

## Neutrino Properties

J. W. F. Valle <sup>1</sup>

Instituto de Física Corpuscular - C.S.I.C.  
Departament de Física Teòrica, Universitat de València  
46100 Burjassot, València, Spain

### Abstract

A brief sketch is made of the present observational status of neutrino properties, with emphasis on the hints from solar and atmospheric neutrinos, as well as cosmological data on the amplitude of primordial density fluctuations. Implications of neutrino mass in particle accelerators, astrophysics and cosmology are discussed.

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<sup>1</sup>valle@flamenco.uv.es; URL <http://neutrinos.uv.es>

# Neutrino Properties

J. W. F. Valle<sup>a †</sup>

<sup>a</sup>Instituto de Física Corpuscular - C.S.I.C.  
 Departament de Física Teòrica, Universitat de València  
 46100 Burjassot, València, Spain

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## 1. INTRODUCTION

It is beyond any doubt that, although very successful, our present standard  $SU(2) \otimes U(1)$  model leaves open too many fundamental issues in particle physics to be an ultimate theory of Nature. One of the most fundamental ones refers to the masses and properties of neutrinos. Apart from being a theoretical puzzle, in the sense that there is no principle that dictates that neutrinos are massless, as postulated in the standard model, nonzero masses may in fact be required in order to account for the data on solar and atmospheric neutrinos, as well as the dark matter in the universe. The implications of detecting nonzero neutrino masses could be very far reaching for the understanding of fundamental issues in particle physics, astrophysics, as well as the large scale structure of our universe.

One interesting aspect of most extensions of the standard model where neutrino have non-vanishing masses is that they may affect the physics of the electroweak sector in a very remarkable way, which can be experimentally tested. Some of the ways to probe the corresponding physics at accelerator as well as underground experiments will be described.

### 1.1. Laboratory Limits

The most model-independent of the laboratory limits on neutrino mass are those that follow

purely from kinematics, given as [1]

$$m_{\nu_e} \lesssim 5 \text{ eV}, \quad m_{\nu_\mu} \lesssim 250 \text{ keV}, \quad m_{\nu_\tau} \lesssim 23 \text{ MeV}(1)$$

The improved limit on the  $\nu_e$  mass from beta decays was recently given by Lobashev [2], while that on the  $\nu_\tau$  mass comes from the ALEPH experiment [3] and may be substantially improved at a future tau-charm factory [4].

In addition, there are limits on neutrino masses that follow from the non-observation of neutrino oscillations [5]. The 90% confidence level (C.L.) exclusion contours of neutrino oscillation parameters in the 2-flavour approximation are given in Fig. 1, taken from ref. [6]. Improvements are expected from the ongoing CHORUS and NOMAD experiments at CERN, with a similar proposal at Fermilab [7]. There are also good prospects for substantial progress at future long baseline experiments using CERN and Fermilab neutrino beams aimed at the Gran Sasso and Soudan underground facilities, respectively.

Another important limit follows from the non-observation of neutrino-less double beta decay -  $\beta\beta_{0\nu}$  - i.e. the process by which an  $(A, Z - 2)$  nucleus decays to  $(A, Z) + 2 e^-$ . This process would arise from the virtual exchange of a Majorana neutrino from an ordinary double beta decay process. Unlike the latter, the neutrino-less process violates lepton number and its existence would indicate the Majorana nature of neutrinos. Because of the phase space advantage, this process is a very sensitive tool to probe into the nature of neutrinos. In fact, as shown in ref. [8], a non-vanishing  $\beta\beta_{0\nu}$  decay rate requires

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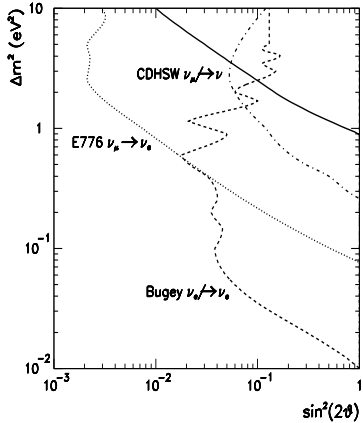


Figure 1. Limits on oscillation parameters.

