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TAU PHYSICS AND TAU FACTORIES*

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ABSTRACT

Substantial progress in tau lepton physics requires larger and cleaner samples of τ's produced in $e^+e^- \to \tau^+\tau^-$. Single-tagging of the τ pair is crucial. Possibilities for such progress at particle factories are discussed with emphasis on the Tau-Charm Factory concept.

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I. INTRODUCTION

Substantial progress in tau lepton physics requires: (i) larger samples of

$$\begin{aligned} &e^+ + e^- \rightarrow \tau^+ + \tau^- \\ &\tau^+ \rightarrow \text{ decay products} \\ &\tau^- \rightarrow \text{ decay products} \end{aligned} \tag{1}$$

events; and (ii) much cleaner separation of τ pair events from

$$e^+ + e^- \rightarrow \text{ anything} \tag{2}$$

In the talk I gave at the Rare Decay Symposium I reviewed the present state of τ physics, including the 1-charged particle decay mode problem. In this written version of the talk I'll reduce that physics review to a list with references, Sec.II; devoting this paper to the requirements for substantial progress: (i) larger samples and (ii) cleaner samples.

Larger samples require a facility which can produce 10^6 to 10^7 τ pairs per year – a τ factory. The Tau-Charm Factor[1,3] concept, Sec. IV, provides one way to meet the large sample requirement. Other possible ways to meet this requirement are a B Factory[3,4,5] and a Z^0 Factory[6], Sec. V. Also discussed as comparisons in Sec.V are BEPC,[7] CESR,[8] and an upgrade of PEP.[9]

Most future research on the τ requires large samples with much less background contamination compared to existing τ data sets. Therefore before discussing τ factories, I introduce in Sec.III the issue of improved tagging of the τ pairs in Eq. 1 compared to the background in Eq. 2. I can only introduce the τ tagging issue because we are in the midst of studying τ tagging for a τ-Charm Factory. I don't know of any detailed τ tagging studies for a B Factory or a Z Factory.

II. SUBJECTS FOR FUTURE TAU RESEARCH

There are many areas of τ research where future research will be interesting and might be startling. Discussions have been given by Pierre,[3] V. de Alfaro,[4] Eichler *et al.*,[5] Burchat,[10] and me.[11] This is my list.[11]

1. The 1-Charged Particle Decay Mode Problem[12–14]

We don't know if this problem is caused by experimental error or is caused by an unexpected property of the τ which affects about 5% of the decays. The problem may not be resolved by τ data samples of present purity and size. If the τ has an unexpected property, new large data samples will allow a thorough study of the anomalous decays.

2. Mass of the τ Neutrino

The goal is to explore limits on m_{ν_τ} of the order of several MeV/c^2, perhaps as small as 1 MeV/c^2.

3. Better Measurements of Conventional Properties of the Tau:
   - (i) τ mass.
   - (ii) τ lifetime.
   - (iii) Structure of τ-γ-τ vertex.[15–17]
   - (iv) Tests for non-point particle properties.[16–18]
   - (v) Limit on electric dipole moment.[19]
4. Detailed Studies of τ-W-ν_τ Weak Interaction Vertex[10,17,20,21]
5. Detailed Studies of τ-Z^0-τ Weak Interaction Vertex[22,23]
6. Study of Purely Leptonic Decay Modes
   - (i) Precise measurement.
   - (ii) Search for anomalies in e and μ momentum.
7. Precise Measurement of Cabibbo Angle in τ Decays
8. Elucidation of 1-Charged Particle Hadronic Decay Modes
   - (i) Multiple π^0 modes.
   - (ii) Multiple η modes.
   - (iii) Non-resonant $\tau^- \rightarrow \pi^-\pi^0\nu_\tau$.
9. Elucidation of 3-Charged Particle and 5-Charged Particle Decay Modes
   - (i) Separation into identified final states.
   - (ii) Analysis for hadronic resonances.
10. Search For 7-Charged Particle Modes

