Study of the $\tau^\pm \rightarrow 3\pi\pi^0\nu_\tau$ decay in Aleph

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Abstract

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Using Aleph data until 1993, the branching fraction of the τ into three charged π s and one π^0 has been measured to be: $B(\tau^\pm \rightarrow 3\pi\pi^0) = (4.21 \pm .09 \pm .14)\%$. The resonant structure of this channel has also been investigated. We find a clear signal for the ω meson corresponding to a branching ratio of: $B(\tau^\pm \rightarrow \omega\pi) = (1.82 \pm .16)\%$. In this sub-channel, we bound the contribution from any 2^{nd} -class current to less than 13% at a 95% confidence level. The non- ω part is found to be consistent with single ρ production i.e. $\rho\pi\pi$. An estimate of the relative rates of the various charges of the ρ is also performed but remains inaccurate because of large interference effects.

1. Introduction

1.1. Theoretical Aspects

The hadronic final state has quantum numbers $I^G = 1^+$. It is known that from a $W \rightarrow u\bar{d}$ decay, pseudo-scalars states are suppressed by a $(m_u + m_d)^2$ factor while scalar ones are even more reduced by $(m_u - m_d)^2$. One thus expects to find the hadrons in a $J^{PG} = 1^{++}$ state or, if one allows G-parity breaking, in an axial state.

Vector states of 4 pseudo-scalar mesons need 1.3 or more relative p-waves. One consequently expects spin 1 resonances to dominate the channel. The best candidates are the ω and ρ mesons. Other possibilities are either coming from 2^{nd} class currents, like $\tau^\pm \rightarrow \nu_\tau b_1$ with $b_1 \rightarrow \omega\pi$ or $\tau^\pm \rightarrow \eta\pi^\pm\nu_\tau$, or cannot be easily spotted because of their heaviness and/or broadness like a_1 , $\rho(1450)$, $\rho(1700)$, ... One thus describes this final state as consisting of $\omega\pi$ in relative p-wave on one side and $\rho\pi\pi$ on the other side.

The ω part is completely determined if one neglects 2^{nd} class currents by [4]:

$$\langle \omega(s, p) \pi(k) | V^\mu | 0 \rangle = iF_3(q^2) \epsilon^{\mu\nu\alpha\beta} s_\nu p_\alpha k_\beta \quad (1)$$

In this formula, s is the spin and p the momentum of ω , k the momentum of the pion and the form factor F_3 simply describes the origin of the $\omega\pi$ system which one can extract from e^+e^- data or model using VDM ρ and ρ' Breit-Wigner shapes.

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Note that this part does not effectively interfere with the $\rho\pi\pi$ one because of the narrowness of the ω resonance. We have measured its relative proportion by fitting the $\pi^+\pi^-\pi^0$ invariant mass spectrum which shows a clear peak from the ω decay.

As for possible 2^{nd} class currents contributions in this sub-channel, we expect to see their effect through the χ angle distribution, χ being the angle in the ω rest frame between the normal to the ω decay plane and the 4^{th} pion. Indeed each different spin-parity of the $\omega\pi$ system implies a characteristic distribution for χ and thus any non-vector current should translate into a deviation from the standard $\sin^2(\chi)$ density.

The $\rho\pi\pi$ part however remains unknown. Various models using different assumptions exist. In TAUOLA [3], the adopted model is based on chiral symmetry enhanced by single ρ enhancements which leads to the hadronic current [5]:

$$J_\mu = \frac{2\sqrt{3}}{f_\pi^2} [2(q_{unl} - q_0)^\nu A_{\mu\nu}^{unl\ 0} F(s_{unl\ 0}) + (q_{lik\ 1} - q_{unl})^\nu A_{\mu\nu}^{1\ unl} F(s_{1\ unl}) + (q_{lik\ 2} - q_{unl})^\nu A_{\mu\nu}^{2\ unl} F(s_{2\ unl})] \quad (2)$$

The tensor structure is given by:

$$A_{\mu\nu}^{ik} = g_{\mu\nu} - \sum_{l \neq i, k} \frac{(Q - 2q_l)_\mu (Q - q_l)_\nu}{(Q - q_l)^2} \quad (3)$$

Q is the total momentum and q_l are the individual pion momenta, F is a Breit-Wigner like form factor which accounts for the various ρ resonances.

