(\gamma))}{B(\tau^- \to e^-\bar{\nu}_e\nu_\tau(\gamma))}} \frac{m_\mu^5}{m_\tau^5} \frac{F_{\text{corr}}(m_\mu, m_\mu)}{F_{\text{corr}}(m_\tau, m_\tau)},$$

(8)
where \( F_{\text{cor}}(m_l, m_j) \) includes radiative corrections and corrections due to different charged lepton masses. The current data \( g_1/g_e = 1.0029 \pm 0.0015, g_{\mu}/g_e = 1.0019 \pm 0.0014, \) and \( g_1/g_\mu = 1.0010 \pm 0.0015 \) \cite{10} are consistent with the universality prediction. As discussed earlier, with the value of \( m_\tau \) 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.

Combining the decays \( \tau \rightarrow P\nu_\tau \) and \( P \rightarrow l\bar{l}l \) with \( P = \pi, K, l = \mu, e, \) and \( \nu_1 = \nu_\mu, \nu_e, \) one can also carry out universality tests as the ratio of their decay widths is proportional to \( g^2_\tau/g^2_\bar{\tau} \):

\[
R_l = \frac{\Gamma(\tau \rightarrow P\nu_\tau)}{\Gamma(P \rightarrow l\bar{l}l)} \frac{m_\tau / (m^2_\tau - m^2_P)}{m_P / (m^2_P - m^2_l)} = \frac{g^2_\tau}{g^2_\bar{\tau}}. \tag{9}
\]

All these decays have been measured experimentally with \( B(\tau^\rightarrow \rightarrow \pi^-\nu_\tau) = (10.82 \pm 0.05)\%, \ B(\tau^- \rightarrow K^-\nu_\tau) = (6.96 \pm 0.10)\%, \ B(\tau^- \rightarrow \mu^-\bar{\nu}_\mu) = (99.9877 \pm 0.0004)\%, \ B(\tau^- \rightarrow e^-\bar{\nu}_e) = (1.23 \pm 0.0004)\%, \ B(K^- \rightarrow \mu^-\bar{\nu}_\mu) = (63.56 \pm 0.11)\%, \) and \( B(K^- \rightarrow e^-\bar{\nu}_e) = (1.582 \pm 0.007)10^{-5} \) \cite{2}. The error bars in the decays \( \tau \rightarrow \pi(K)\nu_\tau \) are presently not as good as in the pure leptonic decays \( \tau \rightarrow \nu_\ell l\bar{l} \), and yield a weaker constraint. But with improved sensitivity for \( \tau \rightarrow \pi(K)\nu_\tau \) (and especially with more monochromatic \( \pi(K) \) near the \( \tau^+\tau^- \) production threshold) at STCF together with improved higher-order theoretical corrections, these decays will provide complementary universality tests.

### 4.2.2 The Michel parameters

The decays \( \tau \rightarrow l\bar{l}l\nu_\tau \) provide sensitive constraints to other forms of interactions due to new physics. Barring exotic interactions such as tensor couplings, the most general form of new physics is parameterized by the Michel parameters \( \rho, \eta, \xi, \) and \( \delta \) \cite{2},

\[
\frac{d^2\Gamma(\tau \rightarrow l\bar{l}l\nu_\tau)}{x^2dx\cos\theta} G^2_FF\tau m_\tau^2 \frac{96\pi^4}{x^2 x - 2} = 3(1 - x) + \rho_l x^2 + \eta_l \frac{m_l}{m_\tau} (1 - x) - P_\tau \xi_l \cos\theta + \delta_l \left[ \frac{8}{3} x - 2 \right], \tag{10}
\]

where \( P_\tau \) is the degree of \( \tau \) polarization, \( x = E_l/E^\text{max}_\tau \), and \( \theta \) is the angle between the \( \tau \) spin and the \( l \) momentum direction. In the SM the Michel parameters are

\[
\rho_l = 3/4, \quad \eta_l = 0, \quad \xi_l = 1, \quad \xi_l \delta_l = 3/4. \tag{11}
\]

Experimentally, the values are \cite{2}

\[
\rho = 0.747 \pm 0.010, \quad \rho_\mu = 0.763 \pm 0.020, \quad \xi = 0.999 \pm 0.040, \quad \xi_\mu = 1.030 \pm 0.059, \quad \eta = 0.013 \pm 0.020, \quad \eta_\mu = 0.094 \pm 0.073, \quad (\xi \delta)_e = 0.734 \pm 0.028, \quad (\xi \delta)_\mu = 0.778 \pm 0.037. \tag{12}
\]

Again experimental measurements are consistent with the SM predictions.

With a larger number of \( \tau \) produced and improved sensitivities, the STCF will be capable of reducing the error bars by at least a factor of 2. In addition, rare decays such as radiative leptonic decays \cite{11, 12, 13} and multi-charged-lepton decays \cite{8, 14} can also be studied at STCF. This will help to examine the SM electroweak interactions and put limits on new physics contributions.
4.2.3 The strong coupling $\alpha_s$ extraction

It is well-known that the strong coupling constant $\alpha_s$ can be extracted from the ratio [15]:

$$R_\tau = \frac{\Gamma(\tau^+ \to \nu_\tau \text{hadrons})}{\Gamma(\tau^+ \to \nu_\tau e^+\nu_e)},$$  \hspace{1cm} (13)

The theoretical predictions of the ratio have been carefully examined in [16, 17]. According to the structure of weak interactions and classification of final states, the ratio can be decomposed as:

$$R_\tau = R_{V,\text{had}} + R_{A,\text{had}} + R_{\tau,s}.$$  \hspace{1cm} (14)

Here $R_{\tau,s}$ is the contribution from final states containing an $s$-quark, while $R_{V,\text{had}}$ ($R_{A,\text{had}}$) comes from nonstrange final states involving an even (odd) number of pions. 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 $R_{V,\text{had}}$ and $R_{A,\text{had}}$. The analysis presented in [9] gives the value

$$\alpha_s(m_\tau) = 0.331 \pm 0.013,$$  \hspace{1cm} (15)

with one set of parameterizations of nonperturbative contributions. To improve the determination, the experimental study at STCF will be important. Specifically, 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 $\tau$ 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 the decay widths for $\tau^+ \to \pi^-\nu_\tau$ and $\tau^+ \to K^-\nu_\tau$, and the other by measuring the ratio $R_\tau = R_{V,\text{had}} + R_{A,\text{had}} + R_{\tau,s}$ discussed earlier. Theoretically

$$\frac{B(\tau \to K^-\nu_\tau)}{B(\tau^+ \to \pi^-\nu_\tau)} = \frac{f_K^2}{f_\tau^2} \left| \frac{V_{us}}{V_{ud}} \right|^2 \frac{(m_\tau^2 - m_K^2)^2}{(m_\pi^2 - m_K^2)^2} \left(1 + \delta R_{\tau/K}\right),$$

$$\left| V_{us} \right|^2 \approx \frac{R_{\tau,s}}{(R_{V,\text{had}} + R_{A,\text{had}})/|V_{ud}|^2 - \delta R_{\text{theory}}}. $$  \hspace{1cm} (16)

With known values from theoretical calculations and experimental measurements [10]: $f_K/f_\tau = 1.1930 \pm 0.0030$, $V_{ud} = 0.97417 \pm 0.00021$, $1 + \delta R_{\tau/K} = 1 + (0.90 \pm 0.22)\%$, $1 + \delta R_{\tau/\pi} = 1 + (0.16 \pm 0.14)\%$, $1 + \delta R_{\text{theory}} = 1 + (-1.13 \pm 0.23)\%$, one obtains respectively from the above two ways

$$\left| V_{us} \right|^2 = 0.2236 \pm 0.0018, \quad \left| V_{us} \right|_{r.s} = 0.2186 \pm 0.0021.$$  \hspace{1cm} (17)