11. Quantum Chromodynamics at 1 GeV Via Hadronic τ Decays

12. Search For Decays Which Violate Lepton Number Conservation[24–26]

13. Use of τ Decays to Search for Evidence of Unknown Particles or Forces

III. TAU PAIR SELECTION AND BACKGROUND REJECTION

A. Backgrounds

The major background in the selection of τ pairs is

$$e^+ + e^- \rightarrow n \text{ charged hadrons } + \ldots \tag{3a}$$

with $n \leq 6$. Worrisome background categories are

$$e^+ + e^- \rightarrow D^+ + D^- \quad , \quad D^0 + \bar{D}^0 \tag{3b}$$

$$e^+ + e^- \rightarrow B^+ + B^- \quad , \quad B^0 + \bar{B}^0 \tag{3c}$$

where the D or B decay to 1 or 3 detected charged particles. Here D represents D, D^* and D_s, and B represents B and B_s.

A related background is

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

Purely leptonic backgrounds include

$$e^+ + e^- \rightarrow e^+ + e^-, \ \mu^+ + \mu \tag{5}$$

$$e^+ + e^- \rightarrow e^+ + e^- + e^+ + e^- \tag{6}$$

$$e^+ + e^- \rightarrow e^+ + e^- - \mu^+ + \mu^- \tag{7}$$

An annoying configuration of the process in Eq. 6 is close angular association of 3 of the $e^{\pm}$ usually called a multiprong Bhabha event. There are also τ backgrounds

$$e^+ + e^- \rightarrow \tau^+ + \tau^- + \gamma \tag{8a}$$

$$e^+ + e^- \rightarrow e^+ + e^- + \tau^+ + \tau^- \tag{8b}$$

B. Double-Tag τ Pair Selection

Almost all studies of τ physics have been done with a double-tag

$$
\begin{array}{ccccc}
e^+ + e^- & \longrightarrow & \tau^+ & + & \tau^- \\
 & & \downarrow & & \downarrow \\
 & & \text{Set 1} & & \text{Set 2} \\
 & & \text{decay states} & & \text{decay states} \\
 & & \uparrow & & \uparrow \\
 & & \text{set 1 selection} & & \text{set 2 selection} \\
 & & \text{criteria applied} & & \text{criteria applied} \\
 & & \text{to this state} & & \text{to this state}
\end{array}
$$

The complexity of the double tag criteria which are presently used is illustrated by two examples reproduced from the literature.

Our Mark II collaboration measurement[27] of the τ lifetime at 29 GeV required the following criteria. Note that some of the restrictions would be difficult to simulate accurately for a precise study of the kinematics of a decay mode.

> "With the exception of a very small branching fraction to 5 prongs, all τ decay modes produce either 1 or 3 charged tracks in the final state. Our sample of 3-prong decays is selected from events with zero total charge which contain either a pair of 3-prong jets in opposite hemispheres or a single track and a 3-prong jet in opposite hemispheres. To ensure that the event originates in an e^+e^- collision we require that the overall event vertex lie within 2 cm of the beam center in the x-y plane, and within 5 cm along the beam axis."
>
> "Further cuts are applied to this sample to minimize anticipated backgrounds. We require that each 3-prong candidate have charge ± 1 and an invariant mass, based on the charged particles, between 0.7 GeV/c^2 and 1.5 GeV/c^2. In addition, we calculate the mass of the tau-like system including nearby neutral energy recorded by the liquid argon calorimeter and require that it be less than 1.0 GeV^2. In two jet (6-prong) events, failure of either jet results in the exclusion of both."
>
> "Tau pairs produced in the two-photon collision process $e^+e^- \rightarrow e^+e^-\tau^+\tau^-$ are rejected through the requirement that the total charged energy in the event exceed 5.0 GeV, and that the energy of each 3-prong exceed 3.0 GeV. We suppress these events because their τ energies are substantially less than the beam energy, and not well determined."

"Finally, we must protect against radiative Bhabha and $\mu^+\mu^-$ events which can mimic the 3 + 1 topology if the photon converts to an electron-positron pair. We therefore require that the total charged energy in each event be less than 0.9 E_{cm}, and that the 3-particle invariant mass, calculated assuming that all tracks are electrons, exceed 300 MeV/c^2."

