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at LEP using tau hadronic decay channels**

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Review of the tau polarisation in Z decays at LEP using tau hadronic decay channels

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Abstract

The measurements of the tau polarisation at LEP, using hadronic decay channels are reviewed. These decay channels carry about 80% of the weight in the LEP average. The $\tau \rightarrow h\nu_\tau$, $\tau \rightarrow \rho\nu_\tau$ and $\tau \rightarrow a_1\nu_\tau$ decay channels are used by each experiment. Advantages and problems for each channel are reviewed. The reconstruction of photons and the charged track identification are the tools needed to classify the decay channel. The measurements are essentially uncorrelated between experiments, and the $\mathcal{A}_\tau$ and $\mathcal{A}_s$ are in good agreement between the different channels and experiments. Finally, the progress since the Montreux workshop is summarised and possible improvements for the final LEP measurements are reviewed.

Figure 1: the $\tau^+\tau^-$ production. The double arrows show the spin projection.

1 INTRODUCTION

The measurement of the tau polarisation and its polar angle dependence is an important piece of the precision test of the electroweak theory. The tau polarisation is defined as the asymmetry of the right- to left-handed cross sections, as shown in figure 1, $P_\tau = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L}$. In the framework of the standard model, the tau polarisation as a function of the production polar angle is given by:

$$P_\tau(\cos\theta) = -\frac{\mathcal{A}_\tau(1 + \cos^2\theta) + \mathcal{A}_e(2\cos\theta)}{(1 + \cos^2\theta) + \frac{4}{3}Afb(2\cos\theta)} \quad (1)$$

Where $Afb = 3/4 \mathcal{A}_\tau \mathcal{A}_e$ is the charge forward-backward asymmetry, $\mathcal{A}_i = 2g_V^i g_A^i / [(g_V^i)^2 + (g_A^i)^2]$ and $g_A^i(g_V^i)$ is the axial(vector) coupling of the lepton to the Z boson, related to the Weinberg angle by $g_V^i/g_A^i = 1 - 4\sin^2\theta_{eff}^i$.

The 4 LEP experiments have measured the tau polarisation [1, 2, 3, 4]. The combined value for $\sin^2\theta_{eff}^\tau$ is one of the most precise among the LEP measurements. For each τ decay channel, a variable, or a set of variables, is defined, which maximise the sensitivity to the tau polarisation. After selection of the decay channel, the tau polarisation is obtained from the fit of the observed data distribution for this variable, by a linear combination of the 2 helicity distributions taken from a $Z \rightarrow \tau^+\tau^-$ Monte Carlo sample.

2 TAU POLARISATION

The structure of the charged current is assumed to be V-A, therefore the neutrino is left-handed. This hypothesis is now well tested with the measurement of the Michel parameters [5].

3 THE OBSERVABLES

3.1 The $\tau \rightarrow h\nu_\tau$ decay channel

In the τ decay to $h\nu$, (h is for pion or kaon), due to the spin zero for the hadron h , the tau polarisation is given in the τ rest frame by the following relation :

$$\frac{1}{\Gamma_\tau} \frac{d\Gamma_\tau}{d\cos\theta^*} = 1/2(1 + \langle P_\tau \rangle \cos\theta^*) \quad (2)$$

The boost in the laboratory frame gives :

$$\frac{1}{\Gamma_\tau} \frac{d\Gamma_\tau}{dX_h} = (1 + \langle P_\tau \rangle (2X_h - 1)) \quad (3)$$

where X_h is the hadron energy normalised to the beam energy, and the tau polarisation is a linear function of X_h .

