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PHYSICS PROSPECTS AT THE TAU-CHARM FACTORY

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Abstract

The τ-charm Factory (τcF) is a high-luminosity e^+e^- collider operating near the thresholds for τ and charm production. This energy region provides a unique experimental environment where the τ lepton and charm hadrons can be studied with unrivalled precision. The physics interest in the τcF has recently been extended by new theoretical developments on CP violation in the lepton and charm sectors. The τcF is an essential component of the next-generation factory machines dedicated to understanding the flavour structure of the standard model, but has yet to be approved. We outline the physics potential of the τ-charm Factory and the status of the design.

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1 Introduction

Experiments explore two complementary frontiers of particle physics: one at high-energy and the other at high-precision and rarity. Traditionally, the main—and almost exclusive—line of new accelerators has been at the high-energy frontier in the search for new particles and interactions. The present such accelerators are HERA, LEP, SLC and the Tevatron collider, and the next-generation machines will be the LHC and eventually a linear collider.

In the past the high-precision frontier has been explored essentially as a spin-off activity at accelerators that were built primarily for the high-energy frontier. A good example is LEP, which was built to study the electroweak sector (Z^0 and $W^\pm$ production) and to search for new massive particles, but where a large experimental effort has subsequently been devoted to precision studies of b quarks and τ leptons. Experiments at LEP and elsewhere have made remarkable progress over the last few years in studying the quarks and leptons, but we are now reaching the experimental limits of these machines.

Further progress at the high precision frontier will in future require *dedicated* machines; parasitic studies will no longer be adequate. This has led to the design of a new generation of intense low-energy accelerators known as particle factories. The primary requirements of a particle factory are to produce specific particles in copious quantities and with low backgrounds. High-luminosity e^+e^- colliders are well-suited to this task. The energies of interest for e^+e^- collider particle factories are summarised in Table 1, and the production cross sections and typical event rates are indicated in Fig. 1. The optimum machine energy to study a particular particle generally corresponds to the region near its pair-production threshold, which can provide the highest cross-sections, lowest backgrounds and other favourable experimental conditions. Other important energies correspond to s-channel production of the narrow vector resonances ($\phi, J/\psi, \psi', \Upsilon, \Upsilon', Z^0 \ldots$) which, in addition to being interesting particles in their own right, constitute clean, high-rate secondary sources of lighter particles.

The basic physics goal of the particle factories is to understand the flavour structure of the standard model: the replication of quark/lepton families—the origin of which is completely obscure—and the associated questions of the origins of the CKM matrix and CP violation for quarks, and of their apparent absence for leptons. Detailed studies of the heavy flavour states—the τ lepton, charm hadrons and beauty hadrons—are of particular interest. These may hold the highest promise of shedding light on the origin of flavour structure since i) heavy-flavoured particles are likely to possess the highest sensitivity to

Table 1: Summary of the energies of interest for e^+e^- collider particle factories.

E_{cm} (GeV)	Particle resonance	Quark/lepton threshold	Accelerator
1	ϕ	$s\bar{s}$	ϕ Factory
3-5.6	J/ψ, ψ'...	$\tau\bar{\tau}$, $c\bar{c}$	τc Factory
9-11	$\Upsilon(1S)$, $\Upsilon(2S)$...	$b\bar{b}$	B Factory
91	Z^0	–	Z Factory
350	–	$t\bar{t}$	T Factory

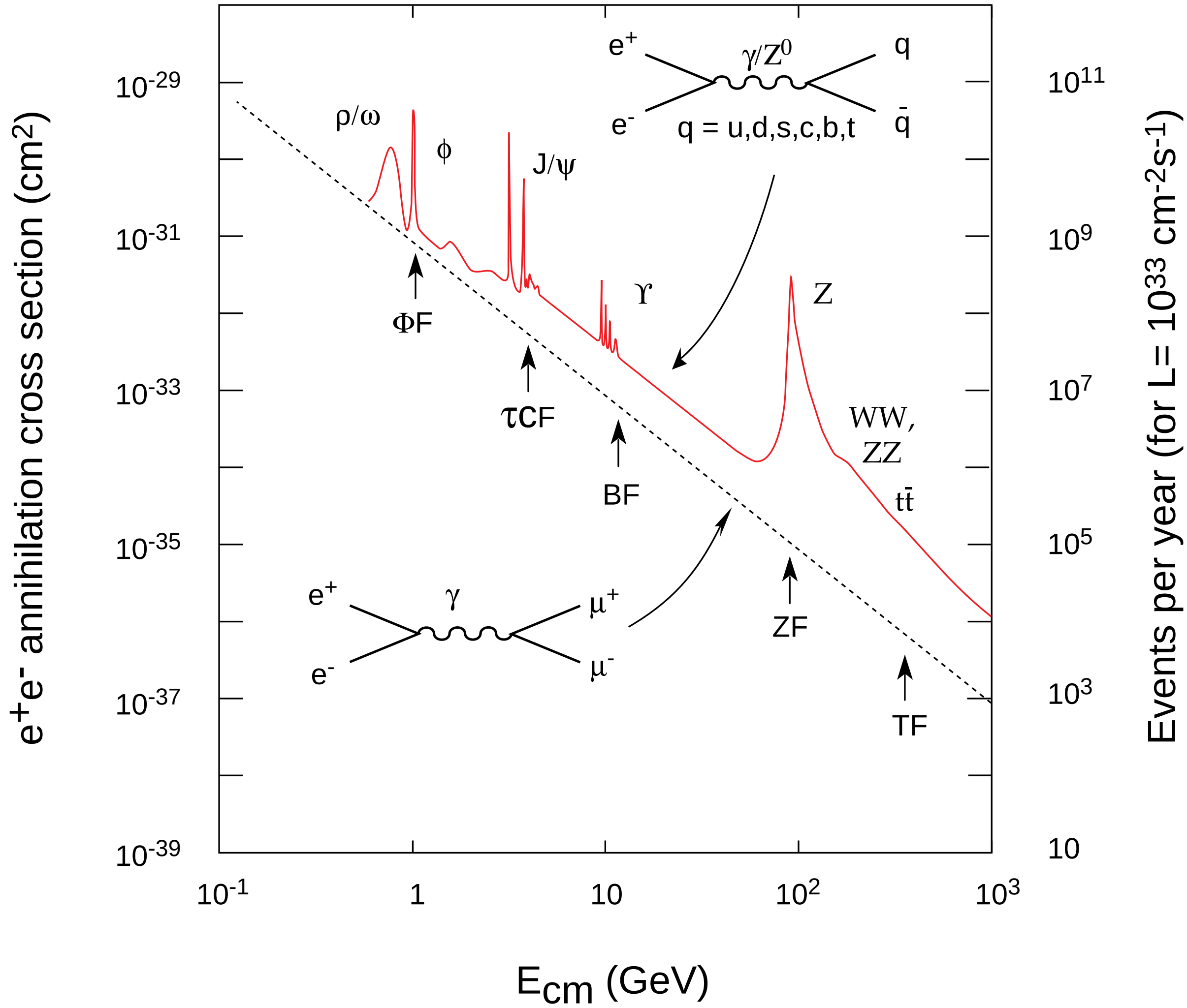

Figure 1: The e^+e^- annihilation cross-section in the energy range 1 GeV $< E_{\rm cm} <$ 1 TeV. The energies of interest for particle factories are indicated, together with the typical event rates.

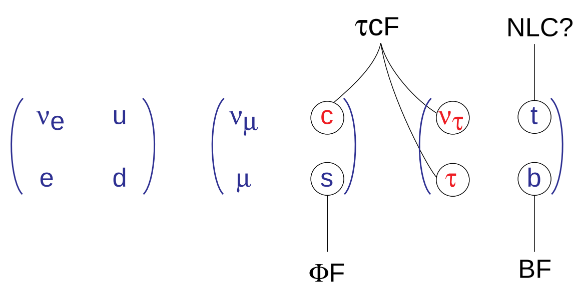

Figure 2: The three lepton/quark families and the next-generation particle factories dedicated to their study.

new physics at high mass scales, ii) they can be treated with more reliable theoretical tools, and iii) despite recent experimental progress, their decays have so far only been superficially explored in comparison with the lighter-flavoured particles.

The essential experimental tools for exploring the heavy-flavoured particles are a beauty Factory (BF) and a τ-charm Factory (τcF) (Fig. 2). Whereas the beauty Factory is optimised for beauty particles and CP violation in B decays, the τ-charm Factory is optimised for the τ lepton, charm particles, and the spectroscopy of charmonium states and light-flavoured hadrons. At the τcF, CP violation will be explored in the charm (D^0, $D^{\pm}$ and $D_s^{\pm}$ mesons), strange (Λ and Ξ hyperons) and lepton (τ) sectors. Although a beauty Factory also generates large τ and charm samples, with statistics comparable to those of a τ-charm Factory (Table 2), most of these measurements are likely in future to be limited by systematic errors and backgrounds. Here the unique experimental environment of the τ-charm Factory should prove an important advantage, as we will now describe.

Table 2: Estimated statistics per year at the τ-charm Factory, at the indicated energies and integrated luminosities. (An integrated luminosity of 10 fb^{-1} per year corresponds to $L_{peak} = 10^{33}$ cm^{-2}s^{-1}.)

Event type	Events/year	C.M. Energy [GeV]	Integrated Luminosity [fb^{-1}]
$D^0\bar{D}^0$	2.9×10^7	$\psi''(3.77)$	10
D^+D^-	2.1×10^7	$\psi''(3.77)$	10
$D_s^+D_s^-/D_s^{\pm}D_s^{*\mp}$	0.9×10^7	4.14	10
$\Lambda_c^+\Lambda_c^-$	0.3×10^7	4.8?	3
$\Sigma_c\bar{\Sigma}_c$	0.1×10^7	5.2?	2
$\Xi_c\bar{\Xi}_c$	0.3×10^6	5.2?	2
$\Omega_c\bar{\Omega}_c$	0.3×10^5	5.6?	1
$\tau^+\tau^-$ (monochromator optics)	0.2×10^7	$2m_\tau + 0.0004$	7
" (standard optics)	0.5×10^7	$2m_\tau + 0.0040$	10
" "	2.0×10^7	3.67	10
" "	3.5×10^7	4.25	10
" (monochromator optics)	6.0×10^7	$\psi'(3.69)$	7
J/ψ (standard optics)	1.3×10^{10}	$J/\psi(3.10)$	6
" (monochromator optics)	8.0×10^{10}	$J/\psi(3.10)$	4
ψ' (standard optics)	0.6×10^{10}	$\psi'(3.69)$	10
" (monochromator optics)	1.6×10^{10}	$\psi'(3.69)$	7

2 Experimental environment

The τ-charm Factory operates at 3–5.6 GeV total energy, with a peak luminosity of 10^{33} cm^{-2}s^{-1} at 4 GeV. This region is rich with resonances and particle thresholds (Fig. 3). The cross-sections for τ and charm production in e^+e^- collisions are higher in this region than at any other energy. Backgrounds from higher-mass particles such a b quarks are completely absent. The high cross-sections are due to their overall ${E_{\mathrm{cm}}}^{-2}$

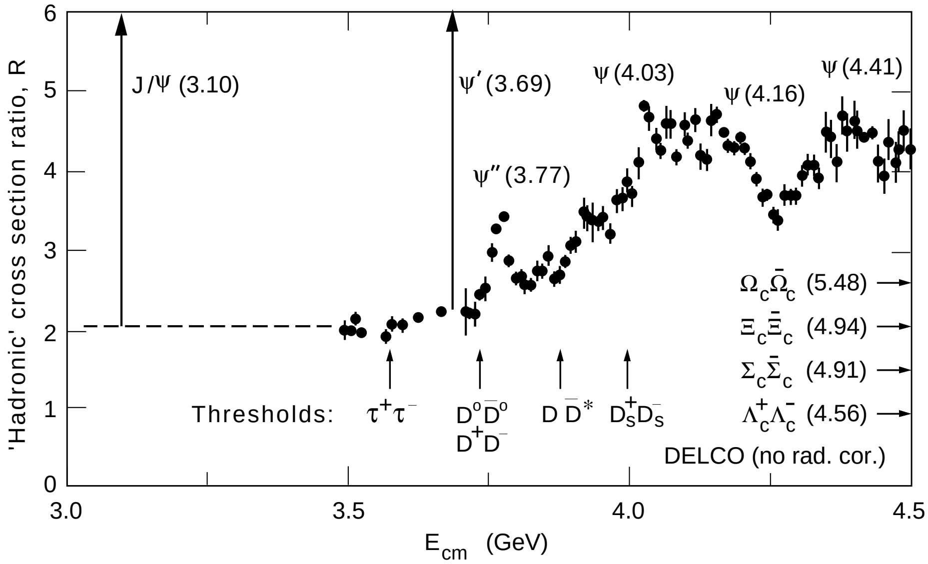

Figure 3: The hadronic cross section ratio, R, in the τ-charm threshold region. The ratio $R = \sigma(\mathrm{e^+e^-} \rightarrow$ 'hadrons') / $\sigma(\mathrm{e^+e^-} \rightarrow \mu^+\mu^-)$, where 'hadrons' include both $\mathrm{q\bar{q}}$ and $\tau^+\tau^-$ events. The data are from DELCO at SPEAR.

dependence (as seen in Fig. 1) and also to the presence of charm resonances such as the $\psi''(3.77)$, which has a peak cross section of 5 nb (over a continuum background of 13 nb) and decays with almost equal probability to pure $\mathrm{D^0\bar{D}^0}$ or $\mathrm{D^+D^-}$ final states.