neutrinos to be majorana particles, *irrespective of which mechanism induces it*. This establishes a very deep connection which, in some special models, may be translated into a lower limit on the neutrino masses. The negative searches for  $\beta\beta_{0\nu}$  in  $^{76}\text{Ge}$  and other nuclei leads to a limit of about two eV [9] on the weighted average neutrino mass parameter  $\langle m \rangle$

$$\langle m \rangle \lesssim 1 - 2 \text{ eV} \quad (2)$$

depending to some extent on the relevant nuclear matrix elements characterising this process [10]. Improved sensitivity is expected from the upcoming enriched germanium experiments. Although rather stringent, this limit in eq. (2) may allow relatively large neutrino masses, as there may be strong cancellations between the contributions of different neutrino types. This happens automatically in the case of a Dirac neutrino as a result of the lepton number symmetry [11].

## 1.2. The Cosmological Density Limit

In addition to laboratory limits, there is a cosmological bound that follows from avoiding the overabundance of relic neutrinos [12]

$$m_{\nu_\tau} \lesssim 92 \Omega_\nu h^2 \text{ eV}, \quad (3)$$

where  $\Omega_\nu h^2 \leq 1$  and the sum runs over all isodoublet neutrino species with mass less than  $O(1 \text{ MeV})$ . Here  $\Omega_\nu = \rho_\nu / \rho_c$ , where  $\rho_\nu$  is the neutrino contribution to the total density and  $\rho_c$  is the critical density. The factor  $h^2$  measures the uncertainty in the determination of the present value of the Hubble parameter,  $0.4 \leq h \leq 1$ . The factor  $\Omega_\nu h^2$  is known to be smaller than 1.

For the  $\nu_\mu$  and  $\nu_\tau$  this bound is much more stringent than the corresponding laboratory limits eq. (1).

Recently there has been a lot of work on the possibility of an MeV tau neutrino [13,14]. Such range seems to be an interesting one from the point of view of structure formation [13,14]. Moreover, it is theoretically viable as the constraint in eq. (3) holds only if neutrinos are stable on the relevant cosmological time scales. In models with spontaneous violation of total lepton number [15] there are new interactions of neutrinos with the majorons which may cause neutrinos to decay into a lighter neutrino plus a majoron, for example [16],

$$\nu_\tau \rightarrow \nu_\mu + J. \quad (4)$$

or have sizeable annihilations to these majorons,

$$\nu_\tau + \nu_\tau \rightarrow J + J. \quad (5)$$

The possible existence of fast decay and/or annihilation channels could eliminate relic neutrinos and therefore allow them to be heavier than eq. (3). The cosmological density constraint on neutrino decay lifetime (for neutrinos lighter than 1 MeV or so) may be written as

$$\tau \lesssim 1.5 \times 10^7 (KeV/m_{\nu_\tau})^2 yr, \quad (6)$$

and follows from demanding an adequate red-shift of the heavy neutrino decay products. For neutrinos heavier than  $\sim 1 \text{ MeV}$ , such as possible for the case of  $\nu_\tau$ , the cosmological limit on the lifetime is less stringent than given in eq. (6).

As we already mentioned the possible existence of non-standard interactions of neutrinos due to their couplings to the Majoron brings in the possibility of fast invisible neutrino decays with Majoron emission [16]. These 2-body decays can be much faster than the visible decays, such as radiative decays of the type  $\nu' \rightarrow \nu + \gamma$ . As a result

the Majoron decays are almost unconstrained by astrophysics and cosmology. For a more detailed discussion see ref. [12].

A general method to determine the Majoron emission decay rates of neutrinos was first given in ref. [17]. The resulting decay rates are rather subtle [17] and model dependent and will not be discussed here. The reader may consult ref. [18,16]. The conclusion is that there are many ways to make neutrinos sufficiently short-lived that all mass values consistent with laboratory experiments are cosmologically acceptable. For neutrino decay lifetime estimates see ref. [16,18,19].

