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The τ polarization measurement at LEP and the nature of the $\tau - W - \nu_\tau$ coupling

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Abstract

The recent measurement of the τ polarization at LEP is explicitly analysed in terms of the $\tau - W - \nu_\tau$ coupling.

When the validity of the neutral current prediction for P_τ and lepton universality in the neutral current sector is assumed, the analysis of the leptonic τ decays excludes the possibility of a (V+A)-(V+A) interaction, which is not constrained by the existing ρ measurement, at 3σ level.

From the semileptonic τ decays, a value of the chirality parameter is obtained:

$$h_{\nu_\tau} = -\frac{2g_V g_A}{g_V^2 + g_A^2} = 1.22 \pm 0.33,$$

which is consistent with $h_{\nu_\tau} = 1$ expected for pure V-A coupling and favours a negative helicity of the ν_τ .

1 Introduction

The weak decays of charged heavy leptons represent a superior probe of a universal weak interaction. The exhaustive and precise measurements of the $\mu \rightarrow e \nu \bar{\nu}$ decay give an impressive confirmation of the V-A structure of the interaction [1] [2]. The situation is not as satisfactory for the τ lepton. So far, only measurements of the ρ parameter in $\tau \rightarrow e \nu \bar{\nu}$ and $\tau \rightarrow \mu \nu \bar{\nu}$ decays were available [3]:

$$\rho = 0.70 \pm 0.06. \quad (1)$$

A more recent measurement of the ARGUS Collaboration [4] gave:

$$\rho = 0.742 \pm 0.035 \pm 0.020. \quad (2)$$

The ARGUS Collaboration has also measured the τ neutrino helicity [5] from a parity violation asymmetry in the $\tau \rightarrow a_1 \nu$ decay into three charged pions, obtaining a value of the chirality parameter:

$$(h_{\nu_\tau})_{\tau \rightarrow a_1 \nu} = -\frac{2g_V g_A}{g_V^2 + g_A^2} = 1.14 \pm 0.34_{-0.17}^{+0.34}. \quad (3)$$

The measurement of $\tau^+ \tau^-$ spin correlation observables [6] with a high statistics sample could drastically improve the present knowledge of the weak charged current τ decay, but no data are available for the moment.

In this context, it is interesting to interpret the τ polarization measurement recently performed at LEP not only in terms of the electroweak mixing parameter $\sin^2 \theta_W$ but also as a test of the structure of the $\tau - W - \nu_\tau$ coupling.

2 The τ polarization measurement at LEP

The electron-positron collisions at the LEP accelerator provide a copious production of $\tau^+ \tau^-$ pairs. The difference in the coupling of the Z^0 to right-handed and left-handed $\tau^\pm$ produces an average longitudinal polarization P_τ :

$$P_\tau = -\frac{2g_V^{nc} g_A^{nc}}{(g_V^{nc})^2 + (g_A^{nc})^2}, \quad (4)$$

where g_V^{nc} and g_A^{nc} are respectively the neutral current vector and axial vector coupling constants. Note that $P_{\tau^+} = -P_{\tau^-}$. In the Standard Model, P_τ is related to the electroweak mixing parameter through:

$$P_\tau = -\frac{2(1 - 4 \sin^2 \theta_W)}{1 + (1 - 4 \sin^2 \theta_W)^2} \approx -2(1 - 4 \sin^2 \theta_W). \quad (5)$$

Also the other final fermions produced through Z^0 exchange present a net polarization, but the τ offers the unique possibility of measuring it using the sensitivity of the decay process [7].

Decay mode	P_τ	Experiment
$\tau \rightarrow \mu\nu\bar{\nu}$	$-0.19 \pm 0.13 \pm 0.06$ $-0.05 \pm 0.19 \pm 0.08$ $-0.17 \pm 0.16 \pm 0.10$	ALEPH DELPHI OPAL
Avrg.	-0.15 ± 0.10	
$\tau \rightarrow e\nu\bar{\nu}$	$-0.36 \pm 0.17 \pm 0.06$ $-0.12 \pm 0.22 \pm 0.08$ $+0.20 \pm 0.13 \pm 0.08$	ALEPH DELPHI OPAL
Avrg.	-0.05 ± 0.10	
$\tau \rightarrow \pi\nu$	$-0.130 \pm 0.065 \pm 0.044$ $-0.35 \pm 0.11 \pm 0.07$ $-0.08 \pm 0.10 \pm 0.07$	ALEPH DELPHI OPAL
Avrg.	-0.17 ± 0.06	
$\tau \rightarrow \rho\nu$	$-0.124 \pm 0.047 \pm 0.051$ $-0.24 \pm 0.09 \pm 0.07$	ALEPH DELPHI
Avrg.	-0.16 ± 0.06	
$\tau \rightarrow a_1\nu$	$-0.15 \pm 0.15 \pm 0.07$	ALEPH

Table 1: The P_τ measurement at LEP: The first error quoted on P_τ is statistical, the second is systematic. The value obtained combining all the experiments for each decay mode is also reported, adding the statistical and systematical error in quadrature.

