PROCEEDINGS OF SCIENCE

Experimental Program at Super Tau-Charm Facility

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In this manuscript, the STCF project proposed by the Chinese particle physics community is introduced. With a peak luminosity over 0.5×10^{35} cm^{-2}s^{-1}, STCF is expected to deliver 1 ab^{-1} data sample per year. With such a high luminosity, the STCF will be one of the crucial precision frontier for exploring the nature of non-perturbative strong ienteractions, understanding the internal structure of hadrons, studying the asymmetry of matter-antimatter in baryon, lepton and charm meson sectors, test the SM with unprecedented precision, and probing physics beyond the SM.

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1. The STCF project

The proposed Super Tau-Charm Facility (STCF) in China [1] is a symmetric electron-positron beam collider designed to provide e^+e^- interactions at center-of-mass (c.m.) energies $\sqrt{s}$ from 2.0 to 7.0 GeV. The peak luminosity is expected to be over 0.5×10^{35} cm^{-2}s^{-1} at $\sqrt{s}$ = 4.0 GeV. The STCF will operate at the transition interval between non-perturbative QCD and perturbative QCD, which serves as an important playground for exploring QCD and exotic hadrons, precisely measurement of flavor physics and searching for new physics beyond the Standard Model (SM).

The conceptual design of STCF accelerator and detector is shown in Fig. 1. The preliminary progress for STCF accelerator can be found in Ref. [2]. The circumference of STCF collide is around 600 m and there are two storage rings and one interaction point . To achieve such a high luminosity, a crab waist scheme is adopted in the accelerator design with large Piwinski angle collision. The energy spread for current design is around 4×10^{-4}. Besides, there is potential to increase luminosity and realize longitudinal electron-beam polarization in future upgrade. The STCF detector, a state-of-the-art 4π-solid-angle particle detector operating at a high luminosity collider, is a general purpose detector [3, 4]. It incorporates a tracking system composed of an inner tracker and main drift chamber that is able to detect the low-momentum particles with a high efficiency, a particle identification system that provides superior identification ability for charged particles, an electromagnetic calorimeter with an excellent energy resolution and position resolution of photon, a super-conducting solenoid and muon detector that provides sufficient μ/π suppression power.

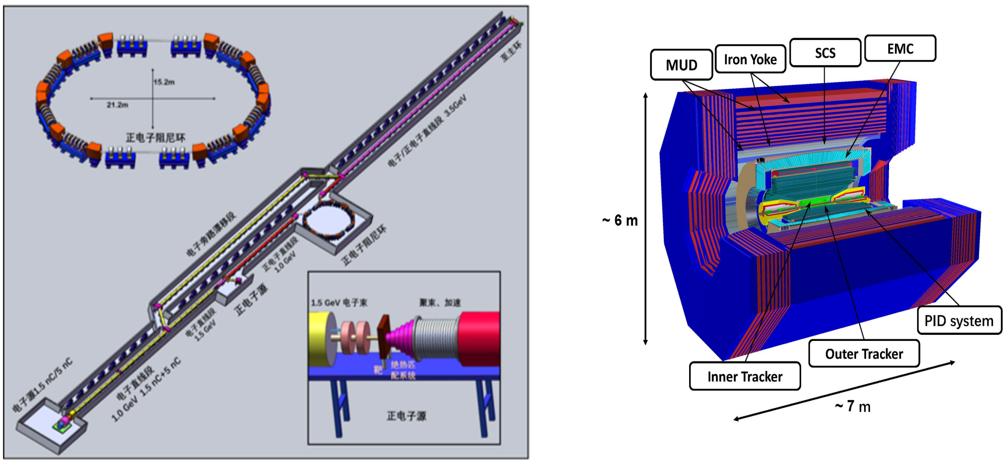

Figure 1: The conceptual design of STCF accelerator and detector.

