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PROPERTIES OF LEPTONS*

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ABSTRACT

The properties of the electron, muon, tau, and their neutrinos are reviewed. Three discrepancies in our understanding of those properties are discussed: the lifetime of orthopositronium, the mass spectra of e^+e^- pairs produced in heavy ion collisions, and the 1-charged particle modes problem in tau decays. The review concludes with a discussion of what we need to learn about the tau and the consequent need for a tau-charm factory.

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I. INTRODUCTION AND HISTORY OF LEPTONS

In a talk given at the XIV International Symposium on Lepton and Photon Interactions I had two purposes: to review our present knowledge of the properties of leptons and to point out mysteries or loose ends in that knowledge. In this shorter written version of the talk I emphasize the second purpose in a context in which one physicist's mystery is another physicist's loose end.

The history of leptons goes back almost 90 years.

A. *Electron, 1895*

The final elucidation of the existence and nature of the electron is due to J. J. Thomson in 1895 using a cathode ray tube. His description of the discovery is in *Phil. Magazine* **44**, 293 (1897), reprinted in part in *Great Experiments in Physics* (Dover Pub., New York, 1987), edited by M. H. Shamos.

Other physicists had worked on the particle nature of the cathode ray—using, for example, magnetic deflection. Thomson was able to consistently use in addition electrostatic deflection by improving the vacuum in the cathode ray tube; a crucial technical advance.

B. *Electron Neutrino, 1930*

W. Pauli suggested the existence of the electron neutrino in 1930. A fascinating description of Pauli's thought was given by L. M. Brown in *Phys. Today*, September, 1978, p. 23.

C. *Muon, 1937*

The classic Letter to the Editor of S. H. Neddemeyer and C. D. Anderson [*Phys. Rev.* **51**, 884 (1937)] describes their discovery of the muon in cosmic rays using a cloud chamber. The Letter is fascinating with its discussion of an "intermediate mass" between the electron and the proton. The understanding of the difference between the muon and the pion required another ten years.

D. *Electron Neutrino, 1956*

In another classic Letter to the Editor, F. Reines and C. L. Cowan, Jr., *Phys. Rev.* **92**, 830 (1956) describe their detection of the electron neutrino. They used a reactor for the source of neutrinos from neutron decay and the most modern counting electronics of the time to detect the e^+ and n from $\overline{\nu}_e + p \rightarrow e^+ + n$.

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E. *Muon Neutrino, 1962*

Yet another technique was used by the 1988 Nobel Prize winners, L. Lederman, M. Schwartz, and J. Steinberger to observe the muon neutrino and separate it from the electron neutrino. A neutrino beam from the AGS and thick plate spark chambers were used [G. Danby *et al.*, *Phys. Rev. Lett.* **9**, 36 (1962)].

F. *Tau, 1975*

The electron–positron storage ring and the reaction $e^+ + e^- \to \tau^+ + \tau^-$ was used to find the τ [M. L. Perl *et al.*, *Phys. Rev. Lett.* **35**, 1489 (1975)]. Important in the history of the discovery of the τ was the development of the theory of heavy lepton decays by Y. S. Tsai [*Phys. Rev.* **D4**, 2821 (1971)] and the heavy lepton searches at ADONE [M. Bernardini *et al.*, *Nuovo Cimento* **17**, 383 (1973) and S. Orioto *et al.*, *Phys. Lett.* **48B**, 165 (1974)].

G. *Tau Neutrino*

The existence and properties of the tau neutrino are deduced from studies of tau decays. The ν_τ has not been detected directly.

In the ninety years since the discovery of the electron, a different experimental technique was used for each discovery. Will we be able to discover new leptons with present experimental methods or will a new method be required? Or are these additional leptons to be discovered?

II. LIMITS ON THE EXISTENCE OF NEW LEPTONS

In connection with the last question, I give in Table 1 some limits[1] as of August 1989 on the existence of additional leptons. This paper is being written before there are complete results from the searches for new leptons in Z^0 decays at LEP and the SLC, hence limits based on Z^0 decay studies are not included. Perhaps the Z^0 decay will be the new experimental technique which allows a new lepton to be discovered.

The search for new lepton pairs (L^-, L^0) requires special care if the L^0 mass m_0 is less than but close to the L^- mass m_-. When $\delta = m_- - m_0$ is less than 4 or 5 GeV/c^2 there is not enough visible energy for the usual search method in $e^+e^- \to L^+L^-$; and there is not enough missing transverse momentum for the usual search method in $W^+ \to L^+ + L^0$. Figure 1 gives the limits[2,3] as of August 1989. Once again searches using Z^0 decays will simplify these studies.

Table 1. Experimental lower limits on masses of charged leptons as of August 1989. Searches using Z^0 are not included because this paper was written before definitive results were published. The C.L. is 95% unless otherwise noted.

Lepton Type	Mass Lower Limit, GeV/c^2	Method
Stable	30.1	e^+e^-,TRISTAN
L^-, L^0: $m_0 << m_-$	41.$^{(a)}$	$\bar{p}p$, UA1
L^-, L^0: $m_0 << m_-$	29.9	e^+e^-,TRISTAN
$e^* \to e + \gamma$	pair: 30.2 single: 60.5	e^+e^-,TRISTAN
$\mu^* \to \mu + \gamma$	pair: 30.1 single: 53.0	e^+e^-,TRISTAN
$\tau^* \to \tau + \gamma$	pair: 29.0 single: 50.0	e^+e^-,TRISTAN
$\tilde{e} \to e + \tilde{\gamma}, m_{\tilde{\gamma}} = 0$	29.5	e^+e^-,TRISTAN
$\tilde{\mu} \to \mu + \tilde{\gamma}, m_{\tilde{\gamma}} = 0$	25.8	e^+e^-,TRISTAN
$\tilde{\tau} \to \tau + \tilde{\gamma}, m_{\tilde{\gamma}} = 0$	24.7	e^+e^-,TRISTAN

$^{(a)}$ 90% C.L.

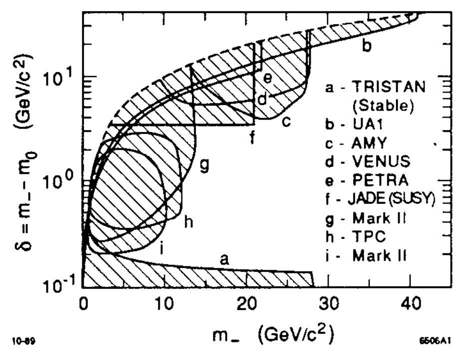

Figure 1: The crosshatched area shows the excluded region in the δ–m_- plane. The figure does not include limits from Z^0 decay studies.

III. FUTURE SEARCHES FOR NEW LEPTONS

Future searches fall into the five classes described next. Here L means L^- or L^0 and m means mass.

A. $m_L \lesssim 45$ *GeV/c*^{2}

This region will be completely explored at the SLC and LEP provided $Z^0 \to L + \overline{L}$.

B. $45 \lesssim m_L \lesssim 80$ *GeV/c*^{2}

This region will be completely explored at LEP II provided $Z^0_{virtual} \to L + \overline{L}$ or $\gamma_{virtual} \to L + \overline{L}$. In addition, $W^+ \to L^+ + L^0$ can be used at $\overline{p}p$ colliders to explore part of this range.

C. $m_L \gtrsim 80$ *GeV/c*$^2 \approx m_W$ *at* e^+e^- *Colliders*

When $m_L > m_W$ there are two changes in the e^+e^- search method.

