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THE FUTURE OF TAU PHYSICS AND TAU-CHARM DETECTOR AND FACTORY DESIGN*

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ABSTRACT

Future research on the tau lepton requires large statistics, thorough investigation of systematic errors, and direct experimental knowledge of backgrounds. Only a tau-charm factory with a specially designed detector can provide all the experimental conditions to meet these requirements. This paper is a summary of three lectures delivered at the 1991 Lake Louise Winter Institute.

A. FUTURE TAU RESEARCH

A.1 Introduction

In Part A of this paper I outline the future research which should be carried out on the tau lepton; I show that much of this research requires large statistics, thorough investigation of systematic errors, and direct experimental knowledge of backgrounds. Only a tau-charm factory (Kirkby 1987, Jowett 1988, Kirkby 1989a) can provide all the experimental conditions to meet these requirements. A tau-charm factory is a very high luminosity electron-positron circular collider operating in the total energy range of 3 to 4.5 GeV. Parts B and C are introductions to the design principles for the tau-charm detector and a tau-charm factory.

As described in this paper, a tau-charm factory with a well-designed tau-charm detector offers great prospects for future research in tau physics. Similarly these instruments offer great prospects in charm physics research: D, D_s, ψ/J, ψ'. I did not have the time in these lectures to discuss this charm physics, I must refer

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you to others: Schindler (1989, 1990a, 1990b), Barish *et al* (1989), Kirkby (1990) and the Proceedings of the Tau-Charm Factory Workshop (Beers 1989).

But the prospects for tau and charm physics which we can foresee will probably only be part of what is learned about particle physics at the tau-charm factory. The most important discoveries at many accelerators have not been foreseen: CP violation and the J at the Brookhaven AGS, neutral currents and the W and Z at CERN, the ψ and the τ itself at SPEAR. And it may be the same with the tau-charm factory. It will be a powerful new instrument for studying particle physics. There are very strong reasons based on the physics we know for building it, and it may bring us discoveries we cannot now conceive.

These lectures are in that spirit. I tell very generally what we know now and what we expect to learn about the τ. I also show how little we know about the τ and that the future of τ research is very open. I encourage speculation and dreams.

The subjects of future τ research and tau-charm detector and factory design are large, but I want to keep this paper brief and introductory. Therefore I use a summary style: equations, tables, brief comments, a few figures.

General references to τ physics are Barish and Stroynowski (1988), Burchat (1988), Gan and Perl (1988), Kiesling (1988), Pich (1990a, 1990b), and Perl (1991). In addition a comprehensive Workshop on Tau Lepton Physics was held in Orsay, France in September 1990. The proceedings of the Workshop, soon to be published, will provide a most valuable summary of our present knowledge of the τ and ν_τ.

In these lectures all measured values are quoted from the Particle Data Group's Review of Particle Properties (Aguilar-Benitez 1990) unless otherwise noted.

A.2 Overview of τ Decays: Present Data

The average measured values (Aguilar-Benitez *et al* 1990) of the branching ratios of the major decay modes of the τ are:

Pure leptonic modes:

$$B_e = B(\tau^- \rightarrow \nu_\tau e^- \bar{\nu}_e) = (17.7 \pm 0.4)\% \qquad (A1a)$$

$$B_\mu = B(\tau^- \rightarrow \nu_\tau \mu^- \bar{\nu}_\mu = (17.8 \pm 0.4)\% \qquad (A1b)$$

1-charged-particle, non-strange, hadronic modes:

$$B_\pi = B(\tau^- \to \nu_\tau \pi^-) = (11.0 \pm 0.5)\% \tag{A2a}$$

$$B_\rho = B_{\pi^-\pi^0,\text{resonant}} = B(\tau^- \to \nu_\tau \rho^- \to \nu_\tau \pi^- \pi^0) = (22.7 \pm 0.8)\% \tag{A2b}$$

$$B_{\pi^-\pi^0,\text{non-resonant}} = \left(0.37^{+0.30}_{-0.22}\right)\% \tag{A2c}$$

$$B_{\pi^-2\pi^0} = B(\tau^- \to \nu_\tau \pi^- \pi^0 \pi^0) = (7.5 \pm 0.9)\% \text{ (See Sec. A.6)} \tag{A2d}$$

3-charged-particle, non-strange, hadronic modes:

$$B_{2\pi^-\pi^+} = B(\tau^- \to \nu_\tau \pi^- \pi^- \pi^+) = (7.1 \pm 0.6)\% \tag{A3a}$$

$$B_{2\pi^-\pi^+\pi^0} = B(\tau^- \to \nu_\tau \pi^- \pi^- \pi^+ \pi^0) = (4.4 \pm 1.6)\% \tag{A3b}$$

In addition there are the strange, hadronic modes such as:

$$B_K = B(\tau^- \to \nu_\tau K^-) = (0.68 \pm 0.19)\% \tag{A4a}$$

$$B_{K^*} = B\left(\tau^- \to \nu_\tau K^{*-}(892)\right) = \left(1.39^{+0.18}_{-0.20}\right)\% \tag{A4b}$$

which are all small, of order $\sin^2\theta_c = 0.05$ times the corresponding non-strange hadronic modes.

Finally there are a great number of large multiplicity modes such as

$$\tau^- \to \nu_\tau + \pi^- + n\pi^0, \quad n > 2 \tag{A5a}$$

$$\tau^- \to \nu_\tau + \pi^- + \eta^0 + n\pi^0, \quad n \geq 1 \tag{A5b}$$

$$\tau^- \to \nu_\tau + 2\pi^- + \pi^+ + n\pi^0, \quad n > 1 \tag{A5c}$$

$$\tau^- \to \nu_\tau + 3\pi^- + 2\pi^+ + n\pi^0, \quad n \geq 0 \tag{A5d}$$

The branching ratios for very few of these modes have been measured, two of the few examples are

$$B(\tau^- \to \nu_\tau 3\pi^- 2\pi^+) = (0.056 \pm 0.016)\% \tag{A6a}$$

$$B(\tau^- \to \nu_\tau 3\pi^- 2\pi^+ \pi^0) = (0.051 \pm 0.022)\% \tag{A6b}$$

and there is the 90% CL upper limit

$$B(\tau^- \to \nu_\tau 4\pi^- 3\pi^+ n\pi^0, \; n \geq 0) \leq 0.019\% \tag{A7}$$

We know very little about these large multiplicity modes because present techniques are inadequate for isolating modes with three or more neutral mesons:

π^0's and η's. One of the purposes of a tau-charm factory and proper associated detector is to provide the instruments for isolating and studying these modes.

Measurement of a branching ratio is only the first step in studying a τ decay mode if there are three or more particles in the mode. Once there are three or more particles the dynamics of the decay is revealed through the spectra and correlations of momenta, angles and spins. But present statistics and techniques have limited such studies to a few cases: In

$$\tau^- \to \nu_\tau + \pi^- + \pi^0 \tag{A8}$$

the $\pi^-\pi^0$ mass spectrum shows the ρ resonance. In

$$\begin{aligned} \tau^- &\to \nu_\tau + e^- + \bar{\nu}_e \\ \tau^- &\to \nu_\tau + \mu^- + \bar{\nu}_\mu \end{aligned} \tag{A9}$$

the charged lepton spectrum has been extensively studied. In

$$\tau^- \to \nu_\tau + \pi^- + \pi^+ + \pi^- \tag{A10}$$

the spectra of the 3π's has been studied and show the $a_1(1260)$ resonance and its decay mode

$$a_1 \to \rho + \pi \tag{A11}$$

But that is about all that has been done. Present techniques are very restrictive. For example

$$\tau^- \to \nu_\tau + \pi^- + \pi^0 + \pi^0 \tag{A12}$$

has barely been isolated, the various 3π spectra have not yet been studied with care.

A.3 Overview of τ Decays: Standard Model Theory

In the Standard Model of elementary particle physics the decay of the τ takes place through the W exchange processes of Fig. 1. The τ and ν_τ are taken to be spin 1/2 point particles with masses

$$m_\tau = 1784.1^{+2.7}_{-3.6} \text{ MeV} \tag{A13a}$$

$$0 \leq m_{\nu_\tau} \leq 35 \text{ MeV} \tag{A13b}$$

The $\tau - W - \nu_\tau$ vertex is taken to have the V-A form and standard coupling strength. And perfect τ lepton number conservation is assumed.

The goal of τ decay theory is to enable calculation of all the spectra of each decay mode, and integrating over those spectra, to calculate the decay width $\Gamma(i)$ of each mode i.

This goal was achieved for the pure leptonic modes twenty years ago by Tsai (1971) before the τ was discovered. From the diagram in Fig. 1a, the well-known result is

$$\Gamma_\ell = \Gamma(\tau^- \to \nu_\tau \ell^- \nu_\ell) = \frac{G_F^2 m_\tau^5}{192\pi^3} F_\ell(y) \ ; \ \ell = e, \ \mu \tag{A14}$$

where

$$\begin{aligned} &F_\ell(y) = 1 - 8y + 8y^3 - y^4 - 12y^2 \ \ell n \, y \\ &y = m_\ell^2 / m_\tau^2 \\ &m_{\nu_\ell} = 0 \\ &m_{\nu_\tau} = 0 \end{aligned}$$

and G_F is the Fermi coupling constant 1.166×10^{-5} GeV^{-2}. Electromagnetic radiative corrections and a correction for the W mass are given by Marciano and Sirlin (1988), Wu (1990), and Perl (1991).

But at present there is no equivalent usable theory for the hadronic modes which constitute over 60% of the branching ratios. The theory of the W-hadron vertex in Fig. 1b is the theory of quantum chromodynamics *in the 1 GeV energy region.* There is no general and precise way to calculate from this theory.

This serious deficiency is sometimes overlooked because it has become commonplace in discussions of hadronic τ decays to write about the comparison of measured branching ratios with theory. What is meant is the prediction of a τ decay width *using other data and a general theoretical connection.* There are two common examples. The $\tau^- \to \nu_\tau \pi^-$ decay width, Fig. 2a, is given by

$$\Gamma(\tau^- \to \nu_\tau \pi^-) = \frac{G_F^2 f_\pi^2 \cos^2\theta_c m_\tau^3}{16\pi} \left[1 - \frac{m_\pi^2}{m_\tau^2}\right]^2 \tag{A15}$$

where f_π is the pion decay constant. To calculate $\Gamma(\tau^- \to \nu_\tau \pi^-)$ we do not calculate f_π from quantum chromodynamics, we obtain it from the *measured width* for $\pi^- \to \mu^- \bar{\nu}_\mu$ decay:

$$\Gamma(\pi^- \to \mu^- \bar{\nu}_\mu) = \frac{G_F^2 f_\pi^2 \cos^2\theta_c m_\pi m_\mu^2}{8\pi} \left[1 - \frac{m_\mu^2}{m_\pi^2}\right]^2 \tag{A16}$$

The factor f_π appears in both equations because the $W - \pi$ vertex at the energy of the π mass appears in both decay diagrams, Fig. 2. The other common example is that $\Gamma(\tau^- \rightarrow \nu_\tau \rho^-)$ is calculated from the cross section for

$$e^+ + e^- \rightarrow \rho^0 \quad ; \qquad (A17)$$

we have no way at present to precisely calculate from quantum chromodynamics the $W - \rho$ vertex contribution to $\Gamma(\tau^- \rightarrow \nu_\tau \rho^-)$.

