Budker Institute of Nuclear Physics
Siberian Branch Russian Academy of Sciences
(BINP SB RAS)

# *Super Charm – Tau Factory*

## CONCEPTUAL DESIGN REPORT
### physics program

Novosibirsk – 2017

This document is focused on a project of the Super Charm – Tau factory in the Budker Institute of Nuclear Physics (Novosibirsk, Russia). An electron-positron collider will operate in the range of center-of-mass energies from 2 to 5 GeV with unprecedented peak luminosity of about $10^{35}\,\mathrm{cm}^{-2}\mathrm{c}^{-1}$ and longitudinally polarized electrons at interaction point. To achieve this extremely high luminosity we are going to apply a novel idea of a Crab Waist collision scheme. The main goal of experiments at Super Charm – Tau factory is a study of the processes with $c$ quarks or $\tau$ leptons in the final state using data samples, which are by 3–4 orders of magnitude higher than collected by now in any other experiments. We expect that these experiments will be sensitive to effects of new physics not described by the Standard Model.

# Contents

# Introduction

In the nineties of the past century several projects of Super Charm – Tau factories were discussed in high energy physics laboratories around the world. All these facilities were planned to work with beam energy of $1 \div 3$ GeV and a peak luminosity of about $10^{33}$ cm$^{-2}$c$^{-1}$ [1, 2, 3, 4, 5, 6, 7] with exception of a round beam Novosibirsk option with $10^{34}$ cm$^{-2}$c$^{-1}$ [8]. Different variants of monochromatization of the energy of particle collision were considered in order to study narrow resonances as well as the possibility of the production of transversely polarized particles (for precise energy calibration).

The only project from the "family" of those Super Charm – Tau factories which has been realized is the BEPC II collider commissioned at the IHEP laboratory (Beijing) in 2009 [9]. Its designed peak luminosity is $10^{33}$ cm$^{-2}$c$^{-1}$.

The revival of the interest in these subjects and the beginning of work on the project of Super Charm – Tau factory at Budker Institute of Nuclear Physics (BINP) is caused, first, by the outstanding results which were achieved at the $B$ Factories, KEKB (KEK, Japan) and PEP-II (SLAC, US). These works culminated in the 2008 Nobel Prize in Physics to M. Kobayashi and T. Maskawa. Though the high luminosity of the $B$ Factories allowed obtaining some interesting results at low energies with the ISR method, that is proposed and developed at BINP, creation of a highly productive factory specially intended to study the physics of charmed particles and $\tau$ lepton is still a topical issue.

Second, the growing interest in the creation of the next-generation Super Charm – Tau factory resulted from the discovery of a new and promising method of beam collision in electron-positron colliders which allows the luminosity to be raised by two orders of magnitude as compared with the existing factories without a significant increase of the beam intensity or the facility size or reduction of the bunch length. The idea was proposed by an Italian physicist, Pantaleo Raimondi, in 2006 when he studied the possibility of creating a high-luminosity $B$ factory [10]. Later the method was justified in joint works by P. Raimondi, M. Zobov (INFN/LNF, Frascati), and D. Shatilov (BINP, Novosibirsk) [11, 12] with simulation of the collision effects using the LIFETRAC software developed by D. Shatilov. The new approach, described in detail below, was called *"Crab-Waist Collision with Large Piwinski Angle"*. For brevity's sake, we will refer to the new approach as the Crab Waist or CW collision method. Besides the Super Charm – Tau factory in Novosibirsk, the CW collision method is used in the projects of the Super$B$ factory in Italy and the Super$KEKB$ factory (without the CW sextupoles at the moment) in Japan. In other words, all the projects of future electron-positron circular super-colliders are based on this new approach.

In 2008–2009 the new beam collision method was tried at the $\phi$ factory DAΦNE; the experiment results confirm the method to be promising and are in good agreement with the theory [13].

The following scientific goals can be formulated for the new project: the precision study of the processes with $c$ quarks and $\tau$ leptons in the final states, the search of four- and five-quark states, glueballs, hybrid, other exotic states and study of their properties. That requires data samples of $D$ mesons, $\tau$ leptons and data collected on- and off-range of charmonium resonances that are 3–4 orders of magnitude higher than collected today. This allows studying such new phenomena as $CP$ violation in $D$ meson system, $\tau$ leptons and lepton flavor violation in $\tau$ decays.

This program requires a development of a universal magnetic detector with an extremely high momentum resolution for charged particles and high energy resolution for photons, with record parameters for the particle identification system. Extremely high luminosity demands a unique trigger, which can select physics events under very high detector load, as well as digitizing hardware and data acquisition system which is able to read out events at a rate of 300–400 kHz.

On the basis of the scientific tasks, which are discussed in detail in the section of the physics program of the Super Charm – Tau factory, the following main requirements to the accelerator complex were stipulated:

- The beam collision energy in the center-of-mass system must vary from 2 to 5 GeV, which allows experiments spanning from the nucleon-antinucleon production energy to the region of $\psi$ mesons and charmed baryons. Besides, such an energy range will allow us to use the results obtained with the VEPP–2000 and VEPP–4M colliders at BINP.

- The luminosity of the factory shall be not less than $10^{35}$ cm$^{-2}$c$^{-1}$ in the high energy region and $\geq 10^{34}$ cm$^{-2}$c$^{-1}$ in the low energy one.

- The electron beam shall be polarized longitudinally at the interaction point [14, 15].

- Beams shall collide with equal energies; asymmetry is not required.

- Since no schema for collision monochromatization without a significant decrease in the luminosity had been found, it was decided to abandon energy monochromatization, all the more so because the high luminosity allows effective exploration of the narrow resonance states without complicated monochromatization solutions.

- It was decided to abandon the need to have transversely polarized beams for precise calibration of energy. The energy will be measured by means of Compton back scattering of laser radiation on the particles of the circulating beam. This technique has been implemented recently on VEPP–4M [16] and shown a relative accuracy better than $\sim 10^{-4}$, which seems sufficient for the tasks of the new Super Charm – Tau factory.

It is worth to mention among other requirements to the project the possibility of using, after a modernization that will increase the positron production, the BINP injection complex being now under commission. To reduce the cost of the facility its design relies on the existing BINP infrastructure, tunnels, buildings and premises. It was decided to employ in the complex the technical and technological solutions available at BINP (electro- and superconducting magnets, the source of polarized electrons, elements of vacuum chamber and beam diagnostics etc).

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# Chapter 1

# Physics

## 1.1 Introduction

A Super Charm – Tau factory is an electron-positron collider operating in the range of center-of-mass (c.m.) energies from 2 to 5÷6 GeV with a high luminosity of about $10^{35}$cm$^{-2}$c$^{-1}$. In this energy range practically all states with charm can be produced including charmonium mesons, bound states of $c$ and $\bar{c}$ quarks, charmed mesons and baryons comprising one $c$ ($\bar{c}$) quark. In addition, at the c.m. energy above $2m_\tau \approx 3.6$ GeV $\tau$-lepton pairs can be produced. Because of its extremely high luminosity such a collider will be a copious source of charmed particles and $\tau$ leptons. This brings us to the name Super Charm – Tau factory (SCTF).

The main goal of experiments at SCTF is a study of the processes with $c$ quarks or $\tau$ leptons in the final state using data samples that are at least two orders of magnitude higher than those collected in the CLEO$c$ and BESIII experiments. In Table 1.1 we show a list of energies, at which most of Super Charm – Tau factory data will be collected, and a possible distribution of an integrated luminosity of 1 ab$^{-1}$ over these energies. At .eps with a luminosity of $10^{35}$cm$^{-2}$c$^{-1}$ such an integrated luminosity can be collected during half a year ($10^7$ s). The luminosities listed in Table 1.1 correspond to approximately $10^9$ $\tau$ leptons, $10^9$ $D$ mesons and a fantastic number ($10^{12}$) of $J/\psi$ mesons. The total integrated luminosity planned to be collected at the Super Charm – Tau factory is 10 ab$^{-1}$. These data samples will allow a systematic study of all states of quarks of the two first generations ($u$, $d$, $s$ and $c$) as well as searches for states of exotic nature.

A theory of strong interactions, quantum chromodynamics (QCD), in addition to standard mesons and baryons consisting of two and three quarks, respectively, cannot rule out the existence of four- and five-quark states as well as bound states of gluons, carriers of strong interactions [1]. Some of the four- and five-quark states have already been observed but we are very far from understanding their properties. Such states are possible because gluons, in contrast to a photon, an electrically neutral carrier of electromagnetic interactions, possess a strong or color charge. QCD predicts both hybrid quark-gluon states and states consisting of gluons only, glueballs. Hybrids and glueballs are a completely new form of matter that can be formed by strong interactions only. One of the tasks of SCTF is to discover exotic states and study their properties.

Huge data samples of $D$ mesons, charmed baryons and $\tau$ leptons will allow a search for principally new phenomena, such as $CP$ violation in the $D$ meson system and in $\tau$ leptons as well as lepton flavor violation with high sensitivity.

A physics program for SCTF can be subdivided into the following subsections, which are discussed in more detail below:

1. charmonium,

Table 1.1: Energies, at which most of Super Charm – Tau factory data will be collected, and approximate distribution of an integrated luminosity collected during one experimental run ($10^7$ s, 1 $ab^{-1}$) over these energies.

| $E$, GeV | $L$, $fb^{-1}$ | | |
|---|---|---|---|
| 3.097 | 300 | $J/\psi$ | Light meson spectroscopy, rare decays |
| 3.554 | 50 | $e^+e^- \to \tau^+\tau^-$ threshold | Precision measurements of $\tau$ decays |
| 3.686 | 150 | $\psi(2S)$ | Light meson spectroscopy, Charmonium spectroscopy |
| 3.770 | 300 | $\psi(3770)$ | $D$-meson study |
| 4.170 | 100 | $\psi(4160)$ | $D_s$-meson study |
| 4.650 | 100 | maximum of $\sigma(e^+e^- \to \Lambda_c^+\Lambda_c^-)$ | $\Lambda_c$ study |

2. spectroscopy of states of light quarks,
3. physics of $D$ mesons,
4. physics of charmed baryons,
5. $\tau$ lepton physics,
6. measurement of the cross section of $e^+e^- \to$ hadrons,
7. two-photon physics.

## 1.2 Charmonium

A scheme of charmonium levels is shown in Fig. 1.1. All states lying below the threshold of $D$ meson production and therefore decaying into hadrons consisting of the light $u$, $d$ and $s$ quarks (or into a lower mass charmonium) have been discovered. Vector mesons ($J^{PC} = 1^{--}$), i.e., $J/\psi$, $\psi(2S)$, $\psi(3770)$, etc. are directly produced in $e^+e^-$ collisions. In Table 1.2 we list the numbers of $1^{--}$ mesons that can be produced at SCTF during one experimental season.

### 1.2.1 Charmonium states below the $D\bar{D}$ threshold

About $10^{12}$ $J/\psi$ and $10^{11}$ $\psi(2S)$ can be produced during one experimental season. In radiative decays of $J/\psi$ and $\psi(2S)$ mesons [2] about $10^{10}$ $\chi_{cJ}$ and $\eta_c$ mesons each can be obtained. About $10^8$ $h_c$ mesons can be produced in the $\psi(2S) \to h_c\pi^0$ decay, which has a branching fraction of $(8.6\pm1.3)\times10^{-4}$ [2]. For observing $\eta_c(2S)$ one can use a rare, radiative transition $\psi(2S) \to \eta_c(2S)\gamma$ with a branching fraction of $(7 \pm 5) \times 10^{-4}$ [2] or two-photon production (see Sec. 1.8). Such a data sample allows a systematic study of $c\bar{c}$-meson properties. The following items should be mentioned:

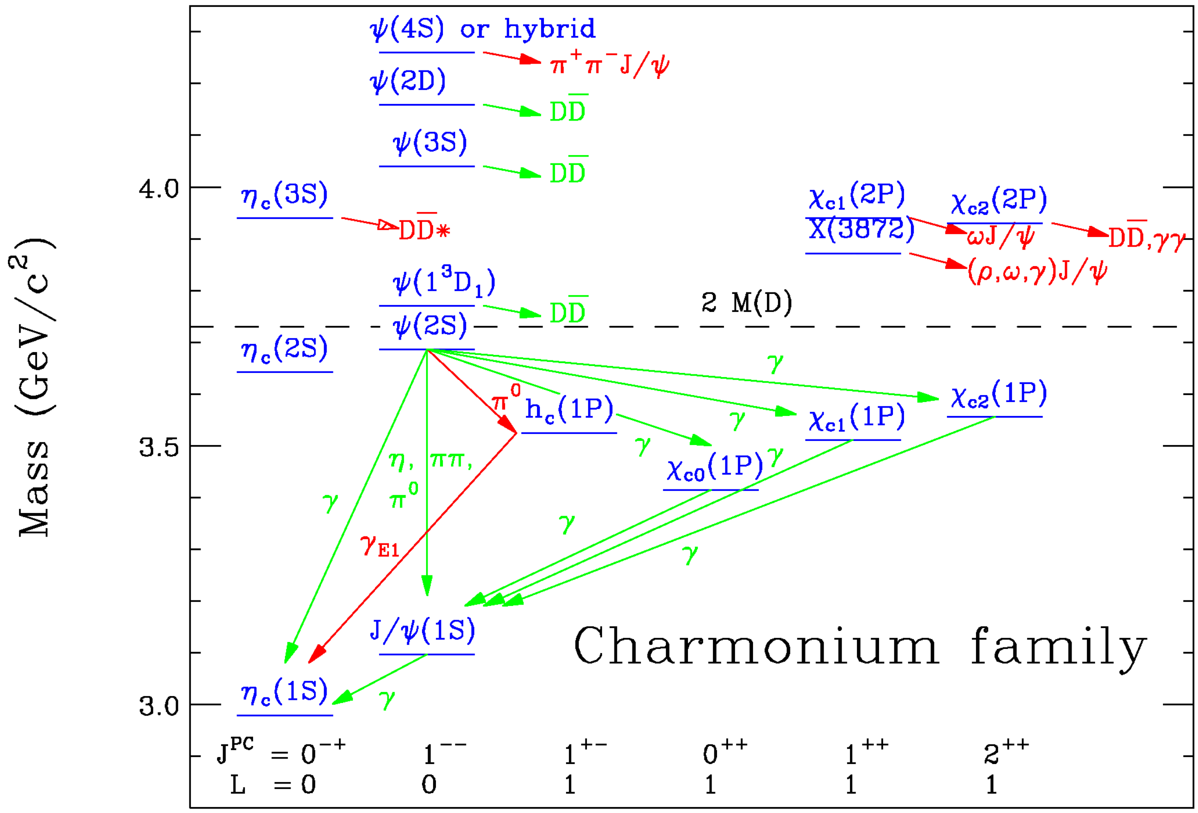


Figure 1.1: Charmonium system and transitions. Red (dark) arrows indicate recently discovered decays and transitions between the levels. The dashed line shows a production threshold for a pair of charmed mesons.

Table 1.2: The number of $c\bar{c}$ mesons that can be produced at SCTF during half a year. Estimates of physical cross sections are based on Refs. [2, 3, 4].

| | $J/\psi$ | $\psi(2S)$ | $\psi(3770)$ | $\psi(4040)$ | $\psi(4160)$ | $\psi(4415)$ |
|---|---|---|---|---|---|---|
| $M$, GeV | 3.097 | 3.686 | 3.773 | 4.039 | 4.191 | 4.421 |
| $\Gamma$, MeV | 0.093 | 0.286 | 27.2 | 80 | 70 | 62 |
| $\sigma$, nb | $\sim$3400 | $\sim$640 | $\sim$6 | $\sim$10 | $\sim$6 | $\sim$4 |
| $L$, fb$^{-1}$ | 300 | 150 | 300 | 10 | 100 | 25 |
| $N$ | $10^{12}$ | $10^{11}$ | $2 \times 10^9$ | $10^8$ | $6 \times 10^8$ | $10^8$ |

1. Precision measurement of probabilities for transitions between low-lying levels of charmonium, their masses, total and leptonic or two-photon widths. These parameters are calculated in potential quark models and can also be obtained within lattice QCD. In close future the accuracy of lattice calculations will reach a level of about 1% or better. At SCTF one will be able to measure probabilities of rare, not yet discovered electric $\eta_c(2S) \to h_c\gamma$ ($2.5\times10^{-3}$), $\psi(3770) \to \chi_{c0}\gamma$ ($2 \times 10^{-4}$) and magnetic $\eta_c(2S) \to J/\psi\gamma$ ($3 \times 10^{-5}$), $h_c \to \chi_{c0}\gamma$ ($\sim 10^{-6}$) dipole transitions. Shown in parentheses are transition probabilities expected in the quark model [1]. From the analysis of angular distributions of photons in the $\chi_{cJ} \to J/\psi\gamma$ and $\psi(2S) \to \chi_{cJ}\gamma$ decays one can extract the amplitudes of $M2$ and $E3$ transitions interfering with the dominating $E1$ transition and determine an admixture of the $D$ wave state in $\psi(2S)$ (see a review in [5] and references therein).

2. Information about decays of low-lying states of charmonium is very incomplete. For the best-studied $J/\psi$ meson about 45% of hadronic decays only have been measured. For other states the situation is even worse. One of the tasks for SCTF is a systematic study of all low-lying charmonium states. This program, in particular, includes a precision measurement of hadronic transitions between charmonium states with emission of one or two $\pi$ mesons, $\eta$ meson, $\psi, h_c \to 3\gamma$ decays, a photon spectrum in the reaction $\psi \to \gamma X$, where $X$ is a hadronic state of light quarks, and direct measurement of the probabilities of $\eta_c, \chi_{c0}, \chi_{c1} \to 2\gamma$ decays.