One readily sees that this current predicts twice as much unlike-charged ρ as neutral ρ (in the zero width approximation) and no like-charged ρ at all. We thus have made use of the available $(\pi\pi)$ mass spectra to reconstruct the observed ones by fitting the relative weights of the 3 possible ρ enhancements: $\rho^{uni}\pi^{lik}\pi^{lik}$, $\rho^{lik}\pi^{uni}\pi^{lik}$ and $\rho^0\pi^{lik}\pi^0$. This procedure assumes that these 3 processes saturate the non- ω part and more importantly that the interference contributions can be neglected which turns out to be a rather poor approximation.

It is also clear that the next orbital momentum configuration which involves 3 p-waves between the pions is strongly disfavoured by the limited available phase space in a τ decay.

Finally we can use isospin rotations to relate the charged hadronic current to the isovector part of the electro-magnetic current. One can then convert the latest $e^+e^- \rightarrow (4\pi)^0$ and $e^+e^- \rightarrow \omega\pi^0$ data to predict the $\tau^\pm \rightarrow 3\pi^\pm\pi^0\nu_\tau$ and $\tau^\pm \rightarrow \omega\pi^\pm\nu_\tau$ branching fraction as well as the hadronic mass spectrum.

1.2. Experimental Overview

As for the $3\pi\pi^0$ branching fraction, we had in this workshop [2] an updated prediction based on CVC of: $B = (4.20 \pm .29\%)$. This figure is in perfect agreement with the present study as is the corresponding Aleph result from the global analysis also presented here [1].

As for the relative fraction of $\tau^\pm \rightarrow \omega\pi$, Argus [6] finds with around 460 candidate events: $\alpha \equiv \frac{\Gamma(\tau^\pm \rightarrow \omega\pi) \times B(\omega \rightarrow \pi^+\pi^-\pi^0)}{\Gamma(\tau^\pm \rightarrow 3\pi\pi^0)} = 33 \pm 4 \pm 2\%$. Here also CVC predicts not only the branching ratio: $B(\tau^\pm \rightarrow \omega\pi) = (1.79 \pm .14\%)$ (from [2]) but the total mass distribution as well. The branching fraction perfectly agrees with the present work and the spectra fairly coincide within the limited statistics as shown on figure 1.

The χ angle distribution was also studied earlier by Argus [8]. With around 150 candidates, they bounded 2^{nd} -class currents to less than 50% with a 90% CL.

Finally, Argus [6] also measured the various $\rho\pi\pi$ weights within the non- ω part of $\tau^\pm \rightarrow 3\pi\pi^0$.

Their result can be rewritten:

$$\begin{cases} \tau^\pm \rightarrow \rho^{uni}\pi^{lik}\pi^{lik} & : 15.6 \pm 4.7 \pm 0.6\% \\ \tau^\pm \rightarrow \rho^{lik}\pi^{uni}\pi^{lik} & : 40.6 \pm 7.8 \pm 1.6\% \\ \tau^\pm \rightarrow \rho^0\pi^{lik}\pi^0 & : 46.9 \pm 6.3 \pm 3.1\% \end{cases} \quad (4)$$

Figure 1. Total mass spectrum for $\omega\pi^\pm$ events (dots) compared with $e^+e^- \rightarrow \omega\pi^0$ from Novosibirsk (circles) and Orsay (squares)

2. Event Selection

We use all Aleph data from 1989 to 1993 which is about 87000 τ pairs. We first start from the standard Aleph preselection of dilepton Z^0 decays. This mainly eliminates the hadronic events from $Z^0 \rightarrow q\bar{q}$ which have a high charged and neutral multiplicity and high invariant masses incompatible with the τ mass. It also eliminates many 2 photon events which have no energetic charged track.

At the LEP energy, we have back to back events

in which we study each side (each τ) separately. The selection mainly needs to eliminate $(3\pi)^{\pm}$ and $(3\pi)^{\pm}2\pi^0$ events so we concentrate on rightly counting the number of π^0 (s). The Bhabha background, although large, can hardly mimic the signal and hence will be cut later by our selection. As for the 2 photon events, only $\gamma\gamma \rightarrow \tau^+\tau^-$ has potential danger but its cross-section is small. Hadronic events will require recoil hemisphere tagging.