The various τ and charm signals can be turned on or off by adjusting the beam energy above or below each particular threshold. This ability to measure the backgrounds *experimentally* is unique to the τcF. At other machines the backgrounds must be calculated by Monte Carlo simulations, which introduces systematic uncertainties.

Close to threshold, the heavy-flavoured particles appear in simple particle–antiparticle final states. As a consequence, each of the heavy-flavoured particles ($\mathrm{D^0}$, $\mathrm{D^\pm}$, $\mathrm{D_s^\pm}$, $\Lambda_c^\pm$, Σ_c, Ξ_c, Ω_c, etc.) can be cleanly tagged by observing the decay of its partner. This method of tagging each of the charm hadrons is unique to the threshold region. It has several important advantages: high selection efficiency, extremely small backgrounds—smaller than at any other machine, identification of the recoiling particle and measurement of its four vector without pre-selection of its decay mode, absence of additional particles, and exact flux normalisation [which allows measurement of *absolute* branching ratios (Br)].

Near threshold, τ leptons can also been cleanly tagged by observing the partner decay. This is only possible in the energy region below $\mathrm{c\bar{c}}$ and $\mathrm{b\bar{b}}$ thresholds, where the $\tau^+\tau^-$ events can be cleanly isolated with simple selection criteria on only one of the two τ's. For example, the requirement $\mathrm{e} + E_{\mathrm{miss}}$ (which is satisfied by *one* of the two τ's in an event decaying via $\tau^- \rightarrow \mathrm{e}^-\bar{\nu}_e\nu_\tau$) is expected to select $\tau^+\tau^-$ events with 24% efficiency and <0.1% background.

At threshold there is only a small Lorentz boost of the particles. This has several experimental advantages, including monochromatic spectra for two-body decays, decreased overlap of the secondary particles and easier (i.e. cleaner) π/K/p separation.

Finally, a vital requirement for achieving small systematic errors is a precise knowledge of the detector performance: resolutions, efficiencies, particle mis-identifications, etc. Here the τcF is blessed with high-rate calibration sources—the J/ψ (100M events/day) and ψ' (30M events/day)—which provide numerous exclusive physics channels that can be used to calibrate and monitor all parts of the detector. As an example, operating at the J/ψ produces the following event samples for calibrating the particle identification: $\pi^{\pm}/\pi^0/\gamma$ (J/$\psi \rightarrow \rho\pi$, 2M /day), $K^{\pm}$ ($K^{\star}K$, 600k /day), K_L^0 ($K_L^0 K_S^0$, 10k /day), p ($p\bar{p}/p\bar{p}\pi^0/p\bar{p}2\pi^{\pm}$, 1M /day), n ($n\bar{p}\pi^+$ 250k /day), $e^{\pm}$ (e^+e^-, 7M /day) and $\mu^{\pm}$ ($\mu^+\mu^-$, 7M /day).

3 Physics interest

3.1 Introduction

Since the initial idea for a τ-charm Factory [1] in 1987 and the first machine design [2, 3], numerous workshops [4]–[12] have explored the physics potential of the τcF and developed the designs of the accelerator and detector.

During this period, substantial progress in τ and charm physics has been made at BEPC, CESR, LEP, and in fixed-target experiments; and new B factories have been approved at KEK and SLAC. In this light, detailed studies have been made at recent τcF workshops [8]–[15] of the expected progress in τ-charm physics at other accelerators during the next 10 years, and comparisons made with a τcF. In contrast with a machine that opens up a new high-energy region, unique experimental capabilities in precision physics are difficult to demonstrate simply. Comparisons can readily be made at a statistical level. Here the B factory and τ-charm Factory are quite similar—both making an improvement of about a factor 100 over present data samples. Similarly, the reconstructed charm samples in future fixed-target experiments at the Tevatron are expected to be comparable to a τcF (for all-charged decay channels) [16].

However, as mentioned previously, systematic errors are expected to become the limiting factor for many precision measurements, and here the τ-charm Factory has some distinct advantages with respect to other machines: the special experimental environment at threshold (Section 2), longitudinal beam polarisation, and monochromatisation of the collision energy. Together these provide the τcF with an unsurpassed experimental sensitivity to τ and charm physics.

An indication of the scope of the τcF physics programme can be seen in Table 3, which lists some of the physics that will become accessible as the luminosity of the collider progresses. We will describe these experiments in more detail in the remainder of this section.

3.2 Tau physics

3.2.1 Overview

From an experimental viewpoint, the τ lepton holds a special place among the quarks and leptons. As a lepton its decays are tightly constrained in the standard model. The τ decays to a massless neutrino via the charged weak current, with a known, pure V-A, structure. It is the only lepton massive enough to decay to hadronic final states. With its large mass, it is probably the most sensitive lepton to new physics at higher mass scales. It is a third-generation lepton and, since there appear to be only three generations in nature,

Table 3: Physics-reach versus luminosity of the τ-charm Factory.

Luminosity $[\mathrm{cm}^{-2}\mathrm{s}^{-1}]$	Physics-reach per 1 year's data
10^{32}	▹ glueballs, hybrid exotics and hybrid charmonium
	▹ excited ψ and D states
	▹ semi-leptonic D decays to $\mathcal{O}(1\%)$ precision
	▹ τ decay Br's to $\mathcal{O}(0.1\%)$ precision
	▹ $\Lambda_c^{\pm}$, Σ_c, Ξ_c, Ω_c, etc. decays to $\mathcal{O}(5\%)$ precision
	▹ V-A structure in τ decays comparable to precision in μ decays
	▹ doubly Cabibbo suppressed D^0, $D^{\pm}$, $D_s^{\pm}$ decays to $\mathcal{O}(3\%)$ precision
	▹ pure leptonic D decays, f_D and f_{D_s} to $\mathcal{O}(2\%)$ precision
	▹ $\tau \to$ eX limit $\simeq 10^{-5}$; constraints on ν_τ masses below 1 MeV/c^2
10^{33}	▹ $D^0\bar{D}^0$ mixing at 2×10^{-5} level
	▹ rare τ/D/J-ψ decays (LFV, FCNC, etc.) to limits $\simeq 10^{-7} - 10^{-8}$
	▹ direct ν_τ mass limit $\simeq 1$ MeV/c^2
	▹ Direct CP violation in D decays at SM level
	▹ CP violation in τ decays at milliweak level (10^{-3})
	▹ Direct CP violation in Λ, Ξ decays at SM level
	▹ ?
	▹ ?
	▹ ?
10^{34}	▹ ?

it may be the "last" lepton. Finally, in comparison with the lighter leptons, it is barely known experimentally. For these reasons, the τ lepton constitutes an ideal laboratory to test the standard model and search for new physics. Indeed, the τ may perhaps become the experimental successor to the Z^0 for precision tests of the standard model, when the present LEP/SLC programme comes to an end. Some of the main τ experiments [17, 18] are as follows:

- A precise, systematic programme to measure the branching ratios of all τ decay channels and search for signs of discrepancies with the theoretical expectations. In a one-year data sample, the expected precisions on the 1-prong branching ratios are 0.15% (e, μ), 0.2% (π) and 0.8% (K), whereas present errors are 1–6%. These precise measurements will allow a test of the universality of the leptonic charged currents at the 0.05% ($|g_\mu/g_e|$) and 0.16% ($|g_\tau/g_\mu|$) levels.
- Accurate global analysis of all τ decay channels, with notable strengths for decays involving K's and multiple γ's, which are poorly-known at present. This analysis will be sensitive to 'missing' decay modes with an order-of-magnitude higher precision than present experiments. It will also provide a precise determination of the vector- and axial-vector-current spectral functions, both in the Cabibbo-allowed and Cabibbo-suppressed channels. This information will allow many interesting tests of QCD to be made [19].

- Searches for rare and forbidden τ decays with a factor $\gtrsim$100 improvement in sensitivity beyond present experiments. The τcF is especially suited to study two-body decays like $\tau^- \to l^- X$ (l = e, μ; X = Majoron, familon, flavon,...), which lead to the distinctive signature of monochromatic leptons. The expected branching-ratio sensitivity is better than 10^{-5}, to be compared with the present limits of $\sim$0.5%. Second-class-current decays like $\tau^- \to \pi^- \eta \nu_\tau$ will be cleanly measured at the expected standard model level of about 10^{-5}.
- Substantial improvement on the ν_τ-mass limit, through accurate measurements of the end-points of the hadronic energy and invariant-mass distributions in high-visible-mass τ decays like $\tau^- \to 5\pi^\pm \nu_\tau$, $3\pi^\pm 2\pi^0 \nu_\tau$ and $K^- K^+ \pi^- \nu_\tau$. The estimated sensitivity (95% CL) is $\simeq$ 1 MeV, to be compared with the present limit of 24 MeV.
- Precise measurement of the τ mass from the $\tau^+\tau^-$ production cross-section near threshold (expected accuracy $\simeq$ 0.1 %). The τ mass will be determined with an accuracy limited only by the precision of the beam energy (better than 0.5×10^{-5}), i.e. less than 10 keV mass uncertainty.
  Furthermore, a unique test of CPT conservation can be made at the τcF by measuring the mass difference between the τ^- and τ^+. The experiment involves a precise comparison of the momenta of the monochromatic π^- and π^+ in the $\pi^-\nu_\tau$ and $\pi^+\bar{\nu}_\tau$ decay modes at threshold. The mean π momentum is $(m_\tau/2) - (m_\pi^2/2m_\tau)$. With monochromator optics, the τcF could statistically measure a 100 keV (τ^-–τ^+) mass difference as a 3σ effect in one-year's data. The experiment would require control of positive/negative momentum systematics to $\mathcal{O}$ (10keV/1GeV) $\sim 10^{-5}$, using calibration channels at the ψ'.
- Substantial improvement in the measurement of the τ anomalous magnetic moment, $a_\tau^\gamma = (g_\tau^\gamma - 2)/2$, by means of precise measurements of the $\tau^+\tau^-$ cross-section and angular distributions of the τ secondaries. In one year's data, the τcF will reach a sensitivity at the level of the first QED contribution ($\alpha/2\pi$) [20]. This quantity is poorly known at present; the best limit comes from the decay $Z^0 \to \tau^+\tau^-\gamma$: $a_\tau^\gamma < 0.01$ at 95% CL [21].
- Production of the $\tau^+\tau^-$ atom, tauonium [22]. The τcF is the only instrument where we may hope to produce the $\tau^+\tau^-$ atomic system, and to study its properties in search of a possible anomalous interaction. The triplet $^1S_3$ state of tauonium breaks up by τ decay with a 15% Br. The rest of the decays involve $\tau^+\tau^-$ annihilation, mainly to e^+e^- (21%), $\mu^+\mu^-$ (21%) and $q\bar{q}$ (42%). The detection of tauonium would require monochromator optics for the τcF collider (Section 4.1.2), reducing the collision energy spread to 100 KeV or better. The signature for the production of tauonium is a small rise ($\simeq$ 0.15%) in the cross sections for $\mu^+\mu^-$ and *hadrons* as the centre-of-mass energy is swept through the production point ($2m_\tau$ less the ground-state binding energy of 24 keV). A thirty-day run divided between three energies spaced by $\simeq$ 1 MeV and centred on the production point would measure tauonium production as a 4σ resonance in both the $\mu^+\mu^-$ and *hadrons* final states.
- Accurate determination of the leptonic τ-decay Michel parameters, constraining the underlying dynamics with a precision comparable to, or even better than, μ decay.
- Investigation of CP violation in the lepton sector at the milliweak (10^{-3}) level, with τ's polarised by means of longitudinal beam polarisation.

As an illustration of where new physics may be revealed in deeper studies of the τ, we will consider the last two items in more detail.

