PERSPECTIVES ON
TAU-CHARM FACTORY PHYSICS

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ABSTRACT
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the \( \tau \) and \( \nu_\tau \) leptons, the \( c \) quark, and light-quark, glueball and hybrid spectroscopy. An overview of the
broad physics program that this facility will address is presented.

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Perspectives on Tau-Charm Factory Physics

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Abstract
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1 INTRODUCTION

Due to its enormous phenomenological success, the Standard Model (SM) is now generally accepted
as the established theory of the electroweak interactions. However, the SM leaves too many unanswered
questions to be considered as a complete description of the fundamental forces. Clearly, New Physics has
to exist. Although we do not have at present a clear idea about the kind of dynamics which could lie
beyond the SM, we do know the kind of problems it should address. The mechanism responsible for the
spontaneous symmetry breakdown (SSB) of the $SU(2) \otimes U(1)$ symmetry is completely unknown. The
scalar sector of the SM provides a simple way of realizing the SSB, but we do not have at present any
experimental evidence of its correctness. Related to that, there is the problem of fermion-mass generation.
We know that there are three (and only three) families of fundamental fermions, and we have empirically
learned the values of their masses and mixings. We ignore, however, which mechanism generates the
fermionic mass matrices. Why the number of generations is just 3? Why the pattern of masses and
mixings is what it is? Are the masses the only difference among the three families? What is the origin
of the flavour structure of the SM? Which dynamics is responsible for the observed CP violation?

In order to get some hints on all those problems, we need additional experimental information. We
should investigate the existence of the Higgs particle (or whatever new object is playing the role of the
SM Higgs) to learn about the SSB mechanism. This obviously requires to build high-energy machines to
explore energies above the electroweak scale, i.e the 100 GeV to 1 TeV region. The study of the flavour
problem requires, however, a completely different approach: we need high-precision and high-luminosity
machines, producing large amounts of particles of a given flavour; the so-called factories.

The light quarks and leptons are by far the best known ones. Many experiments have analyzed
in the past the properties of $e$, $\mu$, $\nu_e$, $\nu_\mu$, $\pi$, $K$, ... Moreover, future facilities like DAΦNE and KAON
plan to further improve this knowledge. However, one naively expects the heavy fermions to be much
more sensitive to New Physics. It is unfortunate that the present precision in heavy-flavour experiments
is only good enough to study the gross properties of these particles. Obviously, new facilities are needed
to match (at least) the precision attained for the light flavours.

Two different (and complementary) machines have been proposed to perform a detailed study
of heavy flavours: the B Factory (BF) and the Tau-Charm Factory ($\tau$cF). Both are high-luminosity
($\mathcal{L} \geq 10^{33}$cm$^{-2}$sec$^{-1}$) $e^+e^-$ colliders, but with different centre-of-mass energies. The BF would run in
the $\Upsilon$ region, to produce a huge and clean sample of $B$–$\bar{B}$ pairs. It would be a dedicated machine for
investigating the properties of the $b$ quark, and would provide a marvelous tool to perform CP-violation
studies. The $\tau$cF, on the other side, would run at lower energies, around the $\tau^+\tau^-$ and $c\bar{c}$ thresholds, in
order to make a high-precision analysis of the $\tau$, $\nu_\tau$ and $c$ in the absence of any $b$ contamination.

It is worth stressing the special features of the three poorly-known fermions that the $\tau$cF would
study:

• The $\tau$ is a $3^{rd}$ generation lepton with a large number of decay channels, some of which are calculable
  with high-precision in the SM. It is the heaviest known lepton and, moreover, it is the only one heavy

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enough to decay into hadrons. The pure leptonic or semileptonic character of $\tau$ decays provides a

clean laboratory to test the structure of the weak currents and the universality of their couplings
to the gauge bosons.

- The $\nu_\tau$ is a quite unknown particle. We have learn experimentally that the family partner of the
  $\tau$ is different from $\nu_\mu$ and $\nu_e$, and the present data is consistent with the $\nu_\tau$ being a conventional
  sequential neutrino. However, we are very far from clearly establishing its properties.

- The $c$ is the only heavy up-type quark accessible to precision experiments. It has a rich variety of
  weak decays (Cabibbo allowed, Cabibbo forbidden, doubly Cabibbo forbidden, rare second-order
  decays, . . . ), which can be used to learn about the interplay of weak and strong interactions. $D^0-\bar{D}^0$
  mixing and CP-violation studies in the up sector would be of enormous interest. Moreover, the $c$
  quark also provides –through decays of the $J/\psi, \psi', \ldots$ – an ideal tool for light-meson and gluonium
  spectroscopy.

The purpose of the $\tau cF$ is to measure the properties of these particles, with precisions comparable
to the ones attained for the lighter fermions. The $\tau cF$ would cover an exceptionally broad physics
programme, which contains three main elements:

1. Comprehensive precision tests of the electroweak parameters of the SM.

2. Comprehensive precision tests of QCD at the interface of perturbative and non-perturbative
dynamics.

3. Search for new physics.

At the very least, the first two items guarantee a substantial contribution to our knowledge of
the fundamental parameters of the SM. The $\tau cF$ would “write the book” on $\tau$ and charm decays, and
spectroscopy. Moreover, it would be an ideal facility for making detailed tests of non-perturbative QCD;
the $\tau cF$ could well be considered as “the QCD machine of the next decade”. In addition, this program
(item 3) may reveal clues to the origin of the family puzzle or to physics beyond the SM.

The original ideas on the $\tau cF$ [1,2] have been followed by many detailed studies [3–5] on the design
and feasibility of the $\tau cF$ detector and machine, and the physics programme that could be addressed
with this facility. Many new developments have been reported in this workshop. In the following, I will
present a short (and necessarily incomplete) update of the $\tau cF$ physics prospects. I will focus on a few
issues to illustrate the physics potential of this machine. Further details can be obtained from the quoted
references.

2 \textbf{ADVANTAGES OF THE THRESHOLD REGION}

The $\tau cF$ would generate a copious number of $\tau$’s and charm particles, increasing the present data
samples by two or three orders of magnitude. However, as shown in Table 1, this large statistics is not the
main advantage of the $\tau cF$. Although the highest cross-sections for $\tau^{+}\tau^{-}$ and $c\bar{c}$ occur near threshold,
other facilities, like the BF or an hypothetical high-luminosity $Z$ factory, could produce a comparable
(slightly smaller) number of $\tau$’s and $D$’s (but not of $J/\psi$’s).

With the sharp increase in statistics foreseen in the future facilities, the attainable precision will
likely be limited by backgrounds and systematic errors. The decisive advantage that makes the $\tau cF$
the best experimental tool for $\tau$ and charm physics, is its capability of tightly controlling the back-
grounds and systematic errors. The threshold region provides a unique environment, where backgrounds
are both small and experimentally measurable. By adjusting the beam energy above or below a particular
threshold, the backgrounds can be directly measured, avoiding any need for Monte Carlo simulations with
their inevitable uncertainties. Moreover, the data samples are very pure because they are free of heavier
flavour backgrounds. One can collect $\tau$ events that are completely free of $c$ and $b$ contaminations, and
charm samples are free from $b$ backgrounds.
Table 1: Comparison of $\tau$-charm yearly data samples at the Z, B and $\tau$-charm factories. The quoted numbers correspond to integrated luminosities of 2 fb$^{-1}$ ($\mathcal{L} = 2 \times 10^{32}$ cm$^{-2}$ s$^{-1}$) for the Z factory and 10 fb$^{-1}$ ($\mathcal{L} = 10^{33}$ cm$^{-2}$ s$^{-1}$) for the BF and the $\tau$cF.

| Particle     | Z Factory | B Factory | $\tau$cF |
|--------------|-----------|-----------|----------|
| $D^0$ (single) | $1.2 \times 10^7$ | $1.5 \times 10^7$ | $5.8 \times 10^7$ ($\psi''$) |
| $D^+$ (single) | $0.5 \times 10^7$ | $0.7 \times 10^7$ | $4.2 \times 10^7$ ($\psi''$) |
| $D^+_s$ (single) | $0.3 \times 10^7$ | $0.3 \times 10^7$ | $1.8 \times 10^7$ (4.14 GeV) |
| $\tau^+\tau^-$ (pairs) | $0.3 \times 10^7$ | $0.9 \times 10^7$ | $0.5 \times 10^7$ (3.57 GeV) |
| $J/\psi$      | –         | –         | $2.4 \times 10^7$ (3.67 GeV) |
| $\psi''$      | –         | –         | $3.5 \times 10^7$ (4.25 GeV) |
|               |           |           | $1.7 \times 10^{10}$ |
|               |           |           | $0.4 \times 10^{10}$ |

Near threshold, the heavy flavours are produced in simple particle–antiparticle final states ($\tau^+\tau^-$, $D^0\bar{D}^0$, $D^+D^-$, ...). By observing the decay of one particle, its partner is cleanly tagged. This “single-tagging” is a unique feature of the threshold region, which allows to collect a bias-free data sample, without any pre-selection of its decay mode. This property turns out to be crucial to achieve very precise measurements of branching ratios. In addition, the threshold region has also several kinematic advantages that result from the low particle velocities, such as monochromatic spectra for two-body decays.

Another important advantage of the $\tau$cF energy region is the existence of two precisely-known energy points, the $J/\psi$ and $\psi''$, which provide a very high-rate ($\sim$ 1 kHz) signal to calibrate and monitor the detector performance. This allows for a tight control of the systematic errors.

Thus, the $\tau$cF experiment would benefit from a very high statistics, low and measurable backgrounds, and reduced systematic errors. The coincidence of all these features near threshold creates an ideal facility for precision $\tau$-charm studies.