3. A relatively small width of the $J/\psi$ resonance and a huge data sample provided by SCTF allow an observation of weak $J/\psi$ decays. The total probability of weak decays of $J/\psi$ via a $c \to sW^+$ transition is (2–4)$\times10^{-8}$ [6]. Semileptonic $J/\psi \to D_s^* l\nu$, $D_s l\nu$ and hadronic $J/\psi \to D_s^+\rho^-$, $D_s^{*+}\pi^-$ modes have branching fractions of (3–4)$\cdot10^{-9}$ [6, 7] and can be measured at SCTF. In Standard Model (SM) decays with $\Delta S = 0$ are suppressed. For example, the branching fractions of $J/\psi \to D^0\rho^0$ and $J/\psi \to D^0\pi^0$ decays are predicted at the level of $2 \times 10^{-11}$ and $0.6 \times 10^{-11}$ [7], respectively. This makes such decays sensitive to effects of new physics not described by SM, in particular, to the existence of a flavor-changing neutral current (a $c \to u$ transition) [8].

   Another type of weak processes ($c\bar{c} \to s\bar{s}$ with $W$ boson exchange) results in decays violating $C$ parity, such as, e.g., $J/\psi \to \phi\phi$. The expected branching fraction of this decay is sufficiently high ($\sim 10^{-8}$ [9]) for its observation at SCTF.

4. A large sample of $\psi$ meson decays allows a search for phenomena not described by SM, such as violation of $CP$ parity and lepton flavor conservation. Lepton flavor violation can be observed in $J/\psi \to l\bar{l}'$ decays, where $l, l' = e, \mu, \tau$. Branching fractions of such decays can be related in a model-independent way to branching fractions of $\mu$ and $\tau$ decays to three leptons [10]. From the limits $B(\mu \to ee^+e^-) < 10^{-12}$ [2] and $B(\tau \to \mu e^+e^-) < 2.7\times10^{-8}$ [11] one obtains $B(J/\psi \to \mu e) < 2 \times 10^{-13}$ and $B(J/\psi \to \tau l) < 6 \times 10^{-9}$. A limit on the decay $\tau \to \mu e^+e^-$ has been set with a data sample of $5 \times 10^8$ $\tau$ lepton pairs. Thus, at SCTF $J/\psi$ decays can be more sensitive to lepton flavor violation than those of $\tau$ leptons.

   One of physical effects beyond SM is the existence of the non-zero electric dipole moment (EDM) of quarks or leptons leading, in particular, to $CP$ violation. $J/\psi$ decays provide the best opportunity to obtain information about the $c$-quark EDM. To search for $CP$ violation one can use three-body decays, e.g., $J/\psi \to \gamma\phi\phi$. In this case, one can compose a $CP$-odd combination of momenta of final particles and an initial electron and determine a parameter describing $CP$ asymmetry which is proportional to EDM. With $10^{12}$ $J/\psi$ mesons, using the $J/\psi \to \gamma\phi\phi$ decay one can obtain a sensitivity to the $c$-quark EDM at the $10^{-15}$ $e\cdot$cm

Table 1.3: Exotic vector states in $e^+e^-$ annihilation.

| State | $M$, MeV | $\Gamma$, MeV | Production process | |
|---|---|---|---|---|
| $Y(4260)$ | $4251 \pm 9$ | $120 \pm 12$ | $e^+e^- \to J/\psi\pi^+\pi^-$ | [16, 17] |
| $Y(4360)$ | $4346 \pm 6$ | $102 \pm 10$ | $e^+e^- \to \psi(2S)\pi^+\pi^-$ | [18, 19] |
| $Y(4660)$ | $4643 \pm 9$ | $72 \pm 11$ | $e^+e^- \to \psi(2S)\pi^+\pi^-$ | [20, 21] |
| $Y(4008)$ | $3891 \pm 42$ | $255 \pm 42$ | $e^+e^- \to J/\psi\pi^+\pi^-$ | [17] |

level [12]. A two-body $J/\psi \to \Lambda\bar{\Lambda}$ decay, in which polarizations of final baryons can be measured from the $\Lambda \to p\pi^-$ decay, can be also used for a search for $CP$ violation. With $10^{12}$ $J/\psi$ mesons, this decay can be used to set a limit on the Λ-hyperon EDM at the $5 \times 10^{-19}$ e·cm level [13], two orders of magnitude more stringent than the existing limit.

### 1.2.2 Study of exotic charmonium-like states

Over the past decade Belle, BABAR, CLEO-c, CDF, D0, BESIII and LHCb experiments have discovered dozens of charmonium states with masses above the open charm threshold [14]. Only a few of them could be identified as excited $c\bar{c}$ mesons. Many of the found states have nonzero electric charge demonstrating their exotic nature. The nature of the new states remains unclear. While trying to explain the properties of the new states, the theory has to admit the existence of molecular states, four-quark states or hydrocharmonium [15].

Vector charmonium-like states, which can be produced at SCTF in the reaction $e^+e^- \to Y$, are represented in Table 1.3. Masses, widths [2], the processes in which they are produced, as well as references to BABAR and Belle experiments that discovered $Y$ states via radiation return. Existence of three states, the $Y(4260)$, $Y(4360)$ and $Y(4660)$, is reliably established as they were confirmed by at least two experiments. The mass and width of the $Y(4660)$ resonance are consistent within errors with the parameters of the $X(4630)$ state observed by Belle in the process $e^+e^- \to \Lambda_c^+\Lambda_c^-$ [23]. The existence of a broad peak called $Y(4008)$ found by Belle [17] ($7.4\sigma$), but not confirmed by BABAR [22] remains an open question.

Interpretation of the vector $Y$ states as a standard charmonium faces a number of problems: the charmonium spectrum with $J^{PC} = 1^{--}$ quantum numbers is populated with the standard charmonium state and there is no room to accommodate newly observed $Y$ states; the $Y$ states with masses above open charm threshold do not decay to charm mesons unlike expectations; the partial width of the $Y \to J/\psi\pi^+\pi^-$ decays ($> 1$ MeV) exceeds by two orders of magnitude the analogous values for the standard charmonium $\psi(3770)(\psi(2S)) \to J/\psi\pi^+\pi^-$.

The $Y$ states were discovered in $e^+e^- \to J/\psi\pi^+\pi^-$ and $e^+e^- \to \psi(2S)\pi^+\pi^-$ processes. Later other processes were studied: $e^+e^- \to J/\psi\pi^0\pi^0$ [24], $e^+e^- \to J/\psi K^+K^-$ и $e^+e^- \to J/\psi K_S K_S$ [25], $e^+e^- \to J/\psi\eta$ [26, 27], $e^+e^- \to J/\psi\eta'$ [28], $e^+e^- \to J/\psi\eta\pi^0$ [29], $e^+e^- \to h_c\pi^+\pi^-$ [30], $e^+e^- \to \omega\pi^+\pi^-$ [30]. As expected the $Y(4260)$ signal was observed in the $e^+e^- \to J/\psi\pi^0\pi^0$ process. Clear evidence of the $Y$ resonances is not seen in other channels.

Relatively large cross sections (50–100 pb), comparable in magnitude with the $e^+e^- \to J/\psi\pi^+\pi^-$ cross section, were observed in the reactions $e^+e^- \to J/\psi\eta$ and $e^+e^- \to h_c\pi^+\pi^-$. In Ref. [26] the $e^+e^- \to J/\psi\eta$ cross section was fitted by a sum of the $\psi(4040)$ and $\psi(4160)$ resonance contributions. A wide structure was found in the cross section of $e^+e^- \to h_c\pi^+\pi^-$ in $4.2 - 4.5$ GeV energy

Table 1.4: Charged carmonium-like states.

| State | $M$, MeV | $\Gamma$, MeV | Reaction | |
|---|---|---|---|---|
| $Z(3885)^+$ | $3883.9 \pm 4.5$ | $25 \pm 12$ | $Y(4260) \to \pi^-(\bar{D^{*0}}D^+)$ | [32] |
| | | | $Y(4260) \to \pi^-(D^{*+}\bar{D}^0)$ | |
| $Z(3885)^0$ | $3885.7 \pm 9.8$ | $35 \pm 19$ | $e^+e^- \to (D\bar{D}^*)^0$ | [33] |
| $Z(3900)^+$ | $3891.2 \pm 3.3$ | $40 \pm 8$ | $Y(4260) \to \pi^-(J/\psi\pi^+)$ | [34, 35, 36] |
| $Z(3900)^0$ | $3894.8 \pm 3.5$ | $29 \pm 12$ | $Y(4260) \to \pi^0(J/\psi\pi^0)$ | [37] |
| $Z(4020)^+$ | $4022.9 \pm 2.8$ | $7.9 \pm 3.7$ | $Y(4260, 4360) \to \pi^-(h_c\pi^+)$ | [38] |
| $Z(4020)^0$ | $4023.9 \pm 4.3$ | $7.9 \pm 3.7$ | $Y(4260, 4360) \to \pi^0(h_c\pi^0)$ | [39] |
| $Z(4025)^+$ | $4026.3 \pm 4.5$ | $24.8 \pm 9.5$ | $Y(4260) \to \pi^-(\bar{D^{*0}}D^{*+})$ | [40] |
| $Z(4025)^0$ | $4025.5 \pm 4.6$ | $23.0 \pm 6.1$ | $e^+e^- \to (D\bar{D}^*)^0$ | [41] |
| $Z(4055)^+$ | $4032.1 \pm 2.4$ | $26.1 \pm 5.3$ | $Y(4360) \to \pi^-(\psi(2S)\pi^+)$ | [42, 43] |
| $Z(4050)^+$ | $4051^{+24}_{-43}$ | $82^{+51}_{-55}$ | $\bar{B}^0 \to K^-(\chi_{c1}\pi^+)$ | [44] |
| $Z(4200)^+$ | $4196^{+35}_{-38}$ | $370^{+99}_{-110}$ | $\bar{B}^0 \to K^-(J/\psi\pi^+)$ | [45] |
| $Z(4250)^+$ | $4248^{+185}_{-45}$ | $177^{+321}_{-72}$ | $\bar{B}^0 \to K^-(\chi_{c1}\pi^+)$ | [44] |
| $Z(4430)^+$ | $4458 \pm 15$ | $166^{+37}_{-38}$ | $\bar{B}^0 \to K^-(\psi(2S)\pi^+)$ | [47, 48] |
| | | | | [46] |
| | | | $\bar{B}^0 \to K^-(J/\psi\pi^+)$ | [45] |

range [30]. It was fitted in Ref. [30] by a sum of two resonances with masses about 4.22 and 4.39 GeV and widths of about 70 and 140 MeV, respectively. These values differ from the parameters of the $Y$ resonances listed in Table 1.3.

In 2017 BESIII has measured the cross section of $e^+e^- \to J/\psi\pi^+\pi^-$ with a high statistical accuracy (19 points with an integrated luminosity of 8.2 fb$^-1$) [31]. This measurement showed that the structure called by $Y(4260)$ cannot be described by a single resonance. Two close resonances with masses (4222$\pm$3) GeV and (4320$\pm$13) GeV and widths (44$\pm$5) and (101$\pm$27), respectively, are needed to describe the cross section data. The first resonance was found to be in good agreement with the resonance near 4.22 GeV detected in $e^+e^- \to h_c\pi^+\pi^-$ and also with the structure near 4.2 GeV in the cross section of $e^+e^- \to J/\psi\eta$ [26, 27].

Another class of exotic charmonium-like states, so called $Z$ states, is presented in Table 1.4. The families of charged charmonium-like states $Z(3885)$, $Z(3900)$, $Z(4020)$, $Z(4025)$ were discovered in $e^+e^-$ collisions in the reaction $e^+e^- \to Z\pi$ near the maximum of the $Y(4260)$ resonance. The triplets $Z(3900)$ и $Z(3885)$ decaying to $J/\psi\pi$ и $\bar{D}D^*$, respectively, have close masses and widths and therefore are considered as the same state.

The parameters of the isotopic triplet $Z(4020)$ decaying into the $h_c\pi$ final states are consistent with the parameters of the states $Z(4025)$ decaying into open-charm final states $\bar{D}^*D^*$. It is assumed that these two triplets are also one state.

An indication for the existence of a charged state $Z(4055)^+$ decaying into $\psi(2S)\pi^+$ was found in the $Y(4360)$ decays in the Belle experiment [43]. A study of the $Z(4055)^+$ with much larger statistics were performed recently by BESIII [42]. The $Z(4055)^+$ parameters obtained by BESIII and presented in Table 1.4 are in agreement within errors with the parameters of the $Z(4025)^+$. BESIII has shown [42] that the dynamics of the $e^+e^- \to \psi(2S)\pi^+\pi^-$ process strongly depends on energy near the $Y(4360)$ peak and that a model with one resonance decaying into $\psi(2S)\pi^+$ is insufficient for a complete description of the Dalitz distribution.

All the $Z$ states discussed above, observed in the process $e^+e^- \to Z\pi$, have $J^{PC} = 1^{+-}$. The states $Z(4200)$ and $Z(4430)$, observed in $B$-meson decays, have the same quantum numbers and can be searched for in $Y(4660)$ decays.

Neutral charmonium-like states with positive C-parity, such as $X(3872)$, $X(3915)$, $Y(4140)$, $Y(4274)$, and $X(4500)$ [2, 14] can be observed at SCTF in the processes $e^+e^- \to X(Y)\gamma$. Recently one of such processes $e^+e^- \to X(3872)\gamma$ was observed in the BESIII experiment [49].

At SCTF one could study the exotic charmonium-like states with statistics 10-100 times higher than the data accumulated by the BESIII experiment. The energy scan in the range of 3.8-5.0 GeV with integrated luminosity of 100-1000 fb$^{-1}$ provides the detailed measurement of the processes $e^+e^- \to J/\psi\pi\pi$, $\psi(2S)\pi\pi$, $J/\psi KK$, $J/\psi\eta$, $J/\psi\eta\prime$, $h_c\pi\pi$, $\chi_c\omega$, etc.

## 1.3 Spectroscopy of states of light quarks

Charmonium states with a mass smaller than two $D$-meson masses decay into hadrons consisting of light $u$, $d$ and $s$ quarks. Selecting special decay modes of $c\bar{c}$ mesons one can select and study states with practically any quantum numbers. Therefore, SCTF is a unique laboratory to study properties of mesons with mass lighter than 3 GeV consisting of $u$, $d$, and $s$ quarks.

Of special interest is a search for bound states of two gluons (glueballs), and hybrid states ($q\bar{q}g$). With a $\sim 9\%$ probability the $J/\psi$ meson decays into $\gamma gg$ followed by hadronization of two gluons. Thus, the $J/\psi$ radiative decays are the best sources of glueball production. Lattice QCD calculations [50, 51] predict that the lightest glueballs with the quantum numbers $J^{PC} = 0^{++}$, $2^{++}$, and $0^{-+}$ have masses smaller than 3 GeV. The glueball spectrum obtained in Ref. [50] is shown in Fig. 1.2.

One of the characteristic features allowing to distinguish a glueball from a regular two-quark meson is its anomalously small two-photon width. Therefore, a search for glueballs in $J/\psi$ decays should be complemented by a study of two-photon meson production. (see section 1.8). Previous searches for glueballs failed to give an unambiguous result. Most probably, glueballs are mixed with two-quark mesons. To determine a glueball fraction in a meson, one should study in detail meson properties in different processes and decay modes. For example, for a family of scalars ($f_0$, $a_0$, $K_0^*$), one should measure with high precision the processes $J/\psi \to f_0\gamma$, $f_0\phi$, $f_0\omega$, $a_0\rho$, $K^*(892)K_0^*$, and $\gamma\gamma \to f_0$, $a_0$ in different scalar decay modes $f_0, a_0, K_0^* \to PP$, $VP$, $VV$, $V\gamma$, where $V$ and $P$ are vector and pseudoscalar mesons, respectively. A gluon component will reveal itself as a ratio of decay probabilities unusual for two-quark mesons and appearance of an extra $f_0$ meson not fitting the scheme of two-quark states. It is worth noting that in addition to gluonic and two-quark states, QCD predicts existence of exotic four-quark mesons and molecular states of two mesons. Existence of such states and their mixing with two-quark states makes even more complicated the pattern of levels of scalar mesons. Detailed systematization of mesons requires very large data samples of $J/\psi$ decays and two-photon events that can be accumulated at SCTF only.