The first value is 1.1 $\sigma$ away from the value determined by the unitarity relation $|V_{us}|_{\text{uni}} \approx \sqrt{1 - |V_{ud}|^2} = 0.2258 \pm 0.0009$, and the second is 3.1 $\sigma$ away from $|V_{us}|_{\text{uni}}$. These deviations need to be further understood with better precision before claiming new physics beyond the SM. The STCF can measure the values of $R_\tau$ and may therefore confirm or refute 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. There is no enough CP violation in the SM 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 $\tau^- \rightarrow K^0_S \pi^- \nu_\tau$

In the SM, because of CP violation in the $K^0 - K^0$ mixing, a detectable CP violating effect is predicted for this process to be [18]

$$A_Q = \frac{B(\tau^+ \rightarrow K^0_S \pi^+ \bar{\nu}_\tau) - B(\tau^- \rightarrow K^0_S \pi^- \nu_\tau)}{B(\tau^+ \rightarrow K^0_S \pi^+ \nu_\tau) + B(\tau^- \rightarrow K^0_S \pi^- \bar{\nu}_\tau)} = (+0.36 \pm 0.01)\%.$$  \hspace{1cm} (18)

While Belle observed no CP violation in the angular distributions for the exclusive decays [19], BABAR yielded a value for the inclusive decays with $\geq 0\sigma$ in the final states, $A_Q = (-0.36 \pm 0.23 \pm 0.11)$% [67], which is 2.8$\sigma$ away from the SM prediction.

The above deviation poses a challenge for the SM. Theoretical efforts have been made to reconcile the deviation. Even with beyond SM effects included, it is not so easy to obtain the central value of the BABAR data. STCF can provide a crucial check with a large number of the CP tests may show up.

4.3.2 Measurement of the electric dipole moment of $\tau$

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 $\tau$-decays, the CP test can be done with the process $e^+ e^- \rightarrow \tau^+ \tau^-$, as suggested in [20]. By measuring CP-odd observables, one can determine the electric and weak dipole moments of $\tau$. 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. While the weak dipole moment is suppressed at low energy by the large masses of weak gauge bosons, the electric dipole moment $d_\tau^e$ can be probed at $B$ and $\tau$-charm factories. The newest result for the electric dipole moment obtained from the Belle experiment [21] is, in units of $10^{-16}$ e cm,

$$-0.22 < \text{Re}(d_\tau^e) < 0.45, \quad -0.25 < \text{Im}(d_\tau^e) < 0.08.$$  \hspace{1cm} (19)

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

4.3.3 CPV with polarized beam

With polarized $e^+$ and/or $e^-$ beams, one can produce highly polarized $\tau^\pm$s. $\tau$ polarizations normal ($N$) to their production plane can be measured by studying the semileptonic decays $\tau^\pm \rightarrow \pi^\pm/\rho^\pm \bar{\nu}_\tau(\nu_\tau)$. 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 of $\tau^\pm$ [22],

$$A_N^N = \frac{\sigma_L - \sigma_R}{\sigma} = \alpha_\pm \frac{3\beta}{8(3-\beta^2)} \frac{2m_\tau}{e} \text{Re}(d_\tau^e),$$  \hspace{1cm} (20)
where $\sigma$ is the cross section for $e^+e^- \rightarrow \tau^+\tau^- \rightarrow (\pi^+ / \rho^+ )\bar{\nu}_\tau (\pi^- / \rho^- )\nu_\tau$, and $\beta = \sqrt{1 - 4m^2 / s}$. $\alpha_\pm$ is the polarization analyzer in the decays $\tau^\pm \rightarrow \pi^\pm / \rho^\pm \bar{\nu}_\tau (\nu_\tau)$. The Belle II can reach a sensitivity of $3 \times 10^{-9}$ 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 $P_\tau^T \equiv \bar{z} \cdot (\hat{p}_e \times \hat{p}_e')$ from measuring the two pion momenta in the decays $\tau^\pm \rightarrow \pi^\pm \bar{\nu}_\tau (\nu_\tau)$ [23]. Here $P_\tau^T = [(w_{e^-} + w_{e^+})/(1 + w_{e^-} w_{e^+})][(1 + 2a)/(2 + a^2)]$ is the component of the polarization vector of the $\tau$ 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 $\hat{z}$, and $a = 2m_\tau / \sqrt{s}$. If the difference of the triple products for $\tau^+$ and $\tau^-$ is nonzero, it is a signal of CP violation. Since the SM predicts very small values for the triple products, the measurement of a nonzero difference would already signal new physics beyond SM. This can be done at STCF to provide new information about CP violation sources. Similar measurements can be carried out by replacing $\pi^\pm$ by $K^\pm$.

4.4 Flavor Violating $\tau$ Decays

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

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

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

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

Equally interesting are the decays $\tau \rightarrow l\gamma$ with $l = e$, $\mu$. The current limits are a few times $10^{-8}$. Since initial-state radiation effects are strongly suppressed near the $\tau^+\tau^-$ production threshold, STCF is advantageous over the $B$ factories in a search for the decays [24]. One expects to achieve a sensitivity of a few times $10^{-10}$ with one-year running at STCF.

4.4.3 The decays $\tau^- \rightarrow lP_1P_2$

The decays $\tau^\pm \rightarrow l^\pm P_1P_2$ with $P_1 = \pi$, $K$ have been previously searched for with a sensitivity of order $10^{-8}$. Similar to these decays are the lepton-number-violating ones $\tau^\pm \rightarrow l^\pm P_1^\pm P_2^\pm$ whose current bounds are also order $10^{-8}$. At 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.
References

5 Topics of QCD Study and Light Hadron Physics

Formation of observed hadrons from QCD partons is still not understood. Experimentally, an $e^+e^-$ collider is a suitable place to study the hadronization because of its initial states being leptons. 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 latter will provide important information about various parton fragmentation functions. Besides inclusive processes, exclusive processes will be also studied at STCF. There are interesting phenomena near the threshold in the threshold in $e^+e^-$ → $B\bar{B}$ 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 charmonia. The study of exclusive- and inclusive production of quarkonia will provide important tests of theoretical predictions of non-relativistic QCD.

5.1 QCD Physics

5.1.1 R-value

The $R$ value is defined as

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

which is a function of $s$. $R$ has been measured at BES in the early time[1, 2]. Recently, it has been also measured by KEDR collaboration[3]. From experimental measurements of $R$ one can determine 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[4]. Precise measurements of $R$ allow to determine coupling constants in SM. Currently, the possible deviation of $(g - 2)_\mu$ of $\mu$-lepton has stimulated many studies to improve the precision of the theoretical predictions and to explain it as effects of new physics beyond SM. The newest result indicates that there are 4.2 standard deviation between experimentally measured- and theoretically predicted $(g - 2)_\mu$[5]. An important contribution to the uncertainty of $(g - 2)_\mu$ is the contribution of hadronic vacuum polarization. This contribution can be extracted from $R$ measured in experiment. Therefore, A precise measurement of $R$ plays an important role in tests of SM in a precise way. It is absolutely clear that more precise results on the $R$-value will be obtained At STCF.

