

Search for heavy neutrinos mixing with tau neutrinos

NOMAD Collaboration

P. Astierⁿ D. Autiero^h A. Baldisseri^s M. Baldo-Ceolin^m
M. Bannerⁿ G. Bassompierre^a K. Benslamaⁱ N. Besson^s
I. Bird^{h,i} B. Blumenfeld^b F. Bobisut^m J. Bouchez^s S. Boyd^u
A. Bueno^{c,y} S. Bunyatov^f L. Camilleri^h A. Cardini^j
P.W. Cattaneo^o V. Cavasinni^q A. Cervera-Villanueva^{h,w}
G. Collazuol^m G. Conforto^v C. Conta^o M. Contalbrigo^m
R. Cousins^j D. Daniels^c H. Degaudenziⁱ T. Del Prete^q
A. De Santo^h T. Dignan^c L. Di Lella^h E. do Couto e Silva^h
J. Dumarchezⁿ M. Ellis^u T. Fazio^a G.J. Feldman^c R. Ferrari^o
D. Ferrère^h V. Flaminio^q M. Fraternali^o J.-M. Gaillard^a
E. Gangler^{h,n} A. Geiser^{e,h} D. Geppert^e D. Gibin^m
S.N. Gninenko^{h,l} A. Godley^u M.C. Gonzalez-Garcia^w
J.-J. Gomez-Cadenas^{h,w} J. Gosset^s C. Gößling^e M. Gouanère^a
A. Grant^h G. Graziani^g A. Guglielmi^m C. Hagner^s
J. Hernando^w D. Hubbard^c P. Hurst^c N. Hyett^k E. Iacopini^g
C. Josephⁱ F. Jugetⁱ M.M. Kirsanov^l O. Klimov^f
J. Kokkonen^h A.V. Kovzelev^{l,o} N.V. Krasnikov^l
A. Krasnoperov^{a,f} S. Lacaprara^m C. Lachaudⁿ B. Lakić^x
A. Lanza^o L. La Rotonda^d M. Laveder^m A. Letessier-Selvonⁿ
J.-M. Levyⁿ L. Linssen^h A. Ljubičić^x J. Long^b A. Lupi^g
A. Marchionni^g F. Martelli^v X. Méchain^s J.-P. Mendiburu^a
J.-P. Meyer^s M. Mezzetto^m S.R. Mishra^{c,t} G.F. Moorhead^k
D. Naumov^f P. Nédélec^a Yu. Nefedov^f C. Nguyen-Mauⁱ
D. Orestano^r F. Pastore^r L.S. Peak^u E. Pennacchio^v
H. Pessard^a R. Petti^{h,o} A. Placci^h G. Polesello^o D. Pollmann^e
A. Polyarush^l B. Popov^{f,n} C. Poulsen^k P. Rathouit^s J. Rico^y
C. Roda^{h,q} A. Rubbia^{h,y} F. Salvatore^o K. Schahmanecheⁿ
B. Schmidt^{e,h} M. Seviar^k D. Sillou^a F.J.P. Soler^{h,u} G. Sozziⁱ
D. Steele^{b,i} U. Stiegler^h M. Stipčević^x Th. Stolarczyk^s

M. Tareb-Reyesⁱ G.N. Taylor^k V. Tereshchenko^f A.N. Toropin^ℓ
A.-M. Touchardⁿ S.N. Tovey^k M.-T. Tranⁱ E. Tsesmelis^h
J. Ulrichs^u L. Vacavantⁱ M. Valdata-Nappi^{d,p} V. Valuev^{f,j}
F. Vannucciⁿ K.E. Varvell^u M. Veltri^v V. Vercesi^o
G. Vidal-Sitjes^{h,w} J.-M. Vieiraⁱ T. Vinogradova^j F.V. Weber^{c,h}
T. Weisse^e F.F. Wilson^h L.J. Winton^k B.D. Yabsley^u
H. Zaccone^s K. Zuber^e P. Zuccon^m

^a*LAPP, Annecy, France*

^b*Johns Hopkins Univ., Baltimore, MD, USA*

^c*Harvard Univ., Cambridge, MA, USA*

^d*Univ. of Calabria and INFN, Cosenza, Italy*

^e*Dortmund Univ., Dortmund, Germany*

^f*JINR, Dubna, Russia*

^g*Univ. of Florence and INFN, Florence, Italy*

^h*CERN, Geneva, Switzerland*

ⁱ*University of Lausanne, Lausanne, Switzerland*

^j*UCLA, Los Angeles, CA, USA*

^k*University of Melbourne, Melbourne, Australia*

^ℓ*Inst. Nucl. Research, INR Moscow, Russia*

^m*Univ. of Padova and INFN, Padova, Italy*

ⁿ*LPNHE, Univ. of Paris VI and VII, Paris, France*

^o*Univ. of Pavia and INFN, Pavia, Italy*

^p*Univ. of Perugia and INFN, Perugia, Italy*

^q*Univ. of Pisa and INFN, Pisa, Italy*

^r*Roma Tre University and INFN, Rome, Italy*

^s*DAPNIA, CEA Saclay, France*

^t*Univ. of South Carolina, Columbia, SC, USA*

^u*Univ. of Sydney, Sydney, Australia*

^v*Univ. of Urbino, Urbino, and INFN Florence, Italy*

^w*IFIC, Valencia, Spain*

^x*Rudjer Bošković Institute, Zagreb, Croatia*

^y*ETH Zürich, Zürich, Switzerland*

Abstract

We report on a search for heavy neutrinos (ν_4) produced in the decay $D_s \rightarrow \tau\nu_4$ at the SPS proton target followed by the decay $\nu_4 \rightarrow \nu_\tau e^+ e^-$ in the NOMAD detector. Both decays are expected to occur if ν_4 is a component of ν_τ . From the analysis of the data collected during the 1996-1998 runs with 4.1×10^{19} protons on target, a single candidate event consistent with background expectations was found. This allows to derive an upper limit on the mixing strength between the heavy neutrino and the tau neutrino in the ν_4 mass range from 10 to 190 MeV. Windows between the SN1987a and Big Bang Nucleosynthesis lower limits and our result are still open for future experimental searches. The results obtained are used to constrain an interpretation of the time anomaly observed in the KARMEN1 detector.

