Limit on the Tau Neutrino Mass

D. Cinabro,[1] S. Henderson,[1] K. Kinoshita,[1] T. Liu,[1] M. Saulnier,[1] R. Wilson,[1] H. Yamamoto,[1] A. J. Sadoff,[2] R. Ammar,[3] S. Ball,[3] P. Baringer,[3] D. Coppage,[3] N. Copty,[3] R. Davis,[3] N. Hancock,[3] M. Kelly,[3] N. Kwak,[3] H. Lam,[3] Y. Kubota,[4] M. Lattery,[4] J. K. Nelson,[4] S. Patton,[4] D. Perticone,[4] R. Poling,[4] V. Savinov,[4] S. Schrenk,[4] R. Wang,[4] M. S. Alam,[5] I. J. Kim,[5] B. Nemati,[5] J. J. O'Neill,[5] V. Romero,[5] H. Severini,[5] C. R. Sun,[5] M. M. Zoeller,[5] G. Crawford,[6] R. Fulton,[6] D. Fujino,[6] K. K. Gan,[6] H. Kagan,[6] R. Kass,[6] J. Lee,[6] R. Malchow,[6] F. Morrow,[6] Y. Skovpen,[6],[a] M. Sung,[6] C. White,[6] J. Whitmore,[6] P. Wilson,[6] F. Butler,[7] X. Fu,[7] G. Kalbfleisch,[7] M. Lambrecht,[7] W. R. Ross,[7] P. Skubic,[7] J. Snow,[7] P. L. Wang,[7] M. Wood,[7] D. Bortoletto,[8] D. N. Brown,[8] J. Dominick,[8] R. L. McIlwain,[8] T. Miao,[8] D. H. Miller,[8] M. Modesitt,[8] S. F. Schaffner,[8] E. I. Shibata,[8] I. P. J. Shipsey,[8] P. N. Wang,[8] M. Battle,[9] J. Ernst,[9] H. Kroha,[9] S. Roberts,[9] K. Sparks,[9] E. H. Thorndike,[9] C. H. Wang,[9] S. Sanghera,[10] T. Skwarnicki,[10] R. Stroynowski,[10] M. Artuso,[11] D. He,[11] M. Goldberg,[11] N. Horwitz,[11] R. Kennett,[11] G. C. Moneti,[11] F. Muheim,[11] Y. Mukhin,[11] S. Playfer,[11] Y. Rozen,[11] P. Rubin,[11] S. Stone,[11] M. Thulasidas,[11] G. Vasseur,[11] G. Zhu,[11] A. V. Barnes,[12] J. Bartelt,[12] S. E. Csorna,[12] Z. Egyed,[12] V. Jain,[12] P. Sheldon,[12] D. S. Akerib,[13] B. Barish,[13] M. Chadha,[13] S. Chan,[13] D. F. Cowen,[13] G. Eigen,[13] J. S. Miller,[13] J. Urheim,[13] A. J. Weinstein,[13] D. Acosta,[14] M. Athanas,[14] G. Masek,[14] B. Ong,[14] H. Paar,[14] M. Sivertz,[14] A. Bean,[15] J. Gronberg,[15] R. Kutschke,[15] S. Menary,[15] R. J. Morrison,[15] S. Nakanishi,[15] H. N. Nelson,[15] T. K. Nelson,[15] J. D. Richman,[15] H. Tajima,[15] D. Schmidt,[15] D. Sperka,[15] M. S. Witherell,[15] M. Procario,[16] S. Yang,[16] R. Balest,[17] K. Cho,[17] M. Daoudi,[17] W. T. Ford,[17] D. R. Johnson,[17] K. Lingel,[17] M. Lohner,[17] P. Rankin,[17] J. G. Smith,[17] J. P. Alexander,[18] C. Bebek,[18] K. Berkelman,[18] D. Besson,[18] T. E. Browder,[18] D. G. Cassel,[18] H. A. Cho,[18] D. M. Coffman,[18] P. S. Drell,[18] R. Ehrlich,[18] R. S. Galik,[18] M. Garcia-Sciveres,[18] B. Geiser,[18] B. Gittelman,[18] S. W. Gray,[18] D. L. Hartill,[18] B. K. Heltsley,[18] K. Honscheid,[18] C. D. Jones,[18] S. L. Jones,[18] J. Kandaswamy,[18] N. Katayama,[18] P. C. Kim,[18] D. L. Kreinick,[18] G. S. Ludwig,[18] J. Masui,[18] J. Mevissen,[18] N. B. Mistry,[18] C. R. Ng,[18] E. Nordberg,[18] M. Ogg,[18],[b] C. O'Grady,[18] J. R. Patterson,[18] D. Peterson,[18] D. Riley,[18] M. Sapper,[18] M. Selen,[18] H. Worden,[18] M. Worris,[18] F. Würthwein,[18] P. Avery,[19] A. Freyberger,[19] J. Rodriguez,[19] R. Stephens,[19] and J. Yelton[19]

