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Studies for a Tau-Charm Factory[*]

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ABSTRACT

We review the design of the Tau-Charm Factory project and mention some topics from tau-lepton physics which we see as a compelling motivation for its implementation at an early date.

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1. Motivation–Generalities

It has been an extraordinarily rewarding time for e^+e^- annihilation facilities in the 3–5 GeV CM energy range, ever since the discovery of the J/ψ meson in 1974. Not only was this the key discovery that set in motion the definition of our "Standard Model" of particle interactions, but these machines have helped us to understand the details of quark potentials and lepton "universality" such as we see them today. It is no exaggeration if we say that in the absence of these moderate-size machines–even by the standards of the 1970's–our picture of the subnuclear world would be a very incomplete one, indeed.

As we look at this picture in March 1991, it is still far from complete, irrespective of the tremendous strides made in the past 17 years. A short list of open problems may illustrate why the machine we describe in Section 2 is almost assured of advancing our knowledge of vital questions in both the leptonic and the quark sectors.

In the presently available evidence on the phenomenology of elementary particles, such questions that probe both the essence and the limits of the Standard Model include investigation of

–the charmonium level structure,

–the existence of gluonia,

–the mass of the tau neutrino,

–the V–A character of tau lepton decay,

–rare tau decays,

–weak form factors in D-meson decay,

–$\overline{D}D$ mixing,

–rare D meson decays.

Some of these can be studied at $B\overline{B}$ factories, at LEP, or at existing hadron machines. Others, however, can be tackled uniquely well with a dedicated, high-luminosity ($\sim$ 1000 SPEAR's) annihilation facility. This is the true, and compelling, motivation for the proposed Tau-Charm Factory (TFC) project, which we will briefly delineate in the following section.

2. The Tau-Charm Factory Project

The Stanford Linear Accelerator Center has been the historically proper place to study the feasibility and desirability of a machine that would extend the vastly successful SPEAR operation into a new generation of higher-luminosity machines and more precise experimentation: the SLAC discoveries of the ψ and χ states[1] and of the tau lepton[2] led naturally to the notion that a much more ambitious project in the SPEAR energy range could[3] and should[4] be pursued.

A comprehensive study of many related machine and detector issues, as well as of the physics motivation, culminated in the Tau-Charm Workshop held at SLAC in May, 1989.[5] A proposal was subsequently submitted to the SLAC director to build such a facility with a dedicated injector,[6] but was not deemed opportune as a next-generation machine choice for that laboratory. A site-non-specific machine design was then completed at SLAC in January 1990.[7]

Present plans attempt to attract a facility closely similar to this project to Sevilla, Spain. An Orsay machine study[8] and a CERN project feasibility report[9] together with assured political and financial support from national and regional authorities in Spain makes this location a logical choice; in the context of its likely implementation, SLAC is slated to support the activities of a group committed to the realization of the physics goals of the originally proposed Tau-Charm facility.

The SLAC Machine Study[7] starts from the notion that the needed luminosity, at energies $3.0 \leq 2\mathrm{E}_{\mathrm{beam}} \leq 4.4$ GeV/c^2, is $\sim 10^{33}$ cm^{-2} sec^{-1}. Let us recall that the SPEAR ring ran reliably at $\sim \mathcal{L} \geq 10^{30}$ cm^{-2} sec^{-1} in this energy range. Can the increase by three orders of magnitude be safely predicted?

For reasonably flat beams, the luminosity can be approximately defined by

$$\mathcal{L} \sim I \left(\frac{\xi_y}{\beta_y^*} \, E \right),$$

where I is the beam current, ξ_y is the beam-beam tune shift, β_y^* is the β function at the interaction point, E is the total energy. The SLAC study is confidently predicting a factor of 50 increase in beam current, a factor of 1.6 improvement of