### 1.3. The Nucleosynthesis Limit

There are stronger limits on neutrino lifetimes and/or annihilation cross sections arising from cosmological nucleosynthesis considerations. If massive  $\nu_\tau$ 's are stable during nucleosynthesis ( $\nu_\tau$  lifetime longer than  $\sim 100$  sec), one can constrain their contribution to the total energy density from the observed amount of primordial helium. This bound can be expressed through an effective number of massless neutrino species ( $N_\nu$ ). Using  $N_\nu < 3.4 - 3.6$ , the following range of  $\nu_\tau$  mass has been ruled out [20,21]

$$0.5 \text{ MeV} < m_{\nu_\tau} < 35 \text{ MeV} \quad (7)$$

If the nucleosynthesis limit is taken less stringent the limit loosens somewhat. However it has recently been argued that non-equilibrium effects from the light neutrinos arising from the annihilations of the heavy  $\nu_\tau$ 's make the constraint stronger and forbids all  $\nu_\tau$  masses on the few MeV range.

One can show that if the  $\nu_\tau$  is unstable during nucleosynthesis [22] the bound on its mass is substantially weakened translated as a function of the assumed lifetime [22].

Even more important is the effect of neutrino annihilations [23]. Fig. 2 gives the effective number of massless neutrinos equivalent to the contribution of massive neutrinos with different values of the coupling  $g$  between  $\nu_\tau$ 's and  $J$ 's, expressed in units of  $10^{-5}$ . For comparison, the dashed line corresponds to the standard model  $g = 0$  case. One sees that for a fixed  $N_\nu^{max}$ , a wide range of tau neutrino masses is allowed for large enough

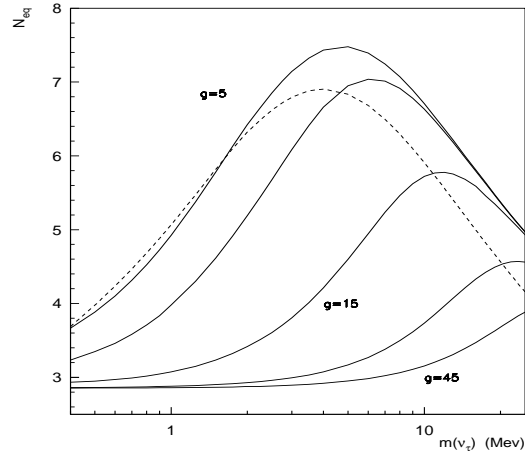


Figure 2. Contribution of a heavy  $\nu_\tau$  to nucleosynthesis in terms of the equivalent number of massless neutrinos.

values of  $g$ . No  $\nu_\tau$  masses below 23 MeV can be ruled out, as long as  $g$  exceeds a few times  $10^{-4}$ . Such values are reasonable in many majoron models [16,24]. For more details see ref. [23]. In short one sees that the constraints on the mass of a Majorana  $\nu_\tau$  from primordial nucleosynthesis can be substantially relaxed if annihilations  $\nu_\tau \bar{\nu}_\tau \leftrightarrow JJ$  are present. More details in the talk by Pastor [25].

As a result of the above considerations one concludes that it is worthwhile to continue the efforts to improve present laboratory neutrino mass limits in the laboratory. One method sensitive to large masses is to search for distortions in the energy spectra of leptons coming from  $\pi, K$  weak decays such as  $\pi, K \rightarrow e\nu$ ,  $\pi, K \rightarrow \mu\nu$ , as well as kinks in nuclear  $\beta$  decays.

## 2. HINTS FOR NEUTRINO MASSES

So far the only indications in favour of nonzero neutrino rest masses have been provided by astrophysical and cosmological observations, with a varying degree of theoretical input. We now turn to these.

## 2.1. Dark Matter

By combining the observations of cosmic background temperature anisotropies on large scales performed by the COBE satellite [26] with cluster-cluster correlation data e.g. from IRAS [27] one finds that it is not possible to fit well the data on all scales within the framework of the popular cold dark matter (CDM) model. Indeed, the best fit is obtained for a mixture, otherwise ad hoc, consisting of about 70% CDM with about 25 % *hot dark matter* (HDM) and a small amount in baryons [28]. The best way to make up for the hot dark matter component is through a massive neutrino in the few eV mass range. It has been argued that this could be the tau neutrino, in which case one might expect the existence of  $\nu_e \rightarrow \nu_\tau$  or  $\nu_\mu \rightarrow \nu_\tau$  oscillations. Searches for these oscillations are now underway at CERN, with a similar proposal also at Fermilab [7]. This mass scale is also consistent with the hints in favour of neutrino oscillations reported by the LSND experiment [29].

