Tau Electroweak Couplings

Alan J. Weinstein*
California Institute of Technology
256-48 Caltech
Pasadena, CA 91125, USA
E-mail: ajw@caltech.edu

Abstract: We review world-average measurements of the tau lepton electroweak couplings, in both decay (including Michel parameters) and in production ($Z^0 \to \tau^+\tau^-$ and $W^- \to \tau^-\overline{\nu}_\tau$). We review the searches for anomalous weak and EM dipole couplings. Finally, we present the status of several other tau lepton studies: searches for lepton flavor violating decays, neutrino oscillations, and tau neutrino mass limits.

1. Introduction

Most talks at this conference concern the study of heavy quarks, and many focus on the difficulties associated with the measurement of their electroweak couplings, due to their strong interactions. This contribution instead focuses on the one heavy flavor fermion whose electroweak couplings can be measured without such difficulties: the tau lepton. Indeed, the tau's electroweak couplings have now been measured with rather high precision and generality, in both production and decay. In all cases, the couplings of the tau are identical, to high precision, to those of the electron and the muon. The leptonic couplings thus form a standard against which the hypothesis of universality of all fermionic (including quark) couplings can be tested.

Because the tau lepton is so massive, it decays in many different ways. The daughter decay products can be used to analyze the spin polarization of the parent tau. This can then be used to study the spin dependence of the tau electroweak couplings. Further, since the tau is the heaviest known lepton and a member of the third family of fermions, it may be expected to be more sensitive to physics beyond the Standard Model (SM), especially to mass-dependent (Higgs-like) currents. This will reveal itself in violations of universality of the fermionic couplings.

Here we review the status of the measurements of the tau electroweak couplings in both production and decay. The following topics will be covered (necessarily, briefly, with little attention to experimental detail). We discuss the tau lifetime, the leptonic branching fractions ($\tau \to e\nu\nu$ and $\mu\nu\nu$), and the results for tests of universality in the charged current decay. We then turn to measurements of the Michel Parameters, which probe deviations from the pure $V - A$ structure of the charged weak current. Next we review the charged current couplings in tau production via $W^- \to \tau^-\overline{\nu}_\tau$ decay. Then we turn to neutral current couplings in tau production via $Z^0 \to \tau^+\tau^-$. We review searches for anomalous weak dipole moment couplings in $Z^0 \to \tau^+\tau^-$, and anomalous electromagnetic dipole moment couplings in $Z^0 \to \tau^+\tau^-\gamma$. We briefly review the searches for flavor changing neutral currents in lepton flavor violating (neutrinoless) tau decays, and searches for neutrino oscillations involving the tau neutrino ν_τ. We present the current limits on the ν_τ mass. Finally, we summarize and review the prospects for further progress in τ physics in the coming years.

Most of these high-precision measurements and sensitive searches for anomalous (non-SM) couplings have been performed, and refined, over

*For the CLEO Collaboration. Work supported by US DOE Grant DE-FG03-92-ER40701.

the last few years. There have been no dramatic new results since the last Heavy Flavors conference, only updated results with higher precision. There are updated leptonic branching fractions from LEP; updated Michel parameter measurements from LEP and CLEO; final results on tau polarization measurements and measurements of the Z^0 couplings from LEP; limits on neutral weak dipole moments from LEP and SLD; new measurements of the rate for $W \to \tau\nu$ from LEP II, results on electromagnetic dipole moments from LEP, new $m(\nu_\tau)$ limits from CLEO; and new limits on lepton flavor violating (neutrinoless) decays from CLEO. I draw heavily from the presentations at the Fifth Workshop on Tau Lepton Physics (TAU'98), from September 1998.

Other than neutrino oscillation observations which may involve $\nu_\mu \to \nu_\tau$ oscillations, all recent measurements confirm the minimal Standard Model predictions to ever increasing precision. Nevertheless, new physics may be just around the corner, waiting to be revealed by even higher precision studies.

2. Leptonic branching fractions, tau lifetime, universality

The rate for tau decays to leptons is given by the universal charged weak current decay rate formula for pointlike massive fermions:

$$\Gamma(\tau \to \nu_\tau \mu \nu_\mu) = \tau_\tau \mathcal{B}(\tau \to \nu_\tau \mu \nu_\mu) \qquad (2.1)$$

$$= \frac{G_F^2 g_\tau^2 g_\mu^2 m_\tau^5}{192\pi^3} f_{\mu\tau} R_{EW} h_\eta \qquad (2.2)$$

Here, the Fermi coupling constant G_F is *measured* in μ decay, assuming $g_\mu g_e$ is 1. Here, we let them vary, in order to test the assumption of universality. The phase space correction $f_{\mu\tau} = f\left(m_\mu^2/m_\tau^2\right)$ is 0.9726 for $\tau \to \mu\nu\nu$ and ≈ 1 for $\tau \to e\nu\nu$. The electroweak correction is

$$R_{EW} = \underbrace{\left(1 + \frac{3}{5}\frac{m_\tau^2}{m_W^2}\right)}_{+0.03\%} \underbrace{\left[1 + \frac{\alpha}{\pi}\left(\frac{25}{4} - \pi^2\right)\right]}_{-0.4\%} \qquad (2.3)$$

and the correction due to possible scalar currents is, in terms of the Michel parameter η,

$$h_\eta = 1/(1 + 4\eta m_\ell/m_\tau) = 1 \text{ in SM.} \qquad (2.4)$$

To test the hypothesis that all of the charged weak current couplings are equal ($g_e = g_\mu = g_\tau$), we must measure the muon lifetime, the branching fraction $\mathcal{B}(\mu \to e\nu\overline{\nu})$, the tau lifetime, and the branching fractions $\mathcal{B}(\tau \to e\nu\overline{\nu})$ and $\mathcal{B}(\tau \to \mu\nu\overline{\nu})$. The muon properties are well measured [1].

2.1 Tau Lifetime

The tau lifetime has been measured by many experiments with many different methods [2]. There are recent measurements from L3 [3] and DELPHI [4].

An example of a decay length distribution, from DELPHI [4], is shown in figure 1. A summary of recent measurements is given in figure 2. The world average from 6 experiments, each with $\lesssim 1\%$ precision, is $\tau_\tau = (290.5 \pm 1.0)$ fs.

2.2 Leptonic Branching Fractions

There are recent results on the tau leptonic branching fractions from ALEPH [5], DELPHI [6] and OPAL [7]. Measurements from 5 experiments [8] are shown in figure 3, leading to the world average values:

$$\mathcal{B}(\tau^- \to e^-\overline{\nu}_e\nu_\tau) = (17.81 \pm 0.07)\% \quad (2.5)$$

$$\mathcal{B}(\tau^- \to \mu^-\overline{\nu}_\mu\nu_\tau) = (17.37 \pm 0.09)\% \quad (2.6)$$

The branching fractions $\mathcal{B}_e$ and $\mathcal{B}_\mu$ are now measured to 0.4% accuracy, *i.e.*, at the level of the radiative corrections (equation 2.3).

