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U. C. Müller

Physikalisches Institut der Universität Bonn

Abstract

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Post address:
Nussallee 12
D-53115 Bonn
Germany

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U. C. Müller ^a

^aUniversität Bonn, Physikalisches Institut, Nussallee 12, D-53119 Bonn, Germany

The hadronic structure of $\tau^- \rightarrow \pi^- \pi^- \pi^+ \nu_\tau$ events observed with the OPAL detector at LEP during 1992-1994 has been measured. A model dependent as well as a model independent approach have been used. Deficiencies of the two theoretical models considered become visible with the available data sample. A non-resonant contribution seems to be required in the model description. Interference terms of axial-vector and non-axial-vector contributions have been measured for the first time in a model independent approach. No evidence for non-axial-vector contributions has been found. Finally, the parity violating asymmetry parameter γ_{VA} has been measured model independently to be $1.29 \pm 0.26 \pm 0.11$ and, for comparison, it has also been measured in a model dependent way.

1. Introduction

While the decay of the τ into the primary quarks in the $\tau^- \rightarrow \pi^- \pi^- \pi^+ \nu_\tau$ decay can be calculated within the Standard Model, the transition from the quark level to the final hadronic state is not yet accessible to theoretical calculations. General theoretical assumptions, such as G-parity conservation or the principle of PCAC, point to a dominance of the axial-vector current in the $\tau^- \rightarrow \pi^- \pi^- \pi^+ \nu_\tau$ decay. The experimental challenge hence is to measure the detailed structure of the decay current and to search for small non-axial-vector contributions in the decay.

There are two possibilities for such a measurement [1]. One possibility is to use model predictions for the decay, adjust the parameters of the model and compare the resulting model prediction to the data. The other way is to use a general parameterization of the hadronic decay current, using the hadronic structure function formalism [2] and extract these structure functions from the data.

Finally, once a description for the hadronic current is found, the leptonic side can be studied, allowing to measure the ν_τ helicity in both a model independent as well as a model dependent way.

2. Selection

Starting from the 1992 - 1994 data sample taken with the OPAL detector [3] at LEP 114381 τ pairs have been selected using the τ pair event selection as described in [4]. From this sample $\tau^- \rightarrow h^- h^- h^+ \nu_\tau$ candidates have been selected using a channel likelihood method [5]. Background from 1-prong decays plus an additional pair of electron and positron tracks from photon conversion is suppressed by separating pions from electrons using the specific energy loss (dE/dx) and employing a 3-dimensional vertex fit, where the three tracks are fitted to a common vertex. The χ^2 of the fit is used as a likelihood variable. 3-prong events with additional neutrals in the final state are separated from the signal channel by using the energy sum divided by the sum of the track momenta and the sum of the energy of the reconstructed photons in the decay. From the selected $\tau^- \rightarrow h^- h^- h^+ \nu_\tau$ sample, final states with kaons are suppressed by using the specific energy loss of the tracks applying a cut method. As the events have to be well reconstructed kinematically for the following structure studies, each event has to satisfy certain quality criteria. 7443 events remain with an estimated purity of $(84.8 \pm 1.9)\%$, where the largest background contribution comes from $\tau^- \rightarrow \pi^- \pi^- \pi^+ \pi^0 \nu_\tau$ events with 11.7%.

Table 1

Model parameters extracted from fitting the KS and IMR models to OPAL data. The errors quoted are statistical, followed by the systematic error. Note that Γ_{a_1} and the D/S ratio for the IMR model are calculated quantities, not parameters of the fit. Also listed are the ratio of the normalization of the fitted 2π mass projections to that of the 3π distribution for the KS model, and the non-resonant background fraction for the IMR model.

	Kühn et al. [6]	Isgur et al. [8]
m_{a_1} (GeV)	$1.262 \pm 0.009^{+0.005}_{-0.007}$	$1.210 \pm 0.007^{+0.002}_{-0.001}$
Γ_{a_1} (GeV)	$0.621 \pm 0.032^{+0.016}_{-0.057}$	$0.457 \pm 0.015^{+0.007}_{-0.016}$
D/S ratio	—	$-0.10 \pm 0.02 \pm 0.01$
$\chi^2/d.o.f.$ for fit to Q^2 only (fig. 1 a)	25.2/20	—
$\chi^2/d.o.f.$ for fit to Q^2 and $s_{1/2}$ (figs. 1 a and c-e)	111/49	91.9/45
$2\pi/3\pi$ normalization	$0.90 \pm 0.06\%$	—
non-resonant background fraction	—	13.8%

