# Electroweak Couplings of the $\tau$ from LEP

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**Abstract.** This note reviews LEP measurements of the couplings of the $\tau$ lepton to the electroweak gauge bosons.

## Introduction

$\tau$ lepton production and decay has been studied at LEP for nearly ten years, and among the profusion of results are fairly detailed analyses of the couplings of the $\tau$ to the electroweak gauge bosons. This note briefly discusses a few of these measurements. The majority of the results discussed are based on the LEPI samples of $e^+e^- \to \tau^+\tau^-$ events.

## Weak neutral current couplings of the $\tau$

Studies of $\tau - Z$ couplings have been largely based on detailed spin analyses of the $\tau$. Unlike the other leptons, $\tau$'s decay inside the LEP detectors and measurements of the energy and angular distributions of the decay products can be used to infer the $\tau$ polarization state. The longitudinal component of the polarization is sensitive to the vector and axial-vector couplings of both the $\tau$ and the electron to the Z, and thus contributes to the precision electroweak measurements discussed elsewhere [1]. In addition to this, correlations among transverse and normal spin components have been extracted from distributions of the aplanarity of $\tau$ decay products [2]. Though these measurements are not competitive with longitudinal polarization in terms of sensitivity to vector and axial vector couplings, transverse-normal spin correlations are potentially sensitive to CP violating effects.

Transverse and normal spin components have also been employed to search for anomalous $Z - \tau - \tau$ couplings, which may be introduced to the theory through an effective Lagrangian:

$$\mathcal{L}_{\mathrm{int}}^{eff} = \frac{1}{2}\frac{eF_2^w}{2m_\tau}\overline{\psi}\sigma^{\mu\nu}\psi Z_{\mu\nu} - \frac{i}{2}\frac{eF_3^w}{2m_\tau}\overline{\psi}\sigma^{\mu\nu}\gamma_5\psi Z_{\mu\nu} \tag{1}$$

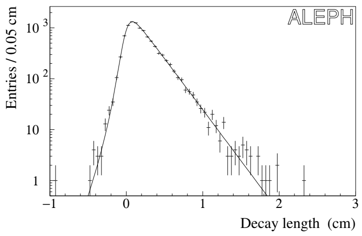
where the so-called weak electric and magnetic dipole moments are given in terms of the form factors, the electric charge, and $\tau$ mass as $d^w_\tau = eF^w_3/2m_\tau$ and $a^w_\tau = F^w_2$ respectively. In the standard model, loops endow $d^w_\tau$ and $a^w_\tau$ with values that are non-zero, but too tiny to measure at LEP [4]; conversely, unexpectedly large values would signal something new. The LEP experiments have determined [3] $Re(d^w_\tau) = (-0.34 \pm 1.50) \times 10^{-18}\text{e} \cdot \text{cm}$, $Im(d^w_\tau) = (0.07 \pm 0.46) \times 10^{-17}\text{e} \cdot \text{cm}$, $Re(a^w_\tau) = (0.0 \pm 2.8) \times 10^{-3}$, and $Im(a^w_\tau) = (-1.0 \pm 5.9) \times 10^{-3}$.

## Charged current couplings of the $\tau$

The first question one may wish to pose concerning the $\tau - W$ coupling is whether its strength is the same as the weak coupling enjoyed by the other leptons. The rate for $\tau$ decays is given by,

$$\Gamma(\tau \to \ell\nu_\tau\bar{\nu}_\ell) = \frac{\mathcal{B}_\ell}{\tau_\tau} = \frac{G_F^2 m_\tau^2}{192\pi^3} f(x_l^2) r_{\text{RC}} \tag{2}$$

where $\ell$ is an electron or muon, $\mathcal{B}_\ell$ indicates the branching fraction, $f(x_l^2)$ is a phase space factor and $r_{\text{RC}}$ contains effects of radiative corrections. The Fermi coupling, $G_F$, is proportional to the product of the coupling constants, $g_\ell$ and $g_\tau$; under lepton universality these are assumed to be identical. From equation 2 and the corresponding expression for muon decay, one can write the ratios $g_\tau/g_\mu$ and $g_\tau/g_e$ in terms of the leptonic branching fractions and the lifetimes and masses of the $\tau$ and muon. LEP is well suited to the $\tau$ lifetime measurement because of the large boost of the $\tau$'s. The figure at the right shows an ALEPH measurement of the distribution of the distance from the $e^+e^-$ interaction point to the $\tau$ decay vertex for the 3 pion mode; the lifetime is clearly visible. All four LEP experiments have performed measurements of the $\tau$ lifetime and leptonic branching fractions [5], and combining them leads to $g_\tau/g_\mu = 0.9996 \pm 0.0025$, $g_\tau/g_e = 0.9989 \pm 0.0024$, which are evidently consistent with the universality hypothesis. In addition, the rates for on-shell W decays to the three different leptons have been measured at LEP2 [1], again supporting universality, though with less precision than the aforementioned measurements.