First, the decay is now

$$\begin{aligned} L^- &\to W^-_{real} + L^0 \ , \ W^-_{real} \to \text{ decay modes} \ , \\ L^0 &\to W^+_{real} + L^- \ , \ W^+_{real} \to \text{ decay modes} \ . \end{aligned} \tag{1}$$

Second, LEP II can only reach 10 or 20 GeV/c^2 into this mass range. The straightforward future search method[4] is to use a TeV-range e^+e^- linear collider for

$$e^+ + e^- \to L^+ + L^- \ . \tag{2}$$

But the cross section is small

$$\sigma = \frac{0.087\,R}{E^2_{cm}\ (\text{TeV})}\ \text{pb} \ , \tag{3a}$$

where, for example,

$$\begin{aligned} E_{cm} &= 0.7 \text{ TeV} : \ R_{L^+L^-} = 1.18 \, , \ R_{L^0\overline{L}^0} = 0.32 \ , \\ E_{cm} &= 2.0 \text{ TeV} : \ R_{L^+L^-} = 1.17 \, , \ R_{L^0\overline{L}^0} = 0.31 \ . \end{aligned} \tag{3b}$$

D. $m_L \gtrsim 80$ *GeV/c*$^2 \approx m_W$ *at pp Colliders*

The power of search methods at the SSC or an LHC using

$$p + p \to L + \overline{L} + \ldots \tag{4}$$

is still obscure. Hinchliff[5] has given a recent discussion.

E. $e^- + p \ \to \ L_e + \ldots$

Provided there is a lepton L_e with the lepton number of the e^-, searches at HERA[5] can reach $m_{L_e} \sim 200$ GeV/c^2. L_e represents L_e^-, L_e^0, L^{*-} and so forth.

IV. ELECTRON

Our present picture of the electron is that it is simply a stable, Dirac point particle which obeys the conventional theory of the electroweak interaction and has a mass of 0.511 MeV/c^2. There are no confirmed deviations from this picture, but there are three loose ends or mysteries, depending on one's point of view. These are: the comparison of measurement and theory for $g_e - 2$; the lifetime of orthopositronium; and the possible existence of e^+e^- resonant states produced in heavy ion collisions. I conclude this section with comments on the evidence for the electron being a point particle obeying standard electroweak theory.

A. $g_e - 2$

H. Dehmelt and his colleagues[6,7] have used the Penning trap technique to find

$$\begin{aligned} \text{Electron:} \ & \frac{1}{2}(g_{e^-} - 2) \times 10^{12} = \\ & 1\ 159\ 652\ 188.4\,(4.3) \ , \\ \text{Positron:} \ & \frac{1}{2}(g_{e^+} - 2) \times 10^{12} = \\ & 1\ 159\ 652\ 187.9\,(4.3) \ . \end{aligned} \tag{5}$$

The major cause of the experimental error is the uncertainty in calculating the frequency shift[8] due to the $e^\pm$ being in a cavity of finite size.

In a recent paper[9] T. Kinoshita discusses the calculations[9,10] of g_e by his colleagues and himself. The calculations and the errors are sensitive to the value of α, the fine structure constant. Kinoshita[9] gives a most recent calculation:

$$\begin{aligned} \text{Theory:} \ & \frac{1}{2}(g_e - 2) \times 10^{12} = \\ & 1\ 159\ 652\ 133\,(29) \ , \end{aligned} \tag{6a}$$

and one based on an earlier value of α:

$$\begin{aligned} \text{Theory:} \ & \frac{1}{2}(g_e - 2) \times 10^{12} = \\ & 1\ 159\ 652\ 133\,(108) \ . \end{aligned} \tag{6b}$$

The agreement between the calculated values in Eqs. (6) and the measurement in Eqs. (5) is marvelous. Still there is a loose end in the dependence of the calculated value of g_e on α and the uncertainty in the precise value of α.

B. Lifetime of Orthopositronium

At present there is a mystery in the comparison of theory with the measurement of the lifetime of orthopositronium. The orthopositronium state is 1^3S_1 and the decay is

$$Ps \to \gamma + \gamma + \gamma \ . \tag{7}$$

Westbrook *et al.*[11] of the University of Michigan measure

$$\Gamma_{exp} = 7.0516 \pm 0.0013\ \mu\text{s}^{-1} \quad ; \tag{8}$$

while present calculations[12,13] give

$$\Gamma_{theor} = 7.03830 \pm 0.00007 \ . \tag{9}$$

If Eqs. (8) and (9) are accepted than Γ_{exp} is larger than Γ_{theor} by many standard deviations and the measured lifetime would be shorter than the calculated lifetime. There are three possibilities, not mutually exclusive. The measurement may have an unknown systematic error; the one usually mentioned is the correction for the decay occurring in a gas. The University of Michigan experimenters[11] believe their gas density correction is right; in addition they are beginning[11,14] an experiment in which the decay occurs in vacuum.

A second explanation of $\Gamma_{exp} > \Gamma_{theor}$ is that the calculation is wrong. Γ is given by

$$\Gamma = \frac{\alpha^6 mc^2}{\hbar} \, \frac{2(\pi^2 - 9)}{9\pi}$$
$$\left[1 + A\,(\alpha/\pi) + \frac{1}{3}\,\alpha^2 \ell n\alpha + B\,(\alpha/\pi)^2 + \ldots\right] \tag{10}$$

Here $A = -10.28$ but B has not been calculated. To increase Γ_{theor} by 0.013 μs^{-1} making it equal to Γ_{exp}, B would have to be about 300. No one has calculated if B can be that large.

A third explanation of the discrepancy is that the e^+e^- 1^3S_1 system decays about 2×10^{-3} of the time through a process not contained in quantum electrodynamics. At present there is no evidence for such a process.[15]

C. e^+e^- Pairs from Heavy Ion Collisions

In the past half decade two groups of experimenters have studied the reaction

$$A + A' \rightarrow e^+ + e^- + (A + A')_{excited} \ . \tag{11}$$

Here A and A' are heavy ions such as Ta, Th, and U. The collision is carried out at energies close to the Coulomb barrier energy. The experimenters find "resonances" or "lines" in

$$E_{kin,sum} = E_{kin,e^+} + E_{kin,e^-} \ . \tag{12}$$

Here E_{kin} is kinetic energy. The measurements are difficult because the signal is small compared to the total e^+ and e^- production and because the signal is sensitive to the energy of the incident ion beam and other parameters. In addition the lines are of different strengths.

In a recent paper[16] the EPOS collaboration reports lines at

$$E_{kin,sum} \approx 610, 750, \text{ and } 810 \text{ keV} \ . \tag{13a}$$

The ORANGE collaboration reports[17] lines at

$$E_{kin,sum} \approx 540, 640, 716, 809, \text{ and } 895 \text{ keV} \ , \tag{13b}$$

with the most pronounced signal at 809 keV.

When these lines were first observed there were many searches for an elementary particle with the decay $\phi \rightarrow e^+ + e^-$ and a mass of $2m_e + E_{kin,sum}$ where m_e is the e mass. As reviewed by Davier[18] these searches have excluded an explanation of the lines by such an elementary particle.

Interest then turned to explanations which assume resonant structures in the e^+e^- system, the structures due to physics outside conventional quantum electrodynamics. There have been many searches for such resonances in Bhabha scattering,

$$e^+ + e^- \rightarrow e^+ + e^- \ , \tag{14}$$

in the barycentric energy range $1.5 \lesssim E_{cms} \lesssim 1.9$ MeV. At present there are no confirmed resonances.[19] Searches have also been made in

$$e^+ + e^- \rightarrow \gamma + \gamma \ . \tag{15}$$

Again there are no confirmed resonances.[20]

These e^+e^- lines observed in heavy ion collisions are the longest standing experimental mystery in the fields of nuclear and particle physics.