3.2 The $\tau \rightarrow \rho\nu_\tau$ decay channel

The τ decay to $\rho\nu$ is complicated by the spin 1 of the rho, which allows 2 helicity amplitudes. A statistical analysis of the rho helicity can be performed to recover the loss of sensitivity. This analysis is done using for variables, the $\pi^\pm\pi^0$ mass and the 2 decay angles, Ψ_τ ($\tau \rightarrow \rho\nu$) and Ψ_ρ ($\rho \rightarrow \pi^\pm\pi^0$), with the following relations :

$$\cos\Psi_\tau = \frac{4m_\tau^2}{m_\tau^2 - m_{\pi^\pm\pi^0}^2} \frac{E_{\pi^0} + E_{\pi^\pm}}{E_{beam}} - \frac{m_\tau^2 + m_{\pi^\pm\pi^0}^2}{m_\tau^2 - m_{\pi^\pm\pi^0}^2} \quad (4)$$

and

$$\cos\Psi_\rho = \frac{m_{\pi^\pm\pi^0}}{\sqrt{m_{\pi^\pm\pi^0}^2 - 4m_\pi^2}} \frac{E_{\pi^\pm} - E_{\pi^0}}{P_{\pi^\pm} + P_{\pi^0}} \quad (5)$$

Using such variables recovers partly the loss of sensitivity, while the ideal case can't be reached without access to the tau direction. ALEPH and DELPHI use a single variable ω , is defined as the asymmetry of the population density for the 2 helicity states, with a linear dependence on the τ polarisation [6]. L3 and OPAL perform a 2-dimensional fit of the 2 decay angles.

3.3 The $\tau \rightarrow a_1\nu_\tau$ decay channel

The τ decay to $a_1\nu$ is more complex, due to the a_1 decay to 3 pions. To recover the loss of sensitivity due to the non-zero spin of the a_1 , the dynamic of the decay is needed, which introduces a model dependence. There are 6 variables which describe the a_1 decay, the 3 pions mass, the 2 combinations of 2 pions mass, the decay angle Ψ_τ of the 3 pions system with respect to the tau line of flight in the tau rest frame, and the 2 angles Ψ_{a_1} and γ_{a_1} , of the decay of the 3 pions system. Ψ_{a_1} is defined as the angle of the normal to the 3 pions plane with respect to the a_1 line of flight in the a_1 rest frame, while γ_{a_1} is the angle of rotation in the 3 pions plane [7]. DELPHI uses the moments of the angles Ψ_τ and Ψ_{a_1} , while ALEPH and OPAL use a single variable built in density space [6], similar to the one of the $\rho\nu$ decay channel.

Table 1: Theoretical weight per channel

Decay mode	Theor. weight
$e\nu\nu$	0.06
$\mu\nu\nu$	0.06
$h\nu$	0.30
$\rho\nu$	0.44
$a1(3\pi^\pm)$	0.14
total hadronic	0.88

Table 2: Status of the measurement in LEP experiments

Expt.	channels	status
ALEPH	$\pi\nu, \rho\nu, a1\nu(3\pi^\pm)$	90-92 final
DELPHI	$\pi\nu, \rho\nu, a1\nu(3\pi^\pm), \pi X\nu$	90-94 prelim.
L3	$\pi\nu, \rho\nu, a1\nu(\pi^\pm 2\pi^0)$	91-94 prelim.
OPAL	$\pi\nu, \rho\nu, a1\nu(3\pi^\pm)$	90-94 final (barrel only)

3.4 The decay channels sensitivity

The different methods to optimise the extraction of the tau polarisation presented above, are summarised in table 1. The theoretical weight is defined as $w_i = (S_i^2 \times BR_i) / \sum_j (S_j^2 \times BR_j)$ where S_i is the sensitivity of the channel i , $S_i = 1/\Delta P_\tau \sqrt{N}$, and BR_i the branching fraction of channel i . The real weights must be corrected for the efficiency of the selection, which is specific to each experiment. Table 2 shows the channels used by each experiment, and the status of the data analyzed. The total weight of the hadronic channels of 88% shows the essential role played by the analysis of these channels.

4 PROBLEMATIC OF THE MEASUREMENTS

The method to extract the tau polarisation is similar in LEP experiments, and consists in fitting the relevant variable distribution observed in data by a linear combination of the 2 helicity distributions taken from $Z \rightarrow \tau^+\tau^-$ Monte Carlo. As a consequence, not to bias the tau polarisation measurement the analysis needs to have a detector simulation as close as possible to the detector response in data. Therefore, the systematics correspond to the test of the detector response in the simulation, compared to the data, for the efficiencies, energy and background. It could be noted that L3 has tried an analytic approach as a check. It uses an analytic expression for the expected spectra, convoluted with the detector and selection effects.