The Lorentz structure of the charged current is also accessible at LEP. The usual approach has been to propose a general derivative-free four-fermion contact interaction:

$$\mathcal{M} = \frac{4G_F}{\sqrt{2}} \sum_{\substack{\gamma=S,V,T \\ \lambda,\iota=R,L}} g^\gamma_{\lambda\iota} < \bar{l}_\lambda|\Gamma^\gamma|(\nu_l)_n >< (\overline{\nu}_\tau)_m|\Gamma_\gamma|\tau_\iota > . \tag{3}$$

where $\gamma$ labels the interaction type as vector, scalar or tensor, and $\lambda$ and $\iota$ indicate whether the incoming and outgoing fermions are right or left handed. In the standard model, the charged current includes only vector interactions between left-handed leptons, that is $g^{\mathrm{V}}_{\mathrm{LL}} = 1$ and all other constants are zero. The well-known Michel parameters are bilinear combinations of these constants. The shapes of the energy distributions of the final state leptons are sensitive to four of the Michel parameters [6] and the $\tau$ polarization, while semileptonic decay spectra can be described in terms of the $\tau$ polarization together with a single parameter, $\xi_{\mathrm{had}}$, which turns out to be the average helicity of the $\nu_\tau$.

The LEP experiments have performed global fits to the joint and single-sided leptonic and semileptonic decay distributions [1] to extract the Michel parameters [7]. The combined results are given in table 1.

**TABLE 1.** Michel parameter measurements from LEP shown separately for electronic and muonic decays as well as for the universality assumption. The electronic mode has no sensitivity to $\eta$.

| Parameter | e | $\mu$ | assuming universality | SM expectation |
|---|---|---|---|---|
| $\rho$ | $0.751 \pm 0.020$ | $0.796 \pm 0.032$ | $0.747 \pm 0.008$ | 0.75 |
| $\eta$ | | | $0.030 \pm 0.029$ | 0 |
| $\xi$ | $1.015 \pm 0.079$ | $1.050 \pm 0.110$ | $0.969 \pm 0.028$ | 1 |
| $\xi\delta$ | $0.800 \pm 0.060$ | $0.791 \pm 0.060$ | $0.744 \pm 0.021$ | 0.75 |
| $\xi_{\mathrm{had}}$ | | | $-0.995 \pm 0.006$ | -1 |

## Anomalous electromagnetic moments of the $\tau$

Reminiscent of the anomalous weak dipole moments discussed previously, electromagnetic form factors can be introduced at the $\tau - \tau - \gamma$ vertex by replacing the $\gamma^\mu$ in the current by a more general Lorentz invariant form,

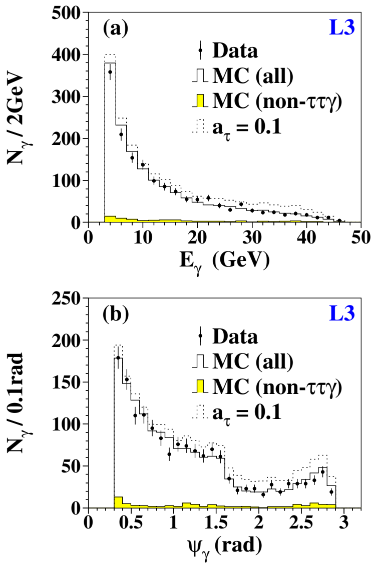
$$F_1(q^2)\gamma^\mu + (iF_2(q^2)/2m_\tau)\sigma^{\mu\nu}q_\nu - F_3(q^2)\sigma^{\mu\nu}\gamma^5 q_\nu \tag{4}$$

If $q^2 = 0$ and if the $\tau$ is on-shell at both sides of the $\tau - \tau - \gamma$ vertex, then two of these form factors correspond to the electric and magnetic dipole moment anomalies for the $\tau$: $F_3(0) = d_\tau/Q_\tau$ and $F_2(0) = a_\tau = (g_\tau - 2)/2$ where $Q_\tau$ is the $\tau$ charge. A non-zero value of $d_\tau$ is forbidden by T invariance, while the standard model predicts $a_\tau = 0.0011773(3)$ [8]. Though this expectation for $a_\tau$ is beyond current experimental reach, new phenomena could increase its value [9].

Large values of $a_\tau$ or $d_\tau$ would alter the energy and angular distributions of the final state particles in $e^+e^- \to \tau^+\tau^-\gamma$ events, generally enhancing production of high energy, isolated photons [10]. Such distributions have been measured [11], and the figure shows an L3 measurement of the distributions of the photon energy, the angle between the photon and the nearest $\tau$ decay product, and an example of what the distribution would look like for a large $a_\tau$. There is

[1] Fitting joint distributions allows disentanglement of the effects of $\tau$ polarization from those of the $\xi$ and $\xi\delta$ parameters.

no evidence in the data for anything unexpected, and the following limits have been placed: $-0.052 < a_\tau < 0.058$ and $-3.7 \times 10^{-16} \mathrm{e} \cdot \mathrm{cm} < d_\tau < 3.7 \times 10^{-16} \mathrm{e} \cdot \mathrm{cm}$.




## Conclusions

Thus far the $\tau$ appears identical to the other leptons in all respects except its mass and apparently distinct (and conserved) lepton number. This note has described some of the LEP contributions to measurements of $\tau$ electroweak couplings; these support the universality hypothesis at the per mil level in some cases. Though the LEP era is now drawing to a close, we can, in the near term, look to the b factories to continue the enterprise.

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