(CLEO Collaboration)

[1]*Harvard University, Cambridge, Massachusetts 02138*
[2]*Ithaca College, Ithaca, New York 14850*
[3]*University of Kansas, Lawrence, Kansas 66045*
[4]*University of Minnesota, Minneapolis, Minnesota 55455*
[5]*State University of New York at Albany, Albany, New York 12222*
[6]*Ohio State University, Columbus, Ohio 43210*
[7]*University of Oklahoma, Norman, Oklahoma 73019*
[8]*Purdue University, West Lafayette, Indiana 47907*
[9]*University of Rochester, Rochester, New York 14627*
[10]*Southern Methodist University, Dallas, Texas 75275*
[11]*Syracuse University, Syracuse, New York 13244*
[12]*Vanderbilt University, Nashville, Tennessee 37235*
[13]*California Institute of Technology, Pasadena, California 91125*
[14]*University of California, La Jolla, California 92093*
[15]*University of California, Santa Barbara, California 93106*
[16]*Carnegie-Mellon University, Pittsburgh, Pennsylvania 15213*
[17]*University of Colorado, Boulder, Colorado 80309-0390*
[18]*Cornell University, Ithaca, New York 14853*
[19]*University of Florida, Gainesville, Florida 32611*

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A limit on the tau neutrino mass M_{ν_τ} is obtained from a study of tau decays in the reaction $e^+e^- \to \tau^+\tau^-$ at center-of-mass energies ~ 10.6 GeV. The result is based on an end-point analysis of the invariant mass spectrum of the decay products in the decay modes $\tau^- \to 3h^-2h^+\nu_\tau$ and

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$\tau^- \to 2h^- h^+ 2\pi^0 \nu_\tau$. The data sample used in this analysis contains 1.77×10^6 tau pairs, corresponding to an integrated luminosity of 1.92 fb^{-1}, and is substantially larger than previous data samples used to place a limit on M_{ν_τ}. The limit obtained for both five-hadron modes together is 32.6 MeV at 95% C.L.

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Massive neutrinos have been invoked as a possible explanation for a rich variety of outstanding problems in particle physics and astrophysics, and they are often features of extensions of the standard model [1]. Most studies placing a limit on the tau neutrino mass M_{ν_τ} have used the spectrum of the invariant mass of the measured tau decay products M_X. The maximum attainable M_X in a given tau decay mode is a function of M_{ν_τ}. This measurement is most sensitive to events with $M_X \sim M_\tau$ since this is where the spectrum varies most dramatically as a function of M_{ν_τ}. The tau decay modes with the least energy available for the tau neutrino are generally more sensitive to M_{ν_τ} and recent studies have concentrated on high-multiplicity tau decays largely for this reason.

The most stringent published result, $M_{\nu_\tau} < 31$ MeV at 95% C.L. from the ARGUS experiment [2], was originally obtained from a sample of twelve (later expanded to twenty) candidate tau-pair events in which one tau decayed via $\tau^- \to 3h^- 2h^+ \nu_\tau$ [3]. The candidate event with the highest invariant mass was removed to account for possible background contamination.

The analysis presented here uses data obtained with the CLEO-II detector [4] at the Cornell e^+e^- storage ring (CESR) at center-of-mass energies $E_{\text{c.m.}} \sim 10.6$ GeV with an integrated luminosity of 1.92 fb^{-1}, corresponding to 1.77×10^6 tau pairs. At these energies, tau leptons are pair-produced chiefly via the process $e^+e^- \to \gamma^* \to \tau^+\tau^-$, and the decay products of each tau are typically distinguishable from one another. A novel feature of this analysis, made possible by the excellent electromagnetic calorimetry of the CLEO-II detector, is the inclusion of a recently observed high-multiplicity tau decay mode containing neutral pions, $\tau^- \to 2h^- h^+ 2\pi^0 \nu_\tau$ [5]. The decay mode $\tau^- \to 3h^- 2h^+ \nu_\tau$ is also investigated in this study.