A search for hybrid states is facilitated by the fact that such a state with a smallest mass of 1.3–2.2 GeV/$c^2$ should have exotic quantum numbers $J^{PC} = 1^{-+}$, impossible in the quark model (see review [52] and references therein). At the present time there are two candidates for the

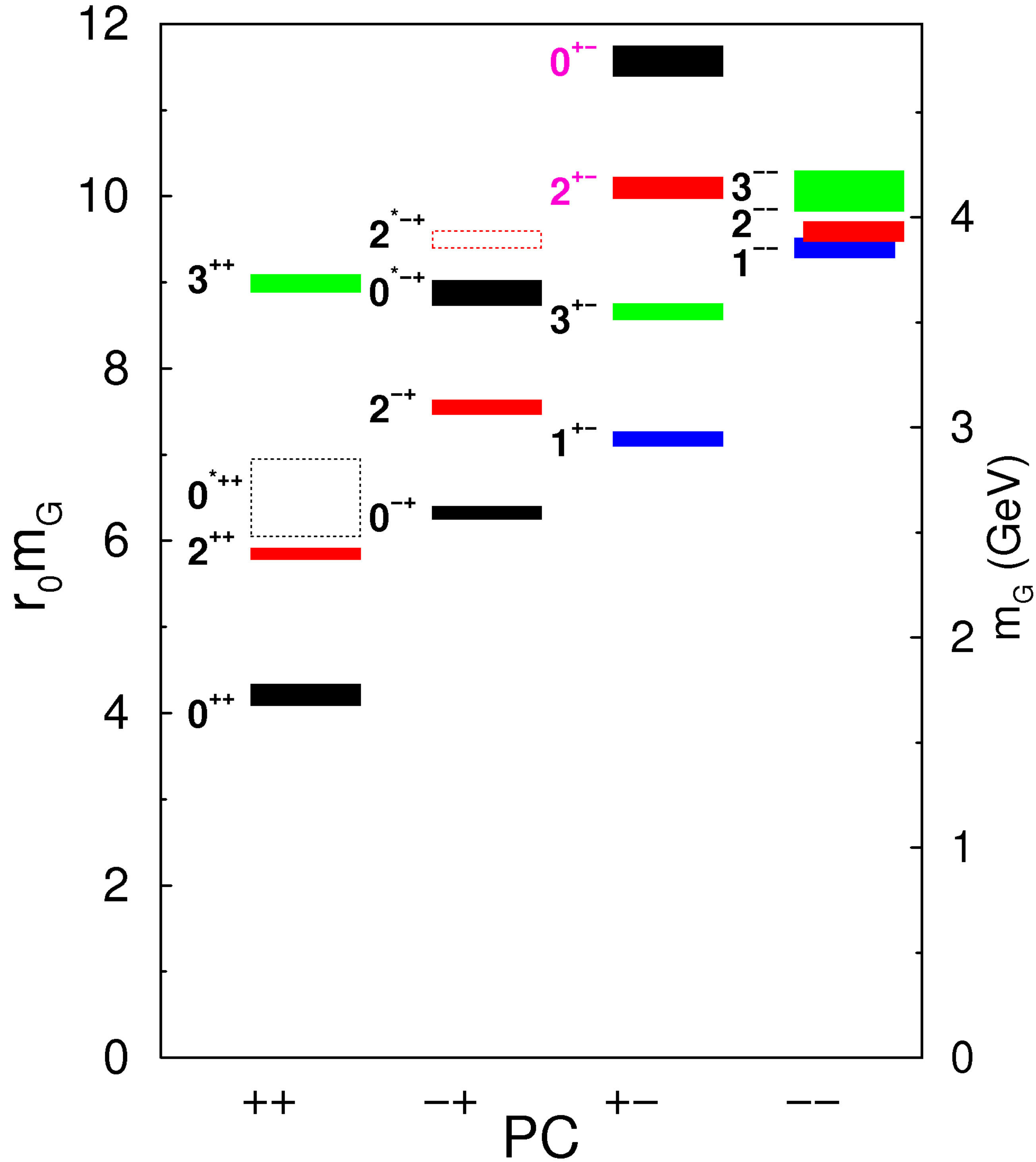


Figure 1.2: Spectrum of glueball masses [50].

Table 1.5: The maximum values of the $e^+e^- \to D\bar{D}^{(*)}$ and $e^+e^- \to D_s\bar{D}_s^{(*)}$ cross sections [61, 62] and the energies where the cross sections are maximal.

| | $D^+D^-$ | $D^0\overline{D}^0$ | $D\overline{D}^*$ | $D_s^+D_s^-$ | $D_s^+D_s^{*-}$ |
|---|---|---|---|---|---|
| $E$, GeV | 3.77 | 3.77 | 4.02 | 4.01 | 4.17 |
| $\sigma$, nb | $2.88 \pm 0.05$ | $3.61 \pm 0.06$ | $7.5 \pm 0.4$ | $0.27 \pm 0.03$ | $0.92 \pm 0.05$ |

light-quark hybrid: $\pi_1(1400)$ and $\pi_1(1600)$. Properties of these states are badly investigated and even their existence should be confirmed. The $\pi_1$ states were observed primarily in diffractive experiments $\pi^- N \to \pi_1^- N$. SCTF allows a study of completely different production mechanisms: $S$-wave decay $\chi_{c1} \to \pi\pi_1$ and $P$-wave decay $J/\psi \to \rho\pi_1$. One should study main decay modes expected for a hybrid: $\rho\pi$, $b_1\pi$, $f_1\pi$, $\eta\pi$, and $\eta'\pi$. It is expected that the lightest state of a hybrid with non-exotic quantum numbers $0^{-+}$ is also in the mass region around 2 GeV. This state can be searched for in the decay $\chi_{c0} \to \pi\pi_1$ as well as in $\psi$ meson decays.

The BESII collaboration observed an anomalously strong near-threshold excess in the $p\overline{p}$ mass spectrum in the $J/\psi \to \gamma p\overline{p}$ radiative decay. The structure ($X(p\overline{p})$) was fitted with an S-wave Breit-Wigner resonance function with mass about 1860 MeV and width less than 30 MeV [53]. This result was confirmed by the CLEO-c [54]. The observed structure can be manifestation of a hypothetical $p\overline{p}$ bound state, baryonium [55].

The study of the structure $X(p\overline{p})$ was continued in the BESIII experiment [56, 57]. The partial-wave analysis of the $J/\psi \to \gamma p\overline{p}$ and $\psi' \to \gamma p\overline{p}$ decays in the $p\overline{p}$ invariant mass region below 2.2 GeV shows that the mass of the $X(p\overline{p})$ is $1832 \pm 20$ MeV, its width is less than 76 MeV, and its $J^{PC} = 0^{-+}$ [57].

In the $J/\psi \to \gamma\eta'\pi^+\pi^-$ decay, the expected contributions of the $f_1(1510)$ and $\eta_c$ resonances together with the new structures $X(1835)$, $X(2120)$, $X(2370)$, and $X(2600)$ were observed in the the $\eta'\pi^+\pi^-$ invariant mass spectrum [58, 59]. The resonance $X(1835)$ has the width about 200 MeV. The photon angular distribution in $J/\psi \to \gamma X(1835)$ decay corresponds to the $X(1835)$ quantum numbers $J^P = 0^-$. The slope of the $X(1835)$ resonance line-shape has a significant abrupt change at the $p\overline{p}$ mass threshold. This may be due to opening the $X(1835) \to p\overline{p}$ decay. So, the $X(1835)$ and $X(p\overline{p})$ may be the same resonance.

The $X(1835)$ signal is seen in the other decay modes. For example, the decay $J/\psi \to \gamma X(1835) \to \gamma K_S K_S \eta (\gamma f_0(980)\eta)$ was observed [60]. The resonance mass, width, and quantum numbers in this decay are in agreement with those in the $J/\psi \to \gamma\eta'\pi^+\pi^-$ decay.

Experiments with the BESIII detector at the tau-charm factory BEPCII indicate the rich resonance physics in the mass region below 3 GeV. Statistics of the BESIII experiment is not enough for unambiguous interpretation of the observed structures. The studies of these states will be an important part of the physical program of Super Charm – Tau factory.

## 1.4 Physics of $D$-mesons

The values of the $D$-meson production cross sections are listed in Table 1.5. With the luminosity distribution given in Table 1.1, about $10^9$ pairs of charged and neutral $D$ mesons, and about $2 \times 10^7$ pairs of $D_s$ mesons can be produced at CTF.

These numbers do not exceed the numbers of $D$ mesons produced at existing $B$-factories at the $e^+e^-$ c.m. energy of 10.58 GeV. There is, however, crucial difference between $D$-meson events at 10.58 and 3.77 GeV, which makes low energy measurements preferable and allows more precise results to be obtained with lower statistics:

- The multiplicity of charged and neutral particles is about two times lower at $\psi(3770)$ than at $\Upsilon(4S)$.

- In contrast to $\Upsilon(4S)$, where $D$ meson production is accompanied by many other particles, at the threshold pure $D\overline{D}$ events are produced. This allows to use additional kinematic constraints for the event reconstruction. In particular, in events with leptonic or semileptonic decay of one of the $D$ mesons, the neutrino is reconstructed with the additional constraint of zero missing mass. Use of the double-tag method, when one of the $D$ mesons is fully reconstructed, while the other is studied, strongly reduces background and allows to perform precise measurements of absolute decay probabilities.

- $D$ and $\overline{D}$ mesons are produced in a quantum-coherent state, for example, with $J^{PC} = 1^{--}$ in the reaction $e^+e^- \to D\overline{D}$ or $J^{PC} = 0^{++}$ in the reaction $e^+e^- \to D\overline{D}\gamma$. The coherence allows to use simple techniques for a study of $D\overline{D}$ mixing, search for $CP$ violation, measurement of strong phases, and probabilities of decays to $CP$ states.

At SCTF a systematic study of $D$-meson properties will be performed.

### 1.4.1 Spectroscopy of $D$ mesons

There are three types of charmed mesons: charged $D^\pm$ mesons with the quark structure of $(cd)$, neutral $D^0$ and $\overline{D}^0$ mesons with the structure of $(cu)$, and $D_s^\pm$ mesons with the structure of $(cs)$.

Let us consider the orbital-excited states of the $D$-meson. Since this meson consists of the heavy $c$-quark and the light antiquark, the heavy quark effective theory could be used to describe this system. In limit of accurate symmetry by flavor and spin $\vec{s}_Q$ of the heavy quark, the total angular momentum of the light quark $\vec{j}_q = \vec{L} + \vec{s}_q$ commutates with the Hamiltonian of the system and conserves its value. In such a case, we can classify the states by the total angular momentum of the light quark $\vec{j}_q$ and spin of the meson $\vec{J} = \vec{j}_q + \vec{s}_Q$. The classification scheme of low-lying levels of $D$ mesons is shown in Fig. 1.3. From the six states shown, the two lowest have $L = 0$, while the four others have $L = 1$. The moment $j_q$ coincides with the spin of the light quark $s_q$ in the case of the zero relative angular momentum $L$ between the light and heavy quarks. The total spin $J$ can be equal to 0 or 1. In the first case, we have the ground state of the $D$ meson with the $J^P_{j_q} = 0^-_{1/2}$, and the second case corresponds to the vector state with the $J^P_{j_q} = 1^-_{1/2}$, which is called the $D^*$ meson.

States with the relative angular momentum $L$ equal to 1 are called the $D^{**}$ mesons. The $D^{**}$ states include two doublets with $j_q = 1/2$ ($J^P_{j_q} = 0^+_{1/2}$, $1^+_{1/2}$) and $j_q = 3/2$ ($J^P_{j_q} = 1^+_{3/2}$, $2^+_{3/2}$). Such a classification is applicable to all three types of $D$ mesons.

Conservation of a P-parity and angular momentum in strong interactions imposes constraints on decays of the $D^{**}$ states to the $D^{(*)}\pi$. Two states with $j_q = 1/2$ decay to the $D^{(*)}\pi$ system in $S$ wave and two other states with $j_q = 3/2$ decay in $D$ wave. Since the decay width is proportional to the nonrelalivistic momentum of the final particles to the power of $2l + 1$, where $l$ is a relative angular momentum between $D^{(*)}$ and $\pi$, the states with $j_q = 3/2$ have small decay widths of order of tens of MeV and are expected to be narrow, but the states with $j_q = 1/2$ are expected to be broad with widths of hundreds of MeV. The spin-flavor symmetry of the heavy quark is not accurate. Therefore, if the powers of $1/m_Q$ are taken into account, the total angular momentum

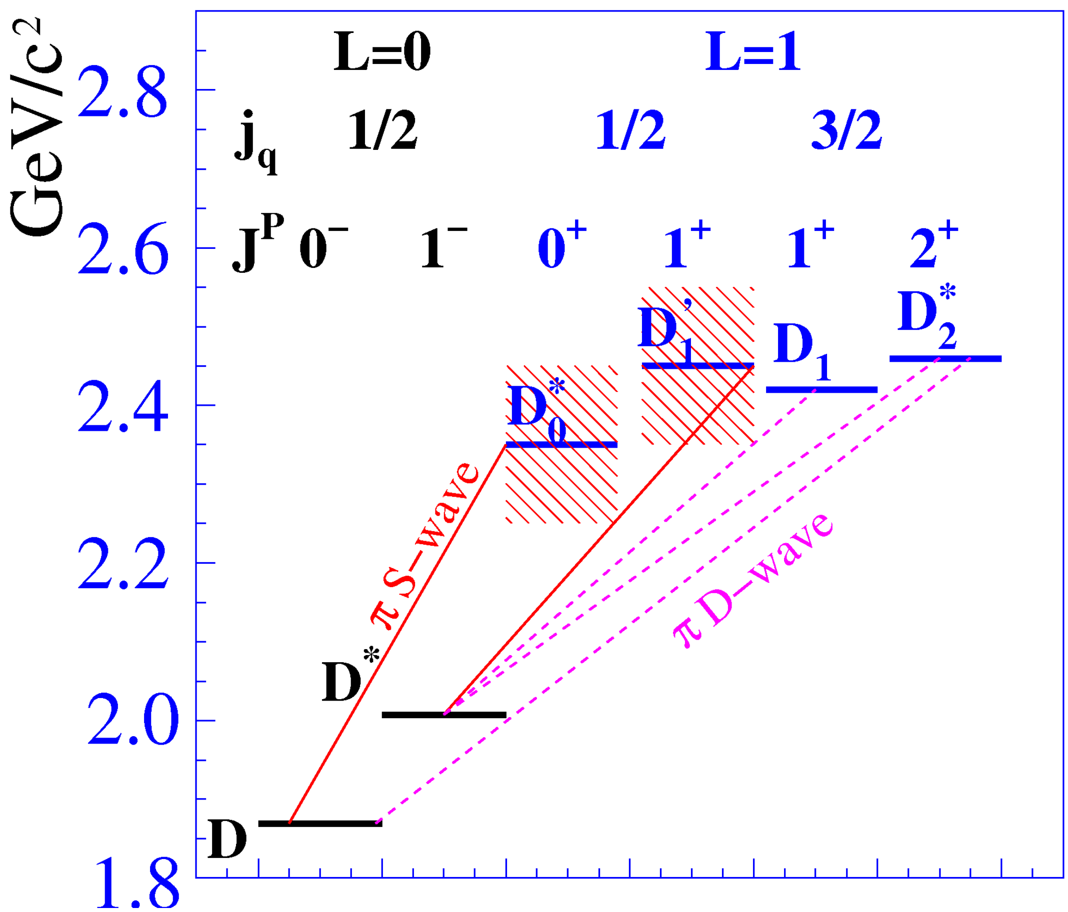


Figure 1.3: The scheme of the $D$-meson levels.

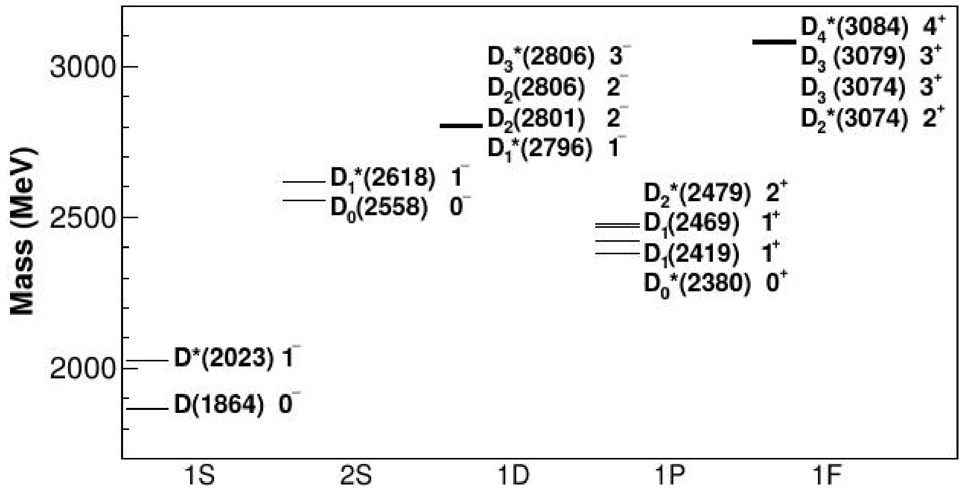


Figure 1.4: The mass spectrum for neutral $D$ mesons in the relativistic quark model [63]. Masses are scaled such that mass of the ground state coincides with mass of the $D^0$ meson.

Table 1.6: The parameters of $D$ and $D_s$ mesons. The masses and widths are given in MeV.

| charge | | $D$ | $D^*$ | $D_0^*$ | $D_1'$ | $D_1$ | $D_2^*$ |
|---|---|---|---|---|---|---|---|
| $\pm$ | $M$ | $1869.58 \pm 0.09$ | $2010.26 \pm 0.05$ | $2351 \pm 7$ | | $2423.2 \pm 2.4$ | $2465.4 \pm 1.3$ |
| | $\Gamma$ | $1040 \pm 7$ fs | $0.083 \pm 0.002$ | $230 \pm 17$ | | $25 \pm 6$ | $46.7 \pm 1.2$ |
| 0 | $M$ | $1864.83 \pm 0.05$ | $2006.85 \pm 0.05$ | $2318 \pm 29$ | $2427 \pm 36$ | $2420.8 \pm 0.5$ | $2460.6 \pm 0.2$ |
| | $\Gamma$ | $410.1 \pm 1.5$ fs | $< 2.1$ | $267 \pm 40$ | $384 \pm 120$ | $31.7 \pm 2.5$ | $47.7 \pm 1.3$ |
| charge | | $D_s$ | $D_s^*$ | $D_{s0}^*$ | $D_{s1}'$ | $D_{s1}$ | $D_{s2}^*$ |
| $\pm$ | $M$ | $1968.27 \pm 0.10$ | $2112.1 \pm 0.4$ | $2317.7 \pm 0.6$ | $2459.5 \pm 0.6$ | $2535.10 \pm 0.06$ | $2569.1 \pm 0.8$ |
| | $\Gamma$ | $500 \pm 7$ fs | $< 1.9$ | $< 3.8$ | $< 3.5$ | $< 0.92 \pm 0.05$ | $16.9 \pm 0.8$ |

is not a "good" quantum number any longer. It leads to the fact that physical $D_1'(2430)^0$ and $D_1(2420)^0$ states are linear combinations of the pure states with $j_q = 1/2$ and $j_q = 3/2$. We use the following nomenclature of the $D^{**}$ states: $D_0^*(2400)$ with $J^P_{j_q} = 0^+_{1/2}$, $D_1'(2430)$ with $J^P_{j_q} = 1^+_{1/2}$, $D_1(2420)$ with $J^P_{j_q} = 1^+_{3/2}$ and $D_2^*(2460)$ with $J^P_{j_q} = 2^+_{3/2}$ (see Fig. 1.3).

