First Upper Limit on the Admixture of a Decaying ν_τ

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Abstract

Recent studies investigating the nature of the ν, specifically those conducted at Super-K and SNO, have produced evidence supporting ν oscillation. This discovery would imply that neutrinos have mass, an inference which raises some significant questions. The existence of massive neutrinos indicates that lepton family number is not necessarily conserved. Are these massive neutrinos the "missing mass" of the Universe? Does the existence of massive neutrinos mean that there exist decaying ν's? It is the answer to this last question which we seek. The purpose of this project is to provide an upper limit on ν decay by searching for evidence of ν_τ decay within the CLEO detector. Although we find no definitive evidence of ν_τ decay, we are able to place an upper limit on the admixture of a decaying ν_τ component.

1 Introduction

The $\nu_\tau$was first directly observed in July 2000 at Fermilab. Physicists at Fermilab used the Tevatron accelerator to generate neutrinos with the expectation that a small fraction of these neutrinos would be tau neutrinos. In order to test this belief the ν beam was shot through a target which would cause one in 10^{12} tau neutrinos to interact and produce a τ lepton, which the DONUT detector could easily identify[1]. This discovery concluded the decades long search for this elusive particle.

The study of the decay of the ν_τ was designed to supplement and extend the research released by Super-K in 1999 and recently supported by SNO [2, 3]. The research done by these groups pertains to the phenomenon of ν oscillation; we expand upon prior research by looking at the previously ignored possibility of ν decay. The purpose of this analysis was to place an upper limit on the decaying component of the ν_τ within the CLEO detector.

The tau neutrinos we wish to study are most easily found as the decay products of the τ. When the $e^+$and e^- beams collide and produce the conditions necessary for our study, the τ's are always produced as τ^+, τ^- pairs. We were able to identify a specific large and clean τ^+ decay mode which would generate the geometric configuration we deemed necessary to the detection of the decay of the ν_τ.

2 Method

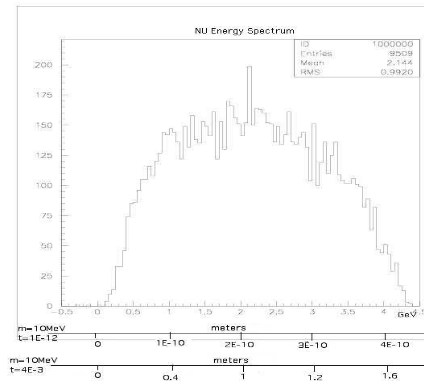
The focus of our study is the decay of the ν_τ, assuming $\nu_\tau \to \gamma X$(where X is some other unidentified particle[1]), generated by a specific τ decay: $\tau^+ \to \rho^+ + \nu_\tau,\rho^+ \to \pi^+\pi^0$. We focus on this decay because the geometry of the decay allows for an easy identification of any photons which may result from the decaying ν. The τ^+ will always be tagged by one of three τ^-decay modes: $\tau^- \to (\pi^- + \nu, e^- + \nu + \nu, or \mu^- + \nu + \nu)$. The decay mode of the τ^- is significant because the charged particle byproducts of these decays are easily identifiable. Having charged particles opposite our signal is important as it allows for easy identification of potential signal events and elimination of background. The signal itself is easily identifiable due to the geometry present in the τ^+ decay; the τ^+ decays into the ρ and the ν_τ. The ν_τ and the ρ form a cone with the ρ traveling along the axis and the ν_τ lying somewhere along the edge. Since the ν_τ mass is small compared to its typical energy, a $\nu_\tau \to \gamma X$ decay will leave a photon along this cone. Using the 4-vector relation $\mathrm{p}_\nu + \mathrm{p}_\rho = \mathrm{p}_\tau$, and the approximation that $\mathrm{m}_\nu = 0$, we obtain for the cosine of the opening angle betwen the ρ and the ν_τ flight direction :

$$< \cos\theta_{\rho\nu} >= \frac{\mathrm{m}_\rho^2 - \mathrm{m}_\tau^2 + 2\mathrm{E}_\rho(\mathrm{E}_\tau - \mathrm{E}_\rho)}{2 \mid \vec{\mathrm{p}}_\rho \mid (\mathrm{E}_\tau - \mathrm{E}_\rho)}$$

3 ν_τ Energy Spectrum

The first thing we looked at was the energy spectrum of the ν_τ. This spectrum was generated in PAW using our Signal Monte Carlo ntuple. The distribution shown below gives a good idea of why we must look at ν_τ decays for low lifetime to mass ratios. The bars beneath the distribution show the approximate decay positions for neutrinos with various lifetime to mass ratios. As one can clearly see the larger the lifetime to mass ratio the less likely it is that the ν_τ will decay within our detector(dimensions on the order of 1m).