A major area in future τ research will be the symbiosis between precise methods for low energy quantum chromodynamics calculations and precise measurements of the properties of the hadronic decay modes of the τ. Some references to present applications of quantum chromodynamics to hadronic τ decay are Braaten (1988, 1989a, 1989b), Pumplin (1989, 1990), Pich (1989), Narison and Pich (1988), Maxwell and Nicholls (1990), Ghose and Kumbhakar (1981).

Table 1. Comparison of B_i/B_e from measurements with predictions from theory and other data. I use $B_e = B(\tau^- \rightarrow \nu_\tau e^- \bar{\nu}_e) = (17.7 \pm 0.4)\%$ from (Aguilar-Benitez 1990).

B_i/B_e	Measurement	Prediction	Reference and notes
$B(\tau^- \rightarrow \nu_\tau \mu^- \bar{\nu}_\mu)/B_e$	1.006 ± 0.032	0.973	use Eqs. A1, A14
$B(\tau^- \rightarrow \nu_\tau \pi^- /B_e$	0.63 ± 0.03	0.607	Smith 1990 use Eqs. A15, A16 and $\Gamma_{meas}(\pi^- \rightarrow \mu^- \bar{\nu}_\mu)$
$B(\tau^- \rightarrow \nu_\tau \rho^- /B_e$	1.26 ± 0.05	1.32 ± 0.05	Smith 1990 use $\sigma_{meas}(e^+e^- \rightarrow \rho^0)$ and CVC
$B(\tau^- \rightarrow \nu_\tau 2\pi^- \pi^+)/B_e$	0.28 ± 0.02	0.3 to 0.7	Smith 1990 very approximate theory
$B(\tau^- \rightarrow \nu_\tau 2\pi^- \pi^+ \pi^0)/B_e$	0.28 ± 0.02	0.28 ± 0.06	Smith 1990 use $\sigma_{meas}(e^+e^- \rightarrow 4\pi)$ and CVC
$B(\tau^- \rightarrow \nu_\tau K^-)/B_e$	0.038 ± 0.01	0.041 ± 0.002	Jain 1990 use $\Gamma_{meas}(K^- \rightarrow \mu^- \bar{\nu}_\mu)$

I conclude this section with, Table 1, a comparison of measured branching ratios with predictions from Standard Model theory *and* other data. In these comparisons, the predictions are ratios of widths, for example

$$\left(\frac{B_\pi}{B_e}\right)_{predicted} = \left(\frac{\Gamma_\pi}{\Gamma_e}\right)_{predicted} = \frac{12\pi^2 f_\pi^2 \cos^2\theta_c}{m_\tau^2}\left[1-\frac{m_\pi^2}{m_\tau^2}\right]^2 \qquad (A18)$$

from (A15) and (A16). Given the errors and uncertainties there are no discrepancies.

A.4 τ Pair Production and Backgrounds at a Tau-Charm Factory

Tau pair production

$$e^+ + e^- \rightarrow \tau^+ + \tau^- \qquad (A19)$$

occurs through γ and Z^0 exchange. All measurements of the cross section, $\sigma_{\tau\tau}$, for (A19) are in agreement with these mechanisms; more precise tests should still be made.

In the tau-charm factory energy region with $E_{tot} \leq 5$ GeV, only γ exchange contributes to $\sigma_{\tau\tau}$. Ignoring electromagnetic radiative corrections.

$$\sigma_{\tau\tau} = \frac{4\pi\alpha^2(\hbar c)^2}{3\,E_{tot}^2}\left[\frac{\beta(3-\beta^2)}{2}\right] \qquad (A20a)$$

where $\alpha, \hbar$, and c are the fine structure constant, Planck constant, and velocity of light, and $\beta = v/c$ where v is the τ velocity. Inserting numerical values

$$\sigma_{\tau\tau} = \frac{87.8}{E_{tot}^2}\left[\frac{\beta(3-\beta^2)}{2}\right]\text{nb} \qquad (A20b)$$

where E_{tot} is in GeV.

Voloshin (1989) has pointed out that close to threshold, $E_{tot} = 2m_\tau$, the Coulombic attraction between the τ^+ and τ^- changes (A20a) to

$$\sigma_{\tau\tau}\text{ (near threshold)} = \frac{4\pi\alpha^2(\hbar c)^2}{3\,E_{tot}^2}\left[\frac{\pi\alpha}{1-\exp(-\pi\alpha/\beta)}\right]\left[\frac{3-\beta^2}{2}\right] \qquad (A21a)$$

so that at threshold $\sigma_{\tau\tau}$ is not 0 but is

$$\sigma_{\tau\tau}\text{ (threshold)} = \frac{\pi^2\alpha^3(\hbar c)^2}{2m_\tau^2} = 0.23\text{ nb} \qquad (A21b)$$

This is important for τ research at the tau-charm factory.

Figure 3 shows $\sigma_{\tau\tau}$ and

$$R_{\tau\tau} = \sigma_{\tau\tau}/\sigma_{point} \qquad (A22)$$

where

$$\sigma_{point} = \frac{4\pi\alpha^2(\hbar c)^2}{3\,E_{tot}^2} \qquad (A23)$$

Also shown in Fig. 3 is $R_{hadrons}$ for

$$e^+ + e^- \rightarrow \text{ hadrons} \qquad (A24)$$

showing the J/ψ, ψ', ψ'' resonances as well as the hadronic continuum. Figure 3 illustrates three important advantages of studying the τ at a tau-charm factory:

(i) The most serious and difficult hadronic backgrounds in τ pair data come from D, D_s and B meson production and decay. By obtaining the τ pair data below the ψ'' energy, these backgrounds are avoided.

(ii) Below the ψ' energy, the nature of the $e^+e^- \rightarrow$ hadrons continuum changes very slowly with energy as the energy goes below the $e^+e^- \rightarrow \tau^+\tau^-$ threshold. Therefore for τ data obtained below the ψ' energy, the hadronic contamination can be directly measured by operating the collider just below the τ threshold.

(iii) At τ threshold $\sigma_{\tau\tau} = 0.23$ nb and 2 MeV above threshold $\sigma_{\tau\tau} = 0.4$ nb. Thus τ pair data can be obtained with the τ's produced almost at rest, an important condition for some τ studies (Gomez-Cadenas, Heusch, and Seiden 1989).

A.5 The Future of τ Physics

No one knows how to break out of the Standard Model. Historically most fundamental advances in particle physics have been made by going to higher energies and more violent collisions; and many particle physicists are following that path through LEP II, HERA, the SSC, or the LHC. But history also has a counterexample. The fundamental discoveries in e^+e^- annihilation of the ψ and ψ', the τ, charmed mesons, and hadron jets from quark were made at energies below 7 GeV. From 7 GeV to the Z^0 there has been much wonderful physics in e^+e^- annihilation such as the identification of hadron jets from gluons and the measurements of τ, D, and B lifetimes; but the discovery record below 7 GeV has not been equaled. Nature was not kind above 7 GeV. At the Z^0 there may yet be major discoveries, the full story is not yet known.

Extensive and precise experiments on the τ, and where possible on the τ neutrino, offer another direction for breaking out of the standard model, another direction for finding new physics beyond the Standard Model. We don't know if nature will be kind to the τ researcher, we don't know what experiments will be crucial; but we do know that there is a world of τ and ν_τ experiments to do. That world is summarized in Table 2 (Perl, 1990). In the remainder of the first part of these lectures I discuss some of the experiments which are best carried out at a tau-charm factory, commenting on the significance of the experiments for testing the Standard Model and on what new physics might be found.

Table 2. Experiments on τ and ν_τ.

Type of Experiment	Search For New Physics	Test Standard Model	Tau-Charm Factory
Understand 1-charged particle modes puzzle	√	√	√
Untangle multiple π^0 and η modes		√	√
Precise measurement of B_e, B_μ, B_π and B_ρ,	√	√	√
Precise measurement of Cabibbo-suppressed modes	√	√	√
Full study of dynamics of $\tau \to e\nu\nu$, $\tau \to \mu\nu\nu$ analogous to $\mu \to e\nu\nu$ in detail	√	√	√
Detailed study of 3, 5, 7-charged particle modes		√	√
Find and study rare allowed modes such as radiative decays and second class currents	√	√	√
Explore forbidden decay modes	√	√	√
Search for anomalous moments of τ	√	√	√
Precise measurement of τ lifetime	√	√	
Explore ν_τ mass to a few MeV/c^2	√	√	√
Detect ν_τ	√	√	
Study interactions of ν_τ	√	√	
Search for ν_τ decays	√	√	√
Precise low energy study of $e^+e^- \to \tau^+\tau^-$, $\tau^+\tau^-\gamma$	√	√	√
Precise high energy study of $e^+e^- \to \tau^+\tau^-$, $\tau^+\tau^-\gamma$	√	√	√
Study of $Z^0 \to \tau^+\tau^-$	√	√	
Study of $W^- \to \tau^-\bar{\nu}_\tau$	√	√	
Measure $B(D^- \to \tau^-\bar{\nu}_\tau)$	?	√	√
Measure $B(D_s^- \to \tau^-\bar{\nu}\tau)$	?	√	√
Measure $B(B^- \to \tau^-\bar{\nu}_\tau)$	?	√	
Make and study $\tau^+\tau^-$ atom	√	√	?

A.6 The 1-Charged Particle Modes Puzzle

This is the only anomaly in elementary particle physics which is discussed in detail in the Review of Particle Properties (Aguilar-Benitez *et al* 1990). I take the text and Table 3, the work of K. G. Hayes, directly from Aguilar-Benitez *et al* (1990), only changing how the references are noted.

Table 3. The 1-charged particle modes puzzle (Aguilar-Benitez 1990.)

