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Experiments at the Super Charm-Tau factory

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Contents

Abstract. **The review discusses the physical program of a new experiment at the Super Charm-Tau factory, the basis of which will be a powerful electron–positron collider with a luminosity of $\sim 10^{35}$ cm^{-2} s^{-1} and an energy in the center of mass system in the range from 3 to 5 GeV. A modern detector located around the beam collision point will provide a new level of measurement accuracy. The longitudinal polarization of the electron beam, along with record luminosity, will allow the unique experiment to successfully compete with the existing Super B-factories Belle II and LHC*b*. The extensive physical program includes the study of the properties and measurement of physical parameters of charmed hadrons, the τ-lepton, the charmonium, and exotic states, as well as the study of the production of light hadrons in e^+e^--annihilation and in two-photon processes. In addition to testing the Standard Model and precisely measuring its parameters, a comprehensive search for New Physics beyond its boundaries is planned.**

Keywords: e^+e^--collider, polarized beams, quantum chromodynamics, τ-lepton, physics of charmed hadrons, New Physics

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1. Introduction

The Standard Model (SM) — a theory describing the three fundamental interactions, strong, weak, and electromagnetic, and the particles of matter participating in them — emerged in the late 1960s thanks to the work of Glashow, Weinberg, and Salam [1–3]. Over the decades of its existence, the SM has overcome numerous experimental tests and is capable of predicting physical processes with unique accuracy. However, despite its outstanding successes, this model has a number of flaws, in particular, incompatibility with the general theory of relativity. In addition, the origin and numerical values of 19 SM free parameters determined experimentally have not yet been explained, nor have phenomena discovered in recent years, such as dark matter, dark energy, and neutrino oscillations. Awareness of the

SM's imperfections naturally motivates a search for a more fundamental theory. Alternatively, in the role of so-called New Physics (NP), various forms of supersymmetric models [4–7], as well as string theory [8], are most often discussed.

Existing NP models offer a variety of ideas for detecting New Physics. The most popular one is the search for particles not predicted within the SM framework. New particles at the maximum available energies are being sought in experiments at the Large Hadron Collider. Another way is to precisely measure SM processes and search for indirect manifestations of NP in interference processes, such as *CP*-violation in the quark and lepton sectors, as well as in rare or forbidden decays, for example, in leptonic flavor violation processes. Similar measurements can be carried out at new generation electron–positron colliders, and since the sensitivity of the experiment to the effects directly depends on the amount of accumulated data, interest in the construction of powerful machines is extremely high today.

Another topical field that is intensively developing at modern e^+e^--colliders is the physics of heavy hadrons. Recent decades have been marked by significant progress in hadron spectroscopy and numerous, including unexpected, discoveries. The main supplier of surprises turned out to be the physics of charm and beauty, which revived interest in the study of excited states of hadrons. In particular, not only were numerous excited states of quark–antiquark mesons and three-quark baryons discovered, but so were a whole series of exotic hadronic states, whose properties do not fit into the routine scheme of the quark model.

The construction of electron–positron colliders operating in a wide energy range with peak luminosities an order of magnitude higher than those achieved, and therefore called 'flavor superfactories,' turned out to be possible thanks to the ingenious 'crab-waist' electron–positron beam collision scheme proposed in 2006 by Raimondi [9]. For the moment, there are two competing projects for a symmetric electron–positron collider designed for precision measurements of the parameters of charmed hadrons and τ-leptons, one Russian [10] and one Chinese [11]. Below, we will discuss the Russian Super Charm-Tau factory (SCTF) project.

1.1 Place of the Super Charm-Tau factory in particle physics

Precision studies of the properties of charmed hadrons and τ-leptons, which occupy a special place in modern particle physics, are carried out mainly in experiments at electron–positron colliders in a wide energy range: at charm-tau factories and B-factories. Today, the Belle II [12, 13] experiment at the SuperKEKB [14] collider at the KEK international scientific center (Tsukuba, Japan) is intensively collecting data in the field of the production of pairs of beauty quarks. However, for the study of charmed hadrons and heavy leptons, it is charm-tau factories that are most in demand. The BESIII experiment at the BEPCII electron–positron collider (Beijing, China) [15] with a luminosity of $10^{33}\ \mathrm{cm^{-2}\,s^{-1}}$ is, at the moment, the only one operating in the energy range in the center of mass system from 2 to 4.6 GeV. This undoubtedly successful charm-tau factory managed to accumulate a volume of data that was almost two orders of magnitude greater than the statistics of its predecessors. At the same time, launched in 2008, BESIII is now no longer able to provide a data set rate that allows precision measurements of the parameters of charmed hadrons and τ-leptons. At the new generation SCTF, the peak luminosity will reach $10^{35}\ \mathrm{cm^{-2}\,s^{-1}}$ with beam energies in the center of mass system in the range from 3 to 7 GeV.

In addition to experiments at electron–positron colliders, heavy hadrons are also studied at the Large Hadron Collider at CERN (Geneva, Switzerland). In particular, the LHC*b* experiment has a record amount of data containing charmed and beauty hadrons. This circumstance, however, does not at all eliminate the need to create charm-tau factories. On the contrary, the difference between experimental conditions at electron–positron and proton colliders provides a unique opportunity for complementary studies of physical processes.

Charm factories are ideally suited for the detailed study of nonrelativistic particles produced at the threshold due to the circumstances listed below.

(1) When τ-leptons and charmed hadrons are produced at the threshold, the particle momentum in the initial state is completely determined, and the multiplicity is small, which creates additional kinematic restrictions for identifying the process under study.

(2) Coherent production of $D^0\bar{D}^0$ pairs, possible only near the threshold, makes it possible to study oscillations of charmed hadrons and *CP*-violation by various methods [16–20], and also to measure the phase difference between the amplitudes of the decays of D^0- and $\bar{D}^0$-mesons.

(3) Full reconstruction of events provides significant background suppression, measurement of the relative probabilities of decays of τ-leptons and charmed hadrons into various final states, and the study of decays into final states with invisible particles.

(4) Polarization of an electron beam increases the sensitivity to *CP*-symmetry violation during the creation and decay of τ-leptons and charmed hadrons and makes it possible to measure the Weinberg angle at the energy of the creation of the J/ψ-state.

1.2 Energy scale of the Super Charm-Tau factory

Within the range of energies available at the SCTF, there are several values of particular interest: the birth thresholds of vector states of charmonium J/ψ, $\psi(2S)$, $\psi(3770)$, and others, the birth threshold of $\tau^+\tau^-$-pairs, and the birth threshold pairs of charmed mesons $D^{(*)}\bar{D}^{(*)}$, $D_s^{(*)}\bar{D}_s^{(*)}$, and pairs of charmed baryons (Fig. 1). All known charmed hadrons can be produced at the SCTF, except for the doubly charmed baryon Ξ_{cc}^{++}, populating the energy range from 3 to 7 GeV. Exclusive cross sections for the production of hadron pairs above 5 GeV have never been measured. The decision on the amount of data collected at specific energies is made during the experiment by an international collaboration in accordance with the interests of the high energy physics community. The preliminary distribution of energy values in the center of mass system for one year of the experiment and the expected number of generated particles are given in Table 1.

1.3 Features of the Super Charm-Tau factory detector

The main components of the SCTF are an electron and positron injection facility, a collider with double storage rings with one interaction region (Fig. 2a), and a universal particle detector surrounding the beam intersection region (Fig. 2b).

The unique features of the installation include the longitudinal polarization of the electron beam near the interaction region, achieved using a photogun source of polarized electrons and significantly enriching the physical program of the experiment. To achieve the required parameters, the

Table 1. Preliminary data-taking plan for SCTF for the first year of operation (10^7 s). Energy in the center of mass system $\sqrt{s}$, corresponding total luminosity L, and the number of events are given.

$\sqrt{s}$, GeV	L, fb^{-1}	Number of events	Production threshold	Key tasks
3.097	300	$\mathcal{O}(10^{12})$	J/ψ	Spectroscopy of light quarks, Weinberg angle, rare decays
3.554	50	—	$\tau^+\tau^-$	Precision measurement of τ-lepton decays
3.686	150	$\mathcal{O}(10^{11})$	$\psi(2S)$	Spectroscopy of light quarks, spectroscopy of charmonium
3.770	300	$\mathcal{O}(10^{9})$	$\psi(3770)$	Decays and mixing of D-mesons, *CP* violation
4.170	100	$\mathcal{O}(10^{8})$	$\psi(4160)$	Decays of D_s-mesons
4.650	100	—	$\Lambda_c^+\Lambda_c^-$	Decays of Λ_c-baryons, form factors

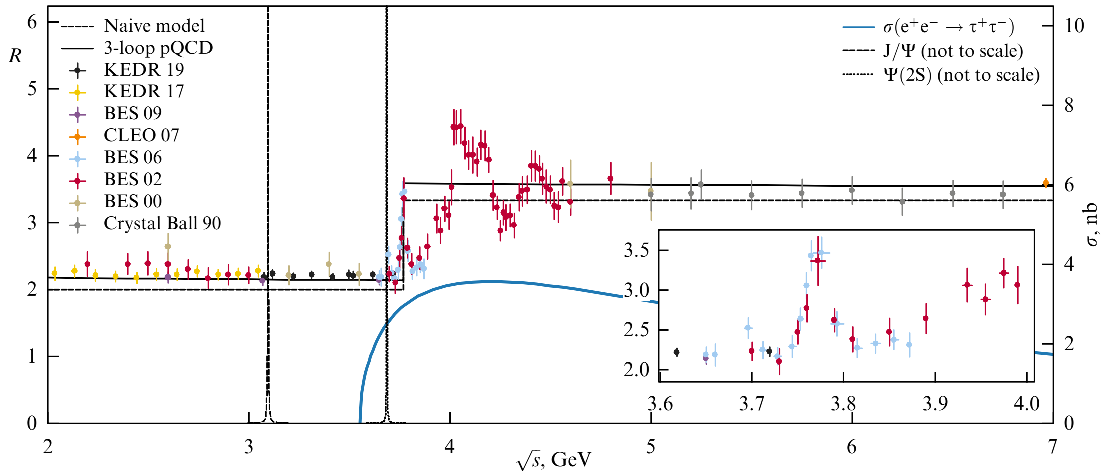

Figure 1. $R \equiv \sigma(e^+e^- \to \text{hadrons})/\sigma_0(e^+e^- \to \mu^+\mu^-)$ for energy from 2 to 7 GeV, measured by various experiments. Data points are shown with dots with error bars, QCD predictions shown with solid and dashed lines. Peaks, corresponding to J/ψ and $\Psi(2S)$ states, are not shown to scale. Blue curve corresponds to $\sigma(e^+e^- \to \tau^+\tau^-)$ cross section. Inset shows region near the charm meson threshold [21].