My second example is from the measurement of $B(\tau^- \to \rho^-\nu_\tau)$ by the ARGUS collaboration[28] in the Υ energy range, 9.4 to 10.6 GeV. This is an excellent measurement of $B(\tau^- \to \rho^-\nu_\tau)$; it illustrates what is required in all present, precise studies of single-prong decay modes of the τ. I quote from Ref. 28.

"The decay $\tau^- \to \rho^-\nu_\tau$ was studied using events of the type

$$
\begin{array}{l}
e^+e^- \to \tau^-\tau^+ \\
\qquad\qquad \hookrightarrow e^+, \mu^+, \pi^+, K^+ + \nu(s) \\
\qquad\qquad \hookrightarrow \rho^-\nu_\tau \\
\qquad\qquad\qquad \hookrightarrow \pi^0\pi^- \\
\qquad\qquad\qquad\qquad \hookrightarrow \gamma\gamma \quad .
\end{array}
$$

The events were required to have exactly two charged tracks with a 1-1 topology and charge sum equal to zero and to have either one or two neutral clusters. Both charged tracks were required to have a polar angle such that $|\cos\theta| \leq 0.75$. The two photons from the π^0 decay may either form two separated neutral clusters in the shower counter array or merge into one cluster. Accordingly the events fall into two categories, those with a single neutral cluster and those with two neutral clusters. These two cases are treated separately."

"In the two cluster case, each cluster was required to have an energy between 50 and 700 MeV, deposited in at least two neighboring shower counters. Bhabhas and other QED events, as well as exclusive resonance decays, were rejected by requiring the total visible energy in the event to be less than 8.0 GeV and the total scalar momentum sum to be less than 9.0 GeV/c. The invariant mass of the two neutral clusters is shown in figure 3. A clear π^0 peak is seen with little background. Accepted π^0 candidates were required to have $\chi^2 < 5$ from a 1-C fit to the π^0 mass ..."

"For the events with a single cluster, the neutral cluster was required to have an energy larger than 1.0 GeV, and a polar angle θ such that $|\cos\theta| \leq 0.75$, in order to ensure good energy resolution. Radiative QED events were rejected by requiring that the neutral track have an angle of separation, α, from the charged track in the same hemisphere satisfying $\cos\alpha < 0.98$. Bhabhas and other QED events, as well as exclusive resonance decays, were rejected by requiring the total energy contained in the event to be less than 6.0 GeV and the total scalar momentum sum to be less than 8.0 GeV/c ..."

In spite of the complexity of double-tag criteria they still can give τ pair samples containing large backgrounds, 5% to 20% is typical. At the same time double-tags are often inefficient with efficiencies in the 3% to 30% range.

Furthermore, complex double-tag selection criteria are not suitable for large-sample studies because of the biases introduced by the criteria. Detailed studies of τ hadronic decays, items 8–11 in Sec. II, will be distorted. Searches for unconventional τ physics, items 1, 6(ii), 12, 13 in Sec. II, will be limited.

C. Single-Tag τ Pair Selection

We must have facilities, colliders and detectors, that allow clean, efficient, single-tagging of τ pairs. That is, we must be able to identify a τ pair by just one of the two decays.

Burchat[29] carried out the only published τ research using a single-tag. When the single-tag was a 1-prong decay, the efficiency was about 5% and the background about 6%. The 3-prong single-tag had about 20% efficiency with about 3% background. This research used the Mark II detector at PEP at 29 GeV.

Future τ research facilities will require much improvement in the efficiency and purity of single-tag τ studies.

IV. TAU-CHARM FACTORY CONCEPT

A. Luminosity and Physics Range

The Tau-Charm Factory, an e^+e^- circular collider, would operate in the total energy range of 3.0 to about 4.2 GeV. In this range, Fig. 1, it would produce large numbers of the following particles: ψ/J, $\tau^\pm$, ψ', $D^\pm, D^0, D_s^\pm$.