These precise results already provide limits on simple extensions to the Standard Model, using equation 2.1. The η parameter (to be discussed in section 3 below) is inferred to be

$$\eta = 0.013 \pm 0.022 \quad (\eta = 0 \text{ in SM}). \qquad (2.7)$$

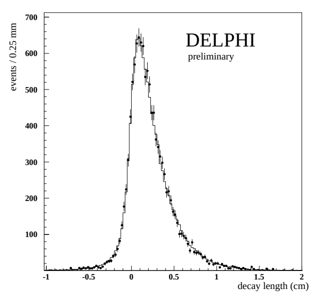

Figure 1: Tau flight length distribution from DELPHI [4].

In addition, the ν_τ mass must be less than 38 MeV [9]. One can also put limits on mixing with a 4^{th} generation, anomalous electromagnetic complings, and compositeness [9].

2.3 $\mathcal{B}(\tau \to \ell\nu\nu\gamma)$ from CLEO 99

CLEO has made precision measurements of tau leptonic decays in the presence of a radiative (decay) photon [10], finding branching fractions in good agreement with Standard Model predictions:

$$\begin{aligned} \mathcal{B}(e^-\overline{\nu}_e\nu_\tau\gamma) &= (1.75 \pm 0.06 \pm 0.17)\% \\ SM &= (1.86 \pm 0.01)\% \qquad (2.8) \\ \mathcal{B}(\mu^-\overline{\nu}_\mu\nu_\tau\gamma) &= (0.361 \pm 0.016 \pm 0.035)\% \\ SM &= (0.368 \pm 0.002)\% \qquad (2.9) \end{aligned}$$

for $E^*_\gamma > 10$ MeV in the τ center of mass.

2.4 Lepton Universality

From the measurements of the tau lifetime and leptonic branching fractions, we can extract ratios which test the universality hypothesis $g_e = g_\mu = g_\tau$:

$$\begin{aligned} \left(\frac{g_\tau}{g_\mu}\right)^2 &\equiv \mathcal{B}_e \left(\frac{\tau_\mu}{\tau_\tau}\right) \left(\frac{m_\mu}{m_\tau}\right)^5 \\ &= (1.000 \pm 0.003)^2 \qquad (2.10) \\ \left(\frac{g_\tau}{g_e}\right)^2 &\equiv \frac{\mathcal{B}_\mu}{f_{\mu\tau}} \left(\frac{\tau_\mu}{\tau_\tau}\right) \left(\frac{m_\mu}{m_\tau}\right)^5 \\ &= (1.000 \pm 0.003)^2 \qquad (2.11) \\ \left(\frac{g_\mu}{g_e}\right)^2 &\equiv \frac{\mathcal{B}_\mu}{f_{\mu\tau}\mathcal{B}_e} \\ &= (1.000 \pm 0.003)^2 \qquad (2.12) \end{aligned}$$

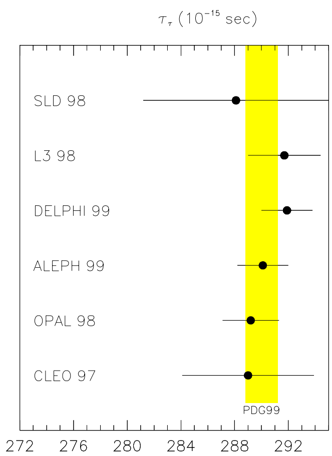

Figure 2: Summary of recent tau lifetime measurements.

We see that the *strength* of the charged current couplings (irrespective of their Lorentz structure) are equal to each other within 0.25%.

2.5 What Could Cause Lepton Universality Violation?

Many extensions to the Standard Model predict violation of lepton universality. In fact, lepton universality is put in to the SM by hand, so that non-universal $W \to \ell\nu$ couplings can naturally appear if the model is not so constrained.

In the Minimal Supersymmetric SM (MSSM), decays via a charged Higgs (which couples more strongly to the heavy tau than to the lighter leptons) can interfere either constructively or destructively with the W-mediated decay, enhancing or suppressing the decay rate [11].

If a fourth-generation massive ν_4 or sterile ν_s exists, and mixes with ν_τ, it will suppress *all* the decay rates and thus the total tau lifetime.

The current accuracy of the measurements do not yield significant limits on any of these models, illustrating the need to further improve their precision.

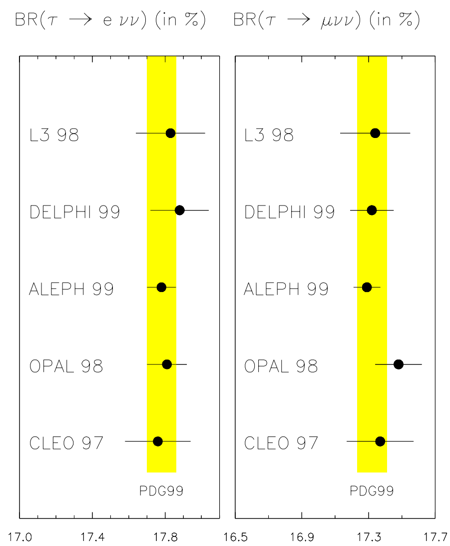

Figure 3: Summary of recent tau leptonic branching fraction measurements.

3. Michel Parameters

Although the strength of the charged weak interaction in decays of the muon and tau are well measured, the Lorentz structure in tau decays is not as well established as it is for the purely $V-A$ structure seen in muon decays. In general, the couplings can have scalar (S), pseudoscalar (P), and tensor (T) terms as well as the vector (V) and axial vector (A) contributions built into the SM. Using a general ansatz for the couplings, including all the lowest-order S, P, V, A, T terms, Michel [12] derived a form for the differential decay rate of the muon (and the tau), integrating over the unobserved ν momenta and daughter $\ell^\pm$ spin. In terms of scaled energy $x = E_\ell/E_{max}$, with $E_{max} = (m_\ell^2 + m_\tau^2)/2m_\tau$, one has:

$$\frac{d\Gamma}{dxd\cos\theta} = \Gamma_0 \frac{x^2}{2}\left[\left(12(1-x) + \frac{4\rho}{3}(8x-6) + 24\eta\frac{m_\ell}{m_\tau}\frac{(1-x)}{x}\right) - \xi\cos\theta\left(4(1-x)+\frac{4}{3}\delta(8x-6)\right)\right] \quad (3.1)$$

$$\propto x^2\left[I(x|\rho,\eta) \pm A(x,\theta|\xi,\delta)\right] \quad (3.2)$$

where Γ_0 is given in equation 2.1.