D. Electron Structure and Quantum Electrodynamic Tests

At present the most stringent tests of the point particle nature of the electron come from high energy measurements of Bhabha scattering at e^+e^- colliders

$$e^+ + e^- \rightarrow e^+ + e^- \ . \tag{16}$$

There are two popular models for testing for structure. One model uses the form factor concept

$$\sigma(e^+e^- \rightarrow e^+e^-) = \sigma_{point}(e^+e^- \rightarrow e^+e^-)\, F^2(x) \ , \tag{17a}$$
$$F(x) = 1 \mp \frac{x}{x - \Lambda_\pm^2} \ . \tag{17b}$$

Here x means s, the square of the total energy, or t, the square of the four-momentum transfer.

The other model uses the contact interaction composite particle concept with

$$L_{eff} = \pm \frac{g^2}{2\Lambda_{\pm}^{c2}} \overline{\psi}_2 \gamma^{\mu} \psi_2 \overline{\psi}_1 \gamma_{\mu} \psi_1 \ , \qquad (18a)$$

and

$$\frac{g^2}{4\pi} = 1 \ . \qquad (18b)$$

This assumes a vector-vector interaction, other interactions have analogous forms.

Measurements[21] by the TASSO collaboration at PETRA give the following typical results for 95% C.L. lower limits:

Form Factor	Contact Interaction (VV)	
$\Lambda_+ > 0.4$ TeV	$\Lambda_+^c > 3.6$ TeV	(19)
$\Lambda_- > 0.6$ TeV	$\Lambda_-^c > 7.1$ TeV	

The experimenters[21] point out that the form factor results can be interpreted that "electrons are point-like objects down to distances of 5×10^{-17} cm."

Although the Λ and Λ^c measurements limit the complexity of the electron at high energy and the $g_e - 2$ measurements (Sec. IV.A) limit the complexity of the electron at low energy, it is still possible that anomalies in electron behavior can be detected at moderate energy. An example is the speculation of Hawkins and myself[22,23] about a neutral particle, λ, which might couple only to charged leptons.

Figure 2(a) shows the $e - \lambda - e$ coupling with $\alpha_{\lambda e} = g_{\lambda e}^2/4\pi$, in analogy to $\alpha = e^2/4\pi$ for a photon. Experimentally excluded areas[22,23] on the $\alpha_{\lambda e} - m_\lambda$ are given in Fig. 3 for λ a vector particle of mass m_λ. In the mass range of $20 \lesssim m_\lambda \lesssim 2000$ MeV/c^2, a very sensitive search method[25] uses the reactions

$$e^- + p \to e^- + p + \lambda \ , \qquad \lambda \to e^+ + e^- \qquad (20)$$

of Fig. 2(b). This is one of the goals of the PEGASYS experiment,[25] an internal gas jet target proposed for PEP. Tsai[26] has made the basic λ production calculations. Experiments at HERA can search for the λ in a high range of m_λ.

V. MUON

Unlike the electron, at this time there are no mysteries or loose ends in the particle physics of the muon. But the ingenuity of the experimenters in muon physics is leading to more precise and more probing studies of the properties of the muon.

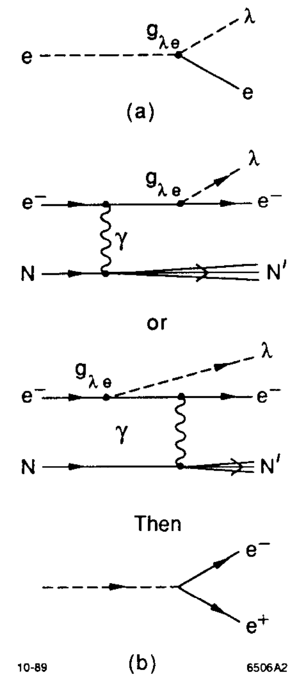

Figure 2: (a) The e–λ–e vertex. (b) Method for searching for the λ using $e^- + N \to e^- + N' + \lambda$ where N and N' are protons or nuclei.

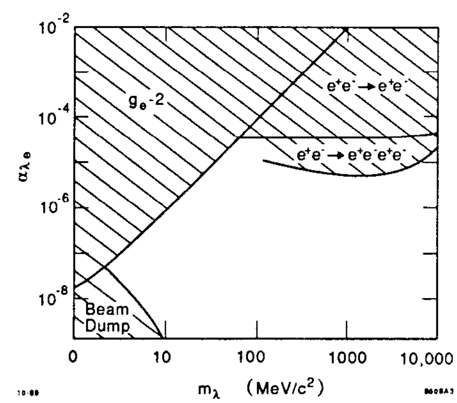

Figure 3: The crosshatched area shows the excluded region in the $\alpha_{\lambda e}$–m_λ plane for vector λ.

A. $g_\mu - 2$

The values of $g_\mu - 2$ from measurement[27] and theory[28] are

$$\text{Experiment}: \ \frac{1}{2}(g_\mu - 2) \times 10^{10} = 11\ 659\ 230\,(84) \ . \qquad (20a)$$

$$\text{Theory}: \ \frac{1}{2}(g_\mu - 2) \times 10^{10} = 11\ 659\ 194.7\,(14.3) \ . \qquad (20b)$$

Thus experiment and theory agree within the errors.

There are plans to reduce both errors. A future experiment at the Brookhaven AGS would reduce the error from 84×10^{-10} to about 4×10^{-10}. Reduction in the theoretical error requires a better calculation of the hadronic contribution to g_μ; and this in turn requires a more precise measurement of $e^+ + e^- \rightarrow$ hadrons below 1 GeV.[29]

B. *Dynamics of* $\mu^- \rightarrow e^- \overline{\nu}_e \nu_\mu$

The basic question is how well does V-A coupling describe the dynamics of the decay

$$\mu^- \rightarrow e^- + \overline{\nu}_e + \nu_\mu \ . \tag{21}$$

If a general four-fermion interaction is assumed and constrained only by the requirement that it be local, nonderivative and lepton-number conserving, then this dynamics is described by 19 real parameters.[30,31] However, only 10 combinations of these parameters can be measured using present experimental techniques, since these techniques cannot detect neutrinos. Within this restriction, all measurements of μ decay dynamics agree with V-A coupling.

C. *Radiative Muon Decays*

Although the radiative decays

$$\mu^- \rightarrow e^- + \overline{\nu}_e + \nu_\mu + \gamma \ , \tag{22a}$$
$$\mu^- \rightarrow e^- + \overline{\nu}_e + \nu_\mu + e^+ + e^- \ , \tag{22b}$$

have long been known and their theory is well known,[32] the measurements have large errors[33] since they are either old or are adjuncts to studies of forbidden muon decay limits. Is a dedicated study of the decays in Eqs. (22) worthwhile?

D. *Limits on Forbidden Muon Decays*

The 90% C.L. upper limits on the branching ratio for unconventional muon decays are

$B(\mu^- \rightarrow e^- \gamma)$	$< 4.9 \times 10^{-11}$	Ref. [34]	(23a)
$B(\mu^- \rightarrow e^- \gamma\gamma)$	$< 7.2 \times 10^{-11}$	Ref. [34]	(23b)
$B(\mu^- \rightarrow e^- e^+ e^-)$	$< 1.0 \times 10^{-12}$	Ref. [35]	(23c)

Certainly experimenters will look for these decays at yet smaller branching ratios, for example $B(\mu^- \rightarrow e^- \gamma)$ will be studied[36] into the 10^{-12} to 10^{-13} range.