2. Physics programs at STCF

The energy region of the STCF covers the pair production thresholds for τ-leptons, charmed hadrons and hyperons, and can directly produce the vector charmonium states. STCF is expected to deliver more than 1 ab^{-1} of integrated luminosity per year. Huge samples of XYZ, J/ψ, D^+, D_s^+ and Λ_c^+ decays could be used to make precision measurements of their properties. Following we present the progress of physics programs that are unique at STCF, with emphasis on reactions that challenge the SM, are sensitive to new physics and address poorly understood features in hadron physics. The topics to be presented are not all-inclusive and the physics sensitivities to be shown are based on 1 ab^{-1} luminosity.

2.1 QCD and Hadronic Physics

It is well known that first-principle QCD calculations are impossibly difficult at distance scales that are relevant to the confinement of quarks in hadrons. Thus, there is no direct connection between the SM theory and the spectrum and properties of particles that are experimentally observed. The unique energy region of STCF makes it an ideal place to study the hadron spectrum and hadron structures at low energy region, which is essential for the understanding of QCD dynamics of confinement.

2.1.1 Charmonium(Like) Spectroscopy

Over the last decades, there are a number of charmonium-like structures observed experimentally, but are in conflict with the theoretical model of charmonium spectrum [5] as shown in Fig. 2. These exotic hadrons are named as XYZ particles. These particles are excellent candidates of exotic hadrons, which include hadronic molecules, tetraquarks, hadro-charmonia and hybrid. Due to the statistics limitation, so far, no clear pattern emerges for the complicated spectrum of XYZ states.

To map out of the properties of XYZ particles, comprehensive measurements of as many decay modes as possible are necessary. Year-long STCF runs will produce large amounts of $X(3872)$, $Y(4260)$, and $Z_c(3900)$ at $\sqrt{s} \approx 4230$ MeV, to be around 5×10^6, 10^{10}, 10^9, respectively. It enables us to draw precision Argand plots, to study rare decays, and to get precise mass and width measurements for these particles. Besides, the $Z_{cs}(3985)$ can also be studied with large statistics in $e^+e^- \to K^\pm Z_{cs}^\mp$. At STCF, the J^{++} states, *e.g.* $X(3915)$, $\chi_{c0}(3860)$ and $\chi_{c2}(3930)$ can be searched via $e^+e^- \to \eta X$, ωX or ϕX transitions. Moreover, hidden-charm pentaquark states can also be studied via $e^+e^- \to J/\psi p\bar{p}$, $e^+e^- \to \Lambda_c \bar{D} \bar{p}$ *etc.*, and doubly charmonium states can be searched via $e^+e^- \to J/\psi\eta_c$ and $J/\psi c\bar{c}$. The broad energy region of STCF enables establishing of the spectrum of XYZ particles and thus important in understanding the effects of hadron thresholds on the spectrum and confinement.

2.1.2 Hadron structure

Formation of observed hadrons from QCD partons is still not understood. An e^+e^- collider provides a clean place for the study of hadronization. The quark-hadron fragmentation process can be parameterized with a fragmentation function (FF). Both unpolarized FFs and Collins FFs can be studied by measuring the inclusive production of one or two hadrons. Recent simulation indicates that the Collins FFs can be studied by the asymmetries of two hadrons with a statistical sensitivity of better than 10^{-3} at STCF [7]. The results will provide valuable input to the interpretation of nucleon spin-structure measurements at Eic [8] and EicC [6].