Figure 1: The cross-section ratio $R \equiv \sigma(e^+e^- \rightarrow \text{hadrons}, \tau^+\tau^-)/\sigma(e^+e^- \rightarrow \mu^+\mu^-)$ in the $\tau$-charm threshold region. The data are from DELCO [8] at SPEAR.

Figure 2 shows the cross-section ratio $R \equiv \sigma(e^+e^- \rightarrow \text{hadrons}, \tau^+\tau^-)/\sigma(e^+e^- \rightarrow \mu^+\mu^-)$ in the $\tau$-charm threshold region [8]. One can identify a series of important operating energy points:

- **$J/\psi$ (3.10):** Intense and clean source of light hadrons and gluonic particles for QCD studies and tests of symmetry principles. High-rate signal for calibration.

- **3.55 GeV:** Just below the $\tau^+\tau^-$ threshold. Experimental measurement of all non-$\tau$ backgrounds.

- **3.56 GeV:** $\tau^+\tau^-$ threshold. Due to the Coulomb interaction, the $\tau^+\tau^-$ production cross-section has a finite value of 0.20 nb [8]. The two body $\tau$ decays ($\tau \rightarrow \pi\nu_\tau, K\nu_\tau$) produce monochromatic secondaries. Very clean signatures and good kinematic separation of the different decay modes.

- **3.67 GeV:** The highest $\tau^+\tau^-$ cross-section below the $\psi''$ and $D-\bar{D}$ thresholds. $\tau$ decay is the only source of prompt single-charged leptons and pront neutrinos.

- **$\psi''$ (3.69):** Another high-rate source of light hadrons for QCD studies and calibration. The highest $\tau^+\tau^-$ cross-section occurs here; background-free experiments, such as neutrinoless rare $\tau$-decays, could be made at this energy.
\begin{itemize}
  \item $\psi''(3.77)$: Pure $D^0\bar{D}^0$ and $D^+D^-$ states, without contamination from other charmed particles. Tagged $D$ decays.
  \item 4.03 GeV: The highest charm cross-section in $e^+e^-$ annihilation. Tagged $D_s^\pm$ decays.
  \item 4.14 GeV: $D_s^\pm$ studies, via $D_s^\pm D_s^{*\mp}$ events.
  \item 4.57 (4.91, 4.93, \ldots) GeV: $\Lambda_c\bar{\Lambda}_c$ ($\Sigma_c^0\bar{\Sigma}_c^0, \Xi_c\bar{\Xi}_c, \ldots$) threshold.
\end{itemize}

3 TAU PHYSICS

3.1 Precise branching ratios

The leptonic or semileptonic nature of $\tau$ decays allows us to make precise theoretical predictions for its decay rates and Dalitz-plot distributions. A systematic study of all $\tau$ decay channels at the $\tau\ell\nu$ could be used to look for signs of discrepancies with the theoretical expectations.

The simplest decay modes, $\tau^- \to e^-\bar{\nu}_e\nu_\tau$, $\mu^-\bar{\nu}_\mu\nu_\tau$, $\pi^-\nu_\tau$, and $K^-\nu_\tau$, are theoretically understood at the level of the electroweak radiative corrections \cite{14}. Within the SM, one can accurately predict the following relation between the leptonic branching ratios $B_l \equiv B(\tau^- \to \ell^-\bar{\nu}_\ell)$ and the $\tau$ lifetime \cite{11}:

$$B_\ell = \frac{B_\mu}{0.97257} = \frac{\tau_\ell}{(1.632 \pm 0.002) \times 10^{-12}} s.$$  \hspace{1cm} (1)

To derive this equation, one uses the value of the Fermi coupling measured in $\mu$ decay, and the recent precise measurement \cite{13} of the $\tau$ mass $[\Gamma(\tau^- \to \nu_\tau l^-\bar{\nu}_l)] \propto G_F^2m_\tau^5$. We can use this relation to test the universality of the charged-current couplings to the $W$ boson. Allowing these couplings to depend on the considered lepton flavour, the ratio $B_\mu/B_\ell$ provides a measurement of $|g_\mu/g_\ell|$, while $|g_\tau/g_\ell|$ can be obtained from the ratio $B_\ell\tau_\mu/\tau_\tau$. The present data \cite{13,14} imply:

$$|g_\tau/g_\mu| = 0.995 \pm 0.007; \quad \frac{g_\mu}{g_\ell} = 1.001 \pm 0.006,$$  \hspace{1cm} (2)

which should be compared with the more accurate value \cite{15} $|g_\mu/g_\ell| = 1.0014 \pm 0.0016$ obtained from pion decay.

The decay modes $\tau^- \to \nu_\tau\pi^-$ and $\tau^- \to \nu_\tau K^-$ can also be used to test universality, provided the dependence on the hadronic matrix elements (the so-called decay constants $f_{\pi,K}$) is eliminated through the ratios $\Gamma(\tau^- \to \nu_\tau\pi^-/K^-)/\Gamma(\pi^-/K^- \to l^-\bar{\nu}_l)$. The theoretical uncertainties from uncalculated higher-order electroweak corrections have been conservatively estimated \cite{16} to be about 1%, but it seems feasible to reduce them to the 0.1% level. From the present data, one obtains:

$$|g_\tau/g_\ell| = 1.007 \pm 0.013; \quad |g_\tau/g_\mu| = 1.010 \pm 0.013.$$  \hspace{1cm} (3)

The formal average of Eqs. \cite{3} and \cite{3}, implies $|g_\tau/g_\ell| = 0.998 \pm 0.006$, in perfect agreement with the expected universality of the charged-current couplings.

In the $\tau\mu\nu$, the expected precisions on the 1-prong branching ratios are 0.1% ($e, \mu, \pi$) - 0.8% (K) in a one-year data sample \cite{13}, whereas present errors are 1% - 30%. These precise measurements would allow a test of the universality of the leptonic charged-currents at the 0.1% level, to be compared with the present accuracies of 0.7%. The experimental requirements to achieve precise $-\mathcal{O}(0.1\%)$- measurements of the $\tau$ branching ratios are very challenging; the normalization, detection efficiency and backgrounds must each be known at the 0.1% level. These requirements can probably be achieved only at the $\tau\mu\nu$, running just above the $\tau^+\tau^-$ threshold at 3.56 GeV, where the decays are kinematically-separated.

The measured ratio between the $\tau^- \to \nu_\tau K^-$ and $\tau^- \to \nu_\tau\pi^-$ decay widths can be used to obtain a value for $\tan^2 \theta_c(f_K/f_\pi)^2$,

$$\tan^2 \theta_c \left( \frac{f_K}{f_\pi} \right)^2 = \left( \frac{m_\pi^2 - m_\tau^2}{m_\tau^2 - m_K^2} \right)^2 \frac{\Gamma(\tau^- \to \nu_\tau K^-)}{\Gamma(\tau^- \to \nu_\tau\pi^-)} = (7.0 \pm 2.0) \times 10^{-2}. \hspace{1cm} (4)$$


The present accuracy (30%) is very poor (a better 12% precision is quoted in preliminary LEP results [13]). The excellent $\pi/K$ separation of the $\tau cF$ will make possible to reach a precision of 0.8% (0.5%) in a one-year (two-year) data sample, which is comparable to the result $(7.56 \pm 0.02) \times 10^{-2}$, obtained from $\Gamma(K^- \rightarrow \mu^- \bar{\nu}_\mu)/\Gamma(\pi^- \rightarrow \mu^- \bar{\nu}_\mu)$.

3.2 Hadronic $\tau$ decays

The semileptonic decay modes of the tau, $\tau^+ \rightarrow \nu_\tau H^-$, probe the matrix element of the left-handed charged current between the vacuum and the final hadronic state $H^-$. Contrary to the well-known $e^+e^- \rightarrow \gamma \rightarrow$ hadrons process, which only tests the electromagnetic vector current, the semileptonic $\tau$-decay modes offer the possibility to study the properties of both vector and axial-vector currents.

Since the hadronic matrix elements are governed by the non-perturbative regime of QCD, we are unable at present to make first-principle calculations for exclusive decays. Nevertheless, we can use our present knowledge on strong interactions at low energies to estimate the gross features of the Lorentz-invariant form factors describing the decay amplitudes. For instance, Chiral Perturbation Theory techniques [19] can be applied to rigorously predict the low hadronic-invariant-mass behaviour, and one can extrapolate to higher values of $p^2$ by using different models of resonance dynamics [20–23].

The hadronic form factors can be experimentally extracted from the Dalitz-plot distributions of exclusive hadronic $\tau$ decays [24]. An exhaustive analysis of those decay modes at the $\tau cF$ would provide a very valuable data basis to confront with theoretical models. The high statistics of the $\tau cF$ would even make possible to perform a study of the $J = 0$ channels, which are very sensitive to the masses of the light quarks; the accurate measurement of certain azimuthal asymmetries could then result in an experimental determination of the running quark masses [25].

At the inclusive level, the present QCD techniques are much more powerful. The total inclusive hadronic width of the $\tau$ can be systematically calculated [26,27] by using analyticity constraints and the Operator Product Expansion. Both perturbative (to order $\alpha_s^3$) and non-perturbative (which have been shown to be suppressed) contributions have been taken into account [28,27], together with the known electroweak corrections [11,28]. The result turns out to be quite sensitive to the value of $\alpha_s$, and has been used to obtain one of the most precise determinations of the strong coupling constant

$$\alpha_s(m_\tau) = 0.35 \pm 0.03.$$  \hfill (5)

After evolution up to the scale $M_Z$, this running coupling constant decreases to $\alpha_s(M_Z) = 0.121 \pm 0.004$, in amazing agreement with the present LEP average [19] (without $\tau$ data) $\alpha_s(M_Z) = 0.123 \pm 0.005$ and with a similar error bar. The comparison of these two determinations of $\alpha_s(\mu)$ in two extreme energy regimes, $m_\tau$ and $M_Z$, provides a beautiful test of the predicted running of the QCD coupling constant.