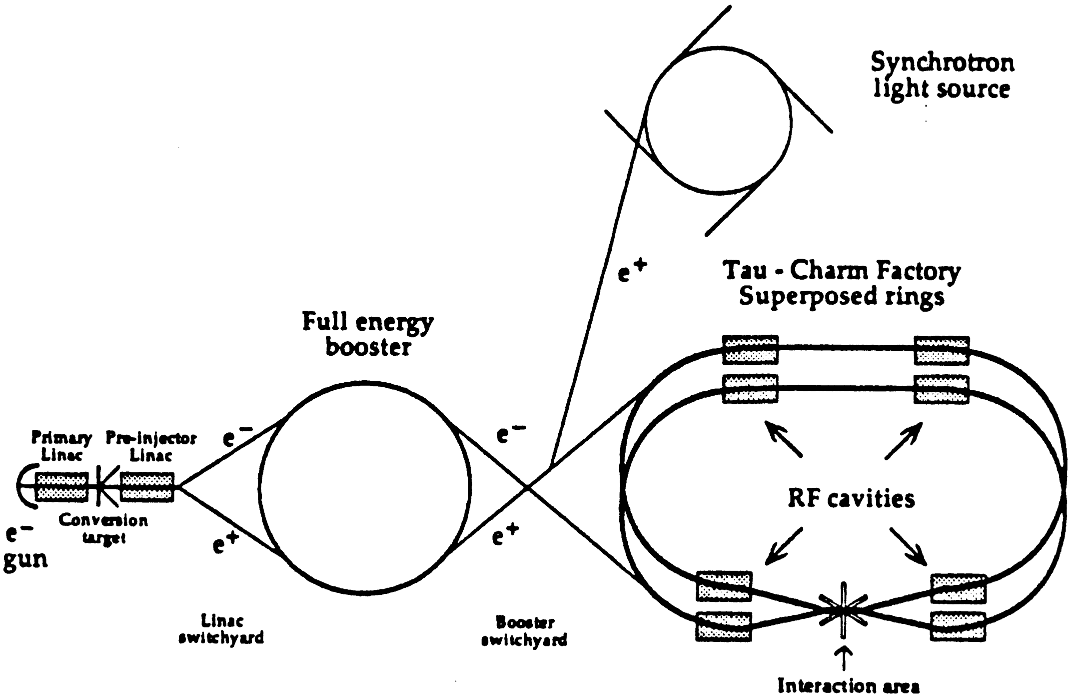


Fig. 1. Schematic layout of the TCF machine design.

the beam-beam tune shift, and the reduction of β_y^* by approximately a factor of 10, for an overall luminosity increase on the order of 800.

The specific design that makes these parameters possible is shown schematically in Fig. 1. It incorporates two 0.5 GeV linacs that feed e^- and e^+ into an accumulator/damping ring, a booster synchrotron that will raise the energy to $\sim$ 2 GeV per beam, and two vertically superimposed storage rings that store e^+, e^- separately, and feed into one interaction point. Some 48 m wide and 140 m long, these "rings" store 21 bunches with 1.6×10^{11} $e^{\pm}$ per bunch, with 15.7 m between bunches, for a total current of 500 mA/beam. The lattice shown in Fig. 2 is specifically designed for stability of beam conditions if we can hold to transverse errors to ≤ 300 μ^-, longitudinal errors to no more than 10 times larger, and if we have a field setting precision $\leq 10^{-8}$. Using sextupoles for chromaticity corrections, horizontal and vertical tunes are expected to amount to 8.873 and 7.762, respectively. With this lattice arrangement, the luminosity is expected to rise to the desired value by the insertion of wigglers.

Electron/positron lifetimes due to beam-gas interactions are projected at 8 hours, due to beam-strahlung at 3.4 hours (assuming 0.5 A currents), for a combined lifetime of 2.4 hours. To maintain an average luminosity at the 75% of $\mathcal{L}_{\max}$ level, a new fill will have to be planned every 65 minutes.

In the following, we explain how the low total energy of this machine gives experimental advantages for a number of case studies—not only due to the large annihilation cross-section

$$\sigma(e^+e^-) \sim \mathrm{s}^{-1} \ ,$$

but also by virtue of advantageous systematic effects: low final-state multiplicities, clean π/K separation, tagging of $D^0, D^\pm, D_S$, and τ leptons.

3. Physics Motivation: The Still Mysterious $\tau - \nu_\tau$ Doublet

It is sobering to think that, as of the present date, there is still the lack of a direct observation of the tau neutrino, ν_τ. What, if any, is its mass? What are its precise interaction characteristics? Persistent questions on the "one-prong" τ lepton branching fraction puzzle remain as an indication that tau physics may well hold the key to new phenomena. These may become visible at the TCF design luminosity of 10^{33} sec^{-1} cm^{-2}. In particular, some rare tau decays may show up at the BR level $\sim 10^{-7}$, giving information well beyond the purview of today's Standard Model.

In Fig. 3, we show the usefulness of choosing beam energies judiciously, while J/ψ production is sharply defined (3a); τ pair production well below the ψ' and the $\psi'' \rightarrow D\overline{D}$ thresholds permits background-depleted running conditions.