1-Prong Branching Fractions of the τ(%)		
Decay Mode	Experiment	Theory[(a)]
$e^- \bar{\nu}_e \nu_\tau$	17.7 ± 0.4	18.0
$\mu^- \bar{\nu}_\mu \nu_\tau$	17.8 ± 0.4	17.5
$\rho^- \nu_\tau$	22.7 ± 0.8	22.7
$\pi^- \nu_\tau$	11.0 ± 0.5	10.8
$K^-(\geq 0 \text{ neutrals})\ \nu_\tau$	1.71 ± 0.23	
$K^{*-}\nu, K^{*-} \to \pi^-(2\pi^0 \text{ or } K_L)$	0.6 ± 0.1	
$\pi^-(2\pi^0)\nu_\tau$	7.5 ± 0.9	$\leq 6.7 \pm 0.4$
$\pi^-(\geq 3\pi^0)\nu_\tau$		< 1.4[(b)]
$\pi^-(\geq 1\eta)(\geq 0\pi^0)\nu_\tau$[(c)]	< 1.3	< 0.8
Sum of measured modes	79.0 ± 1.4	
Theoretical limits of unmeasured modes		< 2.2
Sum of exclusive modes	$< 80.2 \pm 1.4$	
Measured 1-prong branching fraction	86.1 ± 0.3	
Difference	$> 5.8 \pm 1.4$	

(a) Normalized to constrained fit to $e\nu\nu$ and $\mu\nu\nu$ measurements assuming $BF_\mu = 0.973\ BF_e$.
(b) Assumes 15% systematic error on the measured cross section for $e^+e^- \to 2\pi^+2\pi^-$.
(c) Contribution to 1-prong mode only.

"There exists a problem in understanding the 1-charged-particle decay modes of the τ. The problem, first discussed by Truong (1984) and Gilman and Rhie (1985), is that the measured inclusive branching fraction to 1-charged prong is larger than the sum of exclusive 1-charged-particle modes. Since the measurement of exclusive modes with 2 or more neutral hadrons is difficult given the limitations of present detectors, the inequality between the sum of exclusive modes and the inclusive measurements is significant only if theoretical predictions are used to put limits on unmeasured or poorly measured modes."

"The current status of the 1-prong modes is summarized in Table 3. For the theoretical estimates, we use the results of Gilman and Rhie (1985) and Gilman (1987) updated to include new experimental data and electroweak radiative corrections (Marciano and Sirlin 1988)."

"The discrepancy is due to errors in the experimental measurements or theoretical limits, or to the existence of one or more modes not included in Table 3. Early measurements of the inclusive one-prong branching fraction reported significantly lower values but suffered from large backgrounds not present in more recent experiments."

"Systematic errors dominate most measurements, particularly for the $\tau^- \to \tau^- \nu_\tau$ and $\tau^- \to \rho^- \nu_\tau$ modes. The technique used to obtain the experimental averages ignores correlated errors, which can be specially important when systematic errors are dominant. There is a tendency for multiple experimental measurements of a given mode to be more consistent than expected from their quoted errors (Hayes and Perl 1988). This indicates either the existence of systematic errors accounted for by the experimenters which are correlated and should not be averaged, or inflation or experimental errors, or a bias in the experimental measurements. The $\tau^- \to \rho^- \nu_\tau$ measurements show this tendency even if the systematic errors are ignored and only the statistical errors are used."

"Resolution of the missing one-prong puzzle will require either new measurements with much reduced systematic and statistical errors, or an explicit measurement of a mode which is presently unmeasured or very poorly measured."

The measurements of Behrend *et al* (1990) give a possible solution to this puzzle. Compared to the world average values in Table 3, they find larger values for $B(\tau^- \to \nu_\tau e^- \bar{\nu}_e)$, $B(\tau^- \to \nu_\tau \pi^- 2\pi^0)$ and B_3, eliminating the 5% discrepancy in Table 3. This has been discussed by Kiesling (1988, 1989, 1990).

A.7 Untangling Multiple π^0 and η Modes

As discussed in Sec.A.2, we have scanty information on τ decay modes with two or more neutral mesons: π^0's and η's. The untangling and study of these decay modes requires that τ pair data be acquired at low E_{tot} where γ's from π^0 and η's are well separated in angle so that the π^0's and η's can be efficiently reconstructed. Furthermore the backgrounds from $e^+e^- \to$ hadrons must be measured directly. These requirements can only be jointly met at a tau-charm factory. In addition a special detector is required with close-to-4π γ detection efficiency even for low energy γ's (Seiden 1989, Kirkby 1989b, Gan 1989).

A.8 Precise Measurements of B_e, B_μ, B_π and B_ρ

The measured values of B_e, B_μ, B_π and B_ρ, Sec. A.2 have fractional errors

$$0.02 \lesssim \Delta B_i/B_i \lesssim 0.04 \qquad (A25)$$

These are average measured values, the individual experiments have larger fractional errors; in addition we don't understand how to average the systematic errors over the experiments (Hayes and Perl 1988). Thus for at least some of these modes the $\Delta B/B$ may be 0.05.

At a tau-charm factory a single, high-statistics experiment can reduce the fractional errors for B_e, B_μ, B_π and B_ρ to

$$\Delta B_i/B_i \approx 0.005 \quad , \qquad (A26)$$

an improvement by a factor of 10! The method due to Gomez-Cadenas, Heusch and Seiden (1989) collects the τ pair sample at a few MeV above τ pair threshold using the mode.

$$\tau^- \to \nu_\tau + \pi^- \qquad (A27)$$

to tag the τ pairs. Since the τ's are produced almost at rest the τ is almost monochromatic in energy. This combined with efficient $e-\pi$, $\mu-\pi$, and $K-\pi$ separation gives very clean τ pair selection. Backgrounds from $e^+e^- \to$ hadrons will be measured directly by going below τ threshold.

The measurement of B_e, B_μ B_π, and B_ρ with a precision of

$$\Delta B_i/B_i \approx 0.005$$

will be compared with the theoretical predictions for B_μ/B_e, $1-B_\mu/B_e$, B_π/B_e and B_ρ/B_e. Gomez-Cadenas, Heusch and Seiden (1989), Tsai (1989a), Tsai (1989b), Heusch (1989a) and others have discussed how such precise studies can uncover new physics such as a Higgs-like particle or a leptoquark.

A.8 Full Study of Dynamics of $\tau^- \to \nu_\tau e^- \bar{\nu}_e$ and $\tau^- \to \nu_\tau \mu^- \bar{\nu}_\mu$

In the Standard Model the matrix element for the decay

$$\tau^- \to \nu_\tau + e^- + \bar{\nu}_e \tag{A28}$$

has the form

$$M = \frac{G}{\sqrt{2}} \left[\bar{u}_e \gamma^\mu (1-\gamma_5) v_{\bar{\nu}_e}\right] \left[\bar{u}_{\nu_\tau} \gamma_\mu (1-\gamma_5) u_\tau\right] \tag{A29}$$

where the u's and v's are Dirac spinors of particle and antiparticles. If we want to allow some deviation in the $\tau - W - \nu_\tau$ vertex from the Standard Model than we write

$$M = \frac{G}{\sqrt{2}} \left[\bar{u}_e \gamma^\mu (1-\gamma_5) v_{\bar{\nu}_e}\right] \left[\bar{u}_{\nu_\tau} \gamma_\mu (v_\tau + a_\tau \gamma_5) u_\tau\right] \tag{A30}$$

This leads to a formula for the e energy spectrum known since the first theoretical studies of μ decay:

$$\frac{d\Gamma_e}{\Gamma_e dx} = 4\left[3(x^2 - x^3) + 2\rho\left(\frac{4}{3}x^3 - x^2\right)\right] \tag{A31a}$$

$$\rho = \frac{3}{4}\frac{(v_\tau - a_\tau)^2}{(v_\tau - a_\tau)^2 + (v_\tau + a_\tau)^2} \tag{A31b}$$

Here $x = 2E_e/m_\tau$, E_e is the electron energy, ρ is the Michel parameter, and the ν_e, ν_τ, and e masses have been set to zero. The same formula holds for

$$\tau^- \to \nu_\tau + \mu^- + \bar{\nu}_\mu \tag{A32}$$

with $m_\mu = 0$.

In the Standard Model $v_\tau = 1$, $a_\tau = -1$ and $\rho = 0.75$. Stroynowski (1990) gives the average measured values

$$\begin{aligned} \rho_e &= 0.705 \pm 0.041 \\ \rho_\mu &= 0.763 \pm 0.051 \\ \rho_e \text{ and } \rho_\mu &= 0.727 \pm 0.033 \end{aligned} \tag{A33}$$

to be compared with the 0.75 value. So far, so good.

But as discussed in a beautiful paper by Fetscher (1990), the $\tau - W - \nu_\tau$ vertex can be much more general than allowed by (A30). Indeed, this has been known for μ decay for four decades (Scheck 1978) and was discussed for τ decay in the 1970's. In (A30)

$$(v_\tau + a_\tau \gamma_5) = \left(\frac{v_\tau - a_\tau}{2}\right)(1-\gamma_5) + \left(\frac{v_\tau + a_\tau}{2}\right)(1+\gamma_5)$$

Also use the notation

$$\begin{aligned} \frac{1}{2}(1-\gamma_5)u &= u_L \\ \frac{1}{2}(1+\gamma_5)u &= u_R \end{aligned}$$

to denote left-handed (L) and right-handed (R) spinors. Then (A30) is rewritten

$$\begin{aligned} M = \frac{2G}{\sqrt{2}} \Big\{ & (v_\tau - a_\tau)\left[\bar{u}_{eL}\gamma^\mu v_{\bar{\nu}_e}\right]\left[\bar{u}_{\nu_\tau}\gamma_\mu u_{\tau L}\right] \\ + & \left(\nu_\tau + a_\tau\right)\left[\bar{u}_{eL}\gamma^\mu v_{\bar{\nu}_e}\right]\left[\bar{u}_{\nu_\tau}\gamma_\mu u_{\tau R}\right]\Big\} \end{aligned} \qquad (A34)$$

This is now easily generalized. Let $\ell = e$ or μ and let the $\ell - W - \nu_e$ vertex also be non-standard with $1-\gamma_5 \rightarrow v_\ell + a_\ell\gamma_5$. Then, following Fetscher (1990) and Mursula and Scheck (1985) define

$$\begin{aligned} g^V_{LL} &= (v_\ell - a_\ell)(\nu_\tau - a_\tau)/4 \\ g^V_{LR} &= (v_\ell - a_\ell)(v_\tau + a_\tau)/4 \end{aligned} \qquad (A35)$$

and so forth with the superscript V denoting the vector γ^μ coupling. Then (A34) is more generally

$$M = \frac{4G}{\sqrt{2}} \sum_{ij} g^V_{ij} \; \left[\bar{u}_{\ell i}\gamma^\mu v_{\bar{\nu}_\ell}\right]\left[\bar{u}_{\nu_\tau}\gamma_\mu u_{\tau_j}\right] \qquad (A36)$$

with $i = L,\ R$ and $j = L,\ R$. The final generalization adds scalar and tensor coupling with γ^μ in (A36) replaced by 1 and $\sigma^{\mu\nu} = i\left[\gamma^\mu\gamma^\nu - \gamma^\nu\gamma^\mu\right]/2$ respectively. Denoting the coupling operators by Γ^s, Γ^v, and Γ^T.