The analysis can be summarised in 3 steps. Firstly, the event is a Z decay to $\tau^+\tau^-$, secondly, the decay channel classification does not bias the variables used for the measurement, and finally, these variables are not biased in the Monte Carlo. The second point corresponds, in the hadronic channel, to the charged hadron identification

and to the real photon multiplicity, while the third point is essentially related to the energy calibration of the detector. This last point is usually done using Bhabha for the electromagnetic calorimeter, $\mu^+\mu^-$ pairs and K_S decays to $\pi^+\pi^-$ for the momentum calibration.

4.1 The event selection

The selection of $\tau^+\tau^-$ events at LEP achieves very good efficiency and purity. The generic selection is based on the charged track multiplicity for the rejection of Z hadronic decay, on visible energy and acollinearity of the event to reject the 2-photon background, on response of the electromagnetic calorimeter to reject the Bhabha process, and on the charged track energy and muon identification for the Z decay to $\mu^+\mu^-$. DELPHI and OPAL use a global $\tau^+\tau^-$ selection, while ALEPH and L3 reject the non-tau background with specific cuts adapted to each τ decay channel. All the experiments have a fiducial cut including the end-cap, except OPAL which uses only the barrel. The rejection of Bhabha and $Z \rightarrow \mu^+\mu^-$ processes cuts away some $\tau^+\tau^-$ events at high energy, leading to a possible bias of the polarisation. A similar point could be made for the rejection of the 2-photon background, at low τ jet energy.

To some extent, these effects have not been presented, (studied ?) in the details needed for such precision measurement.

The remaining non-tau background populates essentially the region of maximum bias of the τ polarisation, that is the low energy for the 2-photon background and the high energy for the Bhabha and Z decays to $\mu^+\mu^-$.

4.2 The charged track identification

The charged track identification (PID), classifies the tracks in 3 classes, electron, muon and hadron. The PID has been done with different technics, such as a set of cuts on calorimetric response (DELPHI and L3), with likelihood estimator (ALEPH and OPAL), or with neural net (ALEPH and DELPHI). Figure 2 shows the estimators developed by the OPAL collaboration, first to distinguish between $\tau \rightarrow e\nu\nu$ versus $\tau \rightarrow \text{hadron} \nu$ decays, then a specific estimator to separate the channels with π^0 versus the $\tau \rightarrow h\nu$ channel.

The relevant point is the test of the efficiency of the PID in the data versus the one in the Monte Carlo. This is done using "test samples" from the data and compared with Monte Carlo. The test samples are built from kinematically selected lepton pairs, from Bhabha and 2-photon for the electron, from Z decays to $\mu^+\mu^-$ and 2-photon, for muon. The charged pion test sample is usually selected by tagging at least one π^0 in a τ jet. It could also use the 3 charged pion decays of the τ . L3 experiment uses in addition, a sample from test beam data.

4.3 The photon reconstruction

This is one of the crucial point for the measurement, in channels with π^0 , such as the rho channel, but also in the channels without π^0 , where the selection has to deal with fake photon production coming from the charged hadron interaction in the calorimeter, which could have some dependence with the momentum.

Two methods are used to reconstruct the photon(s). The first one, used by ALEPH,

Figure 2: The likelihood estimator developed by the OPAL collaboration.

DELPHI and OPAL, is based on clustering in the transverse energy deposition in the electromagnetic calorimeter (search for local maxima). The second one, used by L3 experiment, is an iterative process. The reference shower profiles expected for the hadronic interaction is subtracted on the electromagnetic shower. The maxima with more than 1 GeV, in this new transverse energy profile are called photon(s). In a second step, the expected energy shower for photon(s) are subtracted from the original shower profile, and combined with the tracking device (TEC), to give a new measurement of the charged pion energy.

While the study of the charged track PID can be done using test samples, as described above, there is no equivalent test sample for photon, thus the test of photon reconstruction algorithm is restricted to a set of checks of consistency between data and Monte Carlo. How well the Monte Carlo simulation reproduces the photon reconstruction efficiency as a function of the photon energy and the rate of production of “fake” photons, coming from debris of the hadronic interaction, are the 2 key points. These 2 points are usually the largest systematic errors in the tau polarisation measurement in the hadronic channels.