E. *Muon Structure*

All measurements agree with the muon being a Dirac point particle. For example, high energy studies[37] of

$$e^+ + e^- \rightarrow \mu^+ + \mu^- \tag{24}$$

give the 95% C.L. lower limits

Form Factor	Contact Interaction (VV)	
$\Lambda_+ > 0.23$ TeV	$\Lambda^c_+ > 5.8$ TeV	(25)
$\Lambda_- > 0.25$ TeV	$\Lambda^c_- > 4.8$ TeV	

This is from the JADE collaboration using data from PETRA.

F. *Other Probes of the Muon*

Other searches for unconventional properties of the muon are based on the hypothetical reactions

$$\mu^- + \text{nucleus} \rightarrow e^- + \text{nucleus} \ , \tag{26a}$$
$$\mu^- + \text{nucleus} \rightarrow e^+ + \text{nucleus} \ , \tag{26b}$$
$$\mu^+ + e^- \rightarrow \mu^- + e^+ \ . \tag{26c}$$

No evidence for these reactions has been found.[30,31] K. K. Gan used the reaction $e^+e^- \rightarrow \mu^+\mu^-$ to place additional limits on unconventional properties of the muon.[38]

VI. NEUTRINOS

In this section I discuss four subjects: the number of small mass neutrinos; the masses of ν_e, ν_μ, and ν_τ; neutrino oscillations; and our present experimental knowledge of solar neutrinos. In this talk I do not have the time to describe the astrophysical and cosmological constraints on neutrino properties, I refer you to the review by Kolb, Schramm, and Turner.[39]

A. *Number of Small Mass Neutrinos*

We know of only three kinds of neutrinos: ν_e, ν_μ, ν_τ. Before August 1989 astrophysical and cosmological considerations as well as various experiments had shown that there are no more than four or five kinds of light neutrinos. Now measurements of the Z^0 width, Table 2, show that there are only three neutrinos with mass much less than $m_{Z^0}/2$ and conventional weak interaction coupling. An amazing simplicity in nature! All we have in this category are ν_e, ν_μ, and ν_τ.

Table 2. Number of types of small mass neutrinos, N_ν determined from Z^0 width. Experiments are listed in alphabetical order.

Experiment	N_ν
ALEPH	3.3 ± 0.3
DELPHI	2.9 ± 0.7
L3	3.4 ± 0.5
MARK II	2.8 ± 0.6
OPAL	3.1 ± 0.4

B. Neutrino Masses

Two general references on neutrino masses are the book by Boehm and Vogel[40] and the review by Langacker.[41]

1. Electron Neutrino Mass

There are two new upper limits on m_{ν_e}. At the Los Alamos National Laboratory, T. J. Bowles *et al.*[42] find

$$m^2_{\nu_e} = (-198 \pm 143) \quad eV^2 \ , \tag{27a}$$

$$m_{\nu_e} < 13.4 eV \ , \ 95\% \ \ \text{C.L.} \tag{27b}$$

The 95% C.L. is based on statistical and systematic errors. The other new limit is from the Institute for Nuclear Study of the University of Tokyo; H. Kawakami *et al.*[43] find

$$m^2_{\nu_e} = (-82 \pm 87) \ \text{eV}^2 \ . \tag{28a}$$

The authors state that "very preliminary analysis" gives

$$m_{\nu_e} < 11 \ \text{eV} \quad . \tag{28b}$$

This limit and its C.L. of 95% are based on statistical error only.

Of course, the incentive for these new experiments was the finding of Boris *et al.*[44]

$$m_{\nu_e} = (26 \pm 5) \ \text{eV} \ , \tag{29}$$

with a "model-independent" range of 17 to 40 eV. The upper limits in Eqs. (27) and (28) disagree with the nonzero value in Eq. (29).

For completeness I list three other m_{ν_e} measurements published in 1987 and 1986.

$m_{\nu_e} < 18$ eV , 95% C.L. Ref. [45]

$m_{\nu_e} < 32$ eV , 95% C.L. Ref. [46]

$m_{\nu_e} < 27$ eV , 95% C.L. Ref. [47]

Thus there is no confirmed evidence for a nonzero mass for ν_e.

2. Muon and Tau Neutrino Masses

In the past year there have been no changes in the upper limits on m_{ν_μ} and m_{ν_τ}:

$$m_{\nu_\mu} < 0.25 \ \text{MeV/c}^2 \ , \quad 90\% \ \text{C.L.} \tag{30}$$

$$m_{\nu_\tau} < \ 35. \ \text{MeV/c}^2 \ , \quad 95\% \ \text{C.L.} \tag{31}$$

If one believes in the hypothesis

$$\frac{m_{\nu_1}}{m_{\nu_2}} = \frac{m_1^2}{m_2^2} \ , \tag{32}$$

then

$$m_{\nu_\mu} \left(\frac{m_e}{m_\mu}\right)^2 < 5.9 \ \text{eV} \ , \tag{33a}$$

$$m_{\nu_\tau} \left(\frac{m_e}{m_\tau}\right)^2 < 2.9 \ \text{eV} \ . \tag{33b}$$

The upper limits in Eqs. (33) are smaller than the upper limits in Eqs. (27b) and (28b).

C. Neutrino Oscillations

There is no *confirmed* evidence for neutrino oscillations.[48] There is a loose end in the findings of Astier *et al.*[49] in a search for $\nu_\mu \rightarrow \nu_e$ oscillations.

D. Solar Neutrinos

The mystery continues of the difference between measured and calculated solar neutrino rates. In the well known experiment of Davis and his colleagues[50] the capture rate of solar neutrinos in ^{37}Cl is measured in SNU units, where 1 SNU = 10^{36} captures/ atom sec. The neutrino energy must be above 0.8 MeV for capture. In a 1988 review Totsuka[51] summarized the ^{37}Cl results:

$$\text{1970–1985 capture rate} \ = 2.1 \pm 0.3 \ \text{SNU} \ , \tag{34a}$$

$$\text{1986–1987 capture rate} \ = 5.0 \pm 0.8 \ \text{SNU} \ . \tag{34b}$$

Conventional solar theory gives[51]

$$\text{Calculated capture rate} = 7.9 \pm 2.6 \ \ \text{SNU} \ . \tag{35}$$

Thus to the old mystery of the difference between the measured capture rate in Eqs. (34) and the calculated rate in Eq. (35), has been added the question of the significance of the difference between the two measured rates in Eqs. (34).

The recent results[52] of the Kamiokande II experiment also show a difference

$$\frac{\text{measured flux}}{\text{predicted flux}} = 0.46 \pm 0.13 \pm 0.08 \quad , \qquad (36a)$$

and Koshiba[52] reported to this meeting very recent data:

$$\frac{\text{measured flux}}{\text{predicted flux}} = 0.39 \pm 0.09 \pm 0.06 \quad . \qquad (36b)$$

Kamiokande II is a water Čerenkov detector with much higher energy thresholds than the ^{37}Cl experiment: 9.3 MeV for the data in Eq. (36a) and 7.5 MeV for the data in Eq. (36b).

We don't know if the calculations of neutrino production by the sun are wrong or if the experiments are wrong or if the difference is due to an unconventional property of the ν_e.

VII. TAU

A. *Allowed Decay Modes*

The τ mass of 1784 MeV/c^2 allows a great number of decay modes. Figure 4, reproduced from the *1988 Review of Particle Properties*,[53] shows 40 different decay modes and their branching ratios. Note that even these 40 modes are limited to those with measured values or upper limits for their branching fractions. For example, there are no listings for $\tau^- \to \pi^- n\pi^0\nu_\tau$, $n = 4, 5, 6\ldots$ Thus the decay structure is rich and many decay quantities are unmeasured.