The aim of this analysis is to obtain as clean an event sample as possible since a single background event near the end point can falsely lower the final limit. Potential backgrounds are minimized by selecting the event topology in which one tau decays leptonically ($\tau^+ \to e^+ \nu_e \bar{\nu}_\tau$ or $\tau^+ \to \mu^+ \nu_\mu \bar{\nu}_\tau$) and the lepton is isolated by at least 90° from the hadronic decay products of the other tau, which decays into five hadrons and a low energy neutrino (the X side). The additional selection criteria which further purify the sample are listed below. They utilize all charged particles and any neutral energy deposits in the calorimeter which are isolated by more than 10° from a charged particle and which satisfy $|\cos\theta| < 0.95$, where θ is the angle with respect to the beam axis.

Exactly four or six charged particles (depending on the decay mode) emanating from the interaction region are required. Events with two charged particles consistent with having come from either a photon conversion, a π^0 Dalitz decay, or a K_S^0 decay are removed. The total energy contained in neutral energy deposits unassociated with either charged particles or neutral pions is required to be less than 600 MeV. In the hemisphere defined by a 90° cone around the lepton, this total energy must be less than 100 MeV in each of the barrel and end-cap regions, defined by $|\cos\theta| < 0.71$ and $0.71 < |\cos\theta| < 0.95$, respectively. In the opposite hemisphere, this total energy must be less than 200 MeV in each region. The total energy of the detected particles on the X side must satisfy $E_X < E_{\text{c.m.}}/2$.

There must be zero or two neutral pions (depending on the decay mode), with $2N_{\pi^0}$ photon showers used uniquely in their reconstruction, and each candidate π^0 must satisfy the requirement that $|m_{\pi^0} - m_{\gamma\gamma}| < 20$ MeV (the resolution on m_{π^0} is ~ 7 MeV). The constituent photon showers of each π^0 must be in the barrel region and have energy $E_\gamma > 60$ MeV. In addition, they must be less than 60° apart and have shower shapes consistent with those of photons. Each candidate π^0 is fitted to the nominal π^0 mass and accepted only if the χ^2 probability of the fit is greater than 0.05.

The kinematics dictate that the magnitude of the summed vector momenta of the observed tau decay products in the tau rest frame on the X side, p^*, must be small. This rest frame is approximated using $E_{\text{c.m.}}$, M_τ, and the direction of the summed momenta of these decay products in the laboratory rest frame. For the decay mode $\tau^- \to 3h^- 2h^+ \nu_\tau$, $p^* < 0.4$ GeV is required. For the decay mode $\tau^- \to 2h^- h^+ 2\pi^0 \nu_\tau$, this requirement is made more restrictive, $p^* < 0.15$ GeV, in order to reduce the background from $\tau^- \to 2h^- h^+ \pi^0 \nu_\tau$ events. Finally, since the signal events produce three undetected neutrinos, the total visible energy of charged and isolated neutral particles must satisfy $E_{\text{vis}} < 0.85 E_{\text{c.m.}}$, assuming all charged particles are pions and all neutral particles are photons.

Potential background comes from other processes which imitate the desired final states [primarily two-photon interactions and the hadronic interactions ($e^+e^- \to q\bar{q}$) and ($e^+e^- \to \Upsilon(4S) \to B\bar{B}$)] the bulk of which do not satisfy the selection criteria listed above. To further reduce the background from two-photon events, the total transverse momentum must satisfy $|\sum \mathbf{p}_t| > 200$ MeV. To minimize the background from hadronic interactions in which particles may have escaped detection, the vector of the missing momentum in the event cannot be directed inside a 20° cone around the beam axis.