The measurements of the τ polarization performed by LEP experiments [8] are reported in Table 1. Combining all LEP results, the mean value obtained is

$$P_\tau = -0.145 \pm 0.035, \quad (6)$$

indicating a parity violation in the process $e^+e^- \rightarrow Z^0 \rightarrow \tau^+\tau^-$. Using Eq. (5), this result corresponds to a value of the electroweak mixing parameter $\sin^2 \theta_W = 0.2319 \pm 0.0044$.

3 The weak decay of a polarized τ

The decay characteristics of the τ lepton were already established in 1971 by Tsai [9], even before the τ lepton was actually discovered. In particular, it was clear that since τ^+ and τ^- decay via weak interactions where parity is not conserved, the angular distribution of decay products in the τ rest frame depends strongly on the spin orientation of the τ and the characteristics of the $\tau - W - \nu_\tau$ vertex.

3.1 $\tau \rightarrow l\nu\bar{\nu}$

The leptonic decay of a polarized τ can be described in the most general way by a

local, derivative-free leptonic four fermion interaction [2]:

$$M = \frac{4G_F}{\sqrt{2}} \sum_{\substack{\gamma = S, V, T \\ \epsilon, \mu = R, L \\ (n, m)}} g_{\epsilon\mu}^\gamma < \bar{l}_\epsilon | \Gamma^\gamma | (\nu_l)_n > < (\bar{\nu}_\tau)_m | \Gamma_\gamma | \tau_\mu >, \quad (7)$$

where γ labels the type of interaction (Γ^S scalar-pseudoscalar, Γ^V vector-axial vector, Γ^T tensor), the indices ϵ and μ indicate the chiral projections (left-handed, right-handed) of the spinors of the observed particles (ϵ the lepton, μ the tau), n indicates the helicity of the lepton antineutrino and m that of the τ neutrino. n and m are uniquely determined for given γ , ϵ , μ .

The normalized lepton energy distribution is:

$$\frac{d\Gamma}{dx} \propto 2 - 6x^2 + 4x^3 + \frac{4}{9}\rho(-1 + 9x^2 - 8x^3) - \xi P_\tau \left[-\frac{2}{3} + 4x - 6x^2 + \frac{8}{3}x^3 + \frac{4}{9}\delta(1 - 12x + 27x^2 - 16x^3) \right], \quad (8)$$

where $x = E_l/E_l^{max}$ in the Laboratory, ρ , δ and ξ are functions of $g_{\epsilon\mu}^\gamma$, and all the terms m_l^2/m_τ^2 have been neglected. A term in $\eta m_l/m_\tau$ has also been dropped in Eq. (8) since only a vector interaction will be considered in the following (that is $g_{\epsilon\mu}^S = g_{\epsilon\mu}^T = 0$ which implies $\eta = 0$). The predictions for different combinations of the interaction at the $l^-\bar{\nu}_l$ and $\tau^-\nu_\tau$ vertices are reported in Table 2. The existing measurement of ρ is already

$l^-\bar{\nu}_l$	$\tau^-\nu_\tau$	ρ	ξ	δ	η
V-A	V-A	$\frac{3}{4}$	1	$\frac{3}{4}$	0
V	V	$\frac{3}{8}$	0	0	0
A	A	$\frac{3}{8}$	0	0	0
V+A	V+A	$\frac{3}{4}$	-1	$\frac{3}{4}$	0
V-A	V	$\frac{3}{8}$	2	$\frac{3}{16}$	0
V-A	A	$\frac{3}{8}$	2	$\frac{3}{16}$	0
V-A	V+A	0	3	0	0

Table 2: The predictions for different combinations of a vector interaction at the $l^-\bar{\nu}_l$ and $\tau^-\nu_\tau$ vertices. A normalization $|g_{LL}^V|^2 + |g_{LR}^V|^2 + |g_{RL}^V|^2 + |g_{RR}^V|^2 = 1$ as in ref. [2] is used.

precise enough to exclude all the possible combinations different from (V-A)-(V-A), apart from the (V+A)-(V+A) which has the same predictions $\rho = \delta = 3/4$. The determination of ξ distinguishes between these two possibilities.