The spectrum of neutral $D$ mesons obtained in the relativistic quark model is shown in Fig. 1.4. The mass spectrum of the $c\bar{u}$ system is shown for the ground states with $nL = 1S$, where $n$ is the radial quantum number, as well as for the orbital excitations with angular momenta $L = 1, 2, 3$ ($1P$, $1D$ and $1F$) and also for the first radial excitation ($2S$). Predictions for the $1S$ and $1P$ states with $J^P = 1^+$ and $J^P = 2^+$ are in good agreement with measurements (within $20 - 30$ MeV). Agreement for the $1P$ states with $J^P = 0^+$ is about 100 MeV. Recently BABAR [64] and LHCb [65] collaborations found excited $2S$ and $1D$ states of $D_J$ mesons as well as the possible superposition of the different $1F$ states.

The known low-lying states of $D$ and $D_s$ mesons [2] are listed in Table 1.6. Study of properties of the excited $D_J$ and $D_{sJ}$ states requires further theoretical and experimental work. Presently, experimental information about the $D_J$ and $D_{sJ}$ mesons is not complete. In the frame of the naive quark model the $P$-wave $D_{sJ}$ states with $j_q = 1/2$ are expected to be broad and should decay to the $DK$ and $D^*K$ systems [66]. However, the measured masses of the $D^*_{s0}(2317)$ and $D'_{s1}(2460)$ states lie by about 40 MeV below the $DK$ and $D^*K$ thresholds. Therefore, they are narrow. To explain this discrepancy, the hypotheses that these $c\bar{s}$ states are not conventional mesons, but have, for example, four-quark or $DK$ molecular structure are suggested.

Precise knowledge of the spectroscopic properties of the $D_J$ and $D_{sJ}$ states is important to determine the CKM matrix elements $|V_{cb}|$ and $|V_{ub}|$, to study semileptonic $b \to c$ decays and to search for "new physics" evidence. The properties of the $D_J$ and $D_{sJ}$ systems can be studied in detail at SCTF, where $D_J$ and $D_{sJ}$ mesons can be produced in the reactions $e^+e^- \to D^*_0\bar{D}^*$, $D_1^{(\prime)}\bar{D}^{(*)}$, $D^*_2\bar{D}^{(*)}$, which have thresholds in the energy range of $4.3 - -4.7$ GeV and the cross sections of about 1 nb [67, 68]. The integrated luminosity of about 50 fb$^{-1}$, collected in the 4.3–5.0 GeV energy range, will be sufficient to perform a careful study of $D_J$ and $D_{sJ}$ properties. A detailed measurement of exclusive charm-production cross sections up to the 5–6 GeV will allow to observe production of the known higher excited $D$ and $D_s$ states ($D_{sJ}(2632)$ [69], $D_{sJ}(2708)$ [70], and $D_{sJ}(2860)$ [71]), and find new states of this family.

### 1.4.2 Charmed-meson decays

Charmed-meson decays are a unique source for studying the dynamics of strong interactions. SCTF allows to perform a detailed study of $D$ and $D_s$ meson decays including high-precision measurements of decay probabilities, Dalitz plot analyses for three-body decays, and dynamics study of four-body decay distributions. It is expected that in the near future many parameters extracted from $D$ and $D_s$ decays, such as the decay constants, $f_D$ and $f_{D_s}$, and form factors of semileptonic decays, will be calculated with high accuracy in the framework of the lattice QCD (LQCD). Precision measurements of $D$ decays will allow to control these calculations and extrapolate them to the $B$ meson region. As a result, a significant decrease of the theoretical uncertainties in the extraction of the CKM matrix elements $V_{cd}$, $V_{cs}$, $V_{td}$, $V_{ts}$, $V_{ub}$ and $V_{cb}$ from the precision measurements of various $B$ meson decays is expected. For a precise measurement of the angles $\beta$ ($\phi_1$) and $\gamma$ ($\phi_3$) of the unitarity triangle at a super-$B$ factory, neutral $D$-meson data are required, such as $D^0 - \bar{D}^0$ mixing parameters, the amplitude ratio of the $D^0$ and $\bar{D}^0$ decays into $K^+\pi^-$, the strong phase difference between these amplitudes, Dalitz distributions for the three-body hadronic decays, for example, into the $K^0_S\pi^+\pi^-$ final state [72, 73]. All these data can be obtained at SCTF. Below, the current status of leptonic and semileptonic $D$ decays and CTF possibilities for their measurements are discussed in more detail.

In SM the width of a leptonic $D^+$ decay is given by

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

where $M_D$ and $m_l$ are the $D$-meson and lepton masses, and $G_F$ is the Fermi constant. A similar formula with the substitution of $V_{cs}$ for $V_{cd}$ is used for a $D_s$ leptonic decay. The most precise experimental data on leptonic decays of the $D$ and $D_s$ mesons obtained in the CLEO [74], BESIII [75] and Belle [76] experiments, are listed in Table 1.7. The $D^+(D_s^+) \to e^+\nu$ branching fractions are expected to be about $10^{-8}(10^{-7})$ and can hardly be measured even at SCTF. The expected branching fraction for the $D^+ \to \tau^+\nu$ (about $1.2 \times 10^{-3}$) is at the level of the CLEO upper limit.

In SM the unitarity constraints allow to determine the CKM matrix elements $V_{cd}$ and $V_{cs}$ from experimental data with high precision: $|V_{cd}| = 0.2249(3)$, $|V_{cs}| = 0.97347(7)$ [77]. Therefore, the measured leptonic decay branching fractions can be used to extract the decay constants and their ratio shown in Table 1.8.

Table 1.7: Most presise measurements of the branching fractions of $D$ and $D_s$ meson leptonic decays.

| | $D^+$ | $D_s^+$ |
|---|---|---|
| $e^+\nu$ | $< 8.8 \times 10^{-6}$ [74] | $< 8.3 \times 10^{-5}$ [76] |
| $\mu^+\nu$ | $(3.71 \pm 0.19 \pm 0.06) \times 10^{-4}$ [75] | $(5.31 \pm 0.28 \pm 0.20) \times 10^{-3}$ [76] |
| $\tau^+\nu$ | $< 1.2 \times 10^{-3}$ [74] | $(5.70 \pm 0.21^{+0.31}_{-0.30}) \times 10^{-2}$ [76] |

Table 1.8: The experimental values of the $D$ and $D_s$ decay constants [75, 76] in comparison with the LQCD calculation [78].

| | Experiment | Theory |
|---|---|---|
| $f_D$, MeV | $203.2 \pm 5.3 \pm 1.8$ | $202.3 \pm 2.2 \pm 2.6$ |
| $f_{D_s}$, MeV | $255.5 \pm 4.2 \pm 5.1$ | $258.7 \pm 1.1 \pm 2.9$ |
| $f_{D_s}/f_D$ | $1.26 \pm 0.05 \pm 0.03$ | $1.2788 \pm 0.0264$ |

In the last column of Table 1.8 the results of the most accurate-to-date LQCD calculation [78] are listed. It is seen that, firstly, experimental measurements and theoretical predictions are consistent, and secondly, the claimed accuracy of the predictions has already reached the level of 1–2 % and is better than the experimental accuracy. An additional test of the Standard Model in this case may be checking the lepton universality, i.e., comparing the $D_s$ decay widths into the $\tau\nu$ and $\mu\nu$ final states. The current experimental value of this ratio $10.73 \pm 0.69 \pm^{+0.56}_{-0.53}$ [76] is consistent with the theoretical value $9.762 \pm 0.031$, but has a noticeably lower accuracy. Thus, to confirm the SM predictions confidently, new more accurate experimental data are required.

The total branching fractions of the semileptonic $D$ decays measured by CLEO are $B(D^0 \to Xe^+\nu_e) = (6.46 \pm 0.17 \pm 0.13)\%$, $B(D^+ \to Xe^+\nu_e) = (16.13 \pm 0.20 \pm 0.33)\%$ [79]. For $D_s$ the same branching fraction is $B(D_s^+ \to Xe^+\nu) = (6.52 \pm 0.39 \pm 0.15)\%$. One of the goals of SCTF is a high-statistics study of different exclusive decay modes, including Dalitz plot analyses and extraction of the form factors describing the hadronization of the primary quarks produced in $D$ decays.

The best studied are semileptonic $D$ decays into pseudoscalar $\pi$ and $K$ mesons. These decays are described well with a single form factor. For example, the width for the $D \to Ke\nu$ decay is proportional to

$$\frac{d\Gamma(q^2)}{dq^2} \propto |f_+(q^2)|^2 |V_{cs}|^2,$$

where $q$ is the difference of the $D$ and $K$ four-momenta and $f_+(q^2)$ is $\pi$ and $K$ meson form factor. From measurements, the $q^2$ dependence of the form factor and the product $f_+(0)|V_{cs}|$ are extracted. The value of the form factor $f_+(0)$ can be calculated theoretically, for example, in the framework of LQCD. The current accuracy of these calculations is about 10%. The theoretical values of the form factors, $f_+^\pi(0) = 0.64(3)(6)$ and $f_+^K(0) = 0.73(3)(7)$ [80], are consistent with experimental values. The most precise measurement of the form factors was performed by the BESIII Collaboration [81]:

$f_+^\pi(0) = 0.6372 \pm 0.0008 \pm 0.0044$, $f_+^K(0) = 0.7368 \pm 0.0026 \pm 0.0036$. To obtain these experimental values, the elements of the CKM matrix satisfying the unitarity condition [2] are used. It is expected that the accuracy of theoretical calculations of the form factors will improve to a 1% level. In this case the semileptonic decays can be used for measurements of $V_{cs}$ and $V_{cd}$ and to test the unitarity relation.

Other semileptonic $D$ and $D_s$ decay modes, excluding $D \to K^*\ell\nu$, are measured with low accuracy. For their detailed study, large statistics are needed which can be collected only at SCTF. For example, an integrated luminosity of 100 fb$^{-1}$ is required to measure the $D \to \rho e\nu$ branching fraction with a 0.5% accuracy, and ten times more statistics are needed for the precise measurement of three form factors describing this decay.

### 1.4.3 $D^0$–$\overline{D}^0$ Mixing

One of the main goals of the SCTF is a study of $D^0$–$\overline{D}^0$ mixing. The transitions $D^0 \Leftrightarrow \overline{D}^0$ are a result of the interaction which changes the internal quantum number charm by $\Delta\mathcal{C} = 2$. Due to these transitions of $D$ mesons, the eigenstates of the mass matrix are the following:

$$|D_1\rangle = \frac{1}{\sqrt{|p|^2 + |q|^2}}(p|D^0\rangle + q|\overline{D}^0\rangle),$$

$$|D_2\rangle = \frac{1}{\sqrt{|p|^2 + |q|^2}}(p|D^0\rangle - q|\overline{D}^0\rangle).$$

In case of the $\mathcal{CP}$-invariant interaction $p = q$ and the eigenstates $|D_1\rangle$ and $|D_2\rangle$ have a definite internal $\mathcal{CP}$-parity. As a rule, two non-dimensional parameters are used for a description of mixing:

$$x \equiv \frac{\Delta m}{\Gamma}, \quad y \equiv \frac{\Delta\Gamma}{2\Gamma},$$

where $\Delta m$ and $\Delta\Gamma$ are the differences of masses and widths of the $|D_2\rangle$ and $|D_1\rangle$ states and $\Gamma$ is the average width of a $D^0$ meson. In SM the values of these parameters result from long-distance interactions (due to intermediate-meson transitions) and, therefore, predictions for their values have poor precision [82]. It is predicted that $x$ and $y$ can reach the values of $\sim 0.01$. The most precise data for $D$-meson mixing were obtained in $B$ factory and the LHC$b$ experiments. Averaging the current data, which was done by HFAG [83] under the assumption of $\mathcal{CP}$-invariance, gives the following results:

$$x = \left(4.64^{+1.40}_{-1.51}\right) \times 10^{-3}, \quad y = (6.25 \pm 0.77) \times 10^{-3}. \tag{1.1}$$

In SCTF experiments, $D^0$ and $\overline{D}^0$ mesons will be produced in a coherent state with the odd $\mathcal{C}$-parity in the process $e^+e^- \to D^0\overline{D}^0(n\pi^0)$ and the even one in the process $e^+e^- \to D^0\overline{D}^0\gamma(n\pi^0)$. This can be used for a measurement of mixing. In case of a symmetric SCTF (the energies of colliding electrons and positrons are equal), a study of time evolution of the $D^0\overline{D}^0$ system is not possible due to a small lifetime of the $D$-mesons. Therefore, time integrated values will be analyzed below. The decays to the following final states will be considered as suggested in Ref. [84]:

- Hadron final states $f$ and $\overline{f}$ which do not have a definite $\mathcal{CP}$-parity, for example, $K^-\pi^+$, which is a Cabibbo-favored (CF) decay of $D^0$, or doubly Cabibbo suppressed (DCF) decay of $\overline{D}^0$;

- Semileptonic and leptonic final states, $l^+$ and $l^-$, which, without mixing, uniquely determine the flavor of a $D^0$-meson;

Table 1.9: The ratios of decay probabilities of the $D^0\overline{D}^0$ state to various final states. Only leading-order terms in a power series expansion in $r_f^2$, $x$ and $y$ are given.

| | $C=-1$ | $C=+1$ |
|---|---|---|
| $(1/4)\cdot(\Gamma_{lS_+}\Gamma_{S_-}/\Gamma_{lS_-}\Gamma_{S_+} - \Gamma_{lS_-}\Gamma_{S_+}/\Gamma_{lS_+}\Gamma_{S_-})$ | $y$ | $-y$ |
| $(\Gamma_{fl^-}/4\Gamma_f)\cdot(\Gamma_{S_-}/\Gamma_{lS_-} - \Gamma_{S_+}/\Gamma_{lS_+})$ | $y$ | $-y$ |
| $(\Gamma_{f\bar{f}}/4\Gamma_f)\cdot(\Gamma_{S_-}/\Gamma_{\bar{f}S_-} - \Gamma_{S_+}/\Gamma_{\bar{f}S_+})$ | $y+r_f z_f$ | $-(y+r_f z_f)$ |
| $(\Gamma_f\Gamma_{S_+S_-}/4)\cdot(1/\Gamma_{fS_-}\Gamma_{S_+} - 1/\Gamma_{fS_+}\Gamma_{S_-})$ | $y+r_f z_f$ | $0$ |
| $(\Gamma_{\bar{f}}/2)\cdot(\Gamma_{S_+S_+}/\Gamma_{\bar{f}S_+}\Gamma_{S_+} - \Gamma_{S_-S_-}/\Gamma_{\bar{f}S_-}\Gamma_{S_-})$ | $0$ | $y+r_f z_f$ |
| $\Gamma_{ff}/\Gamma_{f\bar{f}}$ | $R_M$ | $2r_f^2 + r_f(z_f y - w_f x)$ |
| $\Gamma_{fl^+}/\Gamma_{fl^-}$ | $r_f^2$ | $r_f^2 + r_f(z_f y - w_f x)$ |
| $\Gamma_{l^\pm l^\pm}/\Gamma_{l^+l^-}$ | $R_M$ | $3R_M$ |

- The states which are eigenstates of $\mathcal{CP}$ parity, $S_+$ and $S_-$.

Under the assumption of $\mathcal{CP}$ invariance, the probability of producing two $D^0$ mesons in various combinations in the final state depends on the following parameters: $x$, $y$, the amplitudes

$$A_f = \langle f|D^0\rangle, \quad A_l = \langle l^+|D^0\rangle, \quad A_{S_\pm} = \langle S_\pm|D^0\rangle$$

, the absolute value and phase of the ratio for the DCF and CF amplitudes

$$r_f e^{-\delta f} = -\langle f|\overline{D}^0\rangle/\langle f|D^0\rangle$$

. One can also determine the following parameters:

$$R_M \equiv (x^2+y^2)/2, \quad z_f \equiv 2\cos\delta_f, \quad w_f \equiv 2\sin\delta_f$$

. The ratios of decay probabilities of the $D^0\overline{D}^0$ system to various final states are shown in Table 1.9. $\Gamma_{jk}$ means $D^0$ decay to the $j$ state and $\overline{D}^0$ to the $k$ state. $\Gamma_j$ means $D^0$ decay to the $j$ state and $\overline{D}^0$ to any final state.

