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TESTS OF LEPTON UNIVERSALITY FROM TAU DECAYS AT LEP [1]

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Abstract

Recent results from LEP have greatly improved our knowledge of the tau lepton charged current. Results on the Lorentz structure of the current are consistent with the predictions of V−A theory. Precise measurements of the tau leptonic branching ratios and tau lifetime have enabled e-μ-τ universality of the charged current to be confirmed at the 0.3% level.

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1 Introduction

The four LEP experiments have contributed greatly to the understanding of the tau lepton charged current. Recent measurements have enabled the Standard Model expectation of a V$-$A structure to be tested. Furthermore, the Standard Model assumes that the strength of the leptonic charged current is flavour independent. The LEP measurements of the leptonic branching ratios of the tau lepton and its lifetime provide a high precision test of e-μ-τ universality of the charged current. Any deviations from the expected V$-$A structure or indications of flavour dependence of the leptonic charged current would signal deviations from the Standard Model.

2 The Lorentz Structure of the τ Charged Current

The V$-$A theory of weak interactions has been successful in describing the structure of the charged current in muon decay. Recent measurements have addressed the question of whether it also describes the tau lepton charged current.

2.1 Leptonic Decays

The most general Lorentz invariant, derivative free, form for the leptonic charged current can be written as a linear combination of vector (γ^μ), axial-vector ($\gamma^\mu\gamma^5$), scalar (1), pseudo-scalar (γ^5) and tensor ($\sigma^{\mu\nu}$) terms:

$$J_l^\mu = \frac{g_l}{2\sqrt{2}}(\gamma^\mu(g_l^{\mathbf{V}} + g_l^{\mathbf{A}}\gamma^5) + (g_l^{\mathbf{S}} + g_l^{\mathbf{P}}\gamma^5) + g_l^{\mathbf{T}}\sigma^{\mu\nu}). \tag{1}$$

The Standard Model assumes a pure V$-$A form with the only non-zero contributions being $g_l^{\mathbf{V}} = 1$ and $g_l^{\mathbf{A}} = -1$.

The kinematics of the leptonic tau decays can be described by the relative strengths of these couplings for both the tau lepton and the lepton into which it decays (either an electron or a muon). Assuming this general form for leptonic currents, the distribution of the energy of the daughter lepton ($x = E_l/E_\tau$) can be written as:

$$\begin{aligned}\frac{d\Gamma}{dx d\Omega} = x^2\{3(1-x) &+ 2\rho(\frac{4}{3}x - 1) + \eta\frac{m_l}{m_\tau}.6(1-x)x \\ &- P_\tau\xi\cos\theta[(1-x) + 2\delta(\frac{4}{3}x - 1)]\},\end{aligned} \tag{2}$$

where P_τ is the tau polarization and θ is the angle between the lepton momentum and the tau direction. The quantities ρ, η, ξ and δ are the *Michel Parameters*[1)] of the decay. The Michel parameters can be expressed in terms of the couplings that enter in the leptonic currents[2)]. For example, if it is assumed that the electron (or muon) current is described by V$-$A, as is observed experimentally, and the tau leptonic current only has contributions from vector and axial vector couplings then:

$$\rho = \xi\delta = \frac{3}{8}\frac{(g_\tau^{\mathbf{V}} - g_\tau^{\mathbf{A}})^2}{(g_\tau^{\mathbf{V}})^2 + (g_\tau^{\mathbf{A}})^2}, \tag{3}$$

$$\xi = \frac{3}{2} + \frac{g_\tau^{\mathbf{V}} g_\tau^{\mathbf{A}}}{(g_\tau^{\mathbf{V}})^2 + (g_\tau^{\mathbf{A}})^2} \tag{4}$$

$$\text{and} \quad \eta = 0. \tag{5}$$

By measuring the differential decay spectra it is possible to extract values of the Michel parameters which in turn place constraints on couplings contributing to the leptonic currents. Any deviation from the SM expectation for these parameters would indicate contributions from couplings other than V$-$A.