τ DECAY MODES

τ^+ modes are charge conjugates of the modes below

	Mode	Fraction (Γ_i/Γ)	Scale/ Conf.Lev.
Γ_1	$\tau^- \to \mu^-\bar{\nu}_\mu\nu_\tau$	$(17.8 \pm 0.4) \times 10^{-2}$	
Γ_2	$\tau^- \to e^-\bar{\nu}_e\nu_\tau$	$(17.5 \pm 0.4) \times 10^{-2}$	
Γ_3	$\tau^- \to 2\pi^+3\pi^-\nu_\tau$	$(5.6 \pm 1.6) \times 10^{-4}$	
Γ_4	$\tau^- \to 2\pi^+3\pi^-\pi^0\nu_\tau$	$(5.1 \pm 2.2) \times 10^{-4}$	
Γ_5	$\tau^- \to K^+K^-\pi^-\nu_\tau$	$(2.2\ ^{+1.7}_{-1.1}) \times 10^{-3}$	
Γ_6	$\tau^- \to K^-\pi^+\pi^-\ (\geq 0\ \pi^0)\ \nu_\tau$	$(2.2\ ^{+1.6}_{-1.3}) \times 10^{-3}$	
Γ_7	$\tau^- \to K^-\nu_\tau$	$(6.6 \pm 1.9) \times 10^{-3}$	S=1.1
Γ_8	$\tau^- \to \pi^-\omega\nu_\tau$	$(1.6 \pm 0.5) \times 10^{-2}$	
Γ_9	$\tau^- \to \pi^-\rho^0\nu_\tau$	$(5.4 \pm 1.7) \times 10^{-2}$	
Γ_{10}	$\tau^- \to a_1(1260)^-\nu_\tau$		
Γ_{11}	$\tau^- \to K^-\ (\geq 1$ neutral$)\ \nu_\tau$	$(1.05\ ^{+0.27}_{-0.28}) \times 10^{-2}$	
Γ_{12}	$\tau^- \to \pi^-\nu_\tau$	$(10.8 \pm 0.6) \times 10^{-2}$	
Γ_{13}	$\tau^- \to \pi^+2\pi^-\nu_\tau$ (non-resonant)	$< 1.4 \times 10^{-2}$	CL=95%
Γ_{14}	$\tau^- \to \pi^-\eta\nu_\tau$	$< 1.0 \times 10^{-2}$	CL=95%
Γ_{15}	$\tau^- \to \rho^-\nu_\tau$	$(22.3 \pm 1.1) \times 10^{-2}$	
Γ_{16}	$\tau^- \to \pi^+2\pi^-\nu_\tau$	$(6.8 \pm 0.6) \times 10^{-2}$	S=1.5
Γ_{17}	$\tau^- \to \pi^+2\pi^-\gamma(s)\ \nu_\tau$	$(6.4 \pm 0.6) \times 10^{-2}$	S=1.4
Γ_{18}	$\tau^- \to$ hadron$^-$ $(\geq 2$ hadron$^0)\ \nu_\tau$	$(16.3 \pm 1.3) \times 10^{-2}$	
Γ_{19}	$\tau^- \to 2\pi^+3\pi^-\ (\geq 0$ neutrals$)\ \nu_\tau$	$(1.15 \pm 0.27) \times 10^{-3}$	
Γ_{20}	$\tau^- \to K^*(892)^-\nu_\tau$	$(1.43 \pm 0.31) \times 10^{-2}$	
Γ_{21}	$\tau^- \to K_2^*(1430)^-\nu_\tau$	$< 9 \times 10^{-3}$	CL=95%
Γ_{22}	$\tau^- \to K^*(892)^-\ (\geq 0$ neutrals$)\ \nu_\tau$	$(1.4 \pm 0.9) \times 10^{-2}$	
Γ_{23}	$\tau^- \to \pi^-\pi^0$ (non-resonant) ν_τ	$(3.0\ ^{+3.0}_{-1.9}) \times 10^{-3}$	
Γ_{24}	$\tau^- \to \pi^+2\pi^-\pi^0\nu_\tau$	$(4.4 \pm 1.6) \times 10^{-2}$	
Γ_{25}	$\tau^- \to \pi^-3\pi^0\nu_\tau$	$(3.0 \pm 2.7) \times 10^{-2}$	
Γ_{26}	$\tau^- \to \pi^-2\pi^0\nu_\tau$	$(7.5 \pm 0.9) \times 10^{-2}$	
Γ_{27}	$\tau^- \to K^-$ (2 charged) $(\geq 0$ neutrals$)\ \nu_\tau$	$< 6 \times 10^{-3}$	CL=90%
Γ_{28}	$\tau^- \to \pi^+2\pi^-K^0\ (\geq 0\ \gamma)\ \nu_\tau$	$< 2.7 \times 10^{-3}$	CL=90%
Γ_{29}	$\tau^- \to \pi^-\pi^0\eta\nu_\tau$	$< 2.1 \times 10^{-2}$	CL=95%
Γ_{30}	$\tau^- \to 7$hadrons$^\pm\ (\geq 0\pi^0)\ \nu_\tau$	$< 1.9 \times 10^{-4}$	CL=90%
Γ_{31}	$\tau^- \to K^-K^0\nu_\tau$	$< 2.6 \times 10^{-3}$	CL=95%
Γ_{32}	$\tau^- \to K^-K^0\pi^0\nu_\tau$	$< 2.6 \times 10^{-3}$	CL=95%
Γ_{33}	$\tau^- \to \pi^-\eta\ (\geq 0$ neutrals$)\ \nu_\tau$	$< 2.1 \times 10^{-2}$	CL=95%
Γ_{34}	$\tau^- \to \pi^-\eta\eta\ (\geq 0$ neutrals$)\ \nu_\tau$	$< 5 \times 10^{-3}$	CL=90%
Γ_{35}	$\tau^- \to \pi^+\pi^-\pi^-\eta\ (\geq 0$ neutrals$)\ \nu_\tau$	$< 3.0 \times 10^{-3}$	CL=90%
Γ_{36}	$\tau^- \to$ (1 charged) $(\geq 0$ neutrals$)\ \nu_\tau$		
Γ_{37}	$\tau^- \to$ hadron$^-$ $(\geq 1\ \pi^0)\ \nu_\tau$		
Γ_{38}	$\tau^- \to$ hadron$^-$ $(\geq 0$ neutrals$)\ \nu_\tau$		
Γ_{39}	$\tau^- \to \pi^+2\pi^-\ (\geq 0\ \pi^0)\ \nu_\tau$		
Γ_{40}	$\tau^- \to K^-\ (\geq 0$ neutrals$)\ \nu_\tau$		

Figure 4: Allowed decay modes of the τ from the *1988 Review of Particle Properties*.[53]

Table 3 summarizes the world averages of the major branching fractions from Ref. [53] and from the recent review of Kiesling.[54] The averages agree because they are mostly based on the same set of experiments.

B. *Forbidden Decay Modes*

Figure 5, also from Ref. [53], lists 26 hypothetical decay modes in which lepton number conservation would be violated. There is no evidence for such a violation.

