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NEW LEPTONS: AN EXPERIMENTAL REVIEW*

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ABSTRACT

We review experimental knowledge on what are usually called heavy leptons, but we call new leptons. These are leptons other than the electron, muon, and their associated neutrinos. The measured properties of the tau lepton are surveyed, including a discussion of the inconsistencies in present knowledge of its one-charged-particle decay modes. We summarize experimental limits on the existence of other possible leptons. We conclude the review with a discussion of searches which can be made with the new and proposed particle colliders.

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1. INTRODUCTION

1.1 Purpose of Review

In 1974 P. Rapidis and one of the authors (MLP) wrote a review[1] entitled *The Search for Heavy Leptons and Muon–Electron Differences.* In the passage of 13 years one of the two questions raised in that paper has been answered: There is a heavy lepton—the tau.[2] But the other question, the origin of muon-electron differences, has not been answered; it has expanded into the generation problem.[3] The great theoretical and experimental success of the unification of the electromagnetic and weak interactions[4] has deepened the mystery of the source of the tau-muon-electron differences.

In this review we return to the first question, "What is known about leptons other than the electron, muon, and their associated neutrinos?" Such other leptons are usually called "heavy leptons." But we prefer the term "new leptons" to include new small or zero mass leptons.

Properties of the tau and its associated neutrino are summarized in Sec. 2. Then the experimental limits on the existence of additional new leptons are discussed in Secs. 3 and 4. The boundary between the two sections is the theoretical structure[5] given the name "standard model." This review concludes in Sec. 5 with considerations of the range of future searches for new leptons using the new and proposed very high energy particle colliders.

Our classification and discussion of search limits is organized according to types of data and search techniques. Sometimes, as a guide to the reader, we discuss the theoretical motivations and implications relevant to a search, but we do not review the theoretical or speculative literature on new leptons.

In the past few years there have been several surveys[6–9] of the status of new lepton searches. Also, Bullock and Devenish[10] published a complete review of the particle physics of leptons in 1983.

Many limits from search methods using fixed target experiments became obsolete when improved sensitivity was obtained using e^+e^- colliders. A few of the older search methods are discussed in the paper but most are ignored, the reader is referred to older reviews.[1,11]

1.2 Definition of a Lepton

Within the standard model the definition of a lepton is straightforward:

($A1$) A lepton interacts through the electroweak interaction and presumably through the gravitational interaction.

($A2$) A lepton does not interact through the strong interaction.

($A3$) Within the structure of electroweak theory a lepton can be a member of a doublet or can be a singlet. This doublet or singlet classification is connected to a lepton generation conservation rule. Experiment finds no deviation from perfect conservation, but the standard model allows imperfect conservation.

($A4$) A lepton is a fermion.

Going beyond the standard models obscures the boundary between leptons and other particles which avoid the strong interaction: γ, $W^\pm$, Z^0, and the proposed Higgs particles. We fix the boundary by requiring a general lepton conservation rule. Therefore, the broader lepton definition is:

($B1$) A lepton interacts through the electroweak interaction and presumably through the gravitational interaction.

($B2$) A lepton does not interact through the strong interaction.

($B3$) Leptons obey a general conservation rule. If ℓ represents a lepton and $\bar{\ell}$ represents a possibly different antilepton, in all reactions the sum of the total number of ℓ's and the total number of $\bar{\ell}$'s is fixed. For example, in the decay of the supersymmetric partner $\tilde{e}^-$ of the e^-, $\tilde{e}^- \rightarrow e^- + \tilde{\gamma}$, where $\tilde{\gamma}$

is a photino. If the speculative ideas from grand unification are true then this conservation rule can be broken with quark to lepton conversion, for example, $u + u \rightarrow \mu^+ + \bar{s}$, where u and s are the up and strange quarks.

The prohibition against the connection of leptons with the strong interaction has been relaxed in hypothesis about particles such as leptoquarks and colored leptons. For example, the latter particle has the decay scheme $\ell^-_{\mathrm{color}} \rightarrow \ell^- + g$ where g is a gluon. Here, definition $(B3)$ has been retained, but not $(B2)$.

2. THE TAU LEPTON

The tau lepton was discovered[2] in 1975 at the SPEAR e^+e^- storage ring of the Stanford Linear Accelerator Center (SLAC). It has been a subject of extensive study since the discovery. In general, measurements show it is a sequential lepton in the standard model of electroweak interaction, but there are some difficulties in understanding all the measurements. In this section we summarize present understanding of this massive lepton. Other recent reviews are in Refs. 12–14.

2.1 Spin, Mass and Size

The spin and mass of the τ have been determined from the threshold behavior of the production cross section. The QED production cross section for a spin 1/2, point-like particle is

$$\sigma_{\tau\tau} = \frac{4\pi\alpha^2}{3s}\frac{\beta(3-\beta^2)}{2} \quad , \tag{2.1.1}$$

where $\beta = \sqrt{1-4m^2/s}$, m is the mass of the particle, and $\sqrt{s}$ is the center-of-mass energy. The DELCO experiment[15] provided the best measurement of the threshold production cross section and established the τ lepton as a spin 1/2 particle. The world average measurement[16] of the τ mass is (1784 ± 3) MeV/c^2.

Measurements of the production cross section at energies well above the threshold test the point-like nature of the τ. It is customary to parameterize the deviations from the QED prediction by a form factor[17]

$$\sigma_{\tau\tau}(s) = \left(1 \mp \frac{s}{s-\Lambda_\pm^2}\right)\sigma_{\tau\tau} \quad . \tag{2.1.2}$$

The QED cut-off parameter $\Lambda_\pm$ quantitatively, characterizes the validity of QED and measures the point-like nature of the τ. Measurements[18–20] at PETRA find the limits, $\Lambda_\pm > 200$ GeV at the 95% confidence level, indicating the τ is less than 10^{-18} m in size.

2.2 Weak Interaction Properties

In the standard model, the coupling of all leptons to the charged ($W^{\pm}$) and neutral (Z^0) weak currents have the same universal strength; and the leptons couple to the currents with a V–A structure. The V–A coupling of the τ has been studied by analyzing the electron and muon momentum spectra from its decays. The lepton universality of the τ coupling to the charged weak current has been tested by measuring its lifetime and, for the neutral current, by measuring the forward-backward asymmetry in the angular distribution of the $\tau^+\tau^-$ pairs.

2.2.1 Michel Parameter

The momentum spectra of electrons and muons from τ decays depend on the mixture of vector (V) and axial-vector (A) currents. The mixture is usually defined by the Michel parameter ρ.[21] The mixtures V–A, V+A, V and A have the ρ values 0.75, 0.0, 0.375 and 0.375. The average measurement[22] is $\rho = 0.73 \pm 0.07$ and thus consistent with a V–A coupling. More precise measurements of the coupling will be useful.

2.2.2 Lifetime

Measurement of the τ lifetime provides a direct study of the coupling strength of the τ to the charged weak current. In the standard model, the τ decay $\tau^- \to e^-\bar{\nu}_e\nu_\tau$ proceeds in perfect analogy to the μ decay $\mu^- \to e^-\bar{\nu}_e\nu_\tau$. Assuming $\mu - \tau$ universality of the weak coupling and that the τ neutrino is massless, the τ lifetime[23,24] is related to the μ lifetime by

$$\begin{aligned} \tau_\tau &= \left(\frac{m_\mu}{m_\tau}\right)^5 \tau_\mu \, B\left(\tau^- \to e^-\bar{\nu}_e\nu_\tau\right) \\ &= 16.03 \times 10^{-13} B\left(\tau^- \to e^-\bar{\nu}_e\nu_\tau\right) \mathrm{s} \quad . \end{aligned} \tag{2.2.1}$$

Table 1 lists more recent measurements of τ_τ. The conventional way to average such measurements is to add the statistical and systematic errors in quadrative for each measurement and use these combined errors to obtain a weighted average and a final error. We call this the "formal average." There are two problems in this method: (a) there is no general justification for so combining statistical and systematic errors, and (b) if several measurements have the same systematic error, the final error in the formal average is too small. These remarks apply to all the average values of measurements discussed in this section.

The formal average of the measurements in Table 1 is

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

With the formal average measurement (see Sec. 2.3.1) of the electron branching ratio $B_e = (17.7 \pm 0.4\%)$, the predicted lifetime is $\tau_\tau = (2.83 \pm 0.06) \times 10^{-13}$ s. This is in fair agreement with the above averaged measurement.

2.2.3 *Charge Asymmetry*

In the standard model, the reaction $e^+e^- \to \tau^+\tau^-$ proceeds through both the electromagnetic and neutral weak currents. The differential cross section for the reaction is given by

$$\frac{d\sigma}{d\cos\theta} = \frac{\pi\alpha^2}{2s} R_{\tau\tau} \left[1 + \cos^2\theta + \frac{8}{3} A_{\tau\tau} \cos\theta\right] \quad , \tag{2.2.2}$$

where $R_{\tau\tau}$ is the production cross section, normalized to the QED cross section of μ-pair, and $A_{\tau\tau}$ is the forward-backward asymmetry in the differential cross section. $R_{\tau\tau}$ and $A_{\tau\tau}$ are related to the vector (g_v) and axial-vector (g_a) weak coupling constants by

$$R_{\tau\tau} = 1 + 2g_v^e g_v^\tau Re\,\chi + \left(g_v^{e^2} + g_a^{e^2}\right)\left(g_v^{\tau^2} + g_a^{\tau^2}\right)|\chi|^2 \quad ,$$
$$A_{\tau\tau} = \frac{3}{2R_{\tau\tau}}\left[g_a^e g_a^\tau Re\,\chi + 2g_a^e g_v^e g_a^\tau g_v^\tau |\chi\,(s)|^2\right] \quad , \qquad (2.2.3)$$
$$\chi = \frac{1}{4\sin^2\theta_W\cos^2\theta_W}\;\frac{s}{s - m_Z^2 + im_Z\Gamma_Z} \quad .$$

Here, θ_W is the Weinberg angle, and m_Z and Γ_Z are the mass and width of the Z^0, respectively. In the standard model, $g_a^e g_a^\tau = g_a^2 = \frac{1}{4}$ and $g_v^e g_v^\tau = g_v^2 = \frac{1}{4}(1 - 4\sin^2\theta_W)^2$, assuming lepton universality. At PEP and PETRA energies, which are well below the Z^0 pole, the effect of the Z^0 current is detected through its interference with the electromagnetic current. The interference produces both a shift in the production cross section and an asymmetry in the angular distribution. The shift in cross section is too small to be detectable. However, the asymmetry is large enough to be detectable and thus allows a test of the lepton universality in the axial coupling. The average value[12,18–20,25] is $g_a^\tau g_a^e = 0.21 \pm 0.03$, consistent with the prediction of lepton universality.

2.3 Decay Modes and Branching Ratios

The τ decay is a good laboratory for studying many aspects of the standard model. Since the τ appears to have no internal structure to complicate theoretical calculations, many decay branching ratios can be predicted with the present understanding of electroweak interaction. The large lepton mass allows the τ to decay into both purely leptonic states and semi-leptonic states with accompanying hadrons.

The hadronic decay products have distinctive charge conjugation (C) and isospin (and hence G–parity) signatures, a reflection of the quantum number of the charged hadronic weak current. The weak current is classified according to its G–parity:

vector weak current: $G = +1, J^P = 1^-$, e.g., $\rho^-(770)$

axial weak current: $G = -1, J^P = 0^-, 1^+$, e.g., $\pi^-, a_1^-(1270)$.

These are known as the first class currents. Currents with opposite G–parity are called the second class currents, which are suppressed by the order α^2 or 10^{-4} in the standard model. Examples of second class current decays are $\tau^- \to a_0^-(980)\nu_\tau$ and $\tau^- \to b_1^-(1235)\nu_\tau$.

In this section, we review the results on the standard model allowed decay modes. Limits on forbidden decay modes will be surveyed in the next section.

2.3.1 *e and μ Decays*

In the standard model, assuming $e - \mu$ universality, the μ decay branching ratio of the τ is the same as the e decay except for a small phase space suppression factor,[23,24]

$$\frac{B_\mu}{B_e} = F\left(m_\mu/m_\tau\right) = 0.97 \quad , \tag{2.3.1}$$

where

$$F(y) = 1 - 8y^2 + 8y^6 - y^8 - 12y^4 \ln y^2 \quad .$$

The formal average measurements for the branching ratios (Table 2) are $B_e = (17.7 \pm 0.4\%)$ and $B_\mu = (17.7 \pm 0.4\%)$. The ratio of the two measurements is $B_\mu/B_e = 1.00 \pm 0.03$, in agreement with the theoretical prediction based on $e - \mu$ universality.

It is customary to calculate the branching ratios for other decay modes normalized to the electron branching ratio. We will use the formal average measurement of B_e quoted above in the calculations.

2.3.2 π and K Decays

The decays $\tau^- \rightarrow \pi^- \nu_\tau$ and $\tau^- \rightarrow K^- \nu_\tau$ involve the coupling of weak axial-vector current to the pion and kaon, respectively. In the standard model, the branching ratio for $\tau^- \rightarrow \pi^- \nu_\tau$ decay can be calculated[23,24] from the precisely measured pion decay $\pi^- \rightarrow \mu^- \bar{\nu}_\mu$, with the assumption of $\mu - \tau$ universality,

$$\frac{B_\pi}{B_e} = \frac{(f_\pi \cos\theta_C)^2}{m_\tau^2} 12\pi^2 \left[1 - \frac{m_\pi^2}{m_\tau^2}\right]^2 = 0.607 \qquad (2.3.2)$$

where the quantity $f_\pi \cos\theta_C$ is the form factor at the $W - \pi$ vertex. The average measurement of the pion branching ratio (Table 3) is $B_\pi = (10.9 \pm 0.6)\%$. This gives the ratio $B_\pi / B_e = 0.62 \pm 0.04$, in agreement with the theoretical prediction.

The branching ratio[23,24] for $\tau^- \rightarrow K^- \nu_\tau$ decay is related to the kaon decay, $K^- \rightarrow \mu^- \bar{\nu}_\mu$, in a similar manner:

$$\frac{B_K}{B_e} = \frac{(f_K \sin\theta_C)^2}{m_\tau^2} 12\pi^2 \left[1 - \frac{m_K^2}{m_\tau^2}\right]^2 = 0.0395 \quad . \qquad (2.3.3)$$

The DELCO collaboration[26] measured the branching ratio to be $B_K = (0.59 \pm 0.18)\%$, yielding a ratio of $B_K / B_e = 0.033 \pm 0.010$. Within the limited accuracy, the result agrees with the prediction.

2.3.3 ρ and K^* Decays

The ρ branching ratio can be calculated[23,24] by using the conserved–vector–current (CVC)[27] hypothesis to relate the coupling strength of the ρ to the weak charged vector current and the electromagnetic neutral vector current. Gilman and Rhie[28] used the measured cross section for the reaction $e^+e^- \rightarrow \rho$ to calculate the electromagnetic coupling and predicted that $B_\rho / B_e = 1.23$. The former average measurement of the ρ branching ratio (Table 4) is $B_\rho = (22.8 \pm 1.0)\%$, yielding a ratio of $B_\rho / B_e = 1.29 \pm 0.06$, in agreement with the CVC prediction.

The Cabibbo–suppressed K^* decay is related[23,24] to the Cabibbo–favored ρ decay by a phase space factor, the Cabibbo suppression factor $\tan^2\theta_C$, and SU(3) breaking sum rules. Gilman and Rhie[28] predicted $B_{K^*}/B_\rho = 0.052$. The average measurement[29,30] of the K^* branching ratio is $B_{K^*} = (1.6 \pm 0.3)\%$. This gives the ratio $B_{K^*}/B_\rho = 0.070 \pm 0.013$, in agreement with the theoretical expectation.

2.3.4 3π and 4π Decays

The three-pion decay of the τ is mediated by the axial-vector part of the weak interaction and there is no firm prediction for the decay branching ratio. However, isospin conservation imposes a limit on the relative fraction on the branching ratios for $\tau^- \to \pi^- 2\pi^0 \nu_\tau$ and $\tau^- \to \pi^-\pi^+\pi^-\nu_\tau$: $B_{\pi 2\pi^0} \leq B_{3\pi}$. If the decay is dominated by the a_1 resonance as expected, then $B_{\pi 2\pi^0} = B_{3\pi}$. $B_{3\pi}$ has been measured by many experiments. However, there are significant differences between the experiments, as evidenced in Table 5. The formal average measurement of $B_{3\pi}$ is $(6.7 \pm 0.4)\%$. This average includes small contributions from the decays $\tau^- \to K^-\pi^+\pi^-\nu_\tau$ and $\tau^- \to K^-K^+\pi^-\nu_\tau$, but excludes the decay $\tau^- \to K^{*-}\nu_\tau \to \pi^- K_s^0 \nu_\tau \to \pi^-\pi^+\pi^-\nu_\tau$.

The four-pion decay proceeds through the vector current and can be estimated[23] by CVC. Gilman and Rhie[28] use the measured cross sections for $e^+e^- \to \pi^+\pi^- 2\pi^0$ and $e^+e^- \to 2\pi^+ 2\pi^-$ to calculate the branching ratios for $\tau^- \to \pi^-\pi^+\pi^-\pi^0\nu_\tau$ and $\tau^- \to \pi^- 3\pi^0 \nu_\tau$, and predict $B_{3\pi\pi^0}/B_e = 0.275$ and $B_{\pi 3\pi^0}/B_e = 0.055$. The formal average measurement (Table 5) of $B_{3\pi\pi^0}$ is $(5.0 \pm 0.5)\%$. This yields the ratio $B_{3\pi\pi^0}/B_e = 0.28 \pm 0.03$, in agreement with the CVC expectation.

It is difficult to measure the branching ratios for $\tau^- \to \pi^- 2\pi^0 \nu_\tau$ and $\tau^- \to \pi^- 3\pi^0 \nu_\tau$ for two reasons. First, there are several experimental difficulties in deducing the π^0 composition from the detected γ composition. Sometimes the two γ's from the π^0 decay are detected as one γ, sometimes spurious γ's are detected, sometimes very low energy γ's are not detected. Second, decay modes with η mesons such as $\tau^- \to \pi^-\eta\pi^0\nu_\tau$ and $\tau^- \to \pi^- 2\eta \nu_\tau$ can give similar γ

signatures through $\eta \to \gamma\gamma$ and $\eta \to 3\pi^0$. As discussed in the following sections, our present knowledge of decay modes with η mesons is limited.

The CELLO collaboration[31] measured $B_{\pi 2\pi^0}$ and $B_{\pi 3\pi^0}$ by unfolding the observed photon multiplicity spectrum, ignoring the η contributions. The results are

$$\begin{aligned} B_{\pi 2\pi^0} &= (6.0 \pm 3.0 \pm 1.8)\% \\ B_{\pi 3\pi^0} &= (3.0 \pm 2.2 \pm 1.5)\% \quad . \end{aligned}$$

The MARK II collaboration[32] measured the branching ratios by fitting the observed photon multiplicity spectrum. The fit favored additional multiple neutral meson decay modes other than $\tau^- \to \pi^- 2\pi^0 \nu_\tau$ and $\tau^- \to \pi^- 3\pi^0 \nu_\tau$. Using the decay $\tau^- \to \pi^- \eta \pi^0 \nu_\tau$ as an example for the multiple neutral meson decay modes, the fit yields

$$\begin{aligned} B_{\pi 2\pi^0} &= (6.2 \pm 0.6 \pm 1.2)\,\% \\ B_{\pi 3\pi^0} &= \left(0.0 \pm {1.4 \atop 0.0} \pm {1.1 \atop 0.0}\right)\% \\ B_{\pi \eta \pi^0} &= \left(4.2 \pm {0.7 \atop 1.2} \pm 1.6\right)\% \quad . \end{aligned}$$

The MAC collaboration[33] measured $B_{\pi 2\pi^0}$ by using events with two energetic photons. The result is

$$B_{\pi 2\pi^0} = (8.7 \pm 0.4 \pm 1.1)\,\% \quad .$$

Within the errors, all measurements of $B_{\pi 2\pi^0}$ and $B_{\pi 3\pi^0}$ are consistent with the theoretical expectations. The result from MARK II on $B_{\pi\eta\pi^0}$ will be discussed in Sec. 2.3.7.