One can, more generally, consider a mixture of (V-A)-(V-A) and (V+A)-(V+A), which implies:

$$\rho = \delta = \frac{3}{4}, \quad \xi = -\frac{|g_{RR}^V|^2 - |g_{LL}^V|^2}{|g_{RR}^V|^2 + |g_{LL}^V|^2} \quad (9)$$

Another possibility is to fix (V-A) at the $l^-\bar{\nu}_l$ vertex and allow a mixture of (V-A) and (V+A) at the $\tau^-\nu_\tau$ vertex. The matrix element is:

$$M \propto \bar{u}(l)\gamma^\mu(1-\gamma^5)u(\bar{\nu}_l) \cdot \bar{u}(\nu_\tau)\gamma_\mu(g_V + g_A\gamma^5)u(\tau^-) \quad (10)$$

$$g_V = g_{LL}^V + g_{LR}^V, \quad g_A = g_{LR}^V - g_{LL}^V. \quad (11)$$

In this case the decay parameters are:

$$\rho = \frac{3}{8}(1 + h_{\nu_\tau}), \quad \delta = \frac{3}{16} \frac{1 + h_{\nu_\tau}}{1 - \frac{h_{\nu_\tau}}{2}}, \quad \xi = 2 - h_{\nu_\tau}, \quad (12)$$

$$h_{\nu_\tau} = -\frac{2g_V g_A}{g_V^2 + g_A^2}. \quad (13)$$

Notice that the fact of having constrained the $l^-\bar{\nu}_l$ vertex changes the meaning of the observables. In particular, ρ , δ and ξ are determined once one of them is measured.

3.2 $\tau \rightarrow \text{hadron } \nu$

The τ semileptonic decay is determined by the decay amplitude [10]:

$$M \propto \bar{u}(\nu_\tau)\gamma_\mu(g_V + g_A\gamma^5)u(\tau^-) \cdot J^\mu, \quad (14)$$

where J^μ is the matrix element of the hadronic current. The normalized energy distribution for $\tau \rightarrow h\nu$ is:

$$\frac{d\Gamma}{dx} \propto 1 + h_{\nu_\tau} P_\tau S_h(2x - 1), \quad (15)$$

where $x = E_h/E_h^{max}$ in the Laboratory and h_{ν_τ} is the chirality parameter defined in Eq. (13). In the case $\tau \rightarrow \pi\nu$ the τ polarization sensitivity S_π is simply equal to unity, while for $\tau \rightarrow \rho\nu, a_1\nu$ the spin 1 hadron presents both longitudinal and transverse spin states, that give $S_\rho \approx 0.46$ and $S_{a_1} \approx 0.12$. The correspondent reduced sensitivity to P_τ can be recuperated by measuring the helicity of the spin 1 hadron through the decay distribution of the hadronic system [11].

4 The P_τ measurement and the $\tau - W - \nu_\tau$ coupling

The measurement of P_τ , discussed in Sect. 2, is performed by the LEP experiments fitting the experimental distributions to the theoretical expectations. In this procedure,

the V-A form for the weak charged current τ decay is explicitly assumed ($\rho = \delta = 3/4$ and $\xi = h_{\nu_\tau} = 1$).

As a matter of fact, the measurement of P_τ is a measurement of ξP_τ and $h_{\nu_\tau} P_\tau$ (cf. Eq. (8)-(15)), and thus contains interesting informations about the nature of the $\tau - W - \nu_\tau$ coupling.

In order to extract quantitative results one can turn around the usual argument of accepting the charged current prediction of the Standard Model and ‘testing’ the neutral current sector. The latter being extensively tested now, one may assume the validity of the Standard Model prediction for P_τ and lepton universality in the neutral current sector to test the charged current structure of the third generation lepton, the τ . The precise measurement of the Z^0 parameters performed by the four LEP experiments [12]

$$\sin^2 \theta_W = 0.2337 \pm 0.0014, \quad (16)$$

can, thus, be converted in a predicted value for the τ polarization using Eq. (5):

$$P_\tau^{pred} = -0.130 \pm 0.011. \quad (17)$$

It's a simple matter then to extract the chirality parameters for different τ decay modes using the P_τ values of Table 1. For example:

$$\frac{(\xi P_\tau)_{\tau \rightarrow \mu\nu\bar{\nu}}}{P_\tau^{pred}} = \xi_{\tau \rightarrow \mu\nu\bar{\nu}} = 1.17 \pm 0.81. \quad (18)$$

For the leptonic decays, an additional 20% systematic error has been added to take into account variations of ρ within its error and of δ in the interval 0 to 1. The results for each decay mode and the average values of the leptonic ($\xi_{\tau \rightarrow l\nu\bar{\nu}}$) and of the hadronic ($(h_{\nu_\tau})_{\tau \rightarrow h\nu}$) decay modes are summarized in Table 3.