Let us first look for an improved measurement of the ν_τ mass (or an upper limit much better than the present limit of $\sim$ 35 MeV/c^2. While recent indications on $\sim$ "17 KeV" neutrinos may be connected with the ν_τ puzzle, the TCF can push the limit down by about a factor of 10. The method to be employed was worked out by Gomez-Cadenas *et al.*[10] Run the TCF at $\sqrt{s} \simeq 3.68$ GeV, i.e., well above $\tau\bar{\tau}$ threshold and close to $\sigma_{\tau\bar{\tau}}$ (max), but well below $D\overline{D}$ threshold. The low multiplicity then permits the following selection procedure:

- tag τ pairs by identifying a one-prong decay $\tau_1 \rightarrow \mu v\bar{v}$ or $ev\bar{v}$;
- choose pairs where the second τ, τ_2, decays such as to leave little kinetic energy to ν_τ in its decay;
- study the endpoint momentum distributions of charged particles in τ_2 decay.

Case studies involving the decays

$$\begin{array}{ll} \tau_2 \rightarrow \pi\rho^\circ & \rho^\circ\nu_\tau \\ \qquad\ \ \ \llcorner\!\!\rightarrow \pi^+\pi^- & \llcorner\!\!\rightarrow \pi^+\pi^- \\ \tau_2 \rightarrow K\overline{K}\nu_\tau & \end{array}$$

then define the p_π, p_K momentum distributions that are qualitatively similar for any possible rest mass of ν_τ. Putting in all relevant branching fractions, we are