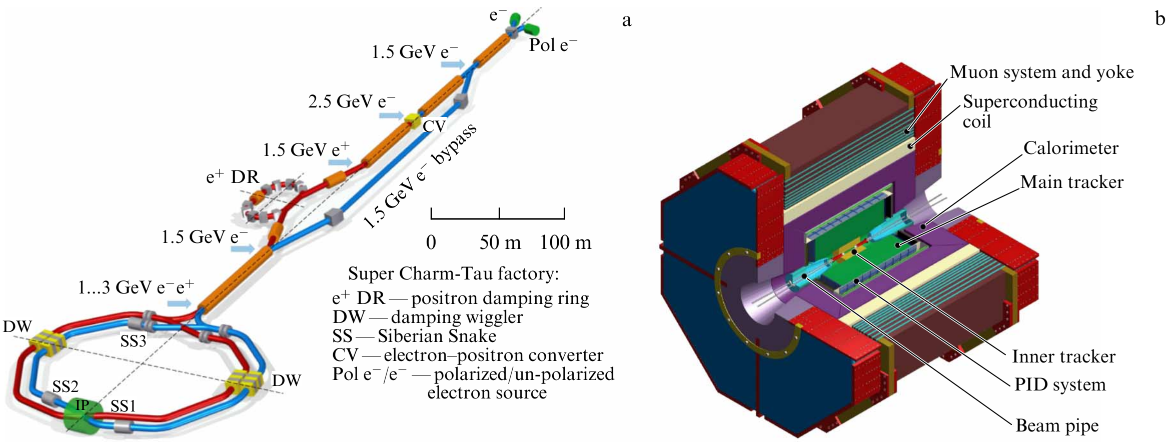

Figure 2. (a) SCTF injector and collider; (b) SCTF detector.

SCTF detector must provide high momentum and energy resolution, as well as have an unrivaled particle identification system. The requirements for the detector to achieve the above characteristics are given below.

• Since the flight path of charmed hadrons and τ-leptons produced near the threshold at a symmetric collider is immeasurably small and the daughter particles have low momentum, the efficiency of recording soft tracks should have a higher priority than the spatial resolution of decay vertices.

• High quality of separation of charged particles by type, especially in the momentum range below 1.5 GeV$/c$, is the most important condition for the SCTF identification system [22].

• The expected frequency of J/ψ-resonance production at the cross-section peak at a luminosity of 10^{35} cm^{-2} s^{-1} and a beam energy spread of 0.1%, which is 300 kHz, determines the maximum permissible event construction time of ~ 1 μs and the high information flow from the data acquisition system (tens of GB s^{-1}).

• The software of the experiment is its prominent component. The Aurora detector user environment at the SCTF, released in 2021 [23], draws on the rich experience of experimental groups, which resulted in the widely used packages Gaudi [24], Geant [25], and ROOT [26]. Subsequent development of Aurora will come from the Key4HEP initiative [27].

2. Charmed hadron spectroscopy at the Super Charm-Tau factory

A substantial part of the SCTF physics program is devoted to hadronic spectroscopy and comprises the following chapters: studies of charmonium states, investigation of conventional $q\bar{q}$ mesons and filling the corresponding multiplets, searches for exotic hadrons with excited gluonic degrees of freedom (glueballs and hybrids), and investigation of multiquark exotic states in the spectrum of the charmonium, including the threshold structures of both the molecular and compact types.

2.1 Spectroscopy of charmonium states

In the framework of the quark model, the charmonium is a bound state of the charmed quark and the corresponding antiquark. The spins of the quarks are summed to the total spin of the system S equal to 0 or 1, and the total momentum of the meson J comes as a sum of the total spin and the angular momentum L, that is, $\mathbf{J} = \mathbf{L} + \mathbf{S}$. The spatial P- and charge C-parity of such a system are calculated according to simple formulae,[1] $P = (-1)^{L+1}$ and $C = (-1)^{L+S}$. Since the quark–antiquark pair can be radially excited, the quark model predicts 8 charmonium states lying below the open-charm threshold (that corresponds to an energy equal to twice the mass of the lightest charmed meson, ~3.73 GeV). They are the pseudoscalar meson η_c and its first radial excitation $\eta_c(2S)$ (the quantum numbers of both states are $J^{PC} = 0^{-+}$), the lightest vector charmonium J/ψ and its first radial excitation $\psi(2S)$ (with the quantum numbers $J^{PC} = 1^{--}$), the axial-vector state h_c (with the quantum numbers $J^{PC} = 1^{+-}$), and the triplet of states χ_{cJ} with $J = 0, 1, 2$ and the quantum numbers J^{++}.

The SCTF is a unique laboratory for a detailed investigation of the spectroscopy of the above 8 charmonia. The vector states J/ψ and $\psi(2S)$ are directly created in e^+e^- annihilation, and their number produced for a year of operation will be $\sim 10^{12}$ and $\sim 10^{11}$, respectively.[2] Then, $\sim 10^{10}$ states χ_{cJ} and η_c will be produced in the consequent decays of J/ψ and $\psi(2S)$. In addition, it is expected that $\sim 4\times10^7$ of h_c's will be produced in the decays $\psi(2S) \to h_c\pi^0$ and $\sim 5\times10^7$ $\eta_c(2S)$'s, in the decays $\psi(2S) \to \eta_c(2S)\gamma$. A physical analysis of this amount of data will allow precisely measuring the partial branching fractions of most of the transitions between the charmonium levels and the masses and widths of the respective states. In particular, for the integrated luminosity of ~ 1 fb^{-1}, the statistical accuracy of the measurements of partial branching fractions for various decays will come to 1%, thus surpassing the capabilities of the lattice calculations in QCD. Scanning in the energy range where narrow resonances are produced will allow measuring the little-known interference phases of their hadronic decay modes. Moreover, SCTF will open the possibility of observing yet unknown transitions between the levels of the charmonium, for example, $\eta_c(2S) \to h_c\gamma$, $\psi(3770) \to \chi_{c2}\gamma$, $\eta_c(2S) \to J/\psi\gamma$, $h_c \to \chi_{c0}\gamma$, with expected partial branching ratios at the level of $10^{-6} - 10^{-3}$.

An equally interesting class of charmonium decays consists of rare decays with a dominating electromagnetic contribution. The upper limit on the probability of one such decay, $J/\psi \to e^+e^-\phi$, obtained recently in the experiment BESIII, $\mathcal{B}(J/\psi \to e^+e^-\phi) < 1,2\times10^{-7}$ [28], exceeds the theoretical prediction of 2.3×10^{-8} by an order of magnitude [29]. Thus, the SCTF enables a critical verification of the theory in this energy range. The physics programme of the SCTF comprises precision measurements of charmonium decays with one or two pions, an η-meson, and photons in the final state, in particular, a direct measurement of the partial branching fractions of the two-photon decays of η_c, χ_{c0}, and χ_{c2}.

The sum of all partial branching fractions of J/ψ decays measured to date constitutes not more than 45% [21], so searches for the yet unknown decays of J/ψ will provide additional information on the dynamics of the strong interaction. Moreover, the high luminosity of the SCTF will allow weak decays of J/ψ to be observed due to the transition $c \to sW^+$ that proceeds with a branching fraction of $\sim 10^{-8}$ [30]. Semileptonic decays of J/ψ to the final states $D_s^*\ell\nu$ and $D_s\ell\nu$ and the hadronic decay modes $D_s^+\rho^-$ and $D_s^{*+}\pi^-$, with a branching fraction of $\sim 10^{-9}$ [30, 31], are also available for measurement at the SCTF. In the SM, the partial branching fractions of J/ψ decays to $D^0\rho^0$ and $D^0\pi^0$ are predicted at the level of $\sim 10^{-11}$ [31] that makes them sensitive to manifestations of the New Physics and, in particular, to the existence of the Flavour Changing Neutral Current $c \to u$ [32]. Another type of weak process ($c\bar{c} \to s\bar{s}$) with W-exchange causes decays, not conserving C-parity, for example, $J/\psi \to \phi\phi$. The expected partial branching fraction of such a decay, $\sim 10^{-8}$ [33], allows one to observe it at the SCTF.

2.2 Spectroscopy of light and exotic hadrons in the mass range below 3 GeV

Despite recent successes of experimental and theoretical physics in low-energy quantum chromodynamics, the spectroscopy of states made of light quarks poses a number of questions to be answered by experiments at the SCTF that allow studying the spectrum of mesons below 3 GeV. The charmonium states with masses below the doubled mass of the D meson decay into hadrons consisting of light u-, d-, and s-quarks. By selecting specific decay modes, one can study hadronic states with almost any quantum number that is important for understanding the nature of the strong interaction. Furthermore, exotic hadrons with excited gluonic degrees of freedom, that is, hybrid mesons and glueballs, can also be produced in such decays. Notably, a promising source of glueballs is provided by the radiative decay of J/ψ with the partial branching fraction $\mathcal{B}(J/\psi \to gg\gamma)$ of $\sim 9\%$. According to lattice simulations, the probability of hadronization of two gluons to a glueball is about $\sim 10^{-3} - 10^{-1}$, depending on the spin parity of the glueball.

A series of candidates for glueballs are found in the radiative decays of J/ψ. Specifically, they are the scalar states

[1] Strictly speaking, angular momentum L is not a conserved quantity, since the Hamiltonian of the system contains the terms mixing the states with the angular momentum different by 2. As seen from the quoted formulae, this does not affect the values of the spatial and charge parities.

[2] Vector states are also produced in the e^+e^- annihilation at higher energies via initial state radiation; however, the corresponding probability is damped by the additional power of the fine structure constant $\alpha = 1/137$.

$f_0(1500)$, $f_0(1710)$, $f_0(2100)$; tensor $f_2(2340)$; pseudoscalar $\eta(2100)$; and others. Since these states can mix with the quark–antiquark and exotic tetraquark states with the same quantum numbers, unambiguous identification of the observed candidates as glueballs requires their further experimental investigation. A specific feature that allows one to tell a glueball from an ordinary quark–antiquark meson is its abnormally little two-photon width, so the search for glueballs in the decays of J/ψ should be supplemented by studies of meson production in two-photon processes.

Searches for hybrid mesons are facilitated by the fact that some of them should possess exotic quantum numbers (for example, $J^{PC} = 1^{-+}$) forbidden for quark–antiquark mesons [34]. Such a state, $\eta_1(1855)$, was first observed by BESIII in the reaction $J/\psi \to \gamma\,\eta\eta'$ [35, 36]. Besides that, other candidates exist, $\pi_1(1400)$, $\pi_1(1600)$, $\pi_1(2015)$, observed in hadronic experiments in the decays of J/ψ and χ_{c1} that still need to be confirmed. Promising channels are the transitions from χ_{c1} to the final states $\eta\pi^+\pi^-$ and $\eta'\pi^+\pi^-$.

One interesting observation of the BESII experiment is the state $X(1835)$ with the quantum numbers $J^{PC} = 0^{-+}$ [38] observed at the $p\bar{p}$ production threshold in the decay $J/\psi \to \gamma p\bar{p}$ [37]. In addition, its decays to the final states $\eta'\pi^+\pi^-$ and $f_0(980)\eta$ [39] were also detected. $X(1835)$ is a candidate for baryonium — a bound state of the proton and antiproton [40]. Further candidates for multiquark states, $f_0(980)$- and $a_0(980)$-mesons, may be $K\bar{K}$ molecules. Many tetraquark states, both molecular-type and compact, are expected to exist and need to be identified.

The mission of the SCTF in studies of light hadrons consists in searching for missing members of light-meson multiplets, and precision measurements of their parameters, including pole positions, quantum numbers, production mechanisms, and decay patterns.

2.3 Spectroscopy of open-charm hadrons

Four ground-state singly-charmed hadrons can be produced at the SCTF: $D^0(c\bar{u})$, $D^+(c\bar{d})$, $D_s^+(c\bar{s})$, and $\Lambda_c^+(udc)$. If the center-of-mass energy of the colliding beams reaches 4.910 (4.934) GeV, production of charmed baryons, $\Sigma_c(udc)$ ($\Xi_c^+(ucs)$ and $\Xi_c^0(dcs)$), will also become possible. The above hadrons possess multiple excitations — some of them have already been studied, but others have not yet been observed because of the difficulties related to their large widths, identification of their decay channels, and low production probabilities. Gaining a better understanding of the nature and spectrum of charmed hadrons requires precision measurements of their decay rates and studies of the corresponding line shapes in various final states.