The non-strange and strange components of the $\tau$ hadronic width can also be predicted separately, and one can decompose these further into vector and axial-vector contributions, which are resolved experimentally according to whether the hadronic final state includes an even or odd number of pions. A consistency check of the theoretical analysis can be done by studying the distribution of the final hadrons in $\tau$ decay. A combined fit of certain weighted integrals [30,31] of the hadronic spectrum would allow to simultaneously measure $\alpha_s(m_\tau)$ and the parameters characterizing the non-perturbative dynamics. Moreover, the measurement of the hadronic spectrum could provide a precise determination of the vector- and axial-vector-current spectral functions, both in the Cabibbo-allowed and Cabibbo-suppressed channels. This information would be very valuable for making many interesting tests of QCD [21].

A pioneering QCD analysis of the tau data has recently been performed by the ALEPH collaboration [32]. Their results are in good agreement with the theoretical expectations; however, the present precision is still not good enough for making a detailed test of the QCD predictions. The $\tau cF$ is ideally suited for this kind of physics [33]: high statistics, low backgrounds, excellent momentum resolution, easy $\pi/K$ identification, high resolution for both charged and neutral measurements, and zero normalization uncertainty (single tagging). The $\tau cF$ could perform a precision global analysis of all $\tau$ decay channels, with notable strengths for decays involving $K$’s and multiple $\gamma$’s, which are poorly measured at present. This should definitively settle present experimental controversies, such as the so-called 1-prong problem,
3.3 Rare and forbidden decays

In the minimal SM with massless neutrinos, there is a separately conserved additive lepton number for each generation. All present data are consistent with this conservation law. However, there are no strong theoretical reasons forbidding a mixing among the different leptons, in the same way as happens in the quark sector. Many models, in fact, predict lepton-flavour or even lepton-number violation at some level. Experimental searches for these processes can provide information on the scale at which the new physics begins to play a significant role.

$K$, $\pi$ and $\mu$ decays, together with $\mu$-$e$ conversion, neutrinoless double beta decays and neutrino oscillation studies, have put already stringent limits [18] on lepton-flavour and lepton-number violating interactions. However, given the present lack of understanding of the origin of fermion generations, one can imagine different patterns of violation of this conservation law for different mass scales. For instance, since the $\tau$ is a third generation lepton, new physics associated with Higgs couplings is expected to give larger effects than for the lighter leptons. Moreover, the larger mass of the tau lepton means that many more decays are kinematically allowed. Several supersymmetric models lead to lepton-number violating rates which may be constrained at the $\tau$C. These type of processes also appear [33] in models with extra neutral isosinglet or vector-like heavy fermions.

The present upper limits on lepton-flavour and lepton-number violating decays of the tau are in the range of $10^{-4}$ to $10^{-5}$, which is far away from the impressive bounds [18] obtained in $\mu$-decay. The $\tau$C could easily improve these limits by about two orders of magnitude.

Figure 2: The combined electron spectra (solid histograms) from the standard decay $\tau^- \rightarrow e^- \bar{\nu}_e \nu_\tau$ mixed with a hypothetical 1% two-body decay $\tau \rightarrow eX$ at centre-of-mass energies of a) 3.57 GeV and b) 10 GeV [33]. The particle $X$ is a massless Goldstone boson. The dashed histograms show conventional (V-A) fits to the combined spectra. Each plot contains 200k $\tau^- \rightarrow e^- \bar{\nu}_e \nu_\tau$, corresponding to two months’ data at 3.57 GeV.

The $\tau$C is especially suited to study two-body decays like $\tau^- \rightarrow l^- X$ ($l = e, \mu; X = $ Majoron, familon, flavon, . . .), which, at threshold, lead to the distinctive signature of monochromatic leptons (Fig. 2a) [33]. In contrast, the sensitivity is much weaker at higher energies since the lepton spectrum from the $l^- X$ decay is broad, spreading over the full spectrum of the standard $l^- \bar{\nu}_l \nu_l$ decay (Fig. 2b). For $\tau^- \rightarrow e^- X$ ($\tau^- \rightarrow e^- X$), the expected branching-ratio sensitivity at the $\tau$C is better than $10^{-5}$ ($10^{-3}$) for one-year’s data [33], to be compared with the present limits of 1-2%. The experimental sensitivity could be improved a further order-of-magnitude if the monochromator optics is successful. Sensitivity to still-lower branching ratios would require improvements in the $\pi e$ rejection of the $\tau$C detector, e.g. with a fast RICH.

The optimum energy to search for other neutrinoless $\tau$ decays is at 3.67 GeV, where a simple and $(\simeq 100\%)$ efficient tag, $E_{\text{miss}} \geq 0.8$ GeV, can be used. The validity of any signal can be convincingly demonstrated by its disappearance at 3.55 GeV. The $\tau$C will be able to place upper limits of $\text{Br} \simeq 10^{-7}$ on these decays [33], or observe them at a higher value. If the monochromator optics is successful, it may be possible to reach even higher sensitivities for certain rare $\tau$ decays at the $\psi’(3.69)$. Here the production rate is at a maximum and the backgrounds for neutrinoless (fully-reconstructed) $\tau$ decays are small.

The $\tau$C would also look for $\tau$ decays which, although allowed in the SM, are highly suppressed. For instance, the decay $\tau^- \rightarrow \pi^- \eta \nu_\tau$ can only occur through second-class weak currents (which have never been observed) or through non-standard mechanisms such as the violation of G parity or the existence of a new scalar particle. The branching ratio expected in the SM due to the violation of G parity (from the $u - d$ quark mass difference) is about $10^{-5}$ [22]. A Monte Carlo study shows that this decay can be cleanly measured at 3.67 GeV [34].
3.4 Lorentz structure of the charged weak current

The V–A structure of the charged current can be tested by studying the distribution of the final charged lepton in the leptonic decay modes of the $\tau$, $\tau^- \to \nu_\tau \bar{\nu}_\tau$ ($l = e, \mu$). This distribution is usually parametrized in terms of the so-called Michel parameters, which have the following SM values: $\rho = \delta = 3/4, \eta = 0$ and $\xi = \xi' = 1$.

Up to now, the experiments were only sensitive to the parameter $\rho$. The first measurement of $\xi$ has been recently reported by ARGUS. Averaging the different experiments one has [11, 35]:

$$\rho_e = 0.717 \pm 0.038, \quad \rho_\mu = 0.762 \pm 0.046,$$

where $\xi$ is a linear combination of vector and axial currents, which have the following SM values:

$$\xi, \omega, \sigma, \lambda$$

The present measurements are in agreement with the V–A hypothesis. Assuming that the $\tau\nu, W$ vertex is a linear combination of vector and axial currents, $g_V V^\mu + g_A A^\mu$, and using the standard V–A form for the $l^-\nu_l$ vertex, one can exclude a vertex of pure V+A, V or A type. However, one can only obtain the upper limit $|(g_V + g_A)/(g_V - g_A)| < 0.33$ (95% C.L.) on a possible mixture of right-handed current structure; a very poor limit indeed.

The most general, local, derivative-free lepton-number conserving four-fermion interaction Hamiltonian ($l = e, \mu$),

$$\mathcal{H} = \frac{G_F}{\sqrt{2}} \sum_{n,\pi,\omega} g_{\omega n} \left[ \bar{\nu}_\tau \Gamma_n (u)_\pi ] \right] \nu_\tau, \xi_n \tau_\omega,$$

contains ten complex coupling constants $\rho$, $\omega$, $\sigma$, $\lambda$ are the chiralities (left-handed, right-handed) of the corresponding fermions, and $n$ labels the type of interaction (scalar, vector, tensor); for given $n, \pi, \omega$, the neutrino chiralities $\eta$ and $\xi$ are uniquely determined. In the SM, $g_{\omega n} = 1$ and all other $g_{\omega n} = 0$. The normalization is conventionally fixed by taking out a common factor $G_F$, which is determined by the total decay rate. With the present experimental information, it is certainly impossible to determine the interaction. For instance, any combination of the six couplings $\mathcal{H}_{\omega n}, g_{\omega n}, g_{\omega n}, g_{\omega n}, g_{\omega n}$ and $g_{\omega n}$, with the other four couplings being zero, yields $\rho = 3/4$.

For the analogous $\mu^- \to \nu_\mu e^- \bar{\nu}_e$ decay, Fetscher et al. [37] have succeed in proving the V–A nature of the $\mu$-decay amplitude, using existing data. The relevant experiments involve measurements of normal $\mu$ decay, including the decay asymmetry relative to the spin of the muon ($\xi, \delta$) and the polarization of the final electron ($\xi'$), together with the cross-section for the inverse $\mu$ decay $\nu_\mu e^- \to \mu^- \nu_e$ and the value of the $\nu_\mu$-helicity, which is known from the decay of the parent pion. It would be desirable to do a similar analysis for the leptonic tau decay modes.

Low energy experiments near the $\tau^+\tau^-$ threshold are best suited for more precise determinations of the $\rho$ parameter, because the energy spectrum is less distorted by the Lorentz boost of the moving $\tau$. The measurement of the low-energy parameter $\eta$ seems possible for the $\tau^- \to \nu_\tau \bar{\nu}_\tau$ mode, where the mass suppression is weaker ($m_\mu/m_\tau \approx 1/17$). Since $\Gamma_{\tau^- \to \nu_\tau \bar{\nu}_\tau} \sim (1 + 4\eta m_\mu/m_\tau)$, the value of $\eta_\mu$ is needed in order to fix the global strength of the interaction, i.e. to derive the Fermi coupling constant and make a test of universality [36]. $\eta \neq 0$ would show that there are at least two different couplings with opposite chiralities for the charged leptons. If we assume the V–A coupling $g_{\LL}^V$ to be dominant, then the second coupling would be a Higgs type coupling $g_{\RR}^S$ with right-handed $\tau$ and $\mu$.