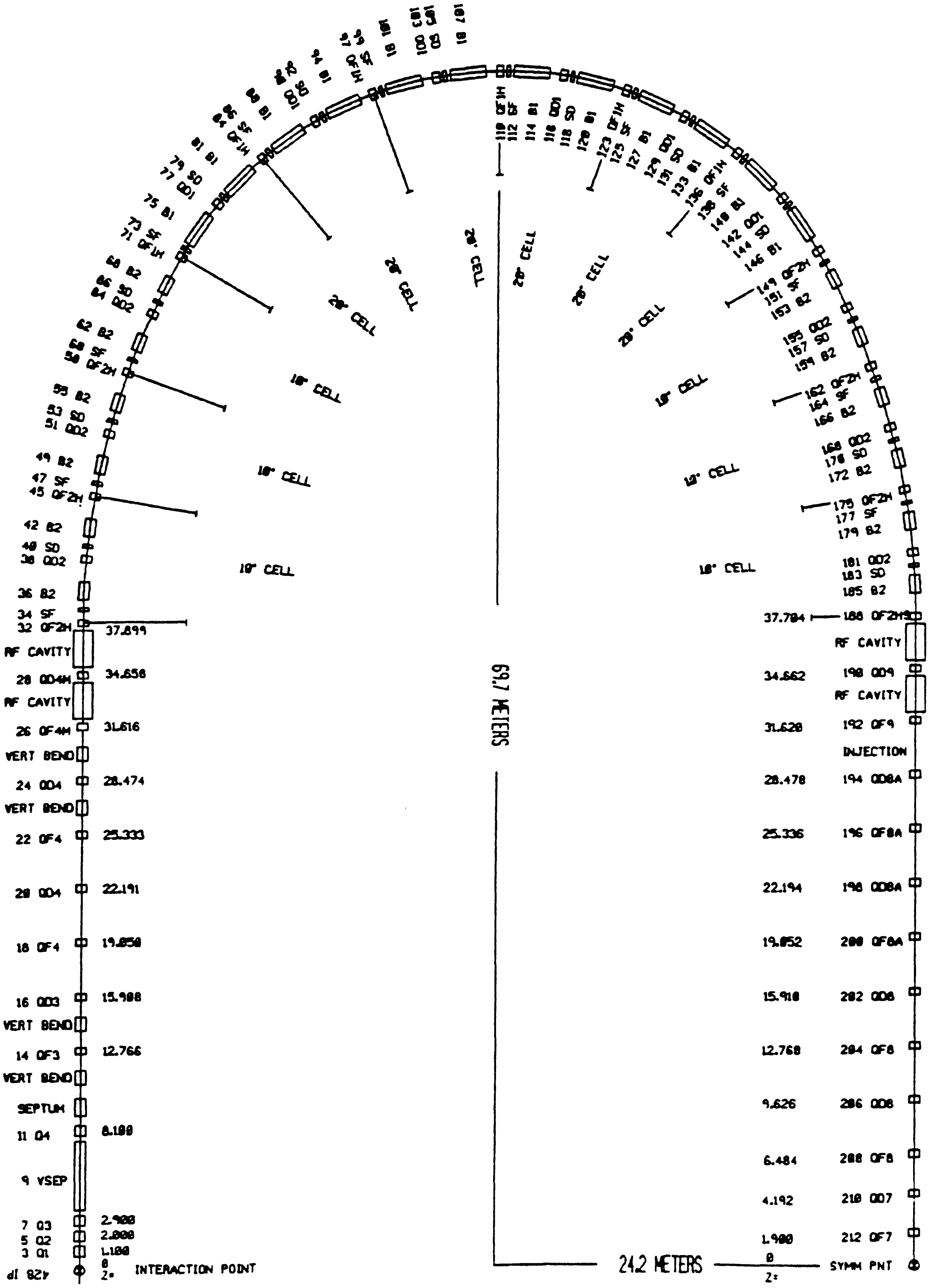


Fig. 2. The lattice structure that permits flat beams of the luminosity required.

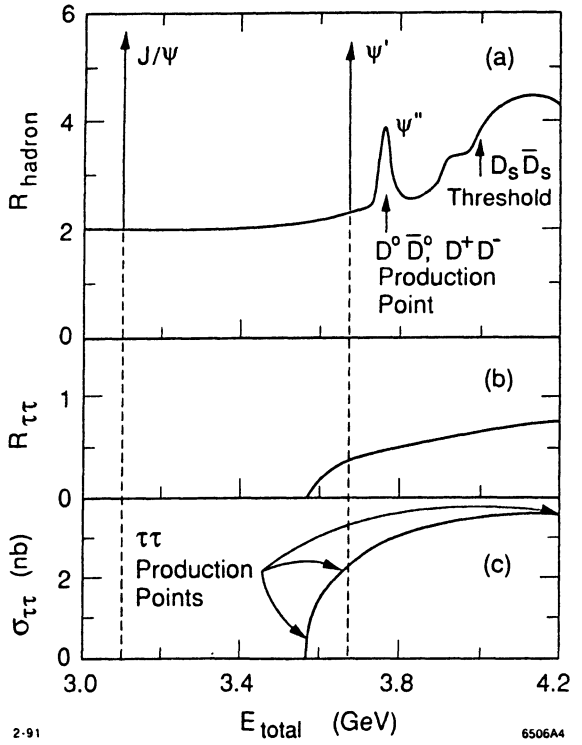


Fig. 3. The cross-sections for τ pair production in e^+e^- annihilation (b,c). The usefulness of various energy choices is discussed in Section 3. For comparison with hadronic "backgrounds", see R_{had} in (a).

able to calculate the $m(\nu_\tau)$ limits from an integrated luminosity of 30 fb^{-1}:

$$\begin{aligned} m(\nu_\tau) &< 3.5\mathrm{MeV/c^2}\ (5\pi\ \nu_\tau)\ , \\ &< 4.7\mathrm{MeV/c^2}\ (\mathrm{K\overline{K}}\ \nu_\tau)\ , \\ &< 2.9\mathrm{MeV/c^2}\ \text{jointly.} \end{aligned}$$

This is illustrated in Fig. 4 (a-d), where a Monte Carlo calculation of the 5-pion invariant mass spectrum is shown for τ decay, assuming various ν_τ rest masses (20, 10, 5, 1 MeV/c^2). We note that an excellent precision for $|\vec{p}_\pi|$ measurement is assumed for the detector (the relevant calibration uses such well-established processes as $D \rightarrow \mathrm{K}\pi\pi$).

The second problem in τ physics that may bring novel findings is the lingering one-prong branching fraction puzzle:[11] we recall that an addition of all individual τ decay fractions that lead to one and only one charged track yields some 77%, whereas the measured inclusive one-prong fraction is (87 ± 0.3)%. Present experimental errors on the ratio of various components of this fraction are way too large to permit a decisive test (Table 1).