As for the charged tracks, we select 3 prong hemispheres with specific requirements. The tracks must be well reconstructed, having enough points in the various tracking devices and pointing to a common vertex close to the interaction point. We further require that none of these 3 tracks is positively identified as an electron to avoid multi-track Bhabha contamination. One or 2 extra electron identified tracks are however allowed since our detector converts about 7% of the photons. We ask those to be consistent with a materialised pair in terms of their relative charges, closest distance of approach and invariant mass. For a single extra electron, we assume that it comes from a conversion in which one of the tracks was lost. When this part of the selection process is completed, we have not only reconstructed the 3 charged pions but also possibly one of the photons from the π^0 (we do not accept both π^0 photons to be converted into e^+e^- pairs).

The most delicate part consists in reconstructing the π^0 . At low energy, we suffer from soft photon losses due to the reconstruction threshold while at high energy, the 2 photons are so boosted that they overlap in the electro-magnetic calorimeter (ECAL) and cannot be disentangled. Furthermore, the charged pions occasionally also interact inside the ECAL creating energy deposits which can fake real photon clusters. We keep candidates with 2 photons of invariant mass between 80 and 200 MeV and possibly one small extra photon if it can be a fake photon that we failed to tag. A photon can either be a conversion as explained above, in which case we require it only to be close in angle to the 3 candidate pion's direction, or an ECAL cluster, in which case we apply further cuts to deal with the pollution from fake photons coming from hadronic interactions inside ECAL. We

ask for conformity to a typical electro-magnetic shower shape, cut out critical zones of the ECAL and use the peculiar distance to track versus energy 2-dimensional distribution of hadronic fake photons to reject them.

Finally, we reject the remaining hadronic events by tagging the opposite hemisphere. In this recoil side, we require:

- at most 3 good tracks
- at most 5 photons within 30° of these good tracks
- at most 15° of opening between the good tracks direction and that of any good track or photon.

To improve on the $\pi^+\pi^-\pi^0$ mass resolution, we refit the reconstructed photon's energies by constraining their invariant mass to be that of a π^0 and using the ECAL resolution at each energy. The total mass of our sample is shown on figure 2.

Figure 2. Invariant mass spectrum for our selection with estimated τ background shaded

Table 1
Relative systematic errors for $B(\tau^\pm \rightarrow 3\pi\pi^0)$ in %

N_τ	non- τ	MC stat	MC b.f.	ε_γ	$m_{\gamma\gamma cut}$	had. fakes	TOTAL
1	1	1.2	.8	1.4	2	1	3.3

3. Branching Fraction Measurement

3.1. Selection Performance

The above selection results in an efficiency of $\epsilon = 28.1\%$ with a τ contamination of $c = 12.6\%$. These figures come from a sample of 2×10^5 Monte-Carlo events. We claim here to simulate adequately all the main background channels. We also simulate the main kaon background channels, $\pi K^0\pi^0$ and $KK^0\pi^0$ in which $K^0 \rightarrow \pi^+\pi^-$, so that our result is free of them down to the per mil (in branching fraction) level. As expected, the τ background consists mainly in 41% of $3\pi 2\pi^0$ and 30% of 3π events. The two photon background is negligible and we find both Bhabha and hadronic background below 5 per mil.

We determine the total number of produced τ s at each energy which yields a total of: $N_{\tau\tau} = 86756$. The data results in $N_D = 2350$ candidates which gives a branching fraction of:

$$B(\tau^\pm \rightarrow 3\pi\pi^0) = (4.21 \pm .09_{stat})\%$$

3.2. Systematic Errors

The main issue is the photon and π^0 reconstruction. We study first our sensitivity to the photon finding algorithm. This yields a possible relative error on the efficiency of 1.4%. Then we compare Data and Monte-Carlo 2 photons mass spectra. The π^0 peak is well reproduced after careful calibration of the ECAL but still, the proportion of events inside the cut zone (80 to 200 MeV) is reproduced with a relative precision of 2%. Finally, we estimate our sensitivity to the hadronic fake photons which are not perfectly accounted for by the Monte-Carlo. This sensitivity was considerably reduced by allowing a small extra photon next to the reconstructed π^0 . We end up with a relative uncertainty on the efficiency of 1%.