3.2.2 Lorentz structure of the τ weak current

The most general form of the matrix element for leptonic τ decay is [23, 24]:

$$M = 4\,\frac{G_F^\tau}{\sqrt{2}} \sum_{\substack{\kappa=S,V,T\\ \varepsilon,\lambda=R,L}} g^\kappa_{\varepsilon\lambda}\langle\overline{\psi}_\varepsilon(\ell)\,|\Gamma^\kappa|\psi_\rho(\nu_\ell)\rangle\langle\overline{\psi}_\omega(\nu_\tau)\,|\Gamma_\kappa|\psi_\lambda(\tau)\rangle$$

where κ labels the type of interaction—scalar, vector and tensor—and ε, λ, ρ and ω label the handedness of l and ν_l. Altogether there are 10 different interactions, each governed by a complex coupling constant to be determined by experiment:

$$\begin{aligned} 1 \quad = \quad & \frac{1}{4}\left(|g^S_{RR}|^2+|g^S_{RL}|^2+|g^S_{LR}|^2+|g^S_{LL}|^2\right) \;+\; 3\;\left(|g^T_{RL}|^2+|g^T_{LR}|^2\right)\\ & +\left(|g^V_{RR}|^2+|g^V_{RL}|^2+|g^V_{LR}|^2+|g^V_{LL}|^2\right) \end{aligned}$$

The standard model (V$-$A current) corresponds to $g^V_{LL}=1$ and all other $g^\kappa_{\varepsilon\lambda}=0$. Four experiments are sufficient to determine completely the coupling constants, $g^\kappa_{\varepsilon\lambda}$ [24]:

1. Determination of the overall normalisation: G_F^τ.
2. Determination of the Michel parameters: ρ,δ,η,ξ.
3. Determination of the polarisation of the daughter μ: ξ'_μ.
4. Measurement of inverse τ decay: $\nu_\tau e^- \to \tau^-\nu_e$.

The Fermi constant in τ decays, G_F^τ, is determined from the τ lifetime, the τ mass and the pure leptonic Br's. It also depends on the Michel parameter η. Assuming that τ_τ will be measured to 0.3% precision at LEP and the B factories, G_F^τ will be determined to 0.16% at the τcF.

In the standard model, the Michel parameters have the values: $\rho=\delta=3/4$, $\eta=0$ and $\xi=\xi'=1$. The Michel parameters are sensitive to new physics and the effects are indicated in Table 4 [25]. They are determined from the pure leptonic decays, $\tau^-\to e^-\bar{\nu}_e\nu_\tau$ and $\mu^-\bar{\nu}_\mu\nu_\tau$. The ρ and η parameters are determined from the energy spectra of the daughter e and μ. The asymmetry parameters, ξ and δ, are determined by analysing the decay distributions of spin-correlated τ pairs. The expected accuracies at the τcF for one-year's data are ρ (±0.002), η_μ (±0.003), ξ (±0.025) and δ (±0.020) [26]. (Longitudinal beam polarisation was not assumed for this study; it will substantially improve the measurements of ξ and δ.) The present world averages for pure leptonic τ decays are ρ (±0.027), η (±0.140), ξ (±0.120) and $\delta\xi$ (±0.110) [27].

In addition, the τcF detector will have the unique capability to measure the average longitudinal polarisation of the μ^+ in $\tau^+\to\mu^+\nu_\mu\bar{\nu}_\tau$, which is equal to ξ'_μ. The polarimeter (Section 4.2.2) covers about half of the barrel region. It includes a weak magnetic field for spin precession, and detectors for measuring the direction and decay time of the stopped μ^+'s. The decay $\mu^+\to e^+\nu_e\bar{\nu}_\mu$ determines the μ^+ spin direction with an analysing power of 1/3. The decay time distribution is an exponential modulated by the μ^+ spin precession, from which the polarisation of the incident μ^+ can be deduced. The Michel parameter ξ'_μ can be measured to a precision of about ±0.02 in one year's data at the τcF. It has not yet been measured.

Table 4: Expected changes in the Michel parameters due to new physics. The interaction is indicated by standard model(SM) + vector(V) or scalar(S), charged(+) or neutral(0).

Michel parameter	SM + V^+	SM + S^+	SM + V^0	SM + S^0
$\rho - 3/4$	< 0	0	0	< 0
$\xi - 1$	$\pm$	< 0	< 0	$\pm$
$(\delta\xi) - 3/4$	< 0	< 0	< 0	< 0
η	0	$\pm$	$\pm$	$\pm$

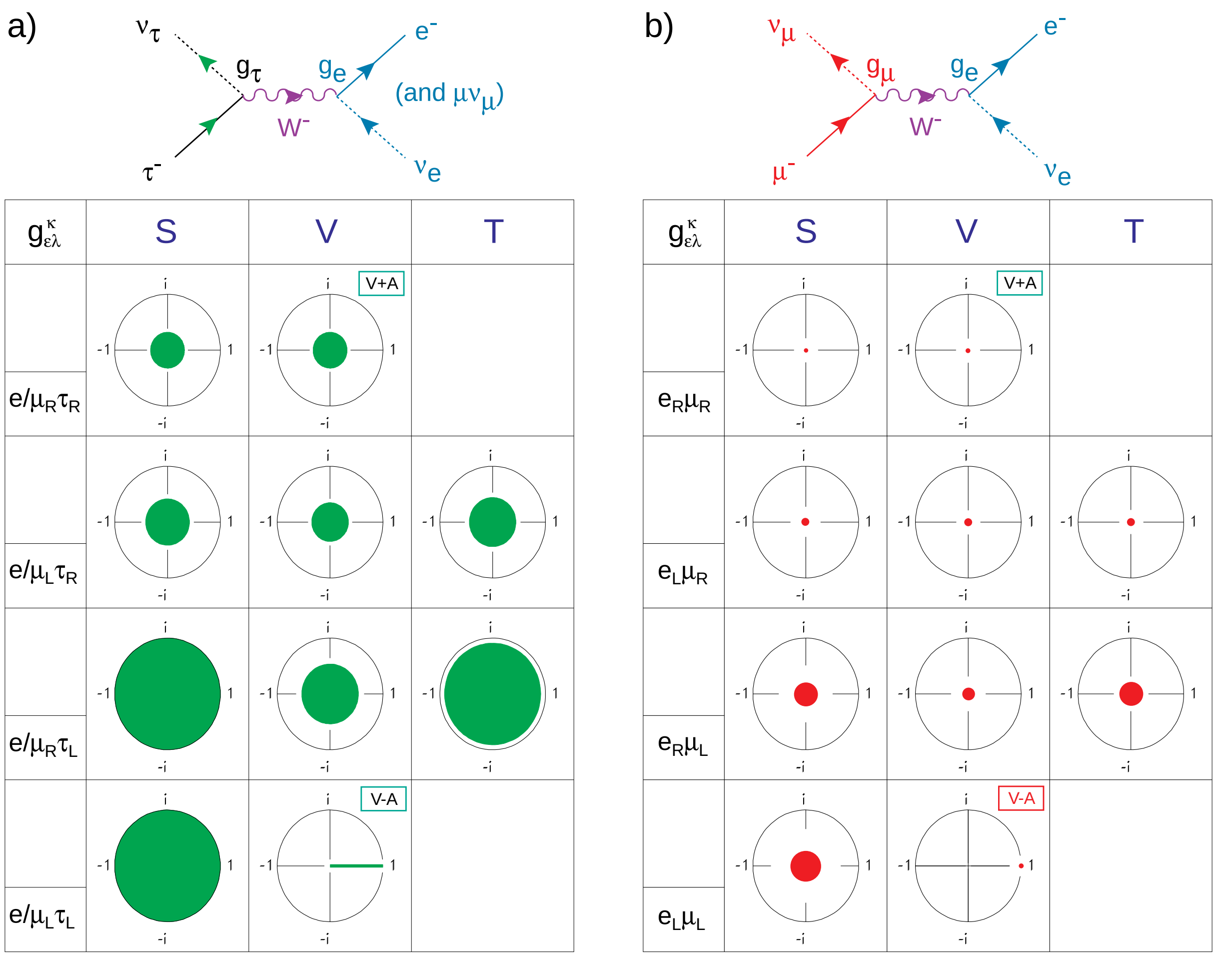

Figure 4: The 90% C.L. limits for the complex couplings, $g^\kappa_{\varepsilon\lambda}$, in a) τ decay and b) μ decay [24, 28]. The interactions are S (scalar), V (vector) and T (tensor). ϵ and λ label the handedness of the lepton. In the standard model, $g^V_{LL} = 1$ and all other $g^\kappa_{\varepsilon\lambda} = 0$.

The current measurements for the τ are shown in terms the coupling constants, $g^{\kappa}_{\varepsilon\lambda}$, in Fig. 4a [24, 28]. The upper limits on anomalous τ couplings are much weaker than those for the μ (Fig. 4b)—which provide the most stringent present experimental test of the pure V-A structure of the charged weak current. The important measurement of ξ'_{μ} can uniquely test the possibility for the μ to be right-handed in τ decay, simultaneously putting upper limits on half of the couplings in Fig. 4a. At the τcF, the Michel parameters for the τ will be measured to precisions comparable to, or even better than, those for the μ.

3.2.3 CP violation in the τ sector

In the standard model, CP violation originates from a single phase in the quark mixing matrix and is predicted to be negligible in the lepton sector. However, experimentally we know very little about CP violation, and we should remain open to the possibility that the current orthodoxy may be wrong. CP violation could arise from many extensions of the standard model, including supersymmetry, left-right models, leptoquarks and extra Higgs bosons (Fig. 5) [29, 30]. There are two experimental approaches to searching for CP violation in the τ sector: finite electric dipole moment (edm), and CP violation in τ decays. These are discussed below.

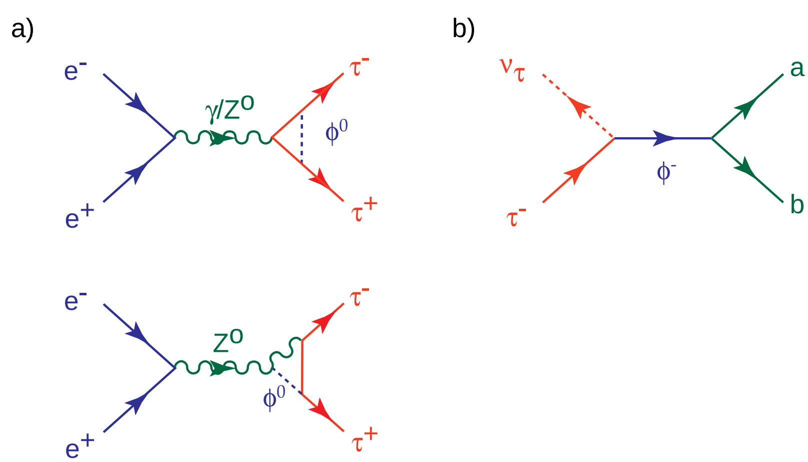

Figure 5: CP-violating contributions to a) τ production and b) τ decay, in models with Higgs bosons ϕ of undefined CP parity. The right-hand vertices in a) also contribute to the electric/weak dipole moment of the τ.

Electric dipole moment of the τ

Leptonic CP violation has mainly been investigated by searching for finite electric/weak dipole moments (Figs. 5a), which violate T invariance and therefore, by CPT conservation, also CP invariance. In the standard model, leptonic CP violation only comes through higher order corrections involving quark mixing. The estimated edm of the leptons is tiny: $\mathcal{O}(m_l \times 10^{-40})$ e-cm, where m_l (MeV) is the lepton mass [31]. Any observation of CP violation in leptonic systems would therefore signal new physics.

The present limit on the τ electric dipole moment, $|d^{\gamma}_{\tau}| < 5 \times 10^{-17}\, e$ cm (95% CL) [21], has been obtained from an analysis of the $Z^0 \rightarrow \tau^+\tau^-$ decay width, assuming that all other couplings take their standard model values. By studying CP-odd observables in $Z^0 \rightarrow \tau^+\tau^-$, OPAL has obtained upper limits for the real and imaginary parts of the weak dipole moment, $|\mathrm{Re}\ d_\tau^{weak}| \leq 7.8 \times 10^{-18}$ e-cm and $|\mathrm{Im}\ d_\tau^{weak}| \leq 4.5 \times 10^{-17}$ e-cm at 95% C.L., respectively [32].

Analysing CP-odd observables by means of momentum correlations of the final $\tau^+\tau^-$ decay products [29], and especially with the use of polarised beams [33], the τcF can reach a sensitivity of $|\mathrm{Re}\ d_\tau^\gamma| = 10^{-19}$ e-cm with one year's data. Recent calculations indicate this precision is at a sensitive level for observing new physics [31].

This precision on the τ edm is to be compared with the present limits on the electric dipole moments of the e and μ: $|d_e^\gamma| < 2 \times 10^{-26}$ e-cm, and $|d_\mu^\gamma| < 7 \times 10^{-19}$ e-cm, respectively. Although the τ edm limit at the τcF is numerically weaker than that of the electron, it is expected that new physics would induce a dipole moment $\propto m_l^n$, where, for example, $n = 3$ in Higgs diagrams like Fig. 5a [29]. Therefore the τ measurements may provide a sensitivity to new physics comparable to, or even better than, the lighter leptons.

CP violation in τ decays

Tsai points out that the most sensitive place to search for leptonic CP violation is probably not in $\tau^+\tau^-$ production (Fig. 5a) but in the *decays* of the τ (Fig. 5b), where the effects are $\mathcal{O}(1)$ if the CP violation is weak and $\mathcal{O}(10^{-3})$ if it is milliweak [30]. Since the initial state in e^+e^- annihilation is CP-even, any finite CP-odd observable in the final state of the $\tau^+\tau^-$ events implies CP violation. Several tests have been proposed, as follows:

1. *With unpolarised τ's:* CP violation can be tested through rate asymmetries, e.g. $\Gamma(\tau^- \rightarrow \pi^-/K^-\pi^0\nu_\tau) \neq \Gamma(\tau^+ \rightarrow \pi^+/K^+\pi^0\bar{\nu}_\tau)$ [30]. However this requires strong final state interactions in the decay amplitudes. Another possibility is to study CP-odd asymmetries in the angular distributions of the final hadrons in decay modes such as $\tau^- \rightarrow K^-\pi^-\pi^+\nu_\tau, \pi^-K^-K^+\nu_\tau$ [35] and $\tau^- \rightarrow \pi^-\pi^-\pi^+\nu_\tau$ [36]. In some models of CP-violation involving several Higgs doublets, studies show that CP-violating effects may be seen at a τcF at the 2σ level for one year's data [36].
2. *With polarised τ's:* With polarised e^- and/or e^+ beams, the longitudinal polarisation vectors of the incident leptons can be used to construct CP-odd products [30]. CP can be tested by comparing these products in τ^- and τ^+ decays. Near the $\tau^+\tau^-$ production threshold, the τ's are produced mostly in the s-wave, which implies that their spins are point in the beam direction, independent of the $\tau^+\tau^-$ production angle. When both beams are longitudinally polarised in the same direction, for example by 50%, one can obtain τ pairs with 80% polarisation in the direction of the beam polarisation vector. With this large polarisation, sensitivities of $\mathcal{O}(10^{-3})$ [or even $\mathcal{O}(10^{-4})$ with several years of running] could be achieved at the τcF [30]. In the absence of beam polarisation, CP-violation could still be tested through $\tau^+\tau^-$ correlations [34], but with weaker sensitivity.
3. *With polarised τ's and a μ polarimeter:* Here the CP-violating term $\vec{\sigma_\tau}.(\vec{p_\mu} \times \vec{\sigma_\mu})$ in $\tau \rightarrow \mu\nu_\mu\nu_\tau$ can be measured [30]. In contrast with all the previous tests, it involves only leptons.

The most sensitive tests require longitudinally polarised beams. Compared with spin-correlation techniques, polarisation has been estimated to reduce the statistical error of certain tests by a factor ~7, i.e. equivalent to a factor ~50 in statistics (final reference in [34]). Moreover, polarisation has the important experimental advantage of extremely small systematic errors, since essentially all detector systematic effects are unaffected by the beam polarisation. Therefore, by measuring the CP-odd observable with several concurrent polarisation directions, a real signal could be unambiguously isolated from fake ones.

3.3 Charm physics

3.3.1 Overview

At present charm decays are relatively poorly-known. Although considerable progress has been made in recent years at CESR and in fixed-target experiments, much of our knowledge still relies on e^+e^- data taken 15–20 years ago at SPEAR. There are now compelling reasons for raising charm studies to a higher level of precision; they can be distilled into three main points [37, 38]:

1. In the standard model with three families and a beauty lifetime ~1 psec, the two CKM parameters that govern weak charm transitions (V_{cs} and V_{cd}) are tightly constrained by the unitarity of the CKM matrix. Furthermore, theoretical techniques have emerged that allow a more rigorous treatment of charm decays: QCD sum rules, heavy quark expansions and QCD lattice simulations. Charm decays therefore constitute a unique laboratory to probe QCD *quantitatively* at the interface between the perturbative and non-perturbative regimes.
2. The theoretical tools that are needed to fully exploit the discovery potential of beauty decays must first to be tested and calibrated with charm decays. An example is the determination of $|V_{td}/V_{ts}|$ from radiative B decays ($B \rightarrow \gamma\rho, \gamma\omega, \gamma K^{*0} \ldots$), which are assumed to be dominated by short-distance (penguin) diagrams. This assumption needs to be tested by measuring the equivalent D decays, e.g. $D \rightarrow \gamma K^{*0}$, which will *experimentally calibrate* the long-distance contributions.
   Similarly, precision physics at B factories and at higher energies requires better charm measurements at threshold. One example is precise absolute Br's. Another is the inclusive leptonic branching ratio and energy spectrum in charm decays, which rely on old DELCO and MkIII data from SPEAR (Fig. 6) and are an important source of systematic error in the determination of $Br(Z^0 \rightarrow c\bar{c})$ at LEP/SLC [39].
3. Finally, there is the potential for fundamental surprises in areas such as $D^0\bar{D}^0$ mixing, CP violation in D decays, or rare D (or J/ψ) decays. Although these processes are expected to be very small in the standard model, it is nevertheless important to search since charm decays provide the sole window of opportunity to examine heavy-flavour physics in the up-quark sector. Furthermore charm decays provide a rich variety of weak decays in which to search (Cabibbo–allowed, –suppressed and –doubly suppressed; leptonic, semi-leptonic, 2nd-order weak ...).

Viewed in this framework, the physics at a τ-charm Factory and at a beauty Factory should be seen as complementing each other rather than competing against each other. It is the detailed and comprehensive analysis of charm decays at a τ-charm Factory that will prove essential for precision measurements of beauty decays and for gauging the impact of non-perturbative dynamics. Some of the main charm experiments [37, 38] are as follows:

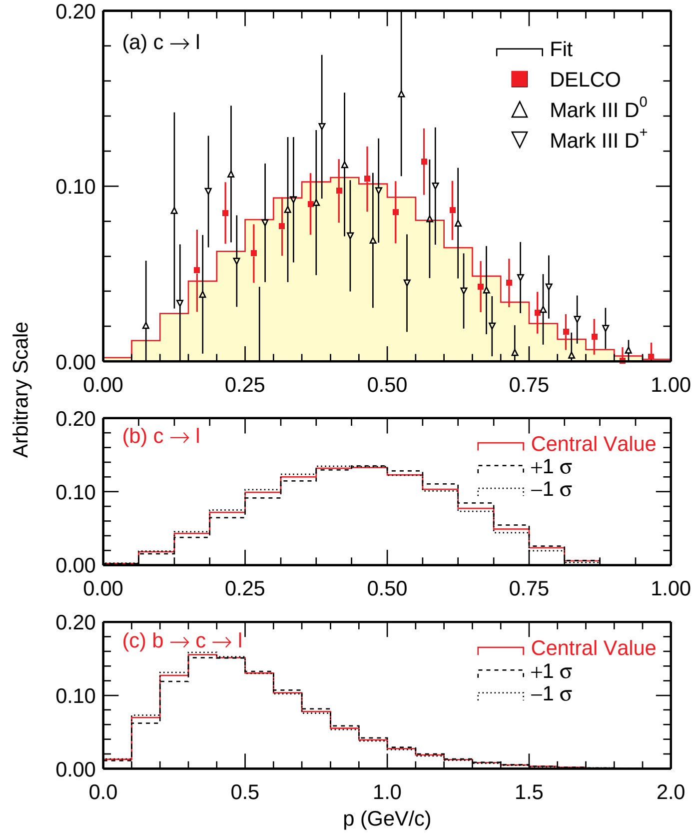

Figure 6: Present world data for the lepton spectrum in charm (D) decays at rest: a) the experimental data, b) the fitted c → l spectrum, and c) the corresponding b → c → l spectrum [39].

– The τcF will precisely determine the decay constants f_D and f_{D_s} by measuring each of the pure leptonic decay branching ratios (Figs. 7):

$$Br(D^+_{(s)} \to l^+\nu_l) = \tau_{D_{(s)}} \frac{G_F^2}{8\pi} f^2_{D_{(s)}} m_{D_{(s)}} \mid V_{cd(cs)} \mid^2 m_l^2 \left(1 - \frac{m_l^2}{m^2_{D_{(s)}}}\right)^2$$

The largest pure leptonic branching ratios are Br($D_s^+ \to \tau^+\nu_\tau$) $\simeq$ 3.3%, Br($D_s^+ \to \mu^+\nu_\mu$) $\simeq 3.6 \times 10^{-3}$, Br($D^+ \to \tau^+\nu_\tau$) $\simeq 10^{-3}$ and Br($D^+ \to \mu^+\nu_\mu$) $\simeq 3.5 \times 10^{-4}$. Each will be measured to 2% accuracy in a one-year data sample (Fig. 8) [40]. A measurement of pure leptonic charm decays at this level of precision can only be made at a τcF. They provide an important test of lattice QCD and are essential to the calculation of f_B, a quantity crucial to the interpretation of B^0-$\bar{B}^0$ mixing and CP violation in B decays. The decay constant f_B is not accessible to direct measurement at a B factory since Br($B^+ \to \tau^+\nu_\tau$) $\sim 7 \times 10^{-5}$, and $\mid V_{bu} \mid$ is poorly known. The best—perhaps only—way to determine f_B precisely is to measure f_D and use lattice QCD to extrapolate from the D to the B region.

– Measurements of the pure- and semi-leptonic decays will provide a precise determination of V_{cs} and V_{cd}. Although unitarity tightly constrains these values (uncertain-

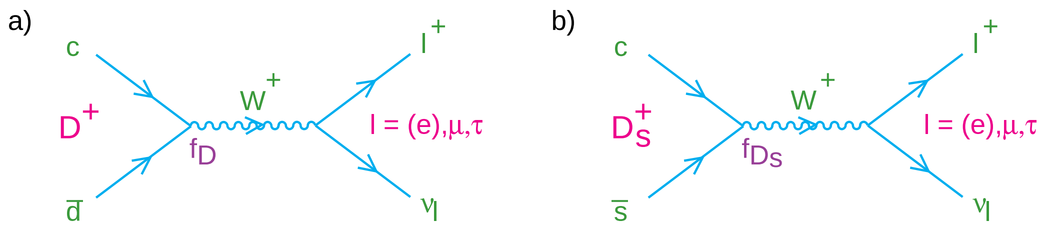

Figure 7: Pure leptonic decay diagrams: a) $D^+ \rightarrow l^+\nu_l$, and b) $D_s^+ \rightarrow l^+\nu_l$.

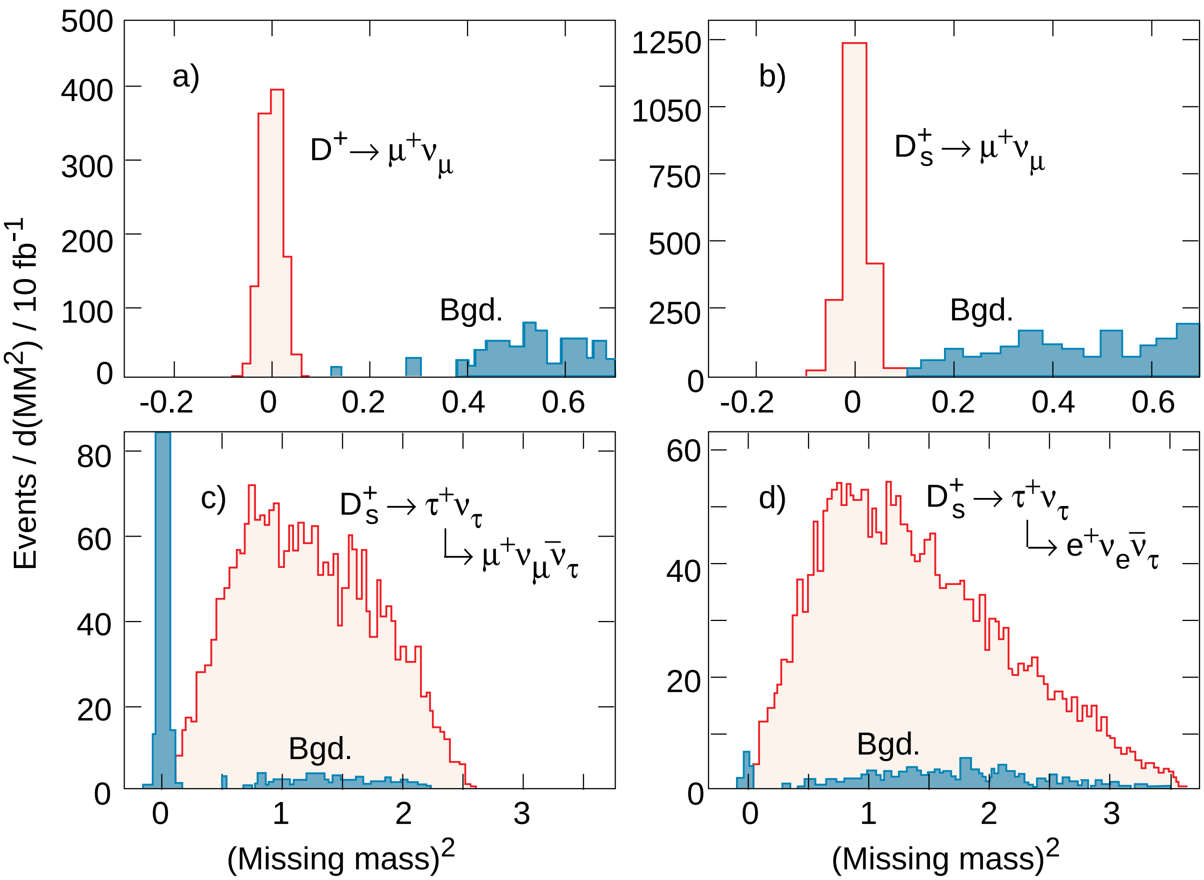

Figure 8: Simulation of pure leptonic D decays at the τcF [40]. Missing masses in tagged events are shown for: a) $D^+ \rightarrow \mu^+\nu_\mu$ ($\simeq$ 1100 events per year); b) $D_s^+ \rightarrow \mu^+\nu_\mu$ ($\simeq$ 2000 events per year); c) $D_s^+ \rightarrow \tau^+\nu_\tau$, $\tau^+ \rightarrow \mu^+\nu_\mu\bar{\nu_\tau}$ ($\simeq$ 2000 events per year); and, d) $D_s^+ \rightarrow \tau^+\nu_\tau$, $\tau^+ \rightarrow e^+\nu_e\bar{\nu_\tau}$ ($\simeq$ 2400 events per year). The indicated statistics correspond to 10 fb^{-1} ($L = 10^{33}$ cm^{-2}s^{-1}) and $f_D \simeq 200$ MeV. The background events are shaded dark.

ties of 0.1% for V_{cs} and 1% for V_{cd}), this has been poorly checked experimentally; the direct measurements have an accuracy of only 10–20%. At a τcF the D semileptonic branching ratios will be measured to an accuracy better than 1%, whereas present errors are 6% for $D^0 \to K^- e^+ \nu_e$ and 30% for $D^0 \to \pi^- e^+ \nu_e$. Overall, $|V_{cd}/V_{cs}|$ can be determined to $\sim 1\%$ at a τcF, which is comparable to the present precision of $\theta_{Cabibbo}$. Again, these measurements will provide an important calibration of the methods used in extracting the CKM parameters V_{cb} and V_{ub} from semileptonic B meson decays.

A comprehensive study of semi-leptonic decays will reveal the status of our understanding of QCD [37]. It should be noted that *inclusive* semileptonic charm decays can only be studied near threshold. Measurements of the semileptonic branching ratios for $D_s^{\pm}$, $\Lambda_c^{\pm}$ and Ξ_c are especially needed, for both exclusive and inclusive modes.

- Although absolute branching ratios have been obtained for D^0 and $D^{\pm}$ mesons with an accuracy of 10–15%, there exist no useful direct measurements of the absolute branching ratios of any other charm hadrons: $D_s^{\pm}$, $\Lambda_c^{\pm}$ and Ξ_c, etc. Moreover, about 20-50% of charm decays have not yet even been seen. Due to its unique tagging capabilities, a τcF provides the only way to precisely measure absolute charm branching ratios. The expected precisions for the main decay modes are as follows: $D^0/D^{\pm}/D_s^{\pm}$ (0.1-0.3% /1-year's data), $\Lambda_c^{\pm}$ (1% /y), $\Sigma_c/\Xi_c/\Omega_c$ (3-10% /y).

  Of particular interest are measurements of the once- and twice-Cabibbo-suppressed modes of D *and* $D_s^{\pm}$; likewise for Cabibbo-allowed and once-suppressed decay modes of $\Lambda_c^{\pm}$. Such data would also allow refined predictions on CP-violating asymmetries in charm decays. The τcF is the only machine where a *comprehensive* analysis of all charm decays can be carried out.

- Searches for rare decays of charm and charmonium can be made with improvements in Br sensitivity of 2–3 orders of magnitude compared with present experiments. These processes include lepton-flavour-violating decays (such as $D^0 \to e^{\pm}\mu^{\mp}/Xe^{\pm}\mu^{\mp}$), which are completely forbidden for massless ν's, and flavour changing neutral-current decays [such as $D^0 \to l^+l^-/Xl^+l^-$ (l=e, μ), $X\nu\bar{\nu}$ and $X\gamma$], which may occur in the standard model but are highly suppressed by the GIM mechanism. Searches for rare decays of D mesons are complementary to those of K or B mesons since the new physics may be flavour-dependent, i.e. different for up-like and down-like quarks.

  The very high statistics and the narrow width of the J/ψ may provide the first opportunity to measure weak decays of a vector meson, such as $J/\psi \to D_s e \nu_e$ (Br $\simeq 10^{-8}$), or the C-violating decay $J/\psi \to \phi\phi$ (Br $\simeq 10^{-8}$). The J/ψ can be tagged via $\psi' \to \pi^+\pi^- J/\psi$ to allow searches for rare processes involving $J/\psi \to$ '*nothing*'. Axions or other evasive neutrals can be produced in $J/\psi \to \gamma$ + '*nothing*'; the expected Br sensitivity is $\simeq 10^{-8}$.

- Within our present knowledge of the standard model, it is expected that D^0-$\bar{D}^0$ mixing is very small, and beyond the range of experimental sensitivity. Consequently, indirect CP violation (due to mixing) is also experimentally negligible. However, some calculations indicate that *direct* CP violation may give rise to asymmetries of the order of 10^{-3} in certain Cabibbo-suppressed D decay channels [$\mathcal{O}(0.5\%)$ Br].

These are within range of the sensitivity of a τcF. As an illustration of where new physics may appear in precision charm studies, we will discuss this item in more detail in the next section.

It may also be possible to observe direct CP violation by measuring differences in the decay parameters of hyperons and anti-hyperons (Λ and Ξ) produced in J/ψ decays [41]. Since the expected differences are small [e.g. $\mathcal{O}(10^{-3})$ in the polarisation asymmetry parameter B'_{Ξ}], very large statistics (>10^{11} J/ψ decays) are required. These may be reached in one-year's operation of the τcF collider with monochromator optics. Alternatively, polarised beams would allow the measurement to be done with the standard luminosity, producing $\mathcal{O}(10^{10})$ polarised J/ψ's per year.

3.3.2 $D^0\bar{D}^0$ mixing and CP violation in D decays

$D^0\bar{D}^0$ mixing

The rate for $\mathrm{D^0\bar{D}^0}$ oscillations in terms of the mass and width differences of the $\mathrm{D}^0_{1,2}$ physical states is (Δm_D and $\Delta\Gamma_D$, respectively):

$$r_D \equiv \frac{\mathrm{Br}(D^0 \to \bar{D}^0 \to \bar{f})}{\mathrm{Br}(D^0 \to f)} \simeq \frac{1}{2}\left[\left(\frac{\Delta m_D}{\Gamma_D}\right)^2 + \left(\frac{\Delta\Gamma_D}{2\Gamma_D}\right)^2\right].$$

In the standard model, mixing receives contributions from short-distance and long-distance processes (Figs. 9).

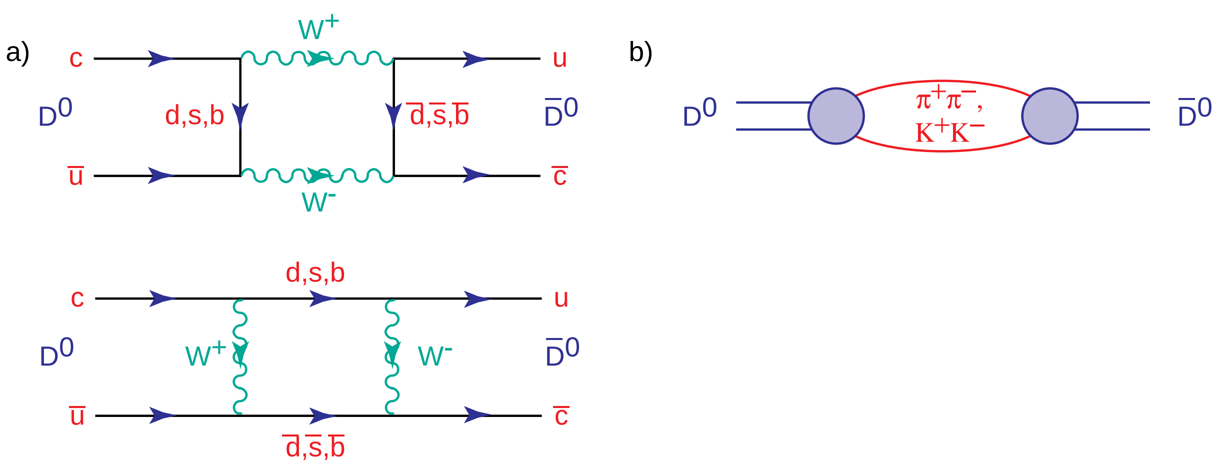

Figure 9: Diagrams for $\mathrm{D^0\bar{D}^0}$ mixing via a) short-range and b) long-range interactions.

Short-distance processes are expected to give an extremely small contribution to Δm_D of the order of 5×10^{-9} eV [42], c.f. the $\mathrm{D^0}$ total width, $\Gamma_D \sim 1.6 \times 10^{-3}$ eV. In contrast with earlier estimates, recent calculations of the long-distance contributions indicate they too are very small: $\Delta m_D \sim (1\text{–}4)\times 10^{-8}$ eV [43]. Therefore, in the standard model, $\mathrm{D^0\bar{D}^0}$ mixing is expected to be negligibly small: $r_D \simeq 10^{-10} - 10^{-9}$.

This apparent disadvantage in fact makes $\mathrm{D^0\bar{D}^0}$ mixing a sensitive channel in which to search for new physics. The suppression is very specific to the standard model and many types of new physics could produce measurable effects in these highly-suppressed 2nd-order-weak processes.

The experimental signatures of mixing are like-sign dileptons ($l^{\pm}l^{\pm}X$), or identical hadronic decays: $(K^+\pi^-)(K^+\pi^-)$ or $(K^-\pi^+)(K^-\pi^+)$. The latter can be separated from doubly-Cabibbo-suppressed decays since quantum statistics yield different correlations in the $D^0\bar{D}^0$ decays from $D^0\bar{D}^0$, $D^0\bar{D}^0\gamma$, and $D^0\bar{D}^0\pi^0$ final states in e^+e^- annihilation [45]. The τcF sensitivity is $r_D \simeq 2 \times 10^{-5}$ per one-year's data [44], to be compared with the present 90% C.L. limit, $r_D < 3 \times 10^{-3}$.

CP violation

In the standard model, CP violation effects are proportional to $A^2\lambda^6\eta$ (using the Wolfenstein notation for the CKM matrix, where $\lambda^2 \sim 0.05$). The total decay rates for the strange, charm and beauty mesons are, respectively:

$$\mathrm{K} \propto \lambda^2; \quad \mathrm{D} \propto 1; \quad \mathrm{B} \propto \lambda^4$$

Thus the D system is not a favoured place to search for effects from CP violation unless Cabibbo-suppressed decays (proportional to λ^2) are used, where a level for CP violation is expected to be similar to that of the K system [$\mathcal{O}(0^{-3})$].

In view of the very small $D^0\bar{D}^0$ mixing, *indirect* CP violation through this process is expected to be negligible. *Direct* CP violation effects—which have not yet been unambiguously observed—are characterised by the CP violation asymmetry

$$A_{CP} = \frac{\Gamma(D \to f) - \Gamma(\overline{D} \to \overline{f})}{\Gamma(D \to f) + \Gamma(\overline{D} \to \overline{f})}$$

A_{CP} has a measurable value if the final state, f, can be reached in two ways which correspond to two different weak and strong amplitudes, respectively, that satisfy the following requirements:

- The two weak phases are different.
- The two strong phases are different (final state interactions).
- One amplitude is not negligible compared with the other.

A model of final state interactions has been developed for D decays that successfully fits many of the measured Br's of the Cabibbo-suppressed decays [46]. This has been applied to predict values for A_{CP} in various channels, and a few are summarised in Table 5. In agreement with the previous simple estimate, A_{CP} is $\mathcal{O}(10^{-3})$ for these decays.

The experimental sensitivity at the τcF [47] is within range of the theoretical expectations (Table 5), although larger event samples would clearly be advantageous. Indeed there are plans for future upgrades of the τcF luminosity to $\sim 3 \times 10^{33}$ cm^{-2}s^{-1} (Section 4.1.2). The experiment requires extremely precise control of asymmetries in the detection of K^+ vs. K^- etc. This can be obtained from the higher-rate Cabibbo-allowed decays, such as $D^+ \to K^-\pi^+\pi^+$, where no CP asymmetries are expected. With respect to systematic errors, the τcF has an important advantage over fixed-target experiments in that the D^+ and D^- states are produced equally in e^+e^- annihilation but with a 10% asymmetry in photoproduction [16].

In summary, $D^0\bar{D}^0$ mixing and CP violation in D decays provide a unique testing ground for the standard model. In the former case, the absence of any expected mixing implies it is a particularly sensitive channel to observe subtle effects from new physics. And in latter case, D hadrons could be a rich laboratory for exploring direct CP violation, about which almost nothing is presently experimentally known.

Table 5: Expected asymmetries, A_{CP}, due to direct CP violation in various D decays [46] and the experimental sensitivity for one-year's data at a τcF with $L = 10^{33}$ cm^{-2}s^{-1} [47].

Channel	Br [%]	Theory A_{CP} [$\times 10^{-3}$]	τcF σ_A [$\times 10^{-3}$]
$D^+ \to \bar{K}^{*o} K^+$	0.4	2.8 ± 0.8	2.3
$D^+ \to \rho^+ \pi^0$	0.4?	2.9 ± 0.8	2.3
$D^+ \to \pi^+ \eta$	0.7	-1.5 ± 0.4	2.3
$D^+ \to \pi^+ \pi^0$	0.2	0	2.8
$D^+ \to \phi \pi^+$	0.6	0	2.4
$D^0 \to \mathrm{K}^+\mathrm{K}^-$	0.5	~ 1	2.5

3.4 Charmonium physics overview

The J/ψ has revolutionised our understanding of light hadrons. Historically, as more J/ψ data have been accumulated, increasingly rich structures have appeared in the final state hadrons, and new states been discovered. This is an area of physics which is still limited by statistics and where a τcF—which will increase the existing world data on J/ψ decays by *three orders of magnitude* (Table 2)—will have a major impact. Some of the main experiments [15, 48] are as follows:

- The decays J/$\psi \to \gamma X$ have proven to be among the most productive in strong interaction studies. These have revealed the $\iota(1440)$ and $\theta(1700)$, which are candidates for glueballs and whose dynamical structure is still controversial. The τcF should definitively settle these controversies.
- The J/ψ is a unique filter of the internal structure of light hadrons. Exploiting the ideal mixing within the ω/ϕ enables the flavour content of associated mesons, M, to be determined via J/$\psi \to$M+ω/ϕ (an example is shown in Fig. 10). Improved data for M $= \iota$ and θ are especially needed. In addition, J/$\psi \to \gamma$A$\to \gamma$ ($\gamma\rho : \gamma\omega : \gamma\phi$) filters the flavour content of all $C = +$ states; this requires τcF statistics since only the channel J/$\psi \to \gamma\gamma\rho$ has been measurable so far. These channels, together with J/$\psi \to$ A+*hadrons*, are particularly interesting in the region $m_A > 2$ GeV. The meson spectrum in the 2–3 GeV mass range is expected to be rich, but has been barely explored in J/ψ decays. Presently there are hints of pseudoscalar states which may be the sign of new physics (hybrid states are predicted to occur in this region).
- Experimentation at the ψ' will, via $\gamma\chi_c$ decays, yield 10^8 χ_c's per month—equivalent to about ten times the present world sample of J/ψ. The χ_c offers special opportunities. In particular, the spin, J, can be fixed at 0, 1 or 2 and thereby the partial wave analysis of hadronic decays can be constrained. Examples include $\chi_{c0} \to f_0(975)$+M which enhances the scalar hadrons, M; and $\chi_{c1} \to \pi$+H which is sensitive to the hybrid exotic sector H ($J^{PC} = 1^{-+}$). These complement the p$\bar{\mathrm{p}}$ experiments at LEAR, providing greater statistics and the added bonus of constrained partial waves. The data on χ_c decays is presently notable for its almost complete absence. For such a

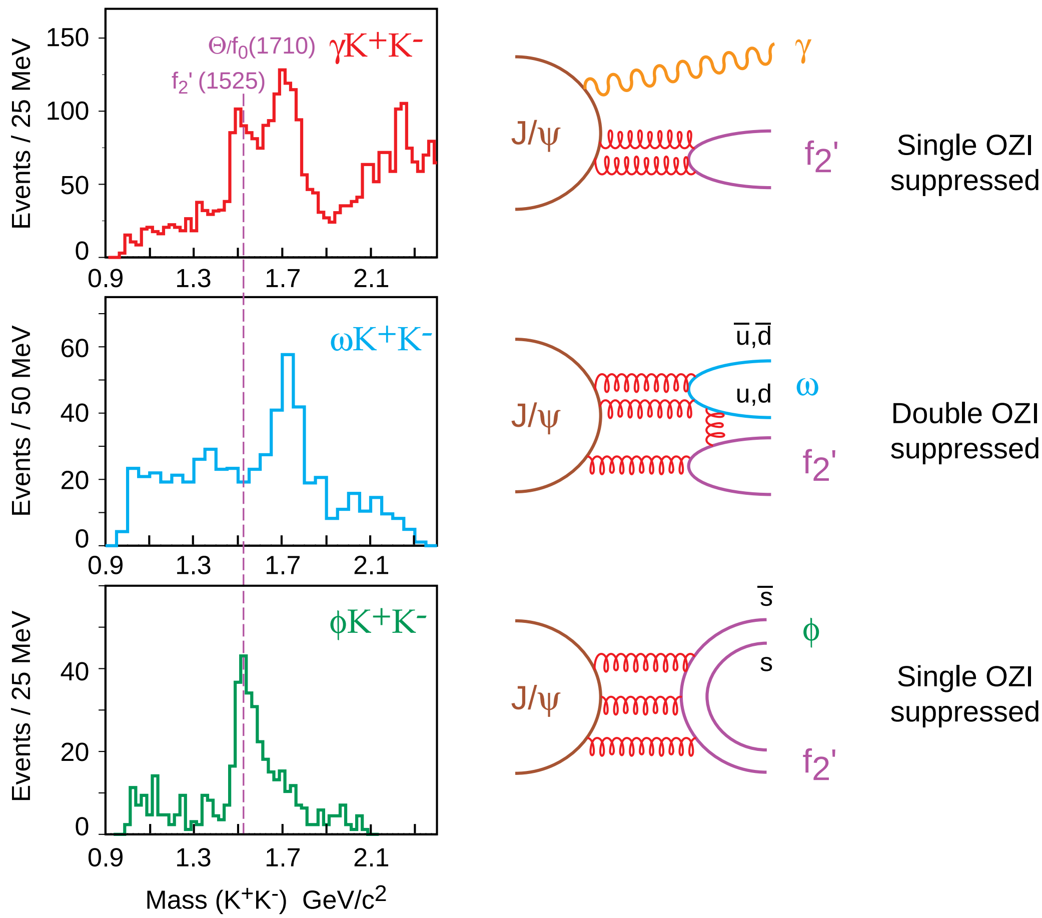

Figure 10: Analysing the quark/gluon content of a particle, M, by comparing its production in J/$\psi \to \gamma$M, ωM and ϕM [49]. In this example, M $\equiv$ $f_2'(1525)$, which is an $s\bar{s}$ state.

potentially rich source of unique information on the structure and dynamics of light hadrons, this is a remarkable gap in our knowledge. With the statistics of the τcF, the physics output from χ_c decays can greatly exceed that already flowing from the J/ψ.

– The Particle Data Group recognises four ψ states above 4 GeV. Nothing is known about their hadronic decays nor even if they are truly resonant states. The relative fractions of D, D^* and D^{**} in their decays will provide important information and tests of Heavy Quark Effective Theory, and can reveal the internal structure of these higher mass ψ states.

– In lattice QCD and related models, hybrid charmonium is predicted to exist within 300 MeV of charm threshold . These hybrids include vector states which can be formed directly in e^+e^- annihilation. Such states have been actively sought in the light quark sector during the last decade. Theory suggests that these states may be more clearly identified in the heavy quark sector and that charm is the optimal flavour (light enough that the states are produced in e^+e^- annihilation with leptonic widths $\mathcal{O}(0.1$ keV) and heavy enough that the conventional quarkonium potential states are well understood and that extra states can be readily identified). A fine-grained energy scan to search for these states can be carried out at a τcF over a period of about one month. This involves measuring the hadronic cross section above charm threshold in 1 MeV steps to an accuracy of 1%.[1)] The 1^- entry channel provides a well-understood, clean production mechanism with an optimal signature for hybrids. If hybrids states exist then it is likely that the τcF will be required for their discovery.

- In addition, the hadronic cross section at energies below the $J/\psi(3.10)$ will be measured at the τcF to a precision of about 1%. The interpretation of precision electroweak data requires a precise knowledge of the fine structure constant evaluated at the Z^0 pole, $\alpha(m_Z^2)$. The dominant source of error in the theoretical calculation of the radiative corrections to $\alpha(m_Z^2)$ [50] is due to the 15–20% experimental uncertainties in the cross-section $\sigma(e^+e^- \to \text{hadrons})$ in the low-energy region, $1 \lesssim E_{\text{cm}} \lesssim 5$ GeV. This is beginning to limit the theoretical precision of the electroweak parameters. For example, the present uncertainty in $1/\alpha(m_Z^2)$ of 0.09 causes an error of 0.00023 in the standard model prediction of $\sin^2\theta_W$ and an error of 4 GeV on m_t [51]. Similarly, the uncertainty in the hadronic cross section at low energies is the dominant source of error in the theoretical calculation of the anomalous magnetic moment of the muon, $a_\mu = (g_\mu - 2)/2$. The present uncertainty due to hadronic vacuum polarisation, $\delta a_\mu \sim 16 \times 10^{-10}$ [50], is substantially larger than the expected precision of the forthcoming BNL experiment, $\delta a_\mu = 4 \times 10^{-10}$.
- A tag on a final-state J/ψ at any operating energy of the τcF above open charm threshold may reveal the existence of further exotic states. An example is $J/\psi + \pi$, which would reveal isovector charmonium, such as $D\bar{D}$ or $D^\star\bar{D}^\star$ molecules. Sighting the J/ψ in association with an η could reveal the existence of ψ^* and complement the direct search $e^+e^- \to \psi^*$, thereby clarifying the dynamical structure of the ψ^*.
- The J/ψ provides a secondary factory for producing high-statistics samples of tagged light mesons. For example, assuming a one-year sample of 10^{10} J/ψ events, a study of the radiative decay modes $J/\psi \to \gamma\eta$ (0.1% Br) and $J/\psi \to \gamma\eta'$ (0.4%) would yield about 10^7 reconstructed events for each. This is be compared with the largest existing η' data sample of about 3×10^3 events. There are many interesting tests of QCD [52] and of the conservation of fundamental symmetries that could be performed with such large and clean samples of η's and η''s.

In summary, the τcF offers a new and unique window on the dynamics and structure of hadrons made of charm or of light flavours, and promises to elucidate the dynamical role of the gluonic degrees of freedom in the non-perturbative sector of QCD. New states of hadronic matter are predicted to exist in the energy range directly probed by the τcF. The high statistics of the τcF, together with a high-resolution detector, will enable important discoveries to be made about hadrons, and potentially fundamental discoveries on the role of gluons in the hadronic spectrum.

[1)] For comparison, the measurements in Fig. 3 have a statistical precision of about 5% and are in 10 MeV steps. DELCO took 12 weeks to record these data at SPEAR; a similar measurement could be done in a single shift at the τcF!

4 Design of the Tau-Charm Factory

4.1 Accelerator

4.1.1 Overview

The design of the τcF accelerator has been developed at several laboratories, including CERN [2, 3, 53], SLAC [54], LAL-Orsay [55], CERN/Spain [56], INP-Novosibirsk [57], JINR-Dubna [58], ITEP-Moscow [59], Argonne National Laboratory [60] and IHEP-Beijing [12, 61, 62]. All studies have confirmed that the τcF collider can achieve its design luminosity with a relatively "conservative" design, assuming previously-achieved performances for the machine parameters.

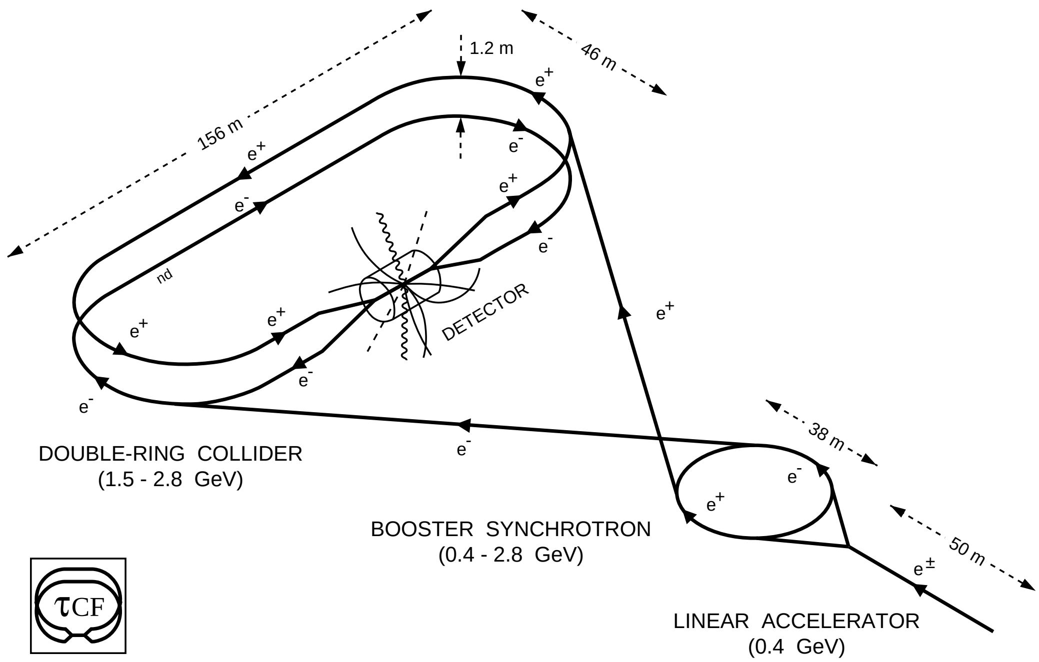

Figure 11: Conceptual layout of the τcF accelerator.

The τcF accelerators comprise an injector system and a double-ring collider (Fig. 11). In the absence of re-usable accelerators, the most cost-effective injector chain involves a linear accelerator, providing intense 0.4 GeV e^-/e^+ beams, followed by a booster cyclotron operating between 0.4 GeV and the maximum beam energy of the collider (to allow rapid injection of fresh beam at collision energy).

The primary energy range of the τcF collider extends from the $J/\psi(3.10)$ to 5.6 GeV total energy, which covers the charm baryon thresholds up to $\Omega_c\bar{\Omega}_c$ production. The collider is also designed to operate at energies below the J/ψ—albeit with substantially reduced luminosity—in order to allow for a precision $[\mathcal{O}(1\%)]$ measurement of the cross-section $\sigma(e^+e^- \rightarrow \text{hadrons})$ (see Section 3.4). The peak luminosity is 10^{33} cm^{-2}s^{-1} at 4 GeV total energy, close to the $\tau^+\tau^-$ and open-charm thresholds. The improvement in luminosity relative to previous machines at this energy (Table 6) is due to a higher stored current and tighter focusing at the interaction point. The τcF has about two orders-of-magnitude higher luminosity than the Beijing Electron Positron Collider (BEPC) [63], which is currently operating in this energy range.

Table 6: Comparison of the Beijing τcF (BTCF) [62] with previous e^+e^- colliders at $E_{beam} \simeq 2.0$ GeV. The luminosity, $L \propto (I\xi_y/\beta_y^*)E_{beam}$.

Item			SPEAR	BEPC	BTCF
Number of bunches	k_b		1	1	32
Effective bunch spacing	S_b	[m]	234	240	12
Current per beam	I	[mA]	10	50	570
Vertical β-function at IP	β_y^*	[m]	0.08	0.10	0.01
Beam-beam tune shift	ξ_y		0.025	0.04	0.04
Luminosity	L	[cm^{-2}s^{-1}]	1.0×10^{30}	1.0×10^{31}	1.0×10^{33}

4.1.2 Operating phases

As indicated previously, the CP violation experiments will push the performance of the τ-charm Factory. The concept of a flexible lattice for the τcF collider was therefore introduced at the Marbella workshop [64, 65] and subsequently further developed by the Orsay-Dubna collaboration [66] and by IHEP-Beijing [12, 62]. It has the following stages:

1. **Initial operation** of the collider at 10^{33} cm^{-2}s^{-1} with a conservative design.
2. **Longitudinal beam polarisation**. There are several possible schemes for generating longitudinally-polarised beams at the τcF. Longitudinal polarisation of a single beam (e^-) can be achieved relatively simply using a SLAC-type polarised electron source, together with spin rotators installed in the collider. Polarisation of both the e^+ and e^- beams can be achieved by two methods. The first is to polarise the beams before they are injected into the collider, by means of an additional small high-field storage ring in the injector chain [67]. The second and preferred method for the Beijing τcF (BTCF) [12] is to use high-field wigglers in the τcF collider, together with spin rotators. In view of the importance of polarisation to the physics programme (Sections 3.2.2 and 3.2.3), it is likely that the necessary hardware for longitudinal beam polarisation would be part of the first-phase operation of the BTCF.
3. **Increased luminosity**, with more bunches and a finite crossing angle, to provide $L \simeq 3 \times 10^{33}$ cm^{-2}s^{-1}. This would involve re-building the experimental insertion but leaving the rest of the collider unmodified.
4. **Monochromator optics** to reduce the collision energy spread from about 1.4 MeV to below 140 keV (at 2 GeV beam energy) [67, 68]. This has several important physics consequences. It increases the production of the narrow J/ψ and ψ' resonances (see Fig. 12), which is important for the measurement of CP violation in hyperon decays at the J/ψ, and in the production of $\tau^+\tau^-$ pairs at the J/ψ (Table 2). It improves the resolution of the $\tau^+\tau^-$ cross-section at threshold (Fig. 13) [69], allowing the detection of tauonium (Section 3.2.1), improving the precision on the measurement of the τ mass, and sharpening the monochromatic spectra of two-body τ decays. Finally, for charm physics, the tighter beam-energy kinematic constraint improves mass resolutions and reduces backgrounds. For example, the mass resolution in the τcF detector (Section 4.2.2) for $D^0 \to K^-\pi^+$ at the $\psi''(3.77)$ improves from $\sigma(m_D) = 1.3$ MeV to 0.6 MeV with monochromator optics [70].

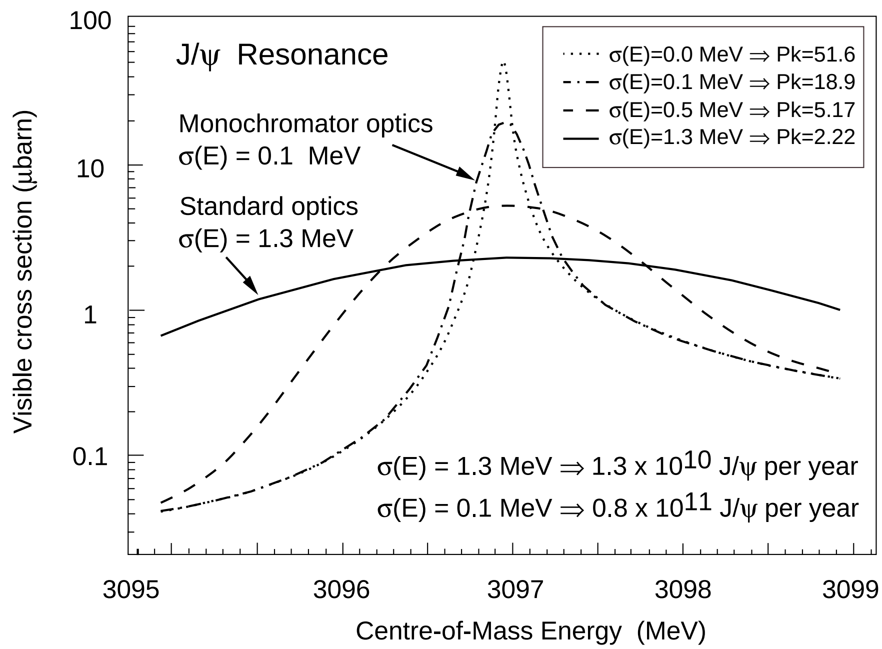

Figure 12: The visible cross section at the J/ψ resonance for several values of the beam collision energy spread σ(E).

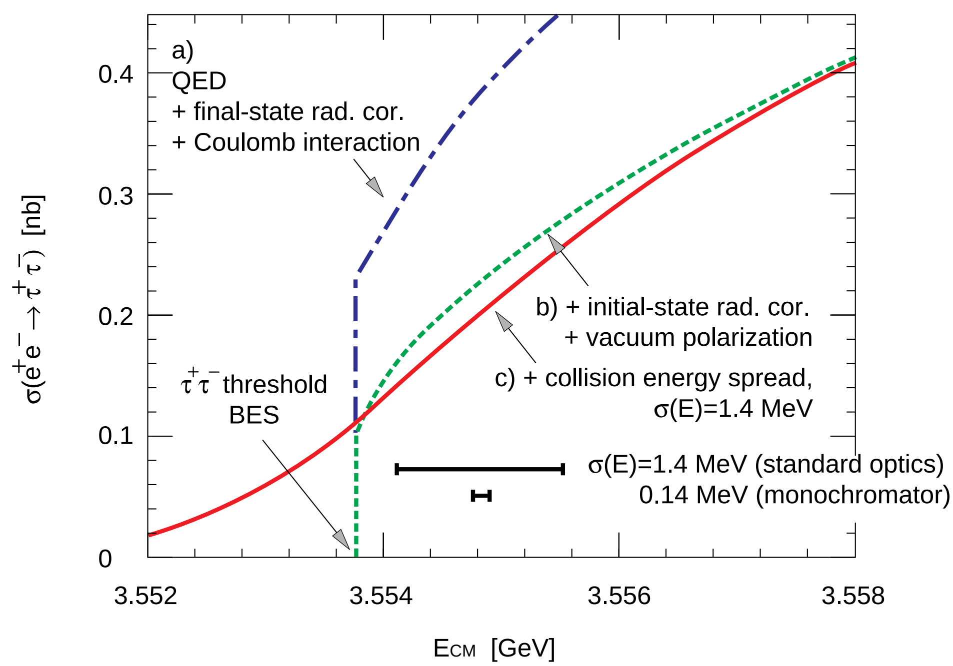

Figure 13: The $\tau^+\tau^-$ cross section at threshold [69], showing various contributions. The effect of the collision energy spread, $\sigma(E)$, is indicated by curve c), which corresponds to standard collider optics. This smearing can be reduced by an order of magnitude with monochromator optics.

In summary, although the τcF is a state-of-art accelerator, it can meet its basic design luminosity of 10^{33} cm^{-2}s^{-1} with relatively conservative design parameters which have already been achieved in other machines. Longitudinal beam polarisation will be part of the first-phase machine. The design will allow for future upgrades that include both increased luminosity and monochromatisation of the collision energy. In view of its flexibility and of the broad physics programme, it seems likely that the τcF would enjoy a long operating period of perhaps two decades.

4.2 Detector

4.2.1 Design requirements

Experiments at the τ-charm Factory are characterised in two ways: i) high-precision measurements, and ii) searches for rare processes. The basic requirement for both is high statistics but, in order to fully exploit the very large data samples generated at the τcF, backgrounds and systematic errors must be small and well understood. As described previously, the *physics* backgrounds at the τcF are small and experimentally measurable. However, special care must be taken to ensure that the *detector-induced* backgrounds and systematic errors are maintained at a comparably low level and are accurately monitored. These may arise from several sources, such as:

- Uncertainties in geometrical acceptance; blind regions in the detector.
- Uncertainties in detector efficiencies.
- Uncertainties in detector resolutions, and non-Gaussian tails.
- Detector mis-measurements, such as:
  - Mis-tracked particles.
  - Overlapping particles.
  - Fake photons ('splitoffs').
  - Particle mis-identification.
- Luminosity measurement errors.

These considerations have shaped the underlying principles in the detector design:

- *Uniform and efficient sub-detectors covering the full solid angle,* for reduced losses, reduced background feed-ins, and reduced uncertainties in efficiency corrections.
- *Highly granular detectors,* for improved precision, improved recognition of secondary interactions and reduced particle overlaps.
- *Redundant measurements,* for cross-checks and improvement of the overall performance.
- *Frequent calibration and monitoring* (at the J/ψ and ψ'), for precise knowledge of the detector performance and resolution distributions.