Constrained by heavy flavor conservation at the SCTF, open-charmed hadrons can be produced only in pairs, and an efficient investigation method for them is the analysis of the exclusive cross sections $e^+e^- \to D_{(s)}\bar{D}_{(s)}X$. A number of these final states were previously studied in the Belle and BaBar experiments employing the initial state radiation technique [41–44]. However, the cross sections of the rarest processes have not been measured yet. Production of charmed hadrons in pairs and the firmly established quantum numbers of the initial state facilitate considerations of a particular reaction, since an amplitude analysis can be employed to identify the studied excitation and its quantum numbers.

2.4 Charmonium-like states

In the last two decades, more than two dozen states in the spectrum of charmonia lying above the open-charm threshold have been found in the experiments Belle, BaBar, CLEO*c*, CDF, D∅, BESIII, and LHC*b* [45]. Only few of them can be identified as excitations of the ordinary $c\bar{c}$ quarkonium, while the others do not fit into the quark model scheme and as such are qualified as exotic 'charmonium-like' [46]. Theoretical approaches employed to interpret these new states include the molecular model [47], the model of compact tetraquarks [48], models of hadrocharmonia [49], and others. Application of the sum rules technique to a hadrons with heavy quarks is discussed in review [50].

Several groups of exotic charmonium states exist. Below, we resort to the historically established XYZ scheme in which the first unexplored states were assigned the letter X, vector states, the letter *Y*, and charged states, the letter Z. Given that a substantial drawback of this scheme is that it is not suitable for an extension to cover further exotic hadronic states such as pentaquarks or doubly-charmed tetraquarks, it is now under substantial revision.

2.5 X-states

The first representative of this family, given both its primogeniture and the number of experimental and theoretical studies devoted to it, is $X(3872)$ [51]. Despite considerable progress gained in its experimental[3] and theoretical investigations, many questions related to its interpretation remain open [46]. Since important information on the exotic state is encoded in its line shape in various decay channels, precision measurements of the open-charm final states at the SCTF, unavailable in experiments at the Large Hadron Collider, will allow us to decipher the nature of $X(3872)$.

Another curious representative of the X family is $X(3915)$, discovered by the Belle collaboration in the reaction $\gamma\gamma \to \omega\, J/\psi$ in a data sample that corresponds to the integrated luminosity of 694 fb^{-1} [55]. A Breit–Wigner approximation of the near-threshold peak allowed determining the $X(3915)$ mass and width, $M = (3915 \pm 3 \pm 2)$ MeV$/c^2$ and $\Gamma = (17 \pm 10 \pm 3)$ MeV. Soon after this, the BaBar collaboration that studied the same process with the statistics of 519.2 fb^{-1} not only confirmed the existence of the state $X(3915)$ but also performed an angular analysis to determine its quantum numbers $J^{PC} = 0^{++}$ [56]. The same state was likely observed in the Belle experiment [57] and then confirmed in the BaBar experiment [58] in the decay $B \to J/\psi\omega K$. It was originally named $Y(3940)$, but later the BaBar collaboration found it to be an overlap of two structures, $X(3872)$ and $X(3915)$ [59]. In view of its measured quantum numbers, there was an attempt to identify $X(3915)$ with the generic charmonium state $\chi_{c0}(2P)$ that had not been observed at that time. It was, however, criticized by theorists for the strong contradiction of the measured properties of $X(3915)$ and the expected parameters of $\chi_{c0}(2P)$ [60, 61]. Today, there is a more promising candidate with the parameters of $\chi_{c0}(2P)$ — the state $\chi_{c0}(3860)$ (originally tagged as $X^*(3860)$) that was found by the Belle collaboration in the reaction $J/\psi D\bar{D}$, with neutral and charged D mesons in the final state, in the analysis of the data sample corresponding to the integrated luminosity of 980 fb^{-1} [62]. The extracted parameters of

[3] See, for example, the latest publications of the LHC*b* [52 – 54] devoted to precision measurements of the $X(3872)$ parameters.

$\chi_{c0}(3860)$ agree well with those predicted in phenomenological studies [60, 63] of the Belle [64] and BaBar [65] data on the transition $\gamma\gamma \to D\bar{D}$ — the discovery mode for the state $\chi_{c2}(3930)$. Therefore, there are good reasons to believe that both these charmonium states may belong to the same multiplet. However, additional studies are necessary to confirm or falsify this hypothesis.

In 2008, the CDF collaboration published a paper [66] stating that, with a significance of 3.8σ obtained with the statistic of 2.7 fb^{-1} in the decay $B^+ \to J/\psi\phi K^+$, a new state X(4140) with a mass of $(4143.0 \pm 2.9 \pm 1.2)$ MeV$/c^2$ and width of $(11.7^{+8.3}_{-5.0} \pm 3.7)$ MeV had been discovered in the final state $J/\psi\phi$. Since X(4140) turned out much narrower than expected for the standard charmonium states lying in this energy range, the discovery of X(4140) attracted a great deal of attention. Further searches for this state had varying success. Neither the Belle [67] nor BaBar [68] nor LHC*b* [69] collaboration could observe it in B-meson decays. Meanwhile, the CDF collaboration, using a large number of statistics corresponding to the luminosity of 6.0 fb^{-1}, not only confirmed the existence of X(4140) with the refined values of the mass and width, $(4143.4^{+2.9}_{-3.0} \pm 0.6)$ MeV$/c^2$ and $(15.3^{+10.4}_{-6.1} \pm 2.5)$ MeV, respectively, but in addition found, with a significance of ~ 3.1 standard deviations, a new structure with a mass of $(4274.4^{+8.4}_{-6.7} \pm 1.9)$ MeV$/c^2$ and width of $(32.3^{+21.9}_{-15.3} \pm 7.6)$ MeV [70]. Later, the CMS and D$\emptyset$ collaborations confirmed manifestations of the state X(4140) in $B^+ \to J/\psi\phi K^+$ decays with a significance exceeding 5.0σ and 3.1σ, respectively [71, 72]. The CMS collaboration confirmed the second peak, previously found by CDF, with, however, a slightly higher mass [71]. The D$\emptyset$ collaboration announced its observation of X(4140) in the final state $\phi J/\psi$ with a mass of $(4152.5 \pm 1.7^{+6.2}_{-5.4})$ MeV$/c^2$ and width of $(16.3 \pm 5.6 \pm 11.4)$ MeV [73]. At the same time, the BESIII collaboration did not observe any significant signal of X(4140) in the process $e^+e^- \to \gamma\phi J/\psi$ at center-of-mass energies $\sqrt{s} = 4.23$, 4.26, 4.36, and 4.60 GeV and only established an upper limit [74, 75]. The LHC*b* collaboration performed a full amplitude analysis of the $B^+ \to K^+\phi J/\psi$ decay for all selected 4289 ± 151 events that correspond to a luminosity of 3 fb^{-1} at the center-of-mass energy of 7 and 8 MeV [76]. A decent description of the data required considering not only the known states X(4140) and X(4274) with the quantum numbers $J^{PC} = 1^{++}$ but also two additional broad resonances, X(4500) and X(4700), with the quantum numbers $J^{PC} = 0^{++}$.

It is obvious that further experimental studies will shed light on the origins of controversial X-states. Precision measurements at the SCTF should finally explain the nature of these exotic states of charmonia.

2.6 Y-states

Vector charmonium-like Y-states can be produced at the SCTF directly in e^+e^- annihilation. The existence of 3 such states, Y(4230) (previously known as Y(4260)), Y(4360), and Y(4660), is regarded as well established, since they are observed in at least two experiments. Originally, the Y-states were found in the reactions $e^+e^- \to J/\psi\pi^+\pi^-$ and $e^+e^- \to \psi(2S)\pi^+\pi^-$. The signal of Y(4230) is also, predictably, seen in the channel $e^+e^- \to J/\psi\pi^0\pi^0$ [77]. However, no clear signals of Y-states were observed in the other studied processes, $e^+e^- \to J/\psi K^+K^-$ and $e^+e^- \to J/\psi K_S K_S$ [78], $e^+e^- \to J/\psi\eta$ [79, 80], $e^+e^- \to J/\psi\eta'$ [81], $e^+e^- \to J/\psi\eta\pi^0$ [82], $e^+e^- \to h_c\pi^+\pi^-$ [83], and $e^+e^- \to \omega\pi^+\pi^-$ [83].

In 2017, the BESIII collaboration provided a high-precision (19 data points in the energy spectrum with the integrated luminosity of 8.2 fb^{-1}) measurement of the cross section of the reaction $e^+e^- \to J/\psi\pi^+\pi^-$ and performed a fit of the obtained data with a sum of 2 resonances with masses of (4222 ± 3) MeV$/c^2$ and (4320 ± 13) MeV$/c^2$) and widths of (44 ± 5) MeV and (101 ± 27) MeV, respectively [84]. The first resonance complies with the state near 4.22 GeV$/c^2$ observed in the process $e^+e^- \to h_c\pi^+\pi^-$, as well as with the structure near 4.2 GeV$/c^2$ in the cross section $e^+e^- \to J/\psi\eta$ [79, 80].

In measurements of the electron–positron annihilation to the final state $\psi(2S)\pi^+\pi^-$ performed by the BESIII collaboration at several values of the center-of-mass energy [85], a nontrivial distribution in the invariant mass of subsystems $\pi\pi$ and $\pi\psi(2S)$ were observed, with the shape substantially changing from one energy of the colliding particles to another. The selected values of the energy, 4.226, 4.258, 4.358, and 4.416 GeV, were not accidental since, presumably, Y-states exist near every such energy. Consequently, the mechanism of the reaction should be sensitive to their nature, which, therefore, reveals itself in the observed line shape.

Theoretical interpretations of vector Y-states encounter a number of obstacles. First, all the slots available for the vector charmonia as predicted by the quark model are exhausted by the standard quarkonia J/ψ, $\psi(2S)$, $\psi(3770)$, $\psi(4040)$, $\psi(4160)$, $\psi(4415)$. Second, the Y-states lying in the spectrum above the open-charm threshold surprisingly do not decay into pairs of charmed mesons, while the partial widths of their decays $Y \to J/\psi\pi^+\pi^-$ (above 1 Mev) exceed by two orders of magnitude similar widths for the standard charmonium, for example, for the transitions $\psi(2S) \to J/\psi\pi^+\pi^-$ and $\psi(3770) \to J/\psi\pi^+\pi^-$.

Although a considerable amount of data on Y-states has been collected in the last few years, it is still not sufficient for a complete theoretical analysis that could allow us to shed light on the origins and properties of these states. No doubt, the record-breaking statistics at the SCTF will make it possible to answer the question of the nature of Y-states.

2.7 Z_c-states

The Z_c family is yet another class of exotic charmonium-like states. The subscript c pinpoints the presence of the charmed quark and its antiquark in their content. Unlike the X- and Y-states, all representatives of the Z_c family are charged and possess a nonzero isospin. Already for this reason alone, they cannot be conventional states of the charmonium, since their minimal quark content is four-quark.

