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THE TAU-CHARM FACTORY: EXPERIMENTAL PERSPECTIVES*

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A THE TAU-CHARM FACTORY CONCEPT

A1 The Concept

In this paper we present an experimental perspective on the tau-charm factory and an overview of the particle physics which will be studied and explored at the tau-charm factory. The tau-charm factory (Kirkby 1987, Kirkby 1989) is a high luminosity, two-ring, electron-positron collider and detector with the following properties:

- Range of total energy = 3.0 to 5.0 GeV
- Design luminosity = 10^{33} cm^{-2} s^{-1} at 4 GeV
- High resolution, large acceptance detector specially designed for tau and charm physics

The recent, extensive studies of particle physics at the Z^0 show that for the foreseeable future, research on the elementary fermions is limited to the three known generations:

GENERATION	LEPTONS		QUARKS	
First	e	ν_e	u	d
Second	μ	ν_μ	[c]	s
Third	[τ]	[ν_τ]	(t)	b

Of these twelve fundamental fermions, there is a tremendous amount more to be studied about the five poorest-known ones : the c, τ, ν_τ, b, and t. Of course the t has not yet been found. The purpose of the tau-charm factory is to enable precise and probing studies of the properties and interactions of the fermions in the boxes, the c,τ, and ν_τ .

These precise and probing studies will be accomplished through the use of the four basic elements of the tau-charm factory concept (Kirkby 1987, Kirkby 1989 Schindler 1989a):

- Control of and direct measurement of backgrounds and contaminations.
- Very large statistics
- Production of particles in known quantum mechanical states.
- Detector with very high quality particle identification, very good momentum and energy resolution, and close to 4π acceptance.

First we discuss the control of and direct measurement of backgrounds and contaminations. The basic particle production processes are:

Tau pair production:	$e^+ + e^- \rightarrow \tau^+ + \tau^-$
Charmed meson production	$e^+ + e^- \rightarrow D^+ + D^-$
	$e^+ + e^- \rightarrow D^0 + \bar{D}^0$
	$e^+ + e^- \rightarrow D^0 + \bar{D}^{*0}$
	$e^+ + e^- \rightarrow D_s^+ + D_s^-$
	$e^+ + e^- \rightarrow D_s^+ + D_s^{*-}$
Charmed baryon production	$e^+ + e^- \rightarrow \Lambda_c + \bar{\Lambda}_c$
Charmonium production:	$e^+ + e^- \rightarrow J/\Psi$
	$e^+ + e^- \rightarrow \Psi'$

In experiments at the tau-charm factory the particles are produced at resonances or at energies a little above production thresholds, as shown in Fig.1. This allows direct determination and study of backgrounds. For example, D^+D^- and $D^0\bar{D}^0$ production is carried out at the Ψ'' resonance. Not only is the D pair production cross section large at the Ψ'', but backgrounds from other processes can be directly determined by running the collider just below the Ψ''.

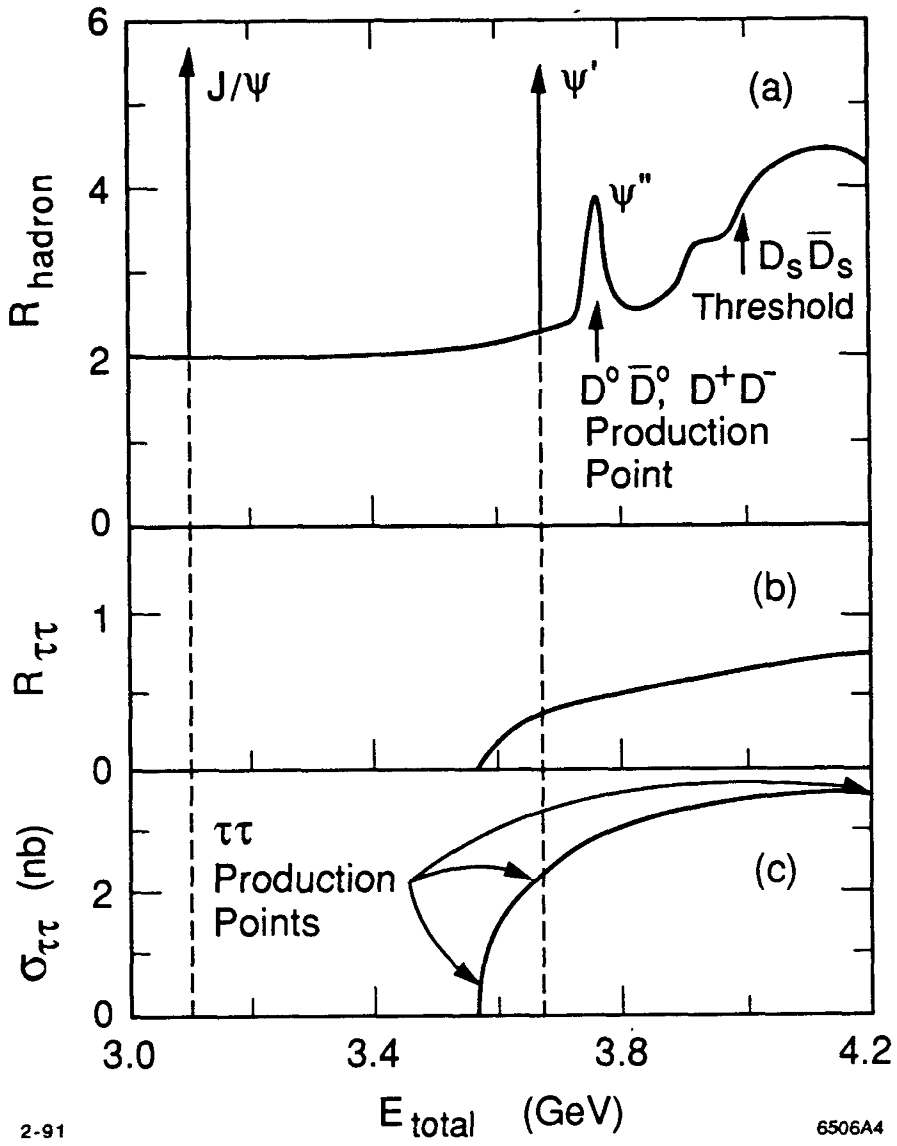

Fig. 1

Similarly, the primary operating energies for τ pair production are:

3.57 GeV: just above the τ pair threshold
3.67 GeV: just below the Ψ' resonance

At these energies there is no production of charm or bottom hadrons, the only background is from ordinary hadrons, and that background is almost constant between these operating energies and the energy just below τ pair threshold. Suppose a surprising small but new phenomenon is observed in tau decays. Is it new physics or is it from hadronic background contamination? This can be settled by operating below the τ pair threshold. In present tau research it is difficult or impossible to answer such a question with certainty because the hadronic backgrounds can only be obtained from models of hadron production.

Thus the operating energy range of the tau-charm factory enables the experimenter to make sure that precise measurements are not compromised by unknown backgrounds, and also allows the experimenter to search for new physics with confidence. But there is a second requirement for precise measurements. It is essential to have very large data sets. With the tau-charm factory very large statistics are obtained through the high luminosity and the large production cross sections in the energy range of operation. Typical particle production rates are summarized in Table 1.