The spectral shape Michel parameters, and their SM ($V-A$) values, are:

$$\rho \simeq \frac{3}{4}\left(\frac{|g^V_{LL}|^2}{|g^V_{LL}|^2 + |g^V_{LR}|^2}\right) = \frac{3}{4}\ \text{(SM)} \quad (3.3)$$

$$\eta \propto \Re(g^V_{LL} g^{S*}_{RR} + \cdots) = 0\ \text{(SM)}. \quad (3.4)$$

The spin polarization-dependent Michel parameters are:

$$\xi \simeq -\left(\frac{|g^V_{LL}| - 3|g^V_{LR}|^2}{|g^V_{LL}|^2 + |g^V_{LR}|^2}\right) = -1\ \text{(SM)} \quad (3.5)$$

$$\delta \simeq \frac{3}{4}\left(\frac{|g^V_{LL}|^2}{|g^V_{LL}|^2 + 3|g^V_{LR}|^2}\right) = \frac{3}{4}\ \text{(SM)}. \quad (3.6)$$

3.1 Michel Parameter measurements

There are updated results from LEP [13, 14, 15, 16] and CLEO [17]. The world averages, compiled for TAU'98 [18], assuming lepton universality, are:

$$\rho_\tau = 0.750 \pm 0.011 \quad (SM = 3/4) \quad (3.7)$$

$$\eta_\tau = 0.048 \pm 0.035 \quad (SM = 0) \quad (3.8)$$

$$\xi_\tau = 0.988 \pm 0.029 \quad (SM = 1) \quad (3.9)$$

$$\xi_\tau\delta_\tau = 0.735 \pm 0.020 \quad (SM = 3/4). \quad (3.10)$$

The tau Michel parameter measurements are now *precision* physics, although they are still far from the precision obtained with muons [1]. They are *consistent* with being entirely $V-A$ in structure (left-handed vector couplings). They strongly limit the probability of right-handed τ couplings to the weak charged current P^τ_R; for example, CLEO [19] sets the the limit $P^\tau_R < 0.044$ at 90% CL. However, for left-handed τ couplings, it is currently not possible to distinguish between scalar, vector, and tensor contributions. Independent information (*e.g.*, from the cross section $\sigma(\nu_\tau e^- \to \tau^-\nu_e)$) is needed to distinguish between the possible left-handed τ couplings.

The limit on right-handed couplings can be interpreted in terms of limits on right-handed W_R bosons. In Left-Right symmetric models [20], two charged boson mass eigenstates M_1, M_2 mix to give the "light" W_L of the SM, and a heavy W_R. The parameters in these models are $\alpha = M(W_1)/M(W_2)$, and the mixing angle ζ; both are zero in the SM. The heavy right-handed $W^\pm_R$ will contribute to the decay of the tau, interfering with the left-handed W^-, and producing deviations from the Standard Model values for the Michel parameters ρ and ξ. CLEO [19] obtains limits on α and ζ in these models, shown in figure 4. For mixing angle $\zeta = 0$, they obtain $M_R > 304$ GeV/c^2 at 90 % CL, and for free mixing angle ζ, they obtain $M_2 > 260$ GeV/c^2 at 90 % CL.

The consistency of the Michel parameters with SM predictions permits a limit to be set on the mass of a (scalar) charged Higgs boson, in the context of the MSSM [11]. For the η parameter,

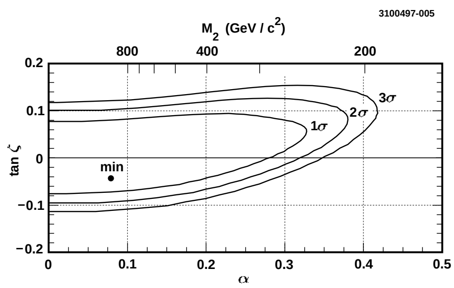

Figure 4: Limits on the mass ratio α and the mixing angle ζ of a Left-Right symmetric model [19].

the dependency is:

$$\eta \approx - \; m_\tau m_\mu tan^2\beta/(2m_H^2), \qquad (3.11)$$

with similar formulas for ξ and $\xi\delta$. Using the world average measurements of η, ξ, and $\xi\delta$ combined, one obtains:

$$m_{H^\pm} > 2.5 \tan\beta \text{ GeV/c}^2 \quad \text{at 90\% CL.} \qquad (3.12)$$

This is competitive with other direct and indirect search limits (shown in figure 5) for two-Higgs-doublet mixing angles $\tan\beta \gtrsim 30$.

DELPHI has taken the analysis one step further, by probing *derivative* terms in the interaction Lagrangian (beyond the Michel ansatz). DELPHI measures [16] the anomalous tensor coupling κ by analyzing the tau leptonic decays with the usual Michel parameters fixed to their SM values. They measure

$$\kappa = -0.029 \pm 0.036 \pm 0.018, \qquad (3.13)$$

in agreement with the SM expectation of $\kappa = 0$.

Once again, many extensions to the SM predict deviations of these parameters from their SM values. It is thus worth improving the precision of these measurements, to push the limits on contributions from charged Higgs, right-handed W's, and other anomalous couplings.

4. $W \to \tau\nu$

The strength of the weak charged current coupling to the τ can also be measured in τ production from real W decays.

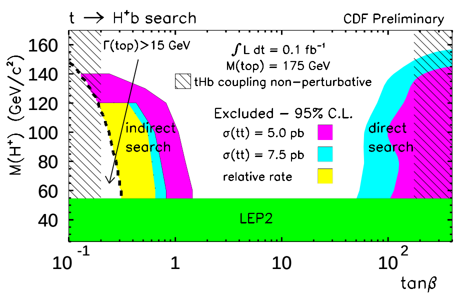

Figure 5: Direct and indirect search limits for charged Higgs mass versus $\tan\beta$.

4.1 $W \to \tau\nu$ at LEP II

All four LEP II experiments use the reaction $e^+e^- \to W^+W^-$ to measure the ratio of rates $(W \to \tau\nu) : (W \to \mu\nu) : (W \to e\nu)$. The results are summarized [21] in figure 6. There is excellent consistency between experiments, final state leptons, and SM predictions. Charged current universality is confirmed to 4.0% via these measurements.

4.2 $W \to \tau\nu$ from $p\bar{p}$

Real W bosons are also produced at $p\bar{p}$ colliders, via the reaction $p\bar{p} \to W^\pm X$, $W \to \ell\nu$. There are measurements of the coupling ratio g_τ/g_e from UA1, UA2, CDF, and D0. The world average [22] is $g_\tau/g_e = 1.003 \pm 0.025$, confirming charged current universality at the 2.5% level. As seen in Section 2 above, charged current universality is tested in tau leptonic decays to 0.25%.

5. Z^0 Couplings

The weak neutral current couplings of the tau are directly measured in tau pair production via $e^+e^- \to Z^0 \to \tau^+\tau^-$. All four LEP experiments, and SLD, measure a large number of relevant observables.