As shown in the Table 1.9, evidence for events $D^0\overline{D}^0 \to (K^-\pi^+)(K^-\pi^+)$ and $D^0\overline{D}^0 \to (K^-e^+\nu_e)(K^-e^+\nu_e)$ in $\psi(3770)$ decays is possible via mixing only. For $10^9$ $D^0\overline{D}^0$ events and for $R_M = 3\times10^{-5}$ obtained using the measured $x$ and $y$ values, it is expected to detect about 60 of these events. Results of Ref. [84] were used for estimation of the detection efficiency, which corresponds to CLEO performance. Thus, a statistical sensitivity for a measurement of $R_M$ using these two decays only is about $4\times10^{-6}$. A systematic uncertainty will mainly depend on the quality of particle identification.

The probabilities of inclusive $D^0\overline{D}^0$ decays to the $S_\pm X$ final states are proportional to $(1\mp y)$ [84]. This allows to measure a $y$ parameter. For double ratios shown in the first and second rows of Table 1.9, the substantial part of systematic errors, which originates from data-MC simulation difference in track reconstruction and particle identification, cancels. A statistical precision of $y$ determined from the ratio $(1/4)\cdot(\Gamma_{lS_+}\Gamma_{S_-}/\Gamma_{lS_-}\Gamma_{S_+} - \Gamma_{lS_-}\Gamma_{S_+}/\Gamma_{lS_+}\Gamma_{S_-})$ was estimated in [85] to be $26/\sqrt{N_{DD}}$, where $N_{DD}$ is the number of produced $D^0\overline{D}^0$ pairs. For $N_{DD}=10^9$ it equals 0.0008, i.e., 2.5 times better than the current experimental precision.

The value of the strong phase $\delta_f$ in the $K^-\pi^+$ final state, which is important, for example, for a measurement of $D^0\overline{D}^0$ mixing at $B$-factories, can be measured using the relations listed in the third and fourth rows of Table 1.9. The expected statistical precision for a measurement of $\cos\delta_f$ is estimated as $444/\sqrt{N_{DD}} = 0.014$ [85], that corresponds to a precision of 0.05 for $\delta_f$. At the present time the average value of this parameter is $0.14^{+0.17}_{-0.20}$.

Measurements, which can be performed with the $D^0\overline{D}^0$ system in the $\mathcal{C}$-even state, have the best sensitivity for $y$. For a measurement of $y$ with a precision of $8\times10^{-4}$ from the ratio $\Gamma_{fl^+}/\Gamma_{fl^-}$, $3\times10^8$ $D^0\overline{D}^0$ pairs are required. This number of $\mathcal{C}$-even $D^0\overline{D}^0$ pairs can be produced in the process $e^+e^-\to D^0\bar{D}^{*0}\to D^0\overline{D}^0\gamma$ with an integrated luminosity of 250 fb$^{-1}$ collected at an energy of 4.02 GeV. This measurement is also sensitive to the parameter $x$. However, as it is shown in Table 1.9, a sensitivity to $x$ is worse than for $y$ due to $\delta_f$ infinitesimality. As it was shown in a recent paper [86], this problem can be successfully solved in case of a three-particle decay of $D^0$, for example, to $K^0_S\pi^+\pi^-$ or $K^+\pi^-\pi^0$. An important feature of the suggested method is that for the $\mathcal{C}$-odd $D^0\overline{D}^0$ state all effects of mixing, which have impact on the density of events on the Dalitz plot, cancel in the first order of $x$ and $y$. In the case of the $\mathcal{C}$-even one, the effects of mixing are doubled compared to a non-coherent $D^0$ decay. Thus, in this experiment there is a possibility to measure $x$ and $y$ by a direct comparison of the distribution of events on the Dalitz plot for the $\mathcal{C}$-even and -odd $D^0\overline{D}^0$ states. As it was shown in Ref. [86], statistical errors for $x$ and $y$ are approximately equal. It is expected that many systematic errors in this measurement will cancel because the states with opposite charge parity will be produced simultaneously and in similar kinematic states during data taking. Furthermore, unlike other methods described above, this method does not require measuring absolute probabilities of $D^0$ decays. It can be estimated that for an integrated luminosity of about 1 ab$^{-1}$, a precision of measuring mixing parameters will be not worse than at the Super $B$ factory for an integrated luminosity of 10 ab$^{-1}$ [87].

### 1.4.4 Search for $\mathcal{CP}$ violation

A search for $\mathcal{CP}$ violation in $D_{(s)}$ decays is one of the most interesting experiments to be performed at SCTF. The Standard Model predicts a very small $\mathcal{CP}$ asymmetry in reactions with charmed particles. The maximum effect of about $10^{-3}$ is expected in the Cabibbo-suppressed (CS) $D$ decays [82]. An observation of a $\mathcal{CP}$ asymmetry in CF and DCS decays at any level or an asymmetry higher than $10^{-3}$ in CS decays will clearly indicate the presence of new BSM physics. The exceptions are the decays to the final states containing $K^0_S$ or $K_L$, for example, $D\to K^0_S\pi$, in which the $\mathcal{CP}$ asymmetry arises from the fact that a $K^0_S$ meson is not a $\mathcal{CP}$ eigenstate. For the decay $D^\pm\to K^0_S\pi^\pm$, a $\mathcal{CP}$ asymmetry is predicted with a relatively high accuracy, $(3.32\pm0.06)\times10^{-3}$ [82].

We can distinguish three types of $\mathcal{CP}$ violation:

- The direct $\mathcal{CP}$ violation in $\Delta\mathcal{C}=1$ transitions reveals itself as an inequality of the amplitude of $D_{(s)}$ meson decay ($A_f$) and the corresponding $\mathcal{CP}$-conjugate amplitude ($\overline{A}_{\overline{f}}$). $\mathcal{CP}$ violation can be observed when the decay amplitude is a sum of two amplitudes with different weak and strong phases:
$$A_f = |A_1|e^{i(\delta_1+\phi_1)} + |A_2|e^{i(\delta_2+\phi_2)}.$$
The weak phase changes its sign under the $\mathcal{CP}$ transformation ($\phi_i\to-\phi_i$), while the strong phase $\delta_i$ does not.

- $\mathcal{CP}$ violation in $D^0$–$\overline{D}^0$ mixing due to $\Delta\mathcal{C}=2$ transitions reveals itself in a deviation of the ratio $R_m=|p/q|$ from unity.

- In decays of neutral $D$ mesons $\mathcal{CP}$ violation can be observed in the interference of decays with mixing ($D^0 \to \overline{D}^0 \to f$) and without it ($D^0 \to f$). This type of $\mathcal{CP}$ violation is described by the parameter

$$\varphi = \arg \lambda_f = \arg \left( \frac{q}{p} \frac{\bar{A}_f}{A_f} \right).$$

$\mathcal{CP}$ violation in mixing leads to the difference between the widths of semileptonic decays with a wrong sign of the decay lepton $\Gamma(\overline{D}^0 \to l^+ X) \neq \Gamma(D^0 \to l^- X)$. For example, in $\psi(3770)$ decays the following asymmetry can be measured

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

For $10^9$ $D^0\overline{D}^0$ pairs, about 20 $(K^\pm e^\mp \nu)(K^\pm e^\mp \nu)$ events are expected to be produced. With these statistics, the $|q/p|$ ratio will be determined with about 6% accuracy. The current value of the parameter $|q/p|$ is $0.89^{+0.08}_{-0.07}$.

Direct $\mathcal{CP}$ violation can be observed as a difference between the decay widths for charged $D$ mesons:

$$A_{\pm}^{\mathcal{CP}} = \frac{\Gamma(D^- \to f^-) - \Gamma(D^+ \to f^+)}{\Gamma(D^- \to f^-) + \Gamma(D^+ \to f^+)}.$$

For neutral $D$ mesons, all three types of $\mathcal{CP}$ violation contribute to the same asymmetry parameter. The current values of the $\mathcal{CP}$ asymmetry measured in $D$ and $D_s$ meson decays are listed in Table 1.10 and Table 1.11, respectively.

In Ref. [61] the $\mathcal{CP}$ asymmetries were measured by the CLEO detector using a data sample of $3.0 \times 10^6$ $D^0\overline{D}^0$ pairs and $2.4 \times 10^6$ $D^+D^-$ pairs. At SCTF, for many decays the statistical error of asymmetry can be decreased to a level of $10^{-3}$-$10^{-4}$. The systematic error is dominated by uncertainties in track reconstruction and particle identification. The reconstruction and identification efficiencies are different for pions and kaons of different charges and are usually not reproduced in simulation with sufficient accuracy. At SCTF a level of $10^{-3}$ for the systematic uncertainty seems achievable. For example, in the BaBar and Belle measurements of the asymmetries for the decays $D^0/\overline{D}^0 \to K^+K^-$, $\pi^+\pi^-$ [100, 101], the systematic uncertainty due to a difference in the detection efficiency for $\pi^+$ and $\pi^-$ mesons used for $D$ tagging was decreased to the $10^{-3}$ level. The thickness of material before and inside the tracking system of the SCTF detector should be minimized to reduce the systematic uncertainty for charge asymmetry measurements.

The $\mathcal{CP}$ asymmetry in decays of neutral $D$ mesons can be represented as a sum of three terms. For example, for the decay into the $\mathcal{CP}$ eigenstate $\eta_f^{\mathcal{CP}} = \pm 1$ [104]

$$A_f^{\mathcal{CP}} = a_f^d + a_f^m + a_f^i,$$

$$a_f^m = -\eta_f^{\mathcal{CP}} \frac{y}{2} (R_m - R_m^{-1}) \cos \varphi,$$

$$a_f^i = \eta_f^{\mathcal{CP}} \frac{x}{2} (R_m + R_m^{-1}) \sin \varphi,$$

where $a_f^d$ is a $\mathcal{CP}$ asymmetry in the decay, $\varphi$ is a relative weak phase between the amplitudes for the decays $D^0 \to f$ and $D^0 \to \overline{D}^0 \to f$. The magnitude of the second term $a_f^m$ is determined mainly by $\mathcal{CP}$ violation in mixing. The third term $a_f^i$ is dominated by $\mathcal{CP}$ violation in the interference. The mixing leads to a difference in the time dependencies of the $D^0$ and $\overline{D}^0$ decay probabilities.

Table 1.10: The current values of the $\mathcal{CP}$ asymmetry measured in $D^0$ and $D^+$ meson decays. The designations $f_{D^0}$ and $f_{D^+}$ denote $D^0$ and $D^+$ meson final state, respectively.

| $f_{D^0}$ | $A_{\mathcal{CP}}$ (%) | $f_{D^+}$ | $A_{\mathcal{CP}}$ (%) |
|---|---|---|---|
| | | $\mu^+\overline{\nu}_\mu$ | $8 \pm 8$ [96] |
| $K^-\pi^+$ | $+0.3 \pm 0.3 \pm 0.6$ [61] | $K^+\pi^0$ | $-3.5 \pm 10.7 \pm 0.9$ [93] |
| $K^0_S\pi^0$ | $-0.20 \pm 0.17$ [88] | $K^0_S\pi^+$ | $-0.41 \pm 0.09$ [83] |
| $K^0_S\eta$ | $+0.54 \pm 0.51 \pm 0.16$ [89] | | |
| $K^0_S\eta'$ | $+0.98 \pm 0.67 \pm 0.14$ [89] | | |
| $K^+K^-$ | $-0.16 \pm 0.12$ [83] | | |
| $K^0_SK^0_S$ | $-2.9 \pm 5.2 \pm 2.2$ [90] | $K^0_SK^+$ | $-0.11 \pm 0.25$ [83] |
| | | $K^0K^+$ | $+0.11 \pm 0.17$ [83] |
| $\pi^+\pi^-$ | $+0.00 \pm 0.15$ [83] | $\pi^+\pi^0$ | $+2.9 \pm 2.9 \pm 0.3$ [93] |
| | | $\pi^+\eta$ | $+1.0 \pm 1.0$ [83] |
| | | $\pi^+\eta'$ | $-0.5 \pm 1.1$ [83] |
| $\pi^0\pi^0$ | $-0.03 \pm 0.64$ [88] | | |
| $K^-\pi^+\pi^0$ | $+0.1 \pm 0.3 \pm 0.4$ [61] | $K^-\pi^+\pi^+$ | $-0.18 \pm 0.16$ [83] |
| $K^+\pi^-\pi^0$ | $-0.6 \pm 5.3$ [91] | | |
| $K^0_S\pi^+\pi^-$ | $-0.05 \pm 0.57 \pm 0.54$ [92] | $K^0_S\pi^+\pi^0$ | $-0.1 \pm 0.7 \pm 0.2$ [61] |
| $K^+K^-\pi^0$ | $-1.00 \pm 1.67 \pm 0.25$ [95] | $K^+K^-\pi^+$ | $+0.32 \pm 0.31$ [83] |
| $\pi^+\pi^-\pi^0$ | $+0.32 \pm 0.42$ [83] | $\pi^+\pi^-\pi^+$ | $-1.7 \pm 4.2$ [97] |
| $K^-\pi^+\pi^+\pi^-$ | $+0.2 \pm 0.3 \pm 0.4$ [61] | $K^-\pi^+\pi^+\pi^0$ | $-0.3 \pm 0.6 \pm 0.4$ [61] |
| $K^+\pi^-\pi^+\pi^-$ | $-1.8 \pm 4.4$ [98] | $K^0_S\pi^+\pi^+\pi^-$ | $+0.0 \pm 1.2 \pm 0.3$ [61] |
| $K^+K^-\pi^+\pi^-$ | $-8.2 \pm 5.6 \pm 4.7$ [99] | $K^0_SK^+\pi^+\pi^-$ | $-4.2 \pm 6.4 \pm 2.2$ [99] |

Table 1.11: The current values of the $\mathcal{CP}$ asymmetry measured in $D_s$ meson decays. The designation $f_{D_s}$ denotes $D_s$ meson final state.

| $f_{D_s}$ | $A_{\mathcal{CP}}$ (%) |
|---|---|
| $\mu^+\overline{\nu}_\mu$ | $+4.8 \pm 6.1$ [102] |
| $\pi^+\eta$ | $+1.1 \pm 3.0 \pm 0.8$ [103] |
| $\pi^+\eta'$ | $-2.2 \pm 2.2 \pm 0.6$ [103] |
| $K^0_S\pi^+$ | $+3.11 \pm 1.54$ [83] |
| $K^0\pi^+$ | $+0.38 \pm 0.48$ [83] |
| $K^0_S K^+$ | $+0.08 \pm 0.26$ [83] |
| $K^+\pi^0$ | $-26.6 \pm 23.8 \pm 0.9$ [93] |
| $K^+\eta$ | $+9.3 \pm 15.2 \pm 0.9$ [93] |
| $K^+\eta'$ | $+6.0 \pm 18.9 \pm 0.9$ [93] |
| $\pi^+\pi^+\pi^-$ | $-0.7 \pm 3.0 \pm 0.6$ [103] |
| $\pi^+\pi^0\eta$ | $-0.5 \pm 3.9 \pm 2.0$ [103] |
| $\pi^+\pi^0\eta'$ | $-0.4 \pm 7.4 \pm 1.9$ [103] |
| $K^0_S K^+\pi^0$ | $-1.6 \pm 6.0 \pm 1.1$ [103] |
| $K^0_S K^0_S\pi^+$ | $+3.1 \pm 5.2 \pm 0.6$ [103] |
| $K^+\pi^+\pi^-$ | $+4.5 \pm 4.8 \pm 0.6$ [103] |
| $K^+K^-\pi^+$ | $-0.5 \pm 0.8 \pm 0.4$ [103] |
| $K^0_S K^-\pi^+\pi^+$ | $+4.1 \pm 2.7 \pm 0.9$ [103] |
| $K^0_S K^+\pi^+\pi^-$ | $-5.7 \pm 5.3 \pm 0.9$ [103] |
| $K^+K^-\pi^+\pi^0$ | $+0.0 \pm 2.7 \pm 1.2$ [103] |

This allows to localize and measure the contribution of the second and third terms. In experiments at $B$-factories [105, 106] the value

$$\delta Y = a_f^m + a_f^i = (-0.12 \pm 0.25) \times 10^{-2}$$

was obtained for the final states $K^+K^-$ and $\pi^+\pi^-$. The formula given above is valid for incoherent production of $D^0$ and $\overline{D}^0$ mesons. At SCTF such an asymmetry will be studied for decays of $D^0$ mesons produced in the reaction $e^+e^- \to D^{*-}D^+ \to \pi^- D^0 D^+$. For coherent $D^0\overline{D}^0$ production, the formula for $A^{\mathcal{CP}}$ is modified and becomes dependent on the decay used for tagging. This makes it possible to separate various contributions to the $\mathcal{CP}$ asymmetry without studying their time dependence. For example, the reaction $D^0\overline{D}^0 \to f_1 f_2$, where $f_1$ and $f_2$ are the states with the same $\mathcal{CP}$ parity, is forbidden at the $\psi(3770)$ resonance if $\mathcal{CP}$ is conserved. The probability of the decay is described by the following formula [107]:

$$\Gamma_{f_1 f_2} = \frac{1}{2R_m^2}\left[(2 + x^2 - y^2)|\lambda_{f_1} - \lambda_{f_2}|^2 + (x^2 + y^2)|1 - \lambda_{f_1}\lambda_{f_2}|^2\right]\Gamma_{f_1}\Gamma_{f_2}.$$

Since the terms corresponding to the contribution of mixing are proportional to the squares of $x$ and $y$, the difference between direct $\mathcal{CP}$ violation for decays $D^0 \to f_1$ and $D^0 \to f_2$ is measured in this reaction.