Table 1 Particle production rates at the tau-charm factory year, based on 10 fb^{-1} per year

Particle	Events per year
D^0 (single)	5.8×10^7 at Ψ''
D^+ (single)	4.2×10^7 at Ψ''
D_s (single)	1.8×10^7 at 4.14 GeV
$\tau^+ \tau^-$ (pairs)	0.5×10^7 at 3.57 GeV
$\tau^+ \tau^-$ (pairs)	2.4×10^7 at 3.67 GeV
$\tau^+ \tau^-$ (pairs)	3.5×10^7 at 4.25 GeV
J/Ψ (events)	1.7×10^{10}
Ψ' (events)	0.4×10^{10}

These are very large data sets by contemporary standards. For example the largest tau data sets which can be produced by existing colliders will contain about

10^6 τ pairs. But data sets from several years of τ studies at the tau-charm factory may contain 10^8 τ - pairs. A B-factory with a luminosity of a few x 10^{33} cm^{-2} s^{-1} can also produce such a large number of τ pairs, but tau data produced in the Υ region will be badly contaminated by B meson and D meson backgrounds. The power and precision of τ research at the tau-charm factory comes from the unique combination of (a) very large data sets with (b) control of and direct measurement of backgrounds and (c) a detector tailored to the physics. The situation is the same with respect to charm particles, where data sets from several years of Ψ'' running at the tau-charm factory may contain 10^8 D mesons, several orders of magnitude greater than those anticipated from fixed target experiments in the same time frame.

The particle production rates in Table 1 are based on the conventional data acquisition period of 1×10^7 seconds per year. The tau-charm factory collider and detector will be built with reliability in mind during all phases of the design and the construction. This can be done because no unconventional technology is employed in either device. As experience is gained with the collider and detector, the data acquisition period will reach 2×10^7 seconds per year, doubling the particle production rates in Table 1.

A final comment on Table 1; the τ pair production cross section at 4.25 GeV, listed in Table 1, is the largest such cross section at any energy - larger for example than the cross section for taus at the Z^0. Therefore, for measurements where background problems are minor, this is the best τ pair production energy.

A2 The Tau-Charm Factory

Jowett (Jowett 1987, Jowett 1988, Jowett 1989) first worked out the basic design for a tau-charm factory which would have the four required properties:

- $3.0 \leq E_{tot} \leq 5.0$ GeV
- $L_{design} = 10^{33}$ cm^{-2} s^{-1}
- Highly flexible and reliable operation
- $\Delta E_{tot} \approx$ few MeV

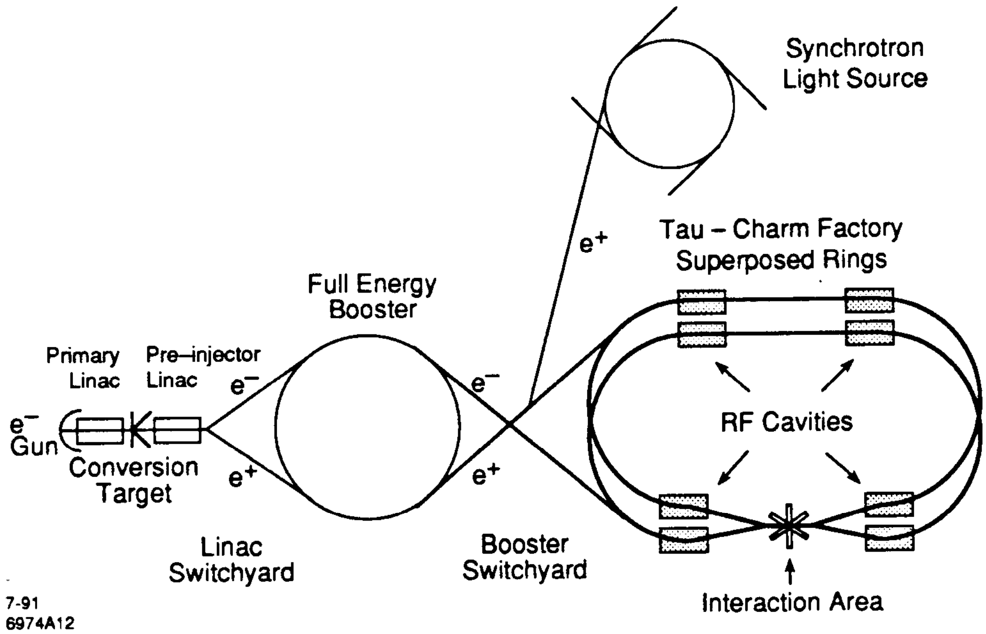

Fig.2

These requirements are met, using the following design principles:

(i) Multiple bunches, about 20 to 30 in each ring to increase the bunch crossing frequency.

(ii) 1-2 $\times 10^{11}$ particles per bunch.

(iii) Only one interaction region at startup.

(iv) Separate e^+ and e^- rings to eliminate all other parasitic bunch crossings.

(v) Strong focussing of the bunches at the interaction point.

(vi) Rings having relatively large radius to minimize the synchrotron radiation power loss and to allow the use of a conventional beam pipe.

(vii) Low frequency superconducting RF with a substantial RF overvoltage and low beam pipe impedence to maintain short bunch lengths.

(viii) A feedback system to control multibunch instabilities.

(ix) A high intensity e^+ and e^- injector to maintain luminosity by "top-off" of the circulating bunches.

After the original work of Jowett, further design work was carried out at the 1989 Tau-Charm Factory Workshop (Beers 1989). This group confirmed that Jowett's $L_{design}=10^{33}$ cm^{-2} s^{-1} was feasible with present technology (Brown, Fieguth, and Jowett 1989) and also published a conceptual design (Barish et al 1990).

A separate conceptual design, also with a luminosity of 10^{33} cm^{-2} s^{-1}, was carried out in France by Gonichen, Le Duff, Mouton, and Travier (Gonichen et al 1990). This report discusses the accelerator physics in more detail, for example comparing flat beam and round beam optics.

Danilov et al (Danilov et al 1990) have also discussed tau-charm factory design.

The most recent design (Baconnier et al 1990) was carried out by physicists from CERN, LAL in France, and CIEMAT in Spain. Figure 2 shows the schematic design. The circumference of this 10^{33} cm^{-2} s^{-1} luminosity collider is 360 m. The high intensity e^+ and e^- injector consists of a linear accelerator followed by a booster synchrotron. Since the lifetime of stored beams in the rings is only 2 hours, the injector must be able to topoff the tau-charm rings in a few minutes each hour. As shown in the figure, the injector would also be used to fill a *separate* synchrotron radiation ring during the balance of the time. This design is the basis for the present planning for a tau-charm factory in Spain.

A3 The Tau-Charm Detector

Just as the tau-charm factory is based on a unique electron-positron collider and injector, so it also has a unique detector. Indeed the collider design and the detector design are closely connected to and tailored to the physics requirements. The general requirements placed on the detector are:

- Emphasis on large solid angle coverage because much of the physics depends upon the full reconstruction of exclusive final states. Each of the the detector subsystems must cover very close to 4π solid angle.

- The search for rare processes requires that all charged particles and photons must be observed down to low momenta and energies with high efficiency. Where particles cannot be well measured, a veto capability must exist.

- It must be known if any missing energy was carried off by neutrinos.