3. Model Dependent Description of the Decay

Two different models have been used to describe the decay. Both are based on the decay chain of the τ as proceeding through the axial-vector meson a_1 : $\tau^- \rightarrow a_1^- \nu_\tau$, $a_1^- \rightarrow \rho^0 \pi^-$, $\rho^0 \rightarrow \pi^+ \pi^-$. The models are described here:

- The first model, from Kühn and Santamaria (KS) [6], is a relatively simple model based on VMD. This model is implemented in the Monte Carlo generator TAUOLA [7]. The only free parameters are the mass and the width of the a_1 meson (m_{a_1} and Γ_{a_1}). They can be extracted from the invariant mass of the 3 pion final state alone ($Q^2 = q_1 + q_2 + q_3$, where q_1 and q_2 are the four-momenta of the two like sign pions and q_3 of the unlike sign pion). The normalization has been adjusted to the data.
- The second model is the model of Isgur, Morningstar and Reader (IMR) [8]. It is based on the flux tube breaking model [9]. The parameters of the fit are the mass of the a_1 meson and three coefficients of a non-resonant background term. Although the

coupling constants are in principle predicted from the model, for the fit they have been released in order to adjust the D-wave to S-wave ratio of the intermediate ($\rho\pi$) state. The width of the a_1 is calculated from the other model parameters. To extract the model parameters it is not sufficient to fit the Q^2 distribution only, but also projections of the Dalitz plot variables ($s_1 = q_2 + q_3$ and $s_2 = q_1 + q_3$) have to be taken into account. The normalization is determined from the data distribution.

The extracted parameters of the model fits are summarized in tab. 1. The data distributions in comparison with the results of the two model predictions after the fits are shown in fig. 1. The KS model reproduces the Q^2 distribution, to which it has been adjusted, quite well. The Dalitz plot projections shown for the KS model (figs. 1 b-e) are derived from the parameters, including the normalization, obtained from the fit to the Q^2 distribution. As can be seen, the KS model overestimates the ρ resonance region compared to the data. To estimate this effect the normalization of the Dalitz plot projections in figs. 1 c-e has been fitted separately using the model parameters extracted from the Q^2 distribution. The ratio of

Figure 1. The model fits to the data: data (points), KS model fit (dashed line) and IMR model fit (dotted line). The dashed dotted line is the non-resonant background term of the IMR model. a) Q^2 distribution, b) uncut Dalitz plot projection for the full Q^2 range, c) - e) Dalitz plot projections in certain Q^2 ranges: c) $0.81\text{GeV}^2 < Q^2 < 1.10\text{GeV}^2$, d) $1.10\text{GeV}^2 < Q^2 < 1.44\text{GeV}^2$, and e) $1.44\text{GeV}^2 < Q^2 < 1.96\text{GeV}^2$; only events in the ρ -bands ($0.5\text{GeV}^2 < s_{1,2} < 0.7\text{GeV}^2$) are considered.

this 2π normalization to the 3π normalization is 0.90, supporting the previous observation.

The IMR model has been fitted to the distributions in figs. 1 a and c-e. The overall agreement is only slightly better than for the KS model (see tab. 1), despite of the fact that the ratio of the ρ resonance region to the region outside the resonance can be adjusted by including a non-resonant background term. This non-resonant background term contributes to the Q^2 and the uncut Dalitz plot distribution (figs. 1 a and b) whereas it is excluded from the Dalitz plot projections where a cut has been made for the ρ resonance region (figs. 1 c-e). The normalization

term for the Q^2 and the uncut Dalitz plot distribution is applied only to the part of the distributions lying above the non-resonant background term. The non-resonant background term contributes 13.8% of the total Q^2 and uncut Dalitz plot distributions.

It is apparent that a non-resonant contribution is required for the model description of the decay. The χ^2 values for the model fits (see tab. 1) demonstrate that improvements in the model descriptions are required to avoid possible biases in those precision measurements which require an understanding of the $\tau^- \rightarrow \pi^- \pi^- \pi^+ \nu_\tau$ decay, e. g. the P_τ measurement in the $\tau^- \rightarrow \pi^- \pi^- \pi^+ \nu_\tau$ channel.