$\xi_{\tau \rightarrow e\nu\bar{\nu}}$	$\xi_{\tau \rightarrow \mu\nu\bar{\nu}}$	$\xi_{\tau \rightarrow l\nu\bar{\nu}}$	$(h_{\nu_\tau})_{\tau \rightarrow \pi\nu}$	$(h_{\nu_\tau})_{\tau \rightarrow \rho\nu}$	$(h_{\nu_\tau})_{\tau \rightarrow a_1\nu}$	$(h_{\nu_\tau})_{\tau \rightarrow h\nu}$
0.39 ± 0.81	1.17 ± 0.81	0.80 ± 0.58	1.26 ± 0.46	1.19 ± 0.47	1.15 ± 1.28	1.22 ± 0.33

Table 3: The leptonic decay parameter ξ and the chirality parameter h_{ν_τ} for the different τ decay modes. The averages for the leptonic ($\xi_{\tau \rightarrow l\nu\bar{\nu}}$) and hadronic ($(h_{\nu_\tau})_{\tau \rightarrow h\nu}$) decay modes are also reported. The values are extracted combining the measurement of the τ polarization and $\sin^2 \theta_W$ at LEP.

Another possible approach is to derive ratios of the chirality parameters for different τ decay modes, using the P_τ values of Table 1. For example:

$$\frac{(\xi P_\tau)_{\tau \rightarrow \mu\nu\bar{\nu}}}{(h_{\nu_\tau} P_\tau)_{\tau \rightarrow \pi\nu}} = \frac{\xi_{\tau \rightarrow \mu\nu\bar{\nu}}}{(h_{\nu_\tau})_{\tau \rightarrow \pi\nu}} = 0.88 \pm 0.66, \quad (19)$$

and one can easily compute all the other combinations. Note that no specific assumption on the origin and the value of P_τ is made to obtain these results. In particular, one can derive the ratios $\xi_{\tau \rightarrow e,\mu\nu\bar{\nu}}/(h_{\nu_\tau})_{\tau \rightarrow a_1\nu}$ and $(h_{\nu_\tau})_{\tau \rightarrow \pi,\rho\nu}/(h_{\nu_\tau})_{\tau \rightarrow a_1\nu}$, which can then be

$\xi_{\tau \rightarrow e \nu \bar{\nu}}$	$\xi_{\tau \rightarrow \mu \nu \bar{\nu}}$	$\xi_{\tau \rightarrow l \nu \bar{\nu}}$	$(h_{\nu_\tau})_{\tau \rightarrow \pi \nu}$	$(h_{\nu_\tau})_{\tau \rightarrow \rho \nu}$	$(h_{\nu_\tau})_{\tau \rightarrow h \nu}$
0.39 ± 0.91	1.15 ± 1.54	0.79 ± 1.06	1.24 ± 1.49	1.18 ± 1.42	1.20 ± 1.40

Table 4: The leptonic decay parameter ξ and the chirality parameter h_{ν_τ} for the different τ decay modes. The values are extracted combining the measurement of the τ polarization at LEP and the ARGUS measurement of $(h_{\nu_\tau})_{\tau \rightarrow a_1 \nu}$.

multiplied by the ARGUS measurement of $(h_{\nu_\tau})_{\tau \rightarrow a_1 \nu}$ (Eq. (3)) to determine the value of ξ and h_{ν_τ} for the various decay channels. The results are summarized in Table 4. However, the present error ($\approx 100\%$) in the measurement of $(h_{\nu_\tau} P_\tau)_{\tau \rightarrow a_1 \nu}$ at LEP (only ALEPH has analyzed this decay so far) is limiting this determination.

5 Conclusions

The measurement of the τ polarization at LEP gives not only a precise measurement of the τ coupling to the Z^0 but also new informations about the structure of the weak charged current τ decay.

Assuming the validity of the neutral current prediction for P_τ and lepton universality in the neutral current sector, the leptonic decay parameter $\xi_{\tau \rightarrow l \nu \bar{\nu}}$ and the chirality parameter $(h_{\nu_\tau})_{\tau \rightarrow h \nu}$ for the semileptonic τ decays are determined.

The leptonic decay parameter value

$$\xi_{\tau \rightarrow l \nu \bar{\nu}} = 0.80 \pm 0.58 \quad (20)$$

excludes a (V+A)-(V+A) interaction (see Sect. 3.1) at 3σ level, and is consistent with a pure (V-A)-(V-A) interaction.