5.1.2 Inclusive Production of Single Hadron

For large enough $\sqrt{s}$ the inclusive production of single hadron in $e^+e^- \rightarrow h + X$ can be predicted from QCD with QCD factorization theorem[6]:

$$\frac{d\sigma(e^+e^- \rightarrow h + X)}{dz} = \sum_{a=q,\bar{q},g} \int \frac{d\xi}{\xi} H_a(\xi, Q^2, \mu^2) D_{a \rightarrow h}(\xi, \mu^2)$$

$$= \sum_q \sigma(e^+e^- \rightarrow q\bar{q})(D_{q \rightarrow h}(z) + D_{\bar{q} \rightarrow h}(z)) + O(\alpha_s),$$

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. $D_a \rightarrow h$’s are parton fragmentation functions describing
hadronization of a parton \( a \) to \( h \). Eq.(22) 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 low energy like the energy region of STCF around 4-5 GeV is specially important, because from the extracted fragmentation functions one can test their energy evolution from a rather low energy scale to high energy scales.

5.1.3 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 can not be used. But, there is another factorization, called Transverse-Momentum-Dependent (TMD) factorization, which holds in this region[7]. The angular distributions in this kinematical region are determined by TMD quark fragmentation functions. These functions describe fragmentation of an initial parton into the observed hadron, where the hadron has a small transverse momentum respectively to the momentum of the initial parton. The general form of angular distributions can be found in [8]. 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 interest. This function describes how a transversely polarized quark fragments into a hadron[9]. It is zero if there is no \( T^{-}\)odd effect. Belle at \( \sqrt{s} = 10.6 \) GeV has performed a study of Collins function[10]. 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 [11]. 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.

5.1.4 Form Factors of Hadrons

Measuring electromagnetic (EM) form factors of a nucleon has played an important role in exploring the inner structure of nucleon. Now they are still the simplest structure observables for testing QCD predictions. In the past, these form factors have been studied mostly in the space-like region. Recently, the study has been extended to the time-like region. In the time like region, it is also possible to measure EM for factors of baryons other than a nucleon. Currently available time-like experiments demonstrate puzzling features EM form factors. Near the threshold, the enhancement has been observed by BES[12] near the threshold of the \( p\bar{p} \) system. BaBar has reported the enhancement in the process \( e^+e^- \rightarrow p\bar{p}, \Lambda\bar{\Lambda}, \Sigma^0\bar{\Sigma}^0 \)[13], respectively. In the space-like regions. The EM form factors of a proton and a neutron in the space-like region has been measured with the precision at \( 1 \sim 2\% \)-level. In the time-like region, the EM form factors of proton is with the precision at \( 3.4\% \)[14], while those of neutron is with the error at \( 20\% \)-level[15]. At STCF with the suggested luminosity, the EM form factors in the time-like can be measured with the accuracy \( 0.4\% \) for proton and \( 2\% \) for neutron. This precision will be comparable with that in space-like region. Moreover, one can study the enhancement in the production of a baryon-antibaryon pair near threshold more precisely to extract information about the interaction between a baryon and antibaryon, and can extend the study to the system of \( \Lambda_c\bar{\Lambda}_c \) to see if the enhancement happens in heavy baryon and antiheavy baryon system.

Processes as \( \gamma\gamma \rightarrow \text{hadrons} \) can be studied at STCF. Besides general interesting in photon-photon physics, a particular quantity is the transition form factor of mesons. These form factors determine
the leading contributions to the hadronic light-light scattering, which is closely related to the precise prediction of the interesting quantity \((g-2)\mu\). Precise results of these form factors will greatly help to reduce uncertainties of the contribution to \((g-2)\mu\) from hadronic light-light scattering.

### 5.1.5 Production of Charmonia

Inclusive production of a charmonium has been observed at Belle. The ratio has been measured as\[16\]:

\[
R_{c\bar{c}} = \frac{\sigma(e^+e^- \rightarrow J/\psi + c + \bar{c} + X)}{\sigma(e^+e^- \rightarrow J/\psi + X_{\text{non},c\bar{c}})} \approx 0.63. \tag{23}
\]

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\[17, 18\], it may be not consistent. If one includes the so-called color-octet contributions estimated from hadroproduction of \(J/\psi\), there is still conflict between experiment and theory(See also \[19\]). Belle has also observed the exclusive production of double charmonia \(e^+ + e^- \rightarrow J/\psi + \eta_c\)[20]. Theoretically, the measured cross-section is still not well-explained even including two-loop predictions in theory\[21\].

With STCF running at \(\sqrt{s}\) larger than 6 GeV, the production processes can be studied more precisely in experiment. This will be helpful to understand the production. In this energy range it offers a unique opportunity to study physics related to the production of two pairs of \(c\bar{c}\). The production cross sections for \(e^+e^- \rightarrow J/\psi\eta_c\) and \(e^+e^- \rightarrow J/\psi c\bar{c}\) from based on the NRQCD calculations in Refs. \[22\] are shown in Fig. 5. This can be tested at STCF.

### 5.2 Spectroscopy

The spectrum of light hadrons serves is an excellent probe of nonperturbative QCD \[23, 24, 25, 26, 27, 28\]. 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, however, predicts a richer spectrum of mesons that takes into account not only the quark degrees of freedom but also the gluonic degrees of freedom. Also excited and exotic hadronic states are sensitive to the details of quark confinement, which is only poorly understood within QCD.
For intermediate and long-distance phenomena such as hadron properties, the full complexity of QCD emerges, which makes it difficult to understand hadronic phenomena at a fundamental level. 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. Whether glueballs made of multi-gluons, and hybrids made of gluons and quarks predicted by QCD really exist is still an open question. These are some of the important issues in hadronic physics understand. Another critical and poorly studied sector is light vector mesons, especially strangeonium states, which can provide critical information on the connection between the light quark and heavy quark sectors. Hadron Production via $e^+e^-$ collisions with ISR [29] play an important role. Current and future experiments present a real opportunity for a dramatic improvement in our knowledge of the spectrum.

At present BESIII remains unique for studying and searching for QCD exotics and new excited baryons [30], as its high-statistics data sets of charmonia provide a gluon rich environment with clearly defined initial and final state properties [31]. At the STCF, much more data sets of charmonian will be obtained. The high statistics data samples of $J/\psi$ and $\psi(3686)$ decays, hadronic and also radiative decay channels, can provide an unprecedented opportunity to obtain a better understanding of light hadron spectroscopy, their properties and their couplings to all the channels in which they appear, and from these to learn about the composition of these states, including glueballs and hybrid states. An interesting example is the study of glueball nature of some states using data from STCF. The production property suggests the prominent glueball nature of $f_0(1710)$ and the flavor octet structure of $f_0(1500)$ [31]. However, the scalar meson sector is the most complex one and the interpretation of the state’s 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. But, the nature of all of these states is still open for discussion. At STCF, a year of operation will provide $\sim 3T J/\psi$ and $\sim 500B \psi'$ events at their peaking cross section for exploring light hadron physics. Glueballs and hybrid states may show their traces in some more confirmed ways. 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. 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. A glueball should have suppressed couplings to $\gamma\gamma$, which can be measured at STCF.