Isotriplet states $Z_c(3900)$ and $Z_c(4020)$ are found in the reaction $e^+e^- \to Z_c\pi$ at the energy of the electron–positron annihilation in the vicinity of the Y(4230) state. Resonance $Z_c(3900)$ decays into the final states $J/\psi\pi$ and $\bar{D}D^*$, and $Z_c(4020)$, into the final states $h_c\pi$ and $\bar{D}^*D^*$. In the decays of Y(4360), the Belle experiment [86] found a hint of the existence of the charged state $Z_c(4055)^+$ decaying into $\psi(2S)\pi^+$. Further studies of this state performed with a substantially larger number of statistics were performed in the BESIII experiment [85]. The parameters of $Z_c(4055)^+$ obtained by BESIII agree with those for $Z_c(4055)^+$ within errors.

As already mentioned in the previous chapter, the dynamics of the process $e^+e^- \to \psi(2S)\pi^+\pi^-$ highly depend on the total energy of the system, so the description of the Dalitz plot obtained in the experiment is only possible if one properly takes into account the nature of the Y- and Z_c-resonances produced as intermediate states in the $e^+e^- \to Y \to Z_c\pi \to \psi(2S)\pi\pi$ cascades. All Z_c-states observed in the reaction $e^+e^- \to Z_c\pi$ have the quantum numbers $J^{PC} = 1^{+-}$. The resonances $Z_c(4200)$ and $Z_c(4430)$, which can be searched for in the decays of Y(4660), have the same quantum numbers.

In publication [87], the BESIII collaboration reports the first measurement of e^+e^- annihilation to the final state $K^+(D_s^- D^{*0} + D_s^{*-} D^0)$ performed in the energy range from 4.628 to 4.698 GeV with the data sample that corresponds to a total integrated luminosity of 3.7 fb^{-1}. In this study, a new state of charmonium with open strangeness is found with a mass of $(3982.5^{+1.8}_{-2.6} \pm 2.1)$ MeV$/c^2$ and width of $(12.8^{+5.3}_{-4.4} \pm 3.0)$ MeV, which was named $Z_{cs}(3982)$. Remarkably, the new state perfectly fits the SU(3) scheme for light quarks and may turn out to be the SU(3) partner of $Z_c(3900)$ found before. In a series of theoretical studies [88–90], the measured line shape of $Z_{cs}(3982)$ is successfully described, and its spin partners are predicted. In particular, if Z(3900) and Z(4020) are treated as spin partners, then, after extending the isospin group of light quarks to SU(3) and taking resonance $Z_{cs}(3982)$ into account, it would be natural to conjecture the existence of the state Z'_{cs} residing near the $\bar{D}_s^* D^*$ threshold. The corresponding predictions are contained in [88, 90] and, in addition, in [90], the scenario of strongly fine-tuned parameters of the system is discussed when the state Z'_{cs} does not appear.

Recently, the LHC*b* collaboration reported the first observation of the exotic state $Z_{cs}(4000)$ decaying to the final state $J/\psi K^+$ [91]. It is unclear yet whether or not this state and the $Z_{cs}(3982)$ structure are manifestations of the same physical object. This is hinted at, for example, by their successful description in a unified coupled-channel framework [89]. Obviously, this matter requires further theoretical studies together with further experimental searches for similar states with open strangeness Z_{cs}, an important task for the SCTF.

3. *CP*-violation study at the Super Charm-Tau factory

Among the most intriguing mysteries of modern physics is the question of why our Universe consists mainly of matter, while antimatter, although found, is present in negligible quantities. To explain the observed dominance of matter in the Universe, it is necessary, among other things, to violate *CP*-symmetry [92], that is, the existence of differences between the properties of particles and antiparticles. This phenomenon means the absence of invariance in the laws of nature with respect to the simultaneous reversal of the direction of the spatial coordinate axes and a change in sign of the charges.

CP-violation was discovered by J Christenson, J Cronin, W Fitch, and R Turley in 1964 [93]. However, it took almost a decade to explain it in the context of the Standard Model of particle physics (being created at the same time). Although the mechanism proposed by M Kobayashi and T Maskawa [94] elegantly and simply explains the occurrence of *CP*-violation, and all experimental data are consistent with their hypothesis that a single parameter is responsible for *CP*-violation — the complex phase of the matrix mixing of quarks — we are convinced that the story of *CP*-violation is not over. As it turned out 20 years later [95], the Kobayashi–Maskawa mechanism does not provide a sufficient magnitude of *CP*-violation necessary for the observed ratio of the amount of matter and antimatter in the Universe, which indicates the existence of additional sources of this phenomenon, which has not yet been identified either theoretically or experimentally. This has caused extraordinary interest in the search for *CP*-violations beyond the SM, because indirect observations of cosmology indicate that this is where New Physics is hiding.

To search for the New Physics and, in particular, new sources of *CP*-violation, it is worth using particles in whose decays a large *CP*-violation is not expected within the framework of the SM. It is only the background that prevents one from discerning manifestations of New Physics. Although the ideal object for studying *CP*-violation within the SM framework is the decays of B-mesons, in which the effect of *CP*-violation is large, it is convenient to look for phenomena beyond the SM in the decays of charmed hadrons and τ-leptons. On the one hand, these particles are heavy and long-lived, which means that the contribution of loop diagrams, in which new heavy particles could participate, is potentially not small for them. On the other hand, within the SM framework, loop effects, in particular *CP*-violation, in the decays under discussion are small (for example, due to the suppression of the GIM by a mechanism) and are not capable of simulating physics outside the SM framework. The contribution of new particles to the decay amplitude can lead to deviations of process parameters from SM predictions by orders of magnitude.

3.1 Search for *CP*-violation in charm baryon decays

One of the most interesting problems in the physics of charmed hadrons is the search for *CP*-violations in the decays of $D_{(s)}$-mesons. For such studies, the SCTF has unique advantages: the creation of pairs of charmed mesons in e^+e^--annihilation at the threshold allows a physical analysis of decays with hard-to-detect particles in the final state, and the low multiplicity of tracks in the event ensures a high efficiency of complete reconstruction. One of the key features of SCTF experiments is the coherent formation of $D^0\bar{D}^0$ pairs in the decay of $\psi(3770)$ states.

The study of *CP*-violation in decays of charmed hadrons has important features. Since in decays of charmed hadrons the initial and final states contain quarks only of the first two generations, the mixing matrix of which is practically unitary, *CP*-violating phases due to interaction with the third generation can arise only through intermediate loop diagrams. However, the latter are so suppressed by the smallness of the V_{cb} constant, as well as by the GIM mechanism, due to the degeneracy of the down quark masses, that, in the most optimistic estimates, the effect of *CP*-violation in the SM does not exceed 10^{-3}, opening up the possibility of searching for phenomena outside the SM.

There are three types of *CP*-violations:

• Direct *CP*-violation in decays of charmed hadrons arises due to the existence of several decay amplitudes of A_f into the final state f with different strong (δ_i) and weak (ϕ_i) phases:

$$A_f = |A_1| \exp[i(\delta_1 + \phi_1)] + |A_2| \exp[i(\delta_2 + \phi_2)] \,. \tag{1}$$

Since the weak phase changes sign during *CP*-conjugation ($\phi_i \to -\phi_i$), and the strong phase remains the same, the probabilities of the conjugate processes turn out to be different: $|\overline{A}_{\bar{f}}| \neq |A_f|$. The main way to search for direct *CP*-

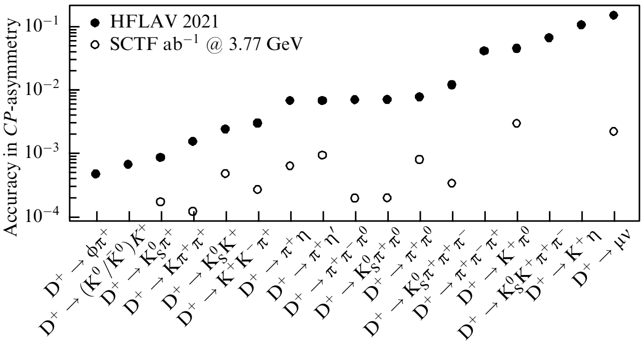

Figure 3. Experimental limits on the accuracy of measuring CP asymmetry in various decay modes of D^+ mesons shown by dots [103]. Expected accuracy in measuring CP asymmetry at SCTF is shown by circles.

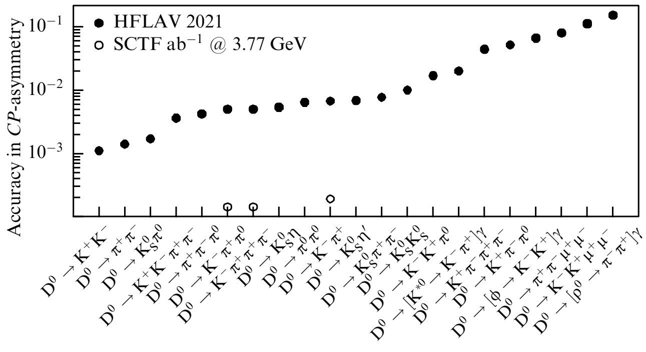

Рис. 4. Experimental limits on CP asymmetry measurement accuracy in various D^0 meson decay modes shown by black dots [103]. Circles indicate expected accuracy of CP asymmetry measurement at SCTF.

violation is to analyze the decays of charged D^+- and D_s^+-mesons. This is the only type of CP-violation that contributes to the amplitude of these processes. The asymmetry of direct CP-violation has the form

$$A_{CP}^{\pm} = \frac{\Gamma(D_{(s)}^- \to f^-) - \Gamma(D_{(s)}^+ \to f^+)}{\Gamma(D_{(s)}^- \to f^-) + \Gamma(D_{(s)}^+ \to f^+)} \,. \tag{2}$$

The measurement accuracy of $A_{CP}^{\pm}$ and the corresponding predicted accuracy at the SCTF for various final states are shown in Fig. 3.

• CP-violation as a result of mixing appears in the decays of neutral D^0-mesons. Since the weak interaction allows transitions with the charm changing by 2, the eigenstates of the Hamiltonian can be represented as

$$|D_{1,2}\rangle = p|D^0\rangle \pm q|\bar{D}^0\rangle \,, \tag{3}$$

where p and q are some coefficients, and $|p|^2 + |q|^2 = 1$. To preserve CP symmetry, the equality $|q/p| = 1$, and any deviation from it leads to CP-violations. The measurement accuracy of $|q/p|$ at the SCTF after one year of data collection corresponding to a luminosity of 1 ab^{-1} is expected to be $\mathcal{O}(10^{-3})$.