Nucleons are composite objects with inner structure. Due to perturbative QCD is inapplicable at low momentum, the nucleon structure should be measured in experiments. The electromagnetic form factors of nucleon are one of the simplest observables that indicate the internal dynamics of

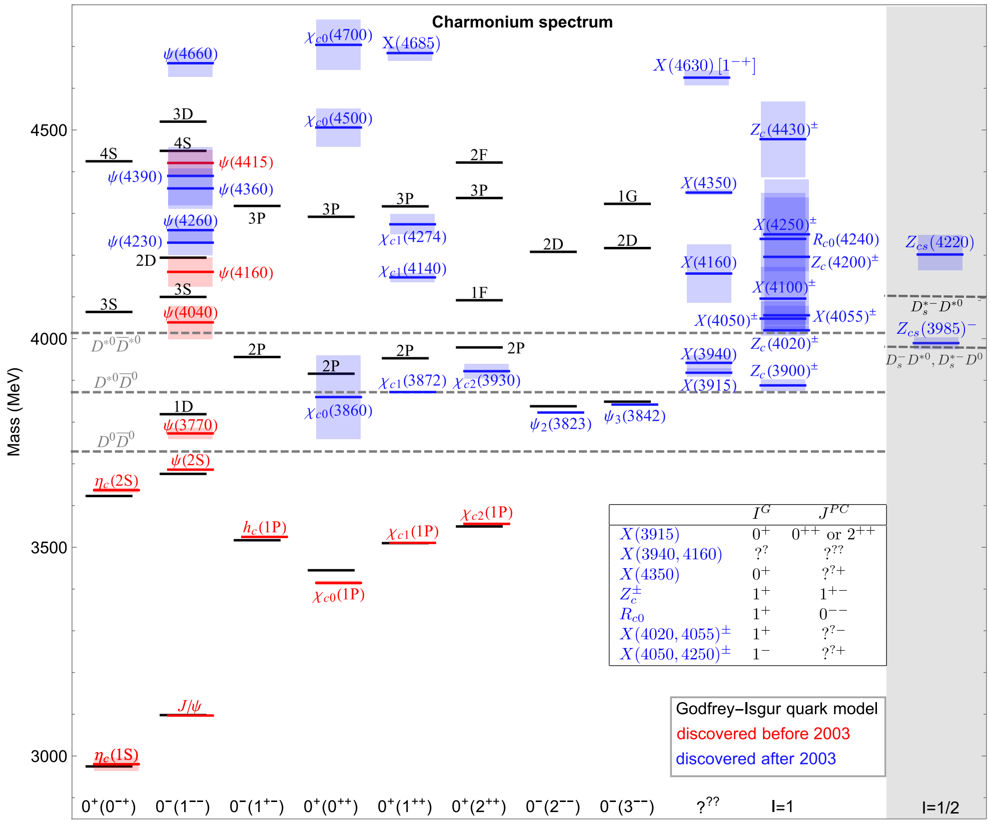

Figure 2: The mass spectrum of charmonia and XYZ states in comparison with the predictions from the Godfrey-Isgur quark model [5]. Plot is provided by F. K. Guo as can be found in Ref. [6].

nucleon. Comparing to space-like, form factors in time-like are playing an increasingly important role. Time-like pair-production measurements are not restricted to nucleons; form-factors of all of the weakly decaying hyperons can be measured and compared, thereby opening a new, previously unexplored dimension. Currently available (statistically limited) time-like experiments demonstrate puzzling features in their threshold cross sections and electric and magnetic form factors [9]. At STCF, time-like nucleon and hyperons form-factors will be measured for four-momentum transfer square Q^2 as high as 40 GeV^2 with precisions that match existing space-like region results. A prospect of the precisions of the baryon pair production at STCF can be found in Fig. 3. Moreover, hyperon polarizations allow new determinations of their parity-violating decay asymmetries and can be used to extract the complex phases between their electric and magnetic form factors.