Key words: neutrino mixing, neutrino decay

1 Introduction

In the Standard Model all fundamental fermions have a right-handed component that transforms as an isosinglet under the $SU(2)_L$ gauge group except neutrinos, which are observed only in left-handed form. However, heavy neutrinos which are decoupled from W and Z bosons and hence are mostly isosinglet (sterile) arise in many models that attempt to unify the presently known interactions into a single gauge scheme, such as Grand Unified Theories or Superstrings inspired models [1]. They are also predicted in models trying to solve the problem of baryo- or leptogenesis in the Universe, in many extended electroweak models, such as left-right symmetric and see-saw models [1]. Their masses are predicted to be within the GeV – TeV range. The existence of a light (\lesssim eV or \ll eV) sterile neutrino is expected in schemes that attempt to solve the presently observed indication from atmospheric, solar and LSND experiments that neutrinos are massive, see e.g. [2] and references therein. More generally one can also look for an isosinglet neutrino with intermediate mass such as in the keV – MeV range. For instance, such neutrinos with masses in the range 1 - 40 keV were recently considered as a candidate for warm dark matter [3].

If heavy neutrinos exist, many crucial questions arise. For example, for massive neutrinos the flavour eigenstates ($\nu_e, \nu_\mu, \nu_\tau, \dots$) need not coincide with the mass eigenstates ($\nu_1, \nu_2, \nu_3, \nu_4 \dots$), but would, in general, be related through a unitary transformation. Such a generalised mixing:

$$\nu_l = \sum_i U_{li} \nu_i; \quad l = e, \mu, \tau, \dots, \quad i = 1, 2, 3, 4, \dots \quad (1)$$

could result in neutrino oscillations when the mass differences are small, and in decays of heavy neutrinos when the mass differences are large. The relevant questions are then, do heavy neutrinos mix with the ordinary neutrinos and, if so, what are the elements of the neutrino mixing matrix U_{li} ?

Since there are no firm predictions for m_{ν_4} , experimental searches of ν_4 have been performed over a wide range of masses. A heavy neutrino in the low mass region (below a few GeV) has been searched for mainly in experiments on the leptonic decay of light mesons and in neutrino experiments [4] resulting in stringent upper limits on $|U_{li}|^2$ down to 10^{-7} , thus constraining the mixing amplitudes $|U_{e4}|^2$ and $|U_{\mu 4}|^2$ for the electron and muon neutrinos, respectively. Concerning the mixing strength $|U_{\tau 4}|^2$ for the MeV mass region studied in this experiment a limit can be derived from some earlier papers [4], see also [5]. Note that stringent limits on $|U_{\tau 4}|^2$ in this mass range have been recently obtained from cosmological and astrophysical considerations [6]. For masses in the 3 GeV to $\simeq 200$ GeV range the LEP experiments have set limits on $|U_{\tau 4}|^2$ varying from 10^{-5} to 10^{-1} depending on the ν_4 mass [7].

The motivation and purpose of this work is to search for a neutral heavy lepton ν_4 which is dominantly associated with the third generation of light neutrinos, ν_τ , via the mixing term $|U_{\tau 4}|^2$. If such a particle exists it might be produced in the decay $D_s \rightarrow \tau \nu_4$ at the SPS proton target followed by the decay $\nu_4 \rightarrow \nu_\tau e^+ e^-$ in the NOMAD detector as is illustrated in Figure 1 (see also Section 3). The experimental signature of these events is clean and they can be selected with small background due to the excellent NOMAD capability for precise measurements of the e^+e^- pair direction. An additional motivation for the present study was the time anomaly observed by the KARMEN1 experiment (see Section 7). Although in this paper we will assume that ν_4 has Dirac mass, the application of our results to the Majorana case is straightforward.

2 WANF and NOMAD detector

The CERN West Area Neutrino Facility (WANF) beam line [8] provides an essentially pure ν_μ beam for neutrino experiments. It consists of a beryllium target irradiated by 450 GeV protons from the CERN SPS. The secondary hadrons of a given sign are focused with two magnetic elements, the horn and the reflector, located in front of a 290 m long evacuated decay tunnel. Protons that have not interacted in the target, secondary hadrons and muons that do

not decay are absorbed by a 400 m thick shielding made of iron and earth. The NOMAD detector is located at 835 m from the neutrino target.

The detector is described in Ref. [9]. It consists of a number of sub-detectors most of which are located inside a 0.4 T dipole magnet with a volume of $7.5 \times 3.5 \times 3.5$ m³: an active target of drift chambers (DC)[10] with a mass of 2.7 tons (mainly carbon), an average density of 0.1 g/cm³ and a total thickness of about one radiation length ($\sim 1.0X_0$) followed by a transition radiation detector (TRD) [11], a preshower detector (PRS), and an electromagnetic calorimeter (ECAL). The PRS is composed of a plane of horizontal and a plane of vertical proportional tubes preceded by a 9 mm thick lead plate ($1.6 X_0$). The ECAL consists of 875 lead-glass counters, each about $19 X_0$ deep, arranged in a matrix of 35 rows by 25 columns [12].

A hadron calorimeter (HCAL) and two muon stations are located just after the magnet coils. A plane of scintillation counters, V , in front of the magnet was used to veto upstream neutrino interactions and muons incident on the detector. Two planes of scintillation counters T_1 and T_2 located before and after the TRD were used for triggering purposes. The trigger for neutrino interactions or decays in the DC target was then $\bar{V}T_1T_2$.

The electron identification efficiency in NOMAD is provided mainly by the TRD which has an efficiency of more than 90% for isolated electrons of momentum 1 – 50 GeV/c for a charged pion rejection factor greater than 10^3 [11].

3 Production and decay

As follows from Eq. (1), any source of ν_τ will produce all kinematically possible massive eigenstates according to the appropriate mixings. In this search the source of ν_τ ($\bar{\nu}_\tau$)'s that can potentially generate ν_4 's is D_s (\bar{D}_s) mesons produced in the reaction $p + Be \rightarrow D_s + X$ at the proton target and subsequently decaying leptonically: $D_s \rightarrow \nu_\tau + \tau$, $\tau \rightarrow \nu_\tau + X$ [14]. Up to a ν_4 mass of 190 MeV, the mass difference between the D_s and the τ , ν_4 's can originate both from the ν_τ produced directly in the D_s decay and from the ν_τ produced indirectly in the subsequent τ decay. For a ν_4 mass larger than 190 MeV only ν_τ 's produced indirectly in τ decay can contribute. However these indirect ν_τ 's have a lower acceptance at NOMAD and a harder energy spectrum (Figure 3) resulting in a smaller probability to observe the decay $\nu_4 \rightarrow \nu_\tau e^+ e^-$ in the NOMAD detector. Therefore this search is limited to ν_4 masses smaller than 190 MeV. If ν_4 is a long-lived particle, the flux of ν_4 's would penetrate the downstream shielding without significant attenuation and would be observed in NOMAD through their $\nu_4 \rightarrow \nu_\tau e^+ e^-$ decays as illustrated in Figure 1.

