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Limit on the tau neutrino mass from the ALEPH experiment

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Abstract

A bound on the tau neutrino mass is established using the data collected from 1991 to 1995 at $\sqrt{s} \simeq m_Z$ with the ALEPH detector. An upper limit of 18.2 MeV/c^2 at 95% confidence level is derived by fitting the distribution of visible energy vs invariant mass in $\tau^- \to 2\pi^- \; \pi^+ \; \nu_\tau$ and $\tau^- \to 3\pi^- \; 2\pi^+ \; (\pi^0) \; \nu_\tau$ decays.

1 The method

In ALEPH, a bound on the neutrino mass is obtained from the study of the $\tau^- \to 2\pi^- \pi^+ \nu_\tau$, $\tau^- \to 3\pi^- 2\pi^+ \nu_\tau$ and $\tau^- \to 3\pi^- 2\pi^+ \pi^0 \nu_\tau$ decay modes[1] of the tau lepton, using a technique based on a two dimensional likelihood fit in the variables invariant mass, m_h, and energy, E_h, of the hadronic systems [1]. The limit on the mass is derived from a maximum likelihood function giving the probability density of obtaining the observed distribution in the plane (m_h, E_h). For a given event i, the probability density function $P_i(m_\nu)$ takes the form:

$$\mathcal{P}(m_\nu) = \frac{1}{\Gamma} \cdot \frac{d^2\Gamma}{dE_h dm_h} \otimes \mathcal{G}(E_{beam}, E_\tau) \otimes \mathcal{R}(m_h, E_h, \rho, \sigma_{m_h}, \sigma_{E_h}, ...) \otimes \varepsilon(m_h, E_h)$$

where $\frac{1}{\Gamma} \cdot \frac{d^2\Gamma}{dE_h dm_h}$ is the theoretical distribution of the given decay mode, $\mathcal{G}(E_{beam}, E_\tau)$ the radiation kernel, $\mathcal{R}(m_h, E_h, \rho, \sigma_{m_h}, \sigma_{E_h}, ...)$ the detector resolution, and $\varepsilon(m_h, E_h)$ the selection efficiency of each mode.

The exact functional form of the spectral functions entering the expression $\frac{1}{\Gamma} \cdot \frac{d^2\Gamma}{dE_h dm_h}$ is not predicted by theory. Nevertheless, since the spectral functions are expected to vary slowly with q^2 in the region close to the kinematic boundary, the uncertainty in their form plays only a minor role in the determination of the bound on m_ν. The decay $\tau^- \to 2\pi^- \pi^+ \nu_\tau$ is described using the model of Kühn and Santamaria (KS) [2], inspired by the asymptotic limit of chiral theory. For the $\tau^- \to 3\pi^- 2\pi^+ (\pi^0) \nu_\tau$ mode, there are very few studies of the spectral functions, mainly because the number of observed candidates is very small. Experimentally, it is seen that the invariant hadronic mass spectrum peaks at high values of q^2 and seems unlikely to be dominated by a single resonance.

2 Data selection and background

The data selection aims at introducing the smallest possible bias towards lower values for the determination of the upper limit. Since at LEP the separation of $\tau^+\tau^-$ events from other processes is relatively easy, the main concern is the rejection of background from misidentified tau decays. The

[1]The inclusion of charge conjugate modes is always implied throughout this paper.

topology of the background which lowers the neutrino mass limit is the one with a true final state multiplicity lower than the observed one, because in this case the reconstructed values of the hadronic mass and energy are systematically higher than the true ones. The event selection has been designed to reduce such contamination to a negligible level, while it tolerates a moderate background from tau decays with multiplicities higher than the observed one.

The analyses presented here are based on the data collected by ALEPH from 1991 to 1995 in the proximity of the Z resonance. The ALEPH detector and its performance are described in detail in [3].