Extracting resonance properties from experimental data is however far from straightforward: resonances tend to be broad and plentiful, leading to intricate interference patterns, or buried under a background in the same and in other waves. The key to success lies in high statistical precision complemented with sophisticated analysis methods. Partial wave or amplitude analysis (PWA) techniques [32] are the state-of-the-art way to disentangle contributions from individual, and even small, resonances and to determine their quantum numbers. Facing the extremely high statistics at STCF, there are new challenges for data handling and processing. High performance computing harnessing heterogenous acceleration (e.g. [33]) is a key requirement. The correct analytical properties of the amplitude are essential for an extrapolation from the experimental data into the complex plane in order to determine the pole positions. A key component of PWA will be the close cooperation between experimentalists and theorists.
5.3 Precision tests with light hadrons

5.3.1 Light meson decays

At STCF, it is expected to collect at least $10^{12}$ $J/\psi$ events produced per year, which makes STCF a factory of light mesons due their high production rate in $J/\psi$ decays. Take $\eta/\eta'$ mesons for example, Table. 8 indicates that about $10^9 \eta/\eta'$ events could be produced through $J/\psi$ radiative or hadronic decays. In this case, the STCF offers a unprecedented opportunity to explore the light meson decays for a variety of physics at low energy scales, including precision tests of effective field theories, investigations of the quark structure of the light mesons, tests of the fundamental symmetries, and searches for new particles.

At low energies nonperturbative QCD calculations are usually performed by an effective field theory called Chiral Perturbation Theory (ChPT). High quality and precise measurements of low-energy hadronic processes are necessary in order to verify the systematic ChPT expansion. Thus, studies of light meson decays are important guides to our understanding of how QCD works in the non-perturbative regime. In particular the $\eta'$ 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. The light meson decays, such as $\eta/\eta'$, $\omega$ as well as the excited states, can provide useful information about chiral perturbation theory through hadronic decays [34, 35], and also anomalous Wess-Zumino-Witten (WZW) processes [36, 37, 38], for example, $\eta' \to \rho^0 \gamma$, which are shown to provide model independent information about low energy meson interaction such as Vector Meson Dominance (VMD) [39, 40]. The decays $\eta/\eta' \to \gamma\gamma\pi^0$ are of particular interest for tests of ChPT at the two-loop level. Since light vector mesons play a critical role in these models, the dynamical role of the vector mesons has to be systematically included in the context of either the VMD or Nambu-Jona-Lasinio model to reach a deeper understanding of these decays.

The $\eta/\eta' \to \gamma\gamma\ell^-\ell^+$ (\(\ell = e, \mu\)) Dalitz decays, where the lepton pair is formed by internal conversion of an intermediate virtual photon and the decay rates are modified by the electromagnetic structure arising at the vertex of the transition, are of special interest. Deviations of measured quantity from their QED predictions are usually described in terms of a timelike transition form factor, which, in addition of being an important probe into the meson’s structure [40], has an important role in the evaluation of the hadronic light-by-light contribution to the muon anomalous magnetic moment (see a nice review [41] for details).

In addition, using the expected large data sample collected at a center-of-mass energy of above $J/\psi$ peak at STCF, the measurements of the spacelike transition form factors in the decay $e^+e^- \to e^+e^-\pi^0(\eta,\eta')$ via $\gamma\gamma$ interactions in the range of the transfer momentum $Q^2$ within [0.3, 10] GeV/c$^2$ are feasible. The measured spacelike transition form factor will uniquely cover the $Q^2$ range that is relevant to the hadronic light-by-light correction for the evaluation of the muon anomaly moment.

The $\eta$ and $\eta'$ mesons are eigenstates of $P$, $C$ and $CP$ whose strong and electromagnetic decays are either anomalous or forbidden to lowest order by $P$, $C$, $CP$ and angular momentum conservation. Therefore, their decays provide a unique laboratory for testing the fundamental symmetries in flavor-conserving processes, which was extensively reviewed in Ref.[42].

A straightforward way to test these symmetries is to search for $P$- and $CP$-violating $\eta/\eta'$ decays into two pions. In the SM, the branching fractions for these modes are very tiny [43], but they may be enhanced by $CP$ violation in the extended Higgs sector of the electroweak theory [44]. 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 SM. Experimentally, $\eta/\eta' \to \ell^+\ell^-\pi^0$ decays could be used to test charge-conjugation invariance. In the SM, this process can proceed via a two-virtual-photon exchange whereas one-photon-exchange violates $C$-parity. Within the framework of the VMD model, the most recent predictions [45] for the branching fraction are on the order of $10^{-8}$ for $\eta \to \ell^+\ell^-\pi^0$ and $10^{-10}$ for
η' → l⁺l⁻π⁰(η). Thus, a significant enhancement of the branching fractions exceeding the two-photon model may be indicative of C violation. With the expected $10^{12}$ $J/\psi$ events at STCF, the branching fraction can reach a new high precision of order of $10^{-9}$, making the investigation of these rare decays very promising. Many other decays of the $\eta/\eta'$ meson, as summarized in Table 9 for $\eta'$ decays, are useful for tests of the SM. For example, the decays $\eta \to \mu^+\mu^-$ and $\eta \to e^+e^-$ are of interest when searching for non-standard physics. Within the framework of the SM, the decays are dominated by a two-photon intermediate state, which have suppressed branching ratios. Beyond SM interactions, such as leptoquark exchange, can enhance the branching ratios. Therefore larger than expected measurements will provide information about non-SM interactions and the same can be concluded for their flavor violating counter parts, $\eta \to e^+\mu^-$. 

<table>
<thead>
<tr>
<th>Decay Mode</th>
<th>$\mathcal{B}$ ($\times 10^{-6}$)</th>
<th>$\eta/\eta'$ events</th>
</tr>
</thead>
<tbody>
<tr>
<td>$J/\psi \to \gamma\eta'$</td>
<td>52.1 ± 1.7</td>
<td>5.21 × $10^7$</td>
</tr>
<tr>
<td>$J/\psi \to \gamma\eta$</td>
<td>11.08 ± 0.27</td>
<td>1.1 × $10^7$</td>
</tr>
<tr>
<td>$J/\psi \to \phi\eta$</td>
<td>7.4 ± 0.8</td>
<td>7.4 × $10^5$</td>
</tr>
<tr>
<td>$J/\psi \to \phi\eta$</td>
<td>4.6 ± 0.5</td>
<td>4.6 × $10^5$</td>
</tr>
</tbody>
</table>

Besides the $\eta/\eta'$ decays, the high production of the other light mesons, $\omega$, $a_0(980)$, $f_0(980)$, $\eta(1405)$, as well as other excited states, is also important source for exploring many aspects of particle physics at low energy. The decay $\omega \to \pi^+\pi^-\pi^0$ could be employed to investigate the $\omega$ decay mechanism by comparing a highstatistics Dalitz plot density distribution with the predictions within the dispersive theoretical framework [46, 47]; the $a_0(980) - f_0(980)$ mixing is sensitive to the quark structure of the light scalars, and the $\eta(1405) \to 3\pi$ may help reveal the the well known triangle singularity mechanism [48].

In general, despite this impressive progress, many light meson decays are still unobserved and need to be explored. With the advantages of high production rates and the excellent performance of STCF, the very abundant and clean samples of $e^+e^-$ annihilations will bring the study of light meson decays into a precision era, and will definitely play an important role in the developments of chiral effective field theory and Lattice QCD, and make significant contributions to understanding of hadron physics in the nonperturbative regime.

5.3.2 Hyperon decays

The ongoing experimental studies of 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 [49, 50, 51]. The first observation of the CP violation for charm mesons was reported in 2019 by the LHCb experiment [52] but so far there is no evidence in the baryon sector. All the observations are consistent with the SM expectation. Baryons with strange quark(s) (hyperons) decays offer promising possibilities for searches of new CP violation effects, since they involve $p$-wave decay amplitudes, that neutral kaon decays are not [54]. 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 hadronic transitions into a baryon and a pseudoscalar meson like $\Lambda \to p\pi^-$, $\mathcal{B} \approx 64 \%$, and $\Xi^- \to \Lambda\pi^-$, $\mathcal{B} \approx 100 \%$ [1]. 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: $\alpha = 2\text{Re}(s^*p)/(|p|^2 + |s|^2)$ and $\phi = \text{arg}((s - p)/(s + p))$. Here, we denote the decay parameter $\alpha$ for $\Lambda \to p\pi^-$.
Table 9: The sensitivity of $\eta'$ 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.