The ARGUS collaboration[34] has found evidence for $\tau^- \to \pi^- \omega \nu_\tau$ in the decay $\tau^- \to \pi^- \pi^+ \pi^- \pi^0 \nu_\tau$, with a branching ratio of $(1.5 \pm 0.3 \pm 0.3)\%$. This result has been confirmed by the CLEO collaboration,[35] which measured a branching ratio of $(1.60 \pm 0.27 \pm 0.41)\%$. From the spin-parity analysis, both experiments found that the $\omega\pi$ system is consistent with a $J^P = 1^-$ state and there is no evidence for second class currents.

2.3.5 5π and 6π Decays

There are no firm theoretical predictions for the five- and six-pion decay branching ratios. The five-charged-particle decay has been observed and the formal average of the measured branching ratios[19,36,37] is $B_5 = (0.11 \pm 0.03)\%$. The HRS collaboration[37] further classified their candidate events into those that contained no photons, and those that contained photons consistent with originating from a single π^0 decay. With this interpretation, $B_{5\pi} = (0.051 \pm 0.020)\%$ and $B_{5\pi\pi^0} = (0.051 \pm 0.022)\%$.

There are no experimental measurements on the decays $\tau^- \to \pi^-\pi^+\pi^-2\pi^0\nu_\tau$, $\tau^- \to \pi^-\pi^+\pi^-3\pi^0\nu_\tau$, $\tau^- \to \pi^-4\pi^0\nu_\tau$ and $\tau^- \to \pi^-5\pi^0\nu_\tau$. However, isospin invariance imposes[28] the limits: $B_{\pi4\pi^0} \leq \frac{3}{4}B_{5\pi} = (0.038 \pm 0.015)\%$ and $B_{\pi5\pi^0} \leq \frac{9}{7}B_{5\pi\pi^0} = (0.066 \pm 0.028)\%$.

2.3.6 $\pi\eta$ Decay

The decay $\tau^- \to \pi^-\eta\nu_\tau$ is suppressed in the standard model because the decay proceeds through a second class current. The $\pi\eta$ system has the parity

$$P(\pi\eta) = P(\pi)P(\eta)(-1)^J = (-1)(-1)(-1)^J = (-1)^J \quad ,$$

and thus the system has $J^P = 0^+$ or 1^-. However, the G–parity of the system is

$$G(\pi\eta) = G(\pi)G(\eta) = (-1)(+1) = -1 \quad ,$$

and thus is opposite to that for a first class current. The decay is expected to be suppressed by the order of α^2 or 10^{-4} relative to the first class decay.

Recently, the HRS collaboration reported[38] evidence for $\tau^- \to \pi^-\eta\nu_\tau$ with $\eta \to \gamma\gamma$. The branching ratio was measured to be $B_{\pi\eta} = (5.1 \pm 1.0 \pm 1.2)\%$. The result was not confirmed by other experiments, as shown in Table 6. The HRS collaboration also searched[40] for the η signal using the decay $\eta \to \pi^+\pi^-\pi^0$ in a subsequent analysis. The low Q^2 of the η decay restricted the $\pi^+\pi^-$ invariant mass to be in a relatively narrow range,

$$280 < m_{\pi^+\pi^-} < 410 \quad \text{MeV/c}^2$$

$$m_{2\pi} \qquad\qquad m_\eta - m_\pi \quad .$$

The analysis took advantage of the excellent momentum resolution of the HRS without using the electromagnetic calorimeter information. No η enhancement was observed, resulting in an upper limit of 2.3% at the 95% confidence level. The TPC collaboration searched[30] indirectly for a second class current in the SU(3) related decay $\tau^- \to K^-K^0\nu_\tau$. The result is $B_{KK^0} < 0.26\%$ at the 95% confidence level. With the assumption of an approximate flavor SU(3) symmetry,[44] the TPC limit corresponds to $B_{\pi\eta} < 5.1 \times B_{KK^0} < 1.3\%$. From the results of all experiments, there is therefore no evidence for second class currents.

2.3.7 $2\pi\eta$ Decay

The decay $\tau^- \to \pi^-\eta\pi^0\nu_\tau$ is allowed in the standard model and is expected to proceed through the ρ (1600) resonance. Gilman used[45] the measured cross section for $e^+e^- \to \eta\pi^+\pi^-$ together with the CVC hypothesis to calculate the branching ratio and found $B_{\pi\eta\pi^0} = 0.15\%$. The HRS upper limit[40] of 2.3% at the 95% confidence level discussed in the previous section also applies here as the limit is insensitive to the number of π^0's accompanying the η. The CLEO collaboration used[35] the same technique and set an upper limit of 2.1%.

As discussed in Sec. 2.3.4, the MARK II collaboration, using the decay $\tau^- \to \pi^-\eta\pi^0\nu_\tau$ as an example of the multiple neutral meson decay modes, obtained $B_{\pi\eta\pi^0} = (4.2 \pm ^{0.7}_{1.2} \pm 1.6)\%$ from a fit of the observed photon multiplicity spectrum.

This is significantly larger than the theoretical prediction. This, however, is not a meaningful comparison as the decay is used as an example of the multiple neutral meson decay modes and the MARK II detector is insensitive to the η signal due to the limited mass resolution and the large combinatorial problem. Note that the results on $B_{\pi 2\pi^0}$ and $B_{\pi 3\pi^0}$ are relatively insensitive to the assumption.

2.3.8 $3\pi\eta$ Decay

There are no theoretical predictions on the branching ratios for the decays $\tau^- \rightarrow \pi^-\eta\pi^+\pi^-\nu_\tau$ and $\tau^- \rightarrow \pi^-\eta 2\pi^0\nu_\tau$. However, the two branching ratios are related by isospin invariance: $B_{\pi\eta 2\pi^0} \leq B_{3\pi\eta}$. The HRS collaboration used[40] the six 5-prong events with photons to set an upper limit on $B_{3\pi\eta}$. The experiment found that all the events had $\pi^+\pi^-$ combinations with invariant mass less than 410 MeV/c^2. Attributing all the events to the η decay yields the limit $B_{3\pi\eta} < 0.4\%$ at the 95% confidence level. From isospin invariance, therefore, $B_{\pi\eta 2\pi^0} < 0.4\%$.

As in the previous section, the limit on $B_{3\pi\eta}$ also applies for the case where the η is accompanied by π^0's. Note that the *experimental* limit on $B_{\pi\eta 2\pi^0}$ is 2.1% (from CLEO).

2.3.9 $\pi 2\eta$ Decay

There is also no theoretical prediction on the branching ratio for $\tau^- \rightarrow \pi^- 2\eta\nu_\tau$. However, there is an experimental limit[40] on the decay from the HRS collaboration. The experiment searched in the 5-prong sample for events that contained at least two separate $\pi^+\pi^-$ combinations with invariant mass less than 410 MeV/c^2 and found one event. This results in the upper limit of $B_{\pi 2\eta} < 0.6\%$ at the 95% confidence level. As before, this limit also applies if the η's are accompanied by π^0's.

2.4 Lepton Number Conservation in Tau Decays

Lepton number conservation is an experimentally observed phenomenon, it is not required in the standard model. The search for lepton number violating decays probes for effects in the energy scale well above the reach of present colliders. The observation of lepton number violating decays might indicate the existence of new particles or interactions. Limits[16] on lepton number violating decays for muon are in the range 10^{-9}–10^{-12}. Limits for τ decay are in the 10^{-3}–10^{-5} range, Table 7. No violation of τ lepton number conservation has been seen. More stringent limits would be useful.

2.5 Comparison of Inclusive and Exclusive Branching Ratios

The inclusive branching ratios for τ decays into final states containing one and three charged particles have been measured in many experiments, as shown in Table 8. The formal average values are $B_1 = (86.6 \pm 0.3)\%$ and $B_3 = (13.3 \pm 0.3)\%$. With most of the exclusive branching ratios for major decay modes measured with high precision, the sum of the exclusive branching ratios can be compared with the inclusive measurements to search[28] for unexpected decay modes. The exclusive measurements are summarized in Table 9b for the three-charged-particle final states. The sum of the two exclusive branching ratios is in fair agreement with the inclusive measurement. For the one-charged-particle final states, the sum of the measured exclusive branching ratios, Table 9a, is significantly less than the inclusive measurement. Thus, there may be a discrepancy between the measured inclusive one-charged-particle branching ratio and the sum of the measured exclusive branching ratios. Gilman and Rhie[28] had an important role in bringing the problem to the attention of elementary particle physicists. Truong[46] was one of the early commentators on this problem.

We discuss the discrepancy from the experimental viewpoint. We will note where measurements are confirmed or contradicted by deductions from weak decay theory and strong isospin conservation, but our emphasis is on the various experimental possibilities for explaining the discrepancy. These possibilities are:

(*i*) Some or all of the major decay branching ratios, $e^-\bar{\nu}_e\nu_\tau$, $\mu^-\bar{\nu}_\mu\nu_\tau$, $\pi^-\nu_\tau$, and $\rho^-\nu_\tau$, are each a few percent larger than presently measured.

(*ii*) The discrepancy lies in mismeasurements or misinterpretations of the one-charged-particle decay modes with multiple neutral mesons.

(*iii*) The inclusive branching ratio measurements are wrong.

(*iv*) An unknown particle or particles occur in some decays of the τ yielding modes that are detected in the inclusive branching ratio measurements, but are missed in the exclusive branching ratio measurements.

We first consider Item (*i*), the hypothesis that some or all of the branching ratios for

$$\begin{aligned} \tau^- &\rightarrow e^- + \bar{\nu}_e + \nu_\tau \\ \tau^- &\rightarrow \mu^- + \bar{\nu}_\mu + \nu_\tau \\ \tau^- &\rightarrow \pi^- + \nu_\tau \\ \tau^- &\rightarrow \rho^- + \nu_\tau \end{aligned} \qquad (2.5.1)$$

are larger than presently measured. This is a possible explanation if the measured branching ratios can be shifted up by two or three times the errors quoted in Table 9a. However, it becomes more difficult to accept this explanation when we consider the agreement between the predictions from weak decay theory and the branching ratio measurements. The agreement means that all the measurements must shift together by two or three times the errors if we accept the theory. At present, we do not understand why all the measurements might be systematically low.

The MARK II collaboration made a special effort[47] to explore the discrepancy by fitting all the one-charge-particle decay modes into known decay modes. They found that B_e, B_μ and B_ρ are larger than the formal averages (see

Table 10). The results can only be regarded as an indication due to the large errors in the measurements.

Another possibility, Item (*ii*), is that the discrepancy is connected with the one-charged-particle decay modes with multiple neutral mesons which give the signature

$$\tau^- \rightarrow \chi^- + n_\gamma \gamma + \nu_\tau \quad , \quad n_\gamma > 2 \quad . \tag{2.5.2}$$

Such a signature has always been explained by taking

$$\chi^- = \pi^- \tag{2.5.3}$$

and assuming the γ's come from modes such as

$$\begin{aligned} \tau^- &\rightarrow \pi^- + 2\pi^0 + \nu_\tau \\ \tau^- &\rightarrow \pi^- + 3\pi^0 + \nu_\tau \\ \tau^- &\rightarrow \pi^- + \pi^0 + \eta + \nu_\tau \quad . \end{aligned} \tag{2.5.4}$$

Two experiments have measured inclusive branching ratio with multiple neutral mesons in the final states. The TPC collaboration[48] reported the weighted sum branching ratio

$$B_{\pi 2\pi^0} + 1.6\ B_{\pi 3\pi^0} + 1.1\ B_{\pi\eta\pi^0} = (13.9 \pm 2.0 \pm 1.9)\% \quad . \tag{2.5.5}$$

The special effort[47] by the MARK II collaboration discussed earlier, ignoring the decay modes containing η's or more than $3\pi^0$'s, found

$$B_{\pi 2\pi^0} + B_{\pi 3\pi^0} = (12.0 \pm 1.4 \pm 2.5)\% \quad . \tag{2.5.6}$$

As discussed in Sec. 2.3.4, a further analysis[32] by the MARK II collaboration which allowed the decay mode $\tau^- \rightarrow \pi^- \eta \pi^0 \nu_\tau$ gives,

$$B_{\pi 2\pi^0} = (6.2 \pm 0.6 \pm 1.2)\%$$

$$B_{\pi 3\pi^0} = \left(0.0 \pm \begin{matrix}1.4\\0.0\end{matrix} \pm \begin{matrix}1.1\\0.0\end{matrix}\right)\% \tag{2.5.7}$$

$$B_{\pi\eta\pi^0} = \left(4.2 \pm \begin{matrix}0.7\\1.2\end{matrix} \pm 1.6\right)\% \quad .$$

Thus the sum is about the same, but the interpretation is different depending upon whether η-containing modes are allowed. This shows some of the difficulties in measuring the branching ratios of these multiple neutral meson modes.

There are really two problems connected with the signature in Eq. 2.5.2. First, does it represent a sum of decay modes with branching ratios large enough to take up the discrepancy? Second, if this signature represents a summed branching ratio as large as 10 or 12 or 14%, what modes comprise it? At present we cannot answer either question.

The third experimental possibility for explaining the discrepancy, Item (*iii*), is that the inclusive branching ratio measurements are wrong. Perhaps B_1 is closer to 80% rather than 86%, with B_3 about 20%. The formal average measurement (Table 8) disagrees with this hypothesis. However, there have been times in physics when a quantity was consistently measured slightly wrong because the "follow-the-crowd" effect led experimenters to seek and correct measurement errors in just one direction.

The fourth possibility, Item (*iv*), is the existence of an unknown decay mode

$$\begin{aligned} \tau^- &\rightarrow X^- + \nu_\tau + \text{neutral particle} \\ \text{neutral particle} &\rightarrow \gamma\text{'s and/or } \nu\text{'s} \quad . \end{aligned} \tag{2.5.8}$$

From the experimental view this is a subtle possibility because the decay mode must be detected in the measurement of B_1, it must not contribute to the decay modes in Eq. 2.5.1, and may or may not contribute to the general signature of

Eq. 2.5.2. Since the event selection criteria in the inclusive branching ratio measurement are usually different from the criteria used for exclusive measurements, perhaps a decay mode could be contrived that passes the former criteria but fails the latter. Related to the speculation of Eq. 2.5.8 is the hypothesis[49] that the τ sometimes couples to a massive neutrino, N_τ, with

$$\tau^- \rightarrow e^- + \bar{\nu}_e + N_\tau \quad , \quad \mu^- + \bar{\nu}_\mu + N_\tau \quad , \quad \pi^- + N_\tau \qquad (2.5.9)$$

a few percent of the time. A sufficiently massive N_τ might yield events which were counted in measuring B_1 but nowhere else. The testing of these sorts of speculations faces the difficulties of a small number of expected events and large backgrounds in existing data.

Summarizing, we do not know the source of the problem in the one-charged-particle decay modes. It is difficult to study the problem with present data because the discrepancy is just at the limit of the statistical and systematic errors of a single experiment. Combining results from different experiments reinforces the discrepancy, but then there is concern about the "follow-the-crowd" effect.

2.6 The Tau Neutrino

2.6.1 Neutrino Mass

The upper limit[50] for the τ neutrino mass it 70 MeV/c^2 at the 95% confidence level. The limit is below the muon mass and thus excludes the decay $\nu_\tau \rightarrow \mu^- e^+ \nu_e$. The limit is still relatively poor compared with the limits[16] for electron and muon neutrinos. Future e^+e^- experiments should have the sensitivity to about 10 MeV/c^2 in the ν_τ mass, before being limited by the uncertainty in the τ mass[16] of ± 3.2 MeV/c^2.

2.6.2 *Other Properties*

The study of the τ decay modes shows that the ν_τ spin is 1/2 and that it obeys conventional weak interaction theory. The latter involves only the charged weak current; we have no experimental knowledge of the neutral weak current behavior of ν_τ, that is, of the $\bar{\nu}_\tau - Z^0 - \nu_\tau$ vertex. Some information will be gained when the Z^0 width is sufficiently well-known to detect the

$$Z^0 \rightarrow \nu_\tau + \bar{\nu}_\tau \tag{2.6.10}$$

contributions.

2.6.3 *Interactions of the Tau Neutrino*

A way to examine the neutral weak current behavior of the ν_τ would be to study the inelastic reactions

$$\nu_\tau + \text{nucleon} \rightarrow \nu_\tau + \text{hadrons} \quad . \tag{2.6.11a}$$

Similarly

$$\nu_\tau + \text{nucleon} \rightarrow \tau^- + \text{hadrons} \tag{2.6.11b}$$

depends on the charged weak current interactions of the ν_τ.

Unfortunately, there is no known way to carry out the measurement in Eq. 2.6.11a because ν_τ beams would be contaminated with ν_e's and ν_μ's. The measurement in Eq. 2.6.11b can be done by producing ν_τ's through the interaction of a high intensity proton beam in a dense target, usually called a beam dump. The process in Eq. 2.6.11b could then be detected in a large mass neutrino detector with properties allowing the detection of the τ. It is an extensive and expensive experiment; it has been proposed,[51,52] but has not been done.

3. SEARCHES WITHIN THE STANDARD MODEL

3.1 INTRODUCTION

In the standard SU(2) × U(1) gauge theory[4] of electromagnetic and weak interactions, the known leptons are classified into left-handed doublets and right-handed singlets under the weak isospin group:

$$\text{left-handed doublets:} \quad \begin{pmatrix} \nu_e \\ e^- \end{pmatrix}_L \quad , \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix}_L \quad , \begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix}_L$$

$$\text{right-handed singlets:} \quad e^-_R \quad , \mu^-_R \quad , \tau^-_R \quad .$$

As the charged leptons form a sequence with increasing mass, this classification has become known as the sequential lepton model. At present, the masses of the neutral leptons (neutrinos) are consistent with being zero.

The standard model has no predictive power on the number of generations of leptons and quarks. The agreement between experiment and theory requires no additional generations. If a new heavy lepton was discovered, it would indicate the existence of a new generation, as was the case in the discovery of the τ.[2]

In this section we first review the searches for heavy charged leptons in the clean laboratory of the e^+e^- colliders and then in the more complex environment of the $\bar{p}p$ collider. We will not review the searches performed in fixed target experiments[1] as they have been superseded by collider experiments. We then discuss searches for heavy neutral leptons using e^+e^- colliders and fixed target experiments. Finally, we discuss indirect searches for neutral leptons by neutrino counting.

