

# Non-standard Interactions: Atmospheric versus Neutrino Factory Experiments

P. Huber <sup>1,2,3</sup> and J. W. F. Valle <sup>1</sup>

<sup>1</sup> *Instituto de Física Corpuscular – C.S.I.C., Universitat de València*

*Edificio Institutos, Aptdo. 22085, E-46071 València, Spain*

<sup>2</sup> *Theoretische Physik, Physik Department, Technische Universität München,*

*James-Frank-Strasse, D-85748 Garching, Germany*

<sup>3</sup> *Max-Planck-Institut für Physik, Postfach 401212, D-80805 München, Germany*

---

## Abstract

We consider the potential of a generic neutrino factory (NUFACT) in probing non-standard neutrino-matter interactions (NSI). We find that the sensitivity to flavour-changing (FC) NSI can be substantially improved with respect to present atmospheric neutrino data, especially at energies higher than approximately 50 GeV, where the effect of the tau mass is small. For example, a 100 GeV NUFAC T can probe FC neutrino interactions at the level of few  $|\varepsilon| < \text{few} \times 10^{-4}$  at 99 % C.L.

*Key words:* neutrino oscillations, atmospheric neutrinos, neutrino mass and mixing, neutrino factory

*PACS:* 14.60.Pq,, 13.15.+g

---



---

*Email addresses:* Patrick.Huber@ph.tum.de (P. Huber <sup>1,2,3</sup>), valle@ific.uv.es (J. W. F. Valle <sup>1</sup>).

## 1 Introduction

A long baseline neutrino factory [1–3] offers a unique tool for addressing basic questions in weak interaction and flavour physics. One outstanding example is the quest for neutrino mass and oscillations, which touches fundamental issues related to Grand Unified Theories. Motivated by the great discoveries of underground experiments [4–8] neutrino mass and oscillation searches have become the center of attention in particle physics research. Apart from being motivated on basic theoretical grounds [9–12] neutrino masses and oscillations offer the simplest and most obvious way to account for the observed anomalies [13]. Nevertheless other mechanisms, based on flavour changing non-standard neutrino interactions have been suggested in connection with both solar [14–16] and atmospheric anomalies [17–20] as well as other astrophysics applications [21,22]. They can either provide alternative solutions [23] or else be severely tested by the data, in the atmospheric case [20]. They may arise in a number of theories beyond the Standard Model [24–27], in particular, in most (but not all) models of neutrino masses [10].

Using neutrinos from an accelerator in order to obtain an independent confirmation of the non-accelerator physics results, is of fundamental interest, as it will bring more light upon the issue of neutrino masses and oscillations. This has been the focus of a number of dedicated recent NUFACT studies [1–3,28]. Following the recent suggestion in [29] we propose the use of a generic neutrino factory (NUFACT) to probe non-standard neutrino-matter interactions (NSI). We show how indeed such an ideal NUFACT can improve our present knowledge of non-standard FC neutrino interactions well beyond what is presently attainable on the basis of the latest atmospheric results and discuss the corresponding energy, luminosity, energy resolution and tau detection

requirements. We find that, for example, a 100 GeV NUFACT can probe FC neutrino interactions at the level of few  $|\varepsilon| < \text{few}^{-4}$  at 99 % C.L. without any assumption about tau charge identification. In contrast no improvement is expected on non-universal (NU) neutrino interactions beyond the present achieved sensitivity.

In order to compare the NUFACT sensitivities to NSI with present atmospheric sensitivities, we will adopt the same approximation as in ref. [20], i.e. we neglect the possible NSI in the production and detection process of neutrinos. It is well understood that NSI can be probed in a near detector with high accuracy (see e.g. [30]). However, the event rates in a near detector depend quadratically on the strength of the NSI, whereas exploiting the non-standard matter effects we obtain a **linear dependence** of the rates in a far detector. A combined treatment of NSI in production, propagation and detection would lead to intriguing interference effects and is beyond the scope of this letter.