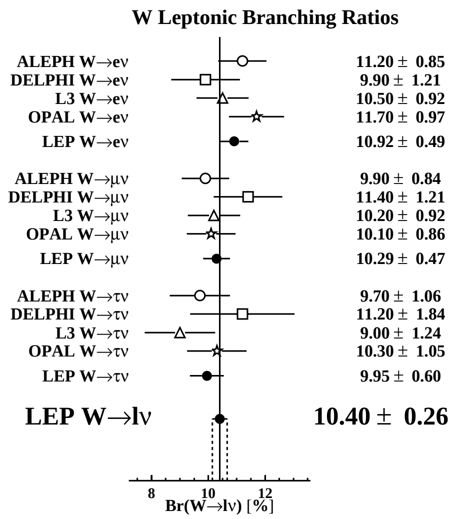

Figure 6: Branching fractions $\mathcal{B}(W \to \ell\nu_\ell)$ measured by the four LEP II experiments [21].

5.1 R_τ and A_{FB}

The LEP experiments measure the ratio $R_\tau = \Gamma(Z \to \text{hadrons})/\Gamma(Z \to \tau\tau)$, and the forward-backward asymmetry $A_{FB}(Z^0 \to \tau^+\tau^-)$. The LEP averages for these quantities [23] and for the analogous quantities for the light leptons, are shown in figure 7. All three lepton species have values consistent with each other and with the SM prediction (assuming universality of the weak neutral current). In particular, the equality $R_e = R_\mu = R_\tau$ is tested to a precision of 0.3%.

5.2 τ polarization at Z^0

All four LEP experiments measure the tau polarization $P_\tau(\cos\theta)$ as a function of the τ production angle θ, using the decay modes $e\nu\nu$, $\mu\nu\nu$, $\pi\nu$, $\rho\nu$, and $3\pi\nu$. From the measured $P_\tau(\cos\theta)$ distributions (see example in figure 8), they extract the asymmetry parameters

$$\mathcal{A}_\ell \equiv (2g_v^\ell g_a^\ell)/((g_v^\ell)^2 + (g_a^\ell)^2) \qquad (5.1)$$

for $\ell = e$ and τ. A summary of the results from LEP [25] is also shown in figure 8. The world average results are

$$\mathcal{A}_\tau = (14.31 \pm 0.45)\%; \quad \mathcal{A}_e = (14.79 \pm 0.51)\%. \qquad (5.2)$$

5.3 $A_{LR}^\tau(\cos\theta)$ from SLD

SLD measures the tau polarization as a function of the τ production angle θ, separately for left- and right-handed beam electron polarizations at the SLC [26]. These are shown in figure 9. From these measurements, they form the asymmetry $A_{LR}^\tau(\cos\theta)$. This allows them to extract values for $\mathcal{A}_e$ and $\mathcal{A}_\tau$ of relatively high precision, despite low statistics. They obtain [26]

$$\mathcal{A}_\tau = (14.2 \pm 1.9)\%; \quad \mathcal{A}_e = (15.0 \pm 0.7)\%. \qquad (5.3)$$

5.4 NC Lepton Universality

The measurements discussed in this section can be combined to extract the vector and axial vector weak neutral current coupling constants g_v and g_a for the tau (and the other leptons). The results from LEP and SLD for all three charged leptons is summarized [27] in figure 10.

There is fine agreement between experiments, and all the leptonic couplings are consistent with each other and with the SM prediction. The latter depends on the SM Higgs mass, and it can be seen that a low-mass Higgs is favored. Non-SM contributions, as measured by the model-independent S and T parameters [28] are strongly constrained [27].

Since all measurements are consistent with the SM predictions, they can be used to extract the value of the SM parameter $\sin^2\theta_{eff}$. This can then be compared with the value, and errors, for this parameter obtained from studies of $Z^0 \to q\bar{q}$. This comparison [27] is shown in figure 11. We see that the measurement of $_\tau$ provides one of the most precise methods for obtaining $\sin^2\theta_{eff}$. The LEP and SLD results are completely consistent for the lepton measurements; the LEP values for R_b, A_{FB}^b, A_{FB}^c pull the LEP average away from SLD, but not very significantly so.

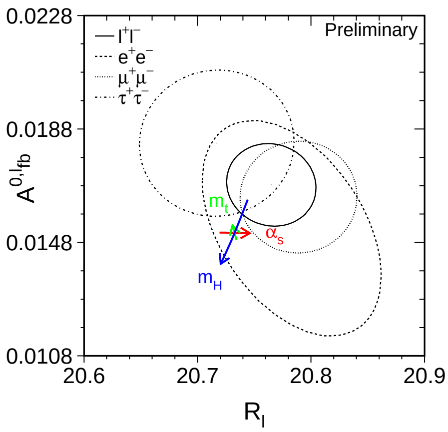

Figure 7: Measurements of R_τ and A_{FB} for $Z^0 \to \ell^+\ell^-$, from LEP [27].

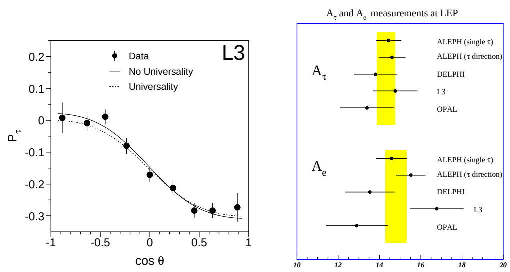

Figure 8: Left: Measurement of $P_\tau(\cos\theta)$ from L3 [24]; Right: summary of the results from LEP on $\mathcal{A}_\tau$ and $\mathcal{A}_e$ from tau polarization [25].

6. Dipole Moments

The pure vector nature of the electromagnetic couplings is modified due to radiative corrections, which induce magnetic dipole tensor couplings. If the lepton or quark is composite, and if CP is violated, electric dipole couplings also appear.

Analogous couplings also appear for the weak interactions. In addition to the SM Lagrangian for $Z^0\tau\tau$, which includes vector and axial vector couplings, it is natural to consider extensions that add tensor couplings, corresponding to weak electric and weak magnetic dipole moment couplings [29].

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{2}\cdot\frac{eF_2^w(q^2)}{2m_\tau}\bar{\psi}\sigma^{\mu\nu}\psi Z_{\mu\nu} - \frac{i}{2}\cdot\frac{eF_3^w(q^2)}{2m_\tau}\bar{\psi}\sigma^{\mu\nu}\gamma_5\psi Z_{\mu\nu}. \quad (6.1)$$

Here, ψ is the quantum field of the tau, $Z_{\mu\nu}$ is the Z^0 field strength tensor, and $F_2^w(q^2)$ and $F_3^w(q^2)$ are the weak magnetic and weak electric form factors, respectively. The anomalous weak magnetic moment, and the CP-violating weak electric dipole moment, of the tau are:

$$a_\tau^w \equiv F_2^w(m_Z^2), \qquad d_\tau^w \equiv \frac{eF_3^w(m_Z^2)}{2m_\tau} \quad (6.2)$$

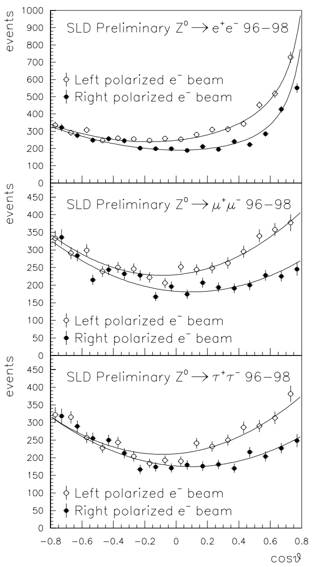

Figure 9: The τ production angle distribution for left- and right-handed beam electron polarizations from SLD [26].