The other sources of error are the normalisation (overall number of tau pairs), the non- τ background, the limited Monte-Carlo statistics and imprecise branching fractions. All the corresponding figures are displayed in table 1. The final result for the branching ratio is thus:

$$B(\tau^\pm \rightarrow 3\pi\pi^0) = (4.21 \pm .09_{stat} \pm .14_{sys})\%$$

4. ω fraction and $\omega\pi$ spin-parity

4.1. Fit of the ω fraction

We expect to see a clear peak at the ω meson mass in the $\pi^+\pi^-\pi^0$ mass distribution. The width of about 25 MeV is almost entirely due to the experimental resolution despite the refitting of the π^0 . We fit to the data the relative proportion of events from the $\tau^\pm \rightarrow \omega\pi$ decay using 2 Monte-Carlo samples. One for $\tau^\pm \rightarrow \omega\pi$ and one for $\tau^\pm \rightarrow \rho\pi\pi$. The latter is tuned using the results of section 5. This is necessary to reproduce correctly the shape of the $\pi^+\pi^-\pi^0$ mass spectrum over its whole range. We also subtract the estimated background for which the recent CLEO result [7] on $\omega\pi\pi^0$ dominance in $\tau^\pm \rightarrow 3\pi 2\pi^0$ is very useful.

The quality of the agreement is measured by a χ^2 per d.o.f. of 1.0 for the fit. This is helped by the fact that the 2 current's interference (by definition absent from the fit) is very small as explained above. We obtain a raw proportion of $\omega\pi$ inside $3\pi\pi^0$ of: $\alpha_{raw} = 39.0 \pm 1.5\%$. This figure is corrected by the ratio of acceptances between the 2 sub-channels: $\epsilon_{\omega\pi}/\epsilon_{\rho\pi\pi} = 1.03 \pm .01\%$ due to the quite different dynamics between $\tau^\pm \rightarrow \omega\pi$ and $\tau^\pm \rightarrow \rho\pi\pi$. We obtain:

$$\frac{\Gamma(\tau^\pm \rightarrow \omega\pi) \times B(\omega \rightarrow \pi^+\pi^-\pi^0)}{\Gamma(\tau^\pm \rightarrow 3\pi\pi^0)} = 38.3 \pm 1.5\%$$

Figure 3. $\pi^+\pi^-\pi^0$ mass spectrum of the data (points) with background shaded and fit result (full line) superimposed

4.2. Systematic errors

The fit is extremely stable with respect to the allowed variations in the background subtraction: overall amount, composition and dynamics of the $3\pi^2\pi^0$ channel. We obtain respective shifts on the result α of: 1, 3 and 2 per mil.

From the limited statistics of the reference Monte-Carlo distributions which are treated as infinite samples we find $\Delta(\alpha) = 7$ per mil

The dominant by far uncertainty remains in our ability to reproduce the "background" contribution of $\rho\pi\pi$ whose dynamics are unknown. As mentioned, we reproduce the data fairly well but a check on it shows a residual possible disagreement. If we allow the corresponding reference spectrum to vary within this discrepancy, we observe on the result a variation as large as 2.4%

On conclusion we find:

$$\frac{\Gamma(\tau^\pm \rightarrow \omega\pi) \times B(\omega \rightarrow \pi^+\pi^-\pi^0)}{\Gamma(\tau^\pm \rightarrow 3\pi\pi^0)} = (38.3 \pm 1.5_{stat} \pm 2.5_{sys}\%)$$

Using the branching ratio for $3\pi\pi^0$ measured in this work and $B(\omega \rightarrow \pi^+\pi^-\pi^0) = 88.8 \pm .6\%$ we

can rewrite this result as:

$$B(\tau^\pm \rightarrow \omega\pi) = (1.82 \pm .16\%)$$

This result is in striking agreement and of the same precision that the new CVC estimate presented in this workshop by S. Eidelman [2].