- Electrons and muons should be detectable to a similar level of reliability and precision.

- The trigger and all subsystems must be able to handle high data rates, particularly at the J/Ψ. These rates substantially exceed those present in previous e^+e^- detectors and will require sophisticated techniques for pileup rejection.

A conceptual design of the detector has been worked out, as shown in Figure 3. The highlights of the design are described here:

- **Momentum Analysis by Low Mass Drift Chamber:** The field is 0.8 Tesla and the chamber employs a low density drift gas and wires.. The momentum resolution is

$$dp/p \leq \sqrt{(0.4\%p)^2 + (0.3\%/\beta)^2} \qquad \text{over} >0.95\times 4\pi \text{ sr.}$$

- **Electromagnetic Calorimeter:** The high resolution and high efficiency barrel calorimeter made of CsI (Th) crystals and the forward calorimeters made of BGO crystals are both inside the magnet coil. Combined, the calorimeters cover 0.994 $\times$ 4π sr.

- **π, K, p, e, μ, Particle Identification:** This is done by a combination of tracking, time-of-flight fiber scintillation counters, dE/dx measurements in the drift chamber, and the muon detector.

- **Muon Detector and Neutral Hadron Veto Calorimeter:** The detector is surrounded by a fine-grained iron-plate muon range system and hadron calorimeter. This system gives excellent μ identification because the μ range will be measured for the lower momentum μ's. For many τ and charm studies it is necessary to know if an event contains missing energy carried off by (and *only* by) neutrinos. Events with missing energy carried off by neutrons or K_L^0's would contaminate these measurements.This muon - hadron system detects the presence of neutrons or K_L^0's by their nuclear interaction and vetoes them.

A4. Workshops on Tau-Charm Factory and Physics

There have been two workshops on the tau-charm factory and tau-charm physics. Their proceedings contain a great deal of information.

Tau-Charm Factory Workshop, May 23-27, 1989,Stanford Linear Accelerator Center, Stanford University, Stanford, California, U.S.A.,Ed. L. Beers (Beers 1989)

Meeting on the Tau-Charm Factory Detector and Machine, 29 April - 2 May,1991, Universidad de Sevilla, Andalucia, Spain, Eds. J. Kirkby and M. Quesada (Kirkby and Quesada 1991)

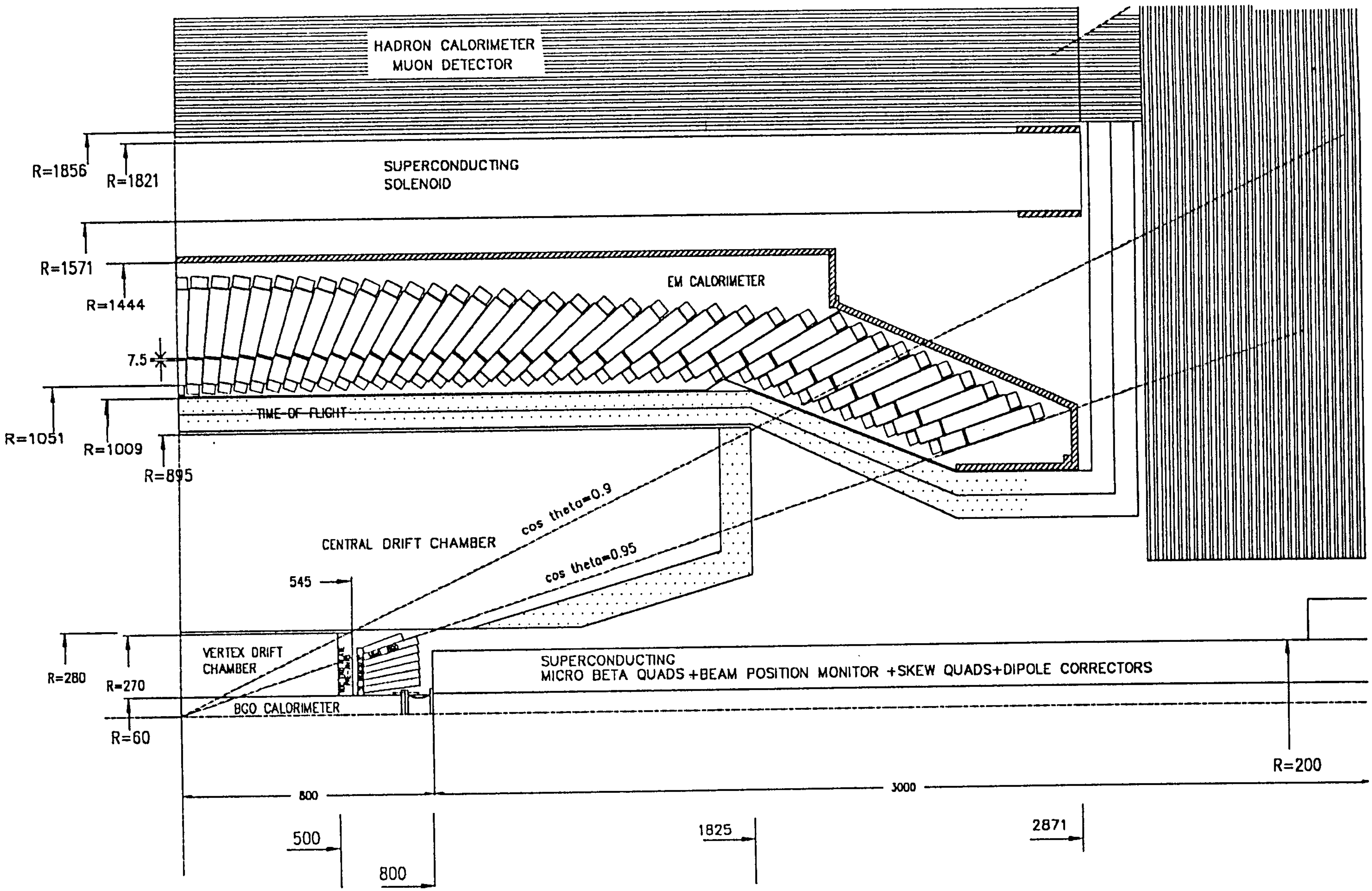
HADRON CALORIMETER
MUON DETECTOR
R=1856
R=1821
SUPERCONDUCTING
SOLENOID
R=1571
R=1444
EM CALORIMETER
7.5
R=1051
R=1009
TIME OF FLIGHT
R=895
cos theta=0.9
CENTRAL DRIFT CHAMBER
cos theta=0.95
545
VERTEX DRIFT
CHAMBER
R=280
R=270
BGO CALORIMETER
R=60
SUPERCONDUCTING
MICRO BETA QUADS+BEAM POSITION MONITOR +SKEW QUADS+DIPOLE CORRECTORS
R=200
800
3000
500
800
1825
2871

Fig. 3

B D AND D_S PHYSICS AT THE TAU-CHARM FACTORY

B1 Introduction

There are six powerful advantages in studying the physics of the charm mesons at the tau-charm factory using the exclusive production processes:

$$e^+ + e^- \rightarrow D^+ + D^-$$
$$e^+ + e^- \rightarrow D^0 + \bar{D}^0$$
$$e^+ + e^- \rightarrow D^0 + \bar{D}^{*0}$$
$$e^+ + e^- \rightarrow D_S^+ + D_S^-$$
$$e^+ + e^- \rightarrow D_S^+ + D_S^{*-}$$

at the Ψ'' and the D_S threshold energies indicated in Fig. 1:

- The ability to produce very large data sets over short collection times.
- The ability to cleanly select D and D_S by single-tagging of the events. That is, only one D or D_S decay is identified in order to select the pair in an event.
- The availability of kinematic constraints using the beam energy for the rejection of backgrounds.
- The production of the D meson pair in an initial state that is also a coherent quantum mechanical state, allowing further background control and also allowing certain unique physics studies to be performed.
- The absence of backgrounds from heavier meson decays, since production is at threshold.
- The ability to *directly measure,* as necessary, backgrounds from non-charm events by moving below the Ψ'' resonance or below the D_S threshold.