[1]in our Monte Carlo we set X=ν_μ and m_{ν_μ}=0



The above distribution shows the ν_τ energy distribution. The two black lines below the image represent the mean distance traveled by the ν_τ before it decays. The top line shows a lifetime to mass ratio on the order of that studied in this analysis, whereas the bottom line shows a lifetime to mass ratio that will place the ν_τ outside the detector often before decay occurs. This distribution clearly shows that this analysis is limited to the study of ν_τ with small lifetime to mass ratios. The relevant ratio is given by the typical $\mathrm{E}_\nu = 1\mathrm{GeV}$ and the detector size(1m). Requiring the decay to be inside the detector, $\gamma\beta c\tau \ll 1$mand using $\beta \approx 1$, $\frac{\mathrm{E}_\nu}{\mathrm{m}_\nu} = \gamma$, we get:$\frac{\mathrm{E}_\nu}{\mathrm{m}_\nu} c\tau_\nu \ll 1\mathrm{m}$ which in turn gives us $\frac{c\tau_\nu}{\mathrm{m}_\nu} \ll \frac{1\mathrm{m}}{\mathrm{GeV}}$ or $\frac{\tau_\nu}{\mathrm{m}_\nu} \ll \frac{3\mathrm{x}10^{-12}\mathrm{sec}}{MeV}$.

4 Data

We skimmed over Tau Generic Monte Carlo and Data tapes(twenty tapes each) for the 4S2 to 4SG re-compress datasets, as well as eleven tapes for the Continuum Monte Carlo 4S7 dataset(Luminosity equivalent of 1/3 of dataset). Signal Monte Carlo was also generated with a mass of 10 MeV/c^2 and a lifetime of $18\mathrm{x}10^{-7}$m.

5 Analysis

5.1 Cuts

5.1.1 Skim Cuts

Our skim was designed to place very basic cuts upon the data while generating an ntuple which would contain enough data to allow for more detailed cuts within PAW. The skim cuts discarded obvious errors such as those arising when the cosine of an angle was not between -1 and 1 or when a particle had an energy higher than that of the beam. The skim also required the following:

- that the product of the charge from the two tracks be negative
- that the track momentum be greater than 500 MeV
- the transverse momentum be greater than 200 MeV
- the missing momentum be pointing into the barrel
- the visible energy be less than 0.9*2*E_{beam}
- $\mid$ Z0CD $\mid \leq$ 10cm
- $\mid$ DBCD $\mid \leq$ 1cm
- KINCD = 0
- $|$CZCD$| \leq 0.7$
- tracks are matched to calorimeter showers

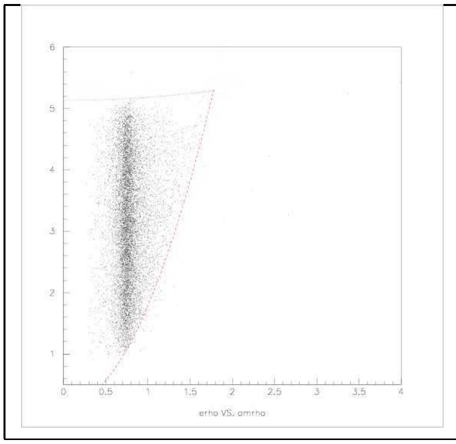
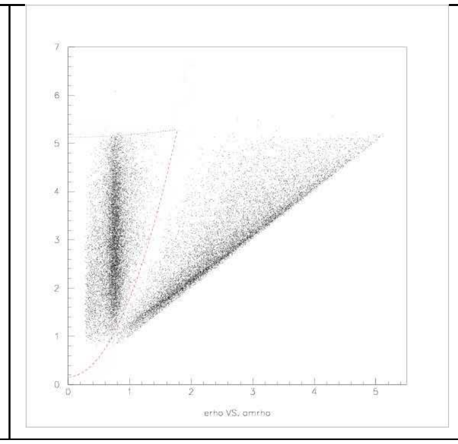
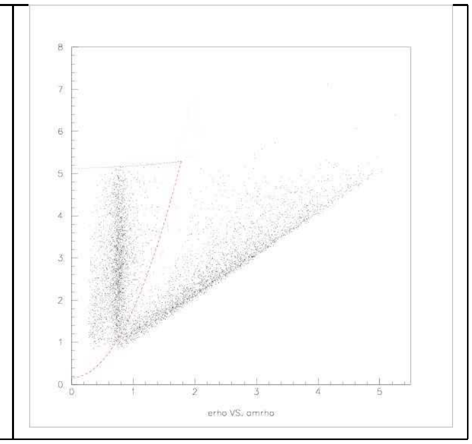
Additional cuts upon the decay photons of the π^0: we require photons from the π^0 to have $E_\gamma > 60$MeV(100MeV) in the barrel(end caps). Furthermore the π^0 mass must be within 3 σ of the nominal π^0 mass. Upon passing this cut, the track closest(in angle) to the π^0, along with the π^0 is dubbed the ρ candidate, with the additional stipulation that the π^0 be at least 90^0 away from the charged track(the τ^-decay). The ntuple generated by the skim contained twenty-two variables which we were then able to use within PAW to place improved cuts on the data.