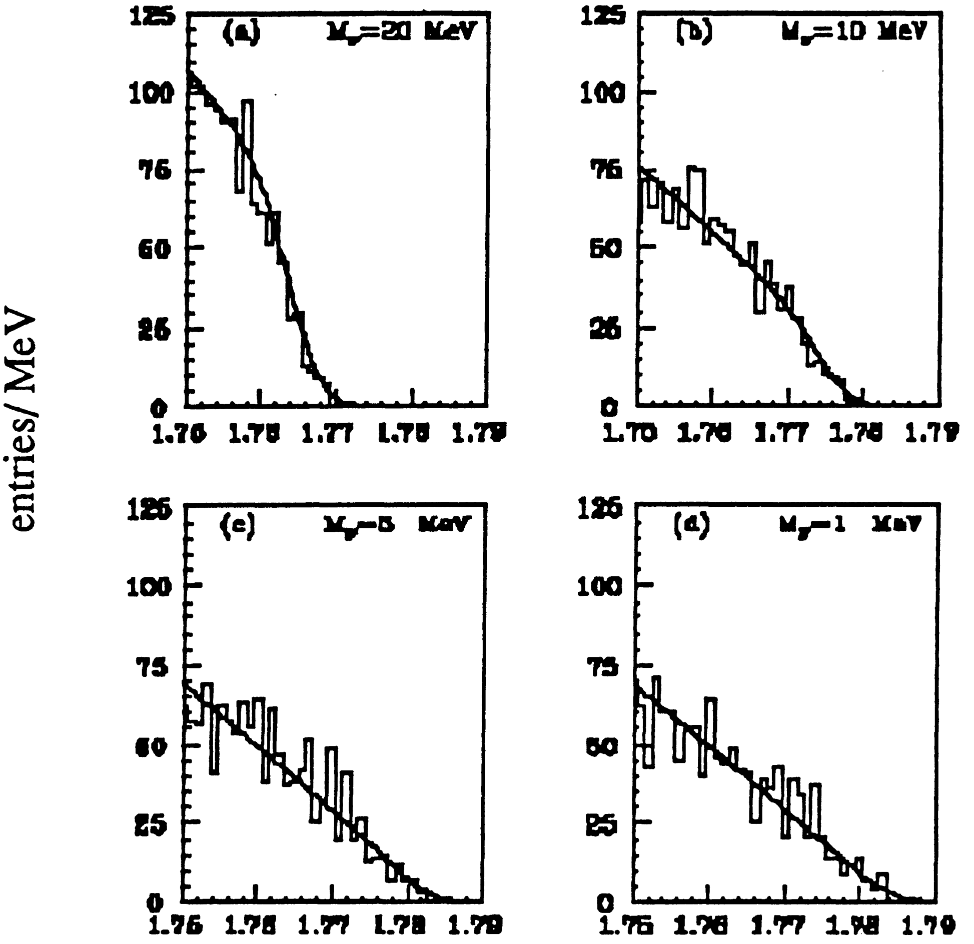


Fig. 4. Invariant-mass distributions for the pions in $(5\pi)\nu$ decays of the τ lepton. These Monte Carlo results illustrate the change of the endpoint spectrum ($m_{5\pi} > 1.75$ GeV/c^2) for $m(\nu_\tau) = 20, 10, 5, 1$ MeV/c^2.

Table 1

Ratio	Experiment	Theory
μ/e	1.02 ± 0.03	0.973
π/e	0.62 ± 0.04	0.601
K/e	0.38 ± 0.11	0.399

The TCF, using a state-of-the-art detector and a one-year run, can bring down errors to the 1% level for individual branching fractions; present values range from 2 to 30%.

This becomes feasible due to the possibility of remaining very close to threshold for $\tau^+\tau^-$ production: Fig. 5a illustrates that, at $\sqrt{s} = 3.6$ GeV, $K^\pm$ and $\pi^\pm$ are neatly resolved in the momentum spectrum, and that e, μ are separated almost completely from them, so that their additional identification in shower counter and muon catcher leads to complete particle separation in the momentum range of interest. At $\sqrt{s} = 4.2$, this situation is no longer present [Fig. 5(b)]. If additional selection criteria are applied on the missing energy [Fig. 6(a)], the multi-hadronic background from the process

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

is reduced such as shown in Fig. 6(b): a narrow peak sits on top of a smooth background, and the systematic errors due to its suppression reduce the systematic uncertainties for $B_e B_\mu, B_\pi$ to 0.3%, for B_K to 1%. The implications are clear: If there is a one-prong problem,[12] and if it carries a special message, the TCF will find out the details.

In addition, the small errors on B_e and B_μ will have important implications for lepton universality presently not available; those on B_π and B_K will tell a tale on the Cabibbo angle in third-family interactions.

A third problem in τ physics the TCF will tackle in a uniquely promising way is that of rare τ decays: this is likely the single most promising place to look for limits to the Standard Model, and for deviations from its current, fuzzily comprehensive, respectability.