C. *The 1-Charged Particle Decay Modes Problem*

There is a mystery in the 1-charged particle decay modes of the τ, a mystery so puzzling that it is described in the *1988 Review of Particle Properties*,[53] Table 4. Reference [55] discusses the puzzle in detail. The sum of measured 1-charged particle branching ratios is 78.3 ± 1.9%. Theoretical limits[55–57] have been set on unmeasured, 1-charged particle modes such as $\pi^-3\pi^0\nu_\tau$, $\pi^-4\pi^0\nu_\tau$, $\pi^-5\pi^0\nu_\tau$, $\pi^-\eta\nu_\tau$, and $\pi^-\eta 2\pi^0\nu_\tau$ to give the total 2.2% upper limit in Table 4. This give the sum of individual 1-charged particle branching fractions as $\leq 80.5 \pm 1.9\%$ yet the topological 1-charged particle branching fraction is 86.6±0.3%. Thus 6% out of the 86.6% is unexplained.

There have been several studies[54,55,58–61] of this puzzle, searching for systematic errors or biases in the many experiments which contribute to the world

Table 3. World averages of major τ branching fractions from *Review of Particle Properties*[53] and Kiesling.[54]

Mode τ^-	Branching Fraction in %	
	Review of Particle Properties	Kiesling Review
1-charged particle	86.6 ± 0.3	86.5 ± 0.3
3-charged particle	13.3 ± 0.3	13.4 ± 0.3
5-charged particle	0.12 ± 0.3	0.14 ± 0.04
7-charged particle	< 0.019	
$e^-\overline{\nu}_e\nu_\tau$	17.5 ± 0.4	17.7 ± 0.4
$\mu^-\overline{\nu}_\mu\nu_\tau$	17.8 ± 0.4	17.8 ± 0.4
$\pi^-\nu_\tau$	10.8 ± 0.6	10.8 ± 0.6
$\rho^-\nu_\tau$	22.3 ± 1.1	22.3
$\pi^-2\pi^0\nu_\tau$	7.5 ± 0.9	

LEPTON NUMBER OR LEPTON FAMILY NUMBER VIOLATING MODES

Γ_{41}	$\tau^- \to \mu^-\gamma$	< 5	$\times 10^{-4}$	CL=90%
Γ_{42}	$\tau^- \to e^-\gamma$	< 6	$\times 10^{-4}$	CL=90%
Γ_{43}	$\tau^- \to \mu^-$ charged particles			
Γ_{44}	$\tau^- \to e^-$ charged particles			
Γ_{45}	$\tau^- \to \mu^-\mu^+\mu^-$	< 2.9	$\times 10^{-5}$	CL=90%
Γ_{46}	$\tau^- \to e^-\mu^+\mu^-$	< 3.3	$\times 10^{-5}$	CL=90%
Γ_{47}	$\tau^- \to \mu^-e^+e^-$	< 3.3	$\times 10^{-5}$	CL=90%
Γ_{48}	$\tau^- \to e^-e^+e^-$	< 4	$\times 10^{-5}$	CL=90%
Γ_{49}	$\tau^- \to \mu^-\pi^0$	< 8	$\times 10^{-4}$	CL=90%
Γ_{50}	$\tau^- \to e^-\pi^0$	< 2.1	$\times 10^{-3}$	CL=90%
Γ_{51}	$\tau^- \to \mu^-K^0$	< 1.0	$\times 10^{-3}$	CL=90%
Γ_{52}	$\tau^- \to e^-K^0$	< 1.3	$\times 10^{-3}$	CL=90%
Γ_{53}	$\tau^- \to \mu^-\rho^0$	< 4	$\times 10^{-5}$	CL=90%
Γ_{54}	$\tau^- \to e^-\rho^0$	< 4	$\times 10^{-5}$	CL=90%
Γ_{55}	$\tau^- \to e^-\pi^+\pi^-$	< 4	$\times 10^{-5}$	CL=90%
Γ_{56}	$\tau^- \to e^+\pi^-\pi^-$	< 6	$\times 10^{-5}$	CL=90%
Γ_{57}	$\tau^- \to \mu^-\pi^+\pi^-$	< 4	$\times 10^{-5}$	CL=90%
Γ_{58}	$\tau^- \to \mu^+\pi^-\pi^-$	< 6	$\times 10^{-5}$	CL=90%
Γ_{59}	$\tau^- \to e^-\pi^+K^-$	< 4	$\times 10^{-5}$	CL=90%
Γ_{60}	$\tau^- \to e^+\pi^-K^-$	< 1.2	$\times 10^{-4}$	CL=90%
Γ_{61}	$\tau^- \to \mu^-\pi^+K^-$	< 1.2	$\times 10^{-4}$	CL=90%
Γ_{62}	$\tau^- \to \mu^+\pi^-K^-$	< 1.2	$\times 10^{-4}$	CL=90%
Γ_{63}	$\tau^- \to e^-K^*(892)^0$	< 5	$\times 10^{-5}$	CL=90%
Γ_{64}	$\tau^- \to \mu^-K^*(892)^0$	< 6	$\times 10^{-5}$	CL=90%
Γ_{65}	$\tau^- \to e^+\mu^-\mu^-$	< 4	$\times 10^{-5}$	CL=90%
Γ_{66}	$\tau^- \to \mu^+e^-e^-$	< 4	$\times 10^{-5}$	CL=90%

Figure 5: Decay modes of the τ which violate lepton number conservation from the *1988 Review of Particle Properties*.[53]

average values in Table 4. But no explanation has been found. Nor has any explanation using unconventional physics been confirmed.

The CELLO collaboration has published[62] and submitted to this meeting[63] their recent measurement of τ branching ratios relevant to the 1-charged particle mode problem. Their branching ratios are compared with the world average branching ratios in Table 5. Compared to the world average values, their $B(\pi^-2\pi^0\nu_\tau)$ is larger by 2.5%, their $B(e^-\overline{\nu}_e\nu_\tau)$ is larger by 0.9%, and their B_1 is smaller by 1.7%. Therefore the discrepancy of about 6% found using world averages, Table 4, disappears in the CELLO data. There is no objective and nonstatistical way to decide between the world averages picture of the 1-charged particle branching ratios and the CELLO picture. If the CELLO collaboration's results are averaged with world-average values, the CELLO results

Table 4. The 1-charged particle decay mode problem from *Review of Particle Properties*.[53] All branching fractions are averages of experiments except the theoretical limits on unmeasured modes.

Decay Mode	Branching Fraction in %
$e^-\nu\nu$	17.7 ± 0.4
$\mu^-\nu\nu$	17.7 ± 0.4
$\rho^-\nu$	22.5 ± 0.9
$\pi^-\nu$	10.8 ± 0.6
$K^-(\geq 0$ neutrals$)$ ν	1.71 ± 0.29
$K^{*-}\nu, K^{*-} \to \pi^-(2\pi^0$ or $K_L)$	0.5 ± 0.1
$\pi^-(2\pi^0)\nu$	7.4 ± 1.4
Sum of measured modes	78.3 ± 1.9
Theoretical limits on unmeasured modes	< 2.2
Sum of exclusive modes	80.5 ± 1.9
Measured 1-prong branching fraction	86.6 ± 0.3
Difference	$> 6.1 \pm 1.9$

Table 5. Comparison of τ branching fractions in percent relevant to 1-charged particle mode problem from Behrend *et al.*,[63] the CELLO collaboration, and the *Review of Particle Properties*.[53]

Decay Channel	CELLO	World Avg
$\tau \to e\nu\nu$	$18.4 \pm 0.8 \pm 0.4$	17.5 ± 0.4
$\tau \to \mu\nu\nu$	$17.7 \pm 0.8 \pm 0.4$	17.8 ± 0.4
$\tau \to \pi\nu$	$11.1 \pm 0.9 \pm 0.5$	10.8 ± 0.6
$\tau \to K\nu$		0.7 ± 0.2
$\tau \to \rho\nu$	$22.2 \pm 1.5 \pm 0.7$	22.3 ± 1.1
$\tau \to \pi 2\pi^0\nu$	$10.0 \pm 1.5 \pm 1.1$	7.5 ± 0.9
$\tau \to \pi \geq 3\pi^0\nu$	$3.2 \pm 1.0 \pm 1.0$	3.0 ± 2.7
B_1	$85.0 \pm 2.4 \pm 1.2$	86.6 ± 0.3

are overwhelmed by the world average values on the basis of statistics.