For neutrino masses below the π^0 -meson mass, $m_{\nu_4} \lesssim m_\pi$, the dominant heavy neutrino visible decay is $\nu e^+ e^-$ with a rate which, for small mixing, is given by [6,15]

$$\tau_4^{-1} \equiv \Gamma(\nu_4 \rightarrow \nu_\tau e^+ e^-) = K \left[\frac{(1 + g_L^2 + g_R^2) G_F^2 m_{\nu_4}^5 |U_{\tau 4}|^2}{192 \pi^3} \right] \quad (2)$$

where $g_L = -1/2 + \sin^2 \theta_W$, $g_R = \sin^2 \theta_W$, $K = 1(2)$ for Dirac(Majorana) particles. The corresponding diagram illustrating the dominant contribution from neutral weak currents to this decay mode is shown in Figure 2b. The branching ratio of the visible decay is given by

$$BR(\nu_4 \rightarrow \nu_\tau e^+ e^-) = \frac{\Gamma(\nu_4 \rightarrow \nu_\tau e^+ e^-)}{\Gamma_{tot}} \simeq 0.14 \quad (3)$$

where the total rate Γ_{tot} is dominated by the $\nu_4 \rightarrow 3\nu$ decay channel.

For $m_{\nu_4} \gtrsim m_\pi$ the two-body decay channel $\nu_4 \rightarrow \nu_\tau \pi^0$ opens up. This mode is phase space favoured and becomes dominant for $m_{\nu_4} \gtrsim 140$ MeV [16].

In this paper we have studied the decay $\nu_4 \rightarrow \nu_\tau e^+ e^-$ as a possible manifestation of the presence of ν_4 's in the neutrino beam. The occurrence of $\nu_4 \rightarrow \nu_\tau e^+ e^-$ decays would appear as an excess of isolated $e^+ e^-$ pairs in NOMAD above those expected from standard neutrino interactions. The decay $\nu_4 \rightarrow \nu_\tau e^+ e^-$ cannot be distinguished from the anti-neutrino decay $\bar{\nu}_4 \rightarrow \bar{\nu}_\tau e^+ e^-$ and the result of this search therefore refers to the sum of these two decays.

The spectra of ν_τ 's produced in the Be target by primary protons were calculated using the approach reported in ref. [17] (see also [18]). The contribution of protons not interacting in the Be target and interacting in the SPS beam dump at the end of the decay tunnel was also taken into account. The simulated energy spectra of ν_τ 's pointing to the NOMAD fiducial area are shown in Figure 3. The flux of heavy neutrinos, $\Phi(\nu_4)$, can then be expressed as follows:

$$\Phi(\nu_4) \propto \int d\sigma(p + N \rightarrow D_s(\bar{D}_s) + X) / dE_{\nu_\tau} \cdot Br(D_s(\bar{D}_s) \rightarrow \tau + \nu_\tau) \cdot \tilde{\lambda}^{1/2} \cdot \tilde{h}^{1/2} \cdot |U_{\tau 4}|^2 \cdot dE_{\nu_\tau} \quad (4)$$

where $\sigma(p + N \rightarrow D_s(\bar{D}_s) + X)$ is the D_s meson production cross-section [17,18], $Br(D_s \rightarrow \tau + \nu_\tau)$ is the τ -decay mode branching ratio of the D_s [14], and $\tilde{\lambda}^{1/2}$, $\tilde{h}^{1/2}$ are the decay phase space and helicity factors, respectively [15].

Once the ν_4 flux was known, the next step was to calculate the e^+e^- spectrum based on the differential $\nu_4 \rightarrow \nu_\tau e^+e^-$ decay rate including polarization effects (see Figure 4) [16]. The decay electrons and positrons were tracked through the DC target including bremsstrahlung photons, their conversion and multiple scattering in the target. The details of the NOMAD simulation and reconstruction are described elsewhere [19].

4 Data analysis and selection criteria

The search for $\nu_4 \rightarrow \nu_\tau e^+e^-$ described in this paper uses the full data sample collected with the \overline{VT}_1T_2 trigger [9] during the years 1996-1998. The data correspond to a total number of protons on target (*pots*) of 4.1×10^{19} . The strategy of the analysis was to identify $\nu_4 \rightarrow \nu_\tau e^+e^-$ candidates by reconstructing in the DC isolated low invariant mass e^+e^- pairs that are accompanied by no other activity in the detector. The measured rate of e^+e^- pairs was then compared to that expected from known sources.

The following selection criteria were applied:

- two and only two tracks forming a vertex within the DC fiducial volume of $2.4 \times 2.4 \times 3.5$ m³ equivalent to a mass of 1.97 tons;
- at least one of the two tracks identified as an electron by the TRD (pion contamination probability $< 10^{-3}$ [11]);
- any additional track or converted photon [20] in the event were allowed only if their energies were less than 0.4 GeV or if they could be identified as due to bremsstrahlung photons from one of the two electron candidates;
- no γ 's in the ECAL with energy $E_\gamma > 0.4$ GeV (or $E_\gamma > 0.3$ GeV for γ 's converted in the PRS), which are incompatible with bremsstrahlung photons from the initial tracks;
- total HCAL energy < 0.4 GeV. This cut serves as an HCAL veto and is confirmed by random trigger events and Monte Carlo (MC) studies [13];
- the total energy of the pair must be greater than 4 GeV and its invariant mass $m_{e^+e^-} < 95$ MeV to remove background from pairs of particles other than e^+e^- .

Only 207 events passed these criteria. At the next step we used a collinearity variable $\mathcal{C} \equiv 1 - \cos\Theta_{\nu e^+e^-}$, where $\Theta_{\nu e^+e^-}$ is the angle between the average neutrino beam direction and the total momentum of the reconstructed e^+e^- pair. A cut on this variable allowed a more effective background suppression. A MC simulation of heavy neutrino decays shows (see Figure 5) that the $\nu_4 \rightarrow \nu_\tau e^+e^-$ events have $\mathcal{C} < 2 \times 10^{-5}$. This was true for a ν_4 mass up to $\simeq 190$ MeV.

In order to avoid biases in the determination of selection criteria, a blind analysis was performed. Events in a signal box defined by $\mathcal{C} < 2 \times 10^{-5}$ were excluded from the analysis of the data until the validity of the background estimate in this region was established. This was done by verifying that the MC simulation of standard processes reproduced the data outside the box.