Next we discuss the charm meson physics which will be done at the tau-charm factory (Schindler 1989, Schindler 1990a, Schindler 1990b, Beers 1989, Kirkby and Quesada 1991) by dividing the physics into:

(i) Pure leptonic decays of the D mesons.

(ii) Semileptonic decays of the D mesons.

(iii) Hadronic decays of the D mesons.

(iv) D meson decays through penguin diagrams.

(v) Rare and forbidden decays of the D mesons.

B2 Pure Leptonic Decays of D Mesons

Figure 4 shows the diagram for the pure leptonic decays of the D^+ and D_S

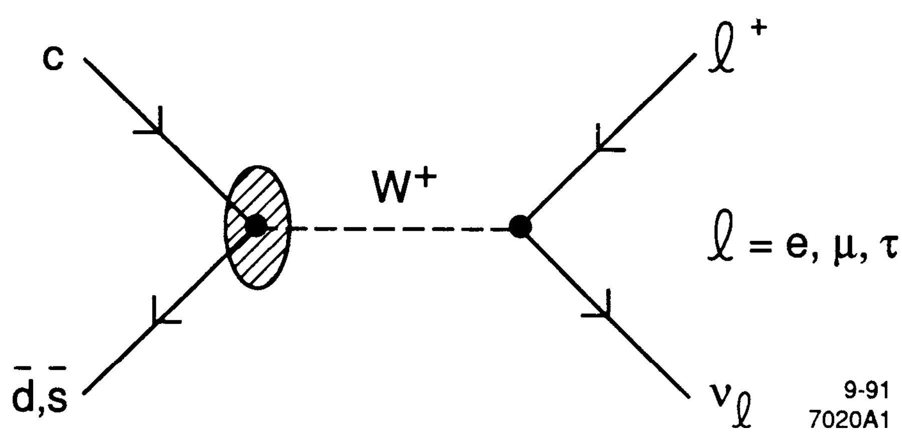

Fig. 4

These are fundamental decays which have never been observed :

$$D^+ \to e^+ + \nu_e$$
$$D^+ \to \mu^+ + \nu_\mu$$
$$D^+ \to \tau^+ + \nu_\tau$$

$$D_s^+ \to e^+ + \nu_e$$
$$D_s^+ \to \mu^+ + \nu_\mu$$
$$D_s^+ \to \tau^+ + \nu_\tau$$

The decay width is given by

$$\Gamma(D^+ \to L^+ + \nu_L) = \frac{G_F^2}{8\pi} f_D^2 M_D M_L^2 |V_{cd}|^2 \left(1 - \frac{M_L^2}{M_D^2}\right)^2$$

Here V_{cd} is the Cabibbo-Kobayashi-Maskawa (CKM) matrix element, f_D is the weak decay constant, and M refers to the meson or lepton mass. The proportionality to M_L^2 makes the τ mode the easiest to observe and the e mode too small to observe. For the μ and τ modes we expect the branching ratios to be in the range:

$$B = 10^{-2} \text{ to } 10^{-4}$$

The basic information to be obtained within the standard model from the observation and measurement of the μ and τ pure leptonic decay modes of the D and D_s is a precise and consistent determination of f_D, f_{D_s}, V_{cd}, and V_{cs}. Using produced DD^* pairs it is also possible to measure the vector meson decay constants as well as the psuedoscalar ones.

In addition, these pure leptonic decays can be used to search for new physics beyond the standard model. For example, the conventional process in Fig. 4 takes place through the exchange of a W^+ boson, but it could also take place through the exchange of an unknown particle such as a charged Higgs (H^+).

Finally measuring *two* distinct decay constants, f_D and f_{D_s} to high precision will provide a benchmark test of the lattice calculation method in QCD. The understanding of these decays in lattice QCD will then lead to calculational reliability of more complicated decays such as second order box diagrams.

B3 Semileptonic Decays of D Mesons

Figure 5 shows the conventional diagram for the semileptonic decays of the D and D_S mesons. The semileptonic decays represent about 20% of all charmed meson decays.

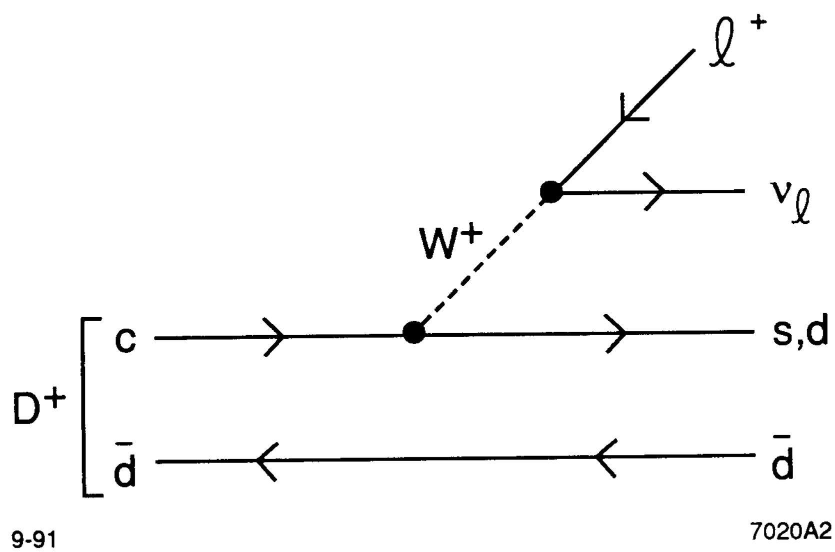

Fig. 5

The general semileptonic decays are:

$$D^+ \rightarrow L^+ + \nu_L + (\text{hadrons})^0$$
$$D^0 \rightarrow L^+ + \nu_L + (\text{hadrons})^-$$

where L means e, μ, or τ . There are analogous decays for the D_S. Unlike the pure leptonic decays, these semileptonic decays have been observed and studied when their branching ratios are in the range:

$$B = 10^{-1} \text{ to } 10^{-2}$$

But the measurements at present, even for the dominant D^0 and D^+ semileptonic decays are confused, and those of the D_s are observed only indirectly. The present experimental techniques cannot reach below $B \approx 10^{-2}$ to study the rarer and more interesting decays.

The studies of the semileptonic decays which will be carried out at the tau-charm factory will give us precise information about V_{cd} and V_{cs} and will provide thorough measurements of the various form factors involved in these decays. Particularly beautiful will be the ability to compare the measurements of the CKM matrix elements made in two different ways, each to high precision, using these semileptonic decays and the previously discussed pure leptonic decays.