5.1.2 Cuts Within PAW

Eleven cuts were used within PAW to reduce the background events present in the ntuples. These cuts placed limits upon the ratio of the actual angle to the expected angle of the cone, the number of charged tracks opposite the signal, the number of un-used photons on the signal and tag sides, and the remaining energy in the endcap and in the barrel; also included was a kinematic cut on the energy of the ρ+γ which depends on the mass of the ρ+γ. These cuts also required that the energy of the photon be greater than 0.5 GeV. Any event must pass all eleven cuts to be considered for our signal. The equation shown below was used to generate our kinematic cut.

$$E_- < E_{\rho\gamma} < E_+$$

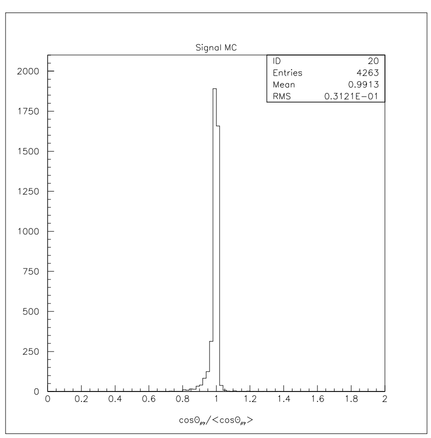
$$E\pm = E_{beam} * 0.5 * (1 + \frac{M_{\rho\gamma}}{m_\tau})^2 \pm 0.94 * \sqrt{(1 + \frac{M_{\rho\gamma}}{m_\tau})^4 - 2 * (\frac{M_{\rho\gamma}}{m_\tau})^2}$$

		
Signal Monte Carlo	Tau Generic Monte Carlo	Data

The above plots were generated in PAW and show $E_{\rho\gamma}$ vs. $M_{\rho\gamma}$ with the dotted lines representing the kinematic limit(and therefore our cut). The plots shown are for Data, Signal Monte Carlo, and Tau Generic Monte Carlo. Upon examination one can see that the cuts remove the tail from both the Data and the Tau Generic Monte Carlo plots. This tail is the result of certain decays faking our signal decay (specifically $\tau^- \to (e, \mu \, \pi) vs \tau^+ \to \pi^+\pi^0\pi^0\nu X$). The use of this cut provides a very strong cut for the removal of this background.

5.2 Signal Monte Carlo

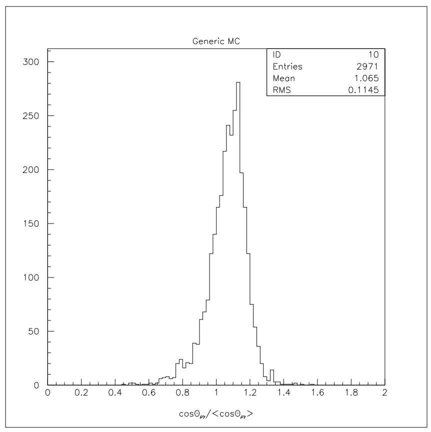
The Signal Monte Carlo used in this analysis was generated using a shell script and then skimmed using a reconstruct script, with $m_{\nu_\tau} = 10 Mev/c^2$ and $\tau_\nu = 18 \times 10^{-7} m$. The resulting ntuple was then input into PAW and the eleven cuts applied, producing the results shown below. These results will be the same for all $\frac{\tau_\nu}{m_\tau} \ll \frac{3\text{x}10^{-12}\text{sec}}{\text{MeV}}$, which we will consider a small lifetime to mass ratio.



Of the 10,000 events generated about 4500 passed all the cuts, giving an efficiency of 42.63%.