The accuracy of the collinearity determination obtained with MC simulations was checked using a $\nu_\mu CC$ data sample with an e^+e^- pair from a photon converted in the DC target at a large ($\gtrsim 100$ cm) distance from the primary vertex. Figure 6 shows the $(1 - \cos\Theta_{e^+e^-})$ distribution of such events in the data and simulation, where $\Theta_{e^+e^-}$ is the angle between the e^+e^- pair momentum and the line joining the primary vertex to the conversion point. The small difference between the MC and data distributions in Figure 6 would result in an overall efficiency correction of less than 6%. However, in order to conservatively account for possible instrumental effects not present in the MC, the MC efficiency was multiplied by the efficiency of reconstructing e^+e^- pairs with a collinearity variable $\mathcal{C} < 2 \times 10^{-5}$ in the data sample of Figure 6 ($\simeq 75\%$). Nonetheless, the two distributions are in reasonable agreement at all energies studied. This validates the resolution in the variable \mathcal{C} (a few mrad in $\Theta_{\nu e^+e^-}$) predicted by the MC program.

The reconstruction efficiency for the $\nu_4 \rightarrow \nu_\tau e^+e^-$ decay in the NOMAD fiducial volume was calculated from the MC simulation as a function of e^+e^- energy in the range 4 GeV to 50 GeV. The MC simulation was used to correct the data for acceptance losses, experimental resolution and reconstruction efficiencies. Two checks using both experimental data and the MC simulation have been performed in order to verify the reliability of the simulation and to estimate the systematic uncertainties in the e^+e^- pair efficiency reconstruction in the energy range predicted by the simulation.

The first method is to select two samples of reconstructed π^0 's, one in which the two decay photons reach the ECAL, $N_{2\gamma}^{\pi^0}$, and another in which one of the photons converts in the drift chambers, $N_{\gamma e^+e^-}^{\pi^0}$. For data and MC events the ratio

$$R_{Data,MC} = \left(\frac{N_{\gamma e^+e^-}^{\pi^0}}{N_{2\gamma}^{\pi^0}} \right)_{Data,MC} \quad (5)$$

was then formed. The value of the double ratio $RR = R_{Data}/R_{MC}$ is then a measure of any differences in e^+e^- reconstruction efficiency between the data and MC. The use of e^+e^- pairs from π^0 decay enhances the purity of the e^+e^- sample.

The method works well mostly for the low energy region, $E_{e^+e^-} \lesssim 10$ GeV, when the 2γ opening angle is relatively large and the distance between the photons in the ECAL is larger than the ECAL cell size. At higher energies the precision of this method is affected by the statistical uncertainties in the number of π^0 's reconstructed in the 2γ mode, because the resolution on the 2γ opening angle becomes worse and the π^0 peak is not well identified anymore.

A similar method allowing a more accurate evaluation of the e^+e^- efficiency correction factor at higher energies is based on the inclusive e^+e^-/γ double ratio RR defined again as $RR = R_{Data}/R_{MC}$ with

$$R_{Data,MC} = \left(\frac{N_{e^+e^-}^\gamma}{N_\gamma^\gamma} \right)_{Data,MC} \quad (6)$$

where N_γ^γ , $N_{e^+e^-}^\gamma$ are the numbers of single isolated photons and e^+e^- pairs in the same data sample of $\nu_\mu CC$ events used for the collinearity check.

It was found that the two methods agree quite well in the low energy region and yield a correction factor close to 1. However, in the high energy region the e^+e^- efficiency correction factor varied from 0.7 ± 0.04 to 0.4 ± 0.03 depending on the e^+e^- energy.

5 Background

The largest contribution to the background is expected from neutrino interactions yielding a single π^0 with little hadronic activity in the final state. Neutrino interactions occurring in the coil and iron upstream of the DC fiducial volume may yield an isolated e^+e^- pair if a photon from a π^0 produced in such an interaction converts in the DC and the accompanying particles are not detected.

Because of the large mass of this upstream material the study of this background would require the simulation of a very large number of events resulting in a prohibitively large amount of computer time. Consequently, only about 10% of the required statistics for $\nu_\mu CC(NC)$ inelastic reactions were simulated, while other background components, such as $\nu_e CC$, coherent π^0 production, quasi-elastic reactions and $\nu_\mu e$ scattering were simulated with a statistics comparable to the number of events expected from these reactions in the data.

The distribution of the variable \mathcal{C} for the sum of all the MC samples is shown in Figure 5. The plot covers the region $\mathcal{C} < 5 \times 10^{-4}$, which is 25 times larger than the size of the signal box. No $\nu_\mu CC(NC)$ event is found in this region. The data outside the box, also shown in Figure 5, are consistent with the MC

prediction (19 events observed and 20 ± 4 events predicted). The estimate of background from $\nu_\mu CC(NC)$ in the signal box is based on the observation that there are *no physical reasons* for this background to be other than flat in the region $\mathcal{C} < 5 \times 10^{-4}$. Two independent methods were used for the background estimation in the signal region.

The first method is based on the MC. The MC background from the fully simulated reactions was found to be 2.5 ± 0.8 events inside the signal region. For the $\nu_\mu CC$ and $\nu_\mu NC$ events for which only 10 % of the data statistics was generated, no event was found in the full enlarged region $\mathcal{C} < 5 \times 10^{-4}$. Assuming that this background is distributed randomly in this interval and taking into account that the simulated sample corresponds to only 10% of data, we estimate the $\nu_\mu CC$ and $\nu_\mu NC$ background contribution to be $0_{-0.0}^{+0.4}$ events inside the signal region.

The second method relies on the data themselves. The agreement between the observed and predicted numbers of events outside the signal box allows to conclude that the number of background events from $\nu_\mu CC$ and $\nu_\mu NC$ processes is negligible. Thus, by extrapolating the 19 observed events to the signal region with the shape of the fully simulated MC events we obtain a second background estimate of 2.4 ± 0.9 .

The final background estimates with the two methods are $N_{bkg}^{MC} = 2.5_{-0.8}^{+0.9}(stat) \pm 0.6(syst)$ events from the MC and $N_{bkg}^{Data} = 2.4_{-0.9}^{+0.9}(stat) \pm 0.7(syst)$ events from the data, thus providing consistent results. The systematic error includes the uncertainties in the number of *pot* (5%) and in the coherent π^0 production cross section (25%). In addition, in the second method we also take into account the systematic errors related to the extrapolation procedure. The total systematic uncertainty was calculated by adding all errors in quadrature. In the following we use the background estimate extracted from the data themselves.

6 Results and calculation of limits

Upon opening the signal box we have found one event that passes our selection criteria. This is consistent with the expected background and hence no evidence for isosinglet neutrino decays has been found. We can then determine the 90% *CL* upper limit for the corresponding mixing amplitude $|U_{\tau 4}|^2$ from the 90% *CL* upper limit for the expected number of signal events, $N_{\nu_4 \rightarrow \nu_\tau e^+ e^-}^{up}$. Using the frequentist approach of ref. [21] and taking into account the uncertainties in the background estimate [22] we obtain $N_{\nu_4 \rightarrow \nu_\tau e^+ e^-}^{up} = 2.1$ events. Since the number of observed events is less than the predicted background, this limit is lower than the corresponding sensitivity, $S_{\nu_4 \rightarrow \nu_\tau e^+ e^-}^{up} = 4.0$. The

sensitivity is defined as the average upper limit obtained in the absence of signal events by an ensemble of experiments with the same expected background [21]. The probability to obtain an upper limit of 2.1 or lower is 29%.