Predictions for the values of these weak dipole moments, in the SM and beyond, are [30, 32]:

$$\begin{aligned} a_\tau^W &= -(2.1+0.6i)\times 10^{-6}(\text{SM}) && (6.3)\\ &\to 10^{-5} \quad (\text{MSSM}) && (6.4)\\ &\to 10^{-3} \quad (\text{composite}) && (6.5)\\ d_\tau^W &= 3\times 10^{-37}\text{e}\cdot\text{cm} \quad (\text{SM-CKM}) && (6.6)\\ &\to \text{few} \quad \times 10^{-20} \quad (\text{MSSM, LQ}) && (6.7)\end{aligned}$$

The $\to$ symbol denotes that predictions can range up to values as large as those shown.

Weak magnetic dipole couplings produce parity-odd azimuthal asymmetries [31]. For example, in $\tau^+ \to \pi^+\bar{\nu}_\tau$, the expectation value for $< \hat{p}_{\tau^+} \times \hat{p}_{e^+}\cdot\hat{p}_{\pi^+} >$ is proportional to a_τ^W. If it is anomalously large, it would be measurable at LEP. L3 has measured this azimuthal asymmetry using $\tau \to \pi\nu$ and $\rho\nu$. Seeing no significant asymmetry, it sets the limits [30]

$$\begin{aligned} Re(a_\tau^W) &= (0.0 \pm 1.6 \pm 2.3)\times 10^{-3} && (6.8)\\ Im(a_\tau^W) &= (-1.0 \pm 3.6 \pm 4.3)\times 10^{-3} && (6.9)\end{aligned}$$

6.1 CP violating Weak-Electric Dipole Moment

A non-zero weak electric dipole moment (weak EDM) of the tau would be evidence for both substructure and CP violation in the lepton sector. It would induce modifications to the spin structure in $e^+e^- \to Z^0 \to \tau^+\tau^-$ [29]. The subsequent tau decays can be used to analyze the

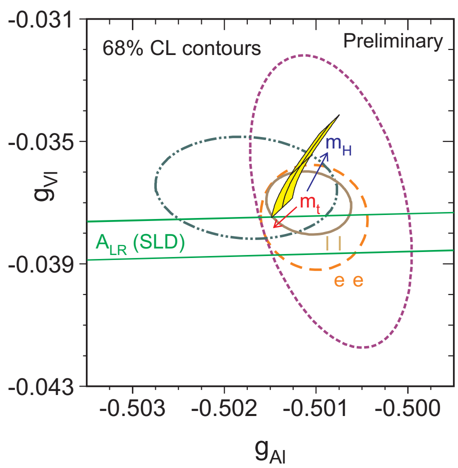

Figure 10: Extracted values for the weak neutral current couplings g_v and g_a for the leptons, from LEP and SLD [27], compared with SM predictions.

spins of both taus in an event, and seach for CP-odd spin polarizations and correlations. These also take the form of triple product observables which are CP-odd.

A set of optimized CP-violating observables have deen defined [29], and have been measured by the LEP experiments [33], using most tau decays (ℓ, π, ρ, a_1) as spin analyzers. Simulated spectra, illustrating the effect for non-zero weak EDM, are shown in figure 12. The measurements of Re(d_τ^W), Im(d_τ^W) from LEP are shown in figure 13, and the limits from the combined data are [32]:

$$|Re(d_\tau^W)| < 3.0 \times 10^{-18} e \cdot cm \quad (6.10)$$
$$|Im(d_\tau^W)| < 9.2 \times 10^{-18} e \cdot cm \quad (6.11)$$
$$|d_\tau^W| < 9.4 \times 10^{-18} e \cdot cm \quad (6.12)$$

6.2 Weak Dipole Moments: SLD

The electron beam longitudinal polarization available at the SLC collider enhances the ability of the SLD detector to measure the weak dipole moments, especially Im(d_τ^W). They do an unbinned likelihood fit to the full event kinematics, using tau pairs which decay to (ℓ, π, ρ). This allows them to measure the real and imaginary parts of both weak dipole moments, and set the limits [34]:

$$Re(a_\tau^W) < 2.47 \times 10^{-3} \quad (6.13)$$
$$Im(a_\tau^W) < 1.25 \times 10^{-3} \quad (6.14)$$
$$Re(d_\tau^W) < 1.35 \times 10^{-17} e \cdot cm \quad (6.15)$$
$$Im(d_\tau^W) < 0.87 \times 10^{-17} e \cdot cm \quad (6.16)$$

which are quite competitive with the LEP averages, despite much smaller statistics.

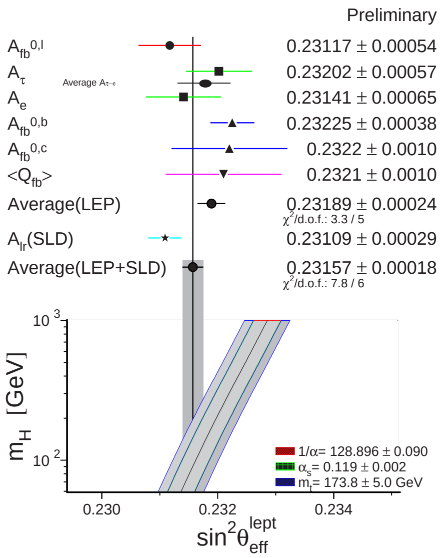

Figure 11: Extracted values for $\sin^2\theta_{eff}$ from measurements at the Z^0 [27].

6.3 EM dipole moments

Despite the dominance of the Z^0 over the virtual photon at LEP I, the electromagnetic dipole moments can be measured using radiative events, $e^+e^- \to Z^0 \to \tau^+\tau^-\gamma$. Anomalously large electromagnetic dipole moments will produce an excess of events with a high energy photon, away from both the beam e^+ and τ^+ momentum axes [35].

L3 [36] and OPAL [37] compare the observed spectra in E_γ vs $\cos\theta_\gamma$ for radiated photons to predictions from the SM with the addition of anomalously large electromagnetic dipole moments, and set limits on a_τ^γ and d_τ^γ. The L3 spectra are shown in figure 14. The resulting limits are [38]:

$$|a_\tau^\gamma| < 0.06 \quad (SM : \frac{\alpha}{2\pi} = 0.011) \quad (6.17)$$
$$|d_\tau^\gamma| < 3.1 \times 10^{-16} \quad (SM : 0(\not{CP})). \quad (6.18)$$

For comparison, the limit on the electric dipole moment of the electron is $|d_e^\gamma| < 5 \times 10^{-25} e \cdot cm$ [1].