2.2 Flavor Physics and CP Violation

The most general tests of the SM that involve the CKM matrix are to confirm its unitarity and the internal consistency of its elements. The SM coupling strengths for the $u \leftrightarrow s$ and $c \leftrightarrow d$ transitions are both equal to $G_F|\sin\theta_c|$ with a small, well understood, $O(10^{-4})$ correction. Here G_F is the Fermi constant, and θ_C Cabibbo angle. Any significant difference in $|\sin\theta_c|$ extracted from different quark transitions would be an unambiguous sign of new physics. The clean environments for D and D_s mesons produced by $\psi(3770) \to D\bar{D}$ and $\psi(4160) \to D_s^*\bar{D}_s$, respectively, that are

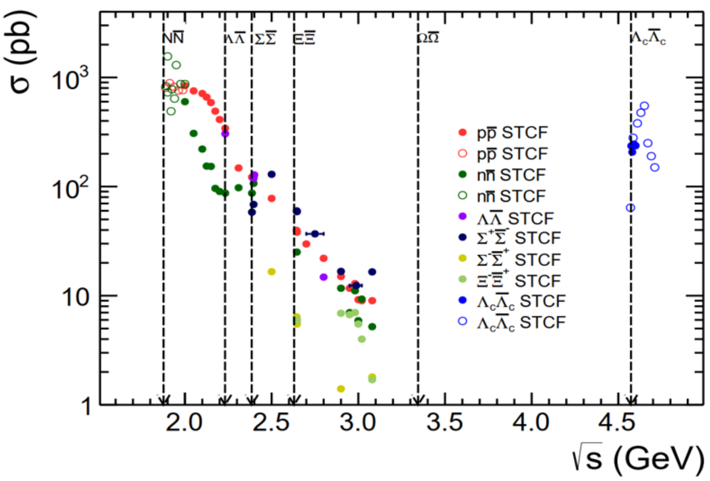

Figure 3: Prospect of the precisions of baryon pair production at STCF.

unique to an STCF-like facility, are especially well suited for low-systematic-error c-quark transition measurements.

2.2.1 Charm Hadron Physics

The STCF can produce large amounts of charm hadron pairs near their production threshold, *e.g.* 4×10^9 pairs of $D^{\pm,0}$, 2.0×10^8 pairs of D_s and 5.6×10^8 Λ_c pairs at the $\sqrt{s} = 3.773$, 4.009 and 4.630 GeV, respectively. The charm hadrons can be tagged with pretty high efficiency and low background with no other associated hadrons produced near threshold.

Precise calibrations of QCD and tests of SM are provided by measuring the leptonic and semi-leptonic decays of charmed hadrons, and lepton flavor universality (LFU) can be probed as well. At STCF, the CKM elements $|V_{cd}, |V_{cs}|$ can be studied with a statistical sensitivity of 0.15% with the purely leptonic decays $D^+ \to l^+\nu_l$ and $D_s^+ \to l\nu_l$, with l denotes μ or τ-lepton. The decay constant f_{D^+} and $f_{D_s^+}$ can be obtained with a statistical precision of 0.15% and 0.09%, respectively, which is comparable with the theoretical precision from lattice QCD. The prospected precisions of f_{D_s} and $|V_{cs}|$ are shown in Fig. 4. Moreover, the LFU can be tested with a statistical precision of 0.4%.

Quantum correlations in threshold data samples provide access to strong phases in the neutral D meson decays. Among the three CKM Unitary triangle angles, γ is of particular importance because it is the only CP violating (CPV) observable that can be determined using tree-level decays. The currently world-best single measurement of γ is $(69 \pm 5)^\circ$ [10] from interference between $B^+ \to \bar{D}^0 K^+$ and $B^+ \to D^- K^+$, The statistical precision of γ will be less than 0.4° in the future LHC upgrade II. Limited knowledge of the strong phases of D decays will systematically restrict the overall sensitivity. STCF will provide constraints to reduce the systematic uncertainty from D strong-phase to be less than 0.1° , by using various D^0 decay modes, *e.g.* CP eigenstates of D^0 decay, double Cabibbo-suppressed decay and Dalitz plot analysis of three-body D^0 decays.