## 2.2. Solar Neutrinos

So far the averaged data collected by the chlorine [30], Kamiokande [31], as well as by the low-energy data on pp neutrinos from the GALLEX and SAGE experiments [32,33] still pose a persisting puzzle. The most recent data can be summarised as:

$$\begin{aligned} R_{Cl}^{exp} &= (2.55 \pm 0.25)\text{SNU} \\ R_{Ga}^{exp} &= (74 \pm 8)\text{SNU} \\ R_{Ka}^{exp} &= (0.44 \pm 0.06)R_{Ka}^{BP95} \end{aligned} \quad (8)$$

where  $R_{Ka}^{BP95}$  is the BP95 SSM prediction of ref. [34]. For the gallium result we have taken the average of the GALLEX [32] and the SAGE measurements [33].

Comparing the data of gallium experiments with the Kamiokande data one sees the need for a reduction of the  ${}^7\text{Be}$  flux relative to standard solar model [34] expectations. Inclusion of the Homestake data only sharpens the discrepancy, suggesting that the solar neutrino problem is indeed a real problem. The totality of the data strongly suggests that the simplest astrophysical solutions are ruled out, and that new physics is

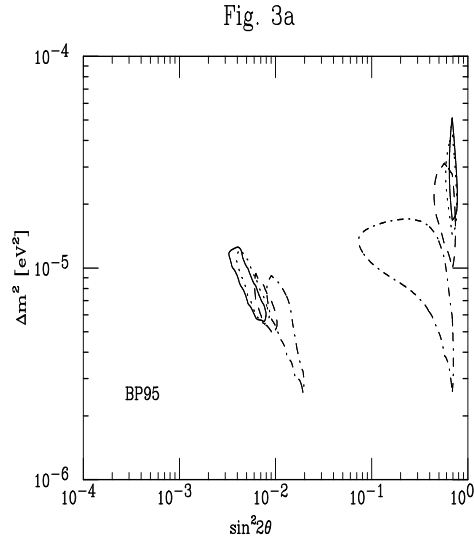


Figure 3. Allowed solar neutrino oscillation parameters for active neutrino conversions.

needed [35]. The most attractive possibility is to assume the existence of neutrino conversions involving very small neutrino masses. In the framework of the MSW effect [36] the required solar neutrino parameters  $\Delta m^2$  and  $\sin^2 2\theta$  are determined through a  $\chi^2$  fit of the experimental data<sup>3</sup>. Fig. 3, taken from ref. [37], shows the 90% C.L. areas for the in the BP95 model for the case of active neutrino conversions. The fit favours the small mixing solution over the large mixing one, due mostly to the larger reduction of the  ${}^7\text{Be}$  flux found in the former. Here  $\xi$  denotes the assumed level of noise fluctuations in the solar matter density [38], not excluded by the SSM nor by present helioseismology studies. The solid curves are for the standard  $\xi = 0$  assumption corresponding to a smooth Sun. The regions inside the other curves correspond to the case where matter density fluctuations are assumed. Noise causes a slight shift of  $\Delta m^2$  towards lower values and a larger shift of  $\sin^2 2\theta$  towards larger values. The corresponding allowed  $\Delta m^2$  range is  $2.5 \times 10^{-6} < \Delta m^2 < 9 \times 10^{-6} \text{ eV}^2$  instead of  $5 \times 10^{-6} < \Delta m^2 < 1.2 \times 10^{-5} \text{ eV}^2$  in the noise-

<sup>3</sup>For simplicity we neglect theoretical uncertainties, earth effects, as well as details of the neutrino production region.

less case. The large mixing area is less stable, with a tendency to shift towards smaller  $\Delta m^2$  and  $\sin^2 2\theta$  values.

It is interesting to note that the  ${}^7\text{Be}$  neutrinos are the solar neutrino spectrum component which is most affected by the matter noise. Therefore the Borexino experiment should be an ideal tool for studying the solar matter fluctuations, if sufficiently small errors can be achieved. Its potential in "testing" the level of solar matter density fluctuations is discussed in ref. [37], summarized in the talk by Rossi [39]. Ref. [37] also contains a discussion of sterile solar neutrino conversions, as well as a comparison with other solar models.