The tau-charm factory studies of these semileptonic decays will also enable the experimenter to look beyond conventional D meson physics, searching for gluon bound states (glueballs) and using the semileptonic decays to study second order weak interactions, such as $D^0\bar{D}^0$ mixing. One should take note that $D^0\bar{D}^0$ mixing is one of the few second order weak processes that will ever be measured. Consider the conventional decays :

$$D^0 \rightarrow K^- + e^+ + \nu_e$$
$$\bar{D}^0 \rightarrow K^+ + e^- + \bar{\nu}_e$$

Thus one of the conventional decay processes of a $D^0\bar{D}^0$ pair is:

$$(D^0\bar{D}^0) \rightarrow (K^- + e^+ + \nu_e) + (K^+ + e^- + \bar{\nu}_e)$$

If there is $D^0\bar{D}^0$ mixing, we would observe the comparatively rare final state

$$(D^0\bar{D}^0) \rightarrow (K^- + e^+ + \nu_e) + (K^- + e^+ + \nu_e)$$

also occuring. This final state is a unique signature for $D^0\bar{D}^0$ mixing, and cannot be mimicked by any other process. The so-called "mixing parameter" is defined:

$$r_D = \frac{\text{events with mixing}}{\text{events without mixing}}$$

It is expected from the standard model to be in the range

$$r_D = 10^{-4} \text{ to } 10^{-5}$$

The present measured upper limit is $r_D < 4 \times 10^{-3}$. In several years of data experimenters using the tau-charm factory will probe to $r_D = 10^{-5}$. No other experiment can reach within a factor of 10 of this sensitivity. Demonstrating the observation of $D^0\bar{D}^0$ mixing at this sensitivity will be the first step in the longer range goal of designing and executing experiments **to search for CP violation in D decay,** at a Tau-Charm Factory.

B4 Hadronic Decays of D Mesons

The hadronic decay modes of the D mesons represent about 80% of all their decays. Many channels have been studied with branching fractions in the range of:

$$B = 10^{-1} \text{ to few} \times 10^{-3}$$

However, even the present data remains imprecise and incomplete. Their understanding is confused both experimentally and theoretically by the presence of strong final state interactions. Over the next five years, the body of knowledge on these decays will be improved, primarily by the fixed target experiments. Those experiments too will leave large gaps in our knowledge, and there will remain several very interesting areas to be explored using the tau-charm factory.

- The simple two-body decay modes are valuable for testing and extending calculational methods in low energy quantum chromodynamics. In particular, the elusive penguin operators, essential for a firm understanding CP violation in heavy mesons, may first emerge in these precision studies.

- The origin of $D^0\bar{D}^0$ mixing will also be studied using pairs of identical hadronic decays such as:

$$D^0 \rightarrow K^- + \pi^+$$
$$\bar{D}^0 \rightarrow K^+ + \pi^-$$

The conventional decay processes of the $D^0\bar{D}^0$ pair is :

$$(D^0\bar{D}^0) \rightarrow (K^- + \pi^+) + (K^+ + \pi^-)$$

But if there is $D^0\bar{D}^0$ mixing there is also the process :

$$(D^0\bar{D}^0) \rightarrow (K^- + \pi^+) + (K^- + \pi^+)$$

Unlike potential mixing measurements in other machines, quantum mechanical selection rules forbid any other background process (eg: doubly Cabibbo suppressed decays) from contaminating the mixing signal, allowing unparalleled sensitivity.

- The study of the rare doubly Cabibbo suppressed decays (DCSD) of the D mesons will provide a further tests of low energy QCD, as they involve different combinations of quarks and antiquarks, than in allowed decays. The branching fraction for the *allowed* mode

$$B\,(D^+ \rightarrow \bar{K}^0 + \pi^+) = (2.8 \pm 0.4) \times 10^{-2}$$

is comparatively large because the c quark in the D^+ decays to the s quark in the $\bar{K}^0$ *without* suppression by a Cabibbo factor of $\tan^2 \theta_C \approx 0.05$. The branching fraction for the *singly* Cabibbo suppressed mode $D^+ \rightarrow \pi^0 + \pi^+$ is expected to be reduced by that factor and at present there is only an upper limit:

$$B(D^+ \rightarrow \pi^0 + \pi^+) < 5.3 \times 10^{-3}$$

The branching fraction for the *doubly* Cabibbo suppressed mode $D^+ \to \pi^0 + K^+$ is expected to be reduced by *another* factor of $\tan^2 \theta_C$. The power of the tau-charm factory experiments will be required to study such DCSD's. In addition to their interest for QCD, these decays have amplitudes which can interfere quantum mechanically with those inducing $D^0\bar{D}^0$ mixing and thereby allow elegant sets of measurements of the mass mixing and decay matrix for charmed mesons, to be made.

B5 D Meson Decays Through Penguin Diagrams.

Direct CP violation in K^0, B and D meson decays is believed to be induced by the presence of amplitudes involving hadronic penguin diagrams. Neither hadronic penguin decays, Fig.6a, nor radiative penguin decays, Fig. 6b, have been directly observed. In the case of B decays, penguin diagrams are dominated by the exchange of the heavy t-quark, allowing their decay rate to be used to estimate the t-quark mass. As the limit on the t-quark mass increases, penguins are more and more likely to be observed in CLEO-II within the next few years. In the case of charm, penguins are strongly suppressed in the standard model and may only be visible if QCD plays a role. Figure 6a illustrates the problem for D decays. The expected branching ratios for radiative penguins is

$$B = 10^{-5} \text{ to } 10^{-6}$$

QCD will also play a role in penguin decays of B mesons, making the connection with the t-quark mass theoretically unclear. However, together, B and D decays will cover the full region of interest necessary to understand theoretically this important class of decays. The smallness of the branching ratio means that *only* a Tau-Charm Factory will observe the decays of charmed mesons through the penguin diagram.

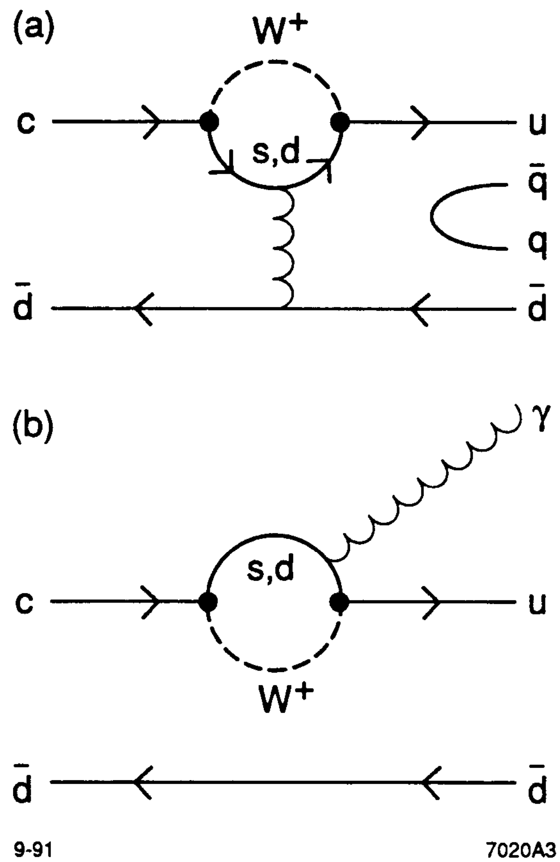

Fig.6

B6 Rare and Forbidden Decays of D Mesons

Figure 7 shows two diagrams for possible rare or forbidden decays of the D meson. In Fig. 7a the leptons are the same, hence this is a quark flavor-changing neutral current process. Such a process is forbidden in the lowest order in the standard model, but can take place through higher order electroweak processes. The branching ratios however are very small. For example the decay

$$D^0 \rightarrow e^+ + e^-$$

has a measured upper limit of $B < 1.3 \times 10^{-4}$. Experiments at the tau-charm factory will be able to probe to $B \approx 10^{-8}$, an improvement by a factor of 10^4. These tau-charm