4. Model Independent Approach

The second possibility for describing the $\tau^- \rightarrow \pi^- \pi^- \pi^+ \nu_\tau$ decay is to use a model independent description in the formalism of hadronic structure functions introduced in [2]. In contrast to the model fits an extended maximum likelihood (EML) fit [10] has been performed using not only the Q^2 , s_1 , and s_2 information but also the decay angles for each event [2]. The events are split into bins in Q^2 , s_1 , and s_2 . For each bin a fit has been performed. The likelihood function is given by:

$$(\ln \mathcal{L})_j = \sum_i^{N_j} \ln \left(\frac{d\Gamma}{dz} (z_i; W_X^j) \frac{N}{C_{corr} \Gamma_{3\pi}} \right) - \Gamma_{\Delta_j} (W_A^j) \frac{N}{C_{corr} \Gamma_{3\pi}}. \quad (1)$$

Here the W_X^j are the average values of the structure functions W_X within bin j . They are the parameters of the fit. N_j is the number of events in bin j whereas N is the total number of selected events. $\Gamma_{3\pi}$ is the partial decay width of the τ decay into three pions calculated from [11]. The decay distribution $d\Gamma/dz$ is defined in terms of the kinematic variables z in [1,2]. The normalization term Γ_{Δ_j} is the integral over the full ranges of the kinematic angles and the bin width.

The analysis has been performed in two steps:

- As the axial-vector current dominates the decay, all structure functions other than

Figure 2. Measured hadronic structure functions w_A , w_C , w_D , and w_E (points) in comparison with the model predictions of the KS model (dashed line) and the IMR model (dotted line).

W_A , W_C , W_D , and W_E are assumed to be zero. To concentrate on the Q^2 -dependence, the structure functions are integrated over the Dalitz plane:

$$w_X(Q^2) = \int W_X(s_1, s_2, Q^2) ds_1 ds_2. \quad (2)$$

The measurement of w_A , w_C/w_A , w_D/w_A , and w_E/w_A in comparison with the model predictions (KS and IMR) is shown in fig. 2. Both models describe reasonably well the angular distribution of the decay presented by w_C , w_D , and w_E whereas the agreement for w_A which corresponds to the Q^2 spectrum, is better described by the KS than the IMR model.

- Next, to study the full structure of the hadronic decay current, and accepting larger errors, the events are split not only in Q^2 but also in (s_1, s_2) bins (see tab. 2). Structure functions which include scalar (W_{SB} and W_{SD}) or vector contributions (W_F ,

Table 2

Binning in Q^2 , s_1 , and s_2 for the most general description (see figs. 4 and 5). $s_1^{min/max}$ and $s_2^{min/max}$, respectively, are the values at the phase space boundaries. Only the lower half of the Dalitz plane is used in the fit.

	$m_{3\pi}$ in (GeV)	s_1 in (GeV ²)	s_2 in (GeV ²)
Bin 1	0.8 – 1.0	$s_1^{min} - 0.4$	$s_2^{min} - s_1$
Bin 2	0.8 – 1.0	0.4 – 0.5	$s_2^{min} - s_1$
Bin 3	0.8 – 1.0	$0.5 - s_1^{max}$	$s_2^{min} - 0.25$
Bin 4	0.8 – 1.0	$0.5 - s_1^{max}$	$0.25 - s_1$
Bin 5	1.0 – 1.1	$s_1^{min} - 0.5$	$s_2^{min} - s_1$
Bin 6	1.0 – 1.1	0.5 – 0.65	$s_2^{min} - 0.35$
Bin 7	1.0 – 1.1	0.5 – 0.65	$0.35 - s_1$
Bin 8	1.0 – 1.1	$0.65 - s_1^{max}$	$s_2^{min} - s_1$
Bin 9	1.1 – 1.2	$s_1^{min} - 0.5$	$s_2^{min} - s_1$
Bin 10	1.1 – 1.2	0.5 – 0.7	$s_2^{min} - 0.3$
Bin 11	1.1 – 1.2	0.5 – 0.7	$0.3 - 0.5$
Bin 12	1.1 – 1.2	0.5 – 0.7	$0.5 - s_1$
Bin 13	1.1 – 1.2	$0.7 - s_1^{max}$	$s_2^{min} - s_1$
Bin 14	1.2 – 1.4	$s_1^{min} - 0.5$	$s_2^{min} - s_1$
Bin 15	1.2 – 1.4	0.5 – 0.7	$s_2^{min} - 0.45$
Bin 16	1.2 – 1.4	0.5 – 0.7	$0.45 - s_1$
Bin 17	1.2 – 1.4	$0.7 - s_1^{max}$	$s_2^{min} - 0.6$
Bin 18	1.2 – 1.4	$0.7 - s_1^{max}$	$0.6 - s_1$
Bin 19	1.4 – 1.7	$s_1^{min} - 0.7$	$s_2^{min} - s_1$
Bin 20	1.4 – 1.7	$0.7 - s_1^{max}$	$s_2^{min} - 0.6$
Bin 21	1.4 – 1.7	$0.7 - s_1^{max}$	$0.6 - s_1$