$$M = \frac{4G}{\sqrt{2}} \sum_{\substack{i,j=L,R \\ N=S,V,T}} g^N_{ij} \; < \bar{u}_{\ell i}\,|\Gamma^N|\, v_{\bar{\nu}_e} > < \bar{u}_{\nu_\tau}\,|\Gamma_N|\, u_{\tau j} > \qquad (A37)$$

Of the 12 g_{ij}^N's, g_{LL}^T and g_{RR}^T are identically zero. Since the g_{ij}^N's can be complex, there are 19 independent parameters ignoring an overall phase. This is in contrast to the Standard Model where

$$g_{LL}^V = 1 \qquad (A38a)$$

$$\text{all other } g_{ij}^N = 0 \qquad (A38b)$$

In μ decay

$$\mu^- \rightarrow \nu_\tau + e^- + \bar{\nu}_e \qquad (A39)$$

a tremendous amount of work has been done to set upper limits on (A38b) (Fetscher, Gerber and Johnson 1986). As discussed by Fetscher (1990), Pich (1990) and others a great deal of work needs to be done to carry out similar investigations of the τ leptonic decays. Evidence in $\tau \rightarrow \nu_\tau \ell^- \bar{\nu}_e$ for any $g_{ij}^N \neq 0$ except g_{LL}^V means the discovery of new physics. The detailed study of τ leptonic decays will make use of the correlated spins of the τ's produced in pairs through correlations of the momenta and angles of the e's and μ's. Many of these studies are best carried out at a tau-charm factory. As noted by Stroynowski in a private communication, it is even possible at a tau-charm factory to study the sequence

$$\begin{aligned} \tau^- &\rightarrow \nu_\tau + \mu^- + \bar{\nu}_\mu \\ \mu^- &\rightarrow \nu_\mu + e^- + \bar{\nu}_e \end{aligned} \qquad (A40a)$$

so that the polarization of the μ^- is measured, an important aspect of studying the g_{ij}^N's.

A.9. Exploring the ν_τ Mass to a Few MeV

The present upper limit on the ν_τ mass (Albrecht *et al* 1988) is

$$m_{\nu_\tau} < 35\ MeV \quad , \quad 95\%\ \text{CL} \qquad (A41a)$$

compared to

$$m_{\nu_e} < 17\ \text{eV} \quad , \quad 95\%\ \text{CL} \qquad (A41b)$$

$$m_{\nu_\mu} < 0.27\ \text{MeV} \quad , \quad 90\%\ \text{CL} \qquad (A41c)$$

Since we have no understanding of the masses of the leptons, indeed since we do not know if neutrinos have non-zero mass, we do not know the significance of the three upper limits in (A41). For example, if one believes in the hypothesis

$$\frac{m_{\nu_1}}{m_{\nu_2}} = \frac{m_1^2}{m_2^2} \tag{A42}$$

then

$$m_{\nu_\mu}\left(\frac{m_e}{m_\mu}\right)^2 < 5.9 \text{ eV} \tag{A43a}$$

$$m_{\nu_\tau}\left(\frac{m_e}{m_\tau}\right)^2 < 2.9 \text{ eV} \tag{A43b}$$

and the limits have comparable significance.

The m_{ν_τ} upper limit (A41a) was obtained by studying the spectrum of the invariant mass of the 5π's in the decay

$$\tau^- \longrightarrow \nu_\tau + 3\pi^- + 2\pi^+ \tag{A44}$$

As discussed by Gomez-Cadenas *et al* (1990) this is still the most promising method for exploring for m_{ν_τ} values in the few MeV range, perhaps down to 3 MeV. A tau-charm factory is required to probe m_{ν_τ} down to this level for several reasons: the contamination in (A44) from $e^+e^- \longrightarrow$ hadrons must be directly measured, the π momentum measurements can be directly calibrated using the decay $D^- \longrightarrow 3\pi^- + 2\pi^+$ at the ψ', and large statistics are needed.

A.10. Rare Decay Modes of the τ

Some hadronic decay modes will have small branching fractions because of large multiplicity, for example

$$B(\tau^- \longrightarrow \nu_\tau\, 4\pi^- 3\pi^+ n\pi^0\,,\, n \geq 0) \leq 1.9 \times 10^{-4}\ , \tag{A45}$$

or because the modes have moderate multiplicity but include K's or η's. At present we don't expect any unusual physics to be associated with such modes as long as they obey the first-class hadronic current rules (Tsai 1971, Barish and Stroynowski 1988, Burchat 1988, Pich 1990). Namely, for non-strange hadronic states the G-parity is $G = +1$ for the weak vector current and $G = -1$ for the weak axial vector current.

On the other hand, second-class weak currents have

$$\text{Vector:}\ G = -1 \quad , \quad J^P = 1^- \tag{A46a}$$

$$\text{Axial vector:}\ G = +1 \quad , \quad J^P = 0^-,\ 1^+ \tag{A46b}$$

Decays with such properties have never been seen in nuclear or elementary particle physics because they have very small branching fractions. The τ offers the best possibility to observe decays through the second class current. Possibilities are (Leroy and Pestieau 1978, Pich 1987, Zachos and Meurice 1987)

$$\tau^- \rightarrow \nu_\tau + \pi^- + \eta \tag{A47a}$$

$$\tau^- \rightarrow \nu_\tau + a_0\,(980) \tag{A47b}$$

$$\tau^- \rightarrow \nu_\tau + b_1\,(1235) \tag{A47c}$$

The $a_0(980)$ has $G = -1, J^P = 1$ so (A47b) obeys (A46a), similarly the b_1 (1235) has $G = +1,\ J^P = 1^+$ so (A47c) obeys (A46b). In (A47a) η has $G = +1,\ J^P = 0^-$; therefore $G(\pi\eta) = -1$ and $J^P(\pi\eta) = 0^-$ or 1^+, so (A47a) obeys (A46b).

In the Standard Model, second-class current decays do not occur if one ignores the electromagnetic corrections to isospin symmetry in the strong interaction. Therefore there are two interests in observing and studying second-class current decays. First, what is the strength of a second-class current decay due to the electromagnetic correction, that is a decay within the Standard Model? Second, are there second-class current decays whose properties cannot be explained by the Standard Model? Interesting discussions are given by Berger and Lipkin (1987) and by Bramon, Navison and Pich (1987).

There are two ways to estimate the strength of a second-class current decay due to the electromagnetic correction. That correction introduces the fine structure constant α in a second-class current decay amplitude. Then

$$K^2 = \frac{\Gamma(\text{second-class current})}{\Gamma(\text{first-class current})} \sim \alpha^2 \sim 10^{-4} \tag{A48}$$

Alternately, the second-class current decay may be thought of as due to the difference of the d quark and u quark current masses: $\Delta m = m_d - m_u \sim 1$ MeV.

$$K^2 = \frac{\Gamma\ (\text{second-class current})}{\Gamma\ (\text{first-class current})} \sim \left(\frac{m_d - m_\mu}{m_\pi}\right) \sim 10^{-4} \tag{A49}$$

More generally the range of such crude estimates is

$$10^{-3} \lesssim K^2 \leq 10^{-5} \tag{A50}$$

Thus for the second-class current decay

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

the estimates are (Pich 1987, Zaches and Maurice 1987)

$$B(\tau^- \rightarrow \nu_\tau \pi^- \eta) \sim K^2 \; B(\tau^- \rightarrow \nu_\tau \pi^-) \sim 10^{-4} \text{ to } 10^{-6} \tag{A51}$$

The observation and study of such a small decay mode requires the experimental conditions of a tau-charm factory: large statistics, good control of errors, and direct knowledge of backgrounds.

The radiative decay modes such as

$$\tau^- \rightarrow \nu_\tau + e^- + \bar{\nu}_e + \gamma \tag{A52a}$$

$$\tau^- \rightarrow \nu_\tau + \mu^- + \bar{\nu}_u + \gamma \tag{A52b}$$

$$\tau^- \rightarrow \nu_\tau + \pi^- + \gamma \tag{A52c}$$

$$\tau^- \rightarrow \nu_\tau + \rho^- + \gamma \tag{A52d}$$

have been extensively discussed theoretically. Wu (1990a) has surveyed the theory for leptonic decays. Hadronic decays are discussed by Queljeiro and Garcia (1988), Dominguez and Sola 1988, Banerjee (1986), Garcia and Riviera-Robolledo (1981), and Kim and Resnick (1979). But there is only one experimental study by Wu *et al* (1990b), a study of the decay.

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

For small values of E_γ

$$\frac{d\Gamma(\tau^- \rightarrow \nu_\tau \mu^- \bar{\nu}_\mu \gamma)}{dE_\gamma} \approx \left[\frac{\alpha}{\pi}\left(2\ell n\frac{m_\tau}{m_\mu} - \frac{17}{6}\right)\right] \frac{\Gamma(\tau^- \rightarrow \nu_\tau \mu^- \bar{\nu}_\mu)}{E_\gamma} \tag{A53}$$

This equation is derived from the treatment of radiative muon decay, $\mu^- \rightarrow \nu_\mu e^- \bar{\nu}_e \gamma$, by Kinoshita and Sirlin (1959). Thus in the simplest approximation there is in the bremsstrahlung spectrum $1/E_\gamma$. But precise studies of the γ energy and angle spectra will provide interesting ways to examine the properties of the τ and its decay dynamics as discussed in the references just given. Finally, an interesting use of the decays in (A52a) and (A52b) is to look for an anomalous value of the g-value of the τ using the radiation zero idea (Laursen, Samuel, and Sen 1984).

A.11 Forbidden Decay Modes of the Tau

Since the early days of τ research, there have been searches (Hayes *et al* 1982) for decays which violate the conservation of τ lepton number. Examples of such proposed decays are

$$\begin{aligned}
&\tau^- \to e^- + \gamma \\
&\tau^- \to \mu^- + \gamma \\
&\tau^- \to e^- + \pi^0 \\
&\tau^- \to \mu^- + \pi^0 \\
&\tau^- \to e^- + e^+ + e^- \\
&\tau^- \to e^- + \mu^+ + \mu^-
\end{aligned} \tag{A54}$$

and so forth. The interest is the same as searches for lepton number non-conservation in decays such as $\mu^- \to e^- + \gamma$ and $K^0 \to \mu^\pm + e^\mp$: the desire to find connections between the leptons, the desire to break out of the Standard Model of elementary particle physics.