### 2.3. Atmospheric Neutrinos

Two underground experiments, Kamiokande and IMB, and possibly also Soudan2, have indications which support an apparent deficit in the expected flux of atmospheric  $\nu_\mu$ 's relative to that of  $\nu_e$ 's that would be produced from conventional decays of  $\pi$ 's,  $K$ 's as well as secondary muon decays [40]. Although the predicted absolute fluxes of neutrinos produced by cosmic-ray interactions in the atmosphere are uncertain at the 20% level, their ratios are expected to be accurate to within 5%. While some of the experiments, such as Frejus and NUSEX, have not found a firm evidence, it has been argued that there may be a strong hint for an atmospheric neutrino deficit that could be ascribed to neutrino oscillations. Recent results from Kamiokande on higher energy neutrinos strengthen the case for an atmospheric neutrino problem. The relevant oscillation parameters are shown in Fig. 4 taken from ref. [41].

### 2.4. Reconciling Present Hints.

One of the simplest extensions of the electroweak theory consists in adding isosinglet neutral heavy leptons (NHLS), such as right handed neutrinos, as in the seesaw model [42]. In this case the NHLS have a large Majorana mass term  $M_R$ , which violates total lepton number, or B-L (baryon minus lepton number), a symmetry that plays an important role in many extended gauge

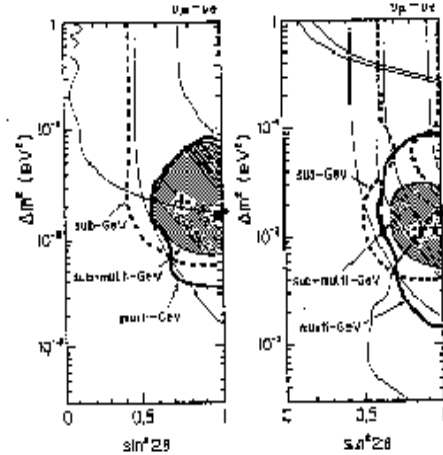


Figure 4. Atmospheric neutrino oscillation parameters from Kamiokande data.

models [43]. The masses of the light neutrinos are obtained by diagonalizing the following mass matrix

$$\begin{array}{c|cc}
 & \nu & \nu^c \\
 \hline
 \nu & 0 & D \\
 \nu^c & D^T & M_R
 \end{array} \quad (9)$$

where  $D = h_D v_2 / \sqrt{2}$  is the Dirac mass matrix and  $M_R = M_R^T$  is the isosinglet Majorana mass. In the seesaw approximation, one finds

$$M_L = -DM_R^{-1}D^T. \quad (10)$$

Although one expects  $M_R$  to be large, one can not make any firm guess, as its magnitude heavily depends on the model. As a result one can not make any real prediction for the corresponding light neutrino masses that are generated through the exchange of the heavy Majorana neutrinos.

#### 2.4.1. Almost Degenerate Neutrinos

The above observations from cosmology and astrophysics do seem to suggest a theoretical puzzle. As can easily be understood just on the basis of numerology, it seems rather difficult to reconcile the three observations discussed above in a framework containing just the three known neutrinos.

The only possibility to fit these observations in a world with just the three known neutrinos is if all of them have nearly the same mass  $\sim 2$  eV [44]. This can be arranged, for example in general seesaw models which also contain an effective triplet vacuum expectation value [45,43] contributing to the light neutrino masses. This term should be added to eq. (10). Thus one can construct extended seesaw models where the main contribution to the light neutrino masses ( $\sim 2$  eV) is universal, due to a suitable horizontal symmetry, while the splittings between  $\nu_e$  and  $\nu_\mu$  explain the solar neutrino deficit and that between  $\nu_\mu$  and  $\nu_\tau$  explain the atmospheric neutrino anomaly [46].

#### 2.4.2. Four Neutrino Models

The alternative way to fit all the data is to add a fourth neutrino species which, from the LEP data on the invisible Z width, we know must be of the sterile type, call it  $\nu_s$ . The first scheme of this type gives mass to only one of the three neutrinos at the tree level, keeping the other two massless [47]. In a seesaw scheme with broken lepton number, radiative corrections involving gauge boson exchanges will give small masses to the other two neutrinos  $\nu_e$  and  $\nu_\mu$  [48]. However, since the singlet neutrino is super-heavy in this case, there is no room to account for the three hints discussed above.