At SCTF with $10^9$ $D^0\overline{D}^0$ pairs the sensitivity level of $10^{-3}$ can be reached for the asymmetry difference between, for example, the $K^+K^-$ and $\pi^+\pi^-$ final states. A similar measurement can be performed using the reaction $e^+e^- \to D^{*0}\overline{D}^0 \to \gamma D^0 \overline{D}^0$. In this case the difference between $\mathcal{CP}$ asymmetries for states with opposite $\mathcal{CP}$ parities is measured.

Another example is a measurement of the asymmetry

$$A_{fl}^{\mathcal{CP}} = \frac{\Gamma(l^- X, f) - \Gamma(l^+ X, f)}{\Gamma(l^- X, f) + \Gamma(l^+ X, f)}.$$

Here one $D$ meson decays semileptonically, while the other to a $\mathcal{CP}$ eigenstate. Neglecting direct $\mathcal{CP}$ violation [108]

$$A_{fl}^{\mathcal{CP}} = (1 + \eta)(a_f^m + a_f^i),$$

where $\eta$ is the $\mathcal{C}$ parity of the $D^0\overline{D}^0$ pair. It is seen that at $\eta = -1$, i.e., in $\psi(3770)$ decays, mixing does not contribute to the measured asymmetry, while for $\eta = 1$, i.e., in the reaction $e^+e^- \to D^{*0}\overline{D}^0 \to \gamma D^0\overline{D}^0$ the mixing contribution to the asymmetry is two times larger than that for $D^0$ mesons produced incoherently. Measurements performed in these two reactions allow to separate the contributions of direct and indirect mixing.

There are other powerful methods to search for $\mathcal{CP}$ violation. In Ref. [109] it is proposed to use the difference between the probabilities of decays of untagged $D^0$ mesons to the charge-conjugate states, for example, $K^-\pi^+$ and $K^+\pi^-$, to extract the parameter $\sin\varphi$. The Dalitz analysis of three-body decays allows to measure $\mathcal{CP}$ asymmetries for different resonant intermediate states (see, for example, the results of Ref. [110]). An interference between the $\mathcal{CP}$-conserving and $\mathcal{CP}$ violating amplitudes in the Dalitz-plot distributions can increase the sensitivity of a search for $\mathcal{CP}$ violation. In the four-body decays, a search for $\mathcal{CP}$ violation can use $T$-odd moments [111] or triple products of momenta [112]. Using these methods at SCTF, one can measure the $\mathcal{CP}$ asymmetry in $D$ decays with an accuracy of about $10^{-3}$ for both direct and indirect mechanisms of $\mathcal{CP}$ violation.

### 1.4.5 $D$ and $D_s$ meson rare decays

Rare decays of $D$ and $D_s$ mesons are a tool to search for new physics beyond the Standard Model. There are three types of decays of charmed mesons, suitable for this purpose:

1. flavor-changing neutral current (FCNC) decays via the weak neutral current, providing the transition between $c$ and $u$ quarks,

2. lepton-flavor-violating (LFV) decays,

3. lepton-number-violating (LV) decays.

Two latter types of decays are forbidden in the Standard Model. In SM decays via a $c \to u$ transition are described by loop diagrams and are strongly suppressed. For example, the probabilities for the $c \to ul^+l^-$ and $c \to u\gamma$ transitions are estimated to be of the order $10^{-8}$. For specific exclusive $D_{(s)}$ decays, however, the contributions of large-distance dynamics should be taken into account. For example, the dominant contribution to the decay $D^+_{(s)} \to \pi^+l^+l^-$ comes from the transition via the intermediate $\pi^+\phi$ state followed by the decay $\phi \to l^+l^-$. As a result, the $D_{(s)} \to X\gamma$ and $D_{(s)} \to Xl^+l^-$ branching fractions, where $X$ is a hadronic state, increase up to $10^{-5}$–$10^{-6}$. For the $D$ mesons, the three decays of these types are measured and have branching fractions consistent with the estimates in SM: $B(D^0 \to \phi\gamma) = (2.78 \pm 0.30 \pm 0.27) \times 10^{-5}$ [114], $B(D^+ \to \pi^+\phi \to \pi^+e^+e^-) = (1.7^{+1.4}_{-0.9} \pm 0.1) \times 10^{-6}$ [115] и $B(D^+ \to \pi^+\phi \to \pi^+\mu^+\mu^-) = (1.8 \pm 0.5 \pm 0.6) \times 10^{-6}$ [116]. In case of $D_s$ meson the followinf branching fraction is measured: $B(D_s^+ \to \pi^+\phi \to \pi^+e^+e^-) = ((0.6^{+0.8}_{-0.4} \pm 0.1) \times 10^{-5}$ [115].

Due to the large-distance contributions, which are difficult to calculate accurately in the framework of SM, decays like $D \to X\gamma$ become weakly sensitive to New Physics effects. But even for these decays, observables having some "New Physics" sensitivity can be found. For example, in Ref. [117] it is proposed to measure the difference $R = B(D^0 \to \rho^0\gamma)/B(D^0 \to \omega\gamma) - 1$, which is estimated to be $(6 \pm 15)\%$ in SM. In the Minimal Supersymmetric Standard Model (MSSM), with some choice of model parameters the probability of the transition $c \to u\gamma$ can reach $6 \times 10^{-6}$ and the value of $R$ can be of the order 1 [117].

In decays $D_{(s)} \to Xl^+l^-$ one can analyze the spectrum of the lepton-pair invariant mass and select mass regions sensitive to the small-distance contributions. In Fig.1.5 taken from Ref. [118] the lepton invariant mass spectra are shown for the decays $D^+ \to \pi^+e^+e^-$ and $D^0 \to \rho^0e^+e^-$ in SM and MSSM. Restrictions on the MSSM parameters can be obtained with a sensitivity to the decay at the level of $10^{-6}$. The predictions for decays $D \to Xl^+l^-$ obtained in different SM extensions can be found in Refs. [113, 118, 119].

Another type of decays with the $c \to u$ transition includes decays of a neutral $D$ meson into the lepton or photon pair. SM predicts $B(D^0 \to \gamma\gamma) \simeq 3.5 \times 10^{-8}$ and $B(D^0 \to \mu^+\mu^-) \sim 10^{-12}$ [118]. The $D^0 \to \mu^+\mu^-$ branching fraction can reach $3.5 \times 10^{-6}$ in supersymmetric models with $R$-parity violation. These models also give large values for the branching fractions of the following LFV decays: $B(D^0 \to \mu^+e^-) < 10^{-6}$, $B(D^+ \to \pi^+\mu^+e^-) < 3 \times 10^{-5}$, $B(D^0 \to \rho^0\mu^+e^-) < 1.4 \times 10^{-5}$.

In Table 1.12 the current upper limits on the rare $D$ and $D_s$ decays are listed. At SCTF a sensitivity of $10^{-8}$ to rare $D$ decays can be reached.

## 1.5 Charmed baryons

Charmed baryons $B_c$), which can be produced at SCTF in the reaction $e^+e^- \to B_c\bar{B}_c$, consist of two light quarks ($u$, $d$, $s$) and a heavy $c$ quark. A pair of light quarks forms two SU(3) flavor

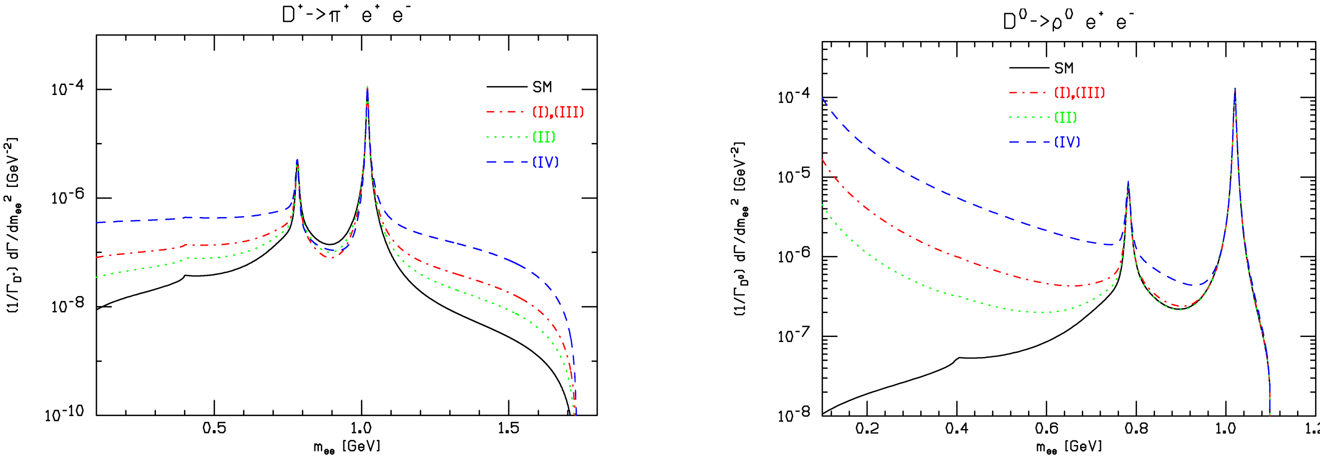


Figure 1.5: The spectra of the lepton-pair invariant mass for the decays $D^+ \to \pi^+ e^+ e^-$ (left) and $D^0 \to \rho^0 e^+ e^-$ (right). The solid curve represents the SM prediction, while the dashed curves indicate the MSSM predictions for different sets of model parameters.

Table 1.12: The experimental upper limits on the rare $D$ and $D_s$ decays in units of $10^{-6}$.

| | | | |
|---|---|---|---|
| $D^0 \to \gamma\gamma$ | 2.2 [120] | $D^+ \to \pi^+ e^+ e^-$ | 1.1 [124] |
| $D^0 \to e^+ e^-$ | 0.079 [121] | $D^+ \to \pi^+ \mu^+ \mu^-$ | 0.073 [125] |
| $D^0 \to \mu^+ \mu^-$ | 0.006 [122] | $D^+ \to \pi^+ e^+ \mu^-$ | 2.9 [124] |
| $D^0 \to \mu^\pm + e^\mp$ | 0.26 [121] | $D^+ \to \rho^+ \mu^+ \mu^-$ | 560 [127] |
| $D^0 \to \pi^0 e^+ e^-$ | 45 [123] | | |
| $D^0 \to \rho^0 e^+ e^-$ | 100 [123] | $D_s^+ \to K^+ e^+ e^-$ | 3.7 [124] |
| $D^0 \to \pi^0 e^\pm \mu^\mp$ | 86 [123] | $D_s^+ \to K^+ \mu^+ \mu^-$ | 21 [124] |
| $D^0 \to \rho^0 e^\pm \mu^\mp$ | 49 [123] | $D_s^+ \to K^+ e^+ \mu^-$ | 14 [124] |

multiplets: the antisymmetric antitriplet and the symmetric sextet ($3 \times 3 = \bar{3}_A \oplus 6_S$). In $S$-wave low-lying baryons, the flavor symmetry and spin are related to each other: the total spin of light quarks is equal to 0 for the antitriplet and 1 for the sextet. In combination with the $c$ quark, the antitriplet produces three states with spin 1/2 ($\Lambda_c^+$, $\Xi_c^+$, $\Xi_c^0$), while the sextet gives six states with spin 1/2 ($\Sigma_c^{++,+,0}$, $\Xi_c^{\prime +}$, $\Xi_c^{\prime 0}$, $\Omega_c^0$) and six states with spin 3/2 ($\Sigma_c^{*++,+,0}$,$\Xi_c^{*+}$, $\Xi_c^{*0}$, $\Omega_c^{*0}$). All 15 $S$-wave charmed baryons have been observed. Their parameters are listed in Table 1.13.

Table 1.13: The parameters of the $S$-wave charmed baryons [2].

| | Structure | $J^P$ | Mass, MeV | Width,MeV | Decay |
|---|---|---|---|---|---|
| $\Lambda_c^+$ | $udc$ | $(1/2)^+$ | $2286.46 \pm 0.14$ | $(200 \pm 6)$ fs | weak |
| $\Xi_c^+$ | $usc$ | $(1/2)^+$ | $2467.8^{+0.4}_{-0.6}$ | $(442 \pm 26)$ fs | weak |
| $\Xi_c^0$ | $dsc$ | $(1/2)^+$ | $2470.88^{+0.34}_{-0.8}$ | $112^{+13}_{-10}$ fs | weak |
| $\Sigma_c^{++}$ | $uuc$ | $(1/2)^+$ | $2454.02 \pm 0.18$ | $2.23 \pm 0.30$ | $\Lambda_c^+\pi^+$ |
| $\Sigma_c^+$ | $udc$ | $(1/2)^+$ | $2452.9 \pm 0.4$ | $< 4.6$ | $\Lambda_c^+\pi^0$ |
| $\Sigma_c^0$ | $ddc$ | $(1/2)^+$ | $2453.76 \pm 0.18$ | $2.2 \pm 0.4$ | $\Lambda_c^+\pi^-$ |
| $\Xi_c^{\prime +}$ | $usc$ | $(1/2)^+$ | $2575.6 \pm 3.1$ | — | $\Xi_c^+\gamma$ |
| $\Xi_c^{\prime 0}$ | $dsc$ | $(1/2)^+$ | $2577.9 \pm 2.9$ | — | $\Xi_c^0\gamma$ |
| $\Omega_c^0$ | $ssc$ | $(1/2)^+$ | $2695.2 \pm 1.7$ | $(69 \pm 12)$ fs | weak |
| $\Sigma_c^{*++}$ | $uuc$ | $(3/2)^+$ | $2518.4 \pm 0.6$ | $14.9 \pm 1.9$ | $\Lambda_c^+\pi^+$ |
| $\Sigma_c^{*+}$ | $udc$ | $(3/2)^+$ | $2517.5 \pm 2.3$ | $< 17$ | $\Lambda_c^+\pi^0$ |
| $\Sigma_c^{*0}$ | $ddc$ | $(3/2)^+$ | $2518.0 \pm 0.5$ | $16.1 \pm 2.1$ | $\Lambda_c^+\pi^-$ |
| $\Xi_c^{*+}$ | $usc$ | $(3/2)^+$ | $2645.9^{+0.5}_{-0.6}$ | $< 3.1$ | $\Xi_c\pi$ |
| $\Xi_c^{*0}$ | $dsc$ | $(3/2)^+$ | $2645.9 \pm 0.5$ | $< 5.5$ | $\Xi_c\pi$ |
| $\Omega_c^{*0}$ | $ssc$ | $(3/2)^+$ | $2765.9 \pm 2.0$ | — | $\Omega_c^0\gamma$ |

Many excited charmed baryons are expected. In particular, the quark model predicts 63 $P$-wave states [128]. Sixteen of the excited states with masses in the range from 2.6 to 3.1 GeV have been observed [2, 129]. Other excited states of charmed baryons were reported recently by LHCb [130, 131] and Belle [132, 133].

In recent years physics of charmed baryons has been studied mainly at $B$-factories and at BESIII. In spite of the large number of produced charmed baryons ($B$ factories produced about $10^7$ $\Lambda_c$), their properties are rather poorly known. There is little or practically no experimental information about the quantum numbers of baryons and absolute branching fractions of their decays. For $\Lambda_c^+$ the situation was improved in 2013, when the first model-independent measurement of the absolute branching fraction of $\Lambda_c^+ \to pK^-\pi^+$ decay was performed by Belle [134] with fivefold improvement in precision over previous model-dependent determinations. This decay mode was used as the golden reference mode in previous measurements for the branching fractions of other $\Lambda_c^+$ decay modes. Later, BESIII measured branching fractions of twelve Cabibbo-favored hadronic decay modes of $\Lambda_c^+$ [135]. For $\Lambda_c^+ \to pK^-\pi^+$ decay mode their result is lower by two standard deviations compared to the Belle result [135, 136].

The potential of SCTF in study of charmed baryons depends strongly on the cross sections for the reactions $e^+e^- \to B_c\bar{B}_c$. For the reaction $e^+e^- \to \Lambda_c\bar{\Lambda}_c$ the cross section was measured by Belle [137]. The cross section is maximal at the energy about 4.65 GeV. The maximal value is about 0.5 nb. Such a large cross section value can be explained by a presence of a new resonance state $Y(4630)$ near the $\Lambda_c\bar{\Lambda}_c$ threshold with mass $M = 4634 \pm 10$ MeV and width $\Gamma = 92 \pm 40$ MeV [137]. Another resonance $Y(4660)$ with mass $M = (4665 \pm 10)$ MeV and width $\Gamma = (53 \pm 16)$ MeV compatible within errors with those of $Y(4630)$ was observed in the invariant mass spectrum of $\psi(2S)\pi^+\pi^-$ in the Belle and BaBar experiments by initial state radiation technique in the $e^+e^-$ annihilation [138]. At present it is not clear if $Y(4630)$ and $Y(4660)$ are different states, or manifestations of the same state, and their inner structures became a subject of hot discussions [138, 139, 140, 141]. If $Y(4630)$ is a $\Lambda_c\bar{\Lambda}_c$-baryonium state, a small admixture of the $\psi(2S)f_0(980)$ molecular component can be associated with the $Y(4660)$ signal. Less exotic assignment of $Y(4630)$ as a $5^3S_1$ charmonium state was also considered. However, it seems its interpretation as a tetraquark state is more favorable [138, 139, 140, 141].

With an integrated luminosity of 200 fb$^{-1}$ SCTF will produce $10^8$ $\Lambda_c\bar{\Lambda}_c$ pairs. This will allow to perform a detailed study of $\Lambda_c$ properties with the use of the double-tag method. For other charmed baryons the experimental data on the reactions $e^+e^- \to B_c\bar{B}_c$ are absent. Without a resonance enhancement the expected cross section does not exceed 10 pb. The physics program for baryons depends on the maximum energy of charm-tau factory. Detailed studies of weak decays of the charmed baryons $\Lambda_c^+(2286)$, $\Xi_c^+(2468)$, $\Xi_c^0(2471)$, and $\Omega_c^0(2695)$ seem feasible. The required maximum energies of the factory are 4.7, 5.1 and 5.5 GeV, respectively.