• For a system of neutral D^0 mesons, CP-violation can manifest itself in the interference of amplitudes with and without mixing. This type of CP-violation is characterized by the parameter

$$\varphi = \arg\left(\frac{q}{p}\frac{\overline{A}_f}{A_f}\right) . \tag{4}$$

The contribution of mixing to CP-violation can be isolated by studying the difference among the widths of semileptonic decays $\Gamma(\bar{D}^0 \to l^+X) \neq \Gamma(D^0 \to l^-X)$. At the SCTF, thanks to the creation of $D^0\bar{D}^0$-pairs in a state of quantum entanglement, it is possible to measure the asymmetry:

$$A_{SL} = \frac{\Gamma_{1^+1^+} - \Gamma_{1^-1^-}}{\Gamma_{1^+1^+} + \Gamma_{1^-1^-}} = \frac{1 - |q/p|^4}{1 + |q/p|^4} \,. \tag{5}$$

All of the listed types of CP-violation can contribute to decays of D^0-mesons. The greatest effect is expected in Cabibbo-suppressed decays [96]. Any observation of CP-violation in such decays exceeding $\mathcal{O}(10^{-3})$ indicates the manifestation of NP. Recently, the LHC*b* collaboration published an intriguing result [97, 98]:

$$\begin{aligned} \Delta A_{CP} &\equiv A_{CP}(D^0 \to K^+K^-) - A_{CP}(D^0 \to \pi^+\pi^-) \\ &= (-1.54 \pm 0.29) \times 10^{-3} \,, \end{aligned} \tag{6}$$

which initiated a wide discussion about whether such asymmetry can be described within the framework of the SM by taking into account radiation in the final state [99, 100] or whether it is a manifestation of NP [101, 102]. To provide convincing evidence of the existence of CP-violations in the decays of charmed hadrons, it is necessary to measure a number of channels, including $D^0 \to \pi^0\pi^0$, $D^0 \to \pi^+\rho^-$, $D^0 \to K^+K^{*-}$, $D^+ \to K^+K^{*0}$, $D^+ \to \eta\eta^+$, $D_s^+ \to \pi^0K^{*+}$, and $D_s \to \pi^+K^{*0}$. The experimentally established upper limits on the contribution of CP-violating processes, as well as the expected accuracy of measurements at the SCTF for decays of D^0-mesons, are shown in Fig. 4.

3.2 *CP*-violation in τ decays

The short lifetime of the τ lepton, 2.9×10^{-13} s, significantly complicates measurement of its electric dipole moment (EDM) d_τ and anomalous magnetic dipole moment $a_\tau = (g-2)_\tau/2$. While the SM predicts the a_τ value with an accuracy of 5×10^{-8} [104], the measurement of this parameter using the precession of τ-lepton spin in a magnetic field, as is done in experiments devoted to the determination of the electron and muon $g-2$, is not feasible. Another promising approach assumes studying τ-pair production with their subsequent decay. Today, in experiments at e^+e^--colliders, the measurement accuracy of a_τ has reached $\mathcal{O}(10^{-2})$ [105], which is just an order of magnitude larger than the leading contribution of the SM to this value, $\simeq 0.001$ [106]; precision measurement of a_τ is another possibility in the search for NP to reveal itself. Since many NP models predict new contributions to a_ℓ value for lepton ℓ to be proportional to m_ℓ^2, where m_ℓ is the mass of the lepton, a_τ turns out to be significantly more sensitive to NP effects than a_μ is. In these scenarios, the existing shift of the muon anomalous magnetic moment $(g-2)$ corresponds to the effect of $\mathcal{O}(10^{-6})$ for a_τ, and, in some models, simple scaling is violated, and a much larger effect is expected [107].

Since the SM predicts an extremely small value for d_τ, which is far beyond the experimental capabilities, a result with a nonzero value of d_τ will be a direct indication of the NP contribution, leading to CP-violation.

The best limit on the EDM of the τ lepton at a 95% confidence level, recently set in the Belle experiment [108], is

$$-1.85 < \mathrm{Re}\,(d_\tau) < 0.61(10^{-17}\,e\ \mathrm{sm}),$$
$$-1.03 < \mathrm{Im}\,(d_\tau) < 0.23(10^{-17}\,e\ \mathrm{sm})\,. \qquad (7)$$

This result was obtained by analyzing the influence of the effective operator for the τ-lepton EDM on the process $e^+e^- \to \tau^+\tau^-$ [109]. A similar approach is proposed for a joint measurement of a_τ together with d_τ in the same process [110]. Effective Lagrangian

$$\mathcal{L}_{a_\tau} = \frac{e}{4m_\tau}\, a_\tau^{\mathrm{NP}}\, \bar{\tau}\sigma_{\mu\nu}\tau F_{\mu\nu} \qquad (8)$$

is used to construct optimal observables proportional to

$$a_\tau^{\mathrm{NP}} \equiv a_\tau - a_\tau^{\mathrm{SM}}\,, \qquad (9)$$

where a_τ^{NP} is the deviation in the τ-lepton anomalous magnetic moment from the value expected in the SM. Although the full integrated luminosity of the Belle II experiment (50 ab^{-1}) allows a a_τ^{NP} measurement accuracy of $\mathcal{O}(10^{-5})$ to be obtained [110], the experimental sensitivity to a_τ^{NP} $\left(\mathcal{O}(10^{-3})\right)$ is limited by the accuracy of up-to-date calculations of the $e^+e^- \to \tau^+\tau^-$ process cross section, including next-to-leading order contributions $\mathcal{O}(\alpha^3)$ [111], while, to achieve a sensitivity to a_τ of $\sim 10^{-5}$, it is necessary to consider corrections of higher orders.

The polarized electron beam at the SCTF significantly improves the sensitivity to d_τ (especially to its real part $\mathrm{Re}\,(d_\tau)$) [112, 113]. The absence of next-to-next-to-leading order corrections to the $e^+e^- \to \tau^+\tau^-$ cross section does not limit the sensitivity to d_τ, since the effective Lagrangian, which depends on d_τ, is a *CP*-odd function, while the SM Lagrangian is a *CP*-even function.

The probabilities of five-body leptonic decays $\tau^- \to \ell^-\ell'^+\ell'^-\bar{\nu}_\ell\nu_\tau$ $(\ell,\ell' = \mathrm{e},\mu)$, suppressed in the SM compared to the probabilities of ordinary leptonic τ-decays by the coefficient α^2, are an important source of background in the search for lepton-flavor-violating decays $\tau \to \ell\ell'^+\ell'^-$, since neutrinos in the final state are not detected. In addition, such processes are convenient both for searching for sterile neutrinos and dark photons [114, 115] and for testing the Lorentz structure of the charged weak interaction [116]. Study [116] proposes to consider correlations that are odd with respect to time inversion (*T*-odd) as a convenient tool for searching for nonstandard *CP*-violation in the lepton sector of the SM and to determine triple products: $\boldsymbol{\zeta}(\mathbf{p}_1 \times \mathbf{p}_2)$, $\boldsymbol{\zeta}(\mathbf{p}_2 \times \mathbf{p}_3)$, and $\boldsymbol{\zeta}(\mathbf{p}_1 \times \mathbf{p}_3)$, where $\boldsymbol{\zeta}$ is the τ polarization vector, and $\mathbf{p}_i$ are momentum vectors of emitted leptons. For such measurements, the experiment at the SCTF with a polarized electron beam and, therefore, with a nonzero average polarization of one τ lepton, has a significant advantage over Belle II.

CP-violation can be observed in hadronic τ-decays in the presence of two interfering amplitudes with different strong and weak phases. Asymmetry $A_{CP} = (\Gamma(\tau^+ \to f^+\nu) - \Gamma(\tau^- \to f^-\nu))/(\Gamma(\tau^+ \to f^+\nu) + \Gamma(\tau^- \to f^-\nu))$ is proportional to $\sin\delta_s \sin\delta_w$, where δ_w and δ_s are relative weak (*CP*-odd) and strong (*CP*-even) phases of two amplitudes, respectively. Since the τ-lepton decays are described with the same amplitude with the exchange of the W boson, the observation of *CP*-violation is a clear sign of physics beyond the SM. The only exception is the $\tau \to K^0_{S(L)}\pi\nu$ decay, in which the *CP* asymmetry of $\sim 10^{-3}$ originates from the SM due to *CP*-violation in neutral-kaon decays [117]. The most promising decays are the following: $\tau^\pm \to K^\pm\pi^0\nu$, $\tau^\pm \to K^0_S\pi^\pm\nu$, $\tau^\pm \to K^0_S\pi^\pm\pi^0\nu$, $\tau \to \rho\pi\nu$, $\tau \to \omega\pi\nu$, $\tau \to a_1\pi\nu$ [118–123].

In addition to the measurement of the decay total width asymmetry, it is proposed to measure the so-called modified asymmetry, as well as the asymmetry in triple products $\boldsymbol{\zeta}_\tau(\mathbf{p}_1 \times \mathbf{p}_2)$, where $\boldsymbol{\zeta}_\tau$ is the τ-lepton polarization vector, and $\mathbf{p}_1$ and $\mathbf{p}_2$ are momenta of two hadrons in the final state. The modified asymmetry is constructed by integrating the measured differential cross section of final hadrons in a certain region of the phase space with some specially selected function. The asymmetry in triple products is proportional to $\cos\delta_s \sin\delta_w$, and, to observe it, a nonzero strong phase difference is not required.

Studies of *CP*-violation in $\tau^- \to \pi^- K_S(\geqslant 0\pi^0)\nu_\tau$ decays in the BaBar experiment [124] and in $\tau^- \to K_S\pi^-\nu_\tau$ decays in the Belle experiment [125] provided important information about *CP*-violation sources in hadronic τ-decays with neutral kaons. The measured asymmetry of total decay widths in the BaBar experiment,

$$\mathcal{A}_{CP} \equiv \frac{\Gamma(\tau^+ \to \pi^+ K_S(\geqslant 0\pi^0)\nu_\tau) - \Gamma(\tau^- \to \pi^- K_S(\geqslant 0\pi^0)\nu_\tau)}{\Gamma(\tau^+ \to \pi^+ K_S(\geqslant 0\pi^0)\nu_\tau) + \Gamma(\tau^- \to \pi^- K_S(\geqslant 0\pi^0)\nu_\tau)}$$
$$= (-0.36 \pm 0.23 \pm 0.11)\%\,, \qquad (10)$$

differs by 2.8 standard deviations from the SM prediction of $\mathcal{A}_{CP}^{K^0} = (+0.36 \pm 0.01)\%$. Asymmetry in the form of the difference between the average values of the kinematic variable combination for the decays of τ^-- and τ^+ leptons, measured in the Belle experiment in several ranges of the squared invariant mass of the $K^0_S\pi^-$ combination, in contrast to the asymmetry of the total widths $\mathcal{A}_{CP}$, is sensitive to *CP*-violating effects associated with additional exchange of a charged scalar boson [120]. Although *CP*-violation was not found in the entire range of invariant masses of the $K^0_S\pi^-$ pair, important limits on the parameters of models with Higgs multidoublets [126, 127] were obtained, in particular, $|\mathrm{Im}(XZ^*)| < 0.15\, m^2_{H^\pm}/(1\ \mathrm{GeV}^2)$, at a 90% confidence level, where $m_{H^\pm}$ is the mass of the lightest charged Higgs boson, and the complex constants Z and X describe the interactions of the Higgs boson with leptons and quarks, respectively.

The unprecedent statistics at the SCTF will ensure searches for *CP*-violation in various hadronic decays of τ-leptons with a sensitivity of $\sim 10^{-4}$. Longitudinal polarization of the electron beam will make it possible to obtain polarized single τ-leptons (to measure the effects of polarization of a τ-lepton, it is not necessary to reconstruct the decay of the second, tagging τ-lepton) and to search for *CP*-violations in hadronic decays τ-leptons, regardless of the value of the relative hadronic phase.