Note that rare decays implying interactions among the first and second families only are tightly limited by experimental evidence: $B(\mu \rightarrow eee) < 10^{-12}, B(K^o \rightarrow \pi\mu e) < 10^{-9}$, etc. The poorly studied third family exhibits weak limits to date and, hence, the chance for major discoveries: limits on $\tau \rightarrow eee$, $e\gamma$, $e\pi^o, \mu ee$, etc., are on the 4×10^{-5} level. The TCF will produce, typically, $5 \times 40^7 \tau$ pairs per year. This rate, combined with the experimental dependability of the detector, permits the expectation that 10^{-7}–10^{-8} admixtures should become detectable.

Criteria that strengthen the notion that this level may be significant include these:

(*a*) New interactions indicated by non-minimal Higgs scalars and by leptoquarks are likely to exhibit mass- or generation-dependent couplings, favoring detectable effects including the τ lepton.

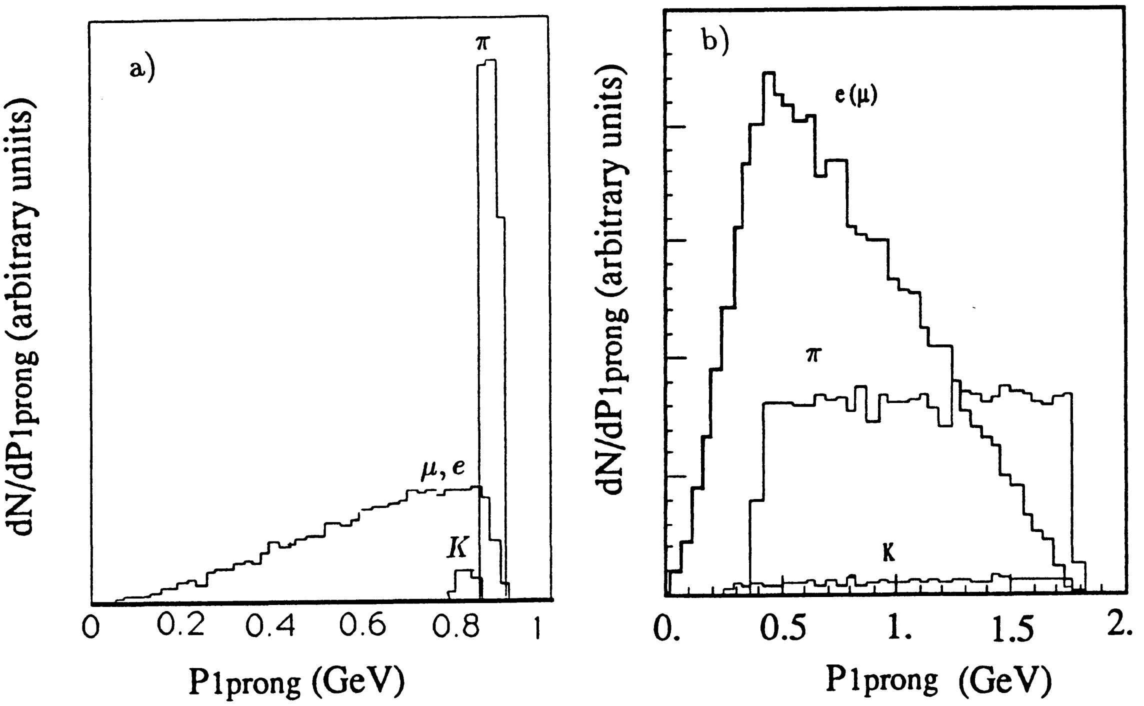


Fig. 5. (a) Momentum spectra for the τ decays to e, μ, π and $K(\sqrt{s} = 3.57$ GeV). (b) same as (a) with $\sqrt{s} = 4.2$ GeV.