## 2 Interplay of Neutrino Oscillations and non-standard Interactions

The Standard Model can be extended to add neutrino masses in a variety of ways [12]. In any massive neutrino gauge theory the charged current (CC) weak interaction is characterized by the lepton mixing matrix  $K_{\alpha j}$ . This neutrino mixing matrix arises from the unitary matrix ( $U$ ) diagonalizing the neutrino mass matrix and the corresponding unitary matrix ( $\Omega$ ) diagonalizing the left-handed charged leptons ( $K = \Omega U$ ) and can be written in the following

parameterization [10]

$$K = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{\text{CP}}} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta_{\text{CP}}} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta_{\text{CP}}} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta_{\text{CP}}} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta_{\text{CP}}} & c_{23}c_{13} \end{pmatrix}. \quad (1)$$

where we see explicitly the usual three neutrino mixing angles  $\theta_{12}$ ,  $\theta_{23}$ ,  $\theta_{13}$  and one CP phase  $\delta_{\text{CP}}$ . This is the analogous of the CP phase found in the quark sector, as the other two Majorana phases were set to zero, since they are not observed in standard total-lepton-number-conserving <sup>1</sup> oscillations.

The above  $3 \times 3$  form applies if there are no  $\text{SU}(3) \times \text{SU}(2) \times \text{U}(1)$  singlet leptons, such as the simplest models where neutrino masses arise radiatively [32,33]. In seesaw type schemes [9,11] the matrix  $K_{\alpha j}$  is rectangular and contains in general many more parameters: twelve mixing angles and twelve CP phases in the three generation seesaw scheme [10]. We assume, however, that singlets are all super-heavy so that the  $K_{\alpha j}$  matrix can be well approximated by a unitary  $3 \times 3$  matrix and parameterized as eq. (1). This is in fact in agreement with the scale of neutrino mass indicated by present neutrino anomalies.

All present neutrino data <sup>2</sup> can be accounted for by eq. (1). The two mass splittings  $\Delta m_{\odot}^2 \equiv \Delta m_{12}^2$  and  $\Delta m_{\text{ATM}}^2 \equiv \Delta m_{23}^2 \approx \Delta m_{13}^2$  as well as the three neutrino mixing angles are all determined by global fits of neutrino data [13] which indicate that two of the angles are large,  $\theta_{13}$  being small due mainly to reactor results [36]. The recent SNO CC data [37] adds support for the

<sup>1</sup> They could be seen only in  $\Delta L = 2$  processes, such as discussed in [31].

<sup>2</sup> Except for the LSND anomaly, which requires a light sterile neutrino. For recent discussions see [34,35]

so-called LMA solar neutrino solution [38], which previously came only from detailed solar recoil electron spectra [39]. Moreover, LMA is also consistent with the the observed SN 1987A neutrino signal [40]. Thus in what follows we will take the parameters appropriate to this solution. However the details of the solar neutrino oscillation parameters do not significantly affect our results.

Many theories beyond the minimal  $SU(3)\times SU(2)\times U(1)$  model also lead to non-standard neutrino interactions. These include most models of generating neutrino masses, which are generically accompanied by NSI, such as the simplest seesaw type schemes [10,12], super-gravity  $SO(10)$  unified theories [25], models of low energy super-symmetry with broken R parity [26] as well as some radiative models of neutrino mass [27]. Exceptional examples exist of situations where FC interactions are unaccompanied by neutrino masses. Models involve neutral heavy leptons at weak scale [41,42] and some super-gravity  $SU(5)$  models [24]. Such non-standard interactions [10,14–16] can be either flavour-changing (FC) or non-universal (NU).

In Refs. [17–19] the atmospheric neutrino data have been analyzed in terms of a pure  $\nu_\mu \rightarrow \nu_\tau$  conversion in matter due to NSI. The disappearance of  $\nu_\mu$  from the atmospheric neutrino flux is due to interactions with matter which change the flavour of neutrinos. A complete analysis of the 79 kton-yr Super-Kamiokande data, including both the low-energy contained events as well as the higher energy stopping and through-going muon events from Super-Kamiokande and MACRO was given in Ref. [20].

We therefore study an extended mechanism of neutrino propagation which combines both oscillation (OSC) and non-standard neutrino-matter interactions (NSI). In order to discuss the sensitