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THE TAU-CHARM FACTORY AND TAU PHYSICS*

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Abstract

An international group of physicists is developing the concept and design of a Tau-Charm Factory: a two-ring, electron-positron, circular collider with $1.5 \leq \sqrt{s} \leq 4.2$ GeV and a design luminosity of 10^{33} cm^{-2} s^{-1}. This paper presents the concept of the facility and outlines the tau lepton physics which can be done. A companion talk by R. Schindler discusses the D^0, $D^{\pm}$, and D_s physics at a Tau-charm Factory.

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I. Concept and Physics Range

An international group of physicists, Table 1, is developing the concept and design of a Tau-Charm Factory: a two-ring, electron-positron circular collider with the parameters:

$$\begin{gathered} 3.0 \leq \sqrt{s} \leq 4.2 \text{ GeV} \\ L = \text{design luminosity } = 10^{33} \text{ cm}^{-2} \text{ s}^{-1} \end{gathered} \tag{1}$$

The ~~facility~~ might operate above 4.2 GeV, perhaps up to 5.0 GeV, but with reduced luminosity.

Table I. Physicists developing the concept and design of the Tau-Charm Factory described in this paper.

K. L. Brown, SLAC
D. Coward, SLAC
J. Gomez-Cadenas, IFIC, Spain
C. Heusch, Univ. of California-Santa Cruz
J. M. Jowett, CERN
J. Kirkby, CERN
G. Mills, Univ. of Michigan
N. Nelson, CERN
M. Perl, SLAC
R. Schindler, SLAC
A. Seiden, Univ. of California-Santa Cruz
W. Toki, SLAC

The proposed luminosity of 10^{33} cm^{-2} s^{-1} is about 100 times the design luminosity of BEPC,[1] the e^+e^- collider at Beijing which is now operating very successfully. And the proposed luminosity is almost 1000 times the luminosity attained at SPEAR in the same energy region.

The objective is to attain the following, very large particle production rates at $L = 10^{33}$ cm^{-2} s^{-1}. I call eight months of data acquisition a physics-year.

- Most studies of tau physics at the Tau-Charm Factory will use τ pair production at about 3.67 GeV, just below the ψ', to eliminate backgrounds from the ψ' and from D

decays. The τ production is

$$\text{Number } \tau \text{ pairs/physics-year } = 4 \times 10^7 \tag{2}$$

- The study of D physics will be carried out at the ψ'' where clean tagging of D pairs can be done. The D production is:

$$\begin{aligned} \text{Number } D^+D^- \text{ pairs/physics-year } &= 9 \times 10^7 \\ \text{Number } D^0\bar{D}^0 \text{ pairs/physics-year } &= 10^8 \end{aligned} \tag{2b}$$

- The best energies for producing the D_s and D_s^* will be determined in an initial energy scan at the Tau-Charm Factory. The rates given next are for $D_s^+D_s^-$ pairs at 4.03 GeV and $D_s^\pm D_s^{\mp *}$ at 4.14 GeV:

$$\begin{aligned} \text{Number } D_s^+D_s^- \text{ pairs/physics-year } &= 10^7 \\ \text{Number } D_s^\pm D_s^{\mp *} \text{ pairs/physics-year } &= 2 \times 10^7 \end{aligned} \tag{2c}$$

- The production rates for the ψ/J and ψ' are so large that I give the rates per physics-month:

$$\begin{aligned} \text{Number } \psi/J \text{ per physics-month } &= 10^9 \\ \text{Number } \psi' \text{ per physics-month } &= 5 \times 10^8 \end{aligned} \tag{2d}$$

The Tau-Charm Factory concept described in this talk began with the work of Jasper Kirkby.[2] The first design of the collider in this concept was initiated and carried out by John M. Jowett.[3] As shown in Table I, Kirkby and Jowett are now working on the further development of the Tau-Charm Factory design.

Two other discussions of Tau-Charm Factories have been initiated. One discussion[4] concerns such a facility being built in Spain. The other discussion[5] concerns such a facility being built at Moscow in the USSR.

II. Four Principles for a Tau-Charm Factory

The physics power, the physics range, and the physics reach of a Tau-Charm Factory depends upon four interlocking principles:

A. Very Large and Very Pure Data Samples: The data samples must be not only very large, but also very pure. This requires D^0 and $D^\pm$ studies at the ψ'' where the D's can be cleanly tagged. Similarly τ physics is studied below the ψ' where the τ pair can be selected by a clean, single-tag.[6] The detector properties must enable these clean tags. Furthermore the experimenters must be able to change the energy, moving off the production point in order to study backgrounds and contaminations.

B. High Peak Luminosity: The design luminosity of 10^{33} cm^{-2} s^{-1} requires very careful design and construction of the collider. Also required is generous provision of machine flexibility, machine instrumentation and acceleration physics time, so that the collider can be brought from the turn-on luminosity to the design luminosity.

C. High Average Luminosity: This principle imposes several requirements on a Tau-Charm Factory. The facility must have its own, dedicated injector for e^- and e^+ to allow filling the rings to full current every hour or so. The dedicated injector is also required for efficient upgrading of the facility from turn-on luminosity to design luminosity. The principle of high average luminosity also requires well built and very reliable accelerator and detector components. These components must be able to perform as specified, and should require only regular, periodic maintenance.

D. Detector Suited to Tau-Charm Physics: The physics of the τ, of charm, of the ψ/J and ψ', imposes special criteria on the detector such as the need for clean tagging of τ pairs and D pairs, and the need to measure very low energy photons and charged particles. A special requirement is a system for detecting neutrons and K_L^0's, so that missing energy due to neutrinos can be measured.

III. Collider Concepts

The first three principles in Sec. II lead to the following general concepts for the collider:

- The electron-positron collider would be circular, not linear.
- There would be two rings, probably with 0° crossing angle.
- The total energy would be 3.0 to about 4.2 GeV; at higher energy there would be much less luminosity.
- The maximum luminosity is 10^{33} cm^{-2} s^{-1}.
- The facility would have a dedicated e^+ and e^- injector.
- There would probably be one interaction region.
- The site requires about 100 m × 200 m, plus space for an injector.

The selection of the circular collider design is based upon the great amount of experience and knowledge gained in the 20 year history of building and operating e^+e^- storage rings. The two-ring design is required by the relatively large current per bunch and the relatively large number of bunches. The range of primary operating energies is kept narrow to maximize the luminosity throughout that range. The design is simplified and the luminosity per interaction region is maximized if there is just one region; the issue of two interaction regions has to be investigated. Jowett[3] has worked out a design for one interaction region.

The selection of a final design for the collider is a large enterprise in which a number of issues conceived with the high luminosity and the two-ring concept must be worked out.

The Tau-Charm Factory Workshop,[7] May 23–27, 1989 is a step in the selection of a collider design.

IV. Detector Concepts

There is not yet a design for a detector for tau-charm physics. Some general concepts are:

- The detector would be magnetic with a drift chamber. A $\sigma_p/p \approx 0.5\%\ p$ (GeV/c) is needed.
- There would be close to 4π sr coverage.
- An electromagnetic calorimeter inside the coil would be designed for: detection of low energy and closely spaced photons, and for good electron-hadron discrimination.
- Very good identification of $\pi^{\pm}$, $K^{\pm}$, p, e and μ would be obtained using: time-of-flight counters, drift chamber dE/dx, the electromagnetic calorimeter, and the muon detection system described next.
- The detector would have a close to 4π sr combined muon detection system and 5 interaction length hadron calorimeter. This combined system would: (a) select μ's through their non-interaction and range and (b) detect K_L^0's and neutrons through their interactions. This latter feature allows selection of events whose missing energy is due only to neutrinos or to particles staying in the beam pipe.

The design of a detector awaits thorough understanding of how to do the physics of the tau-charm region. The detector must provide the power for clean tagging of τ pairs and D pairs. The detector must allow for measurement of photons and charged particles with energies as small as tens of MeV. The clean identification of μ's with momenta less than 1 GeV/c is an important issue. One purpose of the Tau-Charm Workshop[7] is further exploration of the physics leading to the establishment of more precise criteria for detector design.

V. Tau Physics: Overview

Much has been learned about the τ lepton[8–10] since its discovery in 1975. But in the last few years there has been a considerable slowing of progress in τ research. Indeed our understanding of τ physics has become clouded by our failure to solve the problem of 1-charged particle decay modes which seem to be missing.[10–12]

There are three reasons for the slowing of progress in τ research. First, much larger data sets of

$$e^+ + e^- \rightarrow \tau^+ + \tau^- \tag{3}$$

events are needed. Second, the tagging of the events is usually inefficient, often below 10%. The inefficiency is caused by the need to double-tag the event, imposing restrictions on both τ decays.[6] The need to double-tag is caused mostly by the energies at which τ pairs are now

acquired; but some of the need is caused by the insufficiencies of present detectors. The third reason for the slowing of τ research is that present sets of τ data are contaminated by non-τ events by amounts from 5 to 20%.

Most τ studies at a Tau-Charm Factory would be carried out at about 3.67 GeV, which is below the ψ'. The τ pair cross section is still substantial, 2.03 mb, and there is no background from ψ', D, or B decays. The skill of the experimenter in removing remaining background sources can be tested by reducing the energy to just below the τ pair threshold of about 3.58 GeV. There will be very little difference from 3.67 GeV to 3.58 GeV in the behavior of the background processes:

$$e^+ + e^- \rightarrow \text{ hadrons} \tag{4a}$$

$$e^+ + e^- \rightarrow e^+ + e^-,\ \mu^+ + \mu^- \tag{4b}$$

$$e^+ + e^- \rightarrow e^+ + e^- + e^+ + e^-,\ e^+ + e^- + \mu^+ + \mu^- \tag{4c}$$

$$e^+ + e^- \rightarrow e^+ + e^- + \text{ hadrons} \tag{4d}$$

The single-tagging of τ pairs is to be done by using the purely leptonic decays

$$\begin{aligned} \tau^- &\rightarrow e^- + \bar{\nu}_e + \nu_\tau \\ \tau^- &\rightarrow \mu^- + \bar{\nu}_\mu + \nu_\tau \end{aligned} \tag{5}$$

and requiring that the presence of the neutrinos be demonstrated by missing momentum. Of course, the missing momentum must not point along the beam line and must not be caused by an undetected K_L^0 or n. Therefore the detector must be able to detect neutral hadrons by interaction as noted in Sec. IV.

Tau physics is a very broad subject and its full exploration requires a range of techniques. In the next sections I illustrate by examples and comments the areas of tau physics best studied at a Tau-Charm Factory. Other areas of tau physics require higher energies for $e^+e^- \rightarrow \tau^+\tau^-$: PEP energies, TRISTAN energies, or the Z^0 energy. And direct study of the tau neutrino itself requires completely different techniques: beam dump experiments or searches for neutrino oscillations.

VI. Tau Physics at a Tau-Charm Factory: Examples and Comments

In this section I illustrate by examples and comments the parts of tau physics which require, or can be best carried out, at a Tau-Charm Factory.

A. Example: Measurement of ν_τ Mass and τ Mass.

The present 95% CL upper limit[13] on m_{ν_τ} is 35 MeV/c^2 obtained from the decay mode

$$\tau^- \rightarrow \pi^- + \pi^+ + \pi^- + \pi^+ + \pi^- + \nu_\tau \tag{6}$$

The branching fraction for this mode is 6×10^{-4}. With 10^7 produced τ pairs at a Tau-Charm Factory m_{ν_τ} can be explored down to 3 MeV/c^2 by (a) studying[14] the spectrum of the mass of the 5π's in this decay mode, and (b) measuring m_τ to ± 0.6 MeV/c^2.

With more τ pairs and measurement of m_τ to ± 0.2 MeV/c^2, m_{ν_τ} might be explored to 1 MeV/c^2.

B. Example: Precise Study of Purely Leptonic Decays

The decay modes

$$\begin{aligned} \tau^- &\to e^- + \bar{\nu}_e + \nu_\tau \\ \tau^- &\to \mu^- + \bar{\nu}_\mu + \nu_\tau \end{aligned} \tag{7}$$

take place through the virtual W process

$$\tau^- \to \nu_\tau + W^-_{virtual} \tag{8a}$$

$$W^-_{virtual} \to e^- + \bar{\nu}_e,\ \mu^- + \bar{\nu}_\mu \tag{8b}$$

Since the vertices in Eq. 8b have been extensively studied through μ decay, the $\tau - W - \nu_\tau$ vertex can be precisely studied when two requirements are met.

(a) A large, clean sample of τ decays is needed.

(b) The shape of the e or μ momentum spectrum is best measured when the τ's are produced almost at rest. At higher energy the Lorentz boost dominates the spectral shape.

A careful study of the momentum spectra might also reveal effects of unconventional particle physics: a $\tau - W - \nu_\tau$ vertex structure other than V–A; or a particle other than the W which couples with sufficient strength to $\tau - \nu_\tau$ and $e - \nu_e$ or $\mu - \nu_\mu$.

C. Example: Precise Measurement of $B(\tau^- \to K^-\nu_\tau)/B(\tau^- \to \pi^-\nu_\tau)$

When the τ pair is produced at 3.67 GeV the decay modes

$$\begin{aligned} \tau^- &\to K^- + \nu_\tau \\ \tau^- &\to \pi^- + \nu_\tau \end{aligned} \tag{9a}$$

can be distinguished from each other by both momentum range and particle identification. Therefore the ratio $B(\tau^- \to K^-\nu_\tau/B(\tau^- \to \pi^-\nu_\tau)$ can be precisely measured.

This gives a direct measurement of $\theta_{Cabbibo}$ to test against other measurements from K decay and D decay assuming the τ is a conventional lepton. If the τ is unconventional or has a sufficiently strong coupling to an unconventional particle, then there will be a disagreement in the $\theta_{Cabbibo}$ determinations. For example, virtual leptoquark exchange[15] could contribute to $\tau^- \to K\nu_\tau$ more than it contributes to $\tau^- \to \pi^-\nu_\tau$ or $K^- \to \mu^-\bar{\nu}_\tau$.

D. Decay of τ Through a Second Class Current

The decay

$$\tau^- \to \pi^- + \eta + \nu_\tau \tag{10}$$

offers the first opportunity to study a weak decay process through a second-class current.[16,17] In quark language a second class weak current occurs when strong isospin is violated

by the difference between m_d and m_u. Reference 16 gives the estimate

$$B(\tau^- \to \pi^- \eta \nu_\tau) \sim \left(\frac{m_d - m_\mu}{300 \text{ MeV/c}^2} \right)^2 B(\tau^- \to \pi^- \nu_\tau) \tag{11a}$$

$$\sim 10^{-5}$$

But a smaller value

$$B(\tau^- \to \pi^- \eta \nu_\tau) \sim 10^{-6} \tag{11b}$$

is also possible.

The sure discovery of this mode would require that the η be detected in two of its decay modes: $\eta \to \gamma\gamma$ and $\eta \to \pi^+\pi^-\pi^0$. Therefore a large number of 3-prong as well as 1-prong τ decays are needed.

Table II. Summary of the 1-charged particle decay mode problem from Ref. 11.

	Rows	Symbol	Decay Mode of τ^-	Branching Fraction (%)
From direct measurement	1	B_1	1-charged particle inclusive	86.6 ± 0.3
	2	B_e	$\nu_\tau + e^- + \bar{\nu}_e$	17.6 ± 0.4
		B_μ	$\nu_\tau + \mu^- + \bar{\nu}_\mu$	17.7 ± 0.4
		B_π	$\nu_\tau + \pi^-$	10.8 ± 0.6
		B_ρ	$\nu_\tau + \rho^-$	22.5 ± 0.9
			Sum for modes in Rows 2	68.6 ± 1.2
	3	$B_{\pi 2\pi^0}$	$\nu_\tau + \pi^- + 2\pi^0$	7.6 ± 0.8
			$\nu_\tau + mK + n\pi^0$ $\to$ 1-charged particle $m \geq, n > 0, K = K^0$ or K^-	1.8 ± 0.3
			Sum for modes in Rows 3	9.4 ± 0.9
From theory and other data	4		$\nu + \pi^- + n\pi^0$ $n \geq 3$	
			$\nu_\tau + \pi^- + m\eta + n\pi^0$ $\to$ 1-charged particle $m \geq 1, n \geq 0$	
			Sum for modes in Rows 4	≤ 2.7
	5		Sum for modes in Rows 2, 3, and 4	80.7 ± 1.5

?

E. The One-Charged Particle Decay Mode Problem

The 1-charged particle decay mode problem,[10–12] Table II, may or may not be solved with data from existing e^+e^- storage rings. If it is not solved when a Tau-Charm Factory begins operation, the solution of the problem will require a large and clear sample of τ decays. If the problem is caused by the occurrence of unconventional physics in the τ decay process, then that unconventional physics can be studied in detail at a Tau-Charm Factory.

F. Other Tau Physics at a Tau-Charm Factory

There are other areas of tau physics which are best studied at the near-threshold production energy of a Tau-Charm Factory.

- Detailed Studies of Hadronic Decay Modes: The careful sorting out of the hadronic decay modes

$$\tau^- \to \nu_\tau + \text{hadrons} \tag{12a}$$

provides data which can be examined in different ways. From one point of view it is data on

$$W_{virtual} \to \text{ quarks } \to \text{ hadrons} \tag{12b}$$

in the .5–1.5 GeV region. From another point of view it is data on the properties of hadronic resonance in that energy region. The data is broader than that obtained from

$$e^+ + e^- \to \text{ hadrons}$$

in that energy region because the current may be pseudoscalar or axial vector as well as vector.

- Search for Decays Violating Lepton Conservation: Decay modes such as

$$\tau^- \to e^-\gamma,\ \mu^-\gamma,\ e^-e^+e^-, \ldots \tag{13a}$$
$$\tau^- \to e^-\pi^0,\ \mu^-\pi^0 \tag{13b}$$
$$\pi^- \to e^-K^0,\ \mu^-K^0 \tag{13c}$$

can be sought to branching ratios at the 10^{-6} to 10^{-7} level. Present upper limits[18–20] are 10^{-4} to

- Search for Production Violating Lepton Conservation: The lepton non-conservation production processes

$$\begin{aligned} e^+ + e^- &\to \tau^\pm + e^\mp \\ e^+ + e^- &\to \tau^\pm + \mu^\mp \end{aligned} \tag{14}$$

can be sought to a level 10^{-6} to 10^{-7} of $e^+e^- \to \tau^+\tau^-$.

- Radiative Tau Decays: There are four simple radiative decay modes.

$$\tau^- \to e^- + \bar{\nu}_e + \nu_\tau + \gamma \tag{15a}$$
$$\tau^- \to \mu^- + \bar{\nu}_\mu + \nu_\tau + \gamma \tag{15b}$$
$$\tau^- \to \pi^- + \nu_\tau + \gamma \tag{15c}$$
$$\tau^- \to K^- + \nu_\tau + \gamma \tag{15d}$$

as well as more complicated modes with more hadrons or more photons. The quality and quantity of existing tau data sets allow a study[21] of only the radiative decay

in Eq. 15b. The Tau-Charm Factory will allow precise studies of all these radiative modes.

- Is the Tau a Dirac Point Particle?: The conventional way to test[8] the Dirac point particle nature of the τ is to ascribe a form factor to the $\tau - \gamma - \tau$ vertex and to measure $\sigma(e^+e^- \to \tau^+\tau^-)$. In that test method, the higher the production energy the more sensitive the test; and cross section measurements from a Tau-Charm Factory are of no interest. But there is another speculative way in which the behavior of a τ could effectively differ from that of a Dirac point particle, a way in which the deviation does not increase in a simple way with energy. In that speculation[22] there is a neutral particle which couples only to the τ. Precise measurements of $d\sigma(e^+e^- \to \tau^+\tau^-)/d\cos\theta$ as a function of s near threshold might be most sensitive.

- Is the Tau a Sequential Lepton?: The discovery of the τ and most of its research history was and is based on the concept that the τ is a sequential lepton in the series e, μ, τ, ... From time to time a few speculative ideas have arisen that the τ is not simply a sequential lepton, but that it has special properties compared to the e or μ. At this conference two such ideas were presented.

Barbieri[23] considered the question of why the mass of the top quark may be about the same size as m_W. In his model the possibility is enhanced of finding new physics associated with the τ.

Fritzsch[24] has noted that

$$\begin{aligned} m_\tau &\gg m_\mu + m_e \\ m_b &\gg m_s + m_d \ , \end{aligned} \tag{16}$$

and based on the lower limit on m_t

$$m_t \gg m_c + m_u$$

He then considers a mass matrix model in which the third generation has a special role, a role in which the tau is more likely to be associated with detectable effects of new physics.

With these considerations I end my discussion of the tau physics which can be done at a Tau-Charm Factory. That physics extends from numerous basic measurements on the τ and ν_τ to new speculations about the nature of the τ. I see no other way, but a Tau-Charm Factory, to properly do that physics. Other physicists have reached a similar conclusion. Tau-Charm Factories are being considered for Spain[25] and for the Soviet Union.[5]

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