No violations of τ lepton number conservation have been found. Table 4 from Aguilar-Benitez (1990) gives the upper limits on the branching ratios. Most of these limits are from Albrecht *et al* (1987), Keh *et al* (1988) and Hayes *et al* (1982). Searches for these modes are straightforward because all the particles in the final state can be detected, and the mass of the τ reconstructed if there indeed is such a τ decay. Thus in a sample of 10^n τ pairs with one identified τ decay, the upper limit is of order 3×10^{-n} if an event with the unconventional decay is not found.

Baltrusaitis *et al* (1985) have carried out an interesting but null search for a hypothetical light boson G by looking for the decays

$$\begin{aligned}
&\tau^- \to e^- + G \\
&\tau^- \to \mu^- + G
\end{aligned} \tag{A55}$$

Table 4. Upper limits on branching ratios for forbidden decay modes of τ with 90% CL (Aguilar-Benitez 1990).

Mode	Upper Limit on Branching Ratio
$\mu^-\gamma$	5.5×10^{-4}
$e^-\gamma$	2.0×10^{-4}
$\mu^-\pi^0$	8.2×10^{-4}
$e^-\pi^0$	1.4×10^{-4}
$\mu^-\mu^+\mu^-$	2.9×10^{-5}
$e^-\mu^+\mu^-$	3.3×10^{-5}
$\mu^-e^+e^-$	3.3×10^{-5}
$e^-e^+e^-$	3.8×10^{-5}
μ^-K^0	1.0×10^{-3}
e^-K^0	1.3×10^{-3}
$\mu^-\rho^0$	3.8×10^{-5}
$e^-\rho^0$	3.9×10^{-5}
$e^-\pi^+\pi^-$	4.2×10^{-5}
$e^+\pi^-\pi^-$	6.3×10^{-5}
$\mu^-\pi^+\pi^-$	4.0×10^{-5}
$\mu^+\pi^-\pi^-$	6.3×10^{-5}
$e^-\pi^+K^-$	4.2×10^{-5}
$e^+\pi^-K^-$	1.2×10^{-4}
$\mu^-\pi^+K^-$	1.2×10^{-4}
$\mu^+\pi^-K^-$	1.2×10^{-4}
$e^-K^*(892)^0$	5.4×10^{-5}
$\mu^-K^*(892)^0$	5.9×10^{-5}
$e^+\mu^-\mu^-$	3.8×10^{-5}
$\mu^+e^-e^-$	3.8×10^{-5}
$e^-\eta$	2.4×10^{-4}

Compared to the decay modes in (A54) it is much more difficult to conduct a sensitive search for this decay since the τ cannot be reconstructed.

Interesting discussions of the possibilities for violation of lepton number conservation in τ decays are given by Pich (1990a), Masiero (1990), Stroynowski (1990), Barish (1989), Heusch (1989b).

B. DETECTOR DESIGN FOR TAU AND CHARM PHYSICS

B.1 Introduction

In the first part of this paper I described the τ research to be done at a tau-charm factory. This research requires not only the luminosity and energy range of a tau-charm factory, but also requires that the detector have certain properties. The ψ/J, ψ', and charm research to be done at a tau-charm factory (Schindler 1990a, Schindler 1990b, Kirkby 1990, Izen 1990, Heusch 1990, Barish *et al* 1989, Beers 1989) also requires certain properties of the detector. Table 5 from Kirkby (1990) summarizes the connections between the research goals and the overall requirements. I now go on to briefly discuss the requirements using Fig. 4 as the schematic design of the detector.

Table 5. Special detector requirements for some measurements at a tau-charm factory (Kirkby 1990).

	Detector emphasis				
Experiment	Charged particles	Photons	$\pi K p$ i.d.	$e\mu$ i.d.	Hermeticity
$\tau^{\pm}$ physics:					
ν_τ, $\tau^{\pm}$ masses	•	•	•	•	•
$\tau \to \ell\nu_\ell\nu_\tau$ spectra	•	•		•	•
Precise branching ratios		•	•	•	•
Second class currents		•		•	•
Weak hadronic current	•	•	•	•	•
$\tau^{\pm}$ electric dipole moment		•	•	•	•
Rare decays	•	•	•	•	•
D, D_s physics:					
V_{cs}, V_{cd} (semileptonic decays)		•	•	•	•
f_D (pure leptonic decays)		•		•	•
Hadronic decays (CA, CS, DCS)	•	•	•		
$D^0\bar{D}^0$ mixing, CP violation	•		•	•	•
Rare decays	•			•	•
$J/\psi(3.10)$, $\psi(3.69)$ physics:					
Spectroscopy ($c\bar{c}$, gg, hybrid, uds)	•	•	•		
Rare decays		•	•	•	•

B.2 Beam Pipe, Focussing Quadrupoles and Masking

The emphasis in the research to be done at a tau-charm factory is on production of τ pairs and D pairs near or at threshold. Therefore secondary vertex detection is not used and the beam pipe is relatively large, 10 or 12 cm in diameter. This greatly simplifies the construction of the pipe and the masking of the detector from synchrotron radiation.

On the other hand, the tight focussing of the bunches requires that the quadrupoles start 80 to 100 cm from the interaction point. This complicates the design of the detector end sections because most of the detector subsystems must extend to small angles.

B.3 Charged Particle Tracking, Momentum Measurement and Magnet

Precise momentum measurement is required for a variety of tau and charm physics studies, the goal is

$$\sigma_p/p = \left[(0.4\%p)^2) + (0.3\%/\beta)^2\right]^{1/2} \qquad (B1)$$

where p is in GeV/c and $\beta = v/c$. The small multiple Coulomb scattering term assumes that the beam pipe and the tracking chamber cause minimum multiple scattering. This in turn requires a 1 to 1.5 T solenoid magnet, probably with a superconducting coil.

The tracking chamber might be a drift chamber or a TPC. In either case the goal is to track charged particles over 90% of 4π.

Some of the tau and charm physics studies which use the momentum precision of (B1) are: probing the ν_τ mass, studying narrow mass D decays, and searching for rare narrow mass processes such as Higgs particles produced in radiative J/ψ decays.

B.4 Electromagnetic Calorimeter

Several strict requirements are imposed by tau and charm physics goals on the electromagnetic calorimeter. For example, in tau physics when using the τ tag modes (Kirkby 1990, Gomez-Cadenas, Heusch, and Seiden 1989, Barish *et al* 1989)

$$
\begin{aligned}
&\tau^- \rightarrow \nu_\tau + e^- + \bar{\nu}_e \\
&\tau^- \rightarrow \nu_\tau + \mu^- + \bar{\nu}_\mu \qquad (B2) \\
&\tau^- \rightarrow \nu_\tau + \pi^-
\end{aligned}
$$

it is important to know that the *missing energy is carried off by ν's, not by undetected γ's.* Also highly efficient detection and measurement of all γ's are important in untangling multiple π^0 and η decay modes. Similarly in charm physics, highly efficient photon detection and measurement is necessary for clean studies of pure leptonic and semi-leptonic D decays. And of course for both tau and charm physics, it is important to have efficient e identification and excellent e—hadron separation.

Thus the measurement of e and γ energies must be precise, the goal is

$$
\sigma_E/E = \left[\left(2\%/\sqrt{E}\right)^2 + (1\%)^2\right]^{1/2} \qquad (B3)
$$

where E is in GeV. Hence a crystal electromagnetic shower detector such as CsI is required. The noise must be sufficiently low so that γ's with energies as low as 10 MeV can be detected. It is also important that photon angles be well measured; therefore silicon pad shower positron detectors may be used in conjunction with the crystal shower energy detectors.

Another electromagnetic calorimeter design goal is that the photon detection inefficiency be less than 1%, the calorimeter covering almost all of 4π. This is part of the hermeticity requirement of the detector noted in connection with (B2).

B.5 Muon Detector and Hadron Veto Calorimeter.

A unique aspect of the detector is the combined muon identification and hadron veto calorimeter system outside the solenoid and on both ends. This system would consist of thin iron plates, 1. to 2.5 cm thick, separated by tracking devices such as drift chambers with long drift regions. The separation of μ's from π's and K's would be done by the lack of nuclear interactions by the μ and careful range measurement.

This system would also detect hadrons by their nuclear interactions, in particular the neutral hadrons: K^0's and n's. The K^0 and n detection would mostly be used as a signal that energy was being carried off by a neutral particle, although that energy would be poorly measured. Such a signal would veto the use of a τ pair event which had been tagged by the decays in (B2) since the missing energy might be due to a K^0 or n, not due to ν's. Like the electromagnetic calorimeter the muon detector and hadron veto system must cover almost all of 4π.

B.6 Particle Identification and Time-of-Flight Counters

I have already discussed the design goals for e, μ, and γ identification. It is also important, very important for charm physics, to separate π's and K's. Excellent $\pi - K$ separation is required for advanced studies of D decays and D^0 mixing. In the present detector concept π and K identification is accomplished with time-of-flight scintillation counters just outside the tracking chamber and by dE/dx measurements in the tracking chamber. The design goal for the time-of-flight counters is a time resolution of 120 ps.

B.7 Detector Summary

Past and current design work on the detector for tau-charm physics shows that all the requirements on the detector can be met by conventional and well developed detector technology.