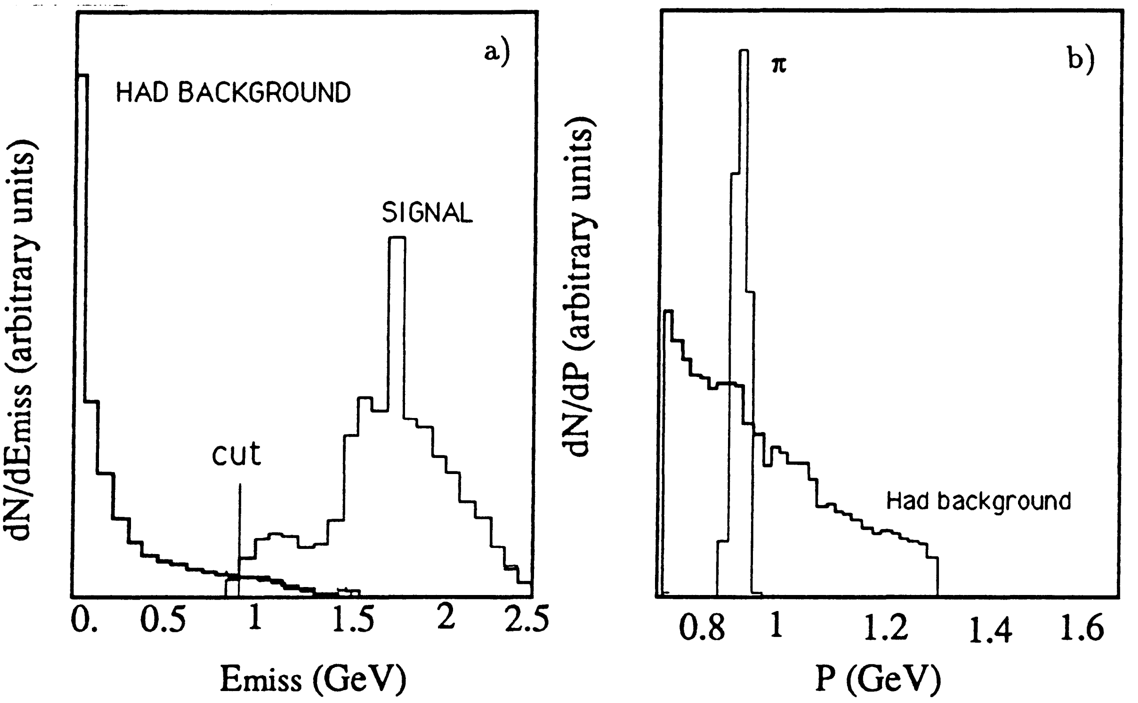


Fig. 6. (a) Missing energy distribution for the $\tau \rightarrow (5\pi)\nu$ decays ("signal") indicating the cut for multihadronic background suppressions. (b) Signal and hadronic backgrounds after the selection cuts.

(*b*) Minimal Standard Model extensions tend to become more visible with larger momentum transfers: $\sigma_{\text{new}}, \Gamma_{\text{new}} \sim Q^2$. Obviously, with $Q^2(\tau \text{ decay}) = 300\ Q^2(\mu \text{ decay})$, they should more readily manifest themselves here.

(*c*) Couplings of inter-family transitions contain mixing angles; they are likely to favor transitions among neighboring families: $\Gamma(\tau \rightarrow \mu ...) > \Gamma(\tau > e ...)$.

(*d*) Certain fashionable (E6-based) models favor[13]

$$\left.\begin{array}{r}\text{up-quark to charged-lepton,}\\ \text{down-quark to neutral-lepton}\end{array}\right\}\text{couplings.}$$

This implies that

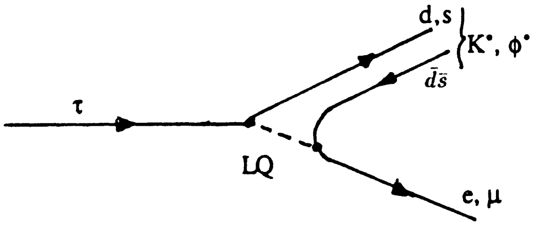
$$\left.\begin{array}{r}(\mathrm{u,c,t}) \leftrightarrow (\mathrm{e}, \mu, \tau)\\ (\mathrm{d,s,b}) \leftrightarrow (\nu_i)\end{array}\right\}\text{connections are favored,}$$

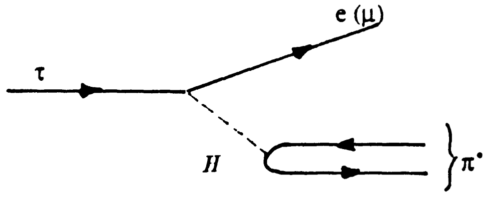
$$\left.\begin{array}{r}(\mathrm{u,c,t}) \leftrightarrow (\nu_i)\\ (\mathrm{d,s,b}) \leftrightarrow (\mathrm{e}, \mu, \tau)\end{array}\right\}\text{transitions are suppressed.}$$