A large expected number ($10^8$) of $\Lambda_c\bar{\Lambda}_c$ pairs makes it possible to undertake a search of $CP$ violation in $\Lambda_c$ decays. Although $CP$ violation is well established in $K$ and $B$ meson decays, until very recently no $CP$ violating signal was seen in the baryonic sector.

The Hyper$CP$ experiment had searched for $CP$ violation signal in strange baryon decays by a 800 GeV proton beam on a Cu target and get for the corresponding $CP$ asymmetry parameter $A_{\Lambda\Sigma} = (0.0 \pm 5.1 \pm 4.4) \cdot 10^{-4}$, which should be compared to the Standard Model predictions $A(\Lambda \to p\pi^-) \sim (0.05 - 1.2) \cdot 10^{-4}$ and $A(\Sigma^- \to \lambda\pi^-) \sim (0.2 - 3.5) \cdot 10^{-4}$ [142]. The first 3.3-standard-deviation evidence for $CP$ violation in the four-body hadronic decay $\Lambda_b^0 \to p\pi^-\pi^+\pi^-$ was found quite recently in the LHCb experiment [143].

Let us briefly discuss $CP$ asymmetry observables on the example of $\Lambda \to p\pi^-$ decay. In the $\Lambda$ rest frame, the final state pion-nucleon system can be either in the $S$-wave, or in the $P$-wave. Denoting the corresponding parity non-conserving and parity-conserving amplitudes as $S$ and $P$, we get for the angular distribution of the produced proton [144]

$$\frac{d\Gamma}{d\Omega} \sim 1 + \gamma\, \vec{\sigma}_i \cdot \vec{\sigma}_f + (1-\gamma)\, (\vec{n}_f \cdot \vec{\sigma}_i)(\vec{n}_f \cdot \vec{\sigma}_f) + \alpha\, \vec{n}_f \cdot (\vec{\sigma}_i + \vec{\sigma}_f) + \beta\, \vec{n}_f \cdot (\vec{\sigma}_f \times \vec{\sigma}_i), \tag{1.2}$$

where $\vec{\sigma}_i$ and $\vec{\sigma}_f$ are unit vectors in the direction of the initial and final baryon spins, $\vec{n}_f$ is the unit vector along the final baryon momentum, and

$$\alpha = \frac{2\mathrm{Re}(S^*P)}{|S|^2 + |P|^2}, \quad \alpha = \frac{2\mathrm{Im}(S^*P)}{|S|^2 + |P|^2}, \quad \gamma = \frac{|S|^2 - |P|^2}{|S|^2 + |P|^2} = \sqrt{1 - \alpha^2 - \beta^2}. \tag{1.3}$$

Under $CP$ transformation $\vec{n}_f \to -\vec{n}_f$, $\vec{\sigma}_{i,f} \to \vec{\sigma}_{i,f}$ and therefore $CP$ symmetry requires $\alpha = -\bar{\alpha}$ and $\beta = -\bar{\beta}$, suggesting to define $CP$ asymmetry parameters as follows

$$A = \frac{\alpha + \bar{\alpha}}{\alpha - \bar{\alpha}}, \quad B = \frac{\beta + \bar{\beta}}{\beta - \bar{\beta}}, \quad \Delta = \frac{\Gamma(\Lambda \to p\pi^-) - \Gamma(\bar{\Lambda} \to \bar{p}\pi^+)}{\Gamma(\Lambda \to p\pi^-) + \Gamma(\bar{\Lambda} \to \bar{p}\pi^+)}. \tag{1.4}$$

Here $\bar{\alpha}$ and $\bar{\beta}$ are angular distribution parameters in the anti-$\Lambda$ decay $\bar{\Lambda} \to \bar{p}\pi^+$. Experiments usually measure the parameter $\alpha$, which controls the decay asymmetry in the angular distribution if the final proton polarization is not measured.

Similar parameters can be defined for the $\Lambda_c^+ \to \Lambda\pi^+$ decay and the FOCUS(E831) experiment at Fermilab in 2005 provided the first measurement of the $CP$ asymmetry parameter $A = -0.07 \pm 0.19 \pm 0.24$ which is consistent with zero albeit with large errors [145]. A Monte Carlo estimation shows that, with an integrated luminosity of 200 fb$^{-1}$, charm-tau factory can reach the precision of about 0.3% in this parameter [144].

Under assumption that $\Lambda_c^+ \to \Lambda\pi^+$ decay is dominated by the $\Delta I = 1/2$ transition, $S$- and $P$-wave amplitudes will contain only one strong $\delta$ and only one weak $\phi$ phases: $S = |S|e^{i(\delta_S+\phi_S)}$, $P = |P|e^{i(\delta_P+\phi_P)}$. Then

$$\alpha = \frac{2|S||P|}{|S|^2+|P|^2}\cos(\delta_P-\delta_S+\phi_P-\phi_S),\;\; \beta = \frac{2|S||P|}{|S|^2+|P|^2}\sin(\delta_P-\delta_S+\phi_P-\phi_S), \tag{1.5}$$

and

$$\bar{\alpha} = \frac{-2|S||P|}{|S|^2+|P|^2}\cos(\delta_P-\delta_S-\phi_P+\phi_S),\;\; \bar{\beta} = \frac{-2|S||P|}{|S|^2+|P|^2}\sin(\delta_P-\delta_S-\phi_P+\phi_S), \tag{1.6}$$

because for $CP$-conjugated decay $\Lambda_c^- \to \bar{\Lambda}\pi^-$ strong phases, which arise from the final-state interactions, are the same (Fermi-Watson theorem), while the remaining part of wave functions undergo complex conjugation and thus weak phases change sign. Overall minus sign appears because of the odd-parity of pions and $(-1)^l$ parity of spatial part of the wave function which means that $S$-wave amplitude acquires an additional minus sign under $CP$, while $P$-wave amplitude does not.

In this approximation [146]

$$A = \frac{\alpha+\bar{\alpha}}{\alpha-\bar{\alpha}} = \tan(\delta_S-\delta_P)\tan(\phi_S-\phi_P), \quad B = \frac{\beta+\bar{\beta}}{\beta-\bar{\beta}} = \frac{\tan(\phi_S-\phi_P)}{\tan(\delta_S-\delta_P)}. \tag{1.7}$$

Therefore, even in the case of significant $CP$ violation in weak interactions, $A$-asymmetry can still be very small if the strong phase difference between the two amplitudes is small. On the contrary, $B$-type asymmetries can be large even with small strong phases. As is evident from (1.2), $B$-type asymmetries are related to the triple product $\vec{n}_f \cdot (\vec{\sigma}_f \times \vec{\sigma}_i)$. Prospects of the charm-tau factory in studying such triple product asymmetries (proportional to $\beta + \bar{\beta} \sim \cos(\delta_S - \delta_P)$) were examined in Ref. [147] with the conclusion that the precision can reach the level of $10^{-3}$.

A unique feature of SCTF is a possible presence of the longitidual polarization in the electron beam. We think this feature will help to investigate and reduce the systematic errors related to various detector asymmetries.

Within the Standard Model $CP$ violation in the charm sector is tiny, which makes this sector an excellent place to search for a new physics beyond the Standard Model. Charmed baryon decays seem very promising in this respect.

## 1.6 $\tau$ lepton physics

At SCTF $\tau$ leptons are produced in the process $e^+e^- \to \tau^+\tau^-$. Its cross section grows rapidly from about 0.1 nb near the threshold of the $\tau^+\tau^-$ production ($2E = 3.55$ GeV) up to 3.6 nb at the top of the $\psi(2S)$ resonance (taking into account the expected beam energy spread). Near the threshold of $D\bar{D}$ production ($2E \approx 3.7$ GeV) it is about 2.9 nb, and reaches 3.5 nb at the $2E = 4.25$ GeV. During the SCTF operation, about $1.1 \times 10^{10}$ $\tau^+\tau^-$ pairs will be produced, an order of magnitude larger than at the $B$ factories, but smaller than expected at the Belle II experiment (about $4.6 \times 10^{10}$).

One should note that the current accuracy of many $\tau$-lepton parameters, e.g., its leptonic and hadronic decay widths, is limited by systematic effects. For precise measurements of the branching fractions and hadronic spectral functions, a dedicated run near the $e^+e^- \to \tau^+\tau^-$ threshold is planned. At the threshold $\tau$ leptons are produced at rest allowing to suppress background by applying an additional condition on kinematics of hadronic decays: $2m_\tau E_{had} = m_\tau^2 + m_{had}^2$, where $E_{had}$ and $m_{had}$ are the energy and invariant mass of the hadronic system, and $m_\tau$ is the $\tau$-lepton mass. Use of this condition allows to select $\tau$ events with the tagging method. The remaining background can be measured running below threshold of $\tau$ lepton production. With an integrated luminosity of 1 ab$^{-1}$ collected near the $\tau^+\tau^-$ production threshold about $10^8$ $\tau$-lepton pairs will be produced.

Branching fractions and spectral functions of the hadronic $\tau$ decays can be used to determine the strong coupling constant $\alpha_s$ [148] (see also Ref. [149]). Data on hadronic decays with $\Delta S = 1$ are also used to determine the $s$-quark mass $m_s$ and the CKM matrix element $V_{us}$ [150]. Potentially $\tau$-lepton decays are the most powerful tool for precise measurements of $\alpha_s$, $m_s$ and $V_{us}$.

A high-precision measurement of the branching fractions of leptonic decays as well as the decays $\tau^+ \to \pi^+\nu$ and $\tau^+ \to K^+\nu$ will result in a significant improvement of lepton-universality tests in interactions of $W$-boson with charged lepton current. The rewiew of the current status of such tests in $\tau$ decays at $B$-factories can be found in Ref. [151].

For precision tests of SM and lepton universality, knowledge of the $\tau$ lepton mass is mandatory. The most precise method of $\tau$ lepton mass determination is a measurement of the energy dependence of the $e^+e^- \to \tau^+\tau^-$ cross section near threshold. Such measurements require high-precision energy calibration of the collider using methods of resonant depolarization or Compton backscattering.

An important test of the SM is a study of the Lorentz structure of the amplitudes of the leptonic $\tau \to \ell\nu\nu$, radiative leptonic $\tau \to \ell\nu\nu\gamma$, and five-lepton $\tau \to \ell\ell'^+\ell'^-\nu\nu$ ($\ell, \ell' = e, \mu$) $\tau$ decays. Thus, lepton energy spectrum in the $\tau \to \ell\nu\nu$ decay depends linearly on four Michel parameters ($\rho$, $\eta$, $\xi$ and $\delta$) [152]. They are experimentally accessible bilinear combinations of the generalized weak coupling constants, and in the Standard Model get values: $\rho = 3/4$, $\eta = 0$, $\xi = 1$, and $\delta = 3/4$. For measurement of the parameters $\xi$ and $\delta$, knowledge of $\tau$-lepton polarization is required. In experiments at $e^+e^-$ colliders with unpolarized beams, the average polarization of a single $\tau$ is zero. However, spin-spin correlations between the $tau^+$ and $tau^-$ produced in the reaction $e^+e^- \to \tau^+\tau^-$ can be exploited to measure $\xi$ and $\delta$ parameters. Events where both $\tau$ leptons decay to the selected final states are analyzed: one $\tau$ lepton decays to the signal mode, while the opposite $\tau$ decays to the $\pi\pi^0\nu$ mode, which has the largest branching fraction and properly studied dynamics. Thus, the total differential cross section of the reaction $e^+e^- \to (\tau \to \ell\nu\nu,\ \tau \to \pi\pi^0\nu)$ linearly depends on all four Michel parameters. A longitudinal polarization of initial beams at SCTF (in this case the average polarization of a single $\tau$ is nonzero) would allow a more efficient usage of the collected data samples and minimize systematic uncertainties of polarization-dependent parameters.

Data samples collected at the $\tau^+\tau^-$ production threshold allow one to suppress the impact of the radiative corrections (to the $e^+e^- \to \tau^+\tau^-$ process) on the lepton energy spectrum and decrease the associated systematic uncertainty.

LFV decays of $\tau$ lepton, such as $\tau \to \ell\gamma$, $\tau \to \ell\ell\ell^{(\prime)}$ or $\tau \to \ell h$, where $\ell$, $\ell'$ are electron or muon, and $h$ is a hadronic system, are sensitive to effects of New Physics. Different models beyond the SM predict branching fractions of these decays at the level of $10^{-7}$–$10^{-10}$ (see, for example, Ref. [153]).

Experimental upper limits on the branching ratios of LFV decays achieved at the $B$ factories are in the range from $10^{-7}$ to $2 \times 10^{-8}$ [2] and already constrain the parameter space of some models. For most of the decays, a much higher sensitivity is expected in future experiments at superKEKB. For some decays an upper limit on the decay probability is determined by background. This is, in particular, true for the $\tau \to \mu\gamma$ decay, which is very important in a search for New Physics. At $B$ factories the upper limit on the probability of this decay is determined by the background from the process $e^+e^- \to \tau^+\tau^-\gamma$. At the SCTF this background is negligible [154]. Hence, in spite of less statistics, the sensitivity to the $\tau \to \mu\gamma$ decay at SCTF (below $10^{-9}$) will be better than at superKEKB [155].

$CP$ violation (CPV) in the quark sector does not explain the observed baryon asymmetry of the Universe. Therefore, it is reasonable to search for CPV in the lepton sector, in particular, in $\tau$ decays. $CP$ violation can be observed in hadronic $\tau$ decays, provided that there are two interfering amplitudes with different strong and weak phases. Under $CP$ transformation, the $e^{i\delta_w + i\delta_s}$ is transformed into $e^{-i\delta_w + i\delta_s}$, where $\delta_w$ and $\delta_s$ are relative strong and weak phases of two amplitudes. This results, for example, in the non-equality of the widths of the $CP$-conjugate decays. The 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 the $\sin\delta_s \sin\delta_w$. In the SM, $\tau$ lepton decays are described by a single amplitude with a $W$-boson exchange. Therefore, observation of the CPV would be an explicit indication of the physics beyond SM. The only exception is $\tau \to K^0_{S(L)}\pi\nu$ decay, in which the $CP$ asymmetry at the level of $3\times10^{-3}$ [156] arises in the SM because of the CPV in the neutral kaons. Suggestions for using various decays to search for CPV are concidered in Refs. [157, 158, 159, 160, 161, 162]. The most promising decays are $\tau^\pm \to K^\pm\pi^0\nu$, $\tau^\pm \to K^0_S\pi^\pm\nu$, $\tau^\pm \to K^0_S\pi^\pm\pi^0\nu$, $\tau \to \rho\pi\nu$, $\tau \to \omega\pi\nu$, $\tau \to a_1\pi\nu$. In addition to measuring the asymmetry in the decay width, $A_{CP}$ defined above, it is also suggested to use a so called modified asymmetry, when experimental differential distributions of the final hadrons are integrated with a specially selected kernel over a limited region of the phase space, and an asymmetry in the triple product $\boldsymbol{\sigma} \cdot (\boldsymbol{p_1} \times \boldsymbol{p_2})$, where $\boldsymbol{\sigma}$, $\boldsymbol{p_1}$, $\boldsymbol{p_2}$ are a $\tau$ polarization vector and momenta of two final hadrons, respectively. It is worth noting that the asymmetry in the triple product is proportional to the $\cos\delta_s \sin\delta_w$, i.e., a nonzero difference of the strong phases is not needed for its observation.

A search for $CP$ violation was performed in the CLEO experiment using $10^7$ $\tau$-lepton pairs for $\tau^\pm \to \pi^\pm\pi^0\nu$ [163] and $\tau^\pm \to K_S\pi^\pm\nu$ [164] decays. The inclusive decay-rate asymmetry $A_{\rm CP} = \frac{\Gamma(\tau^+\to\pi^+K_S(\geq0\pi^0)\nu) - \Gamma(\tau^-\to\pi^-K_S(\geq0\pi^0)\nu)}{\Gamma(\tau^+\to\pi^+K_S(\geq0\pi^0)\nu) + \Gamma(\tau^-\to\pi^-K_S(\geq0\pi^0)\nu)}$ was measured with the data sample of $4.4 \times 10^8$ $\tau^+\tau^-$ pairs at BABAR [165]. The modified asymmetry in the $\tau^- \to K^0_S\pi^-\nu$ decay was investigated with the statistics of $6.4 \times 10^8$ $\tau$ pairs at Belle [166] as a function of the $K^0_S\pi^-$ invariant mass. The obtained result $A_{\rm CP} = (-0.36 \pm 0.23 \pm 0.11)\%$ is about 2.8 standard deviations from the SM expectation $A^{K^0}_{\rm CP} = (+0.36 \pm 0.01)\%$, while the modified asymmetry in the $\tau^- \to K^0_S\pi^-\nu$ decay agree well with no CPV in the whole range of the $K^0_S\pi^-$ invariant masses. Simultaneous analysis of the $\tau^- \to K^0_S\pi^-\nu$ and $\tau^- \to K^0_S\pi^-\pi^0\nu$ decays allows one to study the dynamics of the $K\pi$-system production in more detail and search for CPV on the new level of precision.