Measuring the $\tau$ polarization, two more decay parameters, $\xi$ and $\delta$, can be determined. At LEP $\tau$ is polarized, because of the $Z$ coupling, which makes the measurement feasible [38]; however, one actually measures the product $\xi \mathcal{P}_\tau$. Thus, $\xi = 1$ is usually assumed, to get a determination of the neutral-current couplings via $\mathcal{P}_\tau$. In order to measure the $\tau^-\tau^+$ decay parameters at LEP, one either needs to fix the neutral-current couplings [39] from other observables not related to $\mathcal{P}_\tau$ or perform a correlated analysis of the two $\tau$'s [10].

At the $\tau$F the $\tau$'s are produced unpolarized. Nevertheless, the fact that the spins of the two $\tau$'s are strongly correlated [10] makes the experiment feasible. One considers the process $e^-e^+ \to \tau^-\tau^+ \to (X_1 \nu_\tau...,) (X_2 \bar{\nu}_\tau...)$, and computes the cross-section for the production of the particles $X_1$ and $X_2$, performing a coherent sum over the (unobserved) spins of the $\tau$'s. The correlated distribution of the final products $X_1^-$ and $X_2^+$ carries information on the spin-dependent part of the production amplitude.
Assuming an ideal detector with no systematic uncertainties and 100% efficiency, the expected sensitivity on the Michel parameters for $10^7 \tau^+\tau^-$ pairs is indicated in Table 2. These numbers only take into account the information obtained from correlated events where both $\tau$'s decay into leptons. The estimated error on $\rho$ is about the same as the present error in $\mu$ decay, and $\eta_{\mu}$ could be measured a factor of 5 more precisely than in $\mu$ decay. $\xi$ and $\delta$ could be measured with slightly larger errors than in $\mu$ decay. Since the values of $\xi$ and $\delta$ are strongly anticorrelated, the combination $\frac{1}{2}(1 + \frac{1}{9}(3\xi - 16\delta))$, which gives the probability that the decaying $\tau$ was right-handed, can be measured to 0.3% accuracy [36, 42]; to be precisely measured, with an expected accuracy of 2%.

Table 2: Expected errors [12] on the Michel parameters for $10^7 \tau^+\tau^-$ pairs produced at $\sqrt{s} = 4$ GeV, from energy–energy–angle correlations in pure leptonic decays. Better precisions may be reached if hadronic decays are included (see text). For comparison the present world averages [18] in $\mu$ decay are shown in the last column.

|                  | $\tau^- \rightarrow \nu_\tau e^- \bar{\nu}_e$ | $\tau^- \rightarrow \nu_\tau \mu^- \bar{\nu}_\mu$ | $\mu^- \rightarrow \nu_\mu e^- \bar{\nu}_e$ |
|------------------|-----------------------------------------------|-----------------------------------------------|-----------------------------------------------|
| $\rho$           | $\pm 0.0022$                                  | $\pm 0.0023$                                  | $0.7518 \pm 0.0026$                          |
| $\eta$           | $\pm 0.0200$                                  | $\pm 0.0035$                                  | $-0.0070 \pm 0.0130$                         |
| $\xi$            | $\pm 0.0350$                                  | $\pm 0.0350$                                  | $1.0030 \pm 0.0080$                          |
| $\delta$         | $\pm 0.0270$                                  | $\pm 0.0280$                                  | $0.7490 \pm 0.0040$                          |

The next step would be to measure the polarization of the charged lepton emitted in the $\tau$-decay. This could be possible, in principle, for the decay $\tau^- \rightarrow \mu^- \bar{\nu}_\mu \nu_\tau$ by stopping the muons and detecting their decay products. A precision of about 15% in the corresponding decay parameter $\zeta_{\mu}$ could be reached [36].

Including the correlations of the leptonic decays with the hadronic ones, the number of useful $\tau$ pairs would increase by more than a factor of 6. Moreover, the lepton–hadron correlations are more sensitive to some Michel parameters than the lepton–lepton ones, because of the high spin-analyzing power of the hadronic two-body decays. Therefore, the accuracy could be improved by a substantial amount. Preliminary analyses [13] suggest that it could be possible to reach sensitivities as good as $\pm 0.0002 \ (\rho)$, $0.1 \ (|\eta_{\mu}|)$, $0.001 \ (|\eta_{\mu}|)$, $\pm 0.002 \ (\xi)$ and $0.0003 \ (\delta \times \xi)$. Clearly, more detailed studies are needed in order to get a reliable estimate of the ultimate $\tau\text{C}F$ precision, but the prospects look very encouraging.

Assuming in the hadronic channels an arbitrary combination of vector and axial couplings for the $\tau\nu, W$ vertex, the neutrino helicity

$$h_{\nu_\tau} = \frac{2g_V g_A}{|g_V|^2 + |g_A|^2},$$

which plays the same role as $\xi$ in leptonic decays, could be measured to 0.3% accuracy [24, 22]; to be compared with the present value [44] $h_{\nu_\tau} = -1.01 \pm 0.08$.

None of these estimated accuracies takes efficiencies and systematic errors into account. While it is clear that a BF, with a similar number of $\tau$ pairs, could reach a comparable statistical precision [36, 43], only at the $\tau\text{C}F$ the assumption of negligible systematic errors and 100% efficiency can be justified [43].

3.5 $\nu_\tau$ mass

The possibility of a non-zero neutrino mass is obviously a very important question in particle physics. There is no fundamental principle requiring a null mass for the neutrino. On the contrary, many extensions of the SM predict non-vanishing neutrino masses, which could have, in addition, important implications in cosmology and astrophysics.

The first attempts to place a limit on $m_{\nu_\tau}$ were done by studying the endpoint of the momentum spectrum of charged leptons from the decays $\tau^- \rightarrow \nu_\tau l^- \bar{\nu}_l \ (l = e, \mu)$. The precision which can be
achieved is limited by the experimental momentum resolution of fastest particles, which deteriorates with increasing centre-of-mass energy. Better limits have been set by studying the endpoint of the hadronic mass spectrum of high multiplicity tau decays. The limiting factor is then the resolution of the effective hadronic-mass determination. The strongest bound up to date \cite{46} comes from the $\tau^- \rightarrow 2\pi^+ 3\pi^- \nu_\tau$ decay,

$$m_{\nu_\tau} < 31 \text{ MeV \ (95\% C.L.)}.$$  \hfill (10)

In order to substantially improve the present $m_{\nu_\tau}$ upper bound, it is extremely important to obtain a very clean event sample, since a single background event near the endpoint can falsely lower the final limit \cite{47}. The advantages of the $\tau$CFL for this experiment are then obvious. It has been shown that the study of the decays $\tau^- \rightarrow \nu_\tau l^- \bar{\nu}_l$ could result in a limit of the order of 20 MeV \cite{17,15}, thus providing little improvement of the current limit. The prospects are much better for the hadronic modes $\tau^- \rightarrow 2\pi^+ 3\pi^- \nu_\tau$ \cite{17} and $\tau^- \rightarrow K^- K^+ \pi^- \nu_\tau$ \cite{23}, where mass limits of about 5 and 10 MeV, respectively, could be easily achieved, in a one-year data sample. The limit can be further improved using the decay $\tau^- \rightarrow 2\pi^- \pi^+ 2\pi^0 \nu_\tau$; owing to its high branching ratio, this mode has been shown to be very efficient in a recent CLEO analysis \cite{15,51}. The very good photon resolution of the $\tau$CFL detector would guarantee an optimal use of decays containing neutrals. Adding the information from the the three decay modes, the estimated sensitivity \cite{15} of the $\tau$CFL in a two-year data sample is 2 MeV (95\% C.L.).

For comparison, the best limits on the muon and electron neutrinos are \cite{31} $m_{\nu_\mu} < 270 \text{ KeV \ (90\% C.L.)}$ and $m_{\nu_e} < 7.3 \text{ eV \ (90\% C.L.)}$. Note, however, that in many models a mass hierarchy among different generations is expected, with the neutrino mass being proportional to some power of the mass of its charged lepton partner. Assuming for instance the fashionable relation $m_{\nu_\mu}/m_{\nu_e} \sim (m_{\tau}/m_e)^2$, a sensitivity of 2 MeV for $m_{\nu_\tau}$ is equivalent to 0.2 eV for $m_{\nu_e}$. A relatively crude measurement of $m_{\nu_e}$ may then imply strong constraints on neutrino-mass model building.

### 3.6 $\tau$ mass

The mass is a basic property of any particle, which obviously should be known as accurately as possible. A precise value of $m_\tau$ is needed in order to improve the present bound on $m_{\nu_\tau}$, or to make a test of universality. The recent accurate measurement of $m_\tau$ by the BEPC/BES collaboration \cite{12}, 7 MeV lower than the old value quoted by the particle data group \cite{13}, has shown the relevance of knowing the exact value of this parameter. Given the important implications of this measurement, a confirmation of the $m_\tau$ value to a similar (or better) level of precision by an independent experiment is clearly called for. This can only be done near threshold, by measuring $\sigma(e^+e^- \rightarrow \tau^+\tau^-)$. The $\tau$CFL could get a precision of 0.1 MeV on $m_\tau$, which would represent a factor of 3 improvement over the BES measurement.