2.2 Semi-leptonic Decays

The above formalism applies to leptonic decays but the V$-$A structure of the τ current can also be tested in semi-leptonic decays. If it is assumed that the τ current has only vector and axial vector contributions, then the decay dynamics into hadronic states can be written in the form:

$$\frac{d\Gamma}{d\omega} = F_h(\omega) - h(\nu_\tau)P_\tau G_h(\omega), \tag{6}$$

where ω is calculated from the obsevables of the hadronic state (*e.g.* for $\tau \to \pi\nu_\tau$ decays $\omega = x = E_\pi/E_\tau$). The quantity $h(\nu_\tau)$ is twice the ν_τ helicity and can be expressed in terms of the couplings as:

$$h(\nu_\tau) = -2\frac{g_\tau^{\mathbf{V}} g_\tau^{\mathbf{A}}}{(g_\tau^{\mathbf{V}})^2 + (g_\tau^{\mathbf{A}})^2}, \tag{7}$$

$$\text{where} \quad h(\nu_\tau) = \begin{cases} -1 & \text{for V}-\text{A} \\ +1 & \text{for V+A.} \end{cases} \tag{8}$$

2.3 Measurements of the Michel Parameters and $h(\nu_\tau)$ in τ Decay

Table 1 summarizes the experimental determinations of the Michel parameters for muon decay[3]. The results are consistent with the SM V$-$A hypothesis at the 1 % level. For this reason it is reasonable to assume a V$-$A form for the electron and muon currents in the leptonic decays of the tau.

Parameter	Value	V$-$A Expectation
ρ_μ	0.7518$\pm$0.0026	0.75
η_μ	-0.007$\pm$0.013	0
ξ_μ	1.003$\pm$0.008	1
δ_μ	0.749$\pm$0.004	0.75

Table 1: Michel Parameters for Muon decay compared with expectation.

Until recently measurements of the Michel parameters in the tau sector have been dominated by the ARGUS[4–7] experiment at DESY. These measurements have now been performed at LEP by the ALEPH[8] and L3[9] collaborations. Both experiments take advantage of the fact that tau pairs at LEP are, to a good approximation, produced with opposite helicities. This is a consequence of assuming only vector and axial vector contributions in the decay $Z^0 \to \tau^+\tau^-$. For the case where both taus decay semi-leptonically the joint decay distribution can be written:

$$\frac{1}{\Gamma}\frac{d^2\Gamma}{dx_1 dx_2} = F_1F_2 + h(\nu_\tau)^2 G_1G_2 - P_\tau h(\nu_\tau)(G_1F_2 + G_2F_1), \tag{9}$$

where the functions F_1, F_2, G_1 and G_2 depend on the hadronic decay mode. Leptonic decays are incorporated by writing equation 2 in a similar form to that used for the hadronic decays:

$$i.e.\ \frac{d\Gamma_l}{dx} = F_l(x) - P_\tau G_l(x). \tag{10}$$

Both ALEPH and L3 use binned maximum likelihood fits to the joint decay distribution using identified tau decays (where only one decay mode is identified a one-dimensional fit is performed). ALEPH use decays identified as $\tau \to e\nu_\tau\overline{\nu}_e$, $\tau \to \mu\nu_\tau\overline{\nu}_\mu$, $\tau \to \pi\nu_\tau$, $\tau \to \rho\nu_\tau$ and $\tau \to a_1\nu_\tau$, whereas L3 exclude the a_1 channel. A common fit to all leptonic and semi-leptonic decay channels gives a simultaneous measurement of the Michel parameters $(\rho, \eta, \xi, \delta\xi)$, the neutrino helicity in hadronic decays, $h(\nu_\tau)$, and the tau polarization, P_τ. The results of the fits are shown in table 2 along with a summary of the ARGUS measurements[10]. It is worth noting that fitting the distribution described by equation 9 results in an ambiguity in the sign of $h(\nu_\tau)$. The sign has been determined to be negative from other measurements; *e.g.* from the invariant mass distributions of the decay products in $\tau \to a_1\nu_\tau$[11,12].

	ρ	η	ξ	$\eta\delta$	$h(\nu_\tau)$
ALEPH	0.75±0.05	-0.04±0.18	1.18±0.18	0.88±0.13	-1.01±0.04
ARGUS	0.74±0.04	+0.03±0.22	0.97±0.14	0.65±0.12	-1.02±0.04
L3	0.81±0.05	+0.10±0.23	0.95±0.25	0.73±0.19	-1.02±0.08
Average	0.76±0.03	+0.02±0.12	1.05±0.10	0.75±0.08	-1.012±0.025
SM	0.75	0.00	1.00	0.75	-1.00

Table 2: Measurements of the Michel Parameters for tau decays.