7. Other searches for new couplings

Searches have also been made for other non-SM currents such as the flavor-changing neutral currents (FCNC) $\tau \leftrightarrow e$ and $\tau \leftrightarrow \mu$ in neutrinoless tau decay, and $\nu_\tau \leftrightarrow \nu_e$ and $\nu_\tau \leftrightarrow \nu_\mu$ in neutrino oscillation experiments.

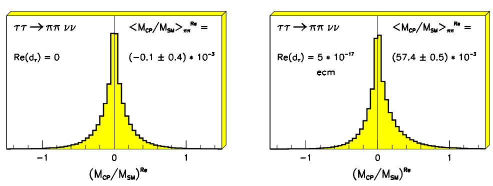

Figure 12: Simulation of the distribution of optimal CP-violating observables in $Z^0 \to \tau^+\tau^-$, for the case of no WEDM (left), and for non-zero WEDM (right) [32].

7.1 Neutrinoless tau decay

All known tau decays proceed via the weak charged current: $\tau^- \to \nu_\tau W^-$. Flavor changing neutral current decays such as $\tau^- \to e^- X^0$ and $\tau^- \to \mu^- X^0$, where X^0 is some neutral current such as the photon, Z^0, or some new current, violate Lepton Flavor conservation. Lepton Flavor Violating (LFV) decays include: $\tau^- \to \ell^- \gamma$, $\ell^-\ell^+\ell^-$ $Z^0 \to \tau^- e^+$, $\tau^-\mu^+$ $\tau^- \to \ell^- M^0$, $\ell^- P_1^+ P_2^-$. Here, ℓ is e or μ, M^0 is a neutral meson, and $P^\pm$ is a charged pseudoscalar meson.

Another class of decays violate Lepton Number conservation, as well. Lepton Number Violating (LNV) decays include: $\tau^- \ell^+ P_1^- P_2^-$, and $\bar{p} X^0$. The latter conserves the difference between baryon number and lepton number $(B - L)$.

SUSY, GUTS, Left-Right symmetric models, and superstring models all predict LFV, LNV, and violations of the universality of the dominant current couplings [39] The effects are small, of the order of 10^{-6} or smaller, and are only now within the reach of experiment [40].

The most sensitive search for neutrinoless decays has been by the CLEO Collaboration, which searches for $\tau^\pm \to \mu^\pm \gamma$ with 12.6 million produced tau pairs, and sets the limit [41]: $\mathcal{B}(\tau^\pm \to \mu^\pm \gamma) < 1.1 \times 10^{-6}$ at 90% CL, which is in the range of model parameters for some supersymmetric models [39].

CLEO also searched for 28 different neutrinoless decay modes, using 4.4 million produced tau pairs [42]. The limits on the branching fractions are on the order of few $\times 10^{-6}$ or greater.

The present bounds are approaching or reaching levels where some model parameter spaces can be excluded. The models can also be pushed above the present limits; so we are already beginning to exclude such efforts. The current limits will be improved by the B Factory experiments, which will push below the 10^{-7}; they will be rare τ decay experiments.

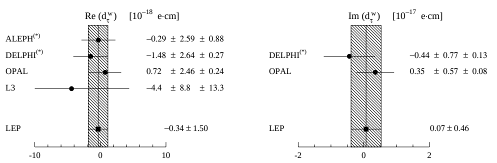

Figure 13: Summary of recent measurements of the weak electric dipole moment of the tau [32].

7.2 Neutrino oscillations

If one or more of the three neutrino flavor eigenstates (ν_e, ν_μ, ν_τ) have mass and can couple to the others, they will mix and induce neutrino oscillations, or (effective) flavor changing neutral currents.

Evidence for neutrino oscillations comes from several different experiments [43]. If the solar, atmospheric, *and* LSND observations are *all* correct, it seems to require a 4^{th} (sterile? very massive?) neutrino [43].

Only the atmospheric neutrino anomaly, in which a deficit of muon neutrinos is observed from cosmic ray showers, is likely to involve the ν_τ. The Super-Kamiokande experiment sees evidence for $\nu_\mu \to \nu_X$ oscillations [44], where ν_X may be a ν_τ or a sterile 4^{th} generation neutrino ν_s; however, some evidence favors $\nu_\mu \to \nu_\tau$ over $\nu_\mu \to \nu_{sterile}$ [45]. The deficit is consistent with maximal neutrino mixing ($\sin^2 2\theta \sim 1$), and mass-squared difference $\Delta m^2_{\mu X} \sim 10^{-2}\mathrm{eV}^2$.

This observation has spawned a host of mid- and long-baseline accelerator experiments, in which a ν_μ neutrino beam from pion decay travels some

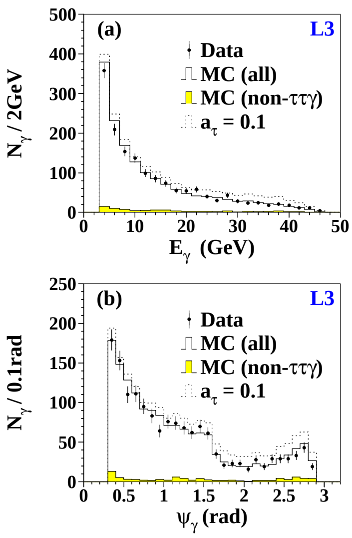

Figure 14: Spectra of E_γ and $\cos\theta_\gamma$ from L3 $\tau^+\tau^-\gamma$ events, compared with MC predictions with and without an anomalously large magnetic dipole moment [36].

distance, allowing it to oscillate into a neutrino of different flavor, which is then detected by a detector capable of distinguishing $\nu_\mu \to \mu X$ from $\nu_\mu \to \nu_\tau \to \tau X$. Two mid-baseline experiments at CERN, CHORUS [46] and NOMAD [47], have completed their run. Having failed to observe the latter reaction, they exclude $\nu_\mu \to \nu_\tau$ for $\Delta m^2 \gtrsim 40$ eV^2, $\sin^2 2\theta \gtrsim 2 \times 10^{-4}$, as shown in figure 15.

In order to reach the small Δm^2 suggested by Super-K, a new generation of long-baseline experiments are being prepared [48], including K2K, FNAL to MINOS, and CERN to Gran Sasso. These experiments will probe the region down to $\Delta m^2 \sim 10^{-3}$ eV^2, $\sin^2 2\theta \gtrsim 10^{-1}$, as illustrated in figure 16. The understanding of these flavor changing neutrino couplings is one of the major goals of particle physics in the next decade.

8. Limits on m_{ν_τ}

Requiring the mass density of neutrinos to be less than that required to over-close the universe excludes stable neutrinos with masses larger than 65 eV [49]. However, if neutrinos decay, they can evade that limit. For lifetimes in the range of $\sim$1 day $< \tau_{\nu_\tau} <\sim$ few years, neutrino masses on the order of $\sim 5 < m_\nu < 20$ MeV are allowed, where the upper bound comes from direct searches in tau decays.