For a given flux $\Phi(\nu_4)$, the expected number of $\nu_4 \rightarrow \nu_\tau e^+ e^-$ decays occurring within the fiducial length L of the NOMAD detector located at a distance L' from the neutrino target is given by

$$N_{\nu_4 \rightarrow \nu_\tau e^+ e^-} = \int \Phi(\nu_4) \cdot \exp(-L' m_{\nu_4}/p_{\nu_4} \tau_4) \cdot [1 - \exp(-L m_{\nu_4}/p_{\nu_4} \tau_4)] \cdot (\Gamma_{e^+ e^-}/\Gamma_{tot}) \cdot \varepsilon \cdot A \cdot dE_{\nu_4} \propto |U_{\tau 4}|^4 \quad (7)$$

where p_{ν_4} is the ν_4 momentum and τ_4 is its lifetime at rest, $\Gamma_{e^+ e^-}$, Γ_{tot} are the partial and total mass dependent ν_4 -decay widths, respectively, and ε is the $e^+ e^-$ pair reconstruction efficiency. The acceptance A of the NOMAD detector was calculated tracing ν_4 's produced in the Be-target or beam dump to the detector taking all relevant momentum and angular distributions into account [17]. As an example for a mass $m_{\nu_4} = 33.9$ MeV, $A = 1.4\%$ and $\varepsilon = 26\%$. The flux $\Phi(\nu_4)$ is given by Eq. (4).

The final 90% CL upper limit curve in the $(m_{\nu_4}; |U_{\tau 4}|^2)$ plane is shown in Figure 7 together with the Big Bang Nucleosynthesis (BBN) and Supernova SN1987a lower limits obtained in ref. [6]. For the mass range $m_{\nu_4} \gtrsim m_\pi$ the shape of the NOMAD limit curve is explained by the contribution from the $\nu_4 \rightarrow \nu_\tau \pi^0$ decay to the ν_4 decay rate: as the $\nu_4 \rightarrow \nu_\tau \pi^0$ decay channel opens up, the branching ratio $BR(\nu_4 \rightarrow \nu_\tau e^+ e^-)$ drops rapidly as m_{ν_4} increases.

7 The KARMEN time anomaly

Our data can also be used to restrict one of the interpretations of the time anomaly observed by the KARMEN experiment [23]. The anomaly is a bump in the time distribution of ν_e and $\bar{\nu}_\mu$ induced events which was expected to be well described by the single exponential from muon decays.¹ The KARMEN Collaboration interpreted the anomaly as being due to an exotic decay of π^+ -mesons into a muon and a 33.9 MeV new fermion X and reported a signal curve for pion branching ratio $BR(\pi^+ \rightarrow \mu^+ + X) \times \Gamma(X \rightarrow e^+ e^- \nu)$ as a function of X -lifetime with a branching ratio $BR(\pi^+ \rightarrow \mu^+ + X)$ as small as 10^{-16} [23]. This and other hypotheses explaining the anomaly have been recently extensively investigated both theoretically [5,25,26] and experimentally

¹ This anomaly, seen in the KARMEN1 data, was not confirmed with the KARMEN2 data [24]. A possible explanation of this effect may be found in ref. [28].

[27,29].

Barger et al. [5] associated the new particle with a 33.9 MeV isosinglet neutrino dominantly mixing with ν_τ . From our limit curve in Figure 7, we have found using Eqs. (2,3) that for $m_{\nu_4} = 33.9$ MeV the lifetime of such a neutrino has to be greater than $\simeq 10^{-2}$ sec while the BBN lower limit of ref. [25] constrain the ν_4 lifetime to be less than 0.1 sec.² Using the KARMEN signal curve [23] results in a small window around $BR(\pi^+ \rightarrow \mu^+ + X) \simeq 10^{-12}$ between our result [16] and BBN one left untested. Note that the recent PSI result on a search for the 33.9 MeV particle in $\pi^+ \rightarrow \mu^+ + X$ decay corresponds to $BR(\pi^+ \rightarrow \mu^+ + X) < 6.0 \cdot 10^{-10}$ at 95% *CL* [27].

8 Conclusion

We found no evidence for the existence of a heavy neutrino, ν_4 , with mass in the range 10 - 190 MeV which mixes dominantly with the ν_τ and decays into $\nu_\tau e^+ e^-$. For the first time an upper limit on the square of the mixing amplitude, $|U_{\tau 4}|^2$, is obtained. Windows between our result and the BBN and SN1987a limits are still of interest for further searches.

Acknowledgements

We gratefully acknowledge the CERN SPS accelerator and beam-line staff for the magnificent performance of the neutrino beam. The experiment was supported by the following funding agencies: Australian Research Council (ARC) and Department of Industry, Science, and Resources (DISR), Australia; Institut National de Physique Nucléaire et Physique des Particules (IN2P3), Commissariat à l’Energie Atomique (CEA), France; Bundesministerium für Bildung und Forschung (BMBF, contract 05 6DO52), Germany; Istituto Nazionale di Fisica Nucleare (INFN), Italy; Russian Foundation for Basic Research, Institute for Nuclear Research of the Russian Academy of Sciences, Russia; Fonds National Suisse de la Recherche Scientifique, Switzerland; Department of Energy, National Science Foundation (grant PHY-9526278), the Sloan and the Cottrell Foundations, USA. F.J.P. Soler is supported by a TMR Fellowship from the European Commission. M.C. Gonzalez-Garcia is supported by the Spanish DGICYT under grants PB98-0693 and PB97-1261, by the Generalitat Valenciana under grant GV99-3-1-01 and by the TMR

² The SN1987a limit obtained is stronger than the BBN one, however the supernova results are more model dependent. One may imagine a case when the supernova arguments are not applicable, while the BBN ones still apply [25].

network grant ERBFMRXCT960090 of the European Union.

We thank Prof. V.Matveev for many interesting discussions and comments. We should like to thank Prof. A.D. Dolgov and Dr. D.V. Semikoz for their interest in our results and for many interesting discussions on the astrophysical and cosmological limits.