4.3. Search for 2^{nd} class currents in $\tau^\pm \rightarrow \omega\pi$

Figure 4. Expected $\cos(\chi)$ distributions for various $J^P(l)$ hypotheses of the $\omega\pi$ system (standard 1^- is $\sin^2(\chi)$)

We are looking for a non- $J^P = 1^-$ component to the $\omega\pi$ state. Each spin-parity entails a characteristic χ distribution (χ being the angle in the ω rest frame between the normal to the ω decay plane and the 4^{th} pion) as shown on figure 4. We compute $\cos(\chi)$ for each event. There is a twofold ambiguity since there are 2 like-charged pions. We use the side-bands subtraction technique which both solves this ambiguity and subtracts the background. To further reduce the very large (about 60%) amount of $\rho\pi\pi$ events still present, we use the standard cut in the Dalitz plot of the ω decay.

We choose the signal band in the data $m_{\pi^+\pi^-\pi^0}$ distribution around the ω mass and 2 control bands, one on each side, close to the signal one. We extract the $\cos(\chi)$ distributions of each band and subtract both side bands to the central one after normalising their sum to the number of entries inside the signal band below the peak.

The resulting spectrum, figure 5, is perfectly

Figure 5. Above: Side bands on the selected part of the data $\pi^+\pi^-\pi^0$ mass spectrum, Middle: Distribution of $\cos(\chi)$ for each, Bottom: Fit of the standard $\sin^2(\chi)$ function

compatible with the theoretical expectation for a purely vector current, which is $p(\chi) \propto \sin^2(\chi)$. The χ^2 of such a fit is 3.6 for 7 degrees of freedom. To bound all second-class currents, we try to fit the relative proportions of the vector current

and of the most similar non-standard one, namely $J^P(l) = 1^-(0)$ (1 is the orbital wave between the ω and the π). We obtain:

$$2^{nd} - class \leq 13\% \text{ (95\%CL)}$$

5. Study of the ρ resonances

5.1. Method

We are looking for ρ resonances and thus will study the 4 available $(\pi\pi)$ mass spectra in $\tau^{lik} \rightarrow \pi^{unl} \pi_1^{lik} \pi_2^{lik} \pi^0$, namely:

- $(\pi\pi)^{unl} =$ unlike to the τ charged π and π^0
- $(\pi\pi)^{dbl} =$ 2 like-charged π s
- $(\pi\pi)^{lik} =$ one of the like-charged π s and the π^0 (2 combinations)
- $(\pi\pi)^0 =$ one of the like-charged π s and the unlike-charged (2 combinations)

We will assume throughout that all the signal that is not $\omega\pi$ is either $\rho^{unl} \pi^{lik} \pi^{lik}$, $\rho^{lik} \pi^{unl} \pi^{lik}$ or $\rho^0 \pi^{lik} \pi^0$. We also neglect all interference terms between these 3 parts. We use as reference spectra for the fit the 3 possible situations for a pair of π s in $\rho\pi\pi$:

[ins]: both π s belong to the ρ (ρ Breit-Wigner)

[mix]: exactly one belongs to the ρ (phase-space like)

[ext]: none belongs to the ρ (similar to [mix] but squeezed to lower mass by neighbourhood of the resonant ρ)

We try to determine simultaneously the 3 weights W_{unl} , W_{lik} and W_{zer} by simultaneously fitting all the $(\pi\pi)$ mass spectra with these 3 reference distributions. In addition, we subtract our estimated background and try to cut out the ω events before performing the fit. We thus need special Monte-Carlo samples to obtain the reference spectra and estimate the respective efficiencies of the selection and more important, of the anti- ω cut.

5.2. Monte-Carlo samples

In addition to the pure ω sample mentioned in 4.1. we need samples from single $\tau^\pm \rightarrow \rho^{uni} \pi^{lik} \pi^{lik}$ and single $\tau^\pm \rightarrow \rho^0 \pi^{lik} \pi^0$ events. From these we obtain our reference spectra: [ins], [mix] and [ext] and check that they are similar. By symmetry they must be identical for $\tau^\pm \rightarrow \rho^{lik} \pi^{uni} \pi^{lik}$ too.