4.2.2 Detector design

The design of a detector for the τ-charm Factory has been developed over the course of several workshops [4, 5, 8], and is being further improved in the BTCF feasibility study [12, 62]. The detector concept, which is shown in Figs. 14 and 15, covers all the foreseen physics and is technically feasible. The main features are as follows:

- A low-mass drift chamber using Al field wires and a He-based gas to optimise the performance for low-momentum particles. The analysing magnetic field is provided by a superconducting solenoid (B = 1 T).

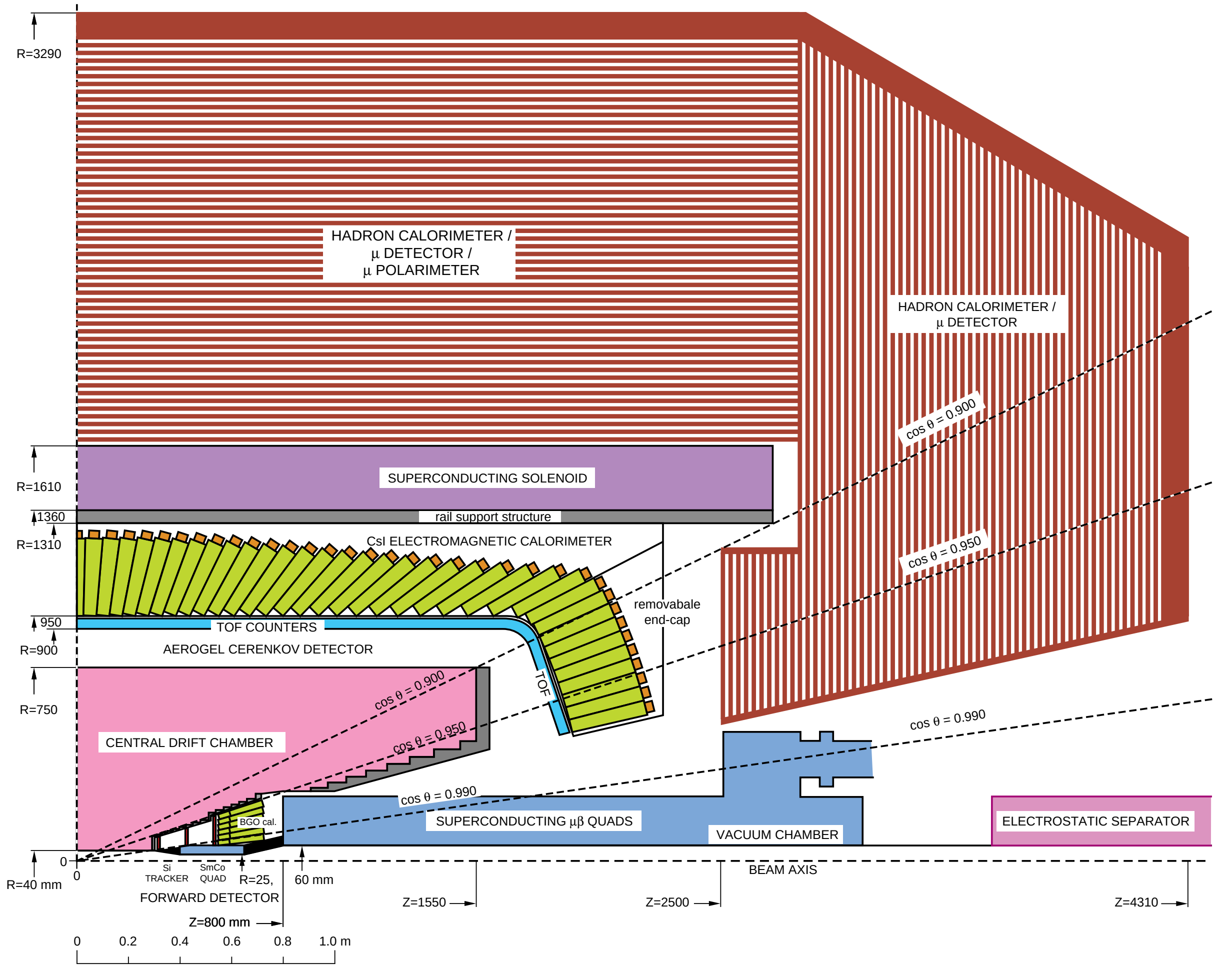

Figure 14: The τcF detector concept; rz view.

- A CsI(Tl) crystal electromagnetic calorimeter to achieve high resolution measurements of γ's, and high efficiency down to low energies, $\mathcal{O}(10)$ MeV.
- High-quality particle identification in the region below about 1.3 GeV/c by a combination of dE/dx measurements in the central drift chamber, time-of-flight measurements based on plastic scintillation counters read out with mesh-dynode phototubes and, finally, a Cerenkov device. Among the options under consideration for the latter, an aerogel counter is perhaps the best-suited.
- A hermetic design for neutrino 'identification'. The hermeticity is completed with a fine-grained outer hadron calorimeter/μ detector and with small-angle detectors comprising Si micro-strip detectors and BGO calorimeters.
- A polarimeter for measuring the average longitudinal polarisation of μ^+'s in τ decay (see Section 3.2.2). In the barrel region of the hadron calorimeter about half of the sectors are made from iron plates and half from copper plates (see Fig. 15). The former provide the flux return and the latter provide the capability to stop μ's up to a momentum of ~1 GeV/c, without de-polarisation. A weak magnetic field, $B \simeq 50$ mT parallel to the z axis, precesses the spin of the stopped μ's. The decay time and

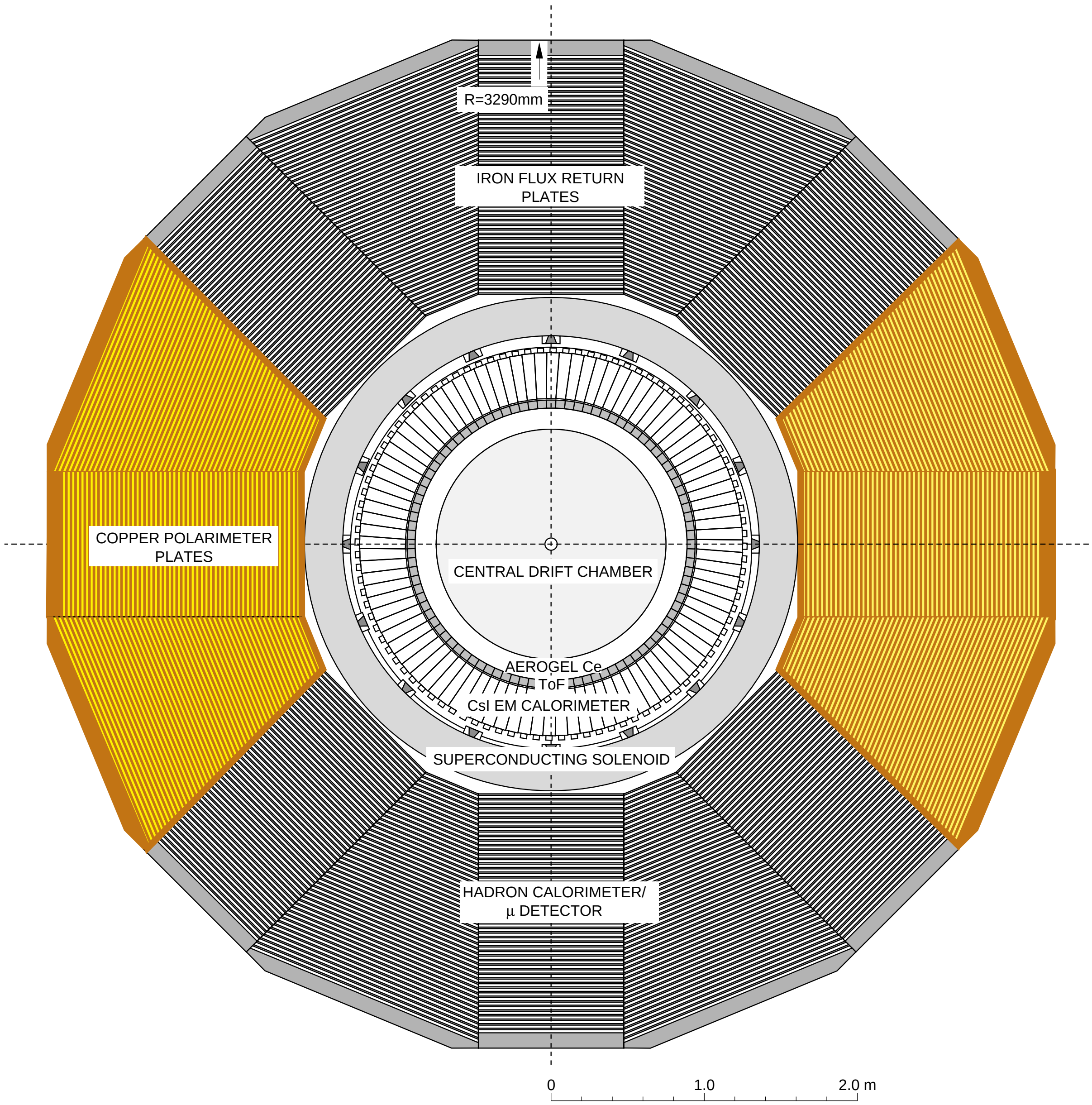

Figure 15: The τcF detector concept; transverse view.

direction are measured with resistive plate chambers (RPC's) in the active gaps.

– A powerful on-line farm of parallel processors to analyse, select and compress the events before writing them to tape. The requirements (at the J/ψ) are about 3×10^4 MIPS on-line CPU power and data storage requirements of about 30 Tbyte per year.

In summary, a detector can be built with present technologies that can maintain low systematic errors and take full advantage of the large increase in statistics at the τ-charm Factory. In comparison with previous detectors at these energies (Table 7), the τcF detector represents a substantial improvement in performance

Table 7: Comparison of the performance of the τcF and BES detectors for charged particles and photons. The symbol '$\oplus$' denotes addition in quadrature.

Item	BES	τcF
Charged particles:		
Momentum resolution: σ_p/p(GeV/c)	$0.7\%p \oplus 1.3\%/\beta$	$0.3\%p \oplus 0.3\%/\beta$
Angular resolution: σ_ϕ (mr)	$2 \oplus 2/\mathrm{p}\beta$	$0.5 \oplus 1.1/\mathrm{p}\beta$
Barrel solid angle ($\times 4\pi$ sr)	70%	90%
Photons:		
Energy resolution: σ_E/E(GeV)	$17\%/\sqrt{E}$	$2\%/E^{\frac{1}{4}} \oplus 1\%$
Angular resolution: $\sigma_{\theta,\phi}$ (mr)	5	$1.7 + 2/\sqrt{E}$ (at $\theta = 90°$)
E^{γ}_{min}(MeV)	100	10

4.3 Cost estimates

A detailed cost estimate for a τcF was prepared by CERN experts in 1993 for the Spanish project [71]. The conclusions were an estimated cost of 290 MCHF for constructing a τcF accelerator on a green-field site, and an estimated personnel requirement of 660 man-y. For an existing laboratory with an injector, these requirements are substantially reduced to approximately 100 MCHF and 315 man-y, respectively. The estimated detector cost is approximately 70 MCHF.

5 Conclusion

Deeper exploration of the high precision frontier is required to understand the puzzling flavour structure of the standard model: the reasons for the three generations of quarks and leptons, the mixing of the quarks and its apparent absence for the leptons, and the origin of CP violation. The next round of precision experiments cannot be done in a 'parasitic' fashion as in the past; it will require dedicated machines, known as particle factories, that are optimised for specific particles.

On a world-wide basis, one B factory (CESR) is in operation, two asymmetric B factories (PEP-II and KEKB) are under construction, and one ϕ factory (DAΦNE) is nearing completion. A τ-charm Factory is the essential part of this programme that is not yet approved. It provides a unique experimental environment for precision τ and charm studies: unprecedented statistics, tagged decays, backgrounds that are small *and* experimentally measurable, and high-rate sources for calibrating the detector. Many of the experiments at the τcF are either unique or cannot be done elsewhere at comparable precision.

In particular, the τcF will make sensitive searches for CP violation in D and τ decays, about which we know almost nothing experimentally. With longitudinal beam polarisation and other features unique to the τcF, the experimental sensitivity reaches the level where effects may be seen in charm decays and where the τ is probed at the milliweak level—similar to where CP violation is observed in K decays.

The designs of the τcF machine and detector have been developed and refined over the last ten years in a series of workshops and studies. China is presently actively preparing a feasibility study for a τcF at IHEP in Beijing, to be completed by the end of 1996. The international particle physics community looks forward to the success of the Beijing Tau-Charm Factory.

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