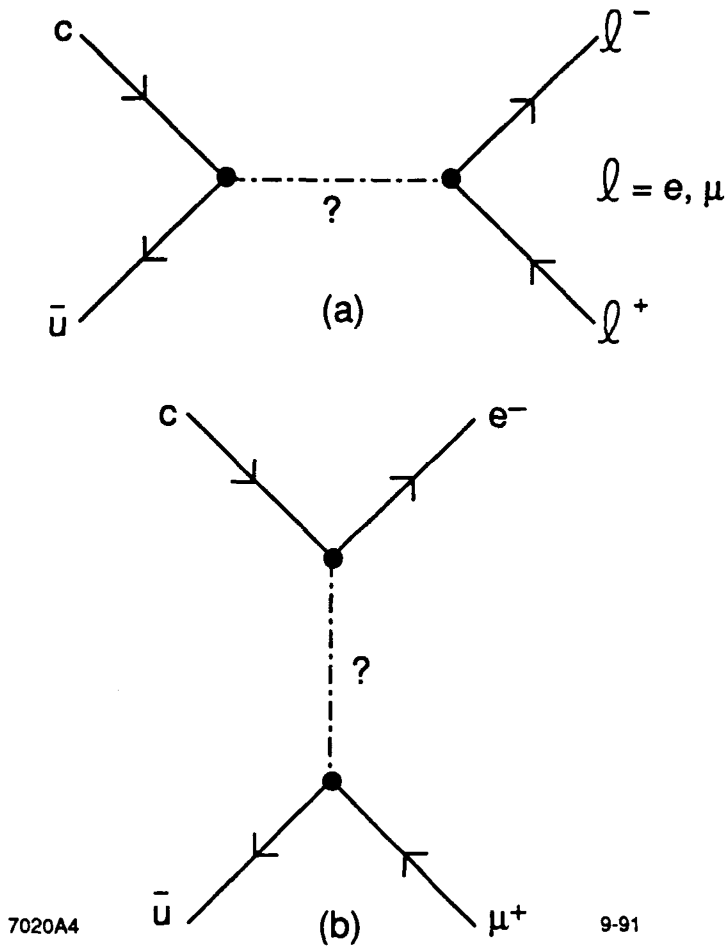

Fig. 7

factory experiments will also have sensitivities of $B \approx 10^{-7}$ - 10^{-8} for the decays:

$$D^0 \text{ or } D^+ \rightarrow L^+ + L^- + \text{hadron}; \qquad L = e \text{ or } \mu$$

The equivalent mass sensitivity to new physics of the L^+L^- process measured at $B \approx 10^{-7}$ to 10^{-8} is only about 100 to 200 GeV, because these decays are helicity suppressed. On the other hand, the (L^+L^- +hadron) decay modes provide sensitivity for new physics into the *extremely high and interesting* mass range of 10 to 100 TeV .

In Fig. 7b the leptons are the different , hence this is an example of a lepton number changing neutral current process. Such a process is forbidden to all orders in the standard model. At present the measured upper limits on the branching fractions for such forbidden decays are not useful; for example all we know is $B < 1 \times 10^{-4}$ for:

$$D^0 \rightarrow e^+ + \mu^-$$

Tau-charm factory experiments will probe these dilepton decays and dilepton decays with hadrons to branching ratios of 10^{-7} - 10^{-8}.

B7. Other D and D_s Physics at the Tau-Charm Factory

In addition to the program outlined in the preceding sections, the study of the charmed quark decays will also include :

- A systematic and precise study of hadronic and semileptonic decays of charmed baryons below 2.5 GeV in mass.

- The absolute branching ratios of all charmed D and D_s mesons and baryons. at the 1 % level of precision.

- Measurement of *all* Cabbibo allowed and singly forbidden hadronic and semileptonic decays of the D mesons , and many of the doubly forbidden hadronic decays.

- Search for other radiative charmed meson and baryon decays.

- Search for other rare multilepton plus hadron final states not protected by gauge principles.

- Search for direct CP violation and CP violation through mixing in charm decays at the 10^{-2} to 10^{-3} level.

C

τ AND ν_τ PHYSICS AT THE TAU-CHARM FACTORY

C1 Introduction

There are four powerful advantages in studying the physics of the tau lepton and tau neutrino at the tau-charm factory using:

$$e^+ + e^- \rightarrow \tau^+ + \tau^-$$

at the major operating energies for τ pair production:

3.57 GeV: just above the τ pair threshold
3.67 GeV: just below the Ψ' resonance

These advantages are:

- The availability of large data sets collected over short times.
- The selection of a τ pair data sample by single-tagging of events. That is, only one τ decay need be identified in order to select the event.
- There are no backgrounds from D or B meson decays.
- The backgrounds from non-τ pair events are *directly* measured as necessary, by moving below the τ pair threshold.

There are a very large number of areas of τ and ν_τ physics which require the tau-charm factory (Pich 1990a,Pich 1990b, Perl 1991, Beers 1989, Kirkby and Quesada 1991). We will briefly discuss five examples:

(i) Precision measurements of branching ratios.

(ii) Complete study of τ-W-ν_τ vertex.

(iii) Untangling multiple π^0 and η decay modes.

(iv) More sensitive probes of the ν_τ mass.

(v) Searches for unconventional and forbidden τ decays.

C2 Precision Measurements of Branching Ratios

There are five τ decay modes whose branching fractions we should try to measure with high precision because we can calculate the relative branching fractions with high precision.These modes and the current average measured values of their branching fractions are:

$$\tau^- \to \nu_\tau + e^- + \bar{\nu}_e \quad (17.7\pm0.4\%)$$

$$\tau^- \to \nu_\tau + \mu^- + \bar{\nu}_\mu \quad (17.8\pm0.4\%)$$

$$\tau^- \to \nu_\tau + \pi^- \quad (11.0\pm0.5\%)$$

$$\tau^- \to \nu_\tau + K^- \quad (0.68\pm0.19\%)$$

$$\tau^- \to \nu_\tau + \rho^- \quad (22.7\pm0.8\%)$$

We are prevented from making exact calculations of the branching fractions for most hadronic decay modes by our ignorance of how to use the theory of quantum chromodynamics in the energy region of τ decays. For the five modes listed above we can however calculate their decay widths, Γ_i , and hence can calculate the ratios of branching fractions:

$$B_i / B_e = \Gamma_i / \Gamma_e$$

We use $B_e = B(\tau^- \to \nu_\tau + e^- + \bar{\nu}_e)$ as the reference branching fraction.