3.2 NEW CHARGED LEPTONS

3.2.1 Production and Decay

In the standard model, sequential charged leptons are pair produced in e^+e^- annihilation by virtual one-photon exchange, Fig. 1*a*. At e^+e^- storage rings with energies comparable to or higher than those at PEP and PETRA, the leptons can also be produced by virtual or real Z^0 exchange, Fig. 1*b*. The lowest order production cross section normalized to the μ-pair cross section is

$$R_{L^+L^-} = \frac{\sigma_{L^+L^-}}{\sigma_{\mu^+\mu^-}} = \beta \left[Q^2 \left(\frac{3-\beta^2}{2}\right) + 2Qg_v^e g_v^L \left(\frac{3-\beta^2}{2}\right) Re\,\chi(s) + \left(g_v^{e^2} + g_a^{e^2}\right)\left(g_v^{L^2}\left(\frac{3-\beta^2}{2}\right) + g_a^{L^2}\beta^2\right)|\chi(s)|^2 \right] , \tag{3.2.1}$$

where

$$\chi(s) = \frac{\sqrt{2}G_F}{4\pi\alpha} \cdot \frac{s m_Z^2}{s - m_Z^2 + i m_Z \Gamma_Z} .$$

Here α is the fine structure constant, G_F is the Fermi coupling constant, m_Z and Γ_Z are the mass and width of the Z^0 boson, $\sqrt{s}$ is the center-of-mass energy, Q is the charge of the lepton, $\beta^2 = 1 - 4m_L^2/s$ and m_L is the L mass. Also, g_v, g_a are the vector and axial-vector couplings of the L to the Z^0 boson. In the standard model, the assumption of lepton universality means that the coupling constants of all leptons are identical:

$$\begin{aligned} g_v^e = g_v^\mu = g_v^\tau = g_v^L &= -\frac{1}{2} + 2\sin^2\theta_W \\ g_a^e = g_a^\mu = g_a^\tau = g_a^L &= -\frac{1}{2} . \end{aligned} \tag{3.2.2}$$

The world average measurement[16] of the Weinberg angle (weak mixing angle) is $\sin^2\theta_W = 0.226 \pm 0.004$. Therefore, the vector coupling g_v is almost zero.

In Eq. 3.2.1, the term independent of G_F is the direct electromagnetic interaction contribution. The term linear in G_F is due to the interference between the electromagnetic and the weak interactions. The quadratic term is the direct contribution from the weak interaction. At PEP and PETRA energies, where most of the searches for heavy charged leptons were performed, the production is dominated by the electromagnetic current with small contribution from the electroweak interference. The weak contribution is negligible.

With the discovery[53] of the $W^\pm$ and Z^0 bosons at the $\bar{p}p$ collider at CERN, a charged lepton with mass less than the W can be produced via W decay, Fig. 1c,

$$W^- \to L^- + \nu_L \tag{3.2.3}$$

and a charged lepton with mass less than half the Z^0 mass can be produced in the Z^0 decay

$$Z^0 \to L^- + L^+ \quad . \tag{3.2.4}$$

The calculations for $W^\pm$ and Z^0 cross sections in $\bar{p}p$ collision involve quantum chromodynamics (QCD) and are complicated. We will not present the formulas here.[54]

The L^- decays into its associated neutrino ν_L plus SU(2) doublet fermions if $m_{\nu_L} < m_L$:

$$\begin{aligned} L^- &\to \nu_L + e^- + \bar{\nu}_e \\ L^- &\to \nu_L + \mu^- + \bar{\nu}_\mu \\ L^- &\to \nu_L + \tau^- + \bar{\nu}_\tau \\ L^- &\to \nu_L + d + \bar{u} \\ L^- &\to \nu_L + s + \bar{c} \quad . \end{aligned} \tag{3.2.5}$$

Figure 2 shows a rough method to estimate the branching ratios. Ignoring the Cabibbo–like suppressed decay modes, such as $s\bar{u}$, $b\bar{u}$, and $d\bar{c}$, and ignoring the mass threshold effects, the branching ratios are:

$$\begin{aligned} &B\left(L^- \to \nu_L e^- \bar{\nu}_e\right) \simeq B\left(L^- \to \nu_L \mu^- \bar{\nu}_\mu\right) \simeq B\left(L^- \to \nu_L \tau^- \bar{\nu}_L\right) \simeq 0.1 \\ &B\left(L^- \to \nu_L d\bar{u}\right) \simeq B\left(L^- \to \nu_L s\bar{c}\right) \simeq 0.35 \quad . \end{aligned} \tag{3.2.6}$$

These branching ratios assume the $L{-}\nu_L$ mass differences is above about 4 GeV/c^2. Since the quark decay modes are enhanced by the color factor of 3, the hadronic decays are the dominant decay modes.

3.2.2 Charged Lepton Searches Using e^+e^- Colliders

The e^+e^- collider provides a definitive way to search for a sequential charged lepton. The search is sensitive to leptons with masses up to near beam energy. The search technique normally used takes advantage of the fact that the neutrinos from the L^- decay carry away a large fraction of the L^- energy. This results in an event with a large acollinearity or acoplanarity angle. The lepton from the purely leptonic decay modes also provides a powerful tag in discriminating against the hadronic background. The τ background can be rejected by requiring one of the heavy charged leptons to decay into a jet of particles with four or more reconstructed charged tracks or with the jet mass greater than the τ mass.

The general search techniques can be summarized as follows:

(*i*) The e versus jet or μ versus jet method uses events with an electron or muon recoiling against a jet of particles. This technique selects the event with one L^- decaying leptonicly while the other decays hadronicly.

(*ii*) The l-prong versus jet method uses events with one charged particle recoiling against a jet of particles. This technique has higher detection efficiency than the last technique since particle identification is not required. It also accepts events where one of the L^- decays into a τ lepton, and the τ lepton decays into a one-charged-particle final state, which is a significant fraction of the τ decay. However, this topology has larger hadronic contamination, which can be rejected by requiring large missing transverse momentum or a large acollinearity angle.

(*iii*) The single jet method uses events with only one jet of particle. This technique is sensitive to charged leptons with masses close to the beam energy. The high mass reduces the boost to the decay products of the lepton and thus the decay products are likely to be emitted at large angle to the original lepton direction. Therefore, this technique selects events where the decay products from one of the leptons lie outside the acceptance of the detector.

(*iv*) The two jet method uses events with two jets, a large acollinearity angle, and large missing transverse momentum. This selects events where both leptons decay hadronicly.

Comprehensive searches[55–58] have been carried out at PETRA with null results. There are no new charged leptons with masses less than 22.5 GeV/c^2 at the 95% confidence level, Table 11. Searches close to the τ mass were conducted by measuring the τ production cross section; a method more sensitive than the techniques discussed earlier.

In the searches just discussed, the experimenters assumed that m_{ν_L} was zero or at least small compared to m_L. Indeed, the search results are not applicable if m_{ν_L} is close to m_L, as discussed in Sec. 3.3.

All the searches discussed are for the case where the charged lepton is heavier than its neutral partner. If the charged lepton is lighter and there is no mixing between the neutral lepton and the neutral leptons from other generations, then the charged lepton will be stable. The MARK J collaboration[59] set a lower limit on the mass of 14 GeV/c^2 at the 95% confidence level. The JADE collaboration[7] used the energy loss measurement in their jet chamber to search for such a stable lepton, and set a lower limit of 21.1 GeV/c^2 at the 95% confidence level.

3.2.3 *Charged Lepton Searches Using $\bar{p}p$ Colliders*

As discussed earlier, the discovery[58] of the $W^{\pm}$ and Z^0 bosons at the $\bar{p}p$ collider at CERN provided a new opportunity for heavy charged lepton search. The UA1 experiment used a sample of 56 candidate events with large missing transverse energy for the search.[60] The experiment looked for the lepton through the decay process:

$$\begin{aligned} W^- &\rightarrow L^- + \bar{\nu}_L \\ L^- &\rightarrow \nu_L + \text{ hadrons} \quad . \end{aligned} \tag{3.2.7}$$

Many of the candidate events were ascribed to the process[61]

$$\begin{aligned} W^- &\rightarrow \tau^- + \bar{\nu}_\tau \\ \tau^- &\rightarrow \nu_\tau + \text{ hadrons} \quad . \end{aligned} \tag{3.2.8}$$

The other major background was from

$$\begin{aligned} p + \bar{p} &\rightarrow Z^0 + \text{ hadron jets} \\ Z^0 &\rightarrow \nu_\ell + \bar{\nu}_\ell \quad , \quad \ell = e, \mu, \text{ or } \tau \quad . \end{aligned} \tag{3.2.9}$$

After taking into account these and other possible sources of background, no heavy lepton signal was observed. This resulted in the lower mass limit of $m_L >$ 41 GeV/c^2 at the 90% confidence level.

3.3 Close–Mass Lepton Pairs

Suppose an (L^-, ν_L) pair exists with $m_L > m_{\nu_L}$, with

$$\delta = m_L - m_{\nu_L} < \text{ several GeV/c}^2 \quad , \tag{3.2.10}$$

and with the decay modes of Eq. 3.2.5 allowed by δ. This is a close-mass lepton pair.[62] In searches using

$$e^+ + e^- \rightarrow L^+ + L^-$$

the maximum visible energy in the event is controlled by δ; the smaller δ, the smaller the maximum visible energy. (Visible energy is the sum of the energies carried by charged leptons, charged hadrons, and neutral hadrons which decay finally to photons.) All the searches summarized in Sec. 3.2.2 used a minimum visible energy criterion to reduce background from the two-virtual-photon processes

$$e^+ + e^- \rightarrow e^+ + e^- + e^+ + e^- \quad , \quad e^+ + e^- + \mu^+ + \mu^- \quad , \quad e^+ + e^- + \text{hadrons} \tag{3.2.11}$$

and would not have found an (L, ν_L) pair if δ were less than 3 or so GeV/c^2.[62]

A reanalysis has begun of MARK II collaboration data from PEP using the close-mass pair concept. No new leptons have been found[63] in the (m_L, δ) region shown in Fig. 3. It may be possible to extend the search to smaller values of δ. Incidently, when $\delta \lesssim m_\pi$, the lifetime of the L^- seems sufficiently long that it can be detected as an apparently stable lepton. The TPC collaboration is also carrying out a search for close-mass pairs.[64]

The analogous problems occurs in the heavy charged lepton search using $\bar{p}p$ colliders (Sec. 3.2.3) when δ is relatively small, there is insufficient unbalanced transverse momentum, to separate the sought signal from backgrounds. This has been explored in Ref. 65.

The general reason for searching for close-mass pairs is that there is no theoretical explanation of the specific masses of the known charged leptons or neutrinos, hence *a priori* a close-mass (L^-, ν_L) pair is as likely as a pair with $m_{\nu_L} \simeq 0$. One specific reason for such a search is a recent hypothesis[66] that the ν_L of close-mass pair could be a type of dark matter.

3.4 New Neutral Leptons

3.4.1 Production and Decay

In the standard model, neutral leptons can be pair produced in e^+e^- annihilation by Z^0 exchange, Fig. 4*a*. The pair production cross section normalized to the μ-pair cross section is

$$R_{L^0\overline{L^0}} = \frac{\sigma_{L^0\overline{L^0}}}{\sigma_{\mu^+\mu^-}} = \beta\left(g_v^{e^2} + g_a^{e^2}\right)\left[g_v^{L^2}\left(\frac{3-\beta^2}{2}\right) + g_a^{L^2}\beta^2\right]|\chi(s)|^2 \quad . \tag{3.4.1}$$

All the symbols are identical to those defined for Eq. 3.2.1, except that the vector and axial-vector couplings for the neutral lepton are different:

$$\begin{aligned} g_v^{\nu_e} = g_v^{\nu_\mu} = g_v^{\nu_\tau} = g_v^L = \frac{1}{2} \\ g_a^{\nu_e} = g_a^{\nu_\mu} = g_a^{\nu_\tau} = g_a^L = \frac{1}{2} \quad . \end{aligned} \tag{3.4.2}$$

In fact, Eq. 3.4.1 is identical to Eq. 3.2.1 with the lepton charge Q set to zero.

In the simplest version of the standard model, the neutral lepton (neutrino) is left-handed and massless. More generally,[67] going slightly beyond the standard model, it is possible to supply a right-handed singlet, heavy neutral lepton so that the left-handed neutral lepton can acquire mass. Then, just like the quark sector, the weak and mass eigenstates will not coincide. It is convenient to express this mixing in a Kobayashi–Maskawa type, unitary matrix U. For example, for the case of four generations, the electron neutrino is a mixture of the four mass eigenstates L_i^0:

$$\nu_e = \sum_{i=1}^{4} U_{ei} L_i^0 \quad . \tag{3.4.3}$$

This mixture of neutral leptons of different generations allows for the production of an electron-type neutral lepton in e^+e^- collision through the W boson exchange, as shown in Fig. 4*b*. The production cross section is[68,69]

$$\sigma\left(e^+e^- \to L^0\overline{\nu}_e\right) = |U_{eL}|^2 \frac{G_F^2 s}{6\pi}\left(1 - m_L^2/s\right)^2\left(1 + m_L^2/2s\right) \tag{3.4.4}$$

for $s \ll m_W^2$. Unlike pair production, $e^+e^- \to L^0\overline{L^0}$, where the mass of the lepton is limited by $E_{\rm cm}/2$, this production mechanism allows for the production of an L^0 with mass up to $E_{\rm cm}$.

With the mixing between neutral leptons of different generations, neutral leptons can also be produced in π and K decays

$$\begin{aligned} \pi^+ &\to e^+ + L^0 \\ \pi^+ &\to \mu^+ + L^0 \\ K^+ &\to e^+ + L^0 \\ K^+ &\to \mu^+ + L^0 \quad ; \end{aligned} \tag{3.4.5}$$

and in the leptonic or semi-leptonic decays of charm and bottom mesons, such as

$$\begin{aligned} D^+ &\to e^+ + L^0 + \text{ hadrons} \\ D^+ &\to \mu^+ + L^0 + \text{ hadrons} \quad . \end{aligned} \tag{3.4.6}$$

The L^0 mass is limited by the mass of the parent meson, therefore, the L^0 mass which can be attained is small compared with that attainable at present e^+e^- colliders. However, the mesons can be produced at high rates, allowing a sensitive search to very small mixing angles.

In the standard model, there is no lepton flavor changing neutral current and the neutral lepton decays through the emission of a W boson. Figure 5 shows a rough method to estimate the decay branching ratios into various SU(2) doublet fermions for the case where the neutral lepton is heavier than its charged partner. In fact, this method is identical to that used for the charged lepton decay discussed earlier, except with the interchange of the charged and neutral leptons at the W vertex. The branching ratios are estimated to be

$$\begin{aligned} &B\left(L^0 \to L^- e^+ \nu_e\right) \simeq B\left(L^0 \to L^- \mu^+ \nu_\mu\right) \simeq B\left(L^0 \to L^- \tau^+ \nu_\tau\right) \simeq 0.1 \\ &B\left(L^0 \to L^- \bar{d} u\right) \simeq B\left(L^0 \to L^- \bar{s} c\right) \simeq 0.35 \quad . \end{aligned} \tag{3.4.7}$$

As before, these branching ratios assume the L^0–L^- mass difference is above about 4 GeV/c^2. One characteristic of the decay is that there are at least two charged particles in the final state, with at least one of them being a lepton.

If the neutral lepton is lighter than its charged partner and there is no mixing between the neutral lepton and the neutral leptons from other generations, then the lepton is stable. On the other hand, if there is mixing, then the lepton L^0 decays through the emission of a W boson into a charged lepton ℓ, with the standard coupling strength multiplied by the mixing parameter $U_{\ell L}$. The lifetime of the neutral lepton depends on the mixing. For example, for an electron-type neutral lepton, the lifetime[23] is

$$\tau_L = \frac{1}{|U_{eL}|^2} \left(\frac{m_\mu}{m_L}\right)^5 B\left(L^0 \rightarrow e^+ e^- \nu_e\right) \tau_\mu \quad . \tag{3.4.8}$$

Here m_μ and τ_μ are the mass and lifetime of the muon and $B(L^0 \rightarrow e^+e^-\nu_e)$ is the electron branching ratio. Therefore, the neutral lepton could have a long lifetime if the mixing is small.

3.4.2 *Neutral Lepton Searches Using e^+e^- Colliders*

The e^+e^- collider allows definitive searches for heavy neutral lepton, as is the case for the charged lepton (Sec. 3.2.2). The mass attainable is $E_{\rm cm}/2$ for the production of a pair of heavy neutral leptons by Z^0 exchange

$$e^+ + e^- \rightarrow Z^0 \rightarrow L^0 + \overline{L^0} \quad ; \tag{3.4.9}$$

and up to $E_{\rm cm}$ for the production of a single heavy neutral lepton through W exchange

$$e^+ + e^- \rightarrow L^0 + \bar{\nu}_e \quad . \tag{3.4.10}$$

However, the production cross section was small[70] at PETRA and PEP energies. At PEP ($E_{\rm cm} = 29$ GeV), from Eq. 3.4.1

$$\sigma\left(e^+e^- \rightarrow L^0\overline{L^0}\right) = 0.33 \text{ pb} \tag{3.4.11}$$

through Z^0 exchange. From Eq. 3.4.4

$$\sigma\left(e^+e^- \to L^0\bar{\nu}_e\right) = 2.35 \times \left|U_{eL}\right|^2 \text{ pb} \qquad (3.4.12)$$

through W exchange with ν_e mixing. These are to be compared with the muon pair cross section of $\sigma_{\mu^+\mu^-} = 100$ pb. The maximum total integrated luminosity accumulated by a PEP detector was about 300 pb^{-1}. This corresponds to about 100 and 700 produced events for the two processes, assuming $\left|U_{eL}\right|^2 = 1$, in Eq. 3.4.12.

Several groups have searched for fourth generation heavy neutral lepton candidates at PEP and PETRA. Since no fourth generation heavy charged lepton was found at these colliders (Sec. 3.2.2), the neutral lepton must decay by mixing to be detectable. For the case where there is no mixing, searches used neutrino counting (Sec. 3.4.4).

To find short-lived heavy leptons, the HRS collaboration[71] searched for events with an isolated electron plus an additional charged particle in one hemisphere recoiling against at least two charged particles in the other hemisphere. Six candidates were found in the search. This is consistent with the background of 5.5 ± 2.2 events expected from conventional sources, hadronic events with charm meson decays or electron misidentification. The experiment is more sensitive to a low mass lepton, $m_L \lesssim 3$ GeV/c^2, where the limited phase space forces the virtual W boson to decay into e or μ:

$$L^0 \to e^-W^+ \to e^-\mu^+\nu_\mu$$

$$L^0 \to \mu^-W^+ \to \mu^-e^+\nu_e$$

$$L^0 \to \tau^-W^+ \to e^-\mu^+\bar{\nu}_e\nu_\mu\nu_\tau \quad .$$

Assuming full mixing with ν_e, ν_μ, or ν_τ, the experiment is at the limit of sensitivity to heavy lepton production, Fig. 6.

The MARK II collaboration[72] searched for a long-lived heavy neutral lepton using candidates that decayed between 0.2 and 10 cm from the e^+e^- interaction point. The candidate events were required to have at least two particles in one hemisphere recoiling against at least two particles in the other hemisphere. Three events were found, consistent with the estimate background of two events. Further examination of the events revealed that they were incompatible with the heavy neutral lepton decays. Since the lifetime, Eq. 3.4.8, is inversely proportional to the square of the mixing matrix elements, the search sweeps out a region in the $|U|^2$ versus m plane. The region excluded is shown as curve 11 in Figs. 7 and 8 for mixing with electron and muon neutrinos, respectively. Similar limits are obtained for mixing with the τ neutrino. The search was sensitive to heavy neutral leptons up to about 13 GeV/c^2 in mass.

The JADE collaboration[55] searched at PETRA for a short-lived, electron-type heavy neutral lepton produced through W exchange. Two different techniques were employed in the search: (i) For a neutral lepton with low mass ($\lesssim$ 6 GeV/c^2) where all the decay products are expected to be boosted forward in the laboratory, events with one jet of particles in one hemisphere recoiling against nothing in the opposite hemisphere were analyzed. (ii) For a neutral lepton with high mass ($\gtrsim$ 6 GeV/c^2) where some of the decay products could move backward in the laboratory due to limited boost, acoplanar two-jet events were studied. No evidence for a heavy neutral lepton was observed, resulting in a lower mass limit of 22.5 GeV/c^2 at the 95% confidence level for full mixing, $|U_{eL}|^2 = 1$.