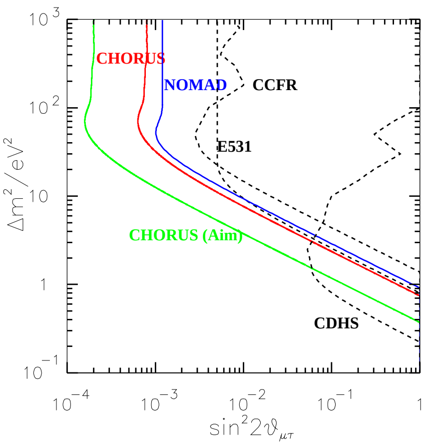

Figure 15: Exclusion limits for $\nu_\mu \to \nu_\tau$ in the space of Δm^2_ν versus $\sin^2 2\theta_{mix}$, from recent mid-baseline experiments. [46].

The technique that has yielded the best limits on the ν_τ mass in the tens-of-MeV region is the study of the two-dimensional mass and energy spectrum of the $n\pi$ final state in $\tau \to (n\pi)^- \nu_\tau$, $n \geq 3$. A deficit of events in the corner of $m_{n\pi}$, $E_{n\pi}$ space indicates the recoil of a massive neutrino. However, the spectrum is falling sharply there, leading to very limited statistics; and the spectral function governing that spectrum is not precisely known. The best limits obtained so far [49] are listed in Table 1.

ALEPH	$5\pi(\pi^0)$	22.3 MeV
ALEPH	3π	30 MeV
ALEPH	both	18.2 MeV
OPAL	5π	39.6 MeV
DELPHI	3π	28 MeV
OPAL	$3\pi - vs - 3\pi$	35 MeV
CLEO (98)	5π, $3\pi 2\pi^0$	30 MeV
CLEO (98)	4π	28 MeV

Table 1: Summary of limits on m_{ν_τ} from $\tau \to (n\pi)^- \nu_\tau$, $n \geq 3$.

It is interesting to note that the limits from CLEO [50] are not as tight as those from LEP, despite much larger statistical samples. Indeed, there are many subtle issues involved in making these measurements, regarding resolution, backgrounds, event migration, spectral functions, and the fluctuations of low statistics. The larger samples expected from the B Factory experiments should help clarify the situation considerably, and

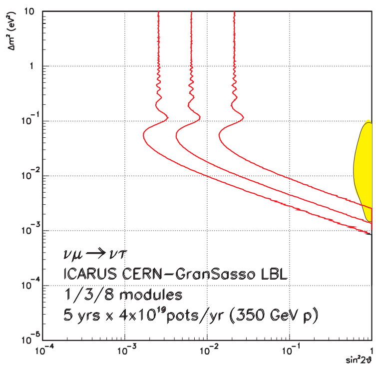

Figure 16: Exclusion limits for $\nu_\mu \to \nu_\tau$ in the space of Δm^2_ν versus $\sin^2 2\theta_{mix}$, expected from the ICARUS long-baseline experiment. The Kamiokande observation is shown in yellow.

potentially improve the limits to the 10 MeV/c^2 range.

9. Future prospects, and conclusions

Experiments at LEP, SLD, and CLEO have produced a wealth of rather precise measurements of the electroweak couplings, including limits on a range of potential couplings beyond the Standard Model ones. But new physics may (hopefully) be just around the corner, and higher precision in these very fundamental measurements may reveal it. The fact that the tau is the heaviest known lepton, free of uncertainties from non-perturbative physics, makes it a particularly sensitive probe of new, high mass scale physics.

The LEP Z^0 program is now over, but the B Factories now coming on line (CLEO III, BaBar, and Belle) will produce on the order of 10^7 $\tau^+\tau^-$ per year. This will permit a wealth of new measurements, including: rare decays ($7\pi\nu$, $\eta\pi\pi\nu$, *etc.*); forbidden (ν-less) decay (limits?); m_{ν_τ} to $\lesssim$ 10 MeV; greater precision on universality tests; greater precision on Michel Parameters, probing Higgs and W_R couplings; weak and EM dipole moments, CP violation; and deeper studies of low-mass meson dynamics. We may also see the observation of $\nu_\mu \leftrightarrow \nu_\tau$ oscillations in the long-baseline experiments now in preparation.

We can expect continued progress in τ physics in the coming years, and maybe (someday) some surprises!

Acknowledgments

The author acknowledges many fruitful conversations with M. Davier. Thanks go also to the members of the LEP and SLD collaborations who provided their latest results. Finally, the author thanks the organizers of Heavy Flavors 8 for a very enjoyable, fruitful, and well-run conference.

References

[1] C. Caso *et al.*, the Particle Data Group, *Eur. Phys. J.* **C 3** (1998) 1.

[2] SR Wasserbaech, in the proceedings of Tau '98, Santander, Spain, September 1998, *Nucl. Phys.* **76** *(Proc. Suppl.)* (1999) 107.

[3] A.P. Colijn for the L3 Collaboration, in the proceedings of Tau '98, *Nucl. Phys.* **76** *(Proc. Suppl.)* (1999) 101.

[4] A. Andreazza *et al.*, DELPHI Collaboration, DELPHI-99-133, submitted to HEP'99, Tampere, Finland, July 1999.

[5] H. Videau *et al.*, ALEPH Collaboration, ALEPH 99-014, submitted to HEP'99, Tampere, Finland, July 1999.

[6] P. Abreu *et al.*, DELPHI Collaboration, *Eur. Phys. J.* **C 10** (1999) 201.

[7] K. Ackerstaff *et al.*, OPAL Collaboration, *Phys. Lett.* **B 447** (1999) 134.

[8] B. Stugu, in the proceedings of Tau '98, *Nucl. Phys.* **76** *(Proc. Suppl.)* (1999) 123.

[9] M.T. Dova, J. Swain and L. Taylor, in the proceedings of Tau '98, *Nucl. Phys.* **76** *(Proc. Suppl.)* (1999) 101.

[10] T. Bergfeld *et al.*, CLEO Collaboration, `hep-ex/9909050`, submitted to *Phys. Rev. D.*

[11] A. Stahl, *Phys. Lett.* **B 324** (1994) 121.

[12] L. Michel, Proc. Phys. Soc. London A **63** (1950) 514; T. Kinoshita and A. Sirlin, Phys. Rev. **108** (1957) 844; C. Bouchiat and L. Michel, Phys. Rev. **106** (1957) 170; L. Okun and A. Rudik, J. Expt. Theor. Phys. (USSR) **32** (1957) 627 [Sov. Phys. JETP **6** (1957) 520].

[13] M. Wunsch for the ALEPH Collaboration, in the proceedings of Tau '98, *Nucl. Phys.* **76** *(Proc. Suppl.)* (1999) 159.

[14] M. Acciarri *et al.*, L3 Collaboration, *Phys. Lett.* **B 438** (1998) 405.

[15] K. Ackerstaff *et al.*, OPAL Collaboration, *Eur. Phys. J.* **C 8** (1999) 3.

[16] P. Seager *et al.*, DELPHI Collaboration, DELPHI-99-129, submitted to HEP'99, Tampere, Finland, July 1999.