Thus the 1-charged particle decay modes problem remains unsolved.

D. Tau Lifetime

The world average tau lifetime[53] is

$$\tau_\tau(\text{measured}) = (3.04 \pm 0.09) \times 10^{-13} \text{ sec} . \quad (37a)$$

The lifetime calculated[60] from world average values of $B(e^-\overline{\nu}_e\nu_\tau)$ and $B(\mu^-\overline{\nu}_\mu\nu_\tau)$ is

$$\tau_\tau(\text{calculated}) = (2.87 \pm 0.04) \times 10^{-13}\text{sec} . \quad (37b)$$

The difference is

$$\tau_\tau(\text{measured}) - \tau_\tau(\text{calculated}) = [0.17 \pm 0.10] \times 10^{-13} \text{ sec} .$$

This is not a significant difference in my opinion.

E. Tau Structure

There is no evidence for structure in the τ. Using the notation of Eqs. (17)-(19), Ref. [37] uses measurements of

$$e^+ + e^- \to \tau^+ + \tau^- , \quad (38)$$

to give the 95% C.L. lower limits:

Form Factor	Contact Interaction (VV)	
$\Lambda_+ > 0.29$ TeV	$\Lambda_+^c > 4.1$ TeV	(39)
$\Lambda_- > 0.21$ TeV	$\Lambda_-^c > 5.7$ TeV	

F. What We Want to Know About the Tau

The new results on the Z^0 width, Sec. VI.A, mean that the τ is the last of the sequential leptons: a charged lepton with a small mass neutrino partner. Eventually other kinds of leptons may be found, but the only leptons upon which we can do research in the foreseeable future are the e, μ, τ and their neutrinos. Research on the τ is crucial because it has the most complex behavior in the lepton family, because of the existing puzzle in the 1-charged particle decay mode, and because the third generation of fermions may have special properties. There are many things we want to know about the τ and ν_τ. As shown in Table 6, the things we want to know will provide powerful probes for new phenomena in particle physics and basic tests of the standard model of particle physics.

Some progress in tau physics will come from the new Beijing e^+e^- storage ring and from CESR, DORIS, PEP, SLC, LEP. But a new kind of facility, a tau-charm factory, is required to carry out powerful and precise tau physics research.

VIII. TAU PHYSICS AT A TAU-CHARM FACTORY

A. Tau-Charm Factory

Figure 6 shows the particle physics range and energy range of a tau-charm factory as first proposed by Kirkby.[64] The tau-charm factory is dedicated to

(i) τ physics,

(ii) D physics,

(iii) D_s physics,

(iv) ψ/J, ψ', and other charmonium physics.

Reference [65] and the May 1989 Tau-Charm Factory Workshop proceedings[66] provide a large amount of information on this physics. In addition, Λ_c and other charm baryon physics is accessible.

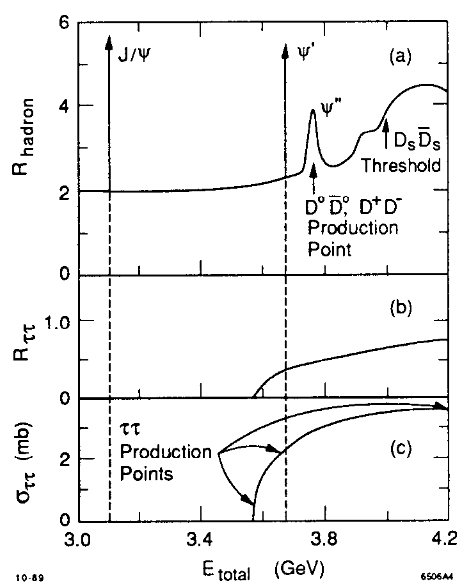

Figure 6: Main particle physics range of a tau-charm factory.

The first collider design was carried out by Jowett.[67] Figure 7 is a schematic and Table 7 gives the parameters of the present design of the machine. The basic design is:

Table 6. What we want to learn about the τ and ν_τ.

Subject	Search for New Physics	Test Standard Model	Tau-Charm Factory
Understand 1-charged particle modes puzzle	√	√	√
Untangle multiple π^0 and η modes in 1-charged particle modes		√	√
Precise measurement of $B(e\nu\nu)$, $B(\mu\nu\nu)$, $B(\pi\nu)$, $B(\rho\nu)$, and their ratio to 0.5%	√	√	√
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	√	√	√
Precise measurement of τ lifetime	√	√	
Explore ν_τ mass to a few MeV/c^2	√	√	√
Detect ν_τ	√	√	
Study interactions of ν_τ	√	√	
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 $W^- \to \tau^-\overline{\nu}_\tau$	√	√	
Measure $B(D^- \to \tau^-\overline{\nu}_\tau)$	?	√	√
Measure $B(D_s^- \to \tau^-\overline{\nu}\tau)$	?	√	√
Measure $B(B^- \to \tau^-\overline{\nu}_\tau)$	?	√	
Make and study $\tau^+\tau^-$ atom	√	√	?

(i) design luminosity = 10^{33} cm^{-2} s^{-1},

(ii) two-ring, e^+e^-, circular collider,

(iii) equal energies and 0^0 crossing angle,

(iv) dedicated e^+ and e^- injector.

Table 8 gives the tau-charm factory particle yields at $L = 10^{33}$ cm^{-2} s^{-1}.

B. Tau Physics at a Tau-Charm Factory

At existing e^+e^- colliders progress in tau physics has been, and continues to be, severely restricted by

(i) insufficient statistics,

(ii) inefficient tagging of τ pairs (3–30%),

(iii) double tagging of τ pairs mostly required,

(iv) impure data sets (5–50% backgrounds),

(v) no direct measurement of backgrounds,

(vi) no control of production energy.

Tau physics research at proposed B-factories will continue to be restricted by problems (ii) through (vi).

Tau physics at a tau-charm factory does not have these restrictions and problems. There are three energies (Fig. 6) at which

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

data will be acquired: (a) several MeV above the threshold energy; (b) at 3.67 GeV, just below the ψ'; (c) at 4.2 GeV, where $\sigma(e^+e^- \to \tau^+\tau^-)$ is a maximum.