4. Precision tests of the Standard Model at the Super Charm-Tau factory

4.1 Testing lepton flavor universality using charmed meson decays

The universality of weak interactions can be tested using leptonic decays of charmed mesons. The width of these decays reads

$$\Gamma\,(D^+ \to l^+\nu) = \frac{G_F^2}{8\pi} f_D^2\, m_l^2\, M_D \left(1 - \frac{m_l^2}{M_D^2}\right)^2 |V_{cd}|^2\,, \qquad (11)$$

where M_{D} and m_{l} are the masses of the charmed D meson and lepton, respectively, G_{F} is the Fermi constant, $|V_{\mathrm{cd}}|$ is an element of the Cabibbo–Kobayashi–Maskawa (CKM) matrix, and $f_{\mathrm{D}_{(s)}}$ is the $\mathrm{D}_{(s)}$ meson form factor. The value of $|V_{\mathrm{cd}}|$ is known with high accuracy from measurements of semileptonic decays of charmed D mesons. The latest lattice calculations allow obtaining the values of $f_{\mathrm{D}_{(s)}}$ with a subpercent uncertainty. Thus, the width of lepton decays of charmed mesons can be calculated with high accuracy.

Leptons of any generation can be produced in the decays of D mesons, but only final states with muons and τ leptons are available for measurement at the moment. The low mass of the electron leads to suppression of the final states with $e^{\pm}$, and the branching fractions of the decays $\mathrm{D}^+ \to e^+\nu_e$ and $\mathrm{D}_s^+ \to e^+\nu_e$ are expected to be very small, $\mathcal{O}(10^{-8})$ and $\mathcal{O}(10^{-7})$, respectively.

Within the framework of the SM, taking into account the difference in the phase space, the ratio of D^+ partial widths can be estimated as follows:

$$R_{\tau/\mu}^{\mathrm{SM}} \equiv \frac{\mathcal{B}(\mathrm{D}^+ \to \tau^+\nu)}{\mathcal{B}(\mathrm{D}^+ \to \mu^+\nu)} = \frac{m_\tau^2\left(1 - m_\tau^2/m_{\mathrm{D}^+}^2\right)^2}{m_\mu^2\left(1 - m_\mu^2/m_{\mathrm{D}^+}^2\right)^2} = 2.67\,. \qquad (12)$$

The measured value, $R_{\tau/\mu}^{\mathrm{exp}} = 3.21 \pm 0.64 \pm 0.43$ [128], agrees with the theoretical estimate within the errors. Both statistical and systematic uncertainties will be reduced significantly at the SCTF.

The expectations around the SM and results of measurements for similar decays of D_s mesons are $R_{\tau/\mu}^{s\,(\mathrm{SM})} = 9.76$ and $R_{\tau/\mu}^{s\,(\mathrm{exp})} = 10.38 \pm 0.80$, respectively. The expected improvement in accuracy at the SCTF is at the percent level.

Measurements of the leptonic decays of charmed mesons, problematic at B factories and in hadron experiments like ATLAS and CMS, are an important part of the SCTF physics program.

4.2 Lepton universality test with τ lepton decays

Lepton flavor universality in the charged sector of the SM is a fundamental assumption about the independence of the charged weak current from the leptonic flavor. It is introduced in theory as equality of the coupling constants for e^-, μ^-, and τ^-: $g_e = g_\mu = g_\tau$.

That universality can be tested experimentally by comparing leptonic decays $\tau^- \to e^-\bar{\nu}_e\nu_\tau$, $\tau^- \to \mu^-\bar{\nu}_\mu\nu_\tau$, and $\mu^- \to e^-\bar{\nu}_e\nu_\mu$. Precision verification requires precise measurements of the τ-lepton's mass and lifetime as well as the relative probabilities of its leptonic decays. At the moment, the averaged lepton universality in the ratios g_τ/g_e and g_τ/g_μ has been confirmed with an accuracy of 0.14% [129]:

$$g_\tau/g_e = 1.0029 \pm 0.0014\,, \; g_\tau/g_\mu = 1.0010 \pm 0.0014\,.$$

At the same time, the LEP Electroweak collaboration showed that the ratio of the probability of the decay of a W^- boson to $\tau^-\bar{\nu}_\tau$ to the average probability of W^--boson decays by $\mu^-\bar{\nu}_\mu$ and $e^-\bar{\nu}_e$ differs from unity by 2.6 standard deviations [130]:

$$\frac{2\mathcal{B}(\mathrm{W}^- \to \tau^-\bar{\nu}_\tau)}{\mathcal{B}(\mathrm{W}^- \to \mu^-\bar{\nu}_\mu) + \mathcal{B}(\mathrm{W}^- \to e^-\bar{\nu}_e)} = 1.066 \pm 0.025\,.$$

Such disagreements indicate the need to further improve the accuracy of measuring the parameters of lepton decays of the τ-lepton, along with precision measurements of its mass and lifetime at the SCTF, which will make it possible to verify leptonic universality in the ratios g_τ/g_e and g_τ/g_μ on a new level.

An alternative way to test lepton universality is to use hadronic decay amplitudes $\tau^- \to \pi^-\nu_\tau$ and $\tau^- \to \mathrm{K}^-\nu_\tau$ [131] and the same amplitudes arising in the hadronic parts of the matrix elements of the decays $\pi^- \to \mu^-\bar{\nu}_\mu$ and $\mathrm{K}^- \to \mu^-\bar{\nu}_\mu$. In the relationship

$$R_{\tau/\mathrm{P}} = \frac{\Gamma(\tau^- \to \mathrm{P}^-\nu_\tau)}{\Gamma(\mathrm{P}^- \to \mu^-\bar{\nu}_\mu)} = \left|\frac{g_\tau}{g_\mu}\right|^2 \frac{m_\tau^3}{2m_{\mathrm{P}}m_\mu^2}\,\frac{(1 - m_{\mathrm{P}}^2/m_\tau^2)^2}{(1 - m_\mu^2/m_{\mathrm{P}}^2)^2}\,(1 + \delta R_{\tau/\mathrm{P}})\,, \qquad (13)$$

where $\mathrm{P} = \pi$, K, the dependence on hadronic matrix elements (decay constants f_{P}) is reduced. Radiative corrections for process amplitudes that differ due to different energy scales $\tau^- \to \mathrm{P}^-\nu_\tau$ and $\mathrm{P}^- \to \mu^-\bar{\nu}_\mu$ are estimated in [131, 132]:

$$\delta R_{\tau/\pi} = (0.16 \pm 0.14)\%\,, \quad \delta R_{\tau/\mathrm{K}} = (0.90 \pm 0.22)\%\,. \qquad (14)$$

Ratios of coupling constants obtained from these values and the known relative probabilities of decays $\tau^- \to \pi^-\nu_\tau$ and $\tau^- \to \mathrm{K}^-\nu_\tau$ [133],

$$\left|\frac{g_\tau}{g_\mu}\right|_\pi = 0.9958 \pm 0.0026\,, \quad \left|\frac{g_\tau}{g_\mu}\right|_{\mathrm{K}} = 0.9879 \pm 0.0063\,, \qquad (15)$$

are consistent with lepton universality [103].

At the SCTF, at an energy near the threshold for the production of $\tau^+\tau^-$ pairs, a charged pion and kaon from the decays of $\tau^- \to \mathrm{K}^-\nu_\tau$ and $\tau^- \to \pi^-\nu_\tau$ are almost monochromatic, which will make it possible to select very pure events and thereby increase the accuracy of measuring the relative probability of these processes. Precision measurement of radiative decays $\tau^- \to \mathrm{P}^-\nu_\tau\gamma$ $(\mathrm{P} = \pi, \mathrm{K})$ at the SCTF will improve the accuracy of calculating corrections $\delta R_{\tau/\pi}$ and $\delta R_{\tau/\mathrm{K}}$ necessary to test lepton universality in the relations $R_{\tau/\pi}$ and $R_{\tau/\mathrm{K}}$ [134]. It is important to note that the angular distribution of the pion escape from the $\tau^- \to \pi^-\nu_\tau$ decay, which determines the polarization of the τ-lepton, makes it possible to control the polarization of the electron beam with an accuracy of $\lesssim 10^{-3}$.

4.3 Measuring the Weinberg angle with J/ψ decays

The polarized electron beam at the SCTF will make it possible to measure the fundamental parameter of the electroweak model — the mixing angle, or Weinberg angle

$$\sin^2\theta_{\mathrm{W}} = 1 - \frac{m_{\mathrm{W}}^2}{m_{\mathrm{Z}}^2}\,, \qquad (16)$$

where m_{W} and m_{Z} are the masses of W and Z bosons, respectively. The coupling constant of the Z boson with fermions has the following form in the SM:

$$v_{\mathrm{f}}^{\mathrm{Z}} = T_{\mathrm{f}} - 2Q_{\mathrm{f}}\sin^2\theta_{\mathrm{eff}}^{\mathrm{f}}\,, \qquad (17)$$

where Q_{f} is electric charge and T_{f} is the third isospin component of the fermion. The effective value $\sin^2\theta_{\mathrm{eff}}^{\mathrm{f}}$ includes radiative corrections and depends on the transmitted momentum:

$$\sin^2\theta_{\mathrm{eff}}^{\mathrm{f}} \equiv \kappa_{\mathrm{f}}(Q^2)\sin^2\theta_{\mathrm{W}}\,. \qquad (18)$$

The most accurate measurements of $\sin^2\theta^{\mathrm{f}}_{\mathrm{eff}}$ were made in experiments at LEP [135–138] and SLD [139] at the Z boson peak [140]. The Weinberg angle $\sin^2\theta^{\mathrm{f}}_{\mathrm{eff}}$ was measured in several experiments at low energies in atomic and neutrino experiments [141]. An SCTF experiment with a beam of polarized electrons will make it possible to obtain the value of $\sin^2\theta^{\mathrm{c}}_{\mathrm{eff}}$ for the charm quark at $Q^2 = m^2_{\mathrm{J}/\psi}$ with high precision by measuring the left-right asymmetry

$$\mathcal{A}_{\mathrm{LR}} \equiv \frac{\sigma_{\mathrm{R}} - \sigma_{\mathrm{L}}}{\sigma_{\mathrm{R}} + \sigma_{\mathrm{L}}}\,, \tag{19}$$

where σ_{R} (σ_{L}) is the total cross J/ψ production section with left-polarized (right-polarized) electrons. Asymmetry produced by interference between the amplitudes of processes $\mathrm{e^+e^-} \to \gamma^*$ and $\mathrm{e^+e^-} \to \mathrm{Z}$ and related to the Weinberg angle has the following form [142]:

$$\mathcal{A}_{\mathrm{LR}} = \frac{3 - 8\sin^2\theta^{\mathrm{c}}_{\mathrm{eff}}}{16\sin^2\theta^{\mathrm{c}}_{\mathrm{eff}}(1-\sin^2\theta^{\mathrm{c}}_{\mathrm{eff}})}\left(\frac{m_{\mathrm{J}/\psi}}{m_{\mathrm{Z}}}\right)^2 \mathcal{P}_{\mathrm{e}} \approx 4.7\times 10^{-4}\mathcal{P}_{\mathrm{e}}\,, \tag{20}$$

where $\mathcal{P}_{\mathrm{e}}$ is the average polarization level of electrons. Measuring the asymmetry requires accurate knowledge of the average polarization level and the number of collisions occurring at different electron polarizations. The average polarization level of electrons can be obtained from data by measuring the process $\mathrm{J}/\psi \to \Lambda\overline{\Lambda}$, $\Lambda \to \mathrm{p}\pi^-$, $\overline{\Lambda} \to \overline{\mathrm{p}}\pi^+$ [143]. The relative accuracy of the asymmetry $\mathcal{A}_{\mathrm{LR}}$ measurement with $\mathcal{P}_{\mathrm{e}} = 0.8$ reaches 5×10^{-3} and the relative accuracy of the Weinberg angle measurement is comparable to the uncertainty of the most precise measurement at the Z boson peak:

$$\frac{\mathrm{d}\sin^2\theta^{\mathrm{c}}_{\mathrm{eff}}}{\sin^2\theta^{\mathrm{c}}_{\mathrm{eff}}} \approx 3\times 10^{-3}\,. \tag{21}$$

Precision measurement of the angle $\sin^2\theta^{\mathrm{c}}_{\mathrm{eff}}$ will make possible the search for indirect manifestations of the NP [144]. The existence of hypothetical particles like Z′, the leptoquark, and others may significantly affect the observable value of the weak charge and, therefore, the weak mixing angle value. Any deviation from the SM prediction will be a clear indication of the NP.