W_G , W_H , and W_I) have also been taken into account, neglecting only those that are pure vector (W_B), pure scalar (W_{SA}), or interference terms between vector and scalar currents (W_{SF}) because they are expected to be very small. As the angular dependencies of W_G and W_{SD} , and of W_I and W_{SB} , respectively, are very similar, these structure functions cannot be separated with the available data sample. Therefore they are combined in the fit parameters $X_1 = -\bar{K}_3/\bar{K}_2 W_G - W_{SD}$ and $X_2 = -\bar{K}_3/\bar{K}_2 W_I + W_{SB}$ (for the definition of $\bar{K}_3$ and $\bar{K}_2$ see [2]).

Figure 3. Comparison of the axial-vector structure functions W_A , W_C , W_D , and W_E between the measurement (for $1.21\text{GeV}^2 < Q^2 < 1.44\text{GeV}^2$) and the KS model prediction (for $Q^2 = 1.3\text{GeV}^2$) in the Dalitz plane. The fit result from the lower half of the Dalitz plane is mirrored to the upper half for better clarity.

In fig. 3 the comparison of the axial-vector structure functions W_A , W_C , W_D , and W_E for the models ($Q^2 = 1.3\text{GeV}^2$) and the fit result ($1.21\text{GeV}^2 < Q^2 < 1.44\text{GeV}^2$) is shown. The full set of the measured structure functions is given for each bin in figs. 4 and 5. For W_A , W_C , W_D , and W_E the model estimates within each bin¹ are also drawn whereas for W_F , W_H , X_1 , and X_2 the comparison to the zero hypothesis for

vanishing scalar and vector contributions is presented.

5. Are there Non-Axial-Vector Contributions?

If there are non-axial-vector contributions in the hadronic decay current they should be visible in the angular distributions and therefore manifest themselves in the hadronic structure func-

¹ $W_A^{\text{bin}} = \frac{\int_{\text{bin}} k(Q^2) W_A^{\text{model}}(Q^2, s_1, s_2) dQ^2 ds_1 ds_2}{\int_{\text{bin}} k(Q^2) dQ^2 ds_1 ds_2}$ with $k(Q^2) = \int L_A(Q^2, \cos \theta^*, \cos \beta, \gamma) d\cos \theta^* d\cos \beta d\gamma$ and

$$W_X^{\text{bin}} = \frac{\int_{\text{bin}} W_X^{\text{model}} \left(\frac{Q_{\text{max}}^2 + Q_{\text{min}}^2}{2}, s_1, s_2 \right) ds_1 ds_2}{\int_{\text{bin}} ds_1 ds_2}$$

for $X = C, D, E$

tions W_F , W_H and the fit parameters X_1 , and X_2 (fig. 5). Therefore the fit result can be compared to the zero prediction of vanishing vector and scalar components. This leads to $\chi^2 = 81.2$ for 84 *d.o.f.* No deviation from the axial-vector current has been observed.

For a quantitative measurement of the non-axial-vector contributions a different method has been applied. Because of strong correlations between W_A , W_B and W_{SA} the fit result for W_A^{fit} includes possible scalar or vector contributions. The pure axial-vector part of W_A can be calculated from W_C , W_D and W_E ($W_A^2 = W_C^2 + W_D^2 + W_E^2$) as these structure functions are independent of vector or scalar contributions². $\Delta^{non-AV} = W_A^{fit} - \sqrt{W_C^2 + W_D^2 + W_E^2}$ estimates the non-axial-vector components. This leads to a model independent limit for non-axial-vector contributions of:

$$\frac{\Gamma^{non-AV}(\tau^- \rightarrow \pi^- \pi^- \pi^+ \nu_\tau)}{\Gamma^{tot}(\tau^- \rightarrow \pi^- \pi^- \pi^+ \nu_\tau)} < 26.1\%$$

at 95% *c. l.*, including statistical and systematic errors.