The measurements of the Michel parameters for tau decay are consistent with the expectation from V−A theory, however, the measurements are an order of magnitude less precise than those for muon decay. Assuming the tau lepton current is a combination of vector and axial-vector contributions then equations 3, 4 and 8 can be used to place limits on the right-handed (V+A) contribution to the tau charged current. The above results imply that right-handed contribution is less than 13 %:

$$\frac{g_R^\tau}{g_L^\tau} \leq 13\% \text{ at the } 90\% \text{ C.L.} \tag{11}$$

3 Tests of Charged Current Coupling Universality

Measurements of the tau lifetime and its leptonic branching ratios provide a test of the universality of the strength of the charged current coupling. The production of boosted tau pairs at LEP, in conjunction with the the excellent detector capabilities of the four experiments, makes it a nearly ideal environment for making these measurements. Consequently over the last few years our knowledge of the parameters of tau decay has improved considerably.

3.1 e-μ Universality

The leptonic width in tau decay (assuming $m(\nu_\tau) = 0$) is given by[13]:

$$\Gamma(\tau \to l\overline{\nu}_l\nu_\tau) = \frac{g_\tau^2 g_l^2}{64 m_W^4}\frac{m_\tau^5}{96\pi^3} f(\frac{m_l^2}{m_\tau^2})(1+\frac{3m_\tau^2}{5m_W^2}).[1+\frac{\alpha(m_\tau)}{2\pi}(\frac{25}{4}-\pi^2)], \tag{12}$$

$$\text{where} \quad f(x) = 1 - 8x + 8x^3 - x^4 - 12x^2 \ln x. \tag{13}$$

By comparing the partial widths for the leptonic decay modes the following relation for the relative strengths of the electron and muon couplings is obtained:

$$\frac{g_\mu^2}{g_e^2} = 1.028\frac{\Gamma(\tau \to \mu\overline{\nu}_\mu\nu_\tau)}{\Gamma(\tau \to e\overline{\nu}_e\nu_\tau)}. \tag{14}$$

The $\tau \to e\overline{\nu}_e\nu_\tau$ and $\tau \to \mu\overline{\nu}_\mu\nu_\tau$ branching ratio measurements from ALEPH[14], DELPHI[15], L3[16] and OPAL[17,18] are shown in figure 1. The new average values, $B_e = 17.78 \pm 0.08$ and $B_\mu = 17.32 \pm 0.09$, give:

$$\frac{g_\mu}{g_e} = 1.002 \pm 0.003, \tag{15}$$

which is in good agreement with hypothesis of e-μ universality. The precision of this result is approaching that of the best test of e-μ universality from $\pi \to l\overline{\nu}_l$ [19] which gives $g_\mu/g_e = 1.0012 \pm 0.0016$.