An SCTF experiment probes the vertex of the Z-boson interaction with the charm quark using $\sin^2\theta^{\mathrm{c}}_{\mathrm{eff}}$ measurements. The only competing experiment is SLD with a polarized beam.

4.4 Michel parameter measurement in τ decays

In the SM, the τ lepton decays through a charged weak current described by the exchange of a vector $\mathrm{W}^{\pm}$ boson, which interacts only with left-handed fermions. Decays $\tau^- \to \ell^-\bar{\nu}_\ell\nu_\tau$, $\tau^- \to \ell^-\bar{\nu}_\ell\nu_\tau\gamma$, and $\tau^- \to \ell^-\ell'^+\ell'^-\bar{\nu}_\ell\nu_\tau$ ($\ell, \ell' = \mathrm{e}, \mu$) are of particular interest, since electroweak interactions in them can be tested without contributions from the strong interaction. This characteristic makes such decays an ideal system for studying the Lorentz structure of a charged weak current.

As for the neutrino and the spin of the charged lepton in the final state not being detected, the predicted energy spectrum of the daughter lepton in the $\tau^- \to \ell^-\bar{\nu}_\ell\nu_\tau$ decay is parameterized by four Michel parameters (ρ, η, ξ, and δ) [145]. The Michel parameters are experimentally measured bilinear combinations of generalized coupling constants of the charged weak interaction, and they have the following values in the SM: $\rho = 3/4$, $\eta = 0$, $\xi = 1$, and $\delta = 3/4$. In the radiative leptonic decay $\tau^- \to \ell^-\bar{\nu}_\ell\nu_\tau\gamma$, three additional parameters arise, $\bar{\eta}$, η'', and $\xi\kappa$ [146]. The Michel formalism for the five-body leptonic decay $\tau^- \to \ell^-\ell'^+\ell'^-\bar{\nu}_\ell\nu_\tau$ is described in [116].

To measure the parameters ξ and δ, it is required to know the direction of the τ-lepton polarization vector. In experiments in $\mathrm{e^+e^-}$ colliders with unpolarized beams, such as Belle II, the average polarization of one τ lepton is zero, and to measure the parameters ξ and δ, one has to use the correlation between spins of τ^+ and τ^- leptons in the process $\mathrm{e^+e^-} \to \tau^+\tau^-$. Currently, in τ-decays, the parameters ρ, η, ξ, and δ are known with an accuracy of (1–4)% [21]. Measurement of Michel parameters in leptonic τ-decays with an integrated luminosity of 485 fb^{-1} collected by the Belle experiment showed that the statistical uncertainty is $\sim 10^{-3}$ [147]. Using a polarized electron beam at the SCTF will allow τ-lepton production with nonzero average polarization, which significantly simplifies the measurement of physical quantities that depend on the polarization of the τ lepton. With the full statistics from the Belle II and SCTF experiments, the statistical uncertainty of the Michel parameters will reach the level of 10^{-4} [148], and systematic ones will become dominant.

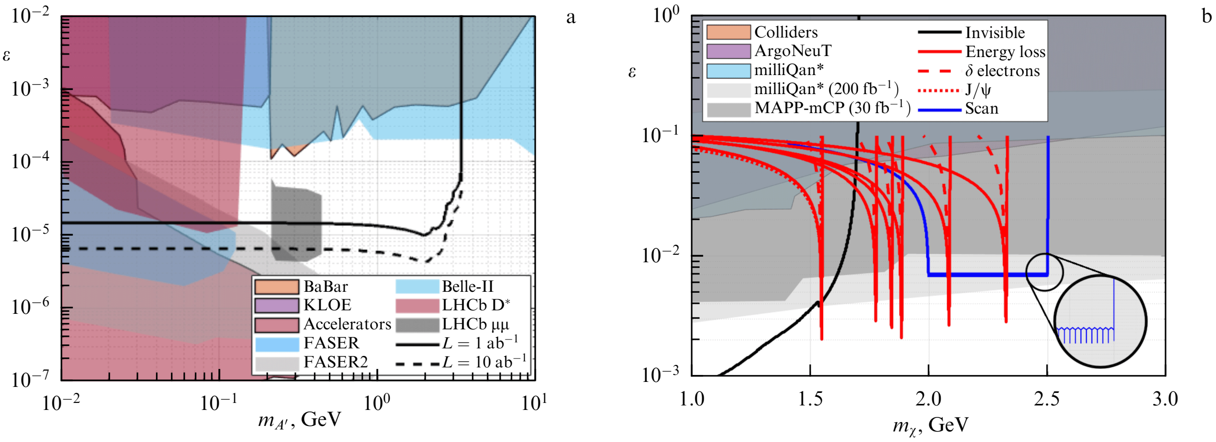

Figure 5. (a) Restrictions on the mass of hidden massive photon A′ [160]. (b) Restrictions on the mass and charge of millicharged particle χ for the SCTF [161].

The first measurement of the Michel parameters in radiative τ decays was conducted in the Belle experiment using the statistics from 646×10^6 $\tau^+\tau^-$ pairs [149]:

$$\bar{\eta} = -1.3 \pm 1.5 \pm 0.8 \, ; \qquad \xi\kappa = 0.5 \pm 0.4 \pm 0.2 \, . \tag{22}$$

The measured values are in agreement with the SM within the limits of experimental accuracy ($\bar{\eta}, \xi\kappa = 0$).

The study of radiative leptonic τ decays in the Belle II and SCTF experiments will improve the accuracy of decay branching fraction measurements with respect to not only next-to-leading order corrections but also the next-to-next-to-leading ones [150]. In addition, these studies are necessary for a reliable estimation of the background from radiative leptonic decays in the search for lepton-flavor-violating decays $\tau^- \to \ell^-\gamma$. A precise measurement of the parameters $\bar{\eta}$ and $\xi\kappa$ will provide a strict constraint on the Lorentz structure of the charged weak current.

In the case of $\tau^- \to \mu^-\bar{\nu}_\mu\nu_\tau$ decay, the muon polarization can be measured in the cascade decay-in-flight $\mu^- \to e^-\bar{\nu}_e\nu_\mu$ in the drift chamber of a detector if the electron is reconstructed [151]. Since the *V–A* Lorentz structure of the weak interaction has been verified in muon decay with high accuracy, it can be considered fixed. Then, the direction of electron emission and its energy spectrum will be associated with additional Michel parameters ξ', ξ'', η'', α'/A, and β'/A [145, 152]. The parameters ξ' and ξ'' are related to $\xi\kappa$ and $\bar{\eta}$ ($\xi' = -\xi - 4\xi\kappa + 8\xi\delta/3$ and $\xi'' = 16\rho/3 - 4\bar{\eta} - 3$), which are also measured in radiative leptonic τ decays.

In SCTF experiments, muon decays can be reconstructed in the drift chamber of the detector, but, since its radius is much smaller than the muon mean free path, such events will be rare. However, the number of cascade decays of muons from $\tau^- \to \mu^-\bar{\nu}_\mu\nu_\tau$ decays, which is required to measure the corresponding Michel parameters, will be provided by a record-breaking number of $\tau^+\tau^-$ pairs produced at the SCTF. The statistical accuracy estimation for the Michel parameter ξ' measurement with the full SCTF statistics gives the value $\sigma_{\xi'} = 0.006$ [152]. And although comparable accuracy for ξ' can be achieved using the full statistics of the Belle II experiment, the advantage of the SCTF is in the polarized beam, which, in addition to ξ', will allow precision measurements of the Michel parameters ξ'', η'', α'/A, and β'/A [152].

5. Search for phenomena beyond the Standard Model

5.1 Production of light exotic particles

As already mentioned, the Standard Model does not explain neutrino oscillations, the baryon asymmetry of the Universe, dark matter phenomena, and other physical phenomena, which stimulates modification of the modern theory of elementary particles. The energy scale at which the effects of the New Physics are possible remains unknown. Heavy particles contribute to the mass of the Higgs boson and, within the Wilsonian approach, destabilize the electroweak scale. One solution to the gauge hierarchy problem is to expand the SM, in which new particles appear lighter or slightly heavier than the electroweak scale [153]. In particular, such particles can be produced directly in electron–positron collisions at the SCTF. Because new particles must interact weakly with SM particles, for example, through portal-type interactions [154], they are difficult to detect and require more data and more precise measurements to find them.

A typical signature of weakly interacting particles is the energy lost in the event, which may indicate the birth of a hidden massive A$'$ photon or Z$'$ boson, historically hypothesized within the Mirror World [155]. Abelian gauge bosons of different gauge groups can mix through kinetic terms [156] and thus be produced in electron–positron collisions. If the new vector boson is long-lived or prefers to decay into light invisible particles from the hidden sector, its birth at the SCTF can be detected by the missing energy.

Another example that exhibits a similar signature is new light bosons or fermions, which carry tiny electrical charges called millicharge particles. In electron–positron collisions, they can be produced as virtual photons, and then, if the charge is small enough, fly away without interacting with the detector matter. Both examples appear in models [157–159] with dark matter candidates from the hidden sector, which determines the interest in their experimental verification. For the proposed project, such a study was carried out in [160]; the expected exclusion area is shown in Fig. 5.

The prospects of searching for events using analyses of the missing energy in an event depend on the model parameters: the number of signal events is proportional to the square of the corresponding new coupling constant. However, this signature is blind to the New Physics responsible for signaling events: there is no way to extract information about the physics of the hidden sector. More promising signatures are associated with processes in which new particles being produced either interact [161] or decay inside the detector volume, which makes it possible to study their spin, charge, mass, and other characteristics. However, the number of such signaling events is proportional to the fourth power of the new coupling constants. Relevant examples are models with new vector particles decaying into Standard Model fermions (such as muons or electrons), and models with axion-like particles decaying into a pair of photons inside a detector.

5.2 Rare and forbidden decays of charmed mesons

Processes with neutral currents that change the flavor may contribute to the amplitude of rare decays of charmed hadrons. The relative probabilities of such decays are suppressed by the Glashow–Iliopoulos–Maiani (GIM) mechanism, and the manifestation of *CP*-asymmetry is additionally suppressed by CKM effects. Such processes are sensitive to the manifestation of phenomena, since new particles and interactions can change the angular distributions of decay products and their polarization, change the probability of decay, and also be an additional source of *CP*-violation. The specs of the SCTF are favorable to searching for rare decays of charmed mesons. And although the SCTF has difficulty competing with the LHC*b* experiment in the analysis of rare decays to final states with dileptons l^+l^-, the study of radiative decays $c \to u\gamma$ looks promising. In addition, the search for decays into invisible final states $c \to u\nu\bar{\nu}$, which is promising for the SCTF, is of particular interest.