One can expect an increase of the sensitivity after analysis of data accumulated at Belle II and SCTF. The longitudinal polarization of the initial beams at the CTF results in the nonzero average polarization of single $\tau$. This opens possibilities to study various effects (CPV, Michel parameters) and search for New Physics in the spin-dependent part of the $\tau$ decay width without reconstruction of the second $\tau$ lepton in the $e^+e^- \to \tau^+\tau^-$ event. Besides the increase in the sensitivity to the spin-dependent effects in $\tau$ decays, this allows one to decrease associated systematic uncertainties.

## 1.7 Measurement of $e^+e^- \to$ hadrons below 5 GeV

A measurement of the total cross section of $e^+e^-$ annihilation into hadrons is usually referred to as an $R$ measurement, where $R$ is the ratio of the Born cross section for $e^+e^- \to$ адроны to the Born cross section for $e^+e^- \to \mu^+\mu^-$:

$$R = \frac{\sigma^{(0)}(e^+e^- \to \text{hadrons})}{\sigma^{(0)}(e^+e^- \to \mu^+\mu^-)}. \tag{1.8}$$

Measurements of $R$ can be utilized to test perturbative QCD and measure $\alpha_s$ [167]. QCD sum rules provide a method of extracting from the values of $R$ such important parameters as quark masses, quark and gluon condensates and the value of $\Lambda_{\text{QCD}}$ [168]. Through dispersion relations $R$ measurements give an input to the calculations of the hadronic corrections to various fundamental quantities: the anomalous magnetic moment of the muon $a_\mu = (g_\mu - 2)/2$ [169], the running fine structure constant $\alpha(s)$ [170], superfine splitting in muonium [171] etc. Depending on the problem, different energy ranges are of importance. For example, for $(g_\mu - 2)/2$ the low energy range up to 2 GeV gives about 93% of the whole leading-order hadronic contribution. However, the region from 2 to 5 Gev also gives a non-negligible contribution, which is about 6%. For $\alpha_{QED}(M_Z^2)$, the corresponding contributions are about equal, 21.0% and 17.1%, respectively (about 45% comes from energies $> 11$ GeV, where pQCD can be used with suitable precision). The total leading-order hadronic contributions are calculated to be $a_\mu^{had\,LO} = (694.91 \pm 4.3) \times 10^{-10}$ and $\Delta\alpha^5_{QED}(M_Z^2) = (276.26 \pm 1.38) \times 10^{-4}$ [172]. New experiments on a measurement of the muon anomalous magnetic moment in FermiLab [173] and J-PARC [174] plan to improve accuracy of the experimental $a_\mu$ value by a factor of at least 4, up to $\sim 1.5 \times 10^{-10}$. Precise tests of electroweak theory in experiments at future colliders such as ILC, CLIC, FCC-ee will require knowledge of the hadronic contribution to $\alpha_{QED}(M_Z^2)$ at the level of $\sim 0.5 \div 0.3 \times 10^{-4}$ [175, 176]. To provide comparable accuracies in the theoretical predictions, the accuracy of integral $R$ measurement must be $\sim 0.2\%$.

The c.m. energy range from 2 to 5 GeV is almost asymptotic for $u$-, $d$-, and $s$-quarks. There are no resonances made of light quarks at these energies. The energy dependence of $R$ is very slow from 2 GeV up to threshold of $D$-meson production (3.73 GeV), except for narrow regions around the $J/\psi$ and $\psi(2S)$ resonances. Its value $R \approx 2.2$ is consistent with the pQCD prediction [177]. The energy region 3.73–5.0 GeV is the resonant region for $c$-quark; it contains several wide $c\bar{c}$ resonances decaying into $D$ mesons. Numerous $R$ measurements exist in the energy range between 2 and 5 GeV: by Crystal Ball [178], PLUTO [179], DASP [180], Mark-I [181, 182], BES [183, 184, 185, 186], KEDR [187, 188]. In general, the measurements of different experimental groups are consistent. The most detailed measurement was performed by BESII at 165 energy points from 2 to 5 GeV with average systematic uncertainty ranged from 7% to 3.3%. The BESIII result is expected soon: the energy scan (125 points with the total integrated luminosity 1.3 fb$^{-1}$) of the energy region 2.00–4.59 GeV was performed in 2012–2015. Currently the best systematic accuracy, about 2%, was reached in the KEDR experiment, which measures $R$ at 20 energy points between 1.84 and 3.72 GeV (Fig. 1.6). However, this accuracy is insufficient for high-precision tests of the Standard Model, which require knowledge of the cross section to at least 1%. To reach such accuracy, we need a detailed scan with a few-MeV step and integrated luminosity of 10 pb$^{-1}$ per point or about 10 fb$^{-1}$ in total in the whole energy range.

Below 2 GeV the total cross section can be measured with a sub-percent accuracy using the radiative return method. This method was used in the KLOE [190], BABAR [191], and BESIII [192] experiments. Since the number of possible hadronic final states in this energy range is relatively small, the total cross section can be determined as a sum of cross sections for various

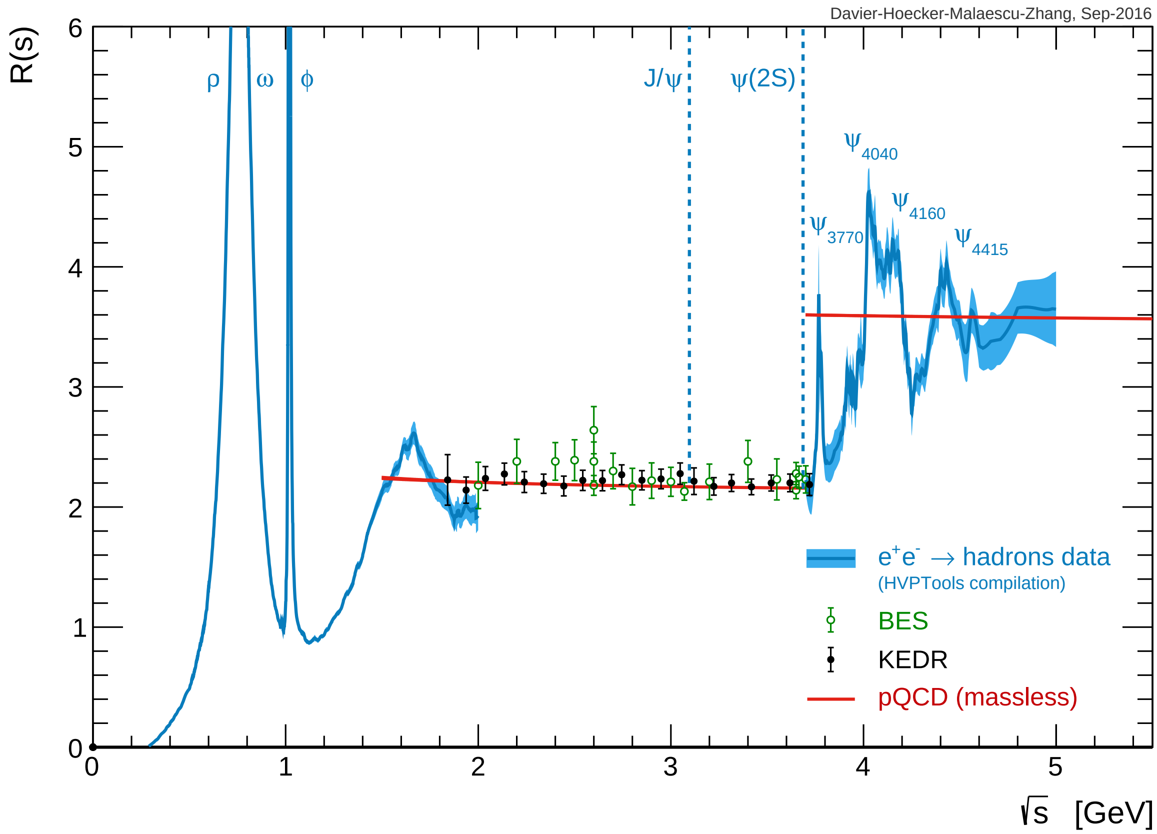


Figure 1.6: The energy dependence of $R = \sigma(e^+e^- \to \text{hadrons})/\sigma(e^+e^- \to \mu^+\mu^-)$ [189]. The points are the BESII and KEDR inclusive data. The shaded areas are a sum of exclusive cross sections at $\sqrt{s} < 2$ GeV and average of all $R$ measurements above $\psi(2S)$.

exclusive channels. The most comprehensive analysis on the measurement of various hadronic channels below 2 GeV was performed in the BABAR experiment. Statistically close results can be achieved in the BESIII experiment. The Belle II experiment at the SuperKEKB collider, which is under commissioning now, will collect a data sample by two orders of magnitude larger than than that collected at BABAR. The design SCTF luminosity provides statistics comparable with Belle II near the $\pi^+\pi^-$ threshold and several times larger at $\sqrt{M^2} \sim 2$ GeV. It shold be noted that it is challenging to reach systematic uncertaity on $R$ of about 0.2% in a single experiment. To reach such an accuracy in the world-average value, several systematically independent $R$ measurement should be performed. The radiative-return measurements at SCTF and SuperKEKB are complementary. They will be performed at significantly different c.m. energies and, therefore, have different sources of systematic uncertainies.

The obtained information on exclusive channels of $e^+e^-$ annihilation to hadrons allow also to investigate mechanisms of light quark hadronization at low energies, perform searches for possible exotic states like tetraquarks, hybrids, and glueballs, and study the $\rho$, $\omega$, and $\phi$ excitations.

After discovery 40 years ago of the family of broad charmonia above open charm threshold, in the next 30 years the properties of these resonances were determined on the measurements of the total hadronic cross-section at DASP [180] and Mark-I [181]. Some progress was achieved after fits to the Crystal Ball [178] and BES [183, 184] data in Refs. [193, 194]. In Ref. [194] the first attempt to include interference between exclusive decays of $\psi$-resonances was performed, but the relations between different decay modes were accounted using a model prediction. A real breakthrough

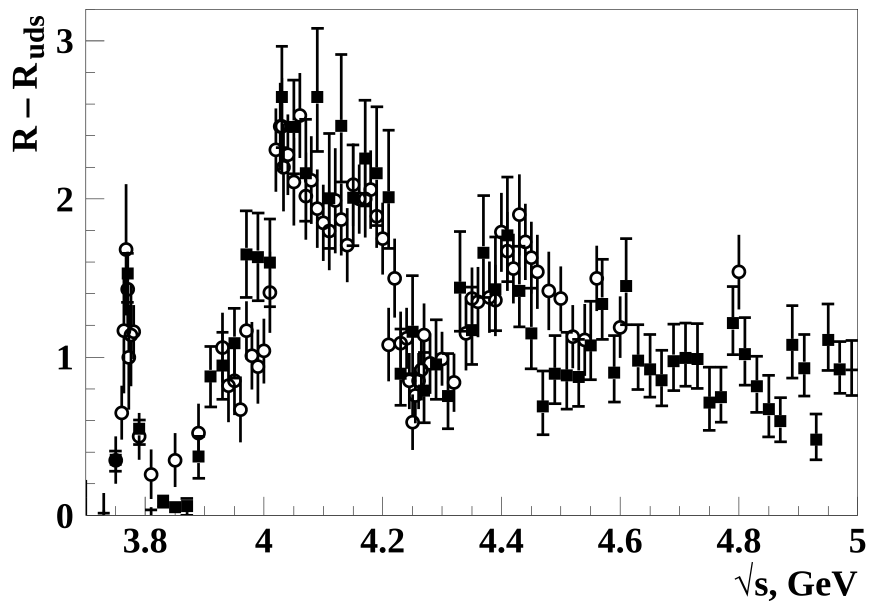


Figure 1.7: Comparison of the inclusive measurement of $R - R_{uds} \equiv R_{cc} = \sigma(e^+e^- \to c\bar{c})/\sigma(e^+e^- \to \mu^+\mu^-)$ ($R_{uds} = 2.121 \pm 0.023 \pm 0.083$), performed by BESII (open circles) with a sum of exclusive channels measured in the Belle experiment (solid squares).

happened recently, after appearance of exclusive cross-section measurements for final states with $D$, $D^*$, $D_s$, and $D_s^*$ mesons. These measurements were performed by the Belle and BABAR collaborations in the energy range from 3 to 5 GeV (see the complete bibliography in Ref. [195]) using the radiative return method, and by CLEO [62] in the range from 3.77 to 4.26 GeV using a direct c.m. energy scan. An important conclusion is that the sum of exclusive cross sections for the final states containing various $D$ mesons saturates the total cross section of $c\bar{c}$ production. The latter is obtained from the inclusive BESII $R$ measurement [196] by subtracting the calculated light-quarks contribution (see Fig. 1.7).

After appearance of the exclusive measurements, numerous attempts were performed to describe the energy behavior of exclusive cross sections of $D$ meson production. For example, in Ref. [197] Belle data on different open-charm channels in the energy range 3.7–4.7 GeV are analysed simultaneously using a unitary approach based on a coupled-channel model. Nevertheless, the situation with the spectroscopy of broad charmonia remains largely uncertain. More accurate measurements of exclusive cross sections in the energy range from 3.7 to 5 GeV, as well as improved methods for theoretical interpretation of the results obtained are required to determine parameters of the resonances of the $\psi$ family and the probabilities of their decays.

It is important to note that for various applications, e.g., for determination of quark masses, it is nesassery to know the component of $R$ coming from specific quark flavor, particularly in the energy range near the quark production threshold. Experimentally, this is a rather complicated problem. A phenomenological approach to this problem is described in Ref. [198] devoted, in particular, to $c$-quark mass determination. For the energy range above 3.73 GeV the authors employ the complete set of available $R$ data. To obtain the charm component, they use extrapolation from the fit to $R$ data below $D\bar{D}$ threshold, and apply non-trivial correction for production of secondary $c\bar{c}$ pairs in $e^+e^-$ annihilation into light quarks. To estimate the error on $R_{cc}$ in this method, a sophisticated analysis of experimental uncertainties is needed. Another possibility to obtain $R_{cc}$ is to measure all exclusive final states containing particles with $c$ quark. As discussed above, at the current level of statistical accuracy $R_{cc}$ is saturated by the contributions from the $D^{(*)}\bar{D}^{(*)}$ and $D_s^{(*)}\bar{D}_s{}^{(*)}$ final states. It is clear that improving accuracy will require the addition of new exclusive channels and a huge integrated luminosity. Substantial progress in the charmonium energy range can be expected in the future experiments, first of all, direct scans at SCTF.

Besides that, running at the threshold of a baryon-antibaryon pair production ($p\bar{p}$, $n\bar{n}$, $\Lambda\bar{\Lambda}$, …) in a polarized mode of SCTF will allow to study of the baryon form factors near threshold, including a unique chance of doing that for polarized baryons [199]. It is particularly interesting for the $\Lambda$-hyperon production, where a final-particle polarization can be determined from the angular distribution in the $\Lambda \to p\pi^-$ decay.

## 1.8 Two-photon physics

Today two-photon physics is an important sector of particle physics. In principle, it is physics for photon colliders extensively discussed now but looks like a matter of a distant future. However, $e^+e^-$ colliders as a source of two-photon collisions have an important advantage, one or both virtual colliding photons may be strongly off-shell. This provides additional possibilities compared to the collisions of real photons. Data on the photon-meson transition form factors of resonances ($\pi^0$, $\eta$, $\eta'$ …) obtained at large momentum transfers $|Q^2| > 4$ GeV$^2$ can be used to test the perturbative QCD calculations. However, of largest interest are data on smaller momentum transfer $|Q^2| < 1.5$ GeV$^2$ (see Ref. [200] and references therein), which an be employed for testing of the form-factor models needed for calculation of the light-by-light contribution to the anomalous magnetic moment of the muon.

Physical tasks of SCTF first of all include a study of $C$-even resonances, both from light quarks and charmonium states, with quantum numbers $J^{PC} = 0^{++}$, $0^{-+}$, $2^{-+}$, $2^{++}$. When one of the photons is off-shell, particles with $J = 1$ can also be produced, including those with exotic quantum numbers $J^{PC} = 1^{-+}$. High luminosity of SCTF will allow not only a determination of the two-photon widths of the resonances, but also a study of their rare decay modes. A separate problem also requiring high luminosity is a measurement of transition form factors for the vertexes $\gamma^* \to \gamma M$ and $\gamma^* \to \gamma^* M$, where $M$ is a $C$-even resonance.

Note also the importance of measuring the total cross sections of $\gamma\gamma \to$ hadrons as well as the cross sections for separate channels like $\gamma\gamma \to M(M')$, where $M$ and $M'$ are mesons ($\pi$, $K$, $\eta$, $\rho$, $\omega$, $\phi$ …) or baryons, starting from the reactions thresholds. For the above mentioned calculation of the light-by-light contribution to the anomalous magnetic moment of the muon, it is of special interest to measure the $Q^2$ dependence of the pion pair poduction cross sections.

In such studies, a high hermeticity of the detector is required to suppress background from $e^+e^-$ annihilation into hadrons. The important additional instrument could be a low-angle tagger (similar to that in the KLOE II experiment) to detect scattered electrons. Design of the tagger strongly depends on configuration of the collider final focus system and requires special studies.

## 1.9 Conclusions

An important difference of SCTF compared to the $B$ factories at SLAC and KEK and the $\phi$ factory at Frascati is its ability to run in the broad energy range whereas the colliders mentioned above run basically at a single c.m. energy. This complicates the experimental facilities, both a collider and a detector, but of course makes much broader a physical program.

And one more rather general conclusion. In the discussed energy range a predictive power of the existing theory is rather limited. Our recent experience shows that some particles, e.g., $Y(4260)$

or $X(2150)$, were discovered accidentally and their interpretation is still unclear. Therefore, an experimental study is still most important and one can hope that SCTF will help to solve many of the existing problems.

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