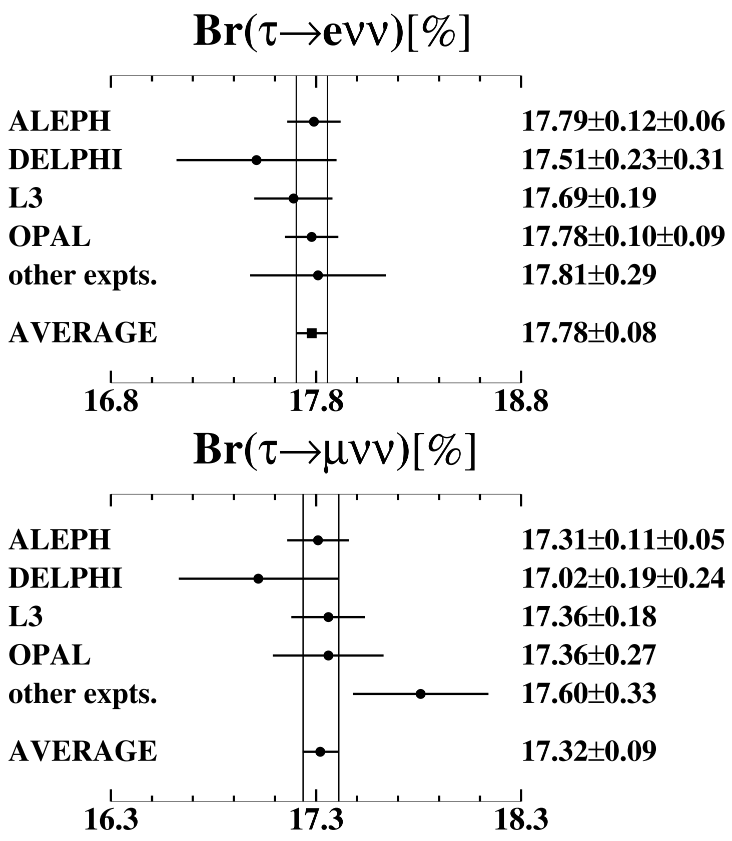

Figure 1: Summary of LEP tau leptonic branching ratio measurements. Also shown are the average of the non-LEP measurements and the overall average value.

3.2 μ-τ Universality

By comparing the widths of the processes of tau decay and muon decay it is possible to test muon-tau universality. The expression for the muon decay rate (analogous to equation 12) is

$$\Gamma(\mu \rightarrow e\overline{\nu}_e\nu_\tau) = \frac{g_\tau^2 g_l^2}{64 m_W^4}\frac{m_\mu^5}{96\pi^3} f(\frac{m_e^2}{m_\mu^2})(1+\frac{3m_\mu^2}{5m_W^2}).[1+\frac{\alpha(m_\mu)}{2\pi}(\frac{25}{4}-\pi^2)]. \tag{16}$$

A comparison with the expression for τ decay gives

$$\frac{\Gamma(\tau \rightarrow e\overline{\nu}_e\nu_\tau)}{\Gamma(\mu \rightarrow e\overline{\nu}_e\nu_\mu)} = 1.004\frac{g_\tau^2}{g_\mu^2}\frac{m_\tau^5}{m_\mu^5}. \tag{17}$$

which results in the universality relation:

$$\frac{g_\tau^2}{g_\mu^2} = 0.9996\frac{\tau_\mu}{\tau_\tau}Br(\tau \rightarrow e\overline{\nu}_e\nu_\tau)\frac{m_\tau^5}{m_\mu^5}. \tag{18}$$

The results included in the 1992 review of particle properties[20] implied a ratio $g_\tau/g_\mu = 0.969 \pm 0.012$, hinting at a possible deviation from muon-tau universality. Recent measurements have resolved this discrepancy. The current world average tau mass is totally dominated by the BES measurement of $m_\tau = 1776.96^{+0.31}_{-0.27}$ MeV[21] and is two sigma different from the average of 1992. In addition there have been large improvements in the precision of the tau lifetime measurements, made possible by the high resolution of the micro-vertex detectors employed by the LEP experiments.

Figure 2 shows a summary of the recent LEP measurements of the tau lepton lifetime[22–25]. These results, in conjunction with the electronic branching ratio imply that

$$\frac{g_\tau}{g_\mu} = 0.9979 \pm 0.0033, \tag{19}$$

is consistent with the hypothesis of μ-τ universality. The present situation is summarized in figure 3 which compares the new results to those of 1992.

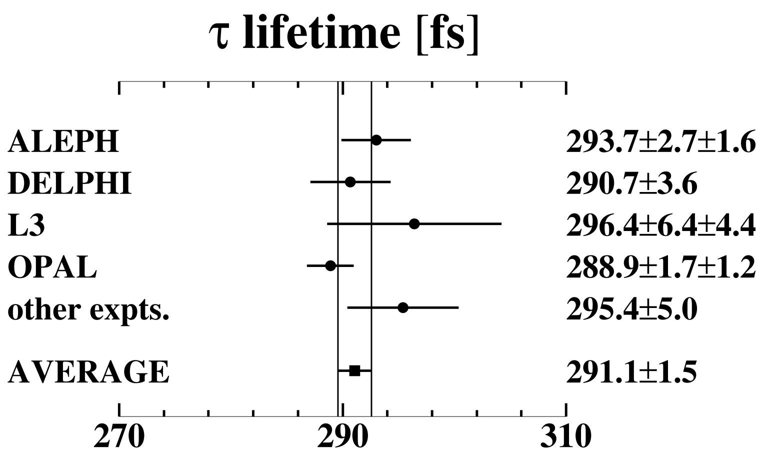

Figure 2: Summary of LEP tau lifetime measurements. Also shown is the average of the non-LEP experiments and the current overall average value.