The chirality parameter determined from the hadronic decay modes

$$(h_{\nu_\tau})_{\tau \rightarrow h \nu} = 1.22 \pm 0.33 \quad (21)$$

is consistent with $h_{\nu_\tau} = 1$ expected for pure V-A coupling at the leptonic $\tau - W - \nu_\tau$ vertex. It also indicates that the ν_τ is a left-handed particle with a significance of more than 6 standard deviations.

If (V-A) is explicitly assumed for the $l^- \bar{\nu}_l$ vertex¹, one can relate the leptonic decay parameter ξ to the chirality parameter using Eq. (12):

$$(h_{\nu_\tau})_{\tau \rightarrow l \nu \bar{\nu}} = 2 - \xi_{\tau \rightarrow l \nu \bar{\nu}} = -\frac{2g_V g_A}{g_V^2 + g_A^2} = 1.20 \pm 0.58, \quad (22)$$

¹Notice that in this case, as discussed in Sect. 3.1, the measurement of the ρ parameter is enough to constraint h_{ν_τ} (see Eq. (12)). The present error of ≈ 0.03 on the ρ parameter corresponds to ≈ 0.08 error on h_{ν_τ} .

which is also consistent with the (V-A) hypothesis, and can now be combined with Eq. (21) to yield:

$$h_{\nu_\tau}^{LEP} = 1.22 \pm 0.28. \quad (23)$$

Preliminary updates[13] of the P_τ measurement at LEP, which include an increased statistics and the L3 experiment, have been recently presented. Performing the same analysis previously described, a more precise value is obtained: $h_{\nu_\tau}^{LEP} = 1.05 \pm 0.20$.

Another method to determine ξ and h_{ν_τ} , which uses the ARGUS measurement of $(h_{\nu_\tau})_{\tau \rightarrow a_1 \nu}$ and makes no assumption on the Standard Model nature of P_τ , has also been discussed, but it is currently limited by the error on the LEP determination of $(h_{\nu_\tau} P_\tau)_{\tau \rightarrow a_1 \nu}$. A more precise measurement of ARGUS[14] is also available: $(h_{\nu_\tau})_{\tau \rightarrow a_1 \nu}^{ARGUS} = 1.25 \pm 0.23^{+0.15}_{-0.08}$.

The increasing statistics collected at LEP will certainly improve the errors on the h_{ν_τ} determination for both methods, and an error $\leq 10\%$ should be easily achieved.

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References

- [1] K. Mursula, M. Roos, F. Scheck, Nucl. Phys. B 219 (1983) 321.
- [2] W. Fetscher, H.-J. Gerber, K. F. Johnson, Phys. Lett. B 173 (1986) 102.
- [3] Review of Particle Properties, Phys. Lett. B 239 (1990).
- [4] ARGUS Collab., H. Albrecht et al, Phys. Lett. B 246 (1990) 278.
- [5] ARGUS Collab., H. Albrecht et al, Phys. Lett. B 250 (1990) 164.
- [6] S.-Y. Pi, A. I. Sanda, Ann. Physics 106 (1977) 171;
W. Fetscher, Phys. Rev. D 42 (1990) 1544;
J. J. Gomez Cadenas, Proceedings of the Tau-Charm Factory Workshop, SLAC-Report-343 (1989), p. 48;
C. A. Nelson, Phys. Rev. D 43 (1991) 1465.
- [7] For more details, see: P. Privitera, "Physics of the τ lepton at LEP", CERN preprint CERN-PPE/91-185 (1991), to appear in the Proceedings of the XIV International Warsaw meeting on Elementary Particle Physics, May (1991), and references therein.
- [8] ALEPH Collab., Phys. Lett. B 265 (1991) 430;
DELPHI Collab., CERN preprint CERN-PPE/92-60 (1992);
OPAL Collab., Phys. Lett. B 266 (1991) 201.
- [9] Y. S. Tsai, Phys. Rev. D 4 (1971) 2821.
- [10] H. Kühn, F. Wagner, Nucl. Phys. B 236 (1984) 16.
- [11] K. Hagiwara, A. D. Martin, D. Zeppenfeld, Phys. Lett. B 235 (1990) 198;
A. Rougé, Z. Phys C 48 (1990) 75.
- [12] The LEP Collab.: ALEPH, DELPHI, L3 and OPAL, Phys. Lett. B 276 (1992) 247.
- [13] M. Dam, CERN preprint CERN-PPE/92-82 (1992), to appear in the Proceedings of the XXVIIth Rencontre de Moriond, Les Arcs, France, March 1992.
- [14] H. Kolanoski, in DESY preprint 91-145 (1991).