<table>
<thead>
<tr>
<th>Decay mode</th>
<th>Best upper limits (90% CL)</th>
<th>STCF limit (1 $\times$ $10^{12}$ $J/\psi$ events)</th>
<th>Theoretical predictions</th>
<th>Physics</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\eta' \rightarrow e^+e^-$</td>
<td>$5.6 \times 10^{-9}$</td>
<td>$5 \times 10^{-10}$</td>
<td>$1.1 \times 10^{-10}$</td>
<td>leptonquark</td>
</tr>
<tr>
<td>$\eta' \rightarrow \mu^+\mu^-$</td>
<td>$-1.1 \times 10^{-10}$</td>
<td>$1.1 \times 10^{-7}$</td>
<td>leptonquark</td>
<td></td>
</tr>
<tr>
<td>$\eta' \rightarrow e^+e^-e^+e^-$</td>
<td>$-8 \times 10^{-10}$</td>
<td>$1 \times 10^{-4}$</td>
<td>$\gamma^\prime\gamma^\prime$</td>
<td></td>
</tr>
<tr>
<td>$\eta' \rightarrow \mu^+\mu^-\mu^+\mu^-$</td>
<td>$-8 \times 10^{-10}$</td>
<td>$4 \times 10^{-7}$</td>
<td>$\gamma^\prime\gamma^\prime$</td>
<td></td>
</tr>
<tr>
<td>$\eta' \rightarrow \pi^+\pi^-e^+e^-$</td>
<td>$(24^{+13}_{-10}) \times 10^{-1}$</td>
<td>$1.4 \times 10^{-7}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\eta' \rightarrow \pi^+\pi^-\mu^+\mu^-$</td>
<td>$2.9 \times 10^{-5}$</td>
<td>$8 \times 10^{-10}$</td>
<td>$2.2 \times 10^{-5}$</td>
<td>VMD, TFF</td>
</tr>
<tr>
<td>$\eta' \rightarrow \pi^0\pi^0\mu^+\mu^-$</td>
<td>$6.0 \times 10^{-5}$</td>
<td>$8 \times 10^{-10}$</td>
<td>C violation</td>
<td></td>
</tr>
<tr>
<td>$\eta' \rightarrow \pi^0e^+e^-$</td>
<td>$1.4 \times 10^{-5}$</td>
<td>$8 \times 10^{-10}$</td>
<td>C violation</td>
<td></td>
</tr>
<tr>
<td>$\eta' \rightarrow \pi^0\pi^0\gamma$</td>
<td>$-7 \times 10^{-10}$</td>
<td></td>
<td>angular momentum</td>
<td></td>
</tr>
<tr>
<td>$\eta' \rightarrow \pi^0\pi^0\pi^0$</td>
<td>$9.0 \times 10^{-4}$</td>
<td>$1 \times 10^{-9}$</td>
<td>CP violation</td>
<td></td>
</tr>
<tr>
<td>$\eta' \rightarrow \pi^+\pi^-\pi^0$</td>
<td>$2.9 \times 10^{-3}$</td>
<td>$5 \times 10^{-10}$</td>
<td>CP violation</td>
<td></td>
</tr>
<tr>
<td>$\eta' \rightarrow \mu^+e^-+\mu^+e^+$</td>
<td>$4.7 \times 10^{-4}$</td>
<td>$5 \times 10^{-10}$</td>
<td>LPV</td>
<td></td>
</tr>
<tr>
<td>$\eta' \rightarrow$ invisible</td>
<td>$5.3 \times 10^{-4}$</td>
<td>$1 \times 10^{-7}$</td>
<td>Dark matters</td>
<td></td>
</tr>
<tr>
<td>$\eta' \rightarrow \eta e^+e^-$</td>
<td>$2.4 \times 10^{-4}$</td>
<td>$2 \times 10^{-9}$</td>
<td>C violation</td>
<td></td>
</tr>
<tr>
<td>$\eta' \rightarrow \eta\mu^+\mu^-$</td>
<td>$1.5 \times 10^{-5}$</td>
<td>$2 \times 10^{-9}$</td>
<td>C violation</td>
<td></td>
</tr>
</tbody>
</table>

and $\Xi^\prime \rightarrow \Lambda \pi^-$ as $\alpha_\Lambda = 0.750(10)$ [61] and $\alpha_\Xi = -0.392$, respectively. In the CP symmetry conserving limit the parameters $\alpha_D/\alpha_B$ and $\phi_D/\phi_B$ for the charge conjugated $D/D\bar{D}$ decay modes have the same absolute values but opposite signs. The CP asymmetry $A_D$ defined as:

$$A_D \equiv \frac{\alpha_D + \alpha_B}{\alpha_D - \alpha_B} = -\tan(\delta_p - \delta_s) \sin(\zeta_p - \zeta_s)$$

(24)

where $\delta_p - \delta_s$ is the strong $(p-s)$-wave phase difference in the decay due to final state interaction and $\zeta_p - \zeta_s$ is the weak CP violating phase difference.

The best limit for CP violation in the strange baryon sector was obtained by comparing the complete decay chains of unpolarized $\Xi$ baryons at the dedicated HyperCP (E871) experiment [55] by determining the asymmetry $A_{\Xi\Lambda} = (\alpha_\Lambda \alpha_\Xi - \alpha_\Lambda \bar{\alpha}_\Xi)/(\alpha_\Lambda \alpha_\Xi + \alpha_\Lambda \bar{\alpha}_\Xi) \approx A_\Xi + A_\Lambda$. The result, $A_{\Xi\Lambda} = (0.0 \pm 5.1 \pm 4.7) \times 10^{-4}$, is consistent with the SM predictions: $|A_{\Xi\Lambda}| \leq 5 \times 10^{-5}$ [56].

Moreover, an improved preliminary HyperCP result presented at the BEACH 2008 Conference suggests a large value of the asymmetry $A_{\Xi\Lambda} = (-6.0 \pm 2.1 \pm 2.0) \times 10^{-4}$ [57]. However, it is difficult to interpret the result in terms of the weak CP violating phase difference. The $A_D$ asymmetries are in general not sensitive probes of the weak CP violating phase difference since the $\tan(\delta_p - \delta_s)$ term is very small and not well known. The values are $-0.097(33)$ for $\Lambda \rightarrow p\pi^-$ and $0.87(33)$ for $\Xi^- \rightarrow \Lambda\pi^-$ as determined from the values of the $\phi_D$ decay parameters using the relation:

$$\tan(\delta_p - \delta_s) \approx -\sqrt{1 - \alpha^2_D} \sin \phi_D$$

(25)

Much more sensitive, independent determination of $\zeta_p - \zeta_s$ is given by comparing $\phi_D$ and $\phi_B$ parameters:

$$\Delta \phi_D \equiv \frac{\phi_D + \phi_B}{2} \approx \frac{\alpha_D}{\sqrt{1 - \alpha^2_D}} \sin(\zeta_p - \zeta_s)$$

(26)
based on the published BESIII analyses using partial data sets [58, 59, 60].

detection e.

parameter is the phase  the dedicated HyperCP experiment will be surpassed at STCF. The SM predictions for the 

A

at SCTF (see Table 10), are given in Table 11. The statistical uncertainty for the  asymmetry from the 

dedicated HyperCP experiment will be surpassed at STCF. The SM predictions for the  and  