C. THE TAU-CHARM FACTORY

C.1 Requirements for a Tau-Charm Factory

In these talks I have only discussed the τ physics to be done at a tau-charm factory, the principle operating part being

$$\begin{aligned} E_{tot} &= 3.57 \text{ GeV (Several MeV above threshold)}: \ \sigma = 0.4 \text{ nb} \\ E_{tot} &= 3.67 \text{ GeV (just below } \psi): \ \sigma = 2.3 \text{ nb} \end{aligned} \tag{C1}$$

There is also a tremendous amount of charm quark physics to do at a tau-charm factory as described in the Proceedings of the Tau-Charm Factory Workshop (Beers, 1989) and by Schindler (1989), Schindler (1990a), Schindler (1990b), Kirkby (1989a), Kirkby (1990), Barish *et al* (1989). The principle operating points are the $c\bar{c}$ resonances

$$\begin{aligned} J/\psi \ \text{ at } \ E_{tot} &= 3.10 \\ \psi' \ \text{ at } \ E_{tot} &= 3.69 \end{aligned} \tag{C2}$$

and the D pair production points

$$\begin{aligned} D^+D^- \text{ at the } \psi'', \ E_{tot} = 3.77 \ \text{ GeV}: \ \ \sigma = 4.2 \ \text{ nb} \\ D^0\bar{D}^0 \text{ at the } \psi'', \ E_{tot} = 3.77 \ \text{ GeV}: \ \ \sigma = 5.8 \ \text{ nb} \end{aligned} \tag{C3}$$

$$D_s\bar{D}_s \text{ at } E_{tot} = 4.03 \text{ GeV}: \quad \sigma = 0.7 \text{ nb}$$
$$D_s\bar{D}_s^* \text{ at } E_{tot} = 4.14 \text{ GeV}: \quad \sigma = 0.9 \text{ nb} \tag{C4}$$

Finally Klein (1989) has suggested

$$\Lambda_c\bar{\Lambda}_c \text{ at } E_{tot} = 4.6 \text{ GeV}: \quad \sigma \sim 0.2 \text{ nb} \tag{C5}$$

Thus the energy range of a tau-charm factory is

$$3.0 < E_{Tot} \lesssim 5.0 \text{ GeV} \tag{C6}$$

The next question is luminosity. Since the maximum luminosity cannot be constant over the E_{tot} range in (C6), the energy of maximum luminosity must be picked. The two operating parts where maximum luminosity is desired are τ pairs at $E_{tot} = 3.67$ GeV and D^+D^-, $D^0\bar{D}^0$ pairs at 3.77 GeV. Then

$$E_{tot}(L_{max}) \approx 3.7 \text{ to } 3.8 \text{ GeV} \tag{C7}$$

The physics to be done at these two operating points requires 10^6 to 10^8 pairs per year of τ's, D^0's or $D^{\pm}$'s. The design luminosity should be set as close to the 10^8 requirement as can be achieved with reliable and conservative collider technology.

A tau-charm factory would be operated 8 months per year for particle physics, the other months would be used for accelerator physics studies, maintenance and upgrading. And unlike other types of accelerators and colliders, a tau-charm factory could achieve 80% efficiency if built with sufficient reliability. This is because the operating mode of the machine is fixed for long-time periods. This means 1.7×10^7 s/year. Then the 10^8 events goal requires for example

$$N_{yr}L_{max} = 2.6 \times 10^{33} \text{ yr cm}^{-2} \text{ s}^{-1} \text{ for } 10^8\tau \text{ pairs}$$
$$N_{yr}L_{max} = 1.4 \times 10^{33} \text{ yr cm}^{-2} \text{ s}^{-1} \text{ for } 10^8 D^{\pm} \text{ pairs} \tag{C8}$$

where N_{yr} is the number of operating years.

Now remembering that 10^8 events is not a rigorous goal but just a rough goal, we see that an L_{max} of 5×10^{33} cm^{-2} s^{-1} would be wonderful, would enable the physics goals to be accomplished in half a year. Eventually $L_{max} \sim 5 \times 10^{33}$

$\text{cm}^{-2}\ \text{s}^{-1}$ may be possible using a "crab-crossing" technique (Voss, Paterson, and Kheifets 1989). But as discussed in the next section

$$L_{max} \approx 10^{33}\ \text{cm}^{-2}\ \text{s}^{-1} \qquad (C9)$$

is the best that can be reliably designed with our present knowledge of collider physics and technology. And this L_{max} is certainly adequate for the 10^8 events goal. Another requirement on a tau-charm factory is that all the particles in the beams have the same energy within an MeV or so:

$$\Delta E_{tot} \sim \text{ few MeV}$$

This is very important for the τ physics studies carried out a few MeV above τ pair threshold, and is useful at other energies, for example at the ψ/J and ψ'.

Summarizing, there are four required properties of a tau-charm factory:

(i) $3.0 \leq E_{tot} \lesssim 5.0$ GeV

(ii) $L_{max} \approx 10^{33}\ \text{cm}^{-2}\ \text{s}^{-1}$

(iii) Highly reliable operation

(iv) $\Delta E_{tot} \sim$ few MeV

It is the second and third property which will enable experiments at a tau-charm factory to make great advances. At $E_{tot} \approx 3.8$ GeV (C3) the L_{max} of the new BEPC storage ring will be about $10^{31}\ \text{cm}^{-2}\ \text{s}^{-1}$ and for SPEAR L_{max} was about $10^{30}\ \text{cm}^{-2}\ \text{s}^{-1}$. Thus in full operation the tau-charm factory will have 100 times the data rate of BEPC and 1000 times that of SPEAR. In addition the improved reliability made possible by new technology will increase these factors on a yearly bases. Even in the first period of tau-charm factory operation when $L \sim 10^{32}$ to $3 \times 10^{32}\ \text{cm}^{-2}\ \text{s}^{-1}$, the data rate will be very, very good.

C.2 Obtaining High Luminosity in a Tau-Charm Factory

I now give a qualitative discussion, following the seminal work of Jowett (1987), on how $L_{max} = 10^{33}\ \text{cm}^{-2}\ \text{s}^{-1}$ is obtained in a tau-charm factory. I start with some basic formulas for just 1 e^+ and 1 e^- bunch, each bunch having N_b particles. At the collision point each bunch has a cross sectional area

$$A = 4\pi\, \sigma_x^*\ \sigma_y^* \qquad (C10)$$

where σ_x^* and σ_y^* are the sigmas of the width and height of the bunch. Let ℓ_c be the circumference of the ring and c the velocity of light. Then

$$L = \frac{c\,N_B^2}{\ell_c\,A} \tag{C11}$$

The obvious first stage in maximizing L is to use *large* N_b, many particles in a bunch. And to use *small* A by tight focussing of the bunches at the interaction point. But there is a *beam-beam interaction* between the e^+ and e^- beams when they collide which perturbs the orbits of the particles. The magnitude of the perturbation increases on the average as N_b/A increases, therefore there is a practical upper limit to N_b/A. There is also a *single bunch instability* upper limit on N_b because a bunch interacts electromagnetically with the walls of the beam pipe as it moves around the ring. This interaction if too strong will disrupt the bunch. Finally, there is a *dynamic aperture* upper limit on A.

Looking back at (C10) with these limits on N_b and A the next step in increasing L is to decrease ℓ_c. But here again there is a limit, a lower limit on ℓ_c. The energy lost per turn by synchrotron radiation in a ring of effective radius ρ is

$$V \,\alpha\, E^4/\rho \tag{C12}$$

This power must be absorbed by the walls of the beam pipe, it is important that this power be kept moderate so that a conventional and simple beam pipe can be used. (A simple beam pipe reduces single-beam instabilities.) For this and other reasons there is a lower limit on ℓ_c.

The way out of these limits is to use multiple bunches, k_b e^+ bunches and $k_b e^-$ bunches. Then (C10) becomes

$$L = \frac{c k_b N_b^2}{\ell_c\;A} \tag{C13}$$

But now, in a simple, single ring collider, a bunch will collide $2k_b$ times during one revolution around the ring and the multiple beam-beam interactions per revolution put a more severe upper limit on N_b/A. To avoid this, bunch collisions must be limited to one or two interaction regions where there are experiments; at $2k_b - 1$ or $2k_b - 2$ potential collision points the bunches must pass by each other without touching. In the tau-charm energy region, Jowett (1987, 1988) found the best solution to this problem is to use separate e^+ and e^- rings with only 1 or 2 places where the ring intersect. Figure 5 from Jowett (1988) is a schematic of the design for 1 interaction point.

Jowett's original design was for L_{max} at E_{tot} = 5 GeV with the following parameters

$$
\begin{aligned}
&\ell_c = 377 \text{ m} \\
&N_b = 1.63 \times 10^{11} \ , \ k_b = 24 \\
&\sigma_x^* = 443 \ \mu\text{m} \ , \ \sigma_y^* = 8 \ \mu\text{m} \\
&L_{max} = 1.6 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}
\end{aligned}
\tag{C14}
$$

Another important bunch shape parameter is the rms length σ_z. In Jowett's original design $\sigma_z = 6.2$ mm. The bunch must be kept so short in order to make use of the tight focussing of the bunches at the collision point. This small σ_z imposes two more requirements on the design of a tau-charm factory. The radio frequency cavities must have a large overvoltage. And once again, the beam pipe must be simple so that it has a small impedance for the electromagnetic interaction of a bunch with the pipe walls.

C.3 History of Tau-Charm Factory Design

The first design of a tau-charm factory was done by Jowett (1987, 1988, 1989) who worked out the basic principles:

- Separate e^+ and e^- rings.
- One interaction region. Later designs allow two.
- Tight focussing of the bunches at the interaction point, called microbeta insertion.
- Multiple bunches, about 20 to 30 in each ring.
- Rings have a large radius to keep synchrotron radiation moderate and allow a conventional beam pipe.
- Substantial RF overvoltage and low beam pipe impedance to produce short bunches.
- Feedback systems to control multibunch instabilities.
- A high intensity e^+ and e^- injector to maintain luminosity by "top-off" of the circulating bunches.

Further design work was carried out by many accelerator physicists at the 1989 Tau-Charm Factory Workshop (Beers 1989). This group confirmed that $L_{max} \approx 10^{33}$ cm^{-2} s^{-1} was feasible with present technology (Brown, Fieguth, and Jowett 1989).

A separate conceptual design was carried out by Gonichen, Le Duff, Mouton, and Travier (1990). This report discusses the accelerator physics in very useful detail, for example comparing flat beams with round beams.

Another conceptual design based more closely on the original Jowet design was prepared by Barish *et al* (1990). Both this design and the Gonichon *et al* design attained $L_{max} \approx 10^{33}$ cm^{-2} s^{-1}.

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

The most recent conceptual design (Baconnier, 1990) was carried out by physicists from CERN, LAL in France, and CIEMAT in Spain and is intended for a tau-charm factory laboratory in Spain. These lectures conclude with a summary of this design.

C.4 The Design of a Tau-Charm Factory for Spain

Figure 6 is the title page of the Baconnier *et al* (1990) design for a tau-charm factory in Spain, Fig. 7. The powerful, high-rate e^+ and e^- injector, Fig. 8, also allows a separate synchrotron light source ring. The collider is designed for L_{max} at $E_{tot} = 4$ GeV. Some of the luminosity connected parameters are

$$\begin{aligned}
&\ell_c = 360\ m \\
&N_b = 1.6 \times 10^{11} \quad k_b = 30 \\
&\sigma_y^* = 280\ \mu\text{m} \quad \sigma_y^* = 14\ \mu\text{m} \\
&\sigma_z = 6\ \text{mm} \\
&L_{max} = 1 \times 10^{33}\ \text{cm}^{-2}\text{s}
\end{aligned} \qquad (C15)$$

where N_b and k_b are the particles per bunch and the number of bunches in a beam, σ_x^* and σ_y^* are the horizontal and vertical rms bunch sizes at the collision point, and σ_z is the bunch length. Figure 9 shows the collider tunnel and magnets.