In fact, each experiment has tried a variety of techniques to assess the sensitivity of the analysis to the shower modelling from photon as well as from hadronic interaction. A non exhaustive list includes :

- the variation of the neutral cluster energy threshold or minimal distance to the closest charged track
- the change of the sign of the charged- to-neutral energy asymmetry of the pion in the rho channel
- the comparison of the proportion of resolved/single photon(s) in the rho decay channel, for data versus Monte Carlo

Figure 3: The single photon fraction in 1992 data in ALEPH, for the rho channel (top figure). Among the single photon fraction, the transverse moments of the electromagnetic shower can be used to estimate the fraction of lost photon versus the unresolved π^0 . This is presented below.

- the comparison of the distribution of energy and distance to the closest charged track for data versus Monte Carlo

This last point is related to the fact that fake photons are produced close to the charged track impact point in electromagnetic calorimeter, and essentially at low energy.

To illustrate these points, figure 3 shows the single photon fraction in the 1992 data from ALEPH. Similarly, figure 4 shows, for OPAL, the same distribution but also the angle between the charged track and the closest neutral cluster. These distributions are in good agreement with the distributions expected from the $\tau^+\tau^-$ Monte Carlo.

5 RESULTS

The results of the τ polarisation measurement using the hadronic channels are now presented. The focus is on the $\mathcal{A}_\tau$ measurements, where the systematic errors are significant, while the asymmetry of polarisation, leading to the $\mathcal{A}_e$ measurement, are almost free of systematic. The results on $\mathcal{A}_e$ are given in a separate section.

5.1 The $\tau \rightarrow h\nu_\tau$ channel

The table 3 presents, for each experiment, the efficiency, contamination, statistical error, and the ratio of the systematic to statistical error, in the $\tau \rightarrow h\nu_\tau$ channel.

Figure 4: The single photon fraction and the angle between the charged track and the closest neutral cluster in the rho channel for OPAL.

Table 3: Status in the $h \nu$ decay channel. All values are in %

expts.	effc.	cont.	$\Delta P\tau$	$\sigma_{syst}/\sigma_{stat}$
ALEPH	62.	7.5	2.3	0.55
DELPHI	55	10	4.0	1.5
L3	65	14.8	1.9	0.95
OPAL	49	19.	1.8	0.86

The selection and method have been already described [8], but for the new result from OPAL based on likelihood estimator to distinguish hadron tau decay with π^0 , versus $h \nu$ decay. This estimator includes electromagnetic energy, reconstructed neutral cluster, etc.. In figure 2, the lower plot shows the distribution of this estimator, giving good separation between the decay channels.

Here again it could be noted that an error of 10^{-4} on the efficiency to reject $Z \rightarrow \mu^+ \mu^-$ gives a bias of about 0.5% on the measured tau polarisation, to be compared with the statistical error of about 2%. As mentioned previously, the background from non-tau processes as well as the effect of the rejection applied to these processes, must be considered as one of the delicate point of this analysis. The main sources of systematic errors given by the experiments are related to the PID(ALEPH and DELPHI), the photon reconstruction (ALEPH), the momentum calibration (OPAL) and the effect of the selection and the remaining non-tau background (L3). The results are summarised in table 4, where the quoted values include the effect of photon exchange and photon/Z interference. This correction is about 0.3%. To illustrate this channel, figure 5 shows the energy distribution of the charged hadrons in ALEPH for the 1992 data.

Table 4: Results in the $h \nu$ decay channel. the χ^2 of the average is 2.4/3 dof

expts.	A_τ %
ALEPH	14.5 ± 2.3
DELPHI	18.0 ± 4.0
L3	15.1 ± 1.9
OPAL	12.1 ± 1.8
average	14.1 ± 1.10

Figure 5: The energy distribution for lepton and $h\nu$ channel in ALEPH.