With these qualitative notions in mind, it is attractive to think of the discovery potential of a search for rare decays at the $10^{-7}$to 10^{-8} level for such tell-tale processes as[13]

$$\begin{aligned}\tau &\rightarrow \pi^o \mu,\\ &\rightarrow \pi^o e,\\ &\rightarrow \rho^o \mu, \text{ etc.,}\end{aligned}$$

that are indicated by leptoquark or Higgs exchanges





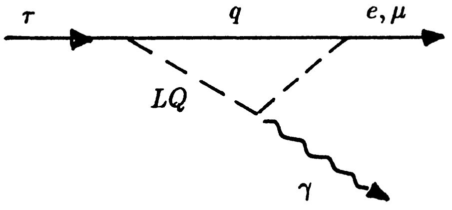
Interchange the $d(\bar{d})$ in the first diagram for an $s(\bar{s})$, and you find a smoking-gun test for the existence of charge-2/3 leptoquarks:

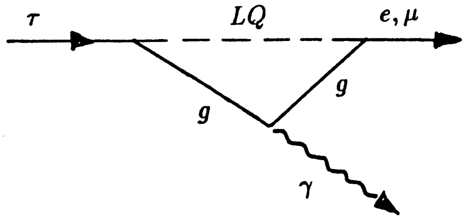
$$\begin{aligned}\tau &\rightarrow K^o \mu(e)\\ &\rightarrow \phi^o \mu(e).\end{aligned}$$

Note that, in a tagged sample of τ's, there is essentially <u>no</u> experimental background to these processes: their occurrences can be established by one or a few events. A sensitivity at the 10^{-7} level, therefore, appears entirely reasonable at the TCF, in strict contrast to higher-energy machines such as LEP or a $B\overline{B}$ factory.

Similarly, non-minimal-Higgs or lepto-quark-mediated processes with unknown (and possibly not much weaker than electromagnetic) couplings can make the "leptonic" transitions

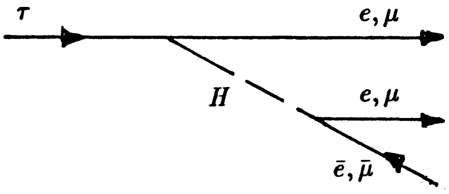
$$\begin{aligned} \tau &\rightarrow \mu\gamma \\ &\rightarrow e\gamma \end{aligned}$$

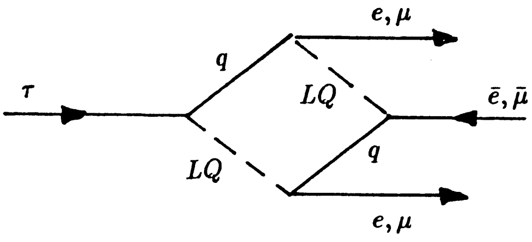




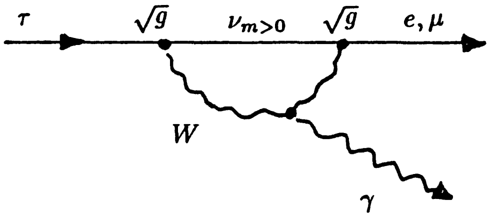
or

$$\begin{aligned} \tau &\rightarrow eee \\ &\rightarrow \mu ee \end{aligned}$$





much more accessible than the doubly weak Standard Model extension



A clean sample of $10^8 \tau$ pairs can make a decisive difference!

4. Conclusion, Outlook

Having picked only a few aspects of tau lepton physics as examples for the physics potential of the projected Tau Charm Factory, we stress that an increase by three orders of magnitude of the data samples collected at SPEAR or DCI will necessarily have a deep impact on all the problems enumerated in Section 1 above:

High-statistics, high-precision data can be assembled by construction of an e^+e^- annihilation facility that will reliably deliver a luminosity of

$$\mathcal{L} = 10^{33}\mathrm{cm}^{-2}\mathrm{sec}^{-1}$$

at $3.0 \leq \sqrt{s} \leq 4.2$ GeV.

Typical samples of these data will contain

J/ψ events,	6×10^8 /month,
η_c events, tagged	10^6 /month,
$\tau^+\tau^-$ pairs, tagged	$> 10^7$ /year,
D^+D^- pairs, tagged	$> 10^7$ /year,
$D^o\overline{D}^o$ pairs, tagged	$> 10^7$ /year,
$D_s\overline{D}_s$ pairs, tagged	$> 10^6$ /year.

A great deal of electroweak, QCD, and "Beyond-the-Standard-Model" problems can be successfully investigated.

While this facility is not likely to be built in the United States, interest in U.S. high-energy community is strong. The presently projected construction of a new laboratory dedicated to this mission in Sevilla, Spain, may guide a contingent of adventurous Americans back to the city from where Christopher Columbus set sail for the Americas exactly 500 years ago.

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