The final selection efficiencies for the $\tau^- \to 2\pi^- \, \pi^+ \, \nu_\tau$, $\tau^- \to 3\pi^- \, 2\pi^+ \, \nu_\tau$ and $\tau^- \to 3\pi^- \, 2\pi^+ \, \pi^0 \, \nu_\tau$ channels are 49%, 24.7% and 7.0%, respectively. The lower efficiency of the last mode is caused by stringent cuts on π^0 reconstruction which are needed to suppress the cross-channel contamination from $\tau^- \to 3\pi^- \, 2\pi^+ \, \nu_\tau$ decays.

The contamination of this selection from $q\bar{q}$ events amounts to 0.3% for the $\tau^- \to 2\pi^- \, \pi^+ \, \nu_\tau$, and 0.1% for the $\tau^- \to 3\pi^- \, 2\pi^+ \, (\pi^0) \, \nu_\tau$ decay modes. The background from tau decays amounts to 6.7%, 7.6% and 0.6% for the three channels, respectively.

A total of 2939 $\tau^- \to 2\pi^- \, \pi^+ \, \nu_\tau$, and 52 (3) $\tau^- \to 3\pi^- \, 2\pi^+ \, (\pi^0) \, \nu_\tau$ candidates are selected in the data, in good agreement with the expectations. The distributions in the upper part of the (E_h, m_h) plane are shown in Fig. 1. Due to the large number of candidates, the selection and the fit in the $\tau^- \to 2\pi^- \, \pi^+ \, \nu_\tau$ channel are restricted to the region of the (E_h, m_h) plane $0.89 < E_h/E_{beam} < 1.07$ and $0.76 < m_h < 1.83$ GeV/c^2. The fitted region is shown in Fig. 1. The size of region has been chosen large enough to make the limit on the tau neutrino mass insensitive to variations of the region boundaries.

3 Results and systematic effects

The fits to the 2939 $\tau^- \to 2\pi^- \, \pi^+ \, \nu_\tau$ and to the 55 $\tau^- \to 3\pi^- \, 2\pi^+ \, (\pi^0) \, \nu_\tau$ events give 95% CL upper limits on the tau neutrino mass of 22.3 MeV/c^2 and 21.5 MeV/c^2, respectively. The 95% confidence level is taken as the point where the logarithm of the likelihood is 1.92 lower than its maximum.

Several sources of systematic errors have been considered. For each source a new fit was performed, having changed in the likelihood the appropriate

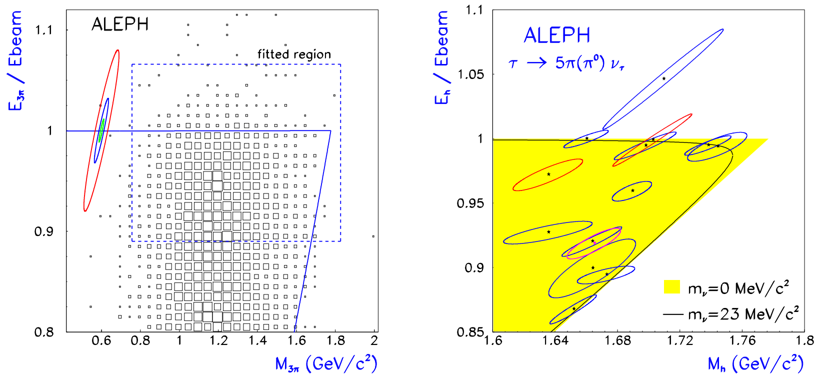

Figure 1: Left: Distribution in the the (m_h, E_h) plane for $\tau^- \to 2\pi^- \ \pi^+ \ \nu_\tau$ candidates in the data (the three ellipses show the typical size of the resolution; Right: Distribution in the (m_h, E_h) plane for $\tau^- \to 3\pi^- \ 2\pi^+ \ (\pi^0) \ \nu_\tau$ candidates in the data

quantity by one standard deviation. The difference between the value of the 95% CL upper limit on m_{ν_τ} obtained from the original fit and the one with the modified likelihood has been taken as the systematic error due to that source. All the variations were then summed in quadrature to give the global systematic error, which was added linearly to the result of the original fit.

