# The Lorentz structure of semi-hadronic tau decays

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# The Lorentz structure of semi-hadronic tau decays.

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**Abstract.** Semi-hadronic tau decays provide a powerful tool to study the Lorentz structure of the weak charged current. Using decays of the $\tau$ into $a_1$ it is possible to extract tau polarisation $P_\tau$ and tau neutrino helicity $\gamma_{VA}$. A method is presented to determine the tau neutrino helicity independent of any tau polarization which may be present.

## INTRODUCTION

In the Standard Model the $l - W - \nu_l$ vertex is supposed to have the V-A structure for any lepton. This fact has been extensively checked for electrons and muons [1]. Efremov et al. [2] have previously examined the possibility of studying the tau charged current using the decay $\tau^- \to a_1^- \nu_\tau$.

Lepton pairs $\tau^+\tau^-$ are created at LEP at energies of the $Z^0$ resonance. The longitudinal polarization of the $\tau^-$ averaged over all the production angles is related to the $\tau^+ - Z^0 - \tau^-$ vertex coupling constants by $P = -2\, v_\tau\, a_\tau / v_\tau^2 + a_\tau^2$. It is usual to define a quantity which characterizes the handedness of the charged leptonic current. This quantity is called the chirality parameter and is given by $\gamma_{\mathrm{VA}} = 2\, g_V\, g_A / g_V^2 + g_A^2$, with coupling constants $g_V$ and $g_A$ for the vector and axial vector tau currents.

We discuss here a method based on the construction of an observable sensitive to $\gamma_{VA}$, but independent of the tau polarisation as well as a description of the how the method can be used in an experimental situation. We also consider the possibility of fitting $P_\tau$ and $\gamma_{VA}$ at the same time from the angular distribution for the decay of the tau into $a_1$.

## $\tau^- \to a_1^-\ \nu_\tau$ decay

The $a_1$ is a pseudovector resonance decaying into three pions. The decay process is as follows:

$$\tau^- \to a_1^- \nu_\tau, \quad a_1 \to \rho^0 \pi^-, \quad \rho^0 \to \pi^+ \pi^-$$

The angular distribution for the decay can be written following reference [3].

$$
\begin{aligned}
d\Gamma &= N\,[h_1^+\,W_A + (h_1^-\,\cos\theta - h_2\,\sin\theta)\,W_A\,\gamma_{\mathrm{VA}}\,P_\tau + h_3\,\cos\beta\,W_E\,P_\tau \\
&\quad +3\,Q^2\,\cos\psi\,\cos\beta\,W_E\,\gamma_{\mathrm{VA}}]\,\frac{(m_\tau^2-Q^2)^2}{Q^2} \\
&\quad \frac{dQ^2}{Q^2}\,ds_1\,ds_2\,\frac{d\cos\theta}{2}\,\frac{d\cos\beta}{2} \qquad (1)
\end{aligned}
$$

where $q_1$, $q_2$ and $q_3$ are the final pion 4-momenta and $Q = q_1 + q_2 + q_3$.
The functions $h_i$ are given by

$$h_1^\pm = m_\tau^2 \pm 2\,Q^2 - (m_\tau^2 \mp Q^2)\,\frac{3\,\cos^2\psi - 1}{2}\,\frac{3\,\cos^2\beta - 1}{2} \qquad (2)$$

$$h_2 = 3\,m_\tau\,\sqrt{Q^2}\,\frac{\sin 2\psi}{2}\,\frac{3\,\cos^2\beta - 1}{2} \qquad (3)$$

$$h_3 = -3\,Q^2\,(\cos\theta\,\cos\psi + \frac{m_\tau}{\sqrt{Q^2}}\,\sin\theta\,\sin\psi) \qquad (4)$$

$$N = \frac{G^2}{8\,m_\tau^3}\,(g_V^2 + g_A^2)\,\cos^2\theta_C\,\frac{1}{64\,(2\,\pi)^5} \qquad (5)$$

and $W_A$ and $W_E$ are given in reference [4].

The $\tau$ rest frame decay angle $\theta$ and the angle $\psi$ between the direction of the $\tau$ and the laboratory as seen from the $a_1$ rest frame, can be reconstructed from the energy of the hadronic system, $\beta$ denotes the angle between the normal $n_\perp$ to the three pion plane and the three pions laboratory line of flight, $\cos\beta$ is obtained from the measured pion momenta using the analytic approximation of reference [5].

The model for the hadronic current (which is contained in the functions $W_A$ and $W_E$) has previously been worked out by J.H.Kuhn and F.Wagner [4] and is implemented in the KORALZ event generator [6] widely used to simulate $\tau$ production and decays.