With high luminosity and clean environment, STCF has great potential to perform precise measurement on the charm hadron decays, which provide rigorous test of SM and probe new physics beyond. By combining measurements of $D \to K_1 l^+ \nu_l$ and $B \to K_1 \gamma$, an unambiguous

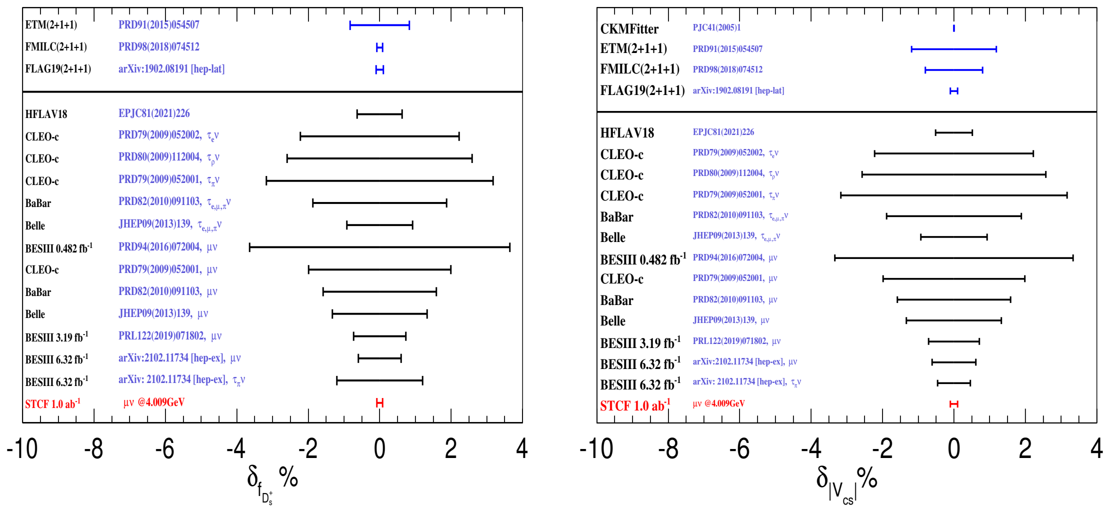

Figure 4: Statistical sensitivity of f_{D_s} and $|V_{cs}|$ at STCF, compared with previous results.

determination of photon polarization in $b \to s\gamma$ can be obtained to probe right-handed couplings in new physics. At STCF, $D^0 \to K_1 e\nu_e$ are studied with the statistical sensitivity for the ratio of up-down asymmetry is estimated to be 1.5×10^{-2} [11].

2.2.2 Tests of CP violations

Searching for a non-SM source of CP violation (CPV) is a promising strategy for uncovering signs of physics beyond the SM. To date, intensive investigations of CPV with beauty & charmed mesons, and in the neutral kaon system, have not demonstrated any deviations from Kobayashi-Maskawa mechanism-based expectations.

At STCF, using quantum-entangled, coherent $\Lambda\bar{\Lambda}$ and $\Xi^-\bar{\Xi}^+$ pairs produced via J/ψ decays, a comprehensive search for non-SM CPV asymmetries would probe the sensitivity level between 10^{-3} and the SM-level of $\sim 6 \times 10^{-5}$ [12]. It is worth noting that sensitivities for CPV in hyperon decays depend linearly on the hyperon polarization and, thus, a future option for an ~80% polarized e^- beam at STCF would boost the discovery potential for hyperon CPV by more than an order of magnitude.

STCF provide a unique place for the study of $D^0 - \bar{D}^0$ mixing and CPV by means of quantum coherence of D^0 and $\bar{D}^0$ produced through $\psi(4140) \to D^0\bar{D}^{*0} \to \pi^0(D^0\bar{D}^0)_{CP=-}$ or $\gamma(D^0\bar{D}^0)_{CP=+}$. Simulation indicates that by measuring $D^0 \to K_s\pi\pi$, $D^0 \to K^-\pi^+\pi^0$ and general CP tag decay modes from the quantum coherence and incoherent processes, the mixing parameters x, y, which denote mass and width differences of two mass eigenstates, can be achieved with a precision better than 0.035% at STCF. Besides, the CPV from direct decay of D meson can be studied at STCF with a precision better than 10^{-3} for $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ processes.