Under the assumption that a scalar contribution can be fully described through the decay chain $\tau^- \rightarrow \pi^- (1300) \nu_\tau$, $\pi^- (1300) \rightarrow \rho^0 \pi^-$ and $\rho^0 \rightarrow \pi^+ \pi^-$, its contribution can be measured model dependently. In this approach the axial-vector current is described by the IMR or the KS model, respectively. The scalar contribution can be incorporated in both the KS and the IMR models. In the extended maximum likelihood fit in eq. 1 the structure functions can now be replaced by the model predictions. The contribution from the scalar current remains as the only fit parameter, leading to:

$$\frac{\Gamma^{scalar}(\tau^- \rightarrow (\pi^- (1300)) \pi^- \pi^- \pi^+ \nu_\tau)}{\Gamma^{tot}(\tau^- \rightarrow \pi^- \pi^- \pi^+ \nu_\tau)} < 0.84\%$$

at 95% *c. l.* The dependence on the different models (KS and IMR) for the axial-vector part of the decay has been investigated and included in the systematic error.

²As W_E is correlated to W_{SF} , scalar and vector components have to be taken separately.

6. The Parity Violating Asymmetry Parameter γ_{VA}

As already mentioned, once the hadronic current can be described, the parity violating asymmetry parameter γ_{VA} ($\gamma_{VA} = (2g_V g_A)/(g_V^2 + g_A^2)$), where $g_V = g_A = 1$ are the vector and axial-vector couplings of the charged current in the Standard Model) and hence the ν_τ helicity can be measured. In addition to the hadronic structure functions, γ_{VA} is also allowed to vary in the EML fit. Non-axial-vector contributions are neglected here. The change in the likelihood function multiplied for all bins is shown in fig. 6, leading to a model independent measurement of $\gamma_{VA} = 1.29 \pm 0.26 \pm 0.11$, consistent with the Standard Model prediction of $\gamma_{VA} = 1$ for left-handed τ neutrinos.

The dominant systematic error comes from the uncertainty in the detector resolution and the background description.

The model independent result can be compared to a model dependent measurement where the fit parameters W_X^j in eq. 1 are replaced by the hadronic structure functions as predicted from the two models (KS and IMR). The model dependent values obtained for the parity violating asymmetry parameter are $\gamma_{VA}^{KS} = 0.87 \pm 0.16 \pm 0.04$ for the KS model and $\gamma_{VA}^{IMR} = 1.20 \pm 0.21 \pm 0.14$ for the IMR model. The systematic error includes the variation of the model parameters within their errors (see tab. 1). The largest systematic error contribution for the IMR model is due to the uncertainty in the D/S ratio. No variation of this parameter is possible with the KS model. The strong model dependence of the γ_{VA} measurement shows how carefully the systematic errors of measurements in the $\tau^- \rightarrow \pi^- \pi^- \pi^+ \nu_\tau$ decay must be treated when model descriptions are used for the hadronic decay current.

7. Conclusions

The structure of the hadronic decay current in $\tau^- \rightarrow \pi^- \pi^- \pi^+ \nu_\tau$ decays has been studied using two different approaches. Already with the available data samples deficiencies of the models become apparent. Model dependent results have

to be studied carefully. A non resonant background term seems to be required by the data. The full Q^2 , s_1 , s_2 distribution of the hadronic structure functions, including interference terms between axial-vector and non-axial-vector contributions, has been measured for the first time. No evidence has been found for non-axial-vector contributions. Finally, the parity violating asymmetry parameter has been measured in a model independent approach to be $1.29 \pm 0.26 \pm 0.11$ showing a deviation from one of the model dependent results.

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Figure 6. Likelihood function (arbitrarily scaled) multiplied for all bins dependent on γ_{VA} . A Gaussian interpolation between the γ_{VA} values considered (points) is shown.

Figure 4. Axial-vector structure functions W_A , W_C , W_D , and W_E bin by bin (see tab. 2 for bin definitions), for data (points), KS model (dashed line) and IMR model (dotted line).

Figure 5. Interference terms between axial-vector and vector (W_F , W_H) and axial-vector and vector as well as axial-vector and scalar (X_1 , X_2) contributions shown for each bin (see tab. 2 for bin definitions).