References

- [1] See for example, R.N. Mohapatra and P.B. Pal in "Massive Neutrinos in Physics and Astrophysics", World Scientific, Singapore, 1991.
- [2] J. Ellis, "Summary of Neutrino 2000", Preprint hep-ph/0008334;
L. Di Lella, "Accelerator and Reactor Neutrino Experiments", Review presented at Lepton-Photons'99, Preprint hep-ex/9912010.
- [3] A.D. Dolgov and S.H. Hansen, Preprint hep-ph/0009083.
- [4] M. Dittmar, M.C. Gonzalez-Garcia, A. Santamaria and J.W.F. Valle, Nucl. Phys. **B332** (1990) 1;
G.J. Feldman et al., Phys. Rev Lett. **54** (1985) 2289;
BEBC Collab., A.M. Cooper-Sarkar et al., Phys. Lett. **160B** (1985) 207;
G. Bernardi et al., Phys. Lett. **B 203** (1988) 332;
CHARM Collab., F. Bergsma et al., Phys. Lett. **128B** (1983) 361;
CHARM Collab., J. Dorenbosch et al., Phys. Lett. **166B** (1986) 473;
CCFR Collab., S.R. Mishra et al., Phys. Rev. Lett. **59** (1987) 1397;
M.E. Duffy et al., Phys. Rev. **D 38** (1988) 2032;
W. Bartel et al., Phys. Lett. **123B** (1983) 353;
CHARM II Collab., P. Vilain et al., Phys. Lett. **B 351** (1995) 387;
K. Assamagan et al., Phys. Lett. **B 434** (1998) 158;
NuTeV Collab., A. Vaitatis et al., Phys. Rev. Lett. **83** (1999) 4943.
- [5] V. Barger, R.J.N. Phillips and S. Sarkar, Phys. Lett. **B352** (1995) 365;
(E) *ibid.* **B 356** (1995) 671.
- [6] A.D. Dolgov, S.H. Hansen, G. Raffelt, and D.V. Semikoz, Nucl. Phys. **B 590** (2000) 562.
- [7] L3 Collab., M. Acciarri et al, Phys. Lett. **B 461** (1999) 397; **B351** (1995) 387;
DELPHI Collab., P. Abreu et al., Z. Phys. **C 74** (1997) 57;
L3 Collab., O. Adriani et al, Phys. Lett. **B 295** (1992) 371;
OPAL Collab., M.Z. Akrawy et al., Phys. Lett. **B 247** (1990) 448.
- [8] G. Acquistapace et al., CERN-ECP/95-14, July 1995.
- [9] NOMAD Collab., J. Altegoer et al, Nucl. Instr. and Meth. **A 404** (1998) 96.
- [10] M. Anfreville et al., "The drift chambers of the NOMAD detector", to be submitted to Nucl. Instr. and Meth..
- [11] G. Bassompierre et al., Nucl.Instr. and Meth. **A 403** (1998) 363;
G. Bassompierre et al., Nucl.Instr. and Meth. **A 411** (1998) 63.
- [12] D. Autiero et al., Nucl.Instr. and Meth. **A 373** (1996) 358;
D. Autiero et al., Nucl.Instr. and Meth. **A 387** (1997) 352;
D. Autiero et al., Nucl.Instr. and Meth. **A 411** (1998) 285.

- [13] J. Altegoer et al., Nucl. Instr. and Meth. **A 428** (1999) 299;
 NOMAD Collab., J. Altegoer et al., Phys. Lett. **B 428** (1998) 197;
 NOMAD Collab., P. Astier et al., Phys. Lett. **B 479** (2000) 371.
- [14] D.E. Groom et al., Review of Particle Physics, Eur. Phys. J. **C 15** (2000) 1.
- [15] R.E. Shrock, Phys. Rev **D 24** (1981) 1232 and 1275.
- [16] S.N. Gninenko et al., “Search for heavy isosinglet neutrinos mixing to tau neutrino”, NOMAD Memo/2000-05 (unpublished).³
- [17] M.C. Gonzalez-Garcia and J.J. Gomez-Cadenas, Phys. Rev. **D 55** (1997) 1297.
- [18] B. Van der Vyver, Nucl. Instr. and Meth., **A 385** (1997) 91.
- [19] NOMAD Collab., P. Astier et al, Phys. Lett. **B 453** (1999) 169.
- [20] D. Autiero et al., Nucl. Instr. and Meth. **A 425** (1999) 190.
- [21] G.J. Feldman and R.D. Cousins, Phys. Rev. **D 57** (1998) 3873.
- [22] A. Stuart and J.K. Ord, “Kendall’s Advanced Theory of Statistics”, vol. 2, “Classical Inference and Relationship”, 5th ed., Oxford Univ. Press, New York, 1991, p.861, Eq.(23.4).
- [23] KARMEN Collab.: B. Armbruster et al., Phys. Lett. **B 348** (1995) 19;
 B. Zeitnitz, in Proc. 17th International Workshop on Weak Interactions and Neutrino, 1999; C. Oehler, in Proc. 6th Topical Seminar on Neutrino and Astroparticle Physics, 1999; M. Drexlin, Talk given at CERN on February 17 1999.
- [24] K. Eitel, Preprint hep-ex/0008002.
- [25] A. D. Dolgov, S. H. Hansen, G. Raffelt, and D. V. Semikoz, Nucl. Phys. **B 580** (2000) 331.
- [26] J. Govaerts, J. Deutsch, and P.M. Van Hove, Phys. Lett. **B 389** (1996) 700;
 D. Choudhury and S. Sarkar, Phys. Lett. **B 374** (1996) 87;
 D. Choudhury, H. Dreiner, P. Richardson, and S. Sarkar, Phys. Rev. **D 61** (2000) 095009;
 M. Kachelrieß, CERN-TH-2000-14, Preprint hep-ph/0001160;
 I. Golman, R. Mohapatra and S. Nussinov, Phys. Lett. **B 481** (2000) 151;
 S.N. Gninenko and N.V. Krasnikov, Phys. Lett. **B 434** (1998) 163;
 R. Bilger et al., Phys. Lett. **B 446** (1999) 363;
 J.M. Levy and F. Vannucci, Preprint hep-ph/0003194;
 A. Lukas and A. Romanino, Preprint hep-ph/0004130.
- [27] M. Daum et al., Phys. Rev. Lett. **85** (2000) 1815.
- [28] F. Atchison, M. Daum, P.R. Kettle, C. Wigger, Preprint hep-ex/0008073.

³ A copy of this Memo is available upon request to the NOMAD Secretariat from Sergei.Gninenko@cern.ch, tel: +41-22-767-6009, fax: +41-22-767-9070

- [29] M. Daum et al., Phys. Lett. **B 361** (1995) 179;
R. Bilger et al., Phys. Lett. **B 363** (1995) 41;
D.A. Bryman and T. Numao, Phys. Rev. **D 53** (1996) 558;
NuTeV Collab., J.A. Formaggio et al., Phys. Rev. Lett. **84** (2000) 4043.