### 3.7 Electromagnetic and weak moments

A precision analysis of the $\tau^+\tau^-$ production cross-section near threshold (expected accuracy at the $\tau$CFL $\sim 0.1\%$) could substantially improve the bound on the $\tau$ anomalous magnetic moment, reaching a sensitivity \cite{51} at the level of the first QED contribution ($\alpha/2\pi$). This quantity is very poorly known at present: $a_\tau^\gamma < 0.11$ \cite{52}.

Non-zero electric dipole moments of leptons, $d_l$, are unambiguous signals of T (CP) violation, and are sensitive probes of physics beyond the SM. The present limit on the $\tau$ electric dipole moment could be improved by more than one order of magnitude by studying T-odd triple correlations of the final $\tau^+\tau^-$ decay products. A conservative estimate of the $\tau$CFL capabilities gave as expected sensitivity $|d_\tau| \leq 10^{-17}$ e cm \cite{53}. As demonstrated by the recent LEP analyses of the analogous weak dipole moment \cite{38}, a much better precision can probably be achieved.

### 4 CHARM PHYSICS

#### 4.1 Semileptonic decays and CKM matrix elements

Semileptonic decays of heavy mesons play a crucial role in the determination of the Cabibbo–Kobayashi–Maskawa (CKM) mixing matrix. The partial decay width associated with the decay $M_i \rightarrow
$M_f l \nu_l$ is given by the product $\Gamma = |V_{Qq}|^2 \bar{\Gamma}$, where $V_{Qq}$ is the relevant quark-mixing factor, and the dynamical information is encoded in the quantity $\bar{\Gamma}$, which depends on the appropriate hadronic matrix element (squared) of the left-handed current (integrated over phase space with trivial leptonic and kinematical factors). Unfortunately, $\bar{\Gamma}$ is governed by non-perturbative hadron dynamics and, therefore, it is very difficult to give a theoretical prediction from first principles. One needs to rely in model-dependent estimates, usually combined with approximate symmetry properties which can (in some cases) fix the hadronic form factors in one point of the phase space, providing the needed normalization. To determine the CKM mixing factor, it is then crucial to have very good data on the distribution of the final decay products, in order to experimentally measure the shape of the hadronic form factors.

There is a dual motivation to perform an accurate analysis of semileptonic charm-decay modes at the $\tau\nu\ell$F:

- The determination of $V_{ub}$ (very poorly known at present) is one of the main purposes of the BF. Any model that makes predictions about $B$-decay matrix elements can be tested in $D$ decays, where non-perturbative effects are magnified. Once the non-perturbative corrections are understood in charm decays, they can be scaled to beauty decays with a considerable degree of confidence.

- Although constrained by SM unitarity to $0.1\%$ ($V_{cs}$) and $1\%$ ($V_{cd}$), the CKM charm matrix elements are poorly measured at present ($\pm 10-20\%$). A direct experimental determination with much better precision should be done.

At the $\tau\nu\ell$F the $D$ semileptonic branching ratios could be measured with an accuracy better than $1\%$ \cite{1, 2, 53}, whereas present errors are $9\%$ for $D^0 \to K^- e^+ \nu_e$ and $50\%$ for $D^0 \to \pi^- e^+ \nu_e$. By systematically measuring the decay rates and the corresponding invariant-mass distributions of the final hadrons, both in $D_s^0$ and $D_{s\bar{s}}$ decays, the $\tau\nu\ell$F could determine with high precision the shape and relative normalization of all relevant axial and vector form-factors, providing the necessary information to select among or improve the existing models \cite{55, 58} of $D$ and $B$ meson decays. A much precise and reliable extraction of CKM matrix elements would then become possible.

Theoretical uncertainties are largely avoided by taking ratios, such as $\Gamma(D \to \pi l \nu)/\Gamma(D \to K l \nu)$, where the form-factor uncertainty is reduced to the level of SU(3) breaking. In this way, $V_{cs}/V_{ts}$ could be determined to $1\%$, which is comparable to the present precision on $\theta_{C}\text{abibbo}$.

The $\tau\nu\ell$F could analyze in detail the semileptonic decays of $D^0$, $D^+$, $D_s^+$, $\Lambda_c$ and $\Xi_c$, providing an exhaustive data basis to confront with the predictions \cite{55, 58} of present theoretical technologies (heavy-quark expansions, QCD sum rules, lattice, ...). A detailed study of the inclusive semileptonic $c \to s$ and $c \to d$ decays would be of particular value \cite{55}.

### 4.2 Leptonic $D$ decays

Pure leptonic decays of $D^{\pm}_{(s)}$ mesons can be rigorously calculated in the SM. The predicted branching ratios are

$$
\text{Br}(D^{+}_{(s)} \to l^+ \nu_l) = \frac{\tau_{D^{+}_{(s)}} G_F^2}{8\pi f_{D^{+}_{(s)} m_{D^{+}_{(s)}}}} |V_{cd(s)}|^2 \times m_l^2 \left(1 - \frac{m_l^2}{m_{D^{+}_{(s)}}^2}\right)^2,
$$

where $f_{D^{+}_{(s)}}$ is the so-called weak decay constant, which measures the wave-function overlap of the $c$ and $d(s)$ quarks in the $D^{\pm}_{(s)}$ meson.

The meson decay constants are used to predict non-leptonic decays and second-order weak processes—including mixing and CP violation—, and are therefore important quantities to be experimentally determined. Precise measurements of these constants would also provide important tests of modern methods of calculation in non-perturbative QCD \cite{57, 58}, thereby providing a firmer ground for attempts to extrapolate to beauty systems (since $f_B$ is experimentally inaccessible) and allowing a better theoretical description of $D^0 - \bar{D}^0$ mixing.
In the SM, leptonic $D$ decays are helicity suppressed, and therefore the decay amplitudes are proportional to the final charged-lepton mass. Taking $f_D \sim 170$ MeV and $f_{D_s} \sim 200$ MeV, the largest pure leptonic branching ratios are estimated to be $\text{Br}(D_s^+ \rightarrow \tau^+ \nu_\tau) \approx 3\%$, $\text{Br}(D_s^+ \rightarrow \mu^+ \nu_\mu) \approx 3 \times 10^{-3}$, and $\text{Br}(D^+ \rightarrow \mu^+ \nu_\mu) \approx 3 \times 10^{-4}$. This should be compared with the upper bounds quoted by the particle data group: $\text{Br}(D_s^+ \rightarrow \mu^+ \nu_\mu) < 3\%$, and $\text{Br}(D^+ \rightarrow \mu^+ \nu_\mu) < 7.2 \times 10^{-4}$. (preliminary evidence of leptonic $D_s$ decays has been reported recently by several experiments).

The theoretical uncertainties associated with the meson decay constants are much smaller for the ratio $f_D/f_{D_s}$, which is only sensitive to SU(3) breaking. A precise measurement of the ratio $\text{Br}(D^+ \rightarrow \mu^+ \nu_\mu)/\text{Br}(D_s^+ \rightarrow \mu^+ \nu_\mu)$ would allow to make an independent determination of $|V_{cd}|/|V_{cs}|$.

Furthermore, the relative value of the $D_s^\pm$ leptonic branching ratios is precisely predicted in the SM:

$$\frac{\text{Br}(D_s^+ \rightarrow \mu^+ \nu_\mu)}{\text{Br}(D_s^+ \rightarrow \tau^+ \nu_\tau)} = \frac{m_\mu^2}{m_\tau^2} \left[ 1 - \left( \frac{m_\mu^2}{m_D^2} \right)^2 \right]^2 = 0.102 \pm 0.001. \quad (12)$$

An accurate measurement of the pure leptonic branching ratios would then provide a novel test of $\mu - \tau$ universality, involving the process:

$$\begin{cases} \text{2nd family quarks} & \text{W}, \chi \rightarrow \text{2nd family leptons} \\
\text{3rd family leptons} & \text{vs.} \end{cases}$$

The ratio (12) is sensitive to new physics ($X$) that does not have the usual helicity suppression of pseudoscalar-meson decay or that has mass-dependent couplings. The absence of $e\nu$ final states would provide a further test of the SM prediction.

Precise measurements of pure leptonic $D$ decays require single-tagged event samples and are therefore uniquely accessible at the $\tau cF$. Tagged event samples are necessary both to suppress backgrounds and to provide a constrained fit for the mass of the missing $\nu$'s. A detailed Monte Carlo study indicates that the signals should be clearly distinguished from background processes. With 1-year’s data, each of the the branching ratios $\text{Br}(D_s^+ \rightarrow \tau^+ \nu_\tau)$, $\text{Br}(D_s^+ \rightarrow \mu^+ \nu_\mu)$ and $\text{Br}(D^+ \rightarrow \mu^+ \nu_\mu)$ could be measured to about 2% accuracy.

### 4.3 Rare decays

In the SM with massless $\nu$'s, lepton-flavour-violating decays (such as $D^0 \rightarrow e^+\mu^-$, $X e^+\mu^-$) are completely forbidden. Flavour-changing neutral-current decays (such as $D^0 \rightarrow l^+l^-$, $X l^+l^-$, $X \nu\bar{\nu}$ and $X\gamma$) may occur in the SM but they are highly suppressed by the GIM mechanism. Rare $D$ decays are then very sensitive to new physics, which may come from contact interactions, leptoquarks, horizontal gauge bosons, substructure, new scalars, technicolor, etc. [4]. Searches for rare decays of $D$ mesons are complementary to those of $K$ or $B$ mesons because the new physics may be flavour-dependent, i.e. different for up-like and down-like quarks. Moreover, the $\tau cF$ is probably the only machine that could measure some radiative decays, such as $D^0 \rightarrow \bar{K}^* 0 \gamma$, at the low levels expected in the SM.