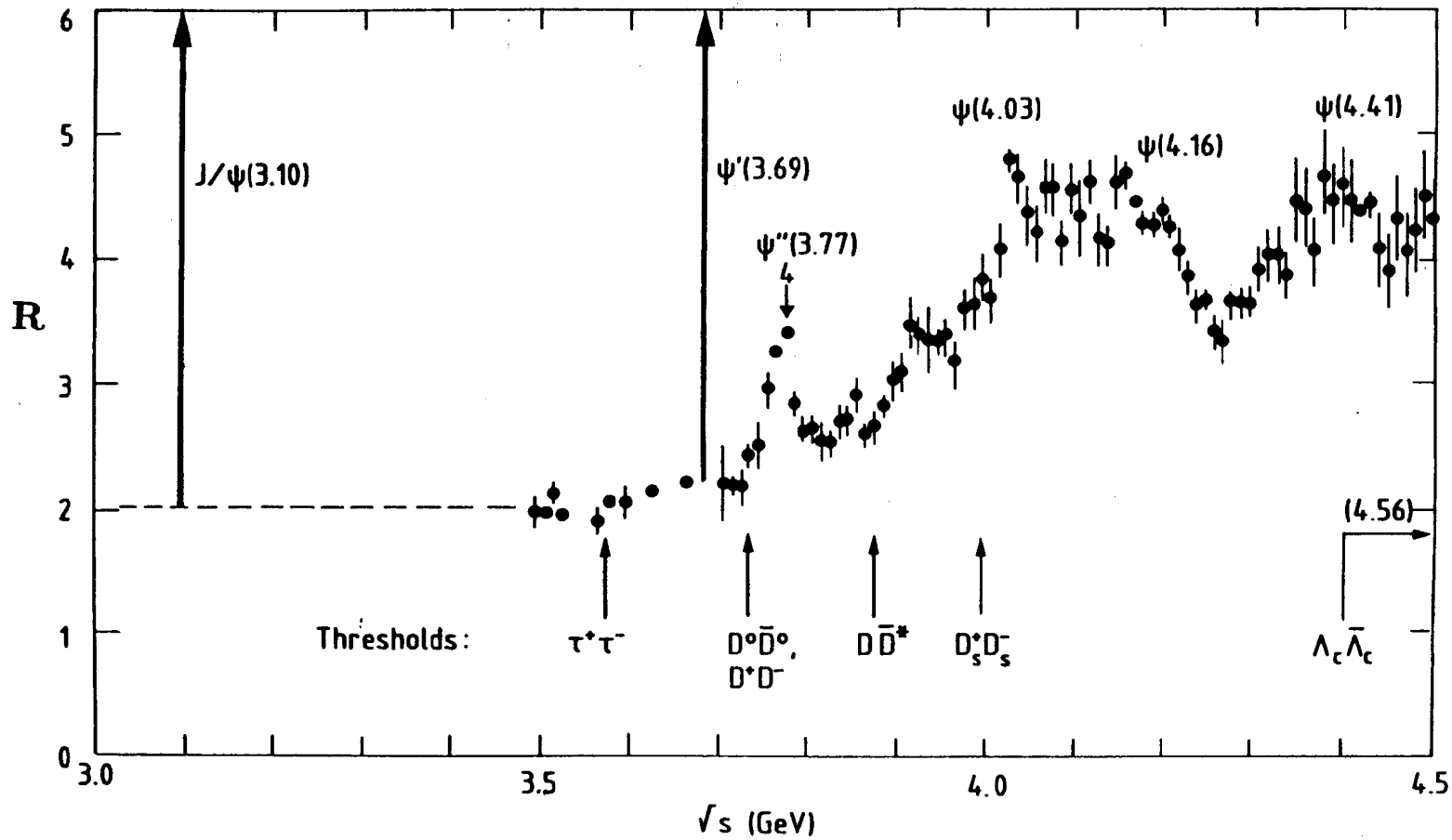

Fig. 1. Physics range of a Tau-Charm Factory. From Ref. 1.

The design luminosity,

$$L_{design} = 10^{33}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$$

would be achieved within about 2 years of the turn-on luminosity.

$$L_{turn-on} = 10^{32}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$$

This turn-on luminosity will immediately provide much new τ, D, D_s, ψ/J, and ψ' physics. These luminosities can be compared with the design luminosity of BEPC[7]

$$L_{BEPC} = 5 \times 10^{30}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$$

in the $\psi/J - \psi'$ region.