Two basic schemes have been suggested to keep the sterile neutrino light due to a special symmetry. In addition to the sterile neutrino  $\nu_s$ , they invoke additional Higgs bosons beyond that of the standard model, in order to generate radiatively the scales required for the solar and atmospheric neutrino conversions. In these models the  $\nu_s$  either lies at the dark matter scale [49] or, alternatively, at the solar neutrino scale [50]. In the first case the atmospheric neutrino puzzle is explained by  $\nu_\mu$  to  $\nu_s$  oscillations, while in the second it is explained by  $\nu_\mu$  to  $\nu_\tau$  oscillations. Correspondingly, the deficit of solar neutrinos is explained in the first case by  $\nu_e$  to  $\nu_\tau$  oscillations, while in the second it is explained by  $\nu_e$  to  $\nu_s$  oscillations. In both cases it is possible to fit all observations together. However, in the first

case there is a clash with the bounds from big-bang nucleosynthesis. In the latter case the  $\nu_s$  is at the MSW scale so that nucleosynthesis limits are satisfied. They nicely agree with the best fit points in Fig. 4, taken from ref. [41]. Moreover, it can naturally fit the recent preliminary hints of neutrino oscillations of the LSND experiment [29].

Another theoretical possibility is that all active neutrinos are very light, while the sterile neutrino  $\nu_s$  is the single neutrino responsible for the dark matter [51].

#### 2.4.3. MeV Tau Neutrino

An MeV range tau neutrino is an interesting possibility to consider for two reasons. First, such mass is within the range of the detectability, for example at a tau-charm factory [4]. On the other hand, if such neutrino decays before the matter dominance epoch, its decay products would add energy to the radiation, thereby delaying the time at which the matter and radiation contributions to the energy density of the universe become equal. Such delay would allow one to reduce the density fluctuations on the smaller scales purely within the standard cold dark matter scenario, and could thus reconcile the large scale fluctuations observed by COBE [26] with the observations such as those of IRAS [27] on the fluctuations on smaller scales.

In ref. [52] a model was presented where an unstable MeV Majorana tau neutrino naturally reconciles the cosmological observations of large and small-scale density fluctuations with the cold dark matter model (CDM) and, simultaneously, with the data on solar and atmospheric neutrinos discussed above. The solar neutrino deficit is explained through long wavelength, so-called *just-so* oscillations involving conversions of  $\nu_e$  into both  $\nu_\mu$  and a sterile species  $\nu_s$ , while the atmospheric neutrino data are explained through  $\nu_\mu \rightarrow \nu_e$  conversions. Future long baseline neutrino oscillation experiments, as well as some reactor experiments will test this hypothesis. The model assumes the spontaneous violation of a global lepton number symmetry at the weak scale. The breaking of this sym-

metry generates the cosmologically required decay of the  $\nu_\tau$  with lifetime  $\tau_{\nu_\tau} \sim 10^2 - 10^4$  seconds, as well as the masses and oscillations of the three light neutrinos  $\nu_e$ ,  $\nu_\mu$  and  $\nu_s$  required in order to account for the solar and atmospheric neutrino data. One can verify that the big-bang nucleosynthesis constraints [20,21] can be satisfied in this model.

### 3. IMPLICATIONS

There is a variety of new phenomena that could be associated with neutrino mass [16]. Although in the simplest models of seesaw type the NHLS are Majorana type and expected to be quite heavy, due to limits on the light neutrino masses, there are interesting variants with light Dirac NHLS [53]. After mass matrix diagonalization there are couplings connecting light to heavy neutrinos [45], restricted only by present constraints on weak universality violation. Through these the NHLS can be singly produced in  $Z$  decays, if their mass is below that of the  $Z$  [54]

$$Z \rightarrow N_\tau + \nu_\tau \quad (11)$$

Subsequent NHL decays would then give rise to large missing momentum events, called zen-events. The attainable rates for such processes can lie well within the sensitivities of the LEP experiments [54]. Dedicated searches for acoplanar jets and lepton pairs from  $Z$  decays have provided stringent constraints on NHL couplings to the  $Z$ , plotted below [55]<sup>4</sup> One sees that the recent DELPHI constraints supersede by far the low energy constraints following, e.g. from weak universality.