The CELLO collaboration[73] searched for (i) the pair production of electron- or muon-type heavy neutral leptons through Z^0 exchange and (ii) for the production of a single electron-type heavy neutral lepton through W exchange. (i) The search for the pair production of heavy neutral leptons used events that contained four or more charged particles with at least two of them being leptons of the same type and opposite charge. No evidence for neutral leptons was observed. Assuming full mixing, electron- and muon-type heavy neutral leptons with masses in the range 3.1–18.0 and 3.2–17.4 GeV/c^2, respectively, were excluded at the 95% confidence level. For small mixing, the experiment searched for candidates with separated vertex. No candidate was found, resulting in the limit on mixing of curve 12 in Figs. 7 and 8. This search considerably extended the region excluded by the MARK II measurement.[72] (ii) The search for the production of a single electron-type heavy neutral lepton used events that contained an electron and a muon or an electron and a jet of four or more particles. No evidence for such leptons was found with masses between 0.6 and 34.6 GeV/c^2 at the 95% confidence level, assuming full mixing.

Gilman and Rhie[74] used the results from monojet searches at PEP to exclude certain values of mixing between the heavy neutral lepton and the electron neutrino. The monojet searches[75] set limits on the production of events with one jet of particles in one hemisphere recoiling against nothing in the other. Since these events can also originate in the production of a relatively short-lived heavy neutral lepton through W exchange, the limits can be used to set limits on mixing. The result is shown as curve 13 in Fig. 7. The JADE group[76] performed a similar analysis on their monojet result. The limit is shown as curve 14.

3.4.3 Neutral Lepton Searches in Fixed Target Experiments

A heavy neutral lepton can be produced in the leptonic or semi-leptonic decay of a meson if it mixes with the neutrino produced in the decay (Sec. 3.4.1). The mass of the new lepton is limited by the mass of the parent meson. In present fixed target experiments, the charmed D meson is the heaviest meson copiously produced. This limits these searches to masses less than about 1.8 GeV/c^2. The copious production of π, K and charm mesons allows very sensitive searches to very small mixing angles. In this section we will not review the results[77] from fixed target experiments that assume full mixing since they are now superseded by the e^+e^- experiments discussed in previous sections. Instead, we will concentrate on experiments that are sensitive to small mixing.

The most direct technique[78] is to study pion and kaon decays at rest and search for additional monochromatic peaks in the electron or muon momentum spectra from the leptonic decays $\pi \rightarrow eL^0, \pi \rightarrow \mu L^0, K \rightarrow eL^0$, or $K \rightarrow \mu L^0$, as appropriate. No evidence for secondary peaks has been observed. Upper limits[79–82] on the mixing parameters between a fourth generation heavy neutral lepton and the electron and muon neutrinos are shown as curves 1, 2 and 3 in Fig. 7 and curves 3 and 4 in Fig. 8. The limits on the mixing are of order 10^{-6} up to masses of about 400 MeV/c^2. Heavy neutral leptons can also be produced[83] when π or K mesons decay in flight and the leptons subsequently decay downstream. It is therefore possible to use the existing neutrino detectors or modification thereof to search for heavy neutral leptons produced in high intensity π or K beams. In these searches, the square of the mixing matrix element enters twice: Once in the production of the heavy neutral leptons when the π or K decays, and again when the leptons decay into ordinary leptons or leptons and quarks. Depending on the beams and the particular sensitivities of the detector, these two mixing matrix elements could be the same or different. Limits[84,85] using π or K beams are shown as curves 5 and 6 in Fig. 7 and curve 5 in Fig. 8. Sensitivities to mixing parameters below 10^{-8} have been reached in these experiments.

Charm meson decays considerably extend the mass range of the searches. In a typical charm decay experiment, a proton beam is dumped onto a high density target to absorb all the long-lived hadrons before they decay. This suppresses the neutrino flux from long-lived hadron decays and enhances the fraction of neutrinos produced in the charm decays. Limits obtained from the experiments[86–88] are shown as curves 7, 8 and 9 in Figs. 7 and 8 for mixing with electron and muon neutrinos, respectively.

For completeness, the limits[89] obtained from the assumptions of $e - \mu$ universality are included as curve 10 in Figs. 7 and 8.

3.4.4 *Neutrino Counting*

The searches for a heavy neutral lepton discussed in Sec. 3.4.2 required the lepton to be unstable and to decay inside the detector. If the neutral lepton is stable or long-lived, then it is not directly observable. Ma and Okada[90] proposed the detection of the radiated photon from the process

$$e^+ + e^- \to L^0 + \overline{L^0} + \gamma \tag{3.4.1}$$

to tag the events. Therefore a measurement of the single photon cross section provides a measurement of the neutral lepton cross section; hence, a measurement of the number of generations of sufficiently small mass neutral leptons. Since most of the radiative photons are soft, it is important to detect the low energy photons in order to maximize the search sensitivity. The dominant background in the search is the radiative process $e^+e^- \to e^+e^-\gamma$ with the e^+ and e^- in the final state scattered at small angles. The reduction of this background requires a detector with the ability to detect and veto electrons at a small angle, θ, to the beam line. For the veto angle θ, the minimum acceptable photon energy is $\sqrt{s}\theta$. Therefore a very small veto angle allows the acceptance of very low energy photon and hence a higher sensitivity measurement. Several experiments[91–93] at PEP and PETRA have carried out this measurement (Table 12); the ASP experiment[93] used a detector designed especially for the search. The combined limit[94] on the number of generations of neutral leptons is 4.8 at the 90% confidence level. These limits are comparable with indirect measurements[95,96] of the Z^0 width from $\bar{p}p$ collider.

4. NEW LEPTON SEARCHES BEYOND THE STANDARD MODEL

4.1 INTRODUCTION

In this section we discuss the experimental limits on the existence of hypothetical leptons whose properties or interactions cannot be encompassed within the standard model. All confirmed searches have been null; their limits can be used to restrict new models or theories. There are a few unconfirmed measurements which may be explained by the existence of a new lepton or by the unconventional behavior of a known lepton, we note most of these proposed anomalies.

Present experimental limits on charged heavy leptons are well understood because of the simplicity of the production process (Fig. 1*a*)

$$e^+ + e^- \rightarrow \gamma \rightarrow L^+ + L^- \quad . \qquad (4.1.1)$$

The limits on charged lepton and neutral lepton combinations are more obscure, hence we outline the possibilities in Sec. 4.2. Then we go beyond the standard model by allowing lepton decays through a neutral, weak current (Sec. 4.3). Next, electromagnetic decays of charged leptons are allowed (Sec. 4.4) introducing the old idea of electromagnetically excited leptons. Limits on the existence of supersymmetric leptons are surveyed in Sec. 4.5. Broadening the discussion in Sec. 4.6, we consider some studies of high energy, multibody, purely leptonic processes which would have disclosed the existence of new leptons or of abnormal lepton behavior. Finally, in Sec. 4.7 we consider a miscellany of searches and speculations: leptons with unexpected charge or spin, very heavy leptons, and leptons connected with the strong interaction.

4.2 Lepton Classification

We classify the simpler models for leptons into nine cases:

(i) Consider an (L^0, L^-) pair with the latter heavier and no generation mixing

$$(L^0, L^-) \quad , \quad m_- > m_0 \quad . \tag{4.2.1}$$

Since there are no new L^- with $m_- < 22.5$ GeV/c^2 (Sec. 3.2.2), then subject to the close-mass pair discussion restrictions in Sec. 3.3, there are no L^0 with $m_0 \lesssim 22.5$ GeV/c^2. The $m_- > 41$ GeV/ c^2 limit of Sec. 3.2.3 is restricted by the discussion in Ref. 65.

(ii) Consider an (L^0, L^-) pair with the former heavier and no generation mixing

$$(L^0, L^-) \quad , \quad m_0 > m_- \tag{4.2.2}$$

Then the L^- is stable, and from Sec. 3.2.2, $m_0 \gtrsim 21.1$ GeV/c^2.

(iii) Consider a pair of neutral leptons

$$(L^0, L^{0\prime}) \quad , \quad m_0 > m_{0'} \tag{4.2.3}$$

with no generation mixing and the neutral current, weak decay

$$L^0 \rightarrow L^{0\prime} + f + \bar{f}' \tag{4.2.4}$$

allowed. Here, $f, \bar{f}'$ represent a lepton, antilepton or quark, antiquark. This case is discussed in the next section.

(iv) Consider a single neutral lepton L^0 without generation mixing. If sufficiently light the limit on its existence is contained in the discussion on the number of neutrino types in Sec. 3.4.4.

(v) Now allowing generation mixing consider an (L^0, L^-) pair with $m_- > m_0$ or $m_- < m_0$. With either choice some of the limits discussed in Sec. 3.4 apply, with the latter choice, Case (ii) above applies also.

(vi) Or allow generation mixing with a single neutral lepton L^0, once again some of the limits given in Sec. 3.4 apply.[9]

(vii) Turning to a pair of new charged leptons

$$(L^-, L^{-\prime}) \quad , \quad m_- > m'_- \tag{4.2.5}$$

one can consider the unconventional neutral current decay

$$L^- \to L^{-\prime} + f + \bar{f} \tag{4.2.6}$$

or an electromagnetic decay

$$L^- \to L^{-\prime} + \gamma \quad . \tag{4.2.7}$$

(viii) Allowing generation mixing one can replace $L^{-\prime}$ by $\ell = e$, μ or τ in Eqs. 4.2.6 and 4.2.7.

(ix) The analogy to Case (iv) is a single stable charged lepton, as discussed in Sec. 3.2.2.

In the next sections we discuss some of these cases not allowed in the standard model.

4.3 DECAYS THROUGH A NEUTRAL WEAK CURRENT

Neutral leptons from the pair (L^0, $\overline{L^0}'$) can be produced (Fig. 4a) via

$$e^+ + e^- \rightarrow Z^0 \rightarrow L^0 + \overline{L^0} \quad , \tag{4.3.1a}$$

$$e^+ + e^- \rightarrow Z^0 \rightarrow L^0 + \overline{L^0}' \quad , \tag{4.3.1b}$$

$$e^+ + e^- \rightarrow Z^0 \rightarrow L^{0\prime} + \overline{L^0}' \quad . \tag{4.3.1c}$$

In this discussion we assume no generation mixing. Search signatures for the reactions in Eqs. 4.3.1a and 4.3.1b are provided by the unconventional decay in Eq. 4.2.4.

Some of these search signatures are topologically identical to the signatures used for neutral lepton searches assuming generation mixing as discussed in Sec. 3.4. Thus for $L^0\overline{L^0}$ pair production (Eq. 4.3.1a) long-lived L^0's could give one or two separated vertexes, the signature used in the monojet searches. The translation of the limits discussed in that section to the case here depends on the particular (L^0, $L^{0\prime}$) model and is left to the reader.

The reactions in Eqs. 4.3.1a and 4.3.1b also have special small multiplicity signatures. As was used in Ref. 97, the two-charged-particle decay modes

$$L^0 \rightarrow L^{0\prime} + e^+ + e^- \quad , \quad L^{0\prime} + \mu^+ + \mu^- \tag{4.3.2a}$$

and 0-charged particle decay modes

$$L^0 \rightarrow L^{0\prime} + \nu_\ell + \bar{\nu}_\ell \quad , \quad \ell = e, \mu, \tau \tag{4.3.2b}$$

give distinctive events with two or four leptons and missing energy. Figure 6 gives an example of a limit[97] that follows from those assumptions.

The decay of a charged lepton through a neutral weak current was considered in the 1970's for various models.[68,98–100] Often a so-called ortholepton[98] was assumed to decay via

$$L^- \to \ell^- + \nu' + \bar{\nu}' \quad , \quad \ell = e, \mu, \tau \tag{4.3.4}$$

because the electromagnetic decay

$$L^- \to \ell^- + \gamma \tag{4.3.5}$$

was suppressed. The null results from e^+e^- searches for unstable and stable charged heavy leptons (Sec. 3) also apply here. With changes in particle theory, there is no interest in charged leptons with neutral weak current decays. Incidently, so-called paraleptons[98] with doubly charged weak current decays

$$L^- \to \ell^+ + \text{(hadrons)}^{--} \tag{4.3.6}$$

were also considered, the same remark applies.

4.4 Excited Charged Leptons

The concept of an excited charged lepton, ℓ^*, with the electromagnetic decay

$$\ell^{*-} \to \ell^- + \gamma \quad , \quad \ell = e, \mu, \tau \tag{4.4.1}$$

is old,[101] but current interest in composite models[102] have renewed interest in the concept. If the ℓ consists of two, three or more elementary particles, the ℓ^* could be an excited state of these particles. In the decay process (Eq. 4.4.1) and in some production reactions, the $\ell^* - \gamma - \ell$ vertex contains the new and unknown physics. The vertex function has an unknown complex strength λe where λ is dimensionless and e is the electron charge. Usually limits are given in terms of λ/m^* where m^* is the assumed mass of the ℓ^*. There is *no* evidence for excited leptons.

Three general methods have been used to search for excited leptons:

(i) Lepton-hadron scattering

$$\ell + \text{ nucleon } \rightarrow \ell^* + \text{hadrons} \quad ; \quad \ell = e, \mu$$
$$\ell^* \rightarrow \ell + \gamma \tag{4.4.2}$$

is the oldest search method.[1,10,11] The fixed target experiments[1,10,11] are obsolete but this method will be very sensitive for e^* searches when the HERA electron-proton collider operates (Sec. 5.3).

(ii) The electron-positron annihilation processes can produce excited leptons in two ways (Figs. 9*a* and 9*b*)

$$e^+ + e^- \rightarrow \ell^{*+} + \ell^{*-} \rightarrow \ell^+ + \ell^- + \gamma + \gamma \tag{4.4.3a}$$
$$e^+ + e^- \rightarrow \ell^{*+} + \ell^- \rightarrow \ell^+ + \ell^- + \gamma \quad . \tag{4.4.3b}$$

Here, ℓ means e, μ or τ. The search method using $\ell^{*+}\ell^{*-}$ production (Eq. 4.4.3*a*) does not depend on λ, therefore assuming the ℓ^* is a point-like particle, a direct lower limit can be set on m^*. Sometimes a form factor[103,104] $|F_{\ell^*}|^2$ is associated with the cross section for this reaction. The sensitivity of the $\ell^{*+}\ell^-$ method (Eq. 4.3.3*b*) depends on λ/m^* and the limit must be given in terms of a maximum value of λ/m^* for each m^*. Figures 10 and 11 are recent examples. Of course the advantage of this method is that the upper limit on m^* is about E_{cm} rather than $E_{\text{cm}}/2$ as in the $\ell^{*+}\ell^{*-}$ method.

The reaction

$$e^+ + e^- \rightarrow \gamma + \gamma \tag{4.4.4}$$

which can occur through e^* exchange (Fig. 9*c*) as well as through e exchange has also been used to search for the e^*.

(iii) The decays of the $W^{\pm}$ or Z° produced in $\bar{p}p$ or pp collisions can also be used to search for excited leptons via

$$W^{-} \to \ell^{*-} + \bar{\nu}_{\ell} \to \ell^{-} + \gamma + \bar{\nu}_{\ell} \qquad (4.4.5a)$$

$$Z^{\circ} \to \ell^{*-} + \ell^{+} \to \ell^{-} + \gamma + \ell^{+} \quad . \qquad (4.4.5b)$$

The data from the UA2 experiment[105] at CERN has been used to search for the e^{*}, the limits are given in Fig. 12. Again there is a dependence on an unknown coupling strength parameter, λ_{mag} or $\lambda_{\text{V-A}}$, but in contrast to the $e^{+}e^{-}$ search method described in (*ii*), it is likely that these λ's are close to 1. For the value 1, the lower limit[105] on m_{e*} is 75 GeV/c^2 at the 90% confidence level.

4.5 Leptons and the Supersymmetry Concept

The supersymmetry concept requires for a lepton ℓ^{-}, the existence of a spin 0 partner, the slepton $\tilde{\ell}^{-}$. The search methods, in part analagous to those used of excited leptons, are diagrammed in Fig. 13. The general production method (Fig. 13*a*) is

$$e^{+} + e^{-} \to \gamma \to \tilde{\ell}^{+} + \tilde{\ell}^{-} \quad , \quad \tilde{\ell} = \tilde{e}, \tilde{\mu}, \tilde{\tau} \quad . \qquad (4.5.1)$$

The $\tilde{e}$ can also be pair produced through a $\tilde{\gamma}$ exchange reaction (Fig. 13*b*). Here the spin 1/2 photino, $\tilde{\gamma}$, is the supersymmetric partner of the photon. Single $\tilde{e}$ production

$$e^{+} + e^{-} \to \tilde{e}^{+} + \tilde{\gamma} + e^{-} \qquad (4.5.2)$$

can occur through diagrams such as Fig. 13*c*. The respective upper limits on the mass search range are

$$m_{\tilde{\ell}} < E_{\text{cm}}/2 \quad \text{and} \quad m_{\tilde{e}} < E_{\text{cm}} - m_{\tilde{\gamma}} \quad .$$

With the $m_{\tilde{e}}$ and $m_{\tilde{\gamma}}$ assumption discussed next, the $m_{\tilde{e}}$ search range can be extended upward using the reaction (Fig. 13*d*)

$$e^+ + e^- \rightarrow \gamma + \tilde{\gamma} + \tilde{\gamma} \quad . \tag{4.5.3}$$

The cross section depends upon the $m_{\tilde{e}}$ mass in the $\tilde{e}$ propagator and upon $m_{\tilde{\gamma}}$.

In using these methods it is conventional to assume (i)

$$m_{\tilde{\ell}} > m_{\tilde{\gamma}} \tag{4.5.4}$$

so that the decay

$$\tilde{\ell}^- \rightarrow \ell^- + \tilde{\gamma} \tag{4.5.5}$$

always occurs; (ii) the $\tilde{\gamma}$ is stable; and (iii) the $\tilde{\gamma}$ is weakly interacting and not detected. There is *no* evidence for supersymmetric particles.[7]

4.6 High Energy, Multibody, Purely Leptonic Processes

The purely leptonic processes

$$\begin{aligned} e^+ + e^- &\rightarrow e^+ + e^- + e^+ + e^- \\ e^+ + e^- &\rightarrow e^+ + e^- + \mu^+ + \mu^- \end{aligned} \tag{4.6.1}$$

have been studied in their own right and as a background to new particle searches. The background problem is serious when just two of the particles are observed in a conventional detector, the other two particles having been emitted along the beam line. At PETRA and PEP energies the processes in Eq. 4.6.1 can be completely calculated using quantum electrodynamics, but the calculation is tedious and Monte Carlo methods must be used to predict cross sections and kinematic distributions. Recently, Berends, Daverveldt and Kleiss[106] made a complete calculation method available.

When all four particles are observed in a conventional detector in the PETRA and PEP energy range, the observed cross section is a fraction of a pb. Hence the two reported measurements have a few tens of events. One experiment, Bartel et al.,[107] using the JADE detector found agreement with the theoretical predictions in many kinematic distributions. The other experiment, Behrend et al.,[108] used the CELLO detector and found an excess of events with large pair masses. At present there are no other published experiments in this area.

4.7 MISCELLANEOUS LEPTON TYPES AND LIMITS

We conclude Sec. 4 with a miscellany of limits on unconventional types of leptons: leptons with connection to the strong interaction, leptons with fractional electric charge, and extremely massive leptons.

4.7.1 *Leptons Connected to the Strong Interaction*

There have been proposals for leptons connected in various ways to the strong interaction, such as leptoquarks[109,110] or colored leptons.[111,112] Leptoquarks would decay into a lepton and a quark

$$L \rightarrow \ell + q \quad ; \tag{4.7.1}$$

colored leptons into a lepton and a gluon

$$L \rightarrow \ell + g \quad . \tag{4.7.2}$$

There is *no* evidence for such interesting objects. The experiment of Bartel et al.[113] is an example of the search methods.