<table>
<thead>
<tr>
<th>Decay mode</th>
<th></th>
<th>Angular distribution parameter $\alpha_\phi$</th>
<th>Detection efficiency</th>
<th>No. events expected at STCF</th>
</tr>
</thead>
<tbody>
<tr>
<td>$J/\psi \to \Lambda \bar{\Lambda}$</td>
<td>$19.43 \pm 0.03 \pm 0.33$</td>
<td>$0.469 \pm 0.026$</td>
<td>40%</td>
<td>$1100 \times 10^6$</td>
</tr>
<tr>
<td>$\psi(2S) \to \Lambda \bar{\Lambda}$</td>
<td>$3.97 \pm 0.02 \pm 0.12$</td>
<td>$0.824 \pm 0.074$</td>
<td>40%</td>
<td>$130 \times 10^6$</td>
</tr>
<tr>
<td>$J/\psi \to \Xi^0 \bar{\Xi}^0$</td>
<td>$11.65 \pm 0.04$</td>
<td>$0.66 \pm 0.03$</td>
<td>14%</td>
<td>$230 \times 10^6$</td>
</tr>
<tr>
<td>$\psi(2S) \to \Xi^0 \bar{\Xi}^0$</td>
<td>$2.73 \pm 0.03$</td>
<td>$0.65 \pm 0.09$</td>
<td>14%</td>
<td>$32 \times 10^6$</td>
</tr>
<tr>
<td>$J/\psi \to \Xi^- \bar{\Xi}^+$</td>
<td>$10.40 \pm 0.06$</td>
<td>$0.58 \pm 0.04$</td>
<td>19%</td>
<td>$270 \times 10^6$</td>
</tr>
<tr>
<td>$\psi(2S) \to \Xi^- \bar{\Xi}^+$</td>
<td>$2.78 \pm 0.05$</td>
<td>$0.91 \pm 0.13$</td>
<td>19%</td>
<td>$42 \times 10^6$</td>
</tr>
</tbody>
</table>

Table 10: 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 $3.4 \times 10^{12}$ $J/\psi$ and $3.2 \times 10^9 \psi'$ 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 [58, 59, 60].

<table>
<thead>
<tr>
<th></th>
<th>$A_\Xi$</th>
<th>$A_\Lambda$</th>
<th>$A_{\Xi \Lambda}$</th>
<th>$(\zeta_p - \zeta_t)_{\Xi}$</th>
<th>$(\zeta_p - \zeta_t)_{\Lambda}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$J/\psi \to \Lambda \bar{\Lambda}$</td>
<td></td>
<td></td>
<td></td>
<td>Eq. (24)</td>
<td>Eq. (26)</td>
</tr>
<tr>
<td>$J/\psi \to \Xi^- \bar{\Xi}^+ (\Delta \Phi = 0)$</td>
<td>$2.2 \times 10^{-4}$</td>
<td>$2.1 \times 10^{-4}$</td>
<td>$2.5 \times 10^{-4}$</td>
<td>$2.4 \times 10^{-3}$</td>
<td>$6.5 \times 10^{-4}$</td>
</tr>
</tbody>
</table>

Table 11: Standard errors for the asymmetry parameters extracted using STCF data samples. The input values of the parameters are from Table 10 and Ref [64].

With a well-defined initial state charmonium decay into a strange baryon-antibaryon pair offers an ideal system to test fundamental symmetries. Vector charmonia $J/\psi$ and $\psi'$ 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 10. The potential impact of such measurements was shown in the recent BESIII analysis using a data set of $4.2 \times 10^5 e^+e^- \to J/\psi \to \Lambda \bar{\Lambda}$ events reconstructed via $\Lambda \to p\pi^- +$ c.c. decay chain [61]. The determination of the asymmetry parameters was possible due to the transverse polarization and the spin correlations of the $\Lambda$ 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. [62]. 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. [63] the formalism was extended to describe processes which include decay chains of multistrange 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 CP odd asymmetries which can be extracted from the exclusive analysis was estimated in Ref. [64]. To study the angular distribution for the $e^+e^- \to \Xi \bar{\Xi}^+$ reaction we fix the decay parameters of the $\Lambda$ and $\Xi$ to the central values from PDG [1]. 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 11 we report the statistical uncertainties in the $J/\psi \to \Xi \bar{\Xi}^+$ decay.

The sensitivities for the $A_\Xi, A_\Lambda$ and $A_{\Xi \Lambda}$ asymmetries with data samples of more than $10^{12} J/\psi$ events at STCF (see Table 10), are given in Table 11. The statistical uncertainty for the $A_{\Xi \Lambda}$ asymmetry from the dedicated HyperCP experiment will be surpassed at STCF. The SM predictions for the $A_\Xi$ and $A_\Lambda$
asymmetries are $-3 \times 10^{-5} \leq A_{\Lambda} \leq 4 \times 10^{-5}$ and $-2 \times 10^{-5} \leq A_{\Xi} \leq 1 \times 10^{-5}$ [56].

Assuming value of 0.037 for the $\phi_{\Xi}$ parameter the five sigma significance requires $3.1 \times 10^5$ exclusive $\Xi^-\Xi^+$ events. To reach the statistical uncertainty of 0.011, as in the HyperCP experiment [65] requires $1.4 \times 10^5 J/\psi \rightarrow \Xi^-\Xi^+$ events, while the single cascade HyperCP result is based on $114 \times 10^6$ events.

The present PDG precision of $\phi_{\Xi}$ can be achieved with just $3 \times 10^2$ $\Xi^0\Xi^0$ events.

The sensitivities for weak phase difference $(\zeta_p - \zeta_s)_{\Xi}$ [54] are also given in Table 11 using the two independent methods. The SM estimate for $(\zeta_p - \zeta_s)_{\Xi}$ is $8 \times 10^{-5}$. 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 $10^{10} J/\psi$. 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.

The large data sample of $\Lambda\bar{\Lambda}$ from $J/\psi$ decay can also be used to study $\Lambda - \bar{\Lambda}$ oscillations. Seesaw mechanism explanation of small neutrino masses [66] predicts existence of $\Delta(B - L) = 2$ interactions and baryon–antibaryon oscillations. Searches for processes that violate baryon number by two units have been performed only in neutron-antineutron oscillation experiments [67]. Searches of $\Lambda - \bar{\Lambda}$ oscillations were proposed in $J/\psi \rightarrow \Lambda\Lambda$ decay at BESIII [68]. With 10 billion $J/\psi$ decay events at BES-III, the expected sensitivity of measurement of $\Lambda - \bar{\Lambda}$ oscillation is $\delta m_{\Lambda\Lambda} < 10^{-15}$ MeV at 90% confidence level. It corresponds to the oscillation time lower limit of $10^{-7}$ s. At STCF the expected constraint on $\delta m_{\Lambda\Lambda}$ can be improved to $10^{-17}$ MeV level or even better. This upper limit is already much larger than the lifetime of $\Lambda$ and further significant improvements would require other approaches such as use of certain long-lived hypernuclei [69].

References


6 New light particles beyond SM

In this section, 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. STCF with high luminosity will be sensitive to light new particles and their interactions with SM particles. 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.