Hadronic interactions containing D^* and/or D mesons which decay into high-multiplicity final states represent a particularly potential form of background. This is due to the similarity in mass of the tau and the D^* or D meson, which enables such hadronic events to have $M_X < M_\tau$ when a charged kaon is misidentified as a charged pion. Moreover, semileptonic D decays with undetected decay products (e.g., $D^+ \to K_L^0 l^+ \nu_l$) can mimic leptonic tau decays. To eliminate this source of background a χ^2 probability with 2 degrees of freedom, P_{χ^2}, is formed using the $D^* - D$ mass difference and the D mass, where D is either D^0 or D^+ and where the K^- mass is assigned to one of the charged particles on the X side. The resolutions on these quantities are well known from previous studies [6]. Only events with $P_{\chi^2} < 10^{-5}$ are accepted. One event passing all the $\tau^- \to 3h^-2h^+\nu_\tau$ selection criteria is removed with $P_{\chi^2} = 0.99$ and a five-pion invariant mass of 1808 ± 4 MeV. The application of this criterion changes the event selection efficiency by less than 1% of itself and does not distort the M_X spectrum. The final event sample is shown in Fig. 1(a). Note that all of these events satisfy $M_X < M_\tau$.

Monte Carlo studies [7] of the acceptance show that it is nearly constant as a function of M_X for the decay mode $\tau^- \to 3h^-2h^+\nu_\tau$, but increases linearly with increasing

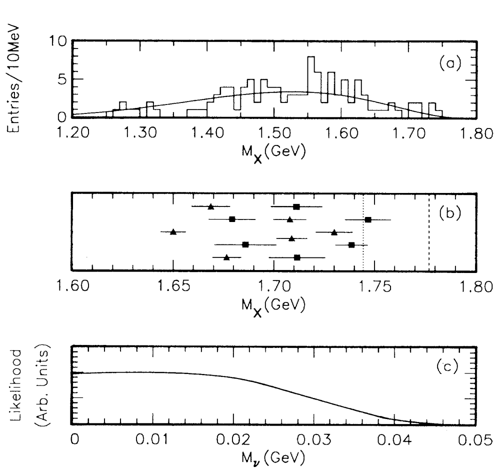

FIG. 1. (a) A histogram of the invariant masses of the measured tau decay products, M_X, for the final data sample of candidate $\tau^- \to 3h^-2h^+\nu_\tau$ and $\tau^- \to 2h^-h^+2\pi^0\nu_\tau$ events. The superimposed curve is the expected distribution for M_X at $M_{\nu_\tau} = 0$. (b) A plot of those individual events satisfying $M_X > 1.65$ GeV, represented by their M_X values with error bars corresponding to the resolution on M_X. The triangles correspond to candidate $\tau^- \to 3h^-2h^+\nu_\tau$ events and the squares to $\tau^- \to 2h^-h^+2\pi^0\nu_\tau$ events. The vertical dashed line corresponds to $M_X = M_\tau$ and the vertical dotted line to $M_X = M_\tau - M_{\nu_\tau}^{95}$, where $M_{\nu_\tau}^{95}$ is the final limit of 32.6 MeV. (c) A plot of the likelihood function obtained from the final data sample. The most likely value for M_{ν_τ} is compatible with zero within less than one sigma.

M_X for the decay mode $\tau^- \to 2h^-h^+2\pi^0\nu_\tau$ due primarily to the $p^* < 0.15$ GeV requirement. The combined acceptance and reconstruction efficiencies are found to be $(7.2 \pm 0.2)\%$ and $(0.79 \pm 0.03)\%$ for the decay modes $\tau^- \to 3h^-2h^+\nu_\tau$ and $\tau^- \to 2h^-h^+2\pi^0\nu_\tau$, respectively (statistical errors only).

Estimation of the non-tau background in the data sample uses simulated event samples consisting of events from hadronic and two-photon interactions. No events remain after applying all the selection criteria to each of these samples. More stringent limits on the background from hadronic interactions have been estimated using portions of the data which are predominantly comprised of such events. Events which have seven or more charged particles constitute such an event sample and are used to estimate the background from hadronic interactions as (0.16 ± 0.03) events and (0.01 ± 0.01) events for the modes $\tau^- \to 3h^-2h^+\nu_\tau$ and $\tau^- \to 2h^-h^+2\pi^0\nu_\tau$, respectively (statistical errors only). This estimate is verified by studying the effect of removing or greatly loosening certain signal selection criteria. In both modes, this alteration results in a small number of events classified as background (defined as $M_X > 2$ GeV) entering the final sample, consistent with the number predicted from events with seven or more charged particles.