Until now, searches for CPV in the τ-sector have been confined to $O(1\%)$-level studies of $\tau \to K_S\pi\nu$ decays using unpolarized τ-leptons [13]. The corresponding CPV sensitivity for one year of STCF data at $E_{\text{c.m.}} = 4.26$ GeV will be of order $O(10^{-3})$ [14], which is the level expected for the well-understood influence of SM CPV effects in the neutral kaon meson system. The future polarized e^- beam option would enable unambiguous probes for new-physics sources of CPV in τ-lepton decays to final states that do not contain neutral kaons, such as $\tau^- \to \pi^-\pi^0\nu$ as discussed in detail in Ref. [15].

2.3 Other New Physics Searches

With high luminosity, a clean collision environment and excellent detector performance, STCF has great potential to search for rare and forbidden decays, and serve as a powerful instrument for investigations of physics beyond the SM. Besides, STCF would serve as a platform to search for proposed low-mass new particles such as dark photons, light scalars and millicharged particles through direct production or rate decays of mesons.

2.3.1 Rare and forbidden decay

At STCF, various rare and forbidden decays can be studied with huge samples of J/ψ, charm meson, τ leptons and so on, including the decays via the flavor-changing neutral current: $D \to \gamma V$, $D \to l^+l^-$, $e^+e^- \to D^*$ *etc.*; the decays via lepton flavor violation: $\tau \to lll/\gamma l/lP_1P_2$, $J/\psi \to ll'$, $D^0 \to ll'$ *etc.*; the decays via lepton or baryon number violation: $D^+_{(s)} \to l^+l^+X^-$, $J/\psi \to \Lambda_c e^-$, $B \to \bar{B}$ *etc.*; the decay via symmetry violation $\eta^{(\prime)} \to ll\pi^0$, $\eta' \to \eta ll$ *etc.*. In above processes, $l^{(\prime)}$, P and B denote the leptons, pesudo-scalar mesons and baryons, respectively.

2.3.2 Dark Particle Searches

At STCF, using electron-position collide, one can search for directly produced dark photons via $e^+e^- \to \gamma A'(\to l^+l^-)$, with a sensitivity for the mixing strength of $O(10^{-4})$ for $m_{A'}$ in the range of 0.6 to 3.7 GeV. The dark photons can also be searched in the decay of mesons, *e.g.* $\phi \to \eta A'$, $\eta \to \gamma A'$, $J/\psi \to e^+e^-A'$ and $\psi(2S) \to \chi_{c1,2}A'$. Light Higgs h' can be searched via $e^+e^- \to A'h'$ process at STCF.

The millicharged particles, whose electric charge is smaller than electron, can be studied via monophoton final states from electron-positron collider, $e^+e^- \to \bar{\chi}\chi\gamma$. At STCF, the millicharged particles can be searched from 4 MeV to 100 MeV with a mixing strength better than 10^{-3}.

3. Summary

The STCF proposed in China is one of the crucial precision frontiers of accelerator physics. Currently, the project is under R&D, with the conceptual design reports finished soon for physics, detector and accelerator, respectively. The project organization is setup and there have been a lot activities to promote the project. An international collaboration with similar project of the Super Charm-Tau at Novosibirsk [16] is built, with regular joint workshops been hold in past years. The STCF is an important playground for studies of QCD, exotic hadrons and new physics search, and is complementary to B factories in the flavor physics. The unprecedented high luminosity in the energy region 2.0 to 7.0 GeV have great physics potential which enable us to have a much more in-depth understanding of the SM and hopefully to provide some clues/solutions to them. It will play a crucial role in leading the high intensity frontier of elementary particle physics worldwide.

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