5.2 The $\tau \rightarrow \rho \nu_\tau$ channel

This channel has the best sensitivity among the tau decays, but it is also the most delicate. This is due to the fact that the regions of high sensitivity to the tau polarisation are at low photon or low charged pion energy. For this channel, in addition to the problem of photon reconstruction, the measurement of the photon energy must be considered. The problem of the photon reconstruction dominates the systematic errors for all experiments, and the estimation of this systematic errors is the delicate point. As explained before, a lot of different approaches have been tried, but without reaching the level of clarity obtained in the $h \nu$ channel, and room for improvements on this side is clearly open. Table 5 gives the status of the analysis in this channel.

The neutral cluster multiplicity in the τ jet and the reconstructed $\pi^\pm \pi^0$ mass as shown in figure 6 for OPAL data, gives a good confidence in the reproducibility of the simulation versus data. A slight excess is anyway observed at low mass in the data, corresponding to a tau background from $h \nu$, with fake photons produced by an interaction of the charged hadron in the electromagnetic calorimeter. However, this

Table 5: Status of the tau polarisation measurement in the $\rho\nu$ decay channel. All values are in %

expts.	effic.	Cont.	ΔP_τ	$\sigma_{syst}/\sigma_{stat}$
ALEPH	51	8.9	2.6	0.95
DELPHI	41	15	3.6	0.85
L3	58	10.5	1.4	0.95
OPAL	41	27	1.7	0.85

excess is rejected by the mass cut, reducing the systematic bias to a limited effect.

Figure 6: The neutral cluster multiplicity in tau jet, and $\pi^+\pi^0$ mass in OPAL

The summary of the results is given in table 6. A reasonable agreement is observed.

Table 6: Results in the $\rho\nu$ decay channel. the χ^2 of the average is 4.3/3 dof

expts.	A_τ %
ALEPH	11.2 ± 2.6
DELPHI	12.0 ± 3.6
L3	15.8 ± 1.4
OPAL	12.0 ± 1.7
average	13.65 ± 0.97

5.3 The $\tau \rightarrow a_1 \nu_\tau$ channel

This channel is analysed by ALEPH, DELPHI and OPAL, in the a_1 decay to 3 charged pion, while L3 uses the a_1 decay to $\pi^\pm 2\pi^0$. This last measurement has not been updated for the 1994 data, the precision is very poor and not discussed here. For the 3 charged pion channel, the tau jet classification consists in selecting 3 charged hadrons, and rejecting jets with photons. Table 7 shows the summary of the efficiency, the contamination, the statistical error, and the ratio of the systematic error to the statistical one. For this channel, the a_1 decay dynamics is common to the experiments. The decay dynamic of the a_1 in the Monte Carlo, is given by models [7, 10]. The measured polarisation is correlated to the model used for the decay. The uncertainty due to the model is estimated to be ± 0.012 for ALEPH [11], ± 0.015 for DELPHI [12] and ± 0.013 for OPAL [4]. The estimation, based on the difference when using different models for the decay dynamics, is clearly not satisfactory, since none of the models reproduce the data, as it has been shown at this workshop [9].

The decay dynamics of the tau background, coming mainly from $3\pi^\pm \pi^0$, is also to be taken into account, and is common to the all experiments. However, the importance of this last effect is related to the tau contamination, and is dependent on each experiment.

Table 7: Status of the tau polarisation measurement in the $a_1 \nu$ decay channel. All values are in %

expts.	effic.	Cont.	ΔP_τ	$\sigma_{syst}/\sigma_{stat}$
ALEPH	58	8.9	4.0	0.57
DELPHI	55	15	4.9	0.85
OPAL	39	25	4.8	0.85

From the selection, the main contribution to the systematic error comes from the rejection of jet with photons. Table 8 shows the results of the tau polarisation measurement in this channel.