Tagging and precise beam-constrained mass measurements suppress backgrounds to these processes. The $\tau cF$ would be sensitive to branching ratios of $\mathcal{O}(10^{-8})$ [5,6,7]. Present limits are in the range of $10^{-3}$ to $10^{-5}$. Thus an improvement of more than 3 orders of magnitude is expected.

### 4.4 $D^0 - \bar{D}^0$ mixing

Meson mixing has only been observed so far in the $K^0 - \bar{K}^0$ and $B^0 - \bar{B}^0$ systems, where the second-order $\Delta F = 2$ ($F = S, B$) transition is associated with a quark of charge $-1/3$ (s, b). The study of mixing in the $D^0 - \bar{D}^0$ system, which contains a quark of charge $+2/3$, is then a fundamental experiment for the understanding of the flavour structure of the weak interaction. The rate for $D^0 - \bar{D}^0$ oscillations is expected to be quite small in the SM [33],

$$r_D \equiv \frac{\text{Br}(D^0 \rightarrow \bar{D}^0 \rightarrow \bar{f})}{\text{Br}(D^0 \rightarrow f)} \sim 10^{-5} - 10^{-4}. \quad (13)$$
The reasons for such a suppression (GIM mechanism) are very specific to the structure of the SM and so many of its extensions (SUSY models, vector-like fermions, E6-like models, etc.) lead to enhanced transition amplitudes. $D^0 - \bar{D}^0$ mixing is an ideal place for non-standard flavour-changing neutral-currents to show up.

Signatures of mixing are like-sign dileptons from dual semileptonic decays ($D^0\bar{D}^0 \rightarrow l^\pm l^\pm X$) or dual identical hadronic decays, such as $D^0\bar{D}^0 \rightarrow (K^\mp \pi^\mp)(K^\pm \pi^\pm)$. At the $\tau\text{cF}$, the latter can be separated from doubly Cabibbo-suppressed decays since quantum statistics yield different correlations in the $D$ decays from $D^0\bar{D}^0$, $D^0\bar{D}^0\gamma$, and $D^0\bar{D}^0\pi^0\gamma$ [66]. When the $D^0$ mesons are in a relative P-wave, Bose statistics forbids them to decay into the same final state without mixing. In an S-wave, however, the same final state can be reached through both, mixing and doubly Cabibbo-suppressed decay amplitudes. By selectively running at different c.m. energies, preparing well defined initial state conditions, the mixing signature can be isolated from doubly-Cabibbo suppressed decays or from new physics involving a violation of the $\Delta C = -\Delta Q_l$ ($Q_l$ denotes leptonic charge) selection rule. Moreover, in the non-leptonic decay modes, the interference with the doubly-Cabibbo suppressed decay amplitude can be used to separate the mixing originating in the mass ($x \equiv \Delta M_{D}/\Gamma_{D}$) and decay ($y \equiv \Delta \Gamma_{D}/2\Gamma_{D}$) matrices ($r_{D} = (x^2 + y^2)/2$) [66].

One can also search for mixing in final states that do not involve only neutral $D$’s. For example one can look [12,13] at $D^+D^-$ final states, with a decay chain: $D^+ \rightarrow K^-\pi^+\pi^+$, $D^- \rightarrow \pi^-D^0 \rightarrow \pi^- + l^\pm X$. These decays have a very nice clean signal because there is only one missing neutrino.

The $\tau\text{cF}$ could observe mixing at the limit $r_{D} \approx 2 \times 10^{-5}$ with one year’s data [12,13,15], to be compared with the present 90% C.L. limit, $r_{D} < 3.7 \times 10^{-3}$. Thus one should be able to bring the limit down to where one can expect to see an effect even in the SM.

4.5 CP violation

In the three-generation SM, CP violation originates from the single phase naturally occurring in the CKM quark-mixing matrix. The present experimental observations are in agreement with the SM expectations; nevertheless, the correctness of the CKM mechanism is far from being proved. Like fermion masses and quark-mixing angles, the origin of the CKM phase lies in the more obscure part of the SM Lagrangian: the scalar sector. Obviously, CP violation could well be a sensitive probe for new physics beyond the SM.

A rate difference between $D^0\bar{D}^0 \rightarrow (l^+X)(f)$ and $\bar{D}^0D^0 \rightarrow (l^-X)(f)$, with $f$ a CP eigenstate (e.g. $K^+K^-$) would provide an unambiguous signal of CP violation, either direct or involving $D^0\bar{D}^0$ mixing. Again, one can exploit quantum statistics [3] to disentangle both effects. Comparing possible CP asymmetries that can emerge in the reactions $e^+e^- \rightarrow D^0\bar{D}^0$, $e^+e^- \rightarrow D^0\bar{D}^0\gamma$ and $e^+e^- \rightarrow D^0\bar{D}^0\gamma$ and $e^+e^- \rightarrow D^0\bar{D}^0\gamma$ and $e^+e^- \rightarrow D^0\bar{D}^0\pi^0$ and h.c. $\rightarrow D^0\bar{D}^0\gamma$ and $e^+e^- \rightarrow D^0\bar{D}^0\pi^0$ and h.c. $\rightarrow D^0\bar{D}^0\pi^0$, it is possible to analyze the origin of the signal. In the absence of direct CP-violation, only the second process, where the $D^0\bar{D}^0$ system is produced in a $C = +$ configuration, could generate a rate asymmetry. Any asymmetry appearing in the other two processes should therefore be due either to direct CP-violation in the decay amplitude or to detector bias. A CP asymmetry of about 1% could be measured [3,8] in a one-year sample of $D^0\bar{D}^0\gamma$ events at $E_{cm} = 4.14$ GeV.

CP violation can also be searched for directly in the rate in the process $\psi''(3.77) \rightarrow D^0\bar{D}^0 \rightarrow f(D^0)f(\bar{D}^0)$, with $f$’s of the same CP parity, such as $f = K^+K^-$. A single event of this type would establish CP violation, since the initial state is CP-even whereas the final state (P-wave) is CP-odd. Although this method is not competitive with the asymmetry measurement for determining the magnitude of the CP-violating amplitude (the rate is proportional to the square of the amplitude, while asymmetries have a linear dependence), it is important in that it is sensitive both to the magnitude and to the quantum mechanical phase of the decay amplitudes [66]. One expects to achieve $10^{-2}$ to $10^{-3}$ sensitivity at the $\tau\text{cF}$, if adequate background rejection is attained [17,8].

In the SM, indirect CP violation from the $D^0 - \bar{D}^0$ mixing is expected to be very small. Much better looks the possibility of detecting direct CP-violating signals. Recent calculations [7] for charged $D$ mesons indicate CP asymmetries of the order of $10^{-3}$ or larger for several final states, and other estimates [66] suggest that direct CP violation from neutral $D$ mesons should be of a similar size. The $D^+$ decay modes $D^+ \rightarrow K^+\bar{K}^0 \rightarrow K^+K^-\pi^+$ and $D^+ \rightarrow \pi^+\eta \rightarrow \pi^+\gamma\gamma$, which are easy to reconstruct and have small backgrounds, look quite promising; a sensitivity of about $2 \times 10^{-3}$ for the corresponding CP
asymmetries, i.e. at the level of the SM prediction, could be achieved in a one-year data sample. Assuming that the indirect CP-violation amplitude is small, a similar sensitivity could be achieved in several \(D^0/\bar{D}^0\) decay modes like \(K^+K^-, \pi^+\pi^-, 2\pi^+2\pi^-, \ldots\).

The \(\tau cF\) would provide an important first window on CP violation in the up-quark sector. This opens up the exciting possibility of exploring the mechanism of CP violation in a system that is complementary to the \(B\) or \(K\) systems and, moreover, sensitive to sources beyond the SM. The measurement of direct CP violation at the level currently predicted by the SM is clearly feasible at the \(\tau cF\), although it will take several years of running to give definite results.

4.6 Non-leptonic decays

Non-leptonic charm decays provide a unique opportunity to probe and understand the strong interactions in the interface between the short-distance and long-distance regime. Non-perturbative effects are much larger in \(c\) decays than in \(b\) decays; but they are not overwhelming as in \(s\) decays. Thus, QCD corrections which need to be understood with high precision in the beauty system, are quantitatively enhanced in charm decays, allowing for a very detailed analysis to be made. Charm decays serve as Nature’s microscope magnifying the non-perturbative corrections affecting beauty decays.

Modern theoretical technologies (heavy-quark expansions, lattice, QCD sum rules, \(1/N_c\) expansion, \ldots) are reaching a level where a treatment of charm (and beauty) decays genuinely rooted on QCD begins to be possible. The rich variety of available charm decay modes (meson and baryon decays; Cabibbo allowed, Cabibbo suppressed, doubly Cabibbo suppressed) offers an ideal laboratory to exhaustively test the different theoretical methods, making possible a reliable extrapolation to beauty decays.

The present experimental precision on charm decay properties is certainly not satisfactory. The largest part of \(D^0\) and \(D^+\) decay modes have an accuracy worse than 20\%, while for the \(D^+\) even the absolute scale of its decay branching fractions is not known in a reliable way. Very few of the charm-baryon decay modes have been measured so far. In many cases, a badly measured charm-decay branching ratio is the bottleneck to precise \(b\) measurements at the BF or at LEP. Fragmentation function studies would greatly benefit from a much better experimental knowledge of charm decays. An accurate data basis on charm branching ratios would also allow us to refine the predictions on CP-violating asymmetries in charm decays.

