

Snowmass2021 - Letter of Interest

[Physics Potential of a Super tau-Charm Facility]

Thematic Areas: (check all that apply ☐/■)

- RF1: Weak decays of b and c quarks
- RF2: Weak decays of strange and light quarks
- ☐ RF3: Fundamental Physics in Small Experiments
- ☐ RF4: Baryon and Lepton Number Violating Processes
- RF5: Charged Lepton Flavor Violation (electrons, muons and taus)
- ☐ RF6: Dark Sector Studies at High Intensities
- RF7: Hadron Spectroscopy

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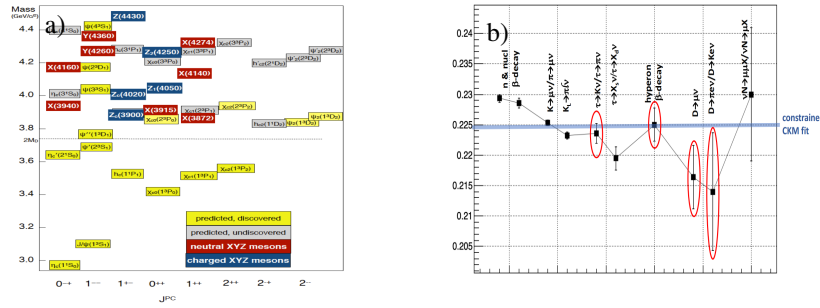
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Abstract: We present the physics potential of a Super tau-Charm Facility (STCF), a state-of-the-art 4π -solid-angle particle detector operating at a high luminosity ($> 0.5 \times 10^{35} \text{ cm}^{-2}\text{s}^{-1}$) e^+e^- collider that spans the $2 \sim 7 \text{ GeV}$ center-of-mass energy range. The energy region covers the pair production thresholds for τ -leptons, charmed mesons & baryons, and all of the strange hyperons. Huge samples of XYZ , J/ψ , D^+ , D_s^+ , and Λ_c^+ decays could be used to make precision measurements of the properties of XYZ particles, search for new ones, and study their rare decays; map out the spectroscopies of QCD hybrids and glueballs; search for new sources of CP violation in the strange-hyperon and τ -lepton sectors with unprecedented sensitivity; make precise independent measurements of the Cabibbo angle (θ_c) to test the unitarity of the CKM flavor-mixing matrix and address the Cabibbo Angle Anomaly; search for anomalous decays with sensitivities extending down to the level of SM-model expectations; qualify Lattice QCD calculations; and provide precise inputs that are essential for the interpretation of results from other experiments. High statistics data samples could also be used to measure nucleon and hyperon time-like form factors over a broad Q^2 range with precisions matching those for the space-like region; and could disentangle the puzzling threshold behavior and peculiar oscillation patterns that have been observed in the baryon pair-production cross sections.

While the Standard Model (SM) is currently universally accepted as the theory of elementary particle interactions, it has a number of shortcomings. The quest for extensions to the SM requires a well-coordinated multi-dimensional program of tests that covers a broad range of energies and/or order-of-magnitude refinements in theoretical and experimental sensitivity and precision. In this Letter, we discuss the physics potential of a super tau-charm facility (STCF), a state-of-the-art 4π -solid-angle particle detector operating at an e^+e^- collider with a high luminosity ($> 0.5 \times 10^{35} \text{ cm}^{-2}\text{s}^{-1}$), center-of-mass energies that covers $2 \sim 7 \text{ GeV}$, and the future option for a polarized e^- beam. The topics presented here are not all-inclusive and, instead, focus on measurements that are unique to an STCF-like facility, with emphasis on reactions that challenge the SM, are sensitive to new physics and address poorly understood features in existing data.

a) QCD confinement and hadron 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. However, Lattice QCD (LQCD) calculations continue to make rapid progress and have recently provided a number of results with sufficient precision to elucidate the spectrum and properties of hadrons.¹ Moreover, there is good reason to expect this progress to continue.

There have been two remarkable recent developments: 1) the failure of hadron models to anticipate the rich charmonium spectrum of hidden-charm states with masses above the open-charm pair threshold²⁻⁴ as shown in Fig. 1(a); 2) the emergence of clear experimental evidence for new, light-hadron spectroscopies of QCD-hybrids and glueballs.⁵⁻⁷ These developments boost confidence that close cooperation between high precision experiments at STCF and the LQCD community will produce a robust, first-principle understanding of the confinement of quarks & gluons in the foreseeable future. The mapping out of the XYZ, glueball and hybrid spectra will require comprehensive measurements of as many decay modes as possible and more sophisticated analysis techniques to extract and interpret exotic mesons that overlap with conventional $q\bar{q}$ states, all in close collaboration with theory. Year-long STCF runs will produce data samples containing $\sim 3\text{T } J/\psi$ & $\sim 500\text{B } \psi'$ events for in depth explorations of light hadron physics. At $E_{\text{c.m.}} \approx 4230 \text{ MeV}$, STCF will function as an "XYZ-meson factory", producing $\sim 1\text{B } Y(4260)$, $\sim 100\text{M}$ each of $Z_c(3900)$ & $Z_c(4020)$, and $\sim 5\text{M } X(3872)$ events per year, enabling precision Argand plots, studies of rare (including, non-hidden charm) decays, precise mass and width measurements,⁸ etc.