When the selection criteria are applied to a sample of simulated $e^+e^- \to \tau^+\tau^-$ events (excluding the decay modes $\tau^- \to 3h^-2h^+\nu_\tau$ and $\tau^- \to 2h^-h^+2\pi^0\nu_\tau$), the resulting event samples have some contamination due to the decay modes $\tau^- \to 3h^-2h^+\pi^0\nu_\tau$ and $\tau^- \to 2h^-h^+\pi^0\nu_\tau$. The background coming from $\tau^- \to 3h^-2h^+\pi^0\nu_\tau$, where the π^0 is not detected, can only increase the final limit, since the omission of the π^0 decreases M_X further below M_τ. On the other hand, background from $\tau^- \to 2h^-h^+\pi^0\nu_\tau$, with spurious neutral energy deposits forming a fake π^0, could artificially increase M_X and falsely lower the final limit [8]. However, although studies of simulated $\tau^- \to 2h^-h^+\pi^0\nu_\tau$ events show that an estimated 0.6 ± 0.3 events (statistical error only) will enter the final $\tau^- \to 2h^-h^+2\pi^0\nu_\tau$ data sample in this fashion, each of the simulated events upon which this estimation is based had $M_X < 1550$ MeV. Hence this channel is only capable of producing < 0.35 events at 90% C.L. in the region $M_X > 1550$ MeV and is not likely to falsely lower the final limit.

The tau neutrino mass limit is determined from a likelihood function which consists of a theoretical estimate of the five-pion invariant mass spectrum convoluted with detector resolution and acceptance functions, where the latter is incorporated as a function of M_X and is determined from studies of simulated event samples. The likelihood is calculated event by event as a function of M_{ν_τ}. The final likelihood curve is a product of the individual event likelihoods and is shown in Fig. 1(c). The default KORALB [9] spectral function and the most recent value of the tau mass [10] are used in its calculation. The 95%

TABLE I. The size of the final event samples, the 95% C.L. limit on M_{ν_τ} after correction for systematic efforts, $M_{\nu_\tau}^{95}$, and the estimated Monte Carlo probability of having obtained this limit, $P_{\rm MC}$, for each of the studied decay modes and for the published ARGUS result. The errors on $P_{\rm MC}$ are statistical only.

Decay mode	Sample size	$M_{\nu_\tau}^{95}$ (MeV)	$P_{\rm MC}$ (%)
$\tau^- \to 3h^-2h^+\nu_\tau$	60	47.5	34.9 ± 0.8
$\tau^- \to 2h^-h^+2\pi^0\nu_\tau$	53	33.7	4.3 ± 0.3
Combined	113	32.6	13.9 ± 0.6
ARGUS	20	31	0.041 ± 0.012

C.L. limit, $M_{\nu_\tau}^{95}$, is defined as the value of M_{ν_τ} at which the integral of the likelihood curve reaches 95% of its total. This integral only covers positive neutrino masses in order to derive a conservative limit [11]. Table I provides a summary of the results obtained from the final data samples in the decay modes studied.

To compare these results to the ARGUS result it is informative to calculate the quantity $P_{\rm MC}$, defined as the percentage of signal Monte Carlo experiments in which a 95% C.L. limit less than or equal to that of the data is obtained. Since each of these experiments is generated at zero neutrino mass with the same number of events as in the given data sample [12], $P_{\rm MC}$ may be interpreted as an estimate of the probability of obtaining a given $M_{\nu_\tau}^{95}$ for a given sample size. For simplicity, no detector simulation is used. The last column of Table I shows $P_{\rm MC}$ for the final event samples and for the most recent ARGUS result [13]. It is important to note that since this limit depends on a few events near the end point, and the yield of such events decreases rapidly as M_X approaches M_τ, one should not expect this limit to improve linearly with increasing sample size.

Systematic errors are estimated by varying the relevant quantity and observing its effect on the final limit. These estimated errors are then incorporated into the final limit using a Gaussian approximation [14]. The largest source of systematic error arises from the uncertainty in the dependence of the acceptance on M_X. This is estimated to contribute 5 MeV by varying the dependence within reasonable bounds. The uncertainty in the mass scale, known from D^0 decays [6], is estimated to contribute 1 MeV. The uncertainty in the mass resolution is estimated to contribute 1 MeV by varying the resolution within reasonable bounds. The slight distortion of the M_X spectra due to backgrounds from other tau decays is estimated to contribute 1 MeV from Monte Carlo studies. The uncertainty in the theoretical model of the decay is estimated to contribute 1 MeV by varying the default spectra function within reasonable bounds. Finally, the uncertainty on M_τ contributes 0.5 MeV [10].