6.1 Particles in dark sector

The existence of a dark sector which weakly couples to the SM sector is well motivated by many BSM theories. Some new physics particles 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 follows from the observations of anomalous cosmic-ray positrons. In 2008, the PAMELA collaboration reported excess positrons above \( \sim 10 \text{ GeV} \) [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 \( \sim \mathcal{O}(\text{TeV}) \) annihilate into a pair of light bosons with masses of \( \sim \mathcal{O}(\text{GeV}) \) to annihilate into a pair of light bosons with masses of \( \sim \mathcal{O}(\text{GeV}) \), which decay into charged leptons [6, 7]. 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 \( \frac{1}{2} F_{\mu \nu} F^\prime_{\mu \nu} \). Since the QED is a well-tested model, the mixing strength \( \epsilon \) should be small. In theory, \( \epsilon \) can be generated by high-order effects [8]. Therefore, \( \epsilon \) is naturally \( \sim 10^{-2} \rightarrow 10^{-3} \) or smaller. The dark photon can acquire a mass through the Higgs mechanism or the Stueckelberg mechanism. Some models could predict that the mass of dark photon is at the \( \sim \mathcal{O}(\text{MeV}) \sim \mathcal{O}(\text{GeV}) \) 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 \( \epsilon \). Fig. 6 shows the constraints on \( \epsilon \) 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 \( e^+ e^- \rightarrow \gamma + A'(\rightarrow l^+ l^-) \) [10, 11, 12, 13, 14]. In comparison with the irreducible QED background \( e^+ e^- \rightarrow \gamma l^+ l^- \), the dark photon production is suppressed by a factor of \( \epsilon^2 \). To reduce the background, a precise reconstruction of the dark photon mass and a high luminosity are important. Such
researches for $T \rightarrow \gamma + A'(\rightarrow \mu^+\mu^-)$ 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 $\epsilon$ is constrained to be smaller than $\sim 2 \times 10^{-3}$ for the dark photon with the mass $\sim 1$ GeV, and can be limited down to $5 \times 10^{-4}$ at SuperB [17]. With 20 fb$^{-1}$ data collected at $\psi(3770)$, the sensitivity of $\epsilon$ for $e^+e^- \rightarrow \gamma + A'(\rightarrow l^+l^-)$ can be down to $2 \times 10^{-3}$ with $m_{A'} \sim 1$ GeV [18]. A similar estimation can be performed at STCF, and the sensitivity of $\epsilon$ will be $O(10^{-4})$ for $m_{A'} \sim 0.6 - 3.7$ GeV with 1 ab$^{-1}$ data as shown in Fig. 7.

If there is also a light Higgs $h'$, which provides the mass of dark photon, with a mass of $\sim O$(MeV) –
$O$(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 $e^+e^- \rightarrow A' + h' \rightarrow 2A'$ will be very clean for the dark sector 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 energy 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 $\sim e^2 \times BR$ (meson $\rightarrow \gamma$) [12, 18]. Since low energy electron-positron colliders produce numerous mesons, such as $\pi$, $\rho$, $K$, $\phi$, and $J/\psi$, it is possible to investigate dark photons in the rare decays of mesons. For instance, one can search for a resonance in the processes $\phi \rightarrow \eta + A'$ and $\pi/\eta \rightarrow \gamma + A'$ with $A' \rightarrow t^+t^-$. At STCF where a large sample of charm mesons are produced, charmonium decay channels, such as $J/\psi \rightarrow e^+e^- + A'$ [10] and $\psi(2S) \rightarrow \chi_{c1,2} + A'$ can be used to probe dark photons. Light $Z'$ bosons that decay predominantly into invisible states can be probed via missing energy final states at electron colliders; see e.g. ref. [21] for the recent Belle II results. Other light particles, such as light axion-like particles, can also be searched for at electron colliders; see e.g. ref. [22] for the recent Belle II results.

### 6.2 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 [23, 24, 25] or Stueckelberg mass mixing [26, 27, 28] mechanism. MCPs have been searched for previously at various mass scales both at terrestrial laboratories and in cosmological/astrophysical processes (see e.g. [29] 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 [30, 31]. At the MeV-GeV energy scale, the existing laboratory constraints on MCPs include the collider constraints [32], the SLAC electron beam dump experiment [33], and the neutrino experiments [34].

A small fraction of the dark matter (DM) can be millicharged. Recently, EDGES experiment detected an anomalous absorption signal in the global 21 cm near redshift $z = 17$ [35]. Millicharged dark matter models have been invoked to provide sufficient cooling to the cosmic hydrogens [36, 37, 38]; because the interaction cross section between millicharged DM and baryons increases as the universe cools, constraints from early universe can be somewhat alleviated.

Because the ionization signals from MCPs is so weak that typical detectors in particle colliders are unable to detect MCPs directly, MCPs can be searched for at the electron colliders via the monophoton final state [30, 31]. The analysis of searching 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 $e^+e^- \rightarrow \chi\bar{\chi}\gamma$ where $\chi$ is the MCP. The irreducible monophoton background processes are $e^+e^- \rightarrow \bar{\nu}\nu\gamma$, where $\nu$ 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 [31].

Fig. (8) 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. [30]. The monophoton cross section for MCPs increases when the colliding energy decreases, as shown in Fig. (8). However,
the monophoton irreducible background grows with the colliding energy. Thus, the electron collider with a smaller colliding energy has a better sensitivity to kinematically accessible MCPs.

To analyze the sensitivity of the proposed STCF experiment to millicharged particles, the STCF detector is 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. (9), 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 $\sim 4$ MeV to 0.1 GeV. MCPs with $\epsilon \lesssim (0.8 - 3) \times 10^{-4}$ and mass from $\sim 4$ 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 [36]. 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 \(\sim 10.6\) GeV. Thus, STCF has the unprecedented sensitivity to millicharge parameter space for MeV-GeV mass that has not been explored by current experiments.

Figure 10: 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. [31].

For simplicity, a single colliding energy \(\sqrt{s} = 4\) GeV with 20 ab\(^{-1}\) is assumed for obtaining the limits in Fig. (9). 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. (10), 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. (10), which outperforms the \(\sqrt{s} = 7\) GeV mode by a factor of \(\sim 5\). The constraints on millicharge at various colliding energies are also shown in Table (12) for some benchmark points.

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Table 12: The expected 95% C.L. upper bound on millicharge \(\epsilon\) with 10 ab\(^{-1}\) data for three STCF \(\sqrt{s}\) values: 2 GeV, 4 GeV, and 7 GeV, analyzed with the bBG cut [31].

References


7 Summary

The proposed STCF is an $e^+e^-$ collider equipped with a 4π-solid-angle particle detector. Its center-of-mass energy is from 2GeV to 7GeV, the luminosity is designed as high as above $0.5 \times 10^{35}$ cm$^{-2}$s$^{-1}$. The future option is the upgrade of the $e^-$-beam to be polarized one.

We have presented the interesting physics potential at STCF, which covers from the study light hadrons to XYZ states, and possible search of new light particles beyond SM. With unprecedented high luminosity, studies of the spectroscopies in the relevant energy ranges, can provide many more precise knowledge about known states and possibly other new and exotic states, and the studies of the decays and how they interact with other SM particles, can gain new insights with most precise information about parameters in SM electroweak interactions, perturbative and non-perturbative nature of strong QCD interactions, about possible new particles and interactions beyond SM. The topics presented are not all-inclusive, but focused on measurements that are unique to STCF, with emphasis on reaction processes that challenge the SM, are sensitive to new physics and address poorly understood features in existing data. We summarize the highlights in the following.

QCD dynamics and hadron physics The energy range of STCF is in the transition interval between non-perturbative and and perturbative QCD. Experimental data from STCF will provide much more needed information to study QCD dynamics of confinement through the study of hadron spectroscopy and interactions of hadrons. The energy region covers the pair production thresholds for the recently discovered double charmed baryon, the XYZ states, charmed baryons, charm mesons, $\tau$-leptons, and the all of the strange hyperons. With high luminosity, the QCD predicted glueballs/hybrids may finally show more firm traces. (and running above 7 GeV, higher mass doubly charmed baryon or other possible new ones may be studied in more details. ?)