5.3 Tau Generic Monte Carlo

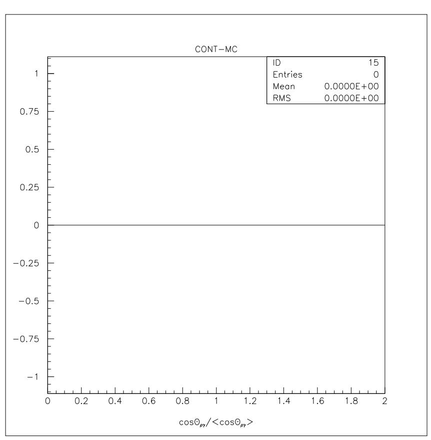
The Tau Generic Monte Carlo used for this project consisted of data skimmed off of the 4S2→4SG datasets (about twenty tapes). The data was then run through our reconstruction script, which generated an ntuple, after which generation we used this ntuple to plot the ratio between $\cos\theta_{\rho\gamma}$ and $< \cos\theta_{\rho\gamma} >$. We then applied the eleven cuts discussed above, thus generating the distributions shown below



Shown above is the Tau Generic Monte Carlo distribution for $\frac{\cos\theta_{\rho\gamma}}{<\cos\theta_{\rho\gamma}>}$

5.4 Continuum Monte Carlo

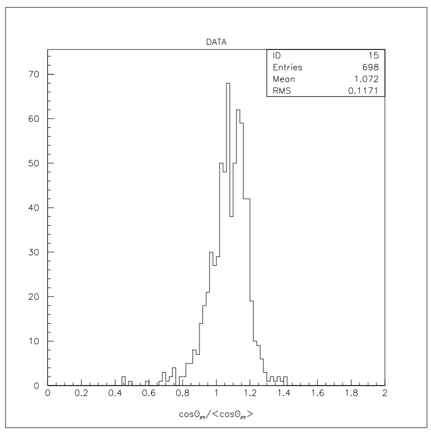
The Continuum Monte Carlo was skimmed off of the 4S7 dataset consisting of eleven tapes. Since the Continuum Monte Carlo does not contain our signal we would hope that the cuts would remove most (if not all) of the events in this ntuple. As is shown below, the cuts are effective in removing the Continuum events. It should be noted that the Continuum Monte Carlo discussed here corresponds to $\approx \frac{1}{3}$ of the total luminosity in data.



Shown here are the same variables plotted for the Continuum Monte Carlo. As would be expected almost all of the Continuum Monte Carlo events are removed by the cuts. Thus the contribution of the Continuum Monte Carlo is negligible in the rest of this work.

5.5 Data

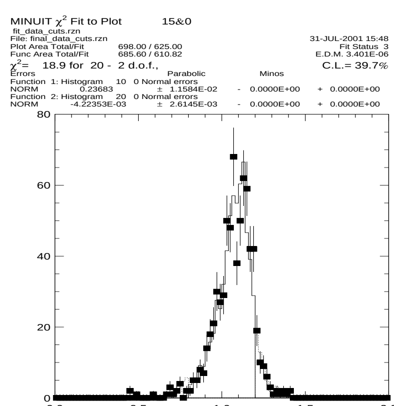
The datasets skimmed for this project were the 4S2→4SG datasets, comprised of twenty tapes from the tauskim. This data was skimmed by our shell script and the resulting ntuple input into PAW. The eleven cuts were then applied, and the distribution shown below was generated.



Shown above is the data plot for $\frac{\cos\theta_{\rho\gamma}}{<\cos\theta_{\rho\gamma}>}$

6 Results

The Data, Signal Monte Carlo, and Tau Generic Monte Carlo histograms(with cuts) were input into MN_Fit; the Signal and Tau Generic histograms were used as a fit on the Data.

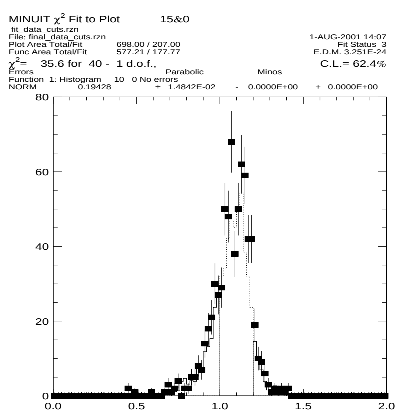


The $\frac{\cos\theta_{\rho\gamma}}{<\cos\theta_{\rho\gamma}>}$ distribution for data fit by a sum of Tau Generic Monte Carlo and decaying ν_τ Signal Monte Carlo. Regions from $0.0 \rightarrow 0.8$ and from $1.2 \rightarrow 2.0$ have been excluded.