Table 8: Results in the $a_1 \nu$ decay channel, using the 3 charged pion decay of the a_1 . the χ^2 of the average is 0.2/2 dof

expts.	A_τ %
ALEPH	13.9 ± 4.0
DELPHI	13.1 ± 4.9
OPAL	15.5 ± 4.8
average	14.3 ± 2.7

5.4 The Inclusive hadron in DELPHI

In addition to the "standard" tau decay channels, DELPHI defines a class of "inclusive pion", with one charged hadron and any number of photons. This class of events recovers tau decays not classified in the standard decay channels. The statistical correlation

is 0.3 with the $\tau \rightarrow h\nu_\tau$ channel and 0.4 with the $\rho\nu$ channel. The method consists in defining 2 angles, similar to the ones used in the $\rho\nu$ decay channel, θ_h for the τ decay, and ψ_h for the hadronic decay, defined as the energy asymmetry between the charged hadron and the neutral cluster(s). The analysis is made independently in 3 regions of jet mass. The regions are defined in order to have each region dominated by one of the important decay channel, $h\nu$, $\rho\nu$ and $a_1\nu$. The increase in selection efficiency costs an increase in the systematic related to τ branching ratio, to the neutral energy, and more important to the migration between mass regions. However, the most important systematics are anti-correlated between regions, giving a ratio of systematic error to the statistical one of 0.81, comparable to what is obtained in the standard decay channel. Figure 7 shows the mass distributions observed for each region. A fair agreement is obtained with the expected distributions from the Monte Carlo. The data from 1990 to 1994 are used to measure $\mathcal{A}_\tau = (13.43 \pm 1.26)\%$ and $\mathcal{A}_e = (13.83 \pm 1.38)\%$.

Figure 7: The mass distributions for each jet mass region in the inclusive one-prong hadronic decay channel used by DELPHI

5.5 The measurements of $\mathcal{A}_e$

The τ polarisation forward-backward asymmetry extracted from equation 1, gives a measurement of the $\mathcal{A}_e$ parameter. For this measurement, the sources of systematics are non-symmetric backgrounds, like the Bhabha contribution, and detector effect, which can contribute if the effect is polar angle and charge dependent. In fact, a more subtle possible bias comes from the a_1 decay model dependence, where the systematic error due to the model depends on the value of the polarisation itself, which could create a bias on the asymmetry and this effect gives a large uncertainty on the $\mathcal{A}_e$ measured in the $\tau \rightarrow a_1\nu_\tau$ decay channel. More generally, to give the correct weight of the events in the fit of $\mathcal{A}_e$, any source of systematic dependent on the polar angle,

must be estimated for each polar angle region. The measurements of the $\mathcal{A}_e$ parameter is summarised in figure 8. The agreement between the measurements is very good.

Figure 8: The summary of the forward-backward polarisation asymmetry

6 PROGRESS REPORT

Since the third tau workshop in 1994, at Montreux, the measurements have been largely improved, not only by the addition of new data, including new channels, such as the $\tau \rightarrow a_1 \nu_\tau$ decay channel, with a_1 decaying to 3 charged pion, now analysed by OPAL, but also in the selection (OPAL estimators), in the check of measurement (analytic approach for L3, analysis of the end-cap and neural net approach for DELPHI). On the side of the method, OPAL introduces a new method, taking into account the correlation between hemispheres, which slightly improves the sensitivity of the measurement. Finally, it could be noted that no new measurements have been presented by ALEPH since the numbers from 1992 data.

An extensive study of the systematic effects has been done, specially on the side of the photon reconstruction. In the future, a similar work is probably needed on the side of the $\tau^+ \tau^-$ selection, where the effect could be dramatic. The a_1 decay dynamic remains the black point in the measurement using the hadronic channels, but so far no improvement is expected.

7 CONCLUSION

The LEP experiments have used successfully the tau hadronic decays to measure the τ polarisation. These measurements are the most sensitive, and correspond to about 80% of the total precision. The agreement of the measure using the different decay

channels, but also between the 4 LEP experiments, where the systematic effects are essentially uncorrelated, gives a good confidence in the measurement. The parameters $\mathcal{A}_e$ and $\mathcal{A}_\tau$ checks the universality in the neutral currents within few percent. Using universality, including the leptonic decay channels of the tau, the measurement of $\sin^2\theta_W^{eff}=0.23251\pm0.00064$, is one of the most precise tests of the neutral current electroweak theory. The significant improvements in the future, will come from ALEPH, when using the data 1993-1995, and OPAL when analysing the end-cap.

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