tions and electric and magnetic form factors.¹¹ At STCF, time-like nucleon and hyperon form-factors will be measured for Q^2 values as high as 40 GeV² with precisions that match existing space-like region results for the proton & neutron. Moreover, hyperon polarizations allow new determinations of their parity-violating decay asymmetries and can be used to extract the complex phases between their electric and magnetic form factors.¹² STCF can also characterize the Collins effect¹³ in inclusive production of two hadrons at the percent level, thereby providing valuable input to the interpretation of nucleon spin-structure measurements at high energy electron-ion colliders that are currently under construction in China¹⁴ and the U.S.¹⁵

b) Flavor physics and CP violation The underlying structure of the SM is flavor physics; most of the 19 fundamental parameters of the SM are the masses of the quarks & leptons and their flavor mixing angles. 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, $\mathcal{O}(10^{-4})$ 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. Figure 1(b) summarizes the current status of $|\sin \theta_c|$ derived from different transitions,^{16–20} where the mutual agreement is poor, the so-called *Cabbibo angle anomaly*. The $\sim 0.2\%$ precision from nuclear β ($|V_{ud}|$) and kaon ($|V_{us}|$) decays, is more than an order of magnitude better than those from D_s ($|V_{cs}|$) and D ($|V_{cd}|$) decays, which are $\sim 3\%$, based on statistics-limited BESIII measurements of $D_s \rightarrow \mu^+ \nu$, $D^+ \rightarrow \mu^+ \nu$ and $D^0 \rightarrow K^-(\pi^-)\ell^+ \nu$ decays. The clean environments for D and D_s mesons produced by $\psi(3770) \rightarrow D\bar{D}$ and $\psi(4160) \rightarrow D_s^* \bar{D}_s$, respectively, that are unique to an STCF-like facility, are especially well suited for low-systematic-error c -quark transition measurements. Year-long STCF runs at 3.773 GeV and 4.160 GeV would reduce the errors on c -quark-related determinations of $|\sin \theta_c|$ to the 0.1–0.2% level, and match those from β and kaon decays.

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.^{21–25} The good agreement between the SM calculation of ϵ'/ϵ with its measured value²⁶ restricts the level of non-SM CPV for non-SM parity-changing decays involving s -quarks to be $< 6 \times 10^{-5}$,²⁷ but allow for asymmetries at $\mathcal{O}(10^{-3})$ in hyperon parity-conserving decay processes such as $\Lambda \rightarrow p\pi^-$ and $\Xi^- \rightarrow \Lambda\pi^-$.²⁸ 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 $\sim 6 \times 10^{-5}$.²⁹ It is worth noting that sensitivities for CPV in hyperon decays depend linearly on the hyperon polarization and, thus, a future option for an $\sim 80\%$ polarized e^- beam at STCF would boost the discovery potential for hyperon CPV by more than an order of magnitude.

Until now, searches for CPV in the τ -sector have been confined to $\mathcal{O}(1\%)$ -level studies of $\tau \rightarrow K_S \pi \nu$ decays using unpolarized τ -leptons.^{30–32} The corresponding CPV sensitivity for one year of STCF data at $E_{c.m.} = 4.26$ GeV will be of order $\mathcal{O}(10^{-4})$, which is the level expected for the well-understood influence of SM CPV effects in the neutral kaon meson system. The future polarized e^- beam option would enable unambiguous probes for new-physics sources of CPV in τ -lepton decays to final states that do not contain neutral kaons, such as $\tau^- \rightarrow \pi^- \pi^0 \nu$ as discussed in detail in ref. 33.

c) 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 other investigations of physics beyond the SM. Such searches can be classified into three categories: (1) decays via the flavor-changing neutral current (FCNC); (2) decays with lepton flavor violation (LFV); (3) decays with lepton number violation (LNV). STCF would support searches for τ -lepton LFV and LNV decays with sensitivities of 10^{-8} to 10^{-9} .³⁴ In addition, it would also serve as a platform to search for proposed low-mass new particles such as dark photons, light scalars and millicharged particles.

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