(a) $E_{total} = 2m_\tau + 2$ or 3 MeV/c^2:

(i) Due to Coulomb interaction $\sigma(e^+e^- \to \tau^+\tau^-)$ is not zero at threshold but is about

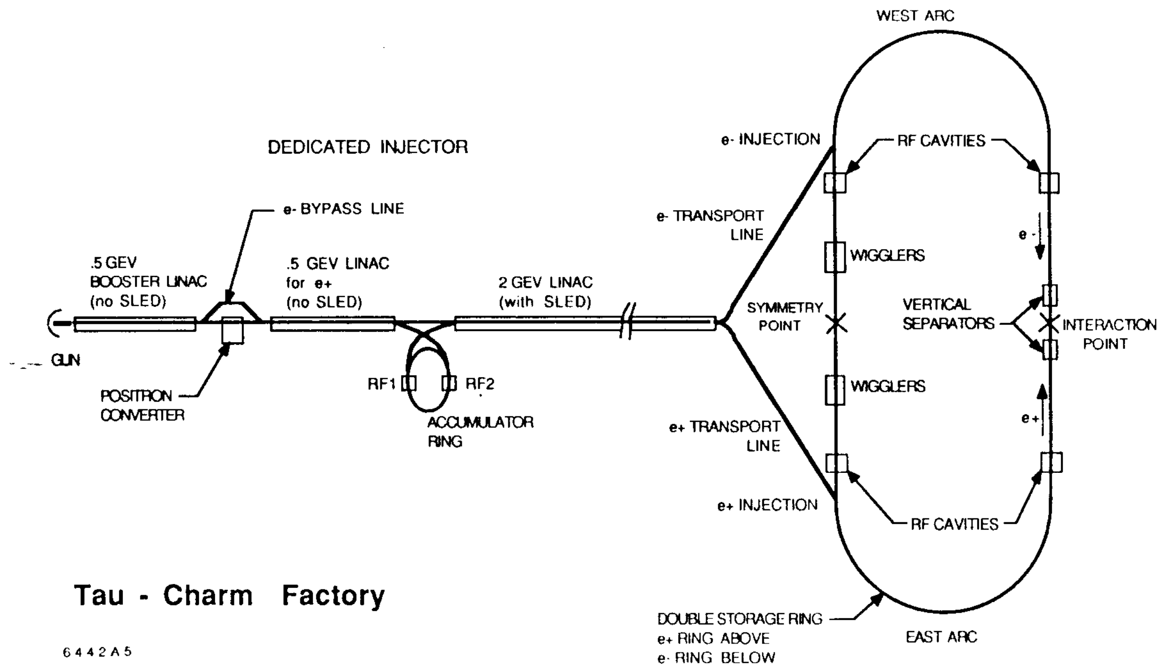

Figure 7: Schematic of a tau-charm factory two-ring collider and injector.

0.2 nb. Just 2 MeV above threshold it is about 0.4 nb. Here $\sigma_{E_{beam}} \approx 1$ MeV.

(ii) Single tagging can be carried out using $\tau^- \to \pi^- \nu_\tau$ because at threshold this π is kinematically separated[68] from the e^-, μ^-, and K^- of the other non-π^0 single-charged particle modes. Particle identification will also be used to isolate the π.

(iii) Single tagging will also be carried out using

$$\begin{aligned} \tau^- &\to e^- + \text{missing energy} , \\ \tau^- &\to \mu^- + \text{missing energy} . \end{aligned} \tag{40}$$

(iv) There is no background from D or B decays.

(v) Hadronic backgrounds are directly measured by going below threshold.

(b) $E_{total} = 3.67$ GeV, just below ψ':

(i) $\sigma(e^+e^- \to \tau^+\tau^-)$ is substantial, 2.0 nb.

(ii) Single tagging will be carried out using the decays in Eq. (40).

(iii) There is no background from D or B decays.

(iv) The light quark background and other backgrounds can be directly measured by reducing E_{total} by just 100 MeV to get below threshold.

(c) $E_{total} \approx 4.2$ GeV:

(i) $\sigma(e^+e^- \to \tau^+\tau^-)$ is a maximum, 2.8 nb.

(ii) Here $v_\tau/c \approx 0.5$, hence spin-dependant measurements can be carried out, such as the study of the dynamics of the $e\nu\nu$ and $\mu\nu\nu$ decay modes.

(iii) Single tagging will be carried out using the decays in Eq. (40).

(iv) There is no background from B decays.

(v) Other backgrounds can be studied by comparing with measurements at 3.67 GeV and at threshold.

Thus the tau-charm factory will produce very large samples of τ data, about 10^8 τ pairs in a few years; the data will be very pure. Therefore the tau-charm factory provides the best way, and in many cases the only way to answer the many experimental questions

Table 7. General parameters of the tau-charm factory at energy per beam of 2.2 GeV.

Energy	E	2.2 GeV
Circumference	C	329.9 m
Revolution frequency	f_o	0.909 MHz
Bending radius	ρ	12 m
β-function at IP	β_x^*	0.2 m
	β_y^*	0.01 m
Betatron coupling	κ^2	0.05
Betatron tunes	Q_x	8.87
	Q_y	7.76
Momentum compaction	α	0.0396
Natural emittance	ϵ_x	424 nm
Fractional energy spread	σ_ϵ	5.44 x 10^{-4}
Energy loss per turn	U_0	0.173 MeV
Damping times	τ_x	28 msec
	τ_y	28 msec
	τ_ϵ	14 msec
RF frequency	f_{RF}	350 MHz
RF voltage	V_{RF}	32 MV
Radiated power per beam	P_{rad}	86 kW
Number of bunches	k_b	21
Bunch separation	S_b	15.71 m
Bunch spacing	τ_b	52.4 ns
Bunch crossing frequency	f_b	19.1 MHz
Total beam current	I	498 mA
Particles per bunch	N_b	1.63 x 10^{11}
r.m.s. bunch length	σ_z	6 mm
Beam sizes at IP	σ_x^*	284 μm
	σ_y^*	14 μm
Beam-beam parameter	ξ_y	0.04
Luminosity	L	1.0 x 10^{33} $cm^{-2}s^{-1}$

Table 8. Tau-charm factory particle yields at 10^{33} cm^{-2} s^{-1}.

e^+e^- Energy	Particle	Produced Events
$J/\psi\,(3.095)$	$J\psi$	2×10^9/month
$\psi'\,(3.680)$	ψ'	8×10^8/month
$2m\,(\tau) + 2$ MeV	$\tau^+\tau^-$	7×10^6 pairs/year
3.67 GeV	$\tau^+\tau^-$	4×10^7 pairs/year
$\psi''\,(3.77)$	D^+D^-	3×10^7 pairs/year
$\psi''\,(3.77)$	$D^0\overline{D}^0$	4×10^7 pairs/year
4.14 GeV	$D_s^\pm D_s^{*\pm}$	10^7 pairs/year
4.2 GeV	$\tau^+\tau^-$	5×10^7 pairs/year

in tau physics, Table 6. Tau-charm factory designs are being considered in

France
Japan
Spain
USSR
USA

and perhaps other countries.

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APPENDIX A

Tau-Charm Factory Machine Design Group

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APPENDIX B

The Tau-Charm Collaboration

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DISCUSSION

M. Samuels, Oklahoma State: To account for the discrepancy in the ortho-positronium decay-rate, the coefficient B of the next-order correction must be +350. Do you think this is possible, and do you believe the experiment is correct?

M. Perl: I don't know of any conclusion based on calculations as to the maximum size of the B coefficient. The University of Michigan experimenters who have measured the decay rate in gas are planning a new experiment studying the decay rate in vacuum.

M. Davier, Orsay: You may have given the impression that the CELLO analysis was aimed at making the few-percent corrections necessary in some decay channel to solve the τ 1-prong problem. This was not the case, in fact; the results came from a comprehensive study of all decay channels simultaneously analyzed in the sense that *all* $\tau^+\tau^-$ events were assigned to given final states. In this analysis, we could make sure that all τ decays were properly accounted for, and we believe this to be the first consistent treatment of τ decay modes. This is why it may not be correct to compare CELLO results with the "world average", where many pieces of data are put together from independent analyses on at most a few channels, with different and sometimes understated systematic effects.

As a final comment, I think you can also add Orsay to your list of laboratories presently studying a τ-charm factory.

M. Perl: The CELLO results may be the right answer to the problem in the 1-prong decay modes of the τ. But at this time there is no way to evaluate the correctness of the CELLO results relative to the many experiments that comprise the world average. We must wait for measurements with much larger statistics and smaller systematic errors. In the written version of my talk I have included the Orsay laboratory as one of the institutions studying τ-charm factory design and potential.