At the τ-Charm Factory design luminosity of 10^{33} cm^{-2} s^{-1} there will be the following rates of particle production. The τ pairs will be produced at about $\sqrt{s} =$ 3.67 GeV, below the ψ' to eliminate D and ψ' background. The radiately corrected cross section is 2.03 nb yielding

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

At the ψ''

$$\text{Number } D^+D^- \text{ pairs} = 9 \times 10^7/\text{physics-year}$$
$$\text{Number } D^0\bar{D}^0 \text{ pairs} = 10^8/\text{physics-year}$$

At 4.03 GeV.

$$\text{Number } D_s^+D_s^- \text{ pairs } = 10^7/\text{physics-year}$$

At 4.14 GeV.

$$\text{Number } D_s^\pm D_s^{\mp *} \text{ pairs } = 2 \times 10^7/\text{physics-year}$$

The ψ/J and ψ' rates are

$$\text{Number } \psi/J = 10^9/\text{physics-month}$$
$$\text{Number } \psi' = 5 \times 10^8/\text{physics-month}$$

The terms physics-year and physics-month are defined in the next section.

B. Collider

The collider would have the following characteristics:

- circular electron-positron collider
- two rings with 0° crossing
- total energy of 3.0 to about 4.2 GeV
- maximum luminosity of 10^{33} cm^{-2} s^{-1}
- dedicated e^+ and e^- injector
- 1 interaction region with a high quality detector
- site requires about 100 m × 200 m plus an injector

Jowett[2] has given a design example with the parameters in Table 1.

Table 1. Design example of Jowett[2] for a Tau-Charm Factory

Minimum E_b (GeV)	1.5
Maximum E_b (GeV)	2.5
Maximum L (cm^{-2} s^{-1})	1.6×10^{33}
Number bunches	24
Total current/beam (mA)	500
Particles/bunch	1.6×10^{10}
β_y^* (cm)	1.
β_x^* (cm)	80.
σ_y^* (μm)	8
σ_x^* (μm)	440
σ_z (mm)	6.2
$\Delta\nu_y$	0.04

The facility would be operated 8 months per year for particle physics and 2 months per year for basic and applied accelerator physics. During these 10 months 1 day every 14 days would be used for collider and detector maintenance. The two remaining months allow for scheduled and emergency down time. A physics-year is thus 8 months long.

C. Detector Concept and Single-Tagging of τ Pairs

The detector, specially designed for tau and charm physics, would have the following general properties.

- The detector would be magnetic with a drift chamber or equivalent tracking device. 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.

τ physics would be carried out at $\sqrt{s} = 3.67$ GeV, below the ψ'. There is no background here from D mesons. The τ pairs would be single-tagged through the use of the purely leptonic decay modes

$$\begin{aligned} \tau &\rightarrow e^- + \bar{\nu}_e + \nu_\tau \\ \tau^- &\rightarrow \mu^- + \bar{\nu}_\mu + \nu_\tau \end{aligned} \tag{9}$$

and the charged conjugate modes. These modes would be selected through very clean e or μ identification and missing energy from at least the two neutrinos, Eq. 9. The neutral hadron detection calorimeter is crucial here.

We have started a detailed study of the efficiency and purity of this single-tag using MARK II data and some old MARK II data from SPEAR. Our first estimate is that this method will single-tag 30% of τ pairs.

V. PHYSICS AT OTHER HIGH-LUMINOSITY e^+e^- COLLIDERS, EXISTING, AND PROPOSED

In this final section I look briefly at tau physics research issues at other high-luminosty e^+e^- colliders, existing and proposed. I proceed in order of increasing energy and use the physics-year definition of Sec. IV.A.

A. BEPC[7]

Using an average design luminosity of 10^{31} cm^{-2} s^{-1} for τ physics in all regions of the BEPC energy range, BEPC will produce

$$\text{Number } \tau^+\tau^- \text{ pairs} = 7. \times 10^5/\text{physics-year}$$

B. Tau Physics in the Upsilon Region

Very important contributions to tau physics have been made at colliders operating in the upsilon energy region of 9.5 to 10.6 GeV: the ARGUS and Crystal Ball experiments at DORIS, the CLEO experiments at CESR. Compared to the τ-charm energy region this energy region has the advantage that the τ's have enough energy to permit some use of opposing directions of flight and separated decay vertices. But at present we do not know how tau research in this energy region will accommodate the criteria for large sample studies discussed in Sec. III. D and B decays may be a serious problem for both tagging and background issues:

(i) Opposing directions of flight help the use of double-tags, but the problems inherent in double-tags, Sec. III, persist.