In summary, using a substantially larger data sample than that used in previous studies, 95% C.L. limits on M_{ν_τ} from the decay modes $\tau^- \to 3h^-2h^+\nu_\tau$, $\tau^- \to 2h^-h^+2\pi^0\nu_\tau$, and both five-hadron decay modes of 47.5, 33.7, and 32.6 MeV, respectively, have been obtained. These limits include the effects of systematic errors. Background has been estimated from both Monte Carlo studies and data, and was found to be substantially less than one event in the sensitive region of the final sample. This is the first time the decay mode $\tau^- \to 2h^-h^+2\pi^0\nu_\tau$ has been used to set a limit on M_{ν_τ}.

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(a)Permanent address: Institute of Nuclear Physics, Novosibirsk, Russia.

(b)Permanent address: Carleton University, Ottawa, Canada K1S 5B6.

[1] *Neutrino Physics*, edited by K. Winter (Cambridge Univ. Press, Cambridge, 1991), and references therein.

[2] ARGUS Collaboration, H. Albrecht *et al.*, Phys. Lett. B **202**, 149 (1988); **292**, 221 (1992). With $M_\tau = 1784$ MeV their limit was $M_{\nu_\tau} < 35$ MeV at 95% C.L. The candidate event ARGUS removed had $M_X = 1804.8 \pm 15.2$ MeV.

[3] Here, and for the remainder of this Letter, h^- denotes π^- or K^-, and the charge conjugate reaction is implied.

[4] CLEO Collaboration, Y. Kubota *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **320**, 66 (1992).

[5] CLEO Collaboration, G. Crawford, in Proceedings of the Second International Workshop on Tau Lepton Physics, 1992, edited by K. K. Gan (World Scientific, Singapore, to be published).

[6] CLEO Collaboration, D. Bortoletto *et al.*, Phys. Rev. Lett. **69**, 2046 (1992).

[7] The CLEO-II Monte Carlo simulation is based on the GEANT package. See computer code GEANT v. 3.14 in R. Brun *et al.*, Report No. CERN DD/EE/84-1 (unpublished).

[8] No other tau decay modes were observed in Monte Carlo studies to feed up to the decay mode $\tau^- \to 2h^-h^+2\pi^0\nu_\tau$.

[9] S. Jadach and Z. Was, Comput. Phys. Commun. **64**, 267 (1991), and references therein. The spectral function used in this event generator is derived from $e^+e^- \to 4\pi$ data and soft pion theorems. Both $\tau^- \to 3h^-2h^+\nu_\tau$ and $\tau^- \to 2h^-h^+2\pi^0\nu_\tau$ are assumed to decay with this spectral function.

[10] BES Collaboration, J. Bai *et al.*, Phys. Rev. Lett. **69**, 3021 (1992); ARGUS Collaboration [2]; CLEO Collaboration, R. Balest *et al.*, Phys. Rev. D **47**, 3671 (1993).

[11] Particle Data Group, K. Hikasa *et al.*, Phys. Rev. D **45**, S1 (1992) p. III.39.

[12] Each event is also assigned a resolution on M_X which is

generated following a Gaussian distribution with mean and width given by the data. For the decay mode $\tau^- \to 3h^- 2h^+ \nu_\tau$, the average resolution on M_X is 9 MeV; for $\tau^- \to 2h^- h^+ 2\pi^0 \nu_\tau$, 14 MeV.

[13] In order to mimic as closely as possible the ARGUS procedure, the value of P_{MC} for the ARGUS 20-event sample is calculated using 20-event Monte Carlo experiments from which the event with the largest M_X is removed.

[14] The approximation used here is $M_{\nu_\tau}^{95}(\text{corr}) = [(M_{\nu_\tau}^{95})^2 + (1.64\sigma_{\text{sys}})^2]^{1/2}$. This is similar to the formulation used by ARGUS. See B. Spaan, Diplom Thesis, Institut für Physik der Universität Dortmund, 100, 1988.