The sources of systematics considered belong to four major categories: tau properties, such as tau mass, energy and polarisation; detector effects, such as absolute momentum calibration and resolution; selection efficiency and background contamination; and tau decay modelling. The corresponding variations of the neutrino mass limit are reported in Table 1. The variations for both three- and five-prong final states are separately summed in quadrature to obtain the two total systematic errors of 4.2 and 0.8 MeV/c^2, respectively. These errors are summed linearly to the measured mass limits to obtain 95% CL upper limits of 25.7 MeV/c^2 and 23.1 MeV/c^2 for the three-prong and five-prong modes, respectively. Interestingly, the $\tau^- \to 2\pi^- \ \pi^+ \ \nu_\tau$ mode is competitive with the $\tau^- \to 3\pi^- \ 2\pi^+ \ (\pi^0) \ \nu_\tau$ mode thanks to the larger number of candidates, which compensate for the less favourable distribution in the (E_h, m_h) plane. The two limits are complementary since the limit derived from the $\tau^- \to 2\pi^- \ \pi^+ \ \nu_\tau$ mode is more sensitive to the energy distribution and the others to the mass distribution of the hadronic system.

Source	Variation of m_ν limit (MeV/c^2)		
	$3\pi^- \ 2\pi^+ \ (\pi^0) \ \nu_\tau$	$2\pi^- \ \pi^+ \ \nu_\tau$	combined
τ mass	0.2	0.3	0.2
beam energy	< 0.1	0.1	0.2
τ polarisation	< 0.1	0.1	0.1
slope of selection efficiency	< 0.1	0.1	0.1
τ background	0.3	0.1	0.2
energy-mass calibration	0.3	2.6	0.9
energy-mass resolution	0.2	3.1	1.1
spectral function	< 0.1	0.3	0.1
modelling of resolution	0.6	1.1	0.6
total	0.8	4.2	1.6

Table 1: Systematic variation of the 95% CL upper limit on m_ν (in MeV/c^2) for the individual and combined $\tau^- \to 3\pi^- \ 2\pi^+ \ (\pi^0) \ \nu_\tau$ and $\tau^- \to 2\pi^- \ \pi^+ \ \nu_\tau$ likelihoods

The combined upper limit has been determined from a new likelihood $\mathcal{L}^{comb}$, constructed as the product of the individual $\tau^- \to 2\pi^- \ \pi^+ \ \nu_\tau$ and $\tau^- \to 3\pi^- \ 2\pi^+ \ (\pi^0) \ \nu_\tau$ likelihoods $\mathcal{L}^{3\pi}$ and $\mathcal{L}^{5(6)\pi}$. This likelihood limits m_{ν_τ} below 16.6 MeV/c^2 at 95% CL. Table 1 summarises the variation of the two limits and the variation of the combined limit, for each source of error. In this way, a total systematic error of 1.6 MeV/c^2 and a final 95% CL limit of 18.2 MeV/c^2 were obtained.

Recently the DELPHI Collaboration has suggested the existence of a hitherto unseen decay mode of the tau lepton in a radial excitation of the a_1 [5]. In that analysis this a' resonance is assigned a mass of 1700 MeV/c^2 and a width of 300 MeV. Its contribution is fitted to be (2.3 ± 0.6) %. If 2.5 % of this resonance is introduced in the fit of the $\tau^- \to 2\pi^- \ \pi^+ \ \nu_\tau$ mode, the agreement between the model and the data deteriorates giving a $\chi^2/n.d.f.$ of 1077/999 with respect to the value of 1059/999 obtained with the KS spectrum alone. If this resonance were considered in the fit, the limit from the $\tau^- \to 2\pi^- \ \pi^+ \ \nu_\tau$ sample would increase by 6 MeV/c^2, and the combined limit would increase from 18.2 to 19.2 MeV/c^2.

4 Conclusions

ALEPH has used the modes $\tau^- \to 2\pi^- \; \pi^+ \; \nu_\tau$ and $\tau^- \to 3\pi^- \; 2\pi^+ \; (\pi^0) \; \nu_\tau$ to bound the tau neutrino mass by fitting the distribution of events in the (m_h, E_h) plane. An upper limit of 18.2 MeV/c^2 on the tau neutrino mass is obtained at 95% confidence level.

References

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