To reject ω events, we simply forbid any of

Figure 6. $\pi^+\pi^-\pi^0$ mass spectra for the 3 samples showing the quality of the “anti- ω ” cut

the 2 $(\pi^+\pi^-\pi^0)$ combinations to lie between 700 and 870 MeV. We must be wary that this cut affects $\rho^{uni} \pi^{lik} \pi^{lik}$ events very differently from $\rho^{lik} \pi^{uni} \pi^{lik}$ or $\rho^0 \pi^{lik} \pi^0$ ones because of simple symmetry reasons (see figure 6). This correction is applied in the fit by introducing a factor $A = \frac{e^{uni}}{e^{zer}} \approx 1.24$.

Once this cut is made, the new contaminations are 14.1% for the background and 4.9% for the remnant of ω events. These figures are derived

from the Monte-Carlo and from the above result for $B(\tau^\pm \rightarrow \omega \pi)$. So are the corresponding $(\pi\pi)$ mass spectra which we will subtract from the data.

5.3. Fit result

The result, shown on figure 7, is:

$$\begin{cases} W_{lik} &= 33.8 \pm 2.6_{stat} \% \\ W_{zer} &= 25.8 \pm 2.6_{stat} \% \\ W_{uni} &= 40.4 \pm 2.3_{stat} \% \end{cases}$$

By construction, we neglect all interference terms and constrain our 3 weights to have unit sum. The neglect of interferences is believed to be largely responsible for the discrepancies observed on figure 7. These are such that one should interpret the above results with care.

As for systematic errors, they are also very difficult to define in view of the relative failure to fit the data. We find $\Delta(W)_{yst} = 2\%$ from the method itself, the background subtraction and the efficiency's estimations. The error from the inadequate dynamics of the Monte-Carlo and neglect of interferences cannot be precisely determined. We estimate although that $\Delta(W)_{yst}$ cannot be lesser than $\approx 4\%$ but could be much larger.

5.4. Double- ρ resonance

We have shown that in $\tau^\pm \rightarrow \rho^\pm \rho^0$, the 2 ρ s must be in a p-wave. This configuration is obviously strongly phase space suppressed. Furthermore, we have no theoretical model so that one might wonder how the ρ Breit-Wigners would show on the $(\pi\pi)$ mass spectra. The simplest idea is to plot one candidate ρ mass versus the other and look for a bump in the (m_ρ, m_ρ) area. We do that after subtracting the background and ω events. It is however unclear where the (m_ρ, m_ρ) area lies. Several places were tried, none showing a $\rho - \rho$ enhancement. We deduce from it that there is no evidence for its existence in our data.

Figure 7. Global fit of all $(\pi - \pi)$ mass spectra neglecting interference terms. This cannot reproduce the data properly.

6. Conclusion

We have used 87000 $Z^0 \rightarrow \tau^+ \tau^-$ decays recorded in the Aleph detector to analyse the decay $\tau^\pm \rightarrow 3\pi\pi^0$. We find 2350 candidates corresponding to a branching fraction of: $\mathcal{B}(\tau^\pm \rightarrow 3\pi\pi^0) = (4.21 \pm .09_{stat} \pm .14_{sys}\%)$. We have shown that it is consistent with a superposition of $\tau^\pm \rightarrow \omega\pi$ and $\tau^\pm \rightarrow \rho\pi\pi$ processes. The fraction of $\omega\pi$ has been determined to be: $(38.3 \pm 1.5_{stat} \pm 2.5_{sys}\%)$ corresponding to: $\mathcal{B}(\tau^\pm \rightarrow \omega\pi) = (1.82 \pm .16)\%$. In this subprocess, we find no evidence for 2nd-class currents. We obtain: $2^{nd} - class \leq 13\%$ (95%CL). As for the non- $\omega\pi$ part, we see ρ resonances in the 3 charges: $\rho^{uni}\pi^{lik}\pi^{lik}$, $\rho^{lik}\pi^{uni}\pi^{lik}$ and $\rho^0\pi^{lik}\pi^0$ but no evidence for double- ρ enhancement. We find $W_{uni} \approx 40\%$, $W_{lik} \approx 34\%$ and $W_{zer} \approx 26\%$

but the poor quality of the fit demonstrates that these figures should be interpreted with care.

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