The amount of Tau Generic Monte Carlo required by this fit($\approx$ 24%) is roughly consistent with the fact that the Generic Tau Monte Carlo represents three times as much luminosity as the data. Since there are 10,000 events in the Signal Monte Carlo the efficiency corrected number of $\nu_\tau \rightarrow \gamma X$ events is $10,000 \times [-4.2 \times 10^{-3} \pm 2.6 \times 10^{-3}] = -42 \pm 26$ events.

7 Systematic Errors

Although we lacked sufficient time to look at all systematic errors, we did have the opportunity to make sure that the Tau Generic Monte Carlo provided a good approximation of the data for the regions outside of our signal region(0.995$\rightarrow$1.115). The plot, showing a fit outside the signal region to only Tau Generic Monte Carlo , would seem to support our belief that the Monte Carlo provides a good approximation of our data: the confidence level of 62.4% is acceptable.



8 Final Analysis

We were unable to find definitive evidence of ν_τ decay; however, our analysis has allowed an upper limit to be placed upon the admixture of a decaying component of the ν_τ. We set the 95% confidence level upper limit at X^{95} defined by:

$$\frac{\int_0^{\mathrm{X}^{95}} G(z, x_0, \sigma) dz}{\int_0^{\infty} G(z, x_0, \sigma) dz} = 0.95$$

where $\mathrm{G}(\mathrm{z},\mathrm{x}_0, \sigma)$ is a Gaussian centered at x_0 and standard deviation of σ.

In order to obtain this limit we wrote a small FORTRAN which approximated an integral from $0 \rightarrow 10 * \sigma$ for a Gaussian distribution with a center and standard deviation taken from the fit shown in Section 6. We thus calculated the integral for a Gaussian with center of x_0 =-42 and standard deviation of σ =26. We wished to find the 95% percentile above zero. Our program found this to be at 30.6, and subsequent checks with statistical tables[4] confirmed that 95% of the events located at a point greater than zero are between zero and thirty. We are then able to use this number to calculate the upper limit on the admixture on the decaying component of ν_τ within CLEO. Since we assume that ν_τ decays within CLEO we also assume that $\frac{\tau_\nu}{m_\nu} \ll \frac{3\text{x}10^{-12}\text{sec}}{\text{MeV}}$; therefore it can be said that our limit applies to small ν_τ lifetime to mass ratios. It is possible that ν_τ may have other decay modes than the one studied here, for example $\nu_\tau \rightarrow e^+e^-$, or some other decay mode. However for the purpose of this study it is assumed that neutrinos have small lifetime to mass ratios and that the admixture of the stable and unstable neutrinos is given by the equation shown below, where β is the amount of the decaying component; our objective is to set an upper limit on β.

$$\nu_\tau = (1-\beta)\nu_\tau^{stable} + \beta\nu_\tau^{decay}$$

$$\beta < \frac{X^{95}}{\frac{2xBR(\tau\rightarrow\rho\nu_\tau)xBR(\tau\rightarrow\mu,e,\pi)}{N_{\tau\bar{\tau}}}} \text{at 95\% C.L.}$$

Where $X^{95} = 30$, $B(\tau \rightarrow \rho\nu_\tau) = 24\%$, $B(\tau \rightarrow \mu, e, \pi) = 18+18+12 = 48\%$, $N_{\tau\tau} = 4.5\text{x}10^6$[5]

9 Conclusions

We see no observable sign of tau neutrino decay within CLEO, and are able to set an upper limit on a decaying tau neutrino component of $2.9\text{x}10^{-5}$ for $\frac{\tau_\nu}{m_\nu} \ll \frac{3\text{x}10^{-12}\text{sec}}{MeV}$

10 Acknowledgments

J. Duboscq, Cornell University, for answering all my questions and guiding me through this difficult analysis.

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References

[1] DONUT Collaboration, K. Kodama et al, Phys. Lett. B504(2001) 218-224.

[2] Y. Fukuda et al, Phys.Rev.Lett. 81 (1998) 1562-1567.

[3] Q.R. Ahmad et al, *Measurement of Charged Current Interactions Produced by B-8 Solar Neutrinos at the Sudbury Neutrino Observatory,* nucl-ex/0106015(2001).

[4] Barlow, R.J. *Statistics: A Guide to the Use of Statistical Methods in the Physical Sciences.* John Wiley & Sons West Sussex England. (1989).

[5] PDG, *The European Physical Journal,* **15**, 1-4(2000).

[6] J. Duboscq CBX97-43(1997).