The total current per beam, I, is 0.6 A, a large current for an e^+e^- collider which in turn requires care in the beam pipe, interaction region, and RF cavity design. But the maximum synchrotron radiation power dissipated in the beam pipe is 1.9 kW/m which is moderate and can be managed by a conventional beam pipe. The total power dissipated per ring is 120 kW which is also moderate. Since I = 0.6 A, this power loss requires an average accelerating voltage per ring of 0.2 MW. However to keep σ_z small the RF cavities produce a large overvoltage, 19 MV. Superconducting RF cavities with a resonant frequency of 500 MHz are proposed.

C.5 Summary

Thus design has reached the stage that we can build a powerful and very general new electron-positron collider – the tau-charm factory. In these lectures I have described the tremendous amount of research which can be foreseen in tau physics. Tremendous amounts of charm research will also be done. And as I said in the introduction, the tau-charm factory may bring us discoveries we cannot now conceive.

ACKNOWLEDGEMENT

It is evident from the references that a very large number of people have contributed to the particle and accelerator physics associated with a tau-charm factory. I am particularly grateful for many conversations with Jasper Kirkby, John Jowett, Juan Antonio Rubio, and Rafe Schindler.

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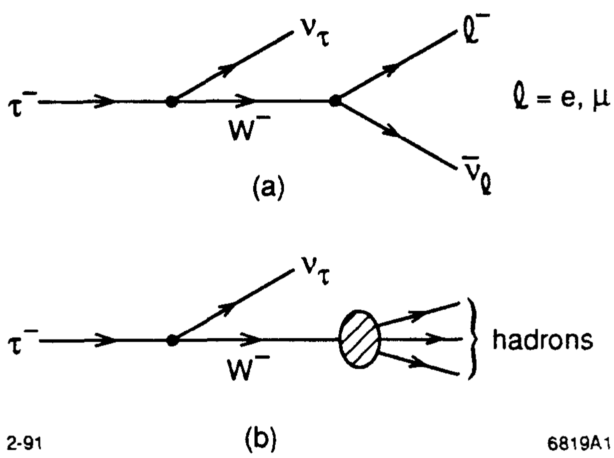

Fig. 1. Feynman diagram for τ decays for (a) pure leptonic decays, (b) hadronic decays.

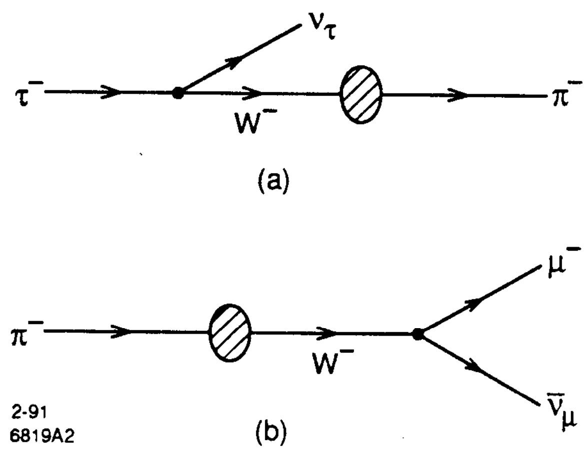

Fig. 2. Feynman diagram for (a) $\tau^- \to \nu_\tau \pi^-$ and (b) $\pi^- \to \mu^- \bar{\nu}_\mu$.

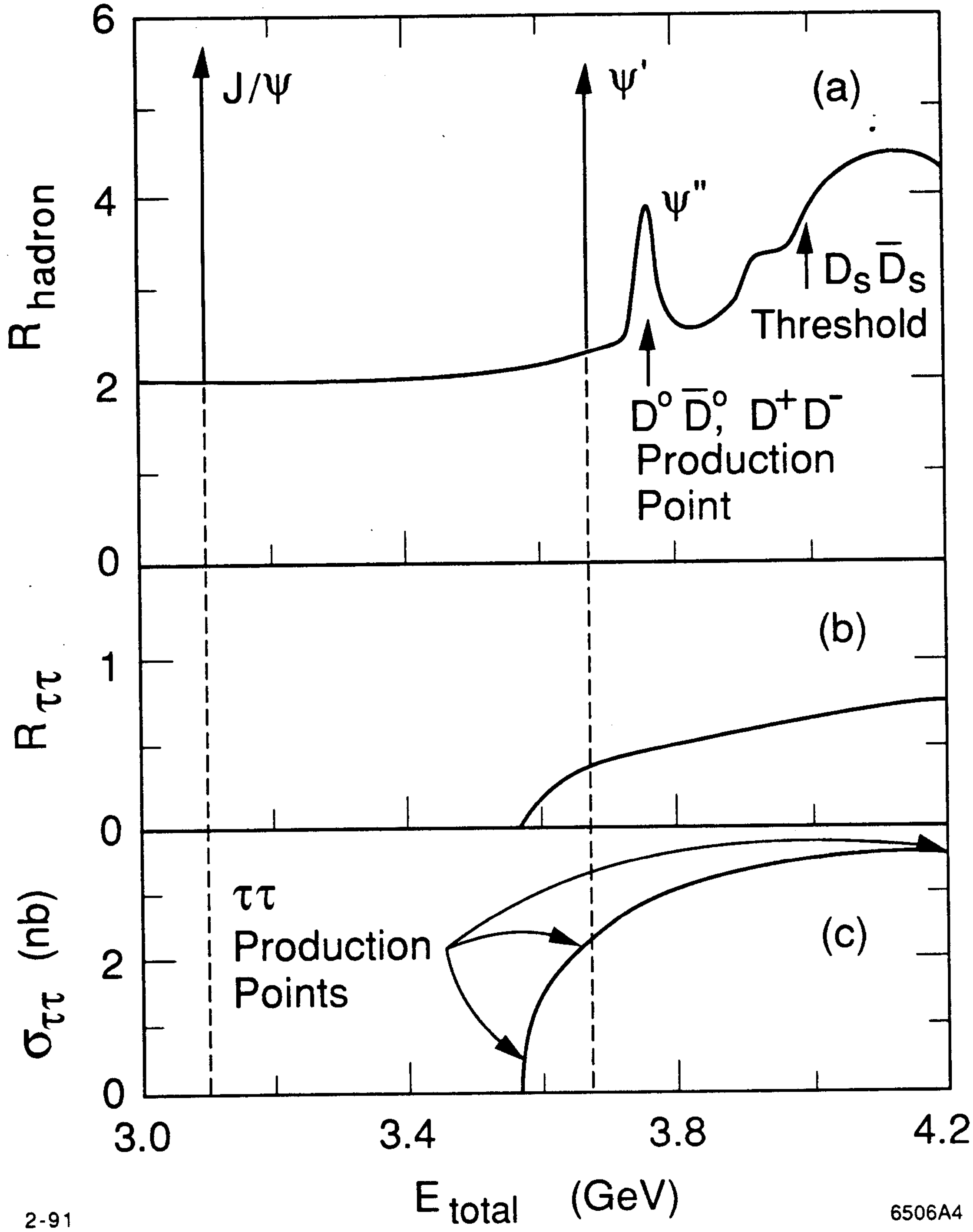

Fig. 3. $\sigma_{\tau\tau}$, $R_{\tau\tau}$, and $R_{hadrons}$ for the main part of the tau-charm factory energy range.

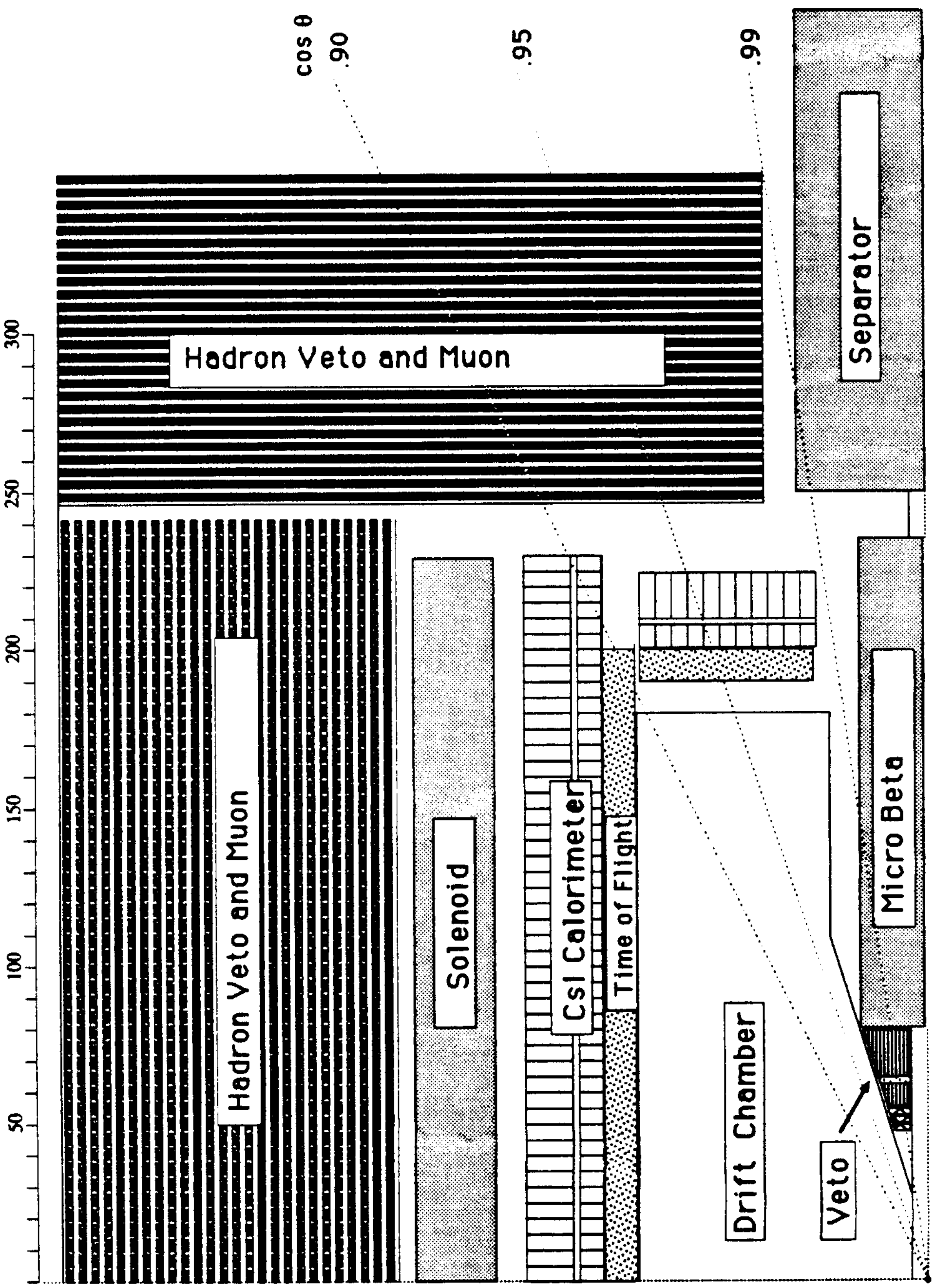

Fig. 4. Schematic design of detector for tau and charm physics research at a tau-charm factory.