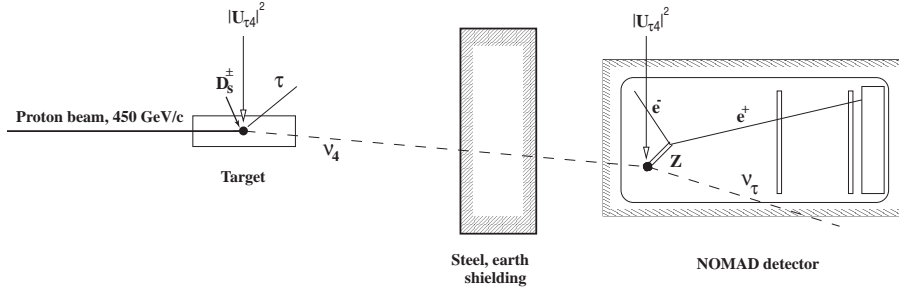


Fig. 1. Schematic illustration of the production of ν_4 and its detection via the $\nu_4 \rightarrow \nu_\tau e^+ e^-$ decay. Because of its short lifetime the D_s decays immediately at the production point.

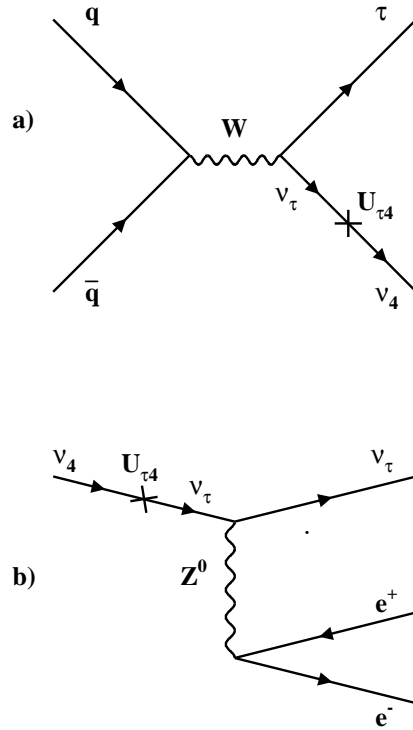


Fig. 2. Feynman diagrams illustrating a) ν_4 production from $D_s(\bar{D}_s)$ decay and b) the decay of an isosinglet neutrino ν_4 .

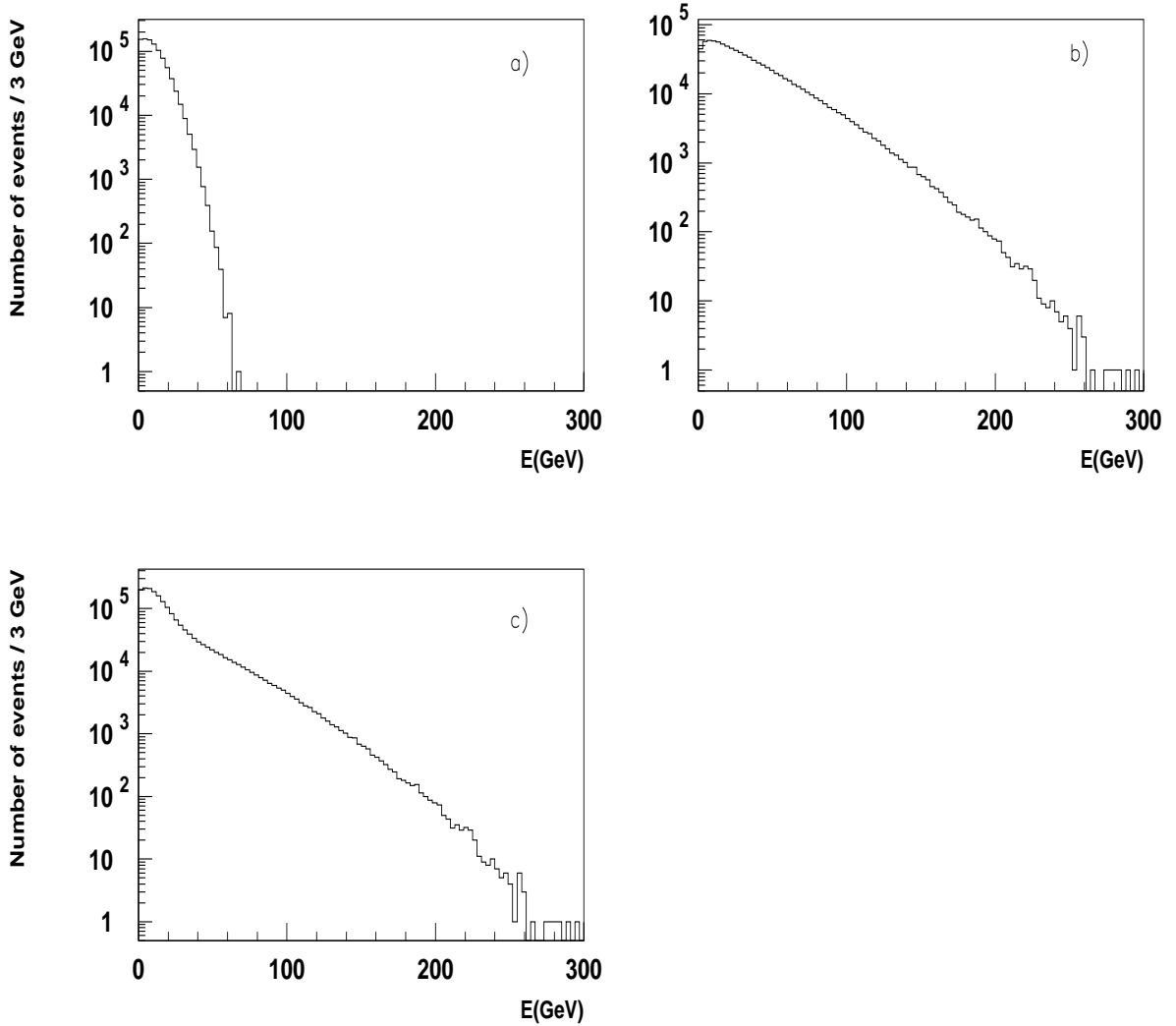


Fig. 3. Combined energy spectra of tau neutrinos pointing towards the NOMAD fiducial area from the proton target and from the beam dump a) originating directly from $D_s(\bar{D}_s)$ decays; b) originating from the decays of τ^\pm produced in $D_s(\bar{D}_s)$ decays; c) the sum of the two. The spectra are calculated for 10^{11} protons on target (pot).