## Determination of the Chirality Parameter

Given that the two negative pions are not distinguishable, there are two possible ways to form the $\rho$-meson. The interference between them makes the $\tau \to a_1\,\nu_\tau$ the unique hadronic channel from which we can disentangle the dependence on the chirality parameter.

A method to obtain an estimator of the chirality parameter [7], which is model dependent though, consists in taking appropriate moments using the distribution function given in equation [1]. The important observation is that it is possible to eliminate the dependence on the $\tau$ polarization by taking the moment of the quantity

$$\mathcal{M} = \frac{\cos\beta\, \cos\theta\, sgn(s_1 - s_2)}{\cos\theta\, \cos\Psi + \frac{m_\tau}{\sqrt{Q^2}} \sin\theta\, \sin\Psi} \tag{6}$$

The Dalitz variables $s_1$ and $s_2$ are defined by $s_i = (q_j + q_+)^2$ ; $(i \neq j = 1, 2)$ where $q_+$ is the momentum of the positive pion.

The function $sgn$ of $(s_1 - s_2)$ is introduced in order to take into account the ambiguity in the direction of the normal to the decay plane, due to the Bose symmetry of the two negative pions.

Finally one can write (8)

$$\langle \mathcal{M} \rangle = -\gamma_{\rm VA}\, A_{LR}(Q^2)\, T(Q^2) \tag{7}$$

where we have introduced the function $A_{LR}$ of reference (4).

$$\begin{aligned} T(Q^2) \quad &= \quad -\frac{1}{(m_\tau^2 - Q^2)}\{[Q^2 + m_\tau^2\,[1 + \frac{3\,m_\tau^2 + Q^2}{3\,K(Q^2)} \log \frac{3\,m_\tau^2 - Q^2 - K(Q^2)}{3\,m_\tau^2 - Q^2 + K(Q^2)} \\ &\quad + \log \frac{m_\tau}{\sqrt{Q^2}}]\} \end{aligned} \tag{8}$$

with

$$K(Q^2) = [(9\,m_\tau^2 - Q^2)(m_\tau^2 - Q^2)]^{1/2} \tag{9}$$

We have performed a Monte Carlo study using the Koralz program to generate samples of 200,000 events with $a_1$ decays assuming pure V-A and pure V+A charged current couplings, as well as 200,000 events with nonstandard values of $\gamma_{\rm VA}$ to represent a hypothetical data sample with $g_V = 0.6$ and $g_V^2 + g_A^2$ unchanged from its standard model value, giving $\gamma_{\rm VA} = -0.768$. A $\chi^2$ fit for the best linear combination of V-A and V+A samples to match the $\gamma_{\rm VA} = -0.768$ sample gave a statistical error of 0.049, which includes errors due to the finite Monte Carlo V-A and V+A samples as well as those due to the finite number of events with nonstandard couplings.

Monte Carlo studies using samples of fully right or left-handedly polarized taus give consistent answers, verifying that the method of this papers gives a method for the determination of the tau neutrino chirality parameter which is independent of the tau polarization.

## New variables in phase space

Introducing 4 functions $H_i$, $i = 1 - 4$ we can rewrite equation (1) as

$$\begin{aligned} d\Gamma &\propto H_1\{1 + P_\tau \gamma_{VA}\ \omega_2 + \gamma_{VA}\ \omega_3 + P_\tau\ \omega_4\}|J|\ d\omega_2\ d\omega_3\ d\omega_4\ ds_1 ds_2\ dQ^2 \\ &= \tilde{H}(\vec{\omega})\ \{1 + P_\tau \gamma_{VA}\ \omega_2 + \gamma_{VA}\ \omega_3 + P_\tau\ \omega_4\}\ d^3\omega \end{aligned} \tag{10}$$

where

$$\vec{\omega} = (\frac{H_2}{H_1}, \frac{H_3}{H_1}, \frac{H_4}{H_1}) \tag{11}$$

$|J|$ is the Jacobian for the change of variables $\{\gamma, \cos\theta, \cos\beta\} \rightarrow \{\omega_2, \omega_3, \omega_4\}$and

$$\tilde{H} = \int ds_1 ds_2 dQ^2 H_1 |J| \tag{12}$$

Now we have reduced the decay rate to a form in which one clearly sees the dependence on $P$, $\gamma_{VA}$, and $P\gamma_{VA}$. We are studying the possibility of using this distribution to fit $P$ and $\gamma_{VA}$ fixing the value of the product of both parameters (8).

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