Even when the isosinglet neutral heavy leptons are heavier than the  $Z$ , they can produce interesting effects. For example, these NHLS may mediate lepton flavour violating (LFV) decays which are exactly forbidden in the standard model. These virtual effects are completely calculable in these models, in terms of the NHL masses and electroweak charged and neutral current couplings. In the simplest models of seesaw type where the NHLS are Majorana type these decays

<sup>4</sup>There have been also inconclusive hints reported by ALEPH [56].

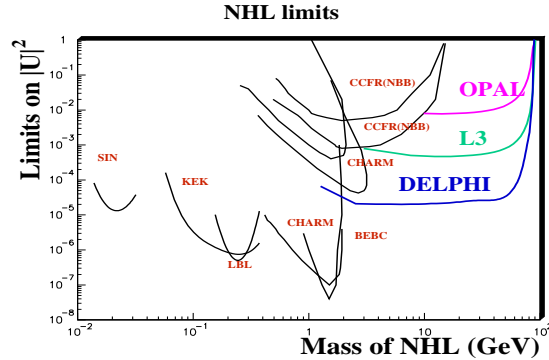


Figure 5. Limits on NHL mass and couplings.

channel	strength
$\tau \rightarrow e\gamma, \mu\gamma$	$\lesssim 10^{-6}$
$\tau \rightarrow e\pi^0, \mu\pi^0$	$\lesssim 10^{-6}$
$\tau \rightarrow e\eta^0, \mu\eta^0$	$\lesssim 10^{-6} - 10^{-7}$
$\tau \rightarrow 3e, 3\mu, \mu\mu e, etc.$	$\lesssim 10^{-6} - 10^{-7}$

Table 1  
Allowed LFV  $\tau$  decay branching ratios.

are expected to be small, due to limits on the light neutrino masses. However, in other variant models with Dirac NHLS [53] this suppression is not present [57,58] and LFV rates are restricted only by present constraints on weak universality violation. These allow for sizeable decay branching ratios, close to present experimental limits [59] and within the sensitivities of the planned tau and B factories [60]. The situation is summarised in the Tables.

The study of these rare  $Z$  decays nicely complements what can be learned from the study of rare LFV muon and tau decays. The stringent limits on  $\mu \rightarrow e\gamma$  preclude the corresponding process  $Z \rightarrow e\mu$  of being sizeable. However the decays  $Z \rightarrow e\tau$  and  $Z \rightarrow \mu\tau$  can occur at the  $\mathcal{O}(10^{-6})$  level. Similar statements can be made also for



channel	strength
$Z \rightarrow e\tau$	$\lesssim 10^{-6} - 10^{-7}$
$Z \rightarrow \mu\tau$	$\lesssim 10^{-7}$

Table 2  
Allowed branching ratios for LFV  $Z$  decays.

the CP violating  $Z$  decay asymmetries in these LFV processes [58]. However, under realistic assumptions, it is unlikely that one will be able to see these decays at LEP without a high luminosity option [61]. In any case there have been dedicated searches which have set good limits in the range from  $10^{-6}$  to  $10^{-4}$  for LFV  $Z$  and  $\tau$  decays at LEP [62]. Finally we note that there can also be large rates for lepton flavour violating decays in models with radiative mass generation [63]. The expected decay rates may lie within the present experimental sensitivities and the situation should improve at PSI or at the proposed tau-charm factories.

Some models of massive neutrinos may lead to quite important and unexpected effects in the electroweak breaking sector which may contain a massless Nambu-Goldstone boson, denoted by  $J$ , in the physical spectrum [15,16]. This leads to a new possibility that the Higgs bosons decay invisibly as [64]

$$h \rightarrow J + J \quad (12)$$

The simplest mode of production of the Higgs boson at LEP is through the Bjorken mechanism. The production and subsequent decay of a Higgs particle which may decay visibly or invisibly involves three independent parameters: its mass  $M_H$ , its coupling strength to the  $Z$ , normalized by that of the standard model,  $\epsilon_B^2$ , and its invisible decay branching ratio. One can use the LEP searches for various exotic channels in order to determine the regions in parameter space that are already ruled out [65].