The amplitude of hard radiative processes $c \to u\gamma$ is influenced by effects associated with the nonperturbative dynamics of the strong interaction. $D \to V\gamma$ ($V = K^*, \phi, \rho, \omega$) decays dominate in the SM due to diagrams in which a photon line is attached to any of the four quark lines in the diagrams $c \to q q_1 q_2$. The measured relative decay probabilities $D \to V\gamma$ ($V = K^*, \phi, \rho$) are in the range of $10^{-6} - 10^{-4}$ [162], and the

Table 2. Prospects for measuring the relative probabilities of decays with lepton flavor violation in the BESIII and SCTF experiments.

	$J/\psi \to e\mu$	$J/\psi \to e\tau$	$J/\psi \to \mu\tau$
Current upper limit	1.6×10^{-7}	8.3×10^{-6}	2.0×10^{-6}
BESIII [191]	6.0×10^{-9}	2.5×10^{-8}	1.5×10^{-8}
SCTF	2.0×10^{-10}	0.8×10^{-9}	0.5×10^{-9}

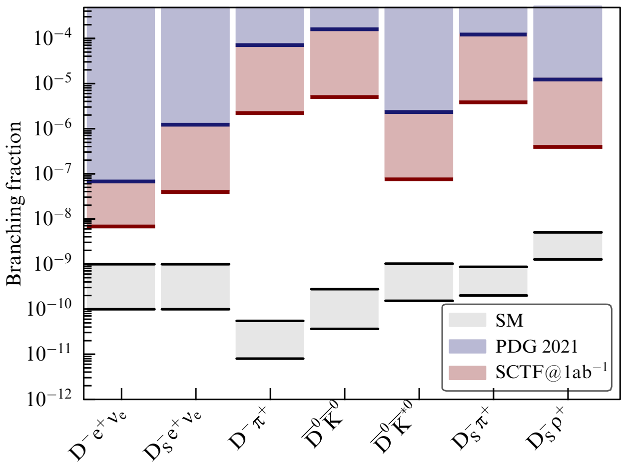

Figure 6. Upper limits on the relative probabilities of decays at a 90% confidence level for weak decays of the J/ψ-state. Dark blue lines correspond to the results of the most accurate measurements, gray areas, SM predictions, red lines, expected results of experiments at the SCTF, respectively.

$D \to \omega\gamma$ decay probability has an upper limit of $\sim 2 \times 10^{-4}$ [163]. The Belle collaboration was the first to determine the value of the *CP* asymmetry in the last decay, which turned out to be compatible with the expectations of the SM, but at the same time did not measure the angular distributions or polarization of photons.

The contribution to the amplitude of rare decays $D^0 \to \gamma\gamma$ occurring at short distances is expected to be insignificant, while the main contribution to the indicated amplitude comes from interactions at large distances, increasing the relative probability of decay to 10^{-8} [164]. NP effects can increase this value even further. The best bound on it, obtained by the Belle collaboration, is 8.5×10^{-7} at a 90% confidence level. Direct extrapolation of this result to the data volume 1 ab^{-1} at the SCTF at the birth energy of the $\psi(3770)$-state leads to the expected sensitivity level of $\sim 10^{-7}$.

Since $D \to F\nu\bar{\nu}$ ($F = \pi, K, \pi\pi, KK$) decays are suppressed by the GIM mechanism in the SM, their relative probability is predicted in the range of 10^{-16} – 10^{-14} [165]. The statistical sensitivity in measuring the relative probability of $D \to F\nu\bar{\nu}$ decays is comparable for the Belle II experiment (at a luminosity of 50 ab^{-1}) and the SCTF. It is interesting to study such processes to test models with the production of light exotic particles in two-particle and three-particle decays of D-mesons, where a new light particle is not detected. Alternatively, the D meson may decay into a pair of SM particles, such as photons or charged leptons, giving a peak in the invariant mass distribution as its signature.

The rare decay $D^0 \to \nu\bar{\nu}$ is strongly suppressed, and, although its relative probability in the SM is estimated to be $\sim 10^{-30}$ [166], it can increase significantly due to the birth of dark matter candidates. The latest measurement by the Belle collaboration has placed an upper limit on the probability of such a decay of 9.4×10^{-5} at a 90% confidence level. The SCTF experiment will improve this result by an order of magnitude.

5.3 Forbidden τ decays

Decays of τ leptons with lepton flavor violation, such as $\tau \to \ell\gamma$, $\tau \to \ell\ell\ell^{(\prime)}$ or $\tau \to \ell h$ (ℓ, ℓ' is an electron or muon, and h is a hadronic system) are sensitive to the effects of New Physics. Existing models outside the SM predict their probabilities in the interval of 10^{-7} – 10^{-10} [167–169], while the upper limits reached previously in experiments at B factories are in the range from 10^{-7} to 2×10^{-8} [21].

Thanks to the record luminosity of the accelerator, the Belle II [170] experiment is highly sensitive to forbidden decays of τ-leptons. However, in a number of cases, there is an insoluble problem of background suppression, in particular, for the $\tau \to \mu\gamma$ decay, which is convenient for the search for New Physics. In B factories, the establishment of an upper limit on its relative probability is limited by the photon emitted in the initial and final states from the radiation process $e^+e^- \to \tau^+\tau^-\gamma$. At the same time, at the SCTF, the indicated background is insignificant [171], and the upper limit of interest to us can be set below the value of 10^{-9}, improving the result of Belle II [172, 173].

Of particular importance for the search for manifestations of NP are the decays of τ-leptons with leptonic flavor violation into invisible particles predicted in the framework of models outside the SM containing axion-like particles [160, 174–177] or new Z' gauge bosons [178–180]. One such process is $\tau \to \ell\alpha$ ($\ell = e, \mu$), where α is an unregistered particle, considered in several models of New Physics [176, 179–183]. Light bosons α are considered candidate dark matter particles [158], and in some approaches these particles help solve the proton radius problem [184].

The search for the decay $\tau \to \ell\alpha$ ($\ell = e, \mu$), where $m_\alpha \leqslant m_\tau - m_\ell$, was first carried out by ARGUS [185] with statistics on $\sim 430{,}000$ τ-pairs. Restrictions on the corresponding relative probabilities of decays were for massless α:

$$\mathcal{B}(\tau \to e\alpha) < 2.7 \times 10^{-3}\,, \quad \mathcal{B}(\tau \to \mu\alpha) < 4.5 \times 10^{-3}\,, \quad (23)$$

at a 95% confidence level. Assuming a small mass α, the upper limit for $\mathcal{B}(\tau \to \mu\alpha)$ is weaker than for $\mathcal{B}(\tau \to e\alpha)$; however, for heavy α, the restrictions become similar. A recent result from the Belle II collaboration using statistics of $\sim 58 \times 10^6$ τ pairs [186] for massless α was

$$\mathcal{B}(\tau \to e\alpha) < 2.0 \times 10^{-4}\,, \quad \mathcal{B}(\tau \to \mu\alpha) < 1.2 \times 10^{-4} \quad (24)$$

at a 95% confidence level. An upper limit on $\mathcal{B}(\tau \to \ell\alpha)$ for massless α in the Belle experiment ($\sim 0.91 \times 10^9$ τ pairs) will improve the result fourfold [186]; in the future, using the full statistics of the Belle II experiment, 46×10^9 τ-pairs, the upper limit on $\mathcal{B}(\tau \to \ell\alpha)$ will reach $\sim 10^{-6}$.

At the SCTF near the threshold for the production of $\tau^+\tau^-$-pairs, the charged lepton from the $\tau \to \ell\alpha$ decay is monochromatic. Moreover, since the emission effect of radiative photons is negligible, the shape of the signal lepton momentum distribution is significantly narrower than in B factories, and the background from ordinary lepton decay is small. The possibility of inclusive reconstruction of the tagging τ-lepton at the SCTF is an advantage in relation to the Belle II experiment. The absence of emission of radiative photons at the SCTF near the $\tau^+\tau^-$ pair production threshold simplifies the search for $\tau \to \ell\alpha\gamma$ decays, which impose restrictions on models beyond the SM [180].

5.4 Forbidden J/ψ decays

The unprecedented statistics of J/ψ-meson production at the SCTF, amounting to $\sim 10^{12}$ year^{-1} at peak luminosity, opens up unique possibilities for searching for NP. One of the main research avenues is weak decays of charmonium, strongly suppressed in the SM, as well as forbidden decays that violate the lepton number: $J/\psi \to \ell_1\ell_2$, where $\ell_1, \ell_2 = e, \mu, \tau$.

The best constraints on the relative probabilities of weak decays of the J/ψ state, established in the BESIII experiment [21], are shown in Fig. 6. The most accurate results were obtained for the decay of $J/\psi \to D^-e^+\nu_e$ using the statistics of $\sim 10.1 \times 10^9$ J/ψ-mesons [187]. The SCTF will collect 100 times more data, and a significant improvement in sensitivity is expected (Fig. 6). Since SM predictions for the probability of weak charmonium decays rarely exceed the 10^{-9} level, the SCTF will allow testing regions where NP may appear.

Of particular interest is the search for decays of charmonia $J/\psi \to D^0\rho^0$ and $J/\psi \to D^0\pi^0$, which in the SM are due to weak tree Cabibbo–suppressed diagrams. Their relative probabilities are negligible (2×10^{-11} and 0.6×10^{-11}, [31]), since J/ψ mostly decays as a result of strong and electromagnetic interactions. Electroweak penguin diagrams, as well as NP loop diagrams, can lead to the same final states, interfering with tree diagrams and increasing the probability of the decays under study. Thus, it becomes possible to observe them and indicate the manifestation of NP.

Recent results of measurements of the decay of $B \to K^{(*)}\ell^+\ell^-$ [188, 189] somewhat contradict the SM, which is attracting attention to the search for processes violating leptonic symmetry, predicted, in particular, in supersymmetric models. The most promising decay for research on the SM is $J/\psi \to \ell_1\ell_2$. Upper limits on its relative probability, as well as expected sensitivity in future experiments, are presented in Table 2. Today, restrictions on processes that violate leptonic symmetry are obtained based on upper limits on the relative probabilities of three-body lepton decays: $\mathcal{B}(\mu \to 3e) \leqslant 2 \times 10^{-13}$ [21] and $\mathcal{B}(\tau \to \ell_1\ell_2\bar{\ell}_2) \leqslant 10^{-6}$ [190].

It is interesting to search for the axion, as well as axion- and dilaton-like particles in two-particle decays $J/\psi \to \gamma X$, where X either flies away or decays into a pair of SM particles, for example, into photons or charged leptons. Similar searches for the hidden vector state can be carried out for the $q\bar{q}$ meson with zero spin.

6. Conclusions

The creation of the SCTF will allow precision measurements of the parameters of charmed hadrons and τ-leptons and an advanced search for New Physics. The obtained experimental results related to nonperturbative QCD phenomena will provide a better understanding of the relevant phenomenology and provide the opportunity to fine-tune various calculation methods such as lattice QCD.

The physical program of the experiment, based on its record luminosity, wide energy range, and polarization of electrons in the beam, opens up the possibility of conducting unique research and solving current problems in particle physics. In particular, the existence of a beam of polarized electrons will make it possible to measure the effective value of the Weinberg angle at the energy of J/ψ-resonance production and to study processes that were previously inaccessible at e^+e^- colliders operating on unpolarized beams.

Of course, successful implementation and operation of the SCTF are only possible if the well-established procedures adopted in large international high-energy physics experiments such as BaBar, Belle II, and LHC*b* are followed. It is necessary to create open international cooperation, independent supervisory committees, and transparent decision-making mechanisms, both during construction and during operation of the SCTF.

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