4.7.2 Leptons with Fractional Electric Charge

Two kinds of searches for the fractionally charged quarks of conventional theory also apply to fractionally charged particles that do not participate in the strong interaction—leptons.

(i) Some quark searches in e^+e^- colliders have simply looked for a pair of fractionally charged stable particles

$$e^+e^- \to \chi^{+c} + \chi^{-c} \quad , \quad c \neq 1 \quad ; \tag{4.7.3}$$

and have not required the produced particle to interact. Such a search is particularly suitable for fractionally charged leptons because it is reasonable to assume the point-particle production cross section. All searches gave null results.[7]

(ii) Quark searches in macroscopic matter have usually not required the particle to participate in the strong interaction. Such searches could have found fractionally charged leptons, if the lepton-atom chemistry allows the lepton to be stored in ordinary matter. All but one[114] of the recent searches have had null results.[115–118] The positive result of Ref. 114 remains difficult to understand, remains unconfirmed, and remains not contradicted by any other results using the same experimental method. However, the null results of Refs. 115-118, particularly the superior sensitivity of Ref. 115, have cast doubt on the positive result of Ref. 114.

In thinking about the significance of these primarily quark searches for leptons, remember that the emphasis was on charges of order 1 with special emphasis on 1/3, 2/3 and 4/3 charges. It is easy to design stable, fractionally charged leptons that would evade these searches and all other searches for stable charged leptons. Simply set the charge to be a sufficiently small fraction of the unit charge, say 0.1 or 0.01 or 0.001.

4.7.3 *Extremely Massive Leptons*

Consider a stable massive lepton with unit charge. If the charge were $+1$, it would behave chemically and electrically in matter as a heavy isotope of hydrogen. If the charge were -1 it could electrically bind to a nucleus of charge Z, the system behaving as a massive nucleus of charge $Z-1$. A variety of methods[110–121] have been used to search for anomalously heavy isotopes of light elements such as H, Li, C, O and N. Searches have extended from less than 10 amu to 10^5 amu with sensitivities in the range of 10^{-10} to 10^{-29} concentration of anomalously heavy isotope to normal isotope. Reference 121 gives a useful summary figure. All searches gave null results.

If one has a model for massive stable lepton production in the early universe, these null searches can be used to exclude the existence of stable charged leptons in some mass ranges.

5. FUTURE SEARCHES FOR NEW LEPTONS

The history of the discovery of the known leptons consists of unconnected experimental techniques: the e found in cathode ray tube research, the μ found in cosmic rays, the ν_e deduced from beta decay spectra and later found through a reactor experiment, the ν_μ separated from the ν_e in an accelerator neutrino experiment, the τ found in an e^+e^- collider experiment, and the ν_τ deduced from τ decay modes. Except for the deduction of a neutrino from the decay of the charged partner, no technique has been used successfully twice. Therefore, we shall not describe a program for searches for new leptons using new particle colliders or new search techniques, rather we shall summarize the type of searches which can be conducted. But first we note the dramatic change that occurs in lepton decay processes when $m_L > m_W$.

5.1 Leptons with Masses Larger than the W Mass

Consider a lepton pair (L^-, L^0) with

$$m_- - m_0 > m_W \quad . \tag{5.1.1}$$

In conventional weak interaction theory the dominant decay mode is

$$\begin{aligned} &L^- \to L^0 + W^-_{\text{real}} \\ &W^-_{\text{real}} \to \ell^- + \bar{\nu}_\ell \text{ or hadrons} \quad , \quad \ell = e, \mu, \tau \quad . \end{aligned} \tag{5.1.2}$$

Similarly, if

$$m_0 - m_- > m_W \tag{5.1.3}$$

the dominant decay is

$$L^0 \to L^- + W^+_{\text{real}} \quad . \tag{5.1.4}$$

The $L^- \to L^0 + W^-$ decay width is[122]

$$\Gamma\left(L^- \to L^0 + W^-\right) = \frac{G_F m_-^3}{8\pi\sqrt{2}}\left(1 - \frac{m_W^2}{m_-^2}\right)^2\left(1 + \frac{2m_W^2}{m_-^2}\right) \tag{5.1.5}$$

ignoring m_0. An analogous equation applies to $L^0 \to L^- + W^+$.

Incidently, the conventional theory of the weak interaction radiative corrections to the masses of the W and Z^0 restricts the L^-, L^0 mass different to[123,124]

$$\left[m_-^2 - m_0^2\right]^{1/2} < 600 \text{ GeV/c}^2 \tag{5.1.6}$$

More speculative as in Sec. 4 $(L^0, L^{0'})$ pairs might exist with the unconventional decay

$$L^0 \to L^{0'} + Z^0_{\text{real}} \quad . \tag{5.1.7}$$

5.2 Future Searches Using e^+e^- Colliders

5.2.1 *Searches Below the Z^0*

The new e^+e^- collider, TRISTAN, enables the searches described in Sec. 3 to be extended to total energies in the 60 to 70 GeV range. The searches at PETRA were at a maximum total energy of about 44 GeV.

5.2.2 *Searches At the Z^0*

The process[125,126]

$$e^+e^- \to Z^0_{\text{real}} \to L + \overline{L} \quad , \quad L = L^- \text{ or } L^0 \tag{5.2.1}$$

where $E_{\text{cm}} \approx m_Z$ offers three great advantages for new lepton searches:

(*i*) The cross section has a strong maximum with

$$\sigma_{Z^0\text{peak}}(e^+e^- \to L^+L^-) = 1100 \text{ pb}$$
$$\sigma_{Z^0\text{peak}}(e^+e^- \to L^0\overline{L^0}) = 2200 \text{ pb} \quad . \tag{5.2.2}$$

The radiative correction to the Z^0 resonance is included. Since the charged lepton accounts for only a small fraction of the total Z^0 width, the increase in the hadronic cross section is much larger than that for the charged lepton; this poses a special problem for the charged lepton search.

(*ii*) The presence of a new L can be detected indirectly through the measurement of the Z^0 width, Γ_Z. For a new lepton, with the conventional weak current couplings, the extra width is

$$\Delta\Gamma_Z(L^-) \approx 80 \text{ MeV/c}^2$$
$$\Delta\Gamma_Z(L^0) \approx 160 \text{ MeV/c}^2 \tag{5.2.3}$$

where $m_L \ll m_Z/2$.

(*iii*) A related method for indirect detection of stable L^0's uses the reaction[90,126,127]

$$e^+e^- \to Z^0 + \gamma \to L^0 + \overline{L^0} + \gamma \tag{5.2.4}$$

with E_{cm} a few GeV larger than m_Z.

These methods will lead to definitive L^- and L^0 searches for

$$m_L \lesssim (m_Z/2 - 5) \text{ GeV/c}^2 \tag{5.2.5}$$

at the SLAC Linear Collider (SLC) and LEP. This includes a definitive measurement of the total number of different neutrino types with masses obeying Eq. 5.2.5.

Analogous methods can be used for the unconventional lepton types discussed in Sec. 4. For example, an $(L^0, L^{0'})$ pair can be produced in

$$e^+e^- \rightarrow Z^0_{\text{real}} \rightarrow L^0 + \overline{L^0}' \tag{5.2.6}$$

provided

$$m_0 + m_{0'} \lesssim (m_Z - 10) \ \text{GeV/c}^2 \quad . \tag{5.2.7}$$

Close-mass pairs with both m_- and m_0 obeying Eq. 5.2.5 will be much easier to detect than at present energies (Sec. 3.3). The background cross sections (Eq. 3.2.11) will be smaller relative to the production cross section (Eq. 5.2.1) and both the L^- and the L^0 will contribute to Γ_Z.

5.2.3 Searches Above the Z^0

The LEP e^+e^- circular collider is designed to generate at total energies up to about 200 GeV.[125] The possibility exists to go to yet higher energies using the linear collider principle,[128,129] perhaps to several TeV or more. As E_{cm} rises to 200 GeV and above several new factors affect lepton searches.

(*i*) As discussed in Sec. 5.1, new leptons obeying conventional weak interaction theory decay via

$$\begin{aligned} L^- &\rightarrow L^0 + W^-_{\text{real}} \\ L^0 &\rightarrow L^- + W^+_{\text{real}} \quad . \end{aligned} \tag{5.2.8}$$

Hence, the signatures are different from those used to detect new leptons at energies below or at the Z^0 mass.

(*ii*) According to conventional theory lepton production will occur through the processes

$$e^+e^- \to \gamma_{\text{virtual}} \to L^+ + L^-$$

$$e^+e^- \to Z^0_{\text{virtual}} \to L + \overline{L} \quad , \quad L = L^-, L^0 \tag{5.2.9}$$

and their interference. The cross section is

$$\sigma(e^+e^- \to L\overline{L}) = \frac{0.087R}{[E_{\text{cm}}(\text{TeV})]^2} \text{ pb} \tag{5.2.10}$$

ignoring the high energy radiative tail of the Z^0. Once $E_{\text{cm}} > 0.2$ TeV the major energy dependence is given by E_{cm}^{-2} as shown in Table 13. Lepton production through the γ is stronger than production through the Z^0 when E_{cm} is beyond the Z^0 peak. Large luminosities are required for a definitive search. For example, at $E_{\text{cm}} = 1$ TeV

$$\sigma(e^+e^- \to L^+L^-) \approx 10^{-37}\text{cm}^2 \quad , \tag{5.2.11}$$

and to produce N events in a 10^7 second year requires an average luminosity of

$$\mathcal{L} = N \times 10^{30}\text{cm}^{-2}\text{s}^{-1} \quad . \tag{5.2.12}$$

5.3 FUTURE SEARCHES USING *ep* COLLIDERS

The HERA *ep* collider[130] provides a powerful way to search for leptons[131] with the lepton number of the e or which mix with ν_e. The reaction (Fig. 14)

$$e^- + p \to E^- + \text{ hadrons} \tag{5.3.1}$$

can occur through γ or Z^0 exchange. The reaction

$$e^- + p \to E^0 + \text{ hadrons} \tag{5.3.2}$$

can occur through W exchange. Here E^- and E^0 are leptons. One example[131] for the E^- is an excited electron e^*. Another example[131] for both the E^- and the E^0 is provided by composite models for leptons.

There is a more general mechanism for new lepton production through a virtual γ, Z^0, or W, for example,

$$\begin{aligned} &e^- + p \rightarrow e^- + \text{ hadrons } + Z^0_{\text{virtual}} \\ &Z^0_{\text{virtual}} \rightarrow L + \overline{L} \quad . \end{aligned} \tag{5.3.3}$$

But the cross sections for such reactions are relatively small and it would be difficult to find the lepton signal amid the very much larger cross section for pure hadron production

$$e^- + p \rightarrow e^- + \text{ hadrons} \quad . \tag{5.3.4}$$

High energy ep collisions can produce leptoquarks (Sec. 4.7) if they are electron related[131] via

$$e^- + q \rightarrow L$$

where q is a u or d quark in the reaction.

5.4 FUTURE SEARCHES USING $\bar{p}p$ AND pp COLLIDERS

5.4.1 Searches Using W Decays

In Sec. 3.2.3 we described a search at the CERN $\bar{p}p$ collider using

$$\begin{aligned} &\bar{p} + p \rightarrow W^\pm + \text{ hadrons} \\ &W^- \rightarrow L^- + L^0 \quad ; \end{aligned} \tag{5.4.1}$$

with the limit $m_- > 41$ GeV/c^2 for $m_0 \approx 0$. The m_- and m_0 ranges of such a search can be increased as the rate of W production increases at the CERN and Tevatron $\bar{p}p$ colliders; background problems rather than m_W may limit that mass range. The analogous process

$$\bar{p} + p \to Z^0 + \text{ hadrons}$$
$$Z^0 \to L + \overline{L} \tag{5.4.2}$$

could be used as a search method, however, the searches using the Z^0 produced in e^+e^- annihilation (Sec. 5.2) are more comprehensive and definitive.

5.4.2 *Searches Using the Drell–Yan Mechanism*

Figure 15*a* shows the process[132]

$$\bar{p} + p \text{ or } p + p \to q + \bar{q}' + \text{ hadrons}$$
$$\text{or} \tag{5.4.3a}$$
$$\bar{p} + p \text{ or } p + p \to q + \bar{q} + \text{ hadrons}$$

with

$$q + \bar{q}' \to W^-_{\text{virtual}} \to L^- + \overline{L^0} \tag{5.4.3b}$$

or

$$q + \bar{q} \to Z^0_{\text{virtual}} \to L + \overline{L} \quad , \quad L = L^- \text{ or } L^0 \quad . \tag{5.4.3c}$$

The subprocesses in Eqs. 5.4.3*b* and 5.4.3*c* have the same size cross sections as the e^+e^- annihilation cross section (Eq. 5.2.9) when

$$E_{\text{cm}}(q\bar{q}') = E_{\text{cm}}(e^+e^-) \quad . \tag{5.4.4}$$

There is, however, a small probability of obtaining an $E_{\text{cm}}(q\bar{q}')$ which is a substantial fraction of $E_{\text{cm}}(\bar{p}p)$ or $E_{\text{cm}}(pp)$. Consider the reaction in Eq. 5.4.3*c* which requires

$$E_{\text{cm}}(q\bar{q}') > 2m_L \quad .$$

Then

$$\sigma(\bar{p}p \text{ or } pp \to L\overline{L} + \text{ hadrons}) \ll \sigma(e^+e^- \to L\overline{L}) \qquad (5.4.5)$$

where Eq. 5.4.4 applies.

The effects of Eq. 5.4.5 and the much larger background in hadron colliders make $\bar{p}p$ or pp searches using the Drell–Yan process much more difficult than searches using e^+e^- colliders. Of course, with very high energy, high luminosity pp colliders, experiments have the possibility of exploring a lepton mass range beyond the reach of the highest energy e^+e^- collider under construction—LEP. The proposed Superconducting Super Collider (SSC) would have a total energy of 40 TeV. The Large Hadron Collider (LHC) being discussed for CERN would have a total energy up to 18 TeV.

At very high energies there are two other recently proposed lepton-production processes which are calculated to have large cross sections for some lepton mass ranges. These are discussed in the next section.

5.4.3 *Searches Using Gauge Boson Fusion and Gluon Fusion*

Figure 15*b* shows lepton production via gauge boson fusion[133]

$$p + p \to W^-_{\text{virtual}} + Z^0_{\text{virtual}} + \text{ hadrons} \qquad (5.4.6a)$$

$$W^-_{\text{virtual}} + Z^0_{\text{virtual}} \to L^- + L^0 \quad . \qquad (5.4.6b)$$

An analogous subprocess is

$$W^+_{\text{virtual}} + W^-_{\text{virtual}} \to L + \overline{L} \quad , \quad L = L^-, L^0 \quad . \qquad (5.4.6c)$$

This process can give a larger cross section than the Drell–Yan process when the lepton masses are large.

The gluon fusion processes,[133] (Fig. 15c) may be important depending on factors such as the total energy relative to the lepton mass and the existence of the Higgs boson.

In conclusion, there are several processes by which massive leptons can be produced in very high energy $\bar{p}p$ or pp collisions. More study is required as to how such leptons can be detected in the presence of the very much larger cross sections for hadron production.

5.5 Miscellaneous Future Searches

We began this section pointing out the erratic history of the experimental methods used to discover new leptons. It may be that the method which will be used to discover the next new lepton will be within the speculations of this section.

5.5.1 Unusual Charged Leptons

In Sec. 4.7 we discussed searches for fractionally charged leptons and extremely massive leptons. As fashions go in theoretical particle physics there is no pressing need to search for such particles. But the search techniques are interesting to experimenters, and as new techniques are invented, there is no basic physics which prevents more sensitive fractional charge searches[134] than those discussed in Sec. 4.7.

5.5.2 Leptons as Dark Matter

These days a number of astronomical observations and cosmological models require the existence of so-called dark matter—matter not detectable through its emission of electromagnetic radiation. Dark matter is also one explanation of the existing discrepancy between *present* data and *present* solar theory on neutrino emission by the sun.

One form of dark matter might be stable, neutral leptons.[135] This speculation was particularly popular when there was data requiring the electron neutrino to have a mass in the range of 20 to 50 eV/c^2. Most recent data[135] gives an upper limit on m_{ν_e} less than 20 eV/c^2, and this idea has lost favor. A number of ingenious methods, however, are begin developed for searching for dark matter. Some of these methods depend only on dark matter having a weak interaction, which is just what is needed for lepton searches.

5.6 L'ENVOIE

The delights of searching for new leptons are the unexpected directions from which the discoveries have come and the simple beauty of leptons—particles free of the confusing strong interaction. The pain of searching for new leptons is that it has taken about one hundred years to find six kinds, counting the neutrinos; or, a new charged lepton every forty years. One of us (MLP), now sixty years old, wonders if another lepton will appear during his lifetime.

Yet there must be more leptons. Could the universe of leptons be so meager that no more leptons will be found with tomorrow's research instruments? Compared to those instruments, the research instruments of the past: cathode ray tubes, thick plate spark chambers and the SPEAR storage ring are toys. So we are optimistic; the question is how to find more leptons.

The answer is the old joke. A winner of a million dollar lottery is asked by a reporter "How did you pick the lucky number 48?" The winner answers "Brains and luck, I know that 7 is a good number so I calculated that $7 \times 7 = 48$ must be a better number." "But $7 \times 7 = 49$" says the reporter. "That's the luck part" replies the winner.

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Table 1. τ lifetime in units of 10^{-13} s. The statistical error is given first, the systematic error second. We list all measurements provided: (a) the statistical and systematic errors are each $\leq 0.40 \times 10^{-13}$ s, (b) the measurement is described in a preprint, journal article, or Ph.D. thesis authored by the experimenters, and (c) the authors have not stated the measurement is superseded by a more recent measurement.

Lifetime	Errors combined in quadrature	Experimental Group	Reference
$2.88 \pm 0.16 \pm 0.17$	± 0.23	MARK II	D. Amidei et al., SLAC–PUB–4362 (1987)
$3.15 \pm 0.36 \pm 0.40$	± 0.54	MAC	E. Fernandez et al., Phys. Rev. Lett. 54, 1624 (1985)
3.09	± 0.19	MAC	H. R. Band et al., Phys. Rev. Lett. 59, 415 (1987)
$3.02 \pm 0.15 \pm 0.08$	± 0.17	HRS	S. Abachi et al., ANL–HEP–PR–87–1 (1987)
$3.25 \pm 0.14 \pm 0.18$	± 0.23	CLEO	C. Bebek et al., Phys. Rev. D36, 690 (1987)
$2.95 \pm 0.14 \pm 0.11$	± 0.18	ARGUS	H. Albrecht et al., DESY 87–128 (1987)
3.04	± 0.09		Formal Average

Table 2. τ leptonic branching ratios in percent. The statistical error is given first, the systematic error second. We list all measurements provided: (a) the statistical and systematic errors are each $\leq 3.0\%$, (b) the measurement is described in a preprint, journal article or Ph.D. thesis authored by the experimenters, and (c) the authors have not stated the measurement is superseded by a more recent measurement.