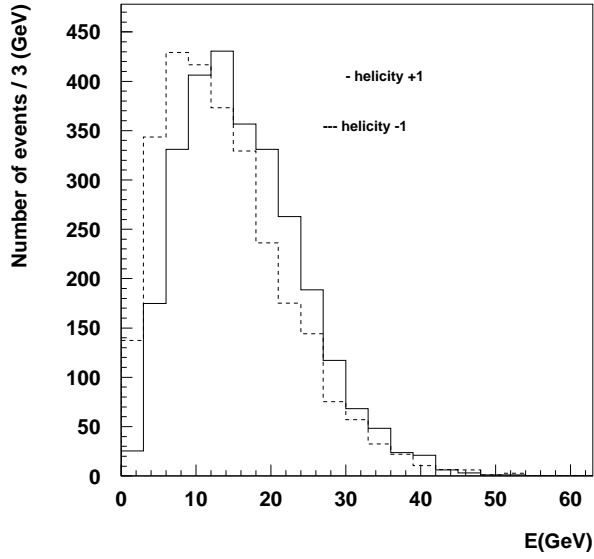


Fig. 4. Energy distribution of e^+e^- pairs from decays of a ν_4 with 33.9 MeV mass for different ν_4 helicities. The average e^+e^- pair energies are $\langle E \rangle_{+1} = 16.4$ GeV and $\langle E \rangle_{-1} = 14.1$ GeV for helicities +1 and -1, respectively.

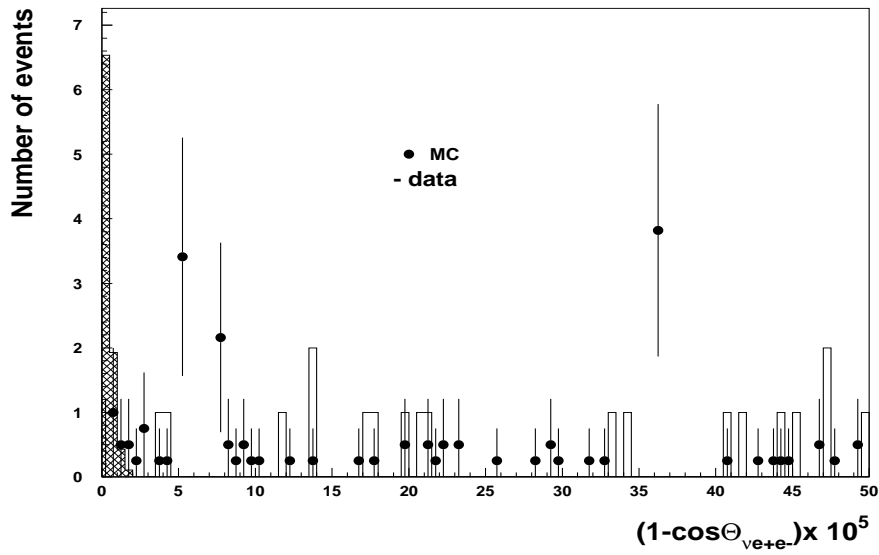


Fig. 5. The final $(1 - \cos\Theta_{\nu_e+e^-})$ distribution for the data and MC. The dashed histogram represents the distribution expected from signal events.

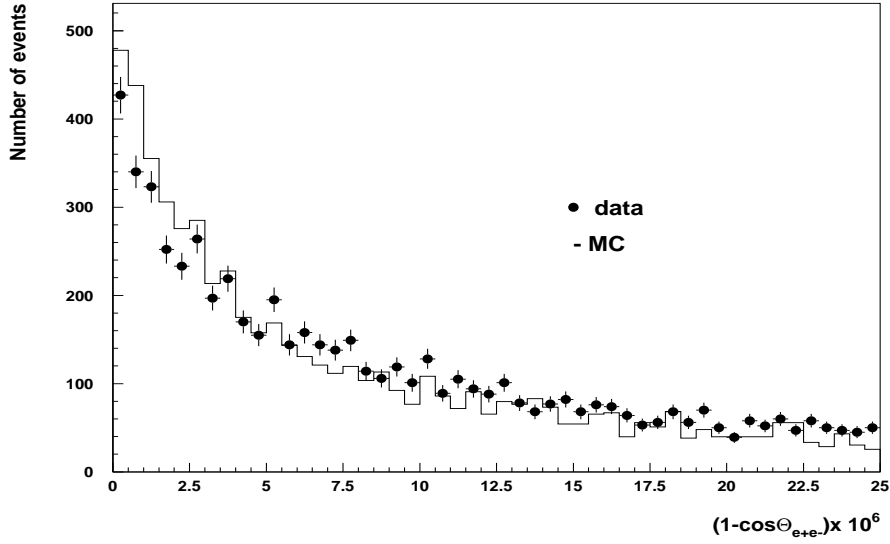


Fig. 6. The $(1 - \cos\Theta_{e^+e^-})$ distribution for e^+e^- pairs from photons converted in the DC target at large distances from the primary vertex for the data and MC.

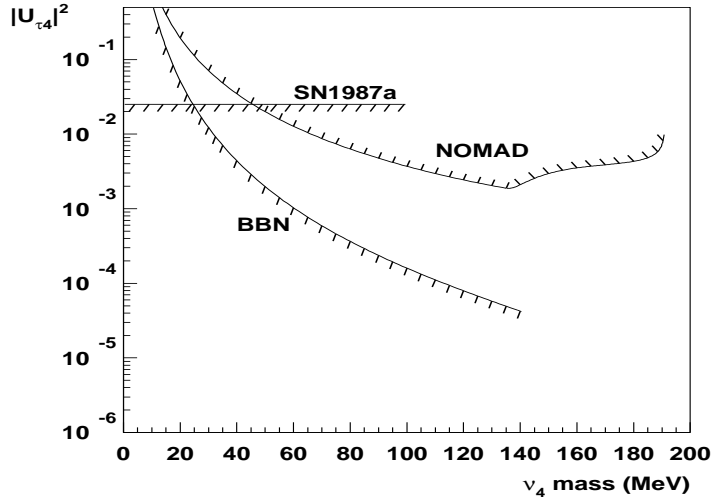


Fig. 7. The NOMAD 90% CL upper limit, and the SN1987a and Big Bang Nucleosynthesis lower limits for the mixing strength $|U_{\tau 4}|^2$ as a function of the heavy neutrino mass. The SN1987a and BBN limits are reproduced from ref. [6]. Note that upper limits of $|U_{\tau 4}|^2 \lesssim 10^{-8}$ from SN1987a and $|U_{\tau 4}|^2 \lesssim 10^{-10} \div 10^{-12}$ from BBN arguments have also been derived for the corresponding mass ranges shown, respectively. For more details see ref. [6].