More detailed discussions for hadron spectroscopies have been provided in relevant sections. Two remarkable recent developments in hadron spectroscopies worth emphasis again: 1) the failure of hadron models to anticipate the rich charmonium spectrum of hidden-charm states with masses above the open-charm pair threshold. 2) the emergence of clear experimental evidence for new, light-hadron spectroscopies of QCD-hybrids and glueballs. These developments boost confidence that more detailed spectroscopy study are needed and will be fruitful. STCF will be an idea place to study related issues. The mapping out of the XYZ, glueball and hybrid spectra will require comprehensive measurements of as many decay modes as possible and more sophisticated analysis techniques to extract and interpret exotic mesons that overlap with conventional $q\bar{q}$ states. STCF with the proposed luminosity will be not only a factory of charmonia and charmed hadrons, but also a factory of XYZ exotic mesons. This enables precision studies of rare decays, mass and width measurements of XYZ, and analytical properties of related amplitudes. With close cooperation between high precision experiments at STCF and the LQCD community will produce a robust, first-principle understanding of the confinement of quarks & gluons in the foreseeable future.

Many of the QCD pertubative properties can also be tested at STCF, such as the determinations of the $R$ values at various energy values and therefore also the strong interaction coupling $\alpha_s$, especially at the $\tau$-threshold. More data from STCF can also test NRQCD predictions for charmonia productions to high precisions.

STCF can also measure in great precision of strong interactions at hadron level. Some of the very interesting measurements are the time-like nucleon and hyperon form factors. Currently available time-like experiments demonstrate puzzling features in their threshold cross sections and electric and magnetic form factors. At STCF, time-like nucleon and hyperon form-factors will be measured for $Q^2$ values as high as 40 GeV$^2$ with precisions that match existing space-like region results for the proton & neutron.
Moreover, hyperon polarizations allow new determinations of their parity-violating decay asymmetries and can be used to extract the complex phases between their electric and magnetic form factors. This opens a new, previously unexplored dimension. At STCF Collins fragmentation function can be extracted from studies of inclusive production of two hadrons at the percent level, thereby providing valuable input for obtaining information about nucleon structure in experiments at high energy electron-ion colliders that are currently under planning in China and the U.S.

Electroweak interaction, Flavor physics and CP violation The electroweak interaction is an integrated part of the SM. Most of the 19 fundamental parameters of the SM are the masses of the quarks & leptons and their flavor mixing angles, which are relevant to the electroweak interaction. Important measurements related to the electroweak part of SM can be made at STCF.

Huge $\tau$-pairs produced at the STCF will provide much more accurate measurement of the electroweak couplings and test the universality of the weak interaction. One of the most important test of SM it to see how well the CKM mechanism works. The most general tests of the SM that involve the CKM matrix are to confirm its unitarity and the internal consistency of its elements. The SM coupling strengths for the $u \leftrightarrow s$ and $c \leftrightarrow d$ transitions are determined by CKM matrix element $V_{us}$ and $V_{cd}$, respectively. Both are equal with a tiny well understood correction at $O(10^{-4})$ level. Any significant difference between different quark transitions would be an unambiguous sign of new physics.

From nuclear $\beta$- and kaon decays $|V_{ud}|$ and $|V_{us}|$ are extracted with $\sim 0.2\%$ precision, which is more than an order of magnitude better than that of $|V_{cd}|$ and $|V_{cs}|$ extracted from $D_s$- and $D$- decays, which are $\sim 3\%$, based on BESIII measurements of $D_s \to \mu^+\nu$, $D^+ \to \mu^+\nu$ and $D^0 \to K^- (\pi^-)\ell^+\nu$ decays. The clean environments for $D$ and $D_s$ mesons produced by $\psi(3770) \to DD$ and $\psi(4160) \to D_s^*D_s$, respectively, that are unique to an STCF-like facility, are especially well suited for low-systematic-error $c$-quark transition measurements. Year-long STCF runs at 3.773 GeV and 4.160 GeV would reduce the errors on $V_{cd}$ and $V_{cs}$, hence $|\sin \theta|_c$ to the 0.1–0.2% level, and match those from $\beta$ and kaon decays. STCF will produce a huge number of $\tau$-pair. More precise measurements of $\tau \to K^-\nu_\tau$ and $\tau \to \pi^-\nu_\tau$ can be carried out. This will also assess to determine the value of $\theta_\tau$.

Searching for a non-SM source of CP violation (CPV) is a promising strategy for uncovering signs of physics beyond the SM. The good agreement between the SM calculation of $e'/e$ with its measured value[] restricts the level of non-SM CPV for non-SM parity-changing decays involving $s$-quarks to be $< 6 \times 10^{-5}$, but allow for asymmetries at $O(10^{-3})$ in hyperon parity-conserving decay processes such as $\Lambda \to p\pi^-$ and $\Xi^- \to \Lambda\pi^-$. At STCF, using quantum-entangled, coherent $\Lambda\overline{\Lambda}$ and $\Xi^+\Xi^-\overline{\Xi}^-$ pairs produced via $J/\psi$ decays, a comprehensive search for non-SM CPV asymmetries would probe the sensitivity level between $10^{-3}$ and the SM-level of $\sim 6 \times 10^{-5}$. It is worth noting that sensitivities for CPV in hyperon decays depend linearly on the hyperon polarization and, thus, a future option for an $\sim 80\%$ polarized $e^-$ beam at STCF would boost the discovery potential for hyperon CPV by more than an order of magnitude.

Various CPV processes involve $\tau$-lepton have been discussed. A particularly interesting one is CPV in $\tau \to K_S\pi\nu$. Until now, searches for CPV in the $\tau$-sector have been confined to $O(1\%)$-level studies of $\tau \to K_S\pi\nu$ decays using unpolarized $\tau$-leptons. The corresponding CPV sensitivity for one year of STCF data at $E_{c.m} = 4.26$ GeV will be of order $O(10^{-4})$, which is the level expected for the well-understood influence of SM CPV effects in the neutral kaon meson system. The future polarized $e^-$ beam option would enable unambiguous probes for new-physics sources of CPV in $\tau$-lepton decays to final states that do not contain neutral kaons, such as $\tau^- \to \pi^-\pi^0\nu$. Searches for CPV violation in heavy hadron decays and $\eta/\eta' \to \pi\pi$ decays can also be carried out at STCF.

Other new physics searches beyond SM With high luminosity, a clean collision environment and excellent detector performance, STCF has great potential to search for rare and forbidden decays (see sections 4 and 5), and serve as a powerful instrument for other investigations of physics beyond the SM.
Such searches can be classified into three categories: (1) decays via the flavor-changing neutral current (FCNC); (2) decays with lepton flavor violation (LFV); (3) decays with lepton number violation (LNV). STCF would support searches for $\tau$-lepton LFV and LNV decays with sensitivities of $10^{-8}$ to $10^{-9}$. In addition, it would also serve as a platform to search for proposed low-mass new particles such as dark photons, light scalars and millicharged particles.

The physics program at the STCF is a multi-dimensional program. We emphasize that the unprecedented high luminosity in the energy region $2 \sim 7$ GeV have great physics potential which enable us to have a much more in-depth understanding challenges facing the SM and hopefully to provide some clues/solutions to them. It will play a crucial role in leading the high intensity frontier of elementary particle physics worldwide.