(ii) Small multiplicity D and B decays may prevent the use of 1-prong single-tags. The purity of 3-prong single-tags has yet to be discussed in a published study.

C. CESR[8]

CESR now has a luminosity of about $1. \times 10^{32}$ cm^{-2} s^{-1}. The average τ production cross section of 0.9 nb gives

$$\text{Number } \tau^+\tau^- \text{ pairs} = 1.8 \times 10^6/\text{physics-year}$$

In about 5 years, CESR may reach a luminosity of 5×10^{32} cm^{-2} s^{-1} giving

$$\text{Number } \tau^+\tau^- \text{ pairs} = 9. \times 10^6/\text{physics-year}$$

D. B-Factories

B-Factories with luminosity in the range of 10^{33} to 10^{34} cm^{-2} s^{-1} are being discussed. The τ-pair yield would be

$$\text{Number } \tau^+\tau^- \text{ pairs} = 10^7 \text{ to } 10^8 \text{ per physics-year}$$

The crucial issue for τ research is how well the tagging and background problems raised in Sec. III and Sec. IV.B can be met.

E. High-Luminosity Upgrade of PEP

Bloom[9] has described a high-luminosity upgrade of PEP, called SBF_0 in Ref. 9. The design luminosity of 1.3×10^{33} at $\sqrt{s} = 25$ GeV would yield:

$$\text{Number } \tau^+\tau^- \text{ pairs} = 4. \times 10^6/\text{physics-year}$$

While these rates are smaller than those discussed for a Tau-Charm Factory or B Factory, the opposing directions of flight and better separated decay vertices provide the opportunity for carrying out important τ research in the near future. An interesting question is how to improve the single-tag work of Burchat.[29]

F. TRISTAN[30]

The small $\sigma(e^+e^- \to \tau^+\tau^-)$ at the upper end of the TRISTAN energy range, 60 to 70 GeV restricts τ pair production to

$$\text{Number } \tau^+\tau^- \text{ pairs} = 1.2 \times 10^4/\text{physics-year} ,$$

using the mini-beta design luminosity[30] of 2×10^{31} cm^{-2} s^{-1}. However, there is interesting τ physics to be done in this region where

$$e^+ + e^- \to Z^0_{virtual} \to \tau^+ + \tau^-$$

is beginning to equal

$$e^+ + e^- \to \gamma_{virtual} \to \tau^+ + \tau^-$$

G. $Z^0 \rightarrow \tau^+\tau^-$ and Z^0-Factories

We do not have any experience with τ research when the τ's are produced at the Z^0 peak

$$e^+ + e^- \rightarrow Z^0 \rightarrow \tau^+ + \tau^-$$

The 3-prong decay modes will be obvious and it may be possible to develop a clean and efficient 3-prong tag. Some τ research will be very productive[22,23]: studies of the $\tau - Z^0 - \tau$ vertex, τ polarization, precise measurement of the τ lifetime. On the other hand, the narrow decay cone for charged particles and photons will prohibit: detailed studies of decay modes, searches for rare decay modes, and searches for new τ physics. The high energy itself will prohibit other τ research such as mass studies.

In the SLC and LEP luminosity range of 10^{30} to 10^{31} cm^{-2} s^{-1} the τ pair yield will be

$$\text{Number } \tau^+\tau^- \text{ pairs} = 2.5 \times 10^4 \text{ to } 2.5 \times 10^5 \text{ per physics-year}$$

There have also been discussions of higher luminosity at a Z^0-Factory. Rubia[6] has described an upgrade of LEP with a luminosity in the range of $3. \times 10^{32}$ to 10^{33} cm^{-2} s^{-1}. Such a Z^0-Factory would produce

$$\text{Number } \tau^+\tau^- \text{ pairs} = 10^7/\text{physics year}$$

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