The \(\tau cF\) is ideally suited to perform a comprehensive analysis of charm decays, including \(D^0\), \(D^+\), \(D^+_s\), \(\Lambda_c\), \(\Xi_c^+\), \(\Xi_c^0\) and \(\Omega_c\) (c.m. energies of about 5.6 GeV have to be reached to look for the heavier baryons). A \(\tau cF\) provides the only way –through the unique capability to single-tag each of the various charm hadrons– to improve the precision of the absolute branching ratios for \(D\) mesons to the per cent level, and to establish absolute branching ratios at the 5\% level for \(D_s\), \(\Lambda_c\), \(\Xi_c\), etc. The high-luminosity of the \(\tau cF\) would turn out to be very useful, since separate runs at different energy settings are clearly needed. Charm \(P\) states could also be easily studied, providing for the first time an absolute measurement of their strong and electromagnetic decay branching ratios.

5 CHARMONIUM PHYSICS AND LIGHT-HADRON DYNAMICS

5.1 Charmonium and gluonium spectroscopies

The charmonium system is an important source of information for QCD studies and hadron spectroscopy. The \(\tau cF\) would provide a huge increase of the existing world data sample and therefore would have a major impact on this area of physics. In one year, the \(\tau cF\) could produce \(1.7 \times 10^{10}\) \(J/\psi\) events, i.e. three orders of magnitude more than the presently accumulated statistics. The radiative decay \(J/\psi \rightarrow \eta_c(1S)\gamma\) would then generate a sample of \(2 \times 10^8\) \(\eta_c(1S)'s\). Running at 3.686 GeV, \(4 \times 10^9\) \(\psi'(3.69)'s\) would be produced in one year, giving rise to the secondary production of \(10^9\) tagged \(J/\psi\)’s (through \(\psi' \rightarrow J/\psi\pi^+\pi^-\)), \(3 \times 10^8\) events of each type \((J = 0, 1, 2)\) of \(\chi_{cJ}\) (via \(\psi' \rightarrow \gamma\chi_{cJ}\) decays), and \(10^7\) \(\eta_c(1S)'s\) and \(\eta_c(2S)'s\) (through the radiative decays \(\psi' \rightarrow \eta_c\gamma\)). Thus, the \(\tau cF\) can in fact be considered as a charmonium factory. Note that these high rates imply a huge number of secondary light mesons; for instance, the decays \(J/\psi \rightarrow \eta_\gamma\), \(\eta_\gamma\gamma\) would give rise to more than \(10^7\) tagged \(\eta\) and \(\eta_\gamma\) mesons, largely improving the existing data samples.
The $c\bar{c}$ wave function could be studied via $J/\psi \to 3\gamma$ and $\eta_c \to 2\gamma$, which constitute direct tests of the charmonium models. Presently open questions on the charmonium electromagnetic couplings could be answered through accurate measurements at the $\tau cF$ [79, 76]. Especially interesting are the M1 decays $J/\psi \to \gamma\eta_c$ and $\psi'\to\eta_c,\gamma\eta_c$, which could discriminate between a wide range of theoretical predictions [74], and the E1 transition $\chi_{c2} \to J/\psi\gamma$, which can be used to study a possible anomalous magnetic moment of the $c$ quark, by measuring the photon angular distribution [74, 77]. The $\tau cF$ detector should be ideally suited for these measurements because of its extremely low threshold ($E_{\min}^\gamma = 10$ MeV) and its $\geq 99\%$ hermeticity [75]. Improved measurements on radiative and hadronic charmonium transitions would allow to test our theoretical understanding of quarkonium dynamics [74]. The huge amount of $\eta_c$ and $\chi$ events could be used to study many hadronic decays of these states [78].

The $\tau cF$ could also complete the charmonium spectroscopy with the confirmation of the $1P_1(3526)$ and $\eta_c'(3590)$ states [75], and the discovery of the missing $^3D_2$ and $^1D_2$ states. Their quantum numbers can be accessed at the $\tau cF$ through the decays: $\psi^* \to \eta^1P_1 (\sqrt{s} > 4$ GeV), $\psi' \to \gamma\eta_c$, $\psi^* \to \eta^3D_2 (\sqrt{s} > 4.5$ GeV) and $\psi^* \to \eta^1D_2 (\sqrt{s} = 4.03$ GeV) [72].

Excited $\psi^*$ states above the $D\bar{D}$ threshold are very badly known at present. It would be important to measure their decay branching fractions to hadronic final states. Measurements of the relative fractions of $D, D^*$ and $D^{**}$ in their decays would provide important information and tests of Heavy Quark Effective Theory, and could reveal the internal structure of these states [72, 74].

The $\tau cF$ would make a systematic search for glueonia and hybrids in a gluon-rich environment: $J/\psi \to \gamma gg$, $ggg; \eta_c \to gg$. For example, the decay $J/\psi \to \gamma gg \to \gamma X$ involves a pure two-gluon intermediate state with a mass $m_{gg} \leq 3.1$ GeV, i.e. in the expected mass region of the glueonium spectrum. Furthermore, the nature of the state $X$ can be tested experimentally by comparing $J/\psi \to \gamma X, \omega X$ and $\phi X$ [80]. Resonances that appear in radiative decays but are suppressed with $\omega$ and $\phi$ are likely to be glueonia. The comparison with the two-photon production process $J/\psi \gamma \gamma \to X$ can further help to discriminate between $gg$ states and glueonium candidates [79, 81]: since gluons do not carry electric charge, glueballs should not couple to $\gamma\gamma$. In addition, $J/\psi \to \gamma X \to \gamma(\gamma\rho : \gamma\omega : \gamma\phi)$ can be used to filter the flavour content of all $C = +$ states; moreover, for $J_X \geq 2$ the relative helicity amplitudes for $X \to \gamma V$ may also be measured and give information on the internal structure of $X$ [79]. This requires the $\tau cF$ statistics since only the channel $J/\psi \gamma \gamma \rho$ has been measurable so far.

At the $\psi'$ peak, the huge number of produced $\chi_{cJ}$'s can be used to constrain the partial wave analysis of hadronic decays, by fixing the spin $J$ of the initial $\chi_c$. For instance, $\chi_{c1} \to \pi H$ is sensitive to the hybrid exotic sector $H (J^{PC} = 1^{--})$, while $\chi_{c0} \to f_0(975)X$ provides a gateway to $0^{++}$ hadrons [72]. At present there is basically no data on the $\chi_{cJ}$ states. With the statistics of the $\tau cF$ the physics output from $\chi_{cJ}$ decays could exceed that already known from the $J/\psi$.

Charm hybrids $H_c$ are expected to occur around the $DD^*$ threshold. These hybrids include vector states which can be formed directly in $e^+e^-$ annihilation. Moreover, theoretical considerations suggest that charm is the optimal flavour to unambiguously identify vector hybrid states: they are light enough to be produced in $e^+e^-$ annihilation with leptonic widths of $O(0.1)$ keV, and heavy enough that the conventional quarkonium states are well understood so that extra states can be readily identified [74]. A fine grained energy scan to search for these states could be carried out at the $\tau cF$ within two weeks; this involves measuring the hadronic cross-section above charm threshold in 1 MeV steps to an accuracy of 2% [74]. The implementation of a monochromator, enabling a very fine scan with higher statistics would be very desirable to clarify the nature of detailed structures. Note, that a precise measurement of the hadronic cross-section in the $\tau cF$ energy range would also provide important information for inclusive tests of QCD; moreover, this information is needed to get accurate predictions on electroweak radiative corrections (e.g. $g - 2$ or LEP physics). The superb hermeticity and high efficiency for hadron detection of the $\tau cF$ detector are ideal for this purpose [79].

Triggering on $J/\psi$'s at any operating energy of the $\tau cF$ may reveal the existence of other exotic states that are not directly produced in $e^+e^-$ annihilation [74]. For instance, it may be possible to detect

* It is worth mentioning that the presence in the $\tau cF$ detector of an electromagnetic calorimeter at small angles allows the detection of single and double tag events in two-photon physics. This is a unique possibility among the existing machines [81].
\( \psi_H \) hybrids through \( e^+e^- \rightarrow \eta\psi_H \rightarrow \eta(\eta J/\psi) \).

The existence of glueballs, hybrids and other exotics, is a natural consequence of QCD. Unfortunately these states have proved to be very elusive and none of them has been experimentally established so far. The main difficulty comes from the absence of clear-cut signatures to distinguish them from the usual \( q\bar{q} \) states. The basic criterion is then the observation of an extra state, which has no room in a \( q\bar{q} \) nonet. One needs detailed knowledge about their production mechanisms and decay patterns, besides measuring their quantum numbers. With its very high statistics and low backgrounds, the \( \tau \)C is certainly the best machine to perform such an exhaustive analysis. The unambiguous identification of a glueball or an hybrid state would be a fundamental discovery.

5.2 Weak decays and axions

The very high statistics and the OZI suppression of the \( J/\psi \) decays, causing a narrow width, may provide the first opportunity to measure weak decays of a vector meson \([73, 82]\), such as \( (J/\psi) \rightarrow \eta \). A glueball or an hybrid state would be a fundamental discovery.

\[ \left( l = e, \mu \right) \]

\[ J/\psi \rightarrow D_s \nu \bar{\nu} \quad [\text{Br} \simeq 10^{-8}], \]

or the C-violating decay \( J/\psi \rightarrow \phi \phi \) [\( \text{Br} \simeq 10^{-8} \)].

The \( J/\psi \) can be tagged via \( \psi' \rightarrow \pi^+\pi^- J/\psi \) to allow searches for rare processes \([73]\) such as the neutral-current decay \( J/\psi \rightarrow \nu \bar{\nu} \), which in the SM is expected at a very low branching ratio of \( N_{\nu} \times 10^{-8} \); if any signal is seen it would be a clear indication of new physics. The limiting background would be \( J/\psi \rightarrow \eta \), which has a branching ratio of 0.18\% \([73]\).