The invisible decay of the Higgs boson may also affect the strategies for searches at higher energies. For example, the ranges of parameters that can be covered by LEP200 searches for various in-

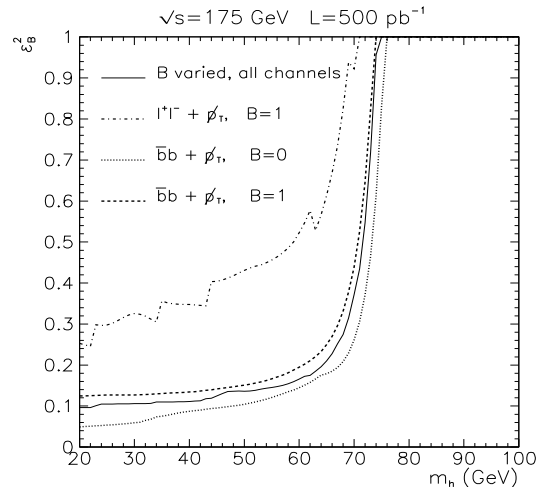


Figure 6. Higgs mass and coupling that can be explored at LEP200.

tegrated luminosities and centre-of-mass energies have been investigated [66], and the results are illustrated in Fig. 6. Another mode of production of invisibly decaying Higgs bosons is that in which a CP even Higgs boson is produced in association with a massive CP odd scalar [67]. This production mode is present in all but the simplest majoron model containing just one complex scalar singlet in addition to the standard Higgs doublet. Present limits on the corresponding coupling strength parameter are given in Fig. 7 as a function of the  $A$  and  $H$  masses, for the case of a visibly decaying  $A$  boson and an invisibly decaying  $H$  boson. This figure is taken from ref. [67] which contains extensive discussion of various integrated luminosities and centre-of-mass energy assumptions. Similar analysis can be made for the case of a high energy linear  $e^+e^-$  collider (NLC) [68], as well as the LHC [69].

#### 4. CONCLUSION

Theory can not yet predict fermion masses, and neutrinos are no exception. Nevertheless neutrino masses are strongly suggested by present

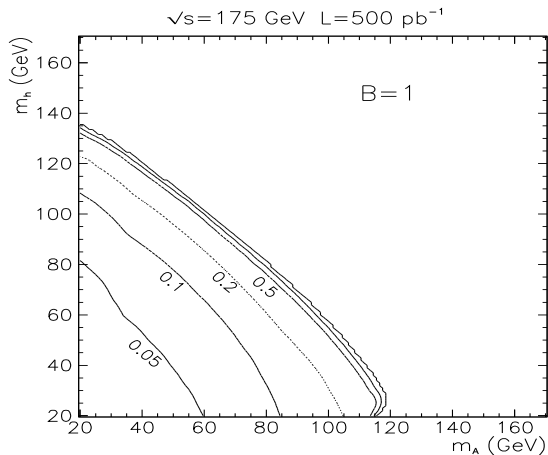


Figure 7. Higgs mass and coupling that can be explored at LEP200 in the  $e^+e^- \rightarrow H A$  production channel.

theoretical models of elementary particles. On the other hand, they seem to be required to fit together present astrophysical and cosmological observations. Neutrino mass studies in nuclear  $\beta$  decays and peak search experiments should continue. Searches for  $\beta\beta_{0\nu}$  decays with enriched germanium could test the quasi-degenerate neutrino scenario of section 2.4.1. Underground experiments at Superkamiokande, Borexino, and Sudbury will shed more light on the solar neutrino issue. Oscillation searches in the  $\nu_e \rightarrow \nu_\tau$  and  $\nu_\mu \rightarrow \nu_\tau$  channels at accelerators should soon improve over the present situation illustrated in Fig. 1, while long baseline experiments both at reactors and accelerators are being considered. These will test the regions of oscillation parameters presently suggested by atmospheric neutrino data, shown in Fig. 4. Finally, new satellite experiments capable of measuring with better accuracy the cosmological temperature anisotropies at smaller angular scales than COBE, will test different models of structure formation, and presumably shed light on the possible role of neutrinos as dark matter.

If neutrinos are massive they could be responsible for a wide variety of implications, covering an impressive range of energies. These could be probed in experiments performed at underground

installations as well as particle accelerators. For example, we saw in section 3 how neutrinos may produce new signatures at high energy physics collider experiments. Although indirectly, these may test neutrino properties in an important way and will therefore complement the efforts at low energies as well as the non-accelerator studies.

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