Use $e-\mu$ Universality	$B(\tau^- \to e^- \bar{\nu}_e \nu_\tau)$ Measurement	Combined Error	$B(\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau)$ Measurement	Combined Error	Experimental Group	Reference
No			15.0	±3.0	PLUTO	J. Burmester et al., Phys. Lett. 68B, 297 (1977)
No	16.0	±1.3			DELCO	W. Bacino et al., Phys. Rev. Lett. 41, 13 (1978)
No			17.8±2.0±1.8	±2.7	PLUTO	Ch. Berger et al., Phys. Lett. 99B, 489 (1981)
Yes*	17.6±0.6±1.0	±1.3	17.1±0.6±1.0	±1.3	MARK II	C. A. Blocker et al., Phys. Lett. 109B, 119 (1982)
No	18.3±2.4±1.9	±3.1	17.6±2.6±2.1	±3.3	CELLO	H. J. Behrend et al., Phys. Lett. 127B, 270 (1983)
No	$20.4 \pm 3.0^{+1.4}_{-0.9}$	$^{+3.3}_{-3.1}$	$12.9 \pm 1.7^{+0.7}_{-0.5}$	±1.8	TASSO	M. Althoff et al., Z. Phys. C26, 521 (1985)
No	13.0±1.9±2.9	±3.5	19.4±1.6±1.7	±2.3	PLUTO	Ch. Berger et al., Z. Phys. C28, 1 (1985)
No	18.2±0.7±0.5	±0.9	18.0±1.0±0.6	±1.2	MARK III	R. M. Baltrusaitis et al., Phys. Rev. Lett. 55, 1842 (1985)
No	17.4±0.8±0.5	±0.9	17.7±0.8±0.5	±0.9	MAC	W. W. Ash et al., Phys. Rev. Lett. 55, 2118 (1985)
Yes*	17.8	±0.5	17.3	±0.5	MAC	Same data as above
No			17.4±0.6±0.8	±1.0	MARK J	B. Adeva et al., Phys. Lett. 179B, 177 (1986)
No	17.0±0.7±0.9	±1.1	18.8±0.8±0.7	±1.1	JADE	W. Bartel et al., Phys. Lett. 182B, 216 (1986)
No	18.4±1.2±1.0	±1.6	17.7±1.2±0.7	±1.4	TPC	H. Aihara et al., Phys. Rev. D35, 1553 (1987)
No	19.1±0.8±1.1	±1.4	18.3±0.9±0.8	±1.2	MARK II	P. R. Burchat et al., Phys. Rev. D35, 27 (1987)
	17.7	±0.4	17.7	±0.4		Formal Average

*Not included in formal average.

Table 3. $\tau^- \rightarrow \pi^- \nu_\tau$ branching ratio in percent. The statistical error is given first, the systematic error second. We list all measurements provided: (a) the statistical and systematic errors are each $\leq 3.0\%$, (b) the measurement is described in a preprint, journal article or Ph.D. thesis authored by the experimenters, and (c) the authors have not stated the measurement is superseded by a more recent measurement.

Measurement	Combined Error	Experimental Group	Reference
$9.0 \pm 2.9 \pm 2.5$	± 3.8	PLUTO	G. Alexander et al., Phys Lett. **78B**, 162 (1978)
$11.7 \pm 0.4 \pm 1.8$	± 1.8	MARK II	C. A. Blocker et al., Phys. Lett. **109B**, 119 (1982)
$9.9 \pm 1.7 \pm 1.3$	± 2.1	CELLO	H. J. Behrend et al., Phys. Lett. **127B**, 270 (1983)
$11.8 \pm 0.6 \pm 1.1$	± 1.3	JADE	W. Bartel et al., Phys. Lett. **182B**, 216 (1986)
$10.7 \pm 0.5 \pm 0.8$	± 0.9	MAC	W. T. Ford et al., Phys. Rev. **D35**, 408 (1987)
$10.0 \pm 1.1 \pm 1.4$	± 1.8	MARK II	P. R. Burchat et al., Phys. Rev. **D35**, 27 (1987)
10.9	± 0.6		Formal Average

Table 4. $\tau^- \to \rho^- \nu_\tau$ branching ratio in percent. The statistical error is given first, the systematic error second. We list all measurements provided: (a) the statistical and systematic errors are each $\leq 3.0\%$, (b) the measurement is described in a preprint, journal article or Ph.D. thesis authored by the experimenters, and (c) the authors have not stated the measurement is superseded by a more recent measurement.

Measurement	Combined Error	Experimental Group	Reference
$22.1 \pm 1.9 \pm 1.6$	± 2.5	CELLO	H. J. Behrend et al., Z. Phys. **C23**, 103 (1984)
$22.3 \pm 0.6 \pm 1.4$	± 1.5	MARK II	J. M. Yelton et al., Phys. Rev. Lett. **56**, 812 (1986)
$23.0 \pm 1.3 \pm 1.7$	± 2.1	MARK III	J. Adler et al., Phys. Rev. Lett. **59**, 1527 (1987)
$25.8 \pm 1.7 \pm 2.5^*$	± 3.0	MARK II	P. R. Burchat et al., Phys. Rev. **D35**, 27 (1987)
22.8	± 1.0		Formal Average

*All $\tau^- \to \pi^- \pi^0 \nu_\tau$ included in $\tau^- \to \rho^- \nu_\tau$.

Table 5. τ branching ratios $B(\tau^- \to \pi^-\pi^+\pi^-\nu_\tau)$ and $B(\tau^- \to \pi^-\pi^+\pi^- n\pi^0\nu_\tau)$, $n \geq 1$, in percent. The statistical error is given first, the systematic error second. We list all measurements provided: (a) the statistical and systematic errors are each $\leq 2.0\%$, (b) the measurement is described in a preprint, journal article or Ph.D. thesis authored by the experimenters, and (c) the authors have not stated the measurement is superseded by a more recent measurement.

$B(\tau^- \to \pi^-\pi^+\pi^-\nu_\tau)$		$B(\tau^- \to \pi^-\pi^+\pi^- n\pi^0\nu_\tau)$		Experimental Group	Reference
Measurement	Combined Error	Measurement	Combined Error		
5.4	±1.7			PLUTO	W. Wagner et al., Z. Phys. C3, 193 (1980)
9.7 ± 2.0 ± 1.3	±2.4			CELLO	H. J. Behrend et al., Z. Phys. C23, 103 (1984)
7.7	±0.8	5.2	±0.8	MAC	E. Fernandez et al., Phys. Rev. Lett. 54, 1624 (1985)
5.4	±1.0	6.4	±1.2	DELCO	W. R. Ruckstuhl et al., Phys. Rev. Lett. 56, 2132 (1986)
7.8 ± 0.5 ± 0.8	±0.9	4.7 ± 0.5 ± 0.8	±0.9	MARK II	W. Schmidke et al., Phys. Rev. Lett. 57, 527 (1986)
5.9	±0.7			ARGUS	H. Albrecht et al., Z. Phys. C33, 7 (1986)
		4.2 ± 0.5 ± 0.9	±1.0	ARGUS	H. Albrecht et al., Phys. Lett. 185B, 223 (1987)
6.7	±0.4	5.0	±0.5		Formal Average

Table 6. Upper limits on the branching ratio in percent for $\tau^- \to \pi^- \eta \nu_\tau$.

Limit	Confidence Level (%)	Technique	Experimental Group	Reference
2.5	90	$\eta \to \gamma\gamma,\ \pi^+\pi^-\pi^0$	MARK III	39
2.3	95	$\eta \to \pi^+\pi^-(\pi^0)$	HRS	40
1.8	95	$\eta \to \pi^+\pi^-\pi^0$	CLEO	35
1.7	95	$\eta \to \gamma\gamma,\ \pi^+\pi^-\pi^0$	CELLO	41
1.3	95	$\eta \to \pi^+\pi^-\pi^0$	ARGUS	42
1.0	95	$\eta \to \gamma\gamma$	MARK II	43
1.3	95	$\tau^- \to K^- K^0 \nu_\tau$	TPC	30

Table 7. Upper limits on branching ratios for τ decay modes that would violate lepton number conservation. Limits at 90% confidence level. ℓ^- means e^- or μ^-.

Decay Mode	Upper Limit	Experimental Group	Reference
$\tau^- \rightarrow e^-e^+e^-$	3.8×10^{-5}	ARGUS	H. Albrecht et al., Phys. Lett. 185B, 228 (1987)
$e^-\mu^+\mu^-$	3.3×10^{-5}		
$\mu^-e^+e^-$	3.3×10^{-5}		
$\mu^-\mu^+\mu^-$	2.9×10^{-5}		
$l^-l^\mp l^\pm$	3.8×10^{-5}		
$e^-\pi^+\pi^-$	4.2×10^{-5}		
$\mu^-\pi^+\pi^-$	4.0×10^{-5}		
$e^-\rho^0$	3.9×10^{-5}		
$\mu^-\rho^0$	3.8×10^{-5}		
$l^\mp\pi^\pm\pi^-$	6.3×10^{-5}		
$e^-\pi^+K^-$	4.2×10^{-5}		
$\mu^-\pi^+K^-$	1.2×10^{-4}		
e^-K^{*0}	5.4×10^{-5}		
μ^-K^{*0}	5.9×10^{-5}		
$l^\mp\pi^\pm K^-$	1.2×10^{-4}		
$e^-\gamma$	3.4×10^{-4}	CRYSTAL BALL	S. Keh, Ph.D Thesis, Wurzburg University, DESY F31-86-06 (1986)
$e^-\pi^0$	4.4×10^{-4}		
e^-K^0	1.3×10^{-3}	MARK II	K. G. Hayes et al., Phys. Rev. D25, 2869 (1982)
μ^-K^0	1.0×10^{-3}		

Table 8. τ topological branching ratios in percent. The statistical error is given first, the systematic error second. We list all measurements provided: (a) the statistical and systematic errors are each $\leq 2.0\%$, (b) the measurement is described in a preprint, journal article or Ph.D. thesis authored by the experimenters, and (c) the authors have not stated the measurement is superseded by a more recent measurement.

B_1 Measurement	B_1 Combined Error	B_3 Measurement	B_3 Combined Error	Experimental Group	Reference
84.0	±2.0	15.0	±2.0	CELLO	H. J. Behrend et al., Phys. Lett. **114B**, 282 (1982)
$86.0 \pm 2.0 \pm 1.0$	±2.2	$14.0 \pm 2.0 \pm 1.0$	±2.2	MARK II	C. A. Blocker et al., Phys. Rev. Lett. **49**, 1369 (1982)
$85.2 \pm 1.9 \pm 1.3$	±2.3	$14.7 \pm 1.5 \pm 1.3$	±2.0	CELLO	H. J. Behrend et al., Z. Phys. **C23**, 103 (1984)
$84.7 \pm 1.1^{+1.6}_{-1.3}$	$^{+1.9}_{-1.7}$	$15.3 \pm 1.1^{+1.3}_{-1.6}$	$^{+1.7}_{-1.9}$	TASSO	M. Althoff et al., Z. Phys. **C26**, 521 (1985)
$86.7 \pm 0.3 \pm 0.6$	±0.7	$13.3 \pm 0.3 \pm 0.6$	±0.7	MAC	E. Fernandes et al., Phys. Rev. Lett. **54**, 1624 (1985)
$86.9 \pm 0.2 \pm 0.3$	±0.4	$13.0 \pm 0.2 \pm 0.3$	±0.4	HRS	C. Akerlof et al., Phys. Rev. Lett. **55**, 570 (1985)
$86.1 \pm 0.5 \pm 0.9$	±1.0	$13.6 \pm 0.5 \pm 0.8$	±0.9	JADE	W. Bartel et al., Phys. Lett. **161B**, 188 (1985)
$87.9 \pm 0.5 \pm 1.2$	±1.3	$12.1 \pm 0.5 \pm 1.2$	±1.3	DELCO	W. Ruckstuhl et al., Phys. Rev. Lett. **56**, 2132 (1986)
$87.2 \pm 0.5 \pm 0.8$	±0.9	$12.8 \pm 0.5 \pm 0.8$	±0.9	MARK II	W. B. Schmidke et al., Phys. Rev. Lett. **57**, 527 (1986)
$84.7 \pm 0.8 \pm 0.6$	±1.0	$15.1 \pm 0.8 \pm 0.6$	±1.0	TPC	H. Aihara et al., Phys. Rev. **D35**, 1553 (1987)
86.6	±0.3	13.3	±0.3		Formal Average

Table 9a. Summary of formal averages of measured branching ratios in percent for modes with 1 charged particle. Values are from Tables 2, 3, 4 and 8 of this paper or Ref. 26.

Type of Measurement	Row	Decay Mode	Branching Ratio	Reference
Exclusive measurement of modes with 0, 1 or $2\pi^0$	A	$e^-\bar{\nu}_e\nu_\tau$	17.7 ± 0.4	Table 2
	B	$\mu^-\bar{\nu}_\mu\nu_\tau$	17.7 ± 0.4	Table 2
	C	$\pi^-\nu_\tau$	10.9 ± 0.6	Table 3
	D	$\rho^-\nu_\tau$	22.8 ± 1.0	Table 4
	E	$\pi^-2\pi^0\nu_\tau$	7.5 ± 0.9	This paper
	F	$K^-\nu_\tau$	0.6 ± 0.2	Ref. 26
	G	$K^{*-}\nu_\tau$	1.6 ± 0.3	This paper
Sum of rows A-G	H		78.8 ± 1.6	
Exclusive measurement of modes with $3\pi^0$	I	$\pi^-3\pi^0\nu_\tau$	$0.0 - 3.0$	This paper
Sum of all exclusive measurements Rows A–G, I	J		$78.8 - 81.8$	
Inclusive measurement*	K	All modes with 1 charged particle	87.0 ± 0.3	Table 8

* Including $\tau^- \to K^{*-}\nu_\tau \to \pi^-K_s^0\nu_\tau \to \pi^-\pi^+\pi^-\nu_\tau$.

Table 9b. Summary of formal averages of measured branching ratios in percent for modes with 3 or 5 charged particles. Values are from Tables 5 or 8 of this paper.

Type of Measurement	Row	Decay Mode	Branching Ratio	Reference
Exclusive Measurement	L M	$\pi^-\pi^+\pi^-\nu_\tau$ $\pi^-\pi^+\pi^- n\pi^0\nu_\tau,\ n \geq 1$	6.7 ± 0.4 5.0 ± 0.5	Table 5 Table 5
Sum of Rows L-M	N		11.7 ± 0.6	
Inclusive Measurement*	O	All modes with 3 charged particles	12.9 ± 0.3	Table 8
Inclusive Measurement	P	All modes with 5 charged particles	0.11 ± 0.03	This paper

* Excluding $\tau^- \to K^{*-}\nu_\tau \to \pi^- K^0_s \nu_\tau \to \pi^-\pi^+\pi^-\nu_\tau$.

Table 10. τ branching ratios in percent from Ref. 47 using an analysis method in which all observed τ decays must be allotted to one of the modes listed here. These measurements are compared with the formal averages from Table 9.

Row	Decay Mode	Measured Branching Ratio	Formal Average Branching Ratio
A	$e^- \bar{\nu}_e \nu_\tau$	$19.1 \pm 0.8 \pm 1.1$	17.7 ± 0.4
B	$\mu^- \bar{\nu}_\mu \nu_\tau$	$18.3 \pm 0.9 \pm 0.8$	17.7 ± 0.4
C	$\pi^- \nu_\tau$	$10.0 \pm 1.1 \pm 1.4$	10.9 ± 0.6
D	$\pi^- \pi^0 \nu_\tau$	$25.8 \pm 1.7 \pm 2.5$	22.8 ± 1.0
E	$\pi^- n\pi^0 \nu_\tau,\ n > 1$	$12.0 \pm 1.4 \pm 2.5$	
F	Sum of rows A-E	85.2	
G	$\pi^- \pi^+ \pi^- \nu_\tau$	$6.7 \pm 0.8 \pm 0.9$	6.7 ± 0.4
H	$\pi^- \pi^+ \pi^- n\pi^0 \nu_\tau,\ n \geq 1$	$6.1 \pm 0.8 \pm 0.9$	5.0 ± 0.5
I	Sum of rows G and H	12.8	11.7
J	Modes containing K meson	2.0 *	
K	Sum of rows F, I and J	100.0	

* Fixed in analysis from other experiments.

Table 11. Lower limits on the mass of a heavy charged lepton at the 95% confidence level.

Limit (GeV/c^2)	Experimental Group	Reference
18.0	JADE	55
22.5	MARK J	56
14.5	PLUTO	57
15.5	TASSO	58

Table 12. Upper limits on number of generations of neutrinos at the 90% confidence level. The neutrino mass is taken to be less than 10 GeV/c^2.

Number of Generations	Experimental Group	Reference
17	MAC	91
15	CELLO	92
7.5	ASP	93
4.8	Combined Limit	94

Table 13. The value of R in Eq. 5.2.10.

$E_{\rm cm}$(TeV)	L^+L^-	$L^0\overline{L^0}$
0.2	1.27	0.50
0.7	1.18	0.32
≥2.0	1.17	0.31

FIGURE CAPTIONS

1. The production of a charged lepton through (a) virtual one-photon exchange, (b) virtual or real Z^0 exchange, (c) the direct decay of a W boson.
2. Crude method for calculating heavy charged lepton branching ratios. The quark decay modes are enhanced by the color factor of 3.
3. (L^-, L°) pairs within the hatched region are excluded with $> 2\sigma$ confidence.
4. (a) The production of neutral leptons through Z^0 exchange, (b) the production of an electron type neutral lepton through W exchange.
5. Crude method for calculating heavy neutral lepton branching ratios. The quark decay modes are enhanced by the color factor of 3.
6. Upper limit on the heavy neutral lepton pair production cross section at 90% confidence level, normalized to the cross section expected in the standard model.
7. Limits on mixing as a function of the heavy neutral lepton mass as obtained from (1) TRIUMF $\pi \to e\nu$, Ref. 79; (2) SIN $\pi \to e\nu$, Ref. 80; (3) KEK $K \to e\nu$, Ref. 81; (5) Brookhaven AGS $\pi \to e\nu$ and $K \to e\nu$, Ref. 84; (6) CERN PS 191 $\pi \to e\nu$ and $K \to e\nu$, Ref. 85; (7) CHARM charm decay, Ref. 86; (8) FERMILAB charm decay, Ref. 87; (9) CERN BEBC charm decay, Ref. 88; (10) $e-\mu$ universality, Ref. 89; (11) MARK II secondary vertex search, Ref. 72; (12) CELLO secondary vertex search, Ref. 73; (13) PEP monojet searches, Ref. 74; (14) JADE monojet search, Ref. 76.
8. Limits on mixing as a function of the heavy neutral lepton mass as obtained from (3) KEK $K \to \mu\nu$, Ref. 81; (4) SIN $\pi \to \mu\nu$, Ref. 82; (5) Brookhaven AGS $K \to \mu\nu$, Ref. 84; (7) CHARM charm decay, Ref. 86; (8) FERMILAB charm decay, Ref. 87; (9) CERN BEBC charm decay, Ref. 88; (10) $e-\mu$ universality, Ref. 89; (11) MARK II secondary vertex search, Ref. 72; (12) CELLO secondary vertex search, Ref. 73.

9. Production through e^+e^- annihilation of (a) an excited lepton pair, and (b) an excited lepton with an ordinary lepton. An excited electron, e^*, may be detected through the e^* exchange diagram contributing to $e^+e^- \rightarrow \gamma\gamma$ in (c).

10. Limits on e^* production from CELLO, Ref. 103.

11. Limits on τ^* production from JADE, Ref. 104.

12. Limits on e^* production from UA2, Ref. 105.

13. Mechanisms for producing spin 0 supersymmetry leptons, $\tilde{\ell}^{\pm}$: (a) $\tilde{\ell}$ pair production, (b) additional process for $\tilde{e}$ pair production, and (c) processes for single $\tilde{e}$ production. The existence of the $\tilde{e}$ may be detected through the reaction $e^+e^- \rightarrow \gamma\tilde{\gamma}\tilde{\gamma}$ as shown in (d).