[17] A.J. Weinstein for the CLEO Collaboration, in the proceedings of Tau '98, *Nucl. Phys.* **76** *(Proc. Suppl.)* (1999) 165.

[18] A. Stahl, in the proceedings of Tau '98, *Nucl. Phys.* **76** *(Proc. Suppl.)* (1999) 173.

[19] J. Alexander, *et al.*, CLEO Collaboration, *Phys. Rev.* **D 56** (1997) 5320.

[20] M.A.B. Bég, R. V. Budny, R. Mohapatra and A. Sirlin, *Phys. Rev. Lett.* **38** (1977) 1252.

[21] T. Moulik, in the proceedings of Tau '98, *Nucl. Phys.* **76** *(Proc. Suppl.)* (1999) 173.

[22] S. Protopopescu, in the proceedings of Tau '98, *Nucl. Phys.* **76** *(Proc. Suppl.)* (1999) 91.

[23] R.J. Sobie, in the proceedings of Tau '98, *Nucl. Phys.* **76** *(Proc. Suppl.)* (1999) 75.

[24] M. Acciarri *et al.*, L3 Collaboration, *Phys. Lett.* **B 429** (1998) 387.

[25] R. Alemany, in the proceedings of Tau '98, *Nucl. Phys.* **76** *(Proc. Suppl.)* (1999) 55.

[26] P.L. Reinertsen for the SLD Collaboration, in the proceedings of Tau '98, *Nucl. Phys.* **76** *(Proc. Suppl.)* (1999) 45. See also `hep-ex/9908006`, 1999.

[27] LEP and SLD Electroweak Working Group, CERN-EP.99-15 (1999).

[28] M.E. Peskin and T. Takeuchi, *Phys. Rev.* **D 46** (1992) 381.

[29] W. Bernreuther, U. Löw, J.P. Ma, and O. Nachtmann, *Z. Physik* **C 43** (1989) 117; W. Bernreuther and O. Nachtmann, *Phys. Rev. Lett.* **63** (1989) 2787; W. Bernreuther, G.W. Botz, O. Nachtmann, and P. Overmann, *Z. Physik* **C 52** (1991) 567; W. Bernreuther, O. Nachtmann, and P. Overmann, *Phys. Rev.* **D 48** (1993) 78; W. Bernreuther and P. Overmann, *Z. Physik* **C 73** (1997) 647; W. Bernreuther, A.Brandenburg, and P. Overmann, *Phys. Lett.* **B 391** (1997) 413.

[30] J. Bernabéu, G.A. González-Sprinberg, M. Tung, J. Vidal, *Nucl. Phys.* **B 436** (1995) 474; W. Hollik, J.I. Illana, C. Schappacher, D. Stöckinger, S. Rigolin, KA-TP-10-1998, `hep-ph/9808408` (1998).

[31] J. Vidal, J. Bernabeu and G. Gonzalez-Sprinberg, `hep-ph/9812373` and in the proceedings of Tau '98, *Nucl. Phys.* **76** *(Proc. Suppl.)* (1999) 165.

[32] A. Zalite, in the proceedings of Tau '98, *Nucl. Phys.* **76** *(Proc. Suppl.)* (1999) 229.

[33] M. Acciarri *et al.*, L3 Collaboration, *Phys. Lett.* **B 426** (1998) 207; K. Ackerstaff *et al.*, OPAL Collaboration, *Z. Physik* **C 74** (1997) 403; D. Busilic *et al.*, ALEPH Collaboration, *Phys. Lett.* **B 346** (1995) 371; M.C. Chen *et al.*, DELPHI Collaboration, DELPHI 97-70 CONF 56 (1997).

[34] K. Abe *et al.*, SLD Collaboration, SLAC-PUB-8163, Submitted to *Phys.Rev.Lett.* (1999).

[35] S.S. Gau, T. Paul, J. Swain, L. Taylor, *Nucl. Phys.* **B 523** (1998) 439.

[36] M. Acciarri *et al.*, L3 Collaboration, *Phys. Lett.* **B 434** (1998) 169.

[37] K. Ackerstaff *et al.*, OPAL Collaboration, *Phys. Lett.* **B 431** (1998) 188.

[38] L. Taylor, in the proceedings of Tau '98, *Nucl. Phys.* **76** *(Proc. Suppl.)* (1999) 237.

[39] R. Barbieri and L.J. Hall, *Phys. Lett.* **B 338** (1994) 212; J. Hisano *et al.*, *Phys. Lett.* **B 357** (1995) 579; J. Hisano and D.Nomura, *Phys. Rev.* **D 59** (1999) 116005; K.S. Babu, B. Dutta and R.N. Mohapatra, *Phys. Lett.* **B 458** (1999) 93; S.F. King and M. Oliveira, *Phys. Rev.* **D 60** (1999) 035003.

[40] R. Stroynowski, in the proceedings of Tau '98, *Nucl. Phys.* **76** *(Proc. Suppl.)* (1999) 185, and references therein.

[41] S. Ahmed *et al.*, CLEO Collaboration, `hep-ex/9910060`, Submitted to *Phys.Rev.Lett.* (1999).

[42] D.W. Bliss *et al.*, CLEO Collaboration, *Phys. Rev.* **D 57** (1998) 5903; and R. Godang *et al.*, CLEO Collaboration, *Phys. Rev.* **D 59** (1999) 091303.

[43] For a review, see, for example, MC. Gonzalez-Garcia, in the proceedings of Tau '98, *Nucl. Phys.* **76** *(Proc. Suppl.)* (1999) 185; and P. Langacker, in *Nucl. Phys.* **77** *(Proc. Suppl.)* (1999) 241.

[44] Y. Fukuda *et al.*, Super-Kamiokande Collaboration, *Phys. Rev. Lett.* **81** (1998) 1562.

[45] T. Kajita, Super-Kamiokande Collaboration, in the proceedings of Neutrino '98, *Nucl. Phys.* **77** *(Proc. Suppl.)* (1999) 123.

[46] E. Eskut *et al.*, CHORUS Collaboration, *Phys. Lett.* **B 434** (1998) 205.

[47] P. Astier *et al.*, NOMAD Collaboration, *Phys. Lett.* **B 453** (1999) 169.

[48] See, for example, contributions from NuMi and MINOS (S.G. Wojcicki, P. 182); CERN-LNGS (P. Picchi, p. 187); K2K (K. Nishikawa, p. 198); in the proceedings of Neutrino '98, *Nucl. Phys.* **77** *(Proc. Suppl.)* (1999) 401.

[49] R. McNulty, in the proceedings of Tau '98, *Nucl. Phys.* **76** *(Proc. Suppl.)* (1999) 409, and references therein.

[50] R. Ammar *et al.*, CLEO Collaboration, *Phys. Lett.* **B 431** (1998) 209; M. Athanas *et al.*, CLEO Collaboration, `hep-ex/9906015`, submitted to *Phys. Rev. Lett.* (1999).