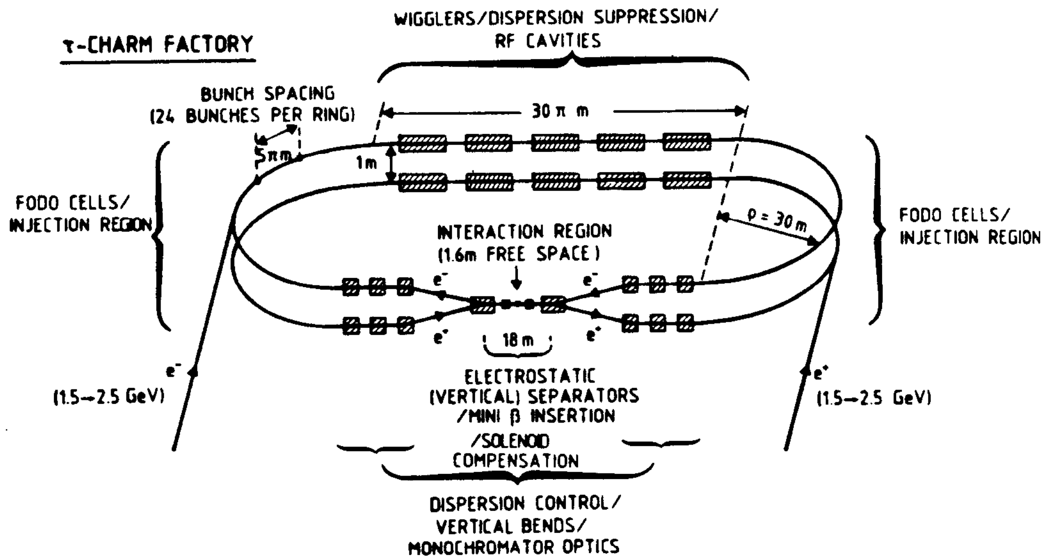

Fig. 5. Schematic design of a tau-charm factory collider from Jowett (1988).

EUROPEAN LABORATORY FOR PARTICLE PHYSICS

CERN/AC/90-07

A TAU-CHARM FACTORY LABORATORY IN SPAIN combined with a SYNCHROTRON LIGHT SOURCE (A conceptual study)

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Abstract

A conceptual design for a τ-charm factory and its associated laboratory is given. It includes the physics interest, a description of the scope and layout of the new laboratory in Spain, the τ-charm factory collider and detector, the injector system and a synchrotron light source, together with estimates of the time-scale and necessary resources.

Geneva, Switzerland

20 November 1990

Fig. 6. Title page from design for a Tau-Charm Factory in Spain (Baconnier 1990).

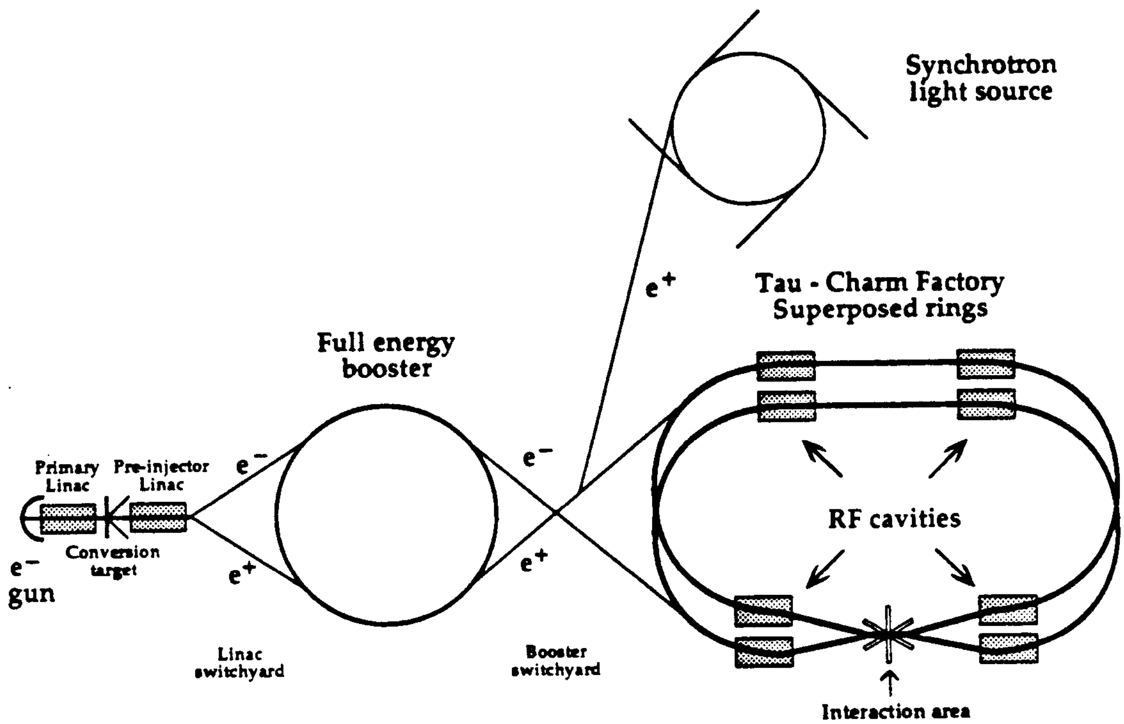

Fig. 7. Schematic representation of the injector, collider, and synchrotron light source from Baconnier (1990). The collider may be designed to allow a second interaction area to be installed later.

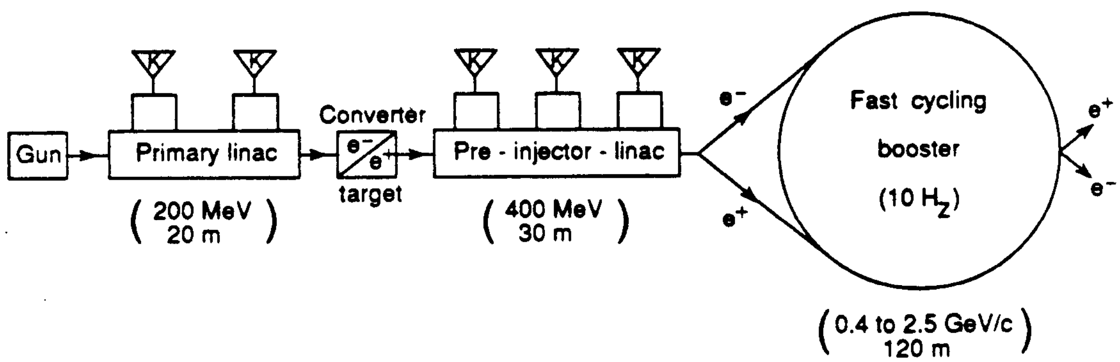

Fig. 8. Injector for tau-charm collider and synchrotron light source from Baconnier (1990).

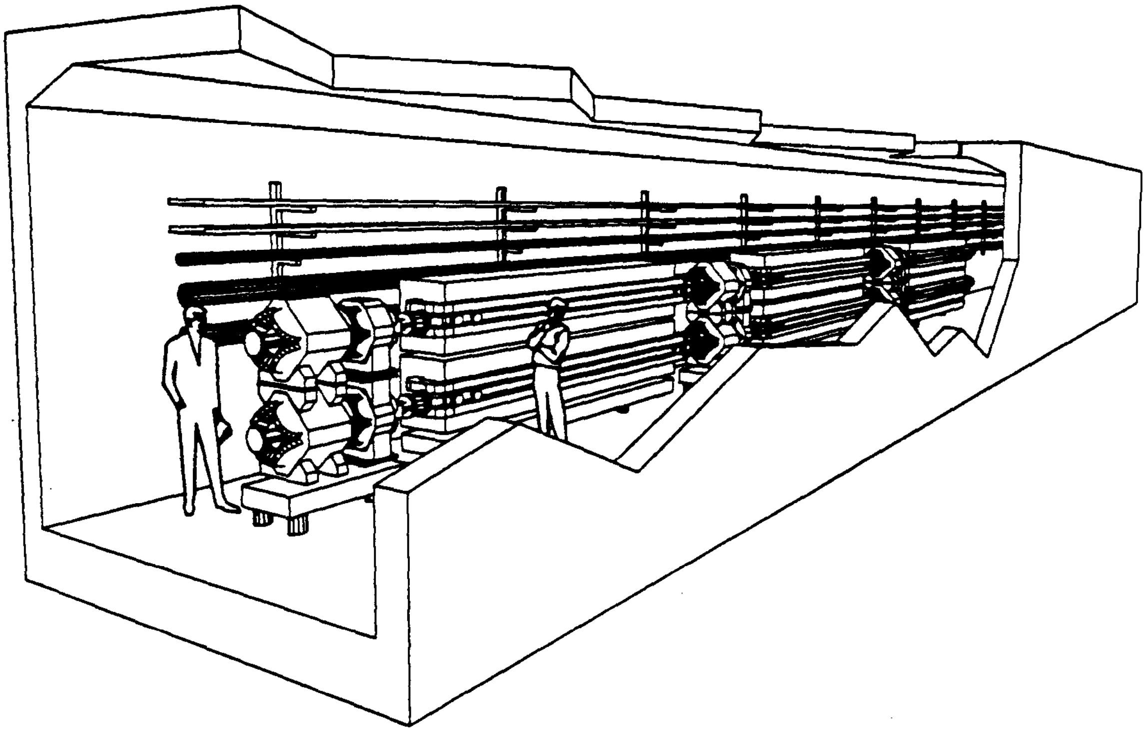

Fig. 9. Collider tunnel and magnets showing the vertically separated rings from Baconnier (1990).