14. Definitive searches for new leptons with the e lepton number can be carried out using ep collisions.

15. Mechanisms for producing new leptons in $\bar{p}p$ or pp collisions: (a) the Drell–Yan mechanisms, (b) gauge boson fusion, and (c) gluon fusion.

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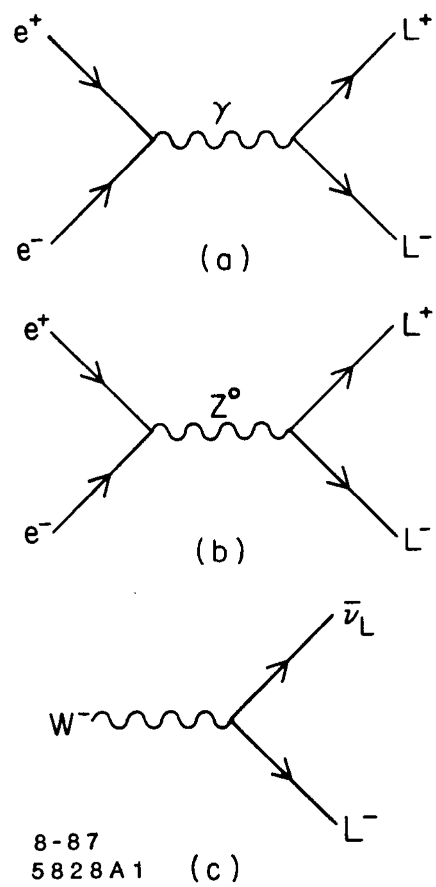
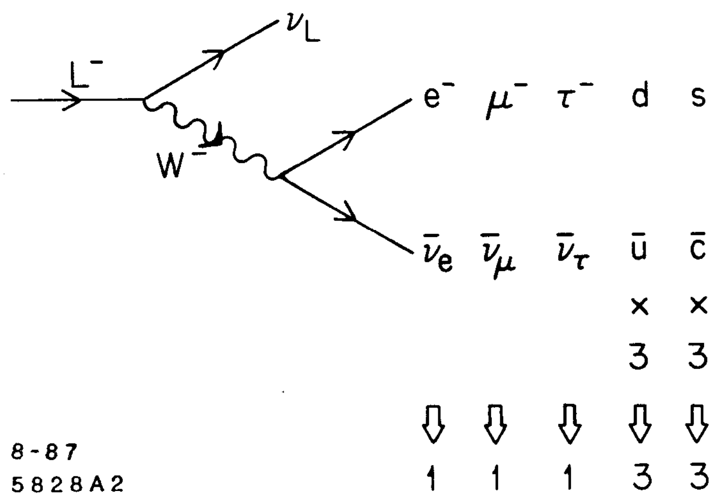
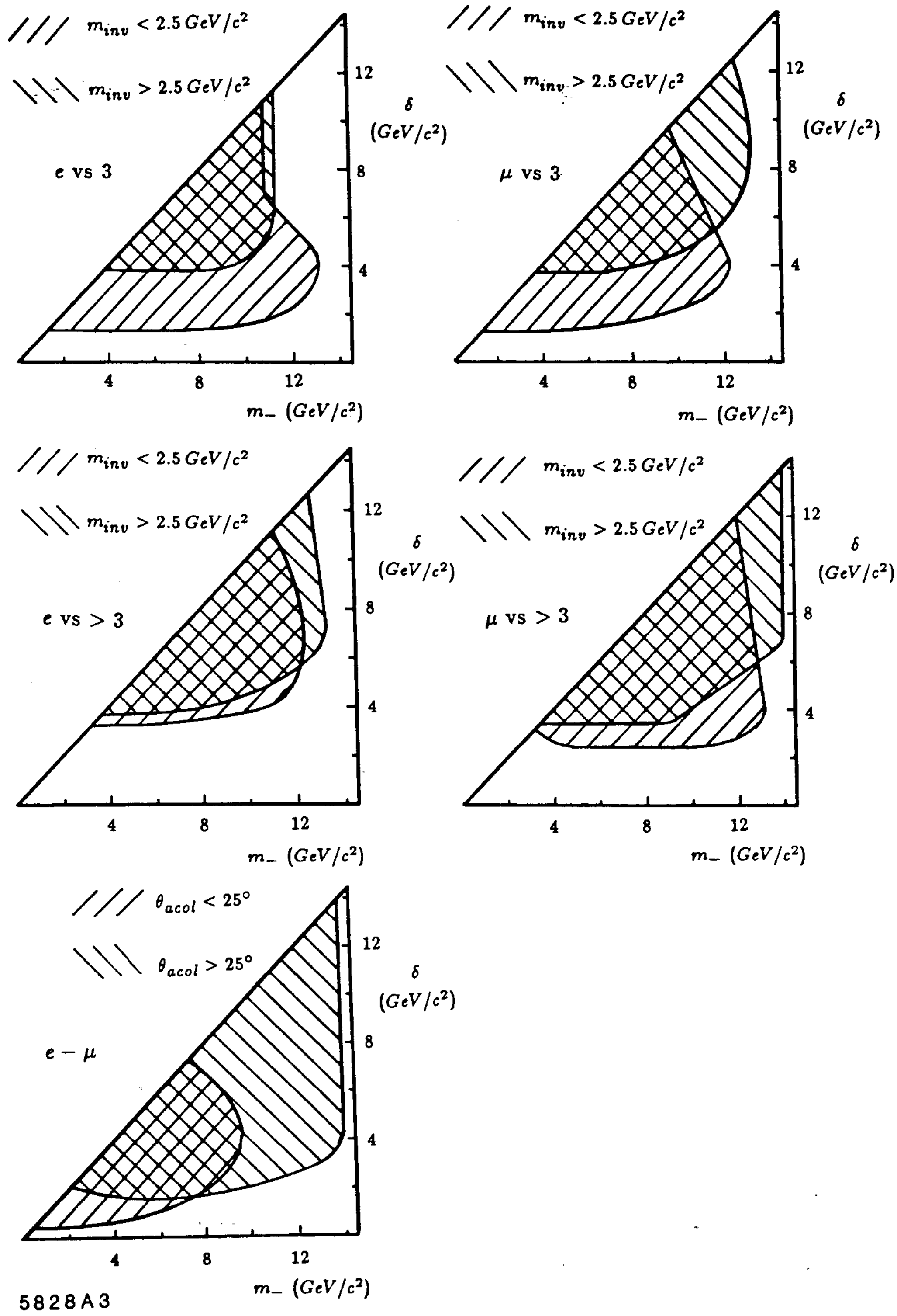


Fig. 1



ν_L
L^-
W^-
e^- μ^- τ^- d s
$\bar{\nu}_e$ $\bar{\nu}_\mu$ $\bar{\nu}_\tau$ $\bar{u}$ $\bar{c}$
× ×
3 3
1 1 1 3 3
8-87
5828A2

Fig. 2



$m_{inv} < 2.5\,GeV/c^2$
$m_{inv} > 2.5\,GeV/c^2$
e vs 3
μ vs 3
e vs > 3
μ vs > 3
$\theta_{acol} < 25°$
$\theta_{acol} > 25°$
$e - \mu$
δ (GeV/c^2)
m_- (GeV/c^2)
4
8
12
5828A3

Fig. 3

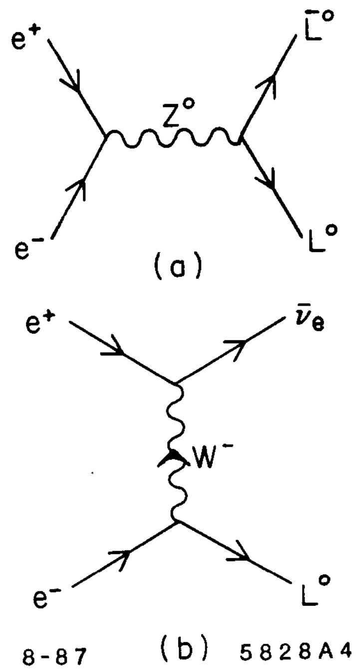


Fig. 4

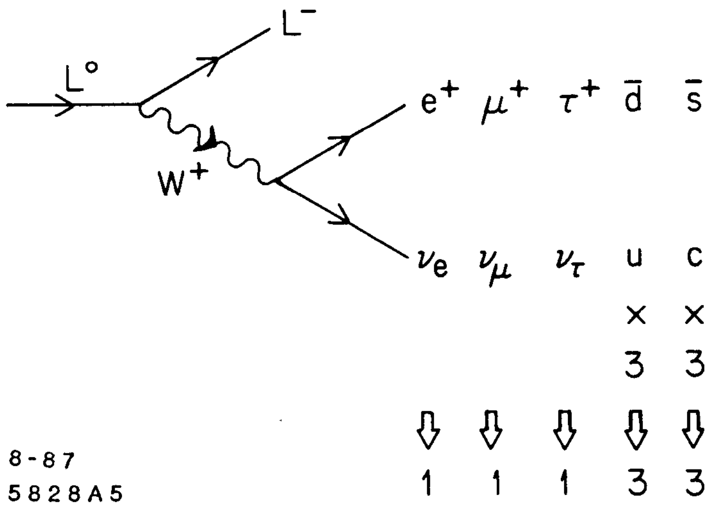
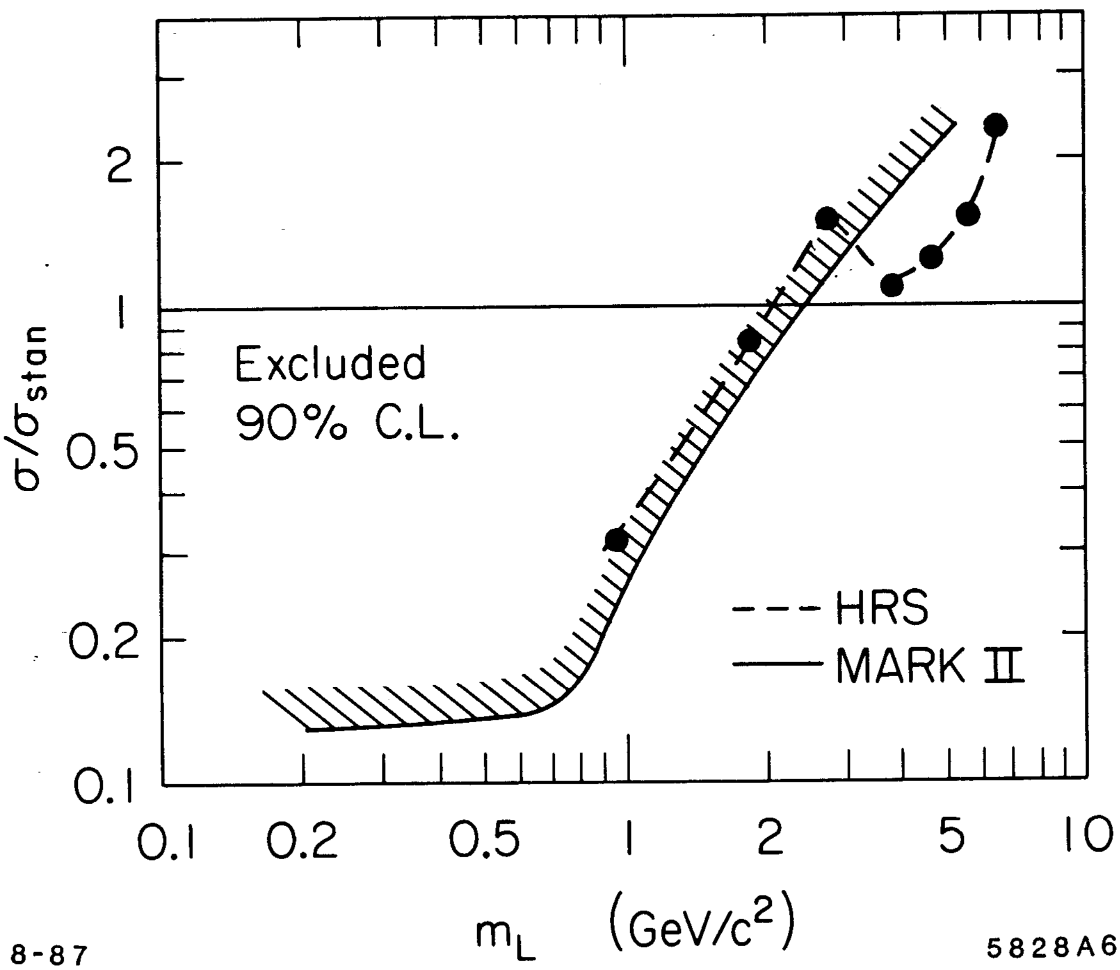
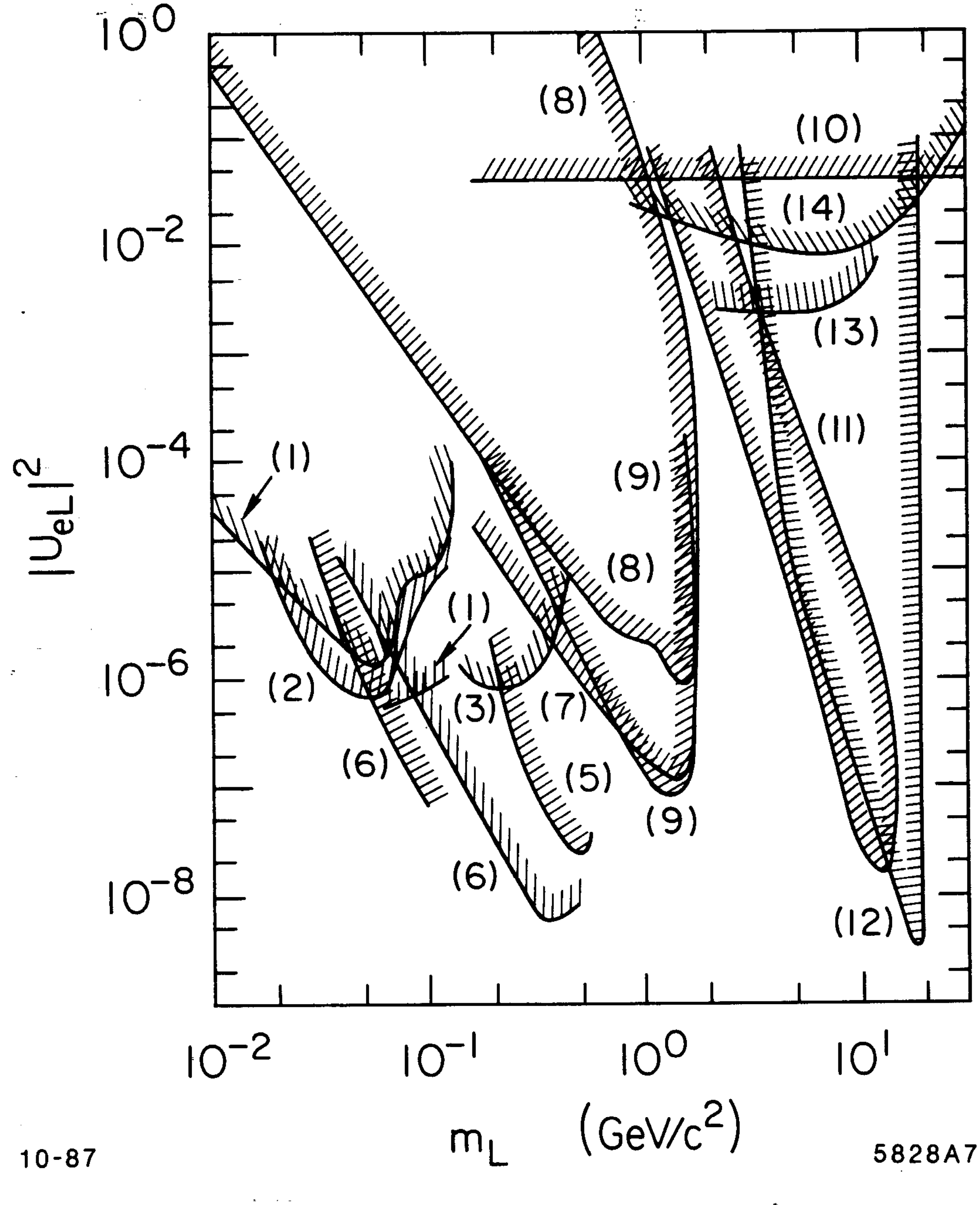


Fig. 5



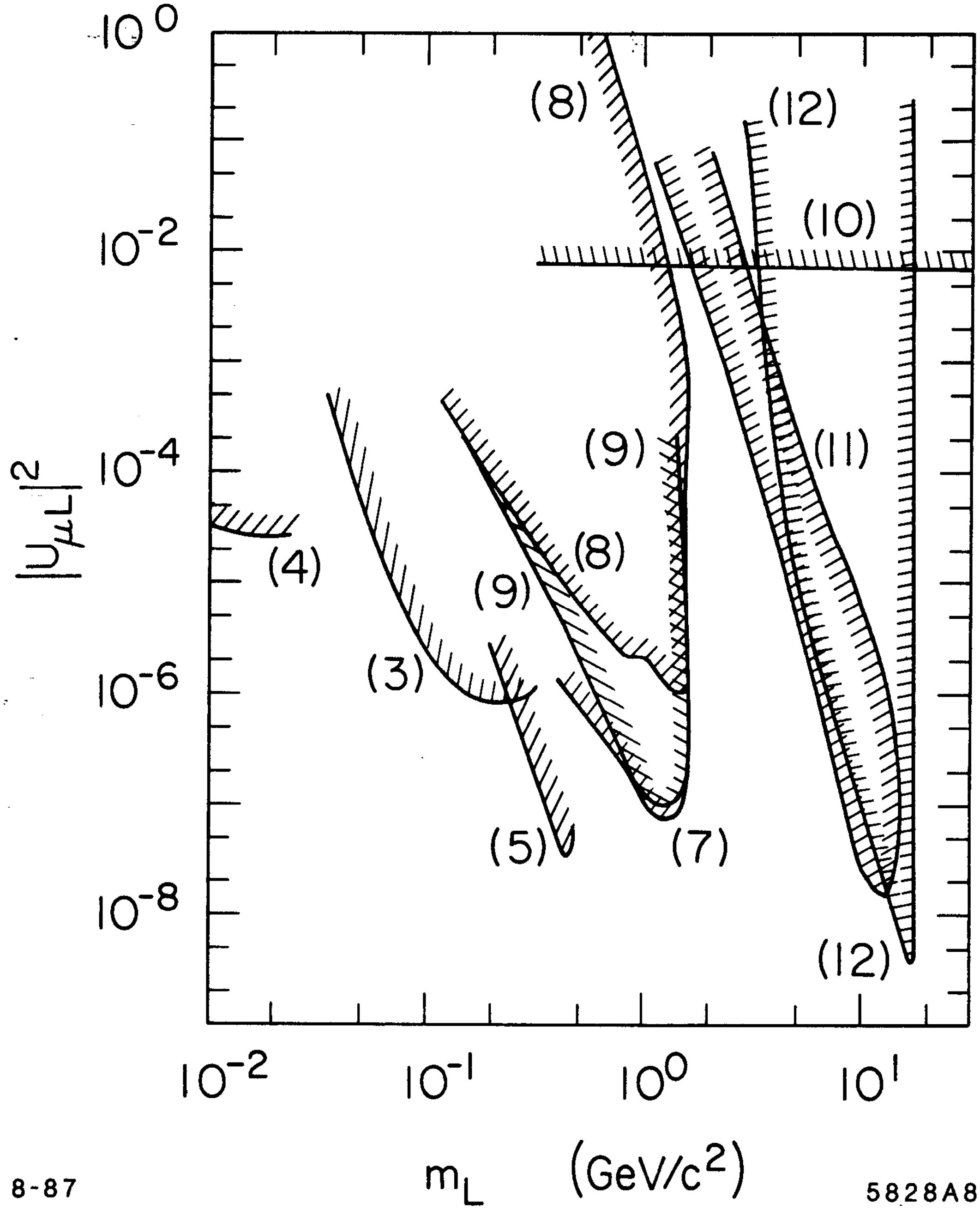
2
1
0.5
0.2
0.1
σ/σstan
Excluded
90% C.L.
HRS
MARK II
0.1
0.2
0.5
1
2
5
10
m_L (GeV/c²)
8-87
5828A6