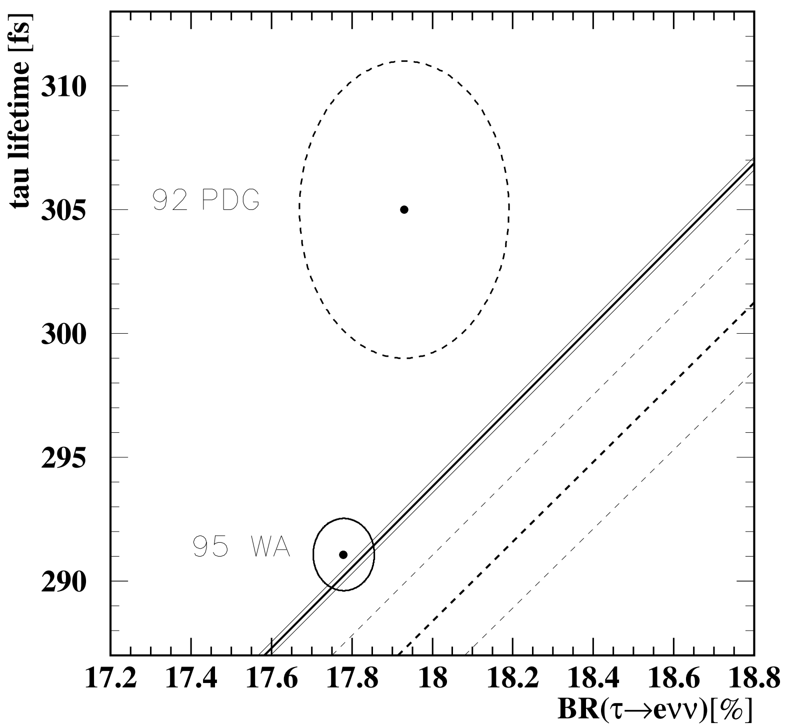

Figure 3: The solid ellipse shows the new world average tau lifetime plotted *vs* the new average electronic branching ratio. The solid diagonal lines show constraint from the tau lepton mass with errors (*i.e.* assuming universality). The dashed lines indicate the situation in 1992.

If electron-muon universality is assumed, *i.e.* combining $B(\tau \to e\overline{\nu}_e\nu_\tau)$ and $B(\tau \to \mu\overline{\nu}_\mu\nu_\tau)$, then the resulting universality constraint is somewhat tighter:

$$\frac{g_\tau}{g_{e/\mu}} = 0.9985 \pm 0.0030. \tag{20}$$

The 0.30% error breaks down into contributions of 0.16% and 0.25% from the branching ratios and the τ lifetime measurement respectively. The contribution from the tau mass measurement is negligible.

3.3 Tau Neutrino Mass Limit

If lepton universality is assumed then the tau leptonic branching ratio and lifetime measurements can be used to place a limit on the tau neutrino mass. In leptonic decays (described by equation 12) the mass (m_l) appearing in the function $f(m_l^2/m_\tau^2)$ refers to the most massive particle produced in the decay. Neglecting changes in the radiative corrections, the approximate limit obtained is:

$$m(\nu_\tau) < 74 \text{ MeV at } 90 \text{ \% C.L.} \tag{21}$$

This limit also indicates the magnitude of a non-zero tau neutrino mass which would influence the conclusions on lepton universality. This should be compared to the current best experimental limit on the tau neutrino mass of $m(\nu_\tau) < 24$MeV (95% C.L.) from ALEPH[26].

4 Conclusions

Measurements of the decay kinematics of the tau lepton indicate that the tau charged current is well described by V−A theory. In particular, if the current is restricted to vector and axial-vector components, the measurements limit the right handed component to be $g_R^\tau/g_L^\tau \leq 13\%$ at 90% C.L. Measurements of the tau leptonic branching ratios and the tau lifetime, when combined with knowledge of the mass of the tau lepton, provide a stringent test of lepton universality in the charged current. Both the leptonic branching ratios and tau lifetime are now known to the 0.5 % level. From these measurements it is found that universality holds within errors, *i.e.* $g_\mu/g_e = 1.002 \pm 0.003$ and $g_\tau/g_\mu = 0.998 \pm 0.003$. The precision of these universality tests of the charged current ($\sim 0.3\%$) is similar to that of the lepton universality tests of the neutral current ($\sim 0.2\%$) from the Z^0 line-shape and asymmetry measurements at LEP and SLD[27].

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