Axions or other evasive neutrals can be produced in \( J/\psi \rightarrow \gamma X \). The signature for such a decay is a single photon in the final state. The limiting factor here will be backgrounds from events with 3 photons in which only one photon is detected. Assuming the photon detection efficiency is 99\%, the expected sensitivity is \( \text{Br}(J/\psi \rightarrow \gamma X) \approx 10^{-8} \).

5.3 CP violation

At the \( J/\psi \) peak, a huge number of hyperon pairs would be produced through the decay \( J/\psi \rightarrow Y \bar{Y} \) \((Y = \Lambda, \Xi)\). The \( 1.7 \times 10^{10} J/\psi \)'s accumulated in one-year’s data, would give rise to \( 2.3 \times 10^7 \Lambda \bar{\Lambda} \) and \( 3.1 \times 10^7 \Xi \bar{\Xi} \) pairs. These numbers could be substantially increased with the implementation of a monochromator (a narrower beam spread implies a much larger visible \( J/\psi \) production cross-section at the peak).

With 100 keV monochromator optics, the \( \tau \)C could produce \( 8 \times 10^{10} J/\psi \) events in one year and, therefore, \( 1.1 \times 10^8 \Lambda \bar{\Lambda} \) and \( 1.4 \times 10^8 \Xi \bar{\Xi} \) pairs would be generated. A high-precision study of hyperon-decay properties would obviously become possible. Moreover, this hyperon factory could be used to search for signals of direct CP violation \([83]\).

A complete description of the decay \( Y \rightarrow B \pi \) involves, in addition to the rate \( \Gamma_Y \), two decay parameters usually denoted \( \alpha_Y \) and \( \beta_Y \). \( \alpha_Y \) regulates the angular distribution of the final baryon in the decay of a polarized hyperon (in the \( Y \) rest frame), while \( \beta_Y \) characterizes the \( B \) polarization in the direction normal to the plane defined by its momentum and the spin of the decaying hyperon. CP invariance requires \( \Gamma_{\bar{Y}} = \Gamma_Y \), \( \alpha_{\bar{Y}} = -\alpha_Y \) and \( \beta_{\bar{Y}} = -\beta_Y \). Thus, one can consider the following CP-violating asymmetries:

\[ \Delta_Y = \frac{\Gamma_Y - \Gamma_{\bar{Y}}}{\Gamma_Y + \Gamma_{\bar{Y}}}, \quad A_Y = \frac{\alpha_Y + \alpha_{\bar{Y}}}{\alpha_Y - \alpha_{\bar{Y}}}, \quad B'_Y = \frac{\beta_Y + \beta_{\bar{Y}}}{\beta_Y - \beta_{\bar{Y}}} \]  \hspace{1cm} (14)

The SM predictions for these asymmetries are quite uncertain, due to the important role of non-perturbative QCD effects in the decay amplitudes. In a model-independent fashion, the relative size of the different signals is expected to be \([84]\):

\[ B'_Y \approx 10 A_Y \approx 100 \Delta_Y. \]  \hspace{1cm} (15)

A recent update of several model-dependent calculations \([84]\) quotes values of \( A_Y \) between \( 10^{-5} \) and \( 10^{-4} \). To get better theoretical estimates, it is necessary to experimentally improve the knowledge of the (CP-conserving) decay amplitudes and the final strong-interaction phases.

Although \( \Delta_Y \) is the easiest to measure, it has the lowest sensitivity; on the other side, a determination of \( B'_Y \) is difficult since it requires information on the spins of both baryons. Therefore, the
experiments have focused mainly in measuring $A_Y$. The best results have been obtained by PS185 (LEAR) with $1.5 \times 10^4 \Lambda \rightarrow p\pi^-$ events, quoting $A_\Lambda = -0.024 \pm 0.057$ [85].

In $e^+e^- \rightarrow J/\psi \rightarrow Y\bar{Y}$, the hyperons are produced unpolarized (assuming parity conservation in the $Y\bar{Y}$ production); nevertheless, their spins are strongly correlated. The information on the spin-dependent part of the production amplitude can then be reconstructed from the correlated distribution of their decay products. Analyzing the process

$$J/\psi \rightarrow \Lambda \bar{\Lambda} \rightarrow (p\pi^-) (\bar{p}\pi^+), \quad (16)$$

one can determine the value of $\alpha_\Lambda\alpha_{\bar{\Lambda}}$ (the spin correlations obviously involve products of both spins). Using the value of $\alpha_\Lambda$ measured somewhere else [3] the asymmetry $A_\Lambda$ is then obtained. A direct separate measurement of $\alpha_\Lambda$ and $\alpha_{\bar{\Lambda}}$ would require polarized $\Lambda$'s; this could be possible with polarized $e^+e^-$ beams.

The decay chain

$$J/\psi \rightarrow \Xi^- \Xi^+ \rightarrow (\Lambda\pi^-) (\bar{\Lambda}\pi^+) \rightarrow (p\pi^-\pi^-) (\bar{p}\pi^+\pi^+), \quad (17)$$

allows to extract a much richer information. The $\Lambda\bar{\Lambda}$ correlation measures $\alpha_\Xi\alpha_{\bar{\Xi}}$, as before, but now $\Lambda$'s are polarized and this polarization is analyzed by the final proton distributions. Making a global analysis of all correlated distributions the separate values of $\alpha_\Xi, \alpha_{\bar{\Xi}}, \beta_\Xi, \beta_{\bar{\Xi}}, \alpha_\Lambda$ and $\alpha_{\bar{\Lambda}}$ can be measured. Therefore, one obtains a determination of the asymmetries $A_\Xi, B'_\Xi$ and $A_\Lambda$. The access to $B'_\Xi$ is a welcome feature, since this asymmetry has the highest sensitivity.

Table 3: Sensitivities [83] to the different CP-odd $J/\psi \rightarrow Y\bar{Y}$ observables at the $\tau cF$, with $8 \times 10^{10} J/\psi$ events (1 year-data with monochromator). Estimates for a possible 40% beam polarization are also given.

| Decay Mode | Beam Polarization | Measured Observable | $\tau cF$ Sensitivity |
|------------|-------------------|---------------------|-----------------------|
| $\Lambda\Lambda$ | No | $A\Lambda$ | $5 \times 10^{-3}$ |
| $\Lambda\Lambda$ | Yes | $A\Lambda$ | $\leq 3 \times 10^{-3}$ |
| $\Xi^-\Xi^+$ | No | $A\Lambda, A_\Xi, B'_\Xi$ | $10^{-3}$, $10^{-3}$, $5 \times 10^{-3}$ |
| $\Xi^-\Xi^+$ | Yes | $A\Lambda, A_\Xi, B'_\Xi$ | $\leq 10^{-3}$, $\leq 10^{-3}$, $\leq 5 \times 10^{-3}$ |

Table 3 [83] shows the expected sensitivity at the $\tau cF$, with $8 \times 10^{10} J/\psi$ events (1 year-data with monochromator). Although still far away from the expected SM signal, the $A_Y$ measurement would represent an improvement better than one order of magnitude over present data. More significant is the estimated accuracy attainable for the asymmetry $B'_\Xi$, reaching sensitivities that are within the values expected in the SM. The big uncertainties of the theoretical predictions would make difficult to extract useful information on the CKM phase from this measurement. Nevertheless, the experimental observation of a non-zero CP-violating asymmetry would be a major milestone in our understanding of CP violation, as it would clearly establish the existence of direct CP violation in the decay amplitudes.

6 SUMMARY

The flavour structure of the SM is one of the main pending questions in our understanding of weak interactions. Although we do not know the reason of the observed family replication, we have learned experimentally that the number of SM fermion generations is just three (and no more). Therefore, we
must study as precisely as possible the few existing flavours, to get some hints on the dynamics responsible for their observed structure. The construction of high-precision flavour factories is clearly needed.

Without any doubt, the τcF is the best available tool to explore the τ and ντ leptons and the charm quark. This facility combines the three ingredients required for making an accurate and exhaustive investigation of these particles: high statistics, low backgrounds and good control of systematic errors. The threshold region provides a series of unique features (low and measurable backgrounds free from heavy flavour contaminations, monochromatic particles from two-body decays, small radiative corrections, single tagging, high-rate calibration sources, . . . ) that create an ideal experimental environment for this physics.

As shown in the previous sections, the τcF would cover an exceptionally broad programme of solid physics. The SM of electroweak interactions would be accurately proved in τ, charm and charmonium decays (universality tests, Lorentz structure of weak interactions, neutrino masses, flavour mixing, CP violation, D0–D̄0 oscillations, lepton-flavour violation, flavour-changing neutral currents, rare decays, . . . ). Moreover, the τcF would constitute a superb laboratory to test QCD at the interface of perturbative and non-perturbative dynamics (the τ is the only lepton with hadronic decays, important interplay of strong interactions in charm decays, light-hadron and gluonium spectroscopy). In fact, as emphasized by several speakers at this workshop, the τcF is optimally suited to be considered as “the QCD machine for the 90’s”.

One can identify a series of different energies that are optimized for specific physics measurements (nevertheless, different studies can share the same energy setting; for instance, τ analyses below the charm threshold allow to measure the backgrounds for charm measurements). The high-luminosity of the τcF is a crucial requirement to efficiently operate the machine at different points. Of course, for specific worth-while investigations (or once an indication for a major discovery surfaces), the high luminosity can be concentrated at the appropriate energy. In any case, it is clear that the τcF is a facility for performing a long-term research programme.

In conclusion, the τcF could address fundamental aspects of the SM that are complementary to those addressed by higher-energy machines. A comprehensive set of precision measurements for τ, charm and light-hadron spectroscopy would be obtained, proving the SM to a much deeper level of sensitivity and exploring the frontier of its possible extensions.

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