Fig. 6



10^0
10^{-2}
10^{-4}
10^{-6}
10^{-8}
$|U_{eL}|^2$
(1)
(2)
(3)
(5)
(6)
(7)
(8)
(9)
(10)
(11)
(12)
(13)
(14)
10^{-2}
10^{-1}
10^0
10^1
m_L (GeV/c^2)
10-87
5828A7

Fig. 7



10^0
10^{-2}
10^{-4}
10^{-6}
10^{-8}
$|U_{\mu L}|^2$
(8)
(12)
(10)
(9)
(11)
(4)
(8)
(9)
(3)
(5)
(7)
(12)
10^{-2}
10^{-1}
10^0
10^1
m_L (GeV/c^2)
8-87
5828A8

Fig. 8

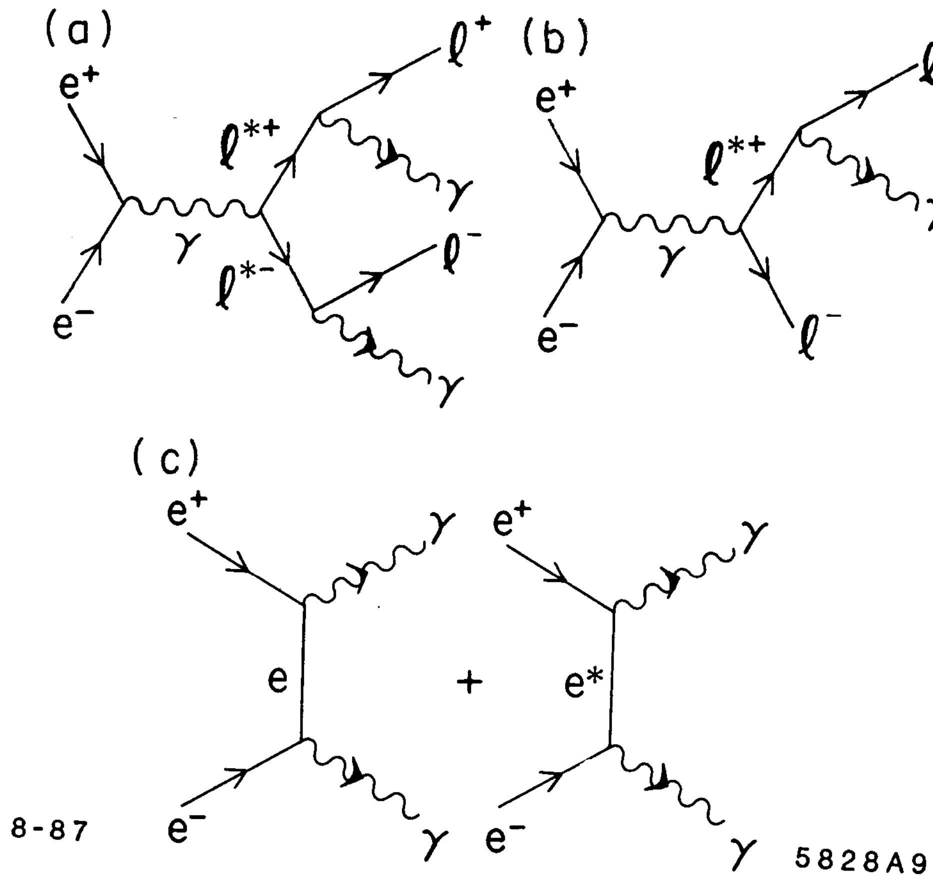


Fig. 9

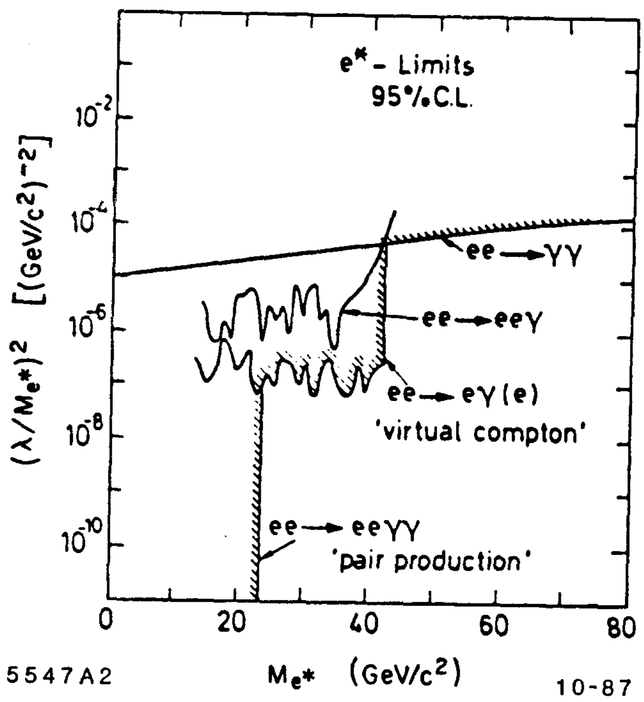
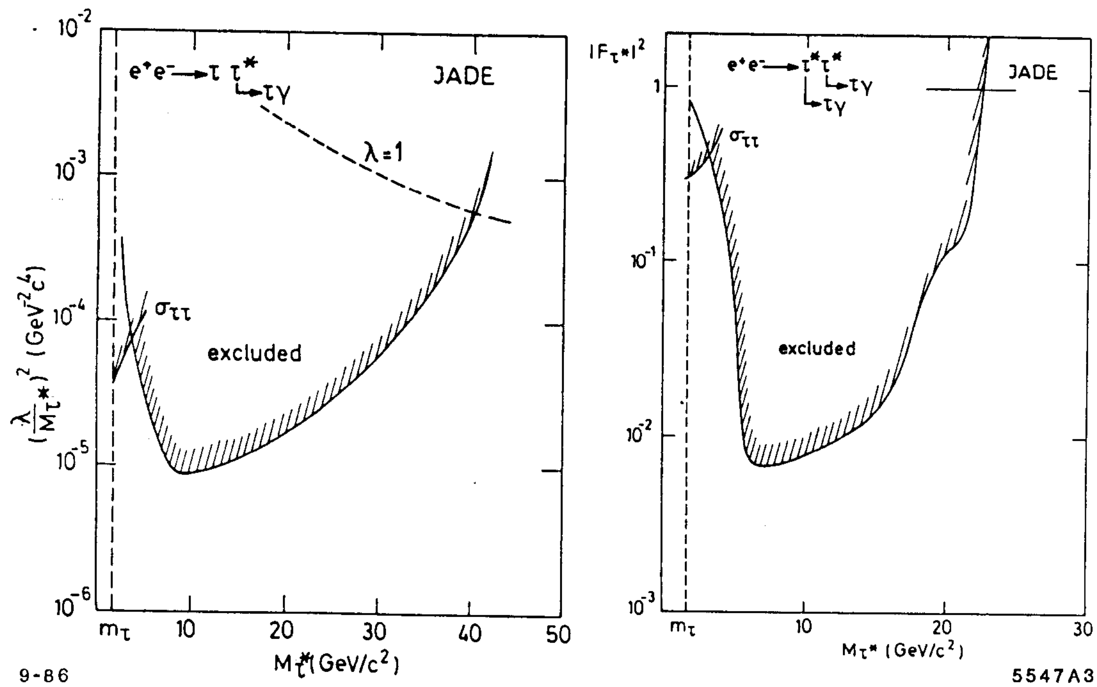
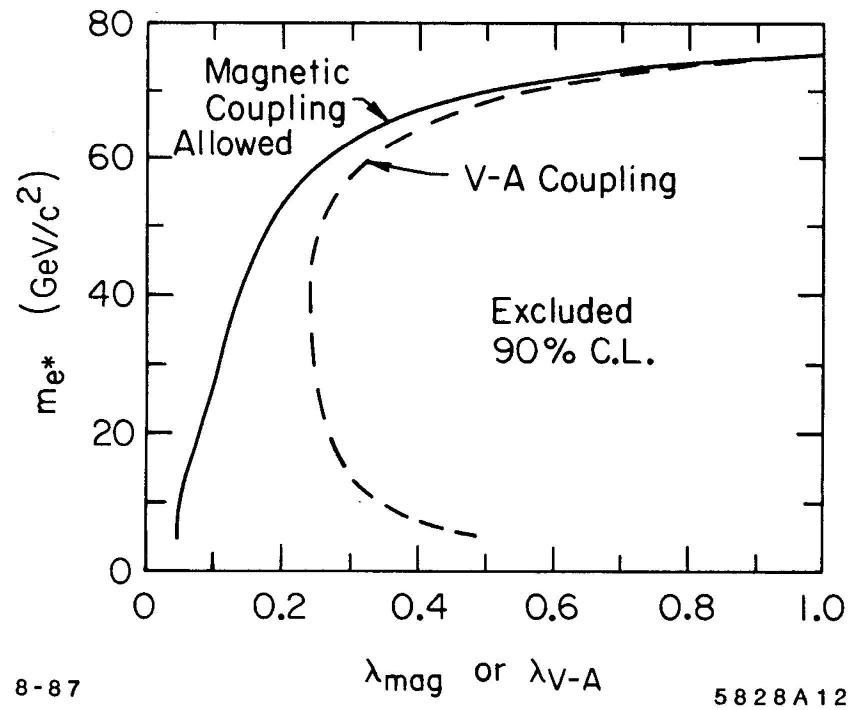

e* - Limits
95% C.L.
ee → γγ
ee → eeγ
ee → eγ (e)
'virtual compton'
ee → eeγγ
'pair production'
$(\lambda/M_{e^*})^2$ [(GeV/c²)⁻²]
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
0
20
40
60
80
M_{e^*} (GeV/c²)
5547A2
10-87

Fig. 10



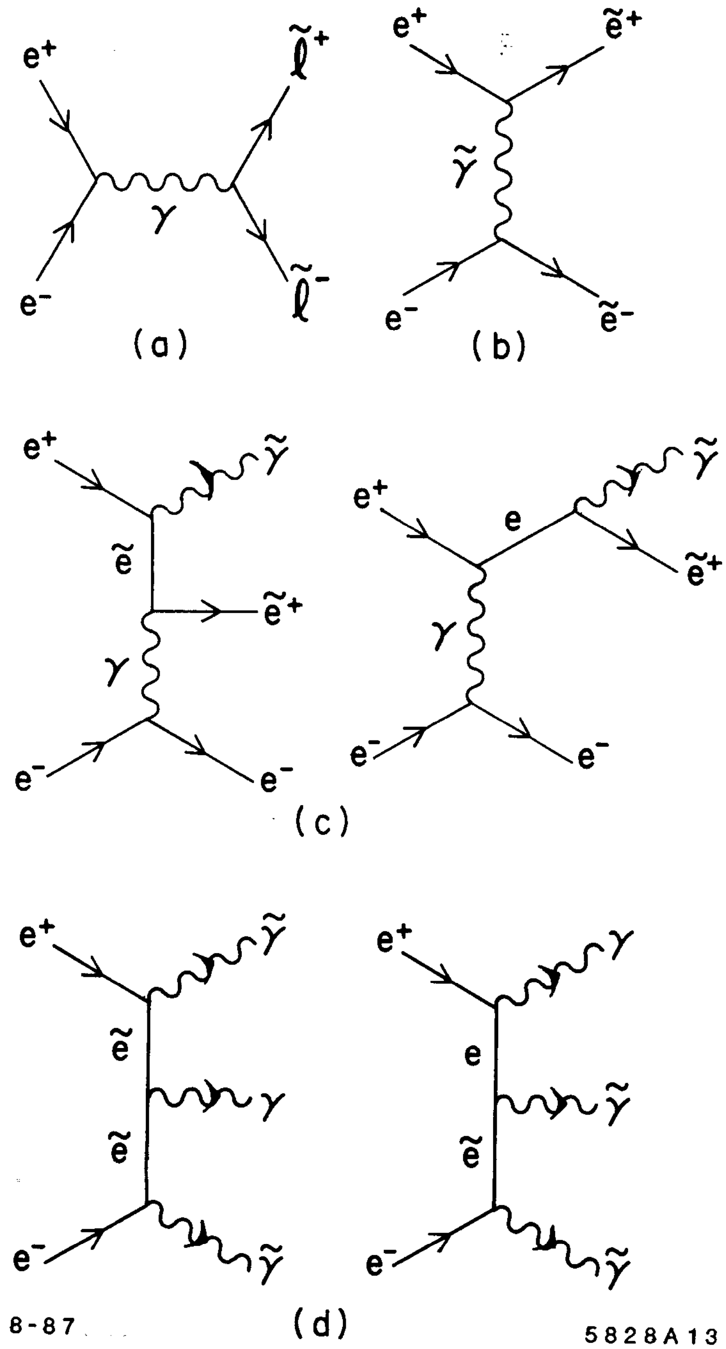
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
$e^+e^- \to \tau\,\tau^*$ $\hookrightarrow \tau\gamma$
JADE
$\lambda = 1$
$\sigma_{\tau\tau}$
excluded
$(\frac{\lambda}{M_{\tau^*}})^2$ $(GeV^{-2}c^4)$
m_τ
10
20
30
40
50
M_{τ^*} (GeV/c^2)
$|F_{\tau^*}|^2$
1
10^{-1}
10^{-2}
10^{-3}
$e^+e^- \to \tau^*\tau^*$ $\hookrightarrow \tau\gamma$ $\hookrightarrow \tau\gamma$
JADE
$\sigma_{\tau\tau}$
excluded
m_τ
10
20
30
M_{τ^*} (GeV/c^2)
9-86
5547A3

Fig. 11



80
60
40
20
0
Magnetic Coupling Allowed
V-A Coupling
Excluded 90% C.L.
m_{e^*} (GeV/c^2)
0
0.2
0.4
0.6
0.8
1.0
λ_{mag} or λ_{V-A}
8-87
5828A12

Fig. 12



e+
e−
γ
ℓ̃+
ℓ̃−
(a)
e+
e−
γ̃
ẽ+
ẽ−
(b)
e+
γ̃
ẽ
ẽ+
γ
e−
e−
e+
e
γ̃
ẽ+
γ
e−
e−
(c)
e+
γ̃
ẽ
γ
ẽ
e−
γ̃
e+
γ
e
γ̃
ẽ
e−
γ̃
8-87
(d)
5828A13

Fig. 13

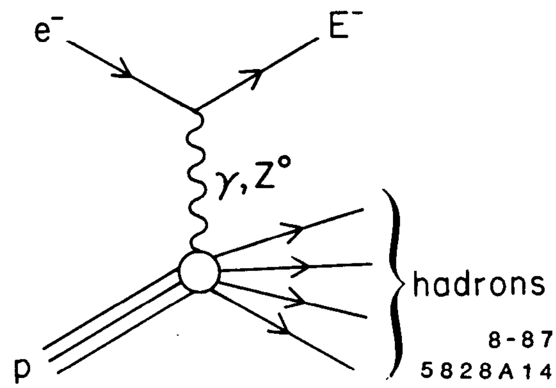


Fig. 14

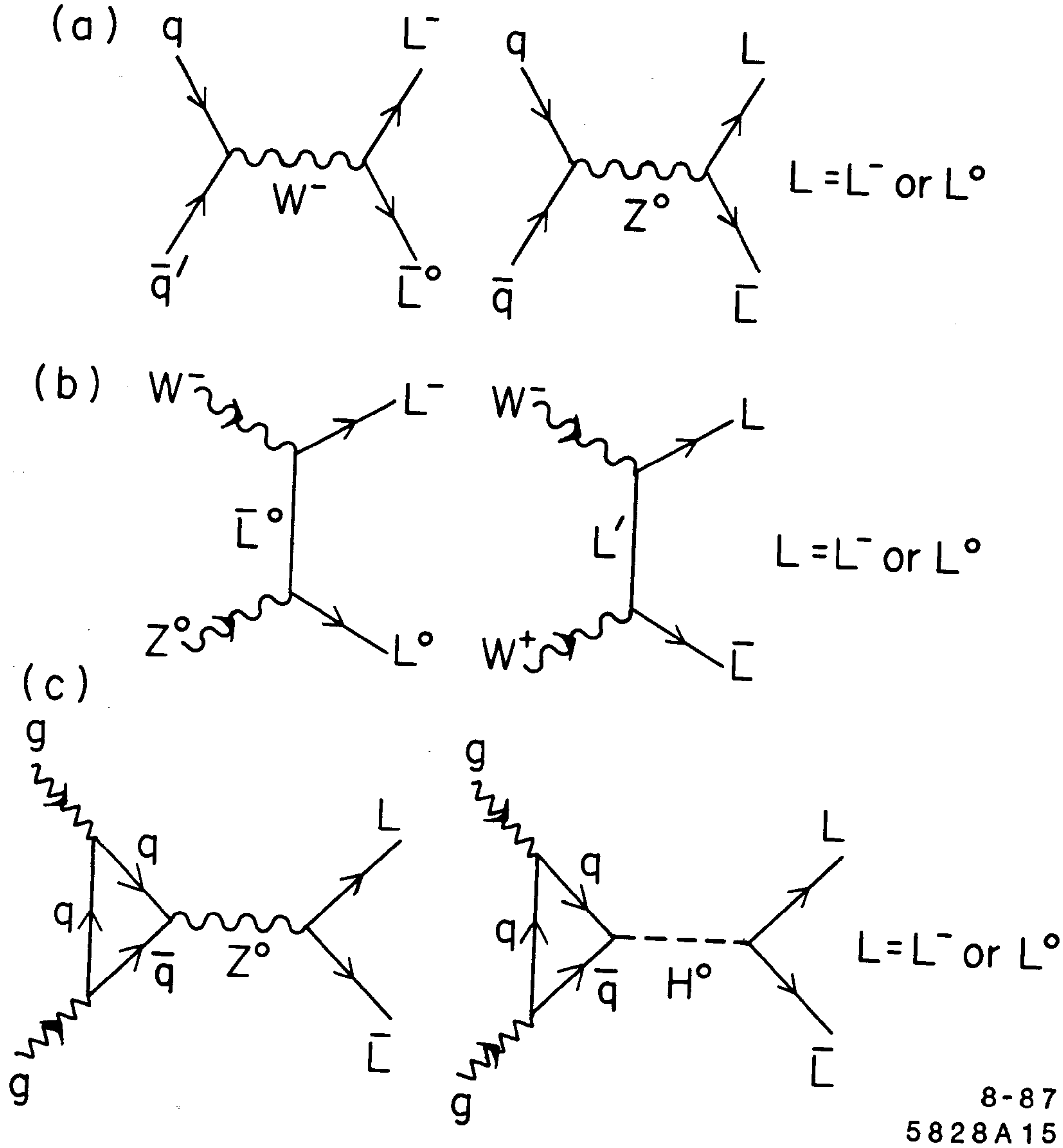

(a)
q
q̄′
W⁻
L⁻
L̄°
q
q̄
Z°
L
L̄
L = L⁻ or L°
(b)
W⁻
Z°
L̄°
L⁻
L°
W⁻
W⁺
L′
L
L̄
L = L⁻ or L°
(c)
g
g
q
q
q̄
Z°
L
L̄
g
g
q
q
q̄
H°
L
L̄
L = L⁻ or L°
8-87
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Fig. 15