The two pure leptonic decays occur through the process in Fig. 8

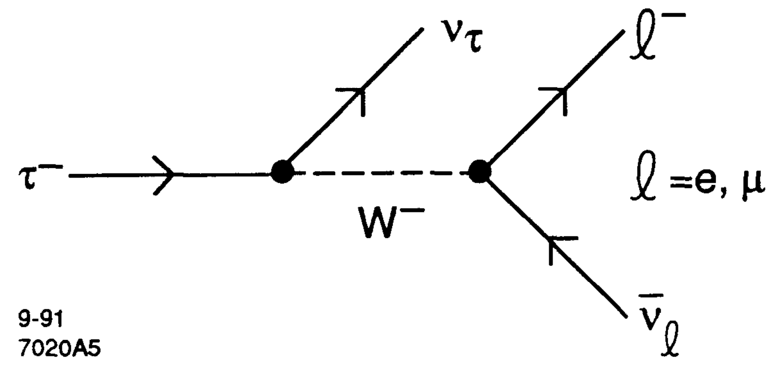

Fig. 8

The decay widths, Γ_e and Γ_μ for these decays can be precisely calculated from first principles using conventional weak interaction theory.

The decay width Γ_π for $\tau^- \to \nu_\tau + \pi^-$ cannot be calculated from first principles but can be calculated using the decay $\pi^- \to \mu^- + \bar{\nu}_\mu$, and the processes in Fig.9.

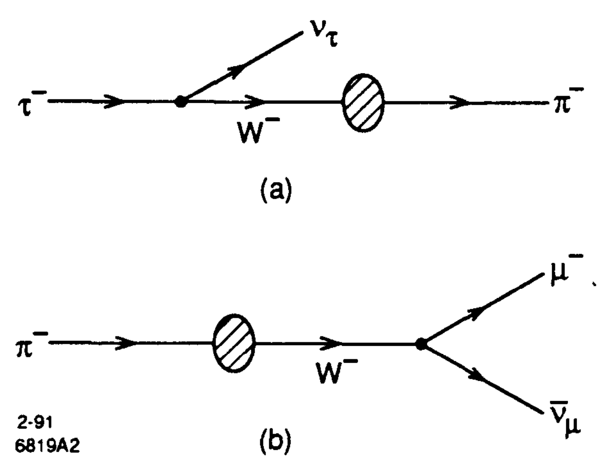

Fig.9

The situation is analogous for Γ_K for the decay $\tau^- \to \nu_\tau + K^-$.

Finally, Γ_ρ for $\tau^- \rightarrow \nu_\tau + \rho^-$ can be calculated from the measured cross section for $e^+ + e^- \rightarrow \rho^0$.

Looking at the errors in the measured B's quoted above, and recognizing that these errors may be underestimated due to correlated systematic errors (Hayes and Perl 1988), we see that even the best measurements give the error in B_i / B_e:

$$\delta (B_i / B_e) \approx 0.05$$

It is important to significantly reduce such errors to allow:

- Precise tests of the standard model .
- Searches for new physics in tau decays. For example new physics might show up by the tau decay occurring through a particle other than the $W^\pm$.

By measuring the above branching fractions close to the τ pair threshold at the tau-charm factory, these errors can be reduced by a factor of 10 or more (Gomez-Cadenas et al 1989)! Experimenters can achieve

$$\delta (B_i / B_e) = 0.002 \text{ to } 0.005$$

Two features of the production and decay of τ's at a tau-charm factory make this precision possible. First, due to the coulombic attraction between the pair of τ's, the cross section at threshold is not zero but instead about 0.2 nb; a few MeV above threshold the cross section rises to about 0.4 nb. Thus, just above threshold, the τ's can be produced *copiously and almost at rest* Because they are nearly at rest, the second special feature comes into play, namely, that the two-body channels of interest (eg: $\tau^- \rightarrow \nu_\tau + \pi^-$) will produce in their decay nearly monochromatic pions, thereby providing an unambiguous τ pair tag.

Precise measurements of these branching fraction ratios can uncover new physics such as a higgs-like particle or leptoquarks (Gomez-Cadenas et al 1989, Tsai 1989a, Tsai 1989b, Heusch 1989)

C3 Full Study of τ-W-ν_τ Vertex.

In the standard model the τ-W-ν_τ vertex is taken to be simply of the V-A. form. But as has been discussed by Fetscher (Fetscher 1990) the τ-W-ν_τ vertex can have a much more general Lorentz structure in which there can be not only V+A coupling but also scalar and tensor couplings. Indeed the vertex can contain up to 19 independent parameters. This has been known for the muon for almost four decades (Scheck 1978). The goal is to investigate the full dynamics of the τ-W-ν_τ vertex with the same thoroughness and precision as has been applied to the μ-W-ν_μ vertex. *Any deviation from the V-A structure of the standard model, implies the existence of new physics.*

To carry out this program it is necessary to systematically and methodically study at several production energies at a tau-charm factory, the leptonic and one prong hadronic decays (Fetscher 1990, Pich 1990a):

$$\tau^- \rightarrow \nu_\tau + e^- + \bar{\nu}_e$$
$$\tau^- \rightarrow \nu_\tau + \mu^- + \bar{\nu}_\mu$$
$$\tau^- \rightarrow \nu_\tau + \pi^-$$

It is even possible at a tau-charm factory to study the decay sequence

$$\tau^- \rightarrow \nu_\tau + \mu^- + \bar{\nu}_\mu$$
$$\mu^- \rightarrow \nu_\mu + e^- + \bar{\nu}_e$$

so that the polarization of the μ^- is measured (Stroynowski 1990)

C4 Untangling Multiple π^0 and η Decay Modes.

Our present knowledge of the τ decay modes with multiple neutral mesons is minimal:

$$\tau^- \rightarrow \nu_\tau + \pi^- + n\,\pi^0, \qquad n > 2$$
$$\tau^- \rightarrow \nu_\tau + \pi^- + \eta + n\,\pi^0, \qquad n > 0$$

All we know for almost all these modes is the upper limit on the branching fractions. Indeed there is even a great deal of confusion about the branching fraction for the simplest of these decays:

$$\tau^- \rightarrow \nu_\tau + \pi^- + 2\,\pi^0$$

which is very important for understanding a possible problem in the one-charged particle decay modes of the τ. The Particle Data Group gives B=(7.5±0.9) %, but recent measurements vary from about 6% to about 10%. *The basic question about these multiple neutral meson modes is whether there any new physics hidden in these unexplored modes?*

The τ decay mode

$$\tau^- \rightarrow \nu_\tau + \pi^- + \eta$$

is of special interest because is can only occur through a second-class weak current. Decays through second-class weak currents have never been observed in either particle or nuclear physics because the branching fractions are very small. For the above mode we expect (Pich 1987, Zachos and Meurice 1987)

$$B \approx 10^{-4} \text{ to } 10^{-6}$$

Such a branching fraction for this mode can be *only* be measured at the Tau-Charm Factory.

C5 More Sensitive Probes of the ν_τ Mass.

The present upper limit on the mass of the tau neutrino is

$$\text{Mass}(\nu_\tau) < 35 \text{ MeV}$$

This limit was obtained by studying the endpoint of the mass spectrum of the system of 5 π's in the decay:

$$\tau^- \rightarrow \nu_\tau + 3\pi^- + 2\pi^+$$

The branching fraction for this decay is small, namely 6×10^{-4}. To probe to smaller masses requires a tau-charm factory experiment for two reasons. First, a large τ pair data set is required, about 10^7. Second, it is necessary to correct the endpoint spectrum of the 5 π's for contamination by non- τ pair events. This can only be done in an detector tailored to this measurement.

Such a measurement (Gomez-Cadenas et al 1990) will initially probe down to:

$$\text{mass}(\nu_\tau) \sim 3 \text{ MeV}$$

and eventually perhaps to 1 or 2 MeV. No one knows if neutrinos have non-zero masses. Most models for non-zero neutrino masses predict that the heavier the charged lepton, the heavier its neutrino. For example a common theoretical model, (the so called "seesaw model"), predicts:

$$\frac{\text{mass}(\nu_1)}{\text{mass}(\nu_2)} = \left[\frac{\text{mass}(L_1)}{\text{mass}(L_2)}\right]^2$$

With this model the upper limit on the ν_τ mass of 35 MeV is equivalent to an upper limit on the ν_e mass of

$$\left[\frac{\text{mass}_e}{\text{mass}_\tau}\right]^2 \times 35 \text{ MeV} = 2.9 \text{ eV},$$

which is already smaller than the current upper limit on the ν_e mass of 17 eV. Thus in some models the measurement of the ν_τ mass probes to the smallest equivalent neutrino mass.

C6 Searches for Unconventional and Forbidden τ Decays.

There have been several searches for tau decays which violate lepton number conservation, modes such as:

$$\tau^- \to e^- + \gamma$$

$$\tau^- \to \mu^- + \gamma$$

$$\tau^- \to e^- + \pi^0$$

$$\tau^- \to e^- + e^+ + e^-$$

No modes violating lepton number conservation have been found and present upper limits on the branching fractions are typically

$$B < 1\text{-}5 \times 10^{-5}$$

The large statistics available in tau-charm factory experiments will allow probing for such forbidden decays to levels of

$$B \approx 10^{-7} \text{ to } 10^{-8}$$

However there is another type of unconventional decay which is much more difficult to search out. These are decays of the class

$$\tau^- \to e^- + X^0$$

$$\tau^- \to \mu^- + X^0$$

where the X^0 is an unconventional weakly interacting particle of integer spin such as a Goldstone boson. Sensitive searches for such decays can only be made at a tau-charm factory because of the need to completely understand contaminations which might mimic such decays. For example the conventional decay $\tau^- \to \pi^- + \nu_\tau$ would be a contamination if the π were incorrectly identified as an e or a μ.

Unconventional decays such as :

$$\tau^- \rightarrow \nu_\tau + e^- + \bar{\nu}_e + X^0$$

$$\tau^- \rightarrow \nu_\tau + \pi^- + X^0$$

are even more difficult to explore and again require a tau-charm factory.

C6. Other τ Physics at the Tau-Charm Factory

There are many other areas of tau and tau neutrino physics which are best studied at a tau-charm factory:

- Study of radiative tau decays.
- Precise, comparative study of Cabibbo-suppressed tau decay modes.
- Detailed study of 5-charged particle and 7-charged particle tau decay modes.
- Study of electromagnetic moments of the tau.
- Tests of tau neutrino stability.

And finally there is the dream of making the τ^+ - τ^- atom , called tauonium, in analogy to the e^+ - e^- atom positronium (Moffat 1975, Avilez et al 1978, Avilez et al 1979).

D CHARMONIUM PHYSICS AT THE TAU-CHARM FACTORY

The tau-charm factory will operate over the center of mass energy range from 3 to 5 GeV. It will be the *first* e^+e^- storage ring in this energy regime to have adequate luminosity to perform detailed probes of all of the $c\bar{c}$ bound and unbound states and the transitions amongst them. These unique measurements of the $c\bar{c}$ interquark potential provide a necessary compliment to similar studies of the $b\bar{b}$ potential at a b-factory and the $t\bar{t}$ potential near threshold at a future linear collider. In combination, these measurements will precisely test the form and the flavor independence of the strong interaction, as predicted by the theory of quantum chromodynamics.

In addition to the detailed exploration of the 3-5 GeV region, several of the known charmonium resonances have special importance either because of their proximity to charmed meson production thresholds (eg: Ψ''), or because their very large cross sections (eg: J/Ψ) can provide copious numbers of light quark mesons, baryons, glueballs and admixtures. For example, the production rate of J/Ψ events is very large at the tau-charm factory:

$$\frac{J/\Psi \text{ events}}{\text{month}} \approx 10^9$$

In the first half decade of operation, the tau-charm factory will probably operate at the J/Ψ and Ψ' resonances for a total of about four weeks per year. These weeks will probably be spread out over the year since events from these resonances are very useful for detector calibration. Even so, this will represent a sample 100X the size of samples that might exist from other storage rings.

There is a large array of measurements to be done with such large data sets in a detector matched well to the physics. For the sake of brevity we only outline here the general physics topics employing J/Ψ decays:

- **J/Ψ Radiative and Hadronic Decays**

  Use to study hadronic resonances and to search for pure gluon bound states. Source for light quark spectroscopy, and baryon spectroscopy. Exotic bound states of quarks and gluons.

- **η_c**

  Study properties and decay modes of η_c.

- **Rare Decays of the J/Ψ**

  There is a large new area of particle physics in the rare decay modes of the J/Ψ. For example the weak decay

  $$J/\Psi \rightarrow D_s + \text{hadrons}$$

  has not been observed. And looking further into the future at the tau-charm factory, a very interesting search can be made for *direct CP violation* in Λ decays using:

  $$\begin{array}{ccccc} J/\Psi \rightarrow & \Lambda & + & \bar{\Lambda} \\ & \downarrow & & \downarrow \\ & p\pi^- & & \bar{p}\pi^+ \end{array}$$

This experiment may require about a year of tau-charm factory operation at the J/Ψ , where the tau-charm rings are run with monochrometer optics to further reduce the beam energy spread, and enhance the cross section. Operation of an e^+e^- storage ring in this mode will also provide a unique accelerator physics experiment.

E

SUMMARY
THE TAU-CHARM FACTORY

Thus a very wide range of charm physics, tau physics, and tau neutrino physics will be studied and explored using the tau-charm factory. The precision, cleanliness, and depth of these studies cannot be equaled by any other experimental technique or at any other accelerator or collider facility. There will be many searches for new physics, searches which cannot be duplicated in any other way. We will greatly extend our knowledge and understanding of the standard model of particle physics. These precise and probing studies will be accomplished through the use of the four basic elements of the tau-charm factory concept

- Control of and direct measurement of backgrounds and contaminations.
- Very large statistics collected over short times.
- Production of particles in known quantum mechanical states.
- Detector with very high quality particle identification, very good momentum and energy resolution, and close to 4π acceptance.

The tau-charm factory itself is a high luminosity, two-ring, electron-positron collider and detector with the following properties:

- Range of total energy = 3.0 to 5.0 GeV
- Design luminosity = 10^{33} cm^{-2} s^{-1} at 4 GeV
- High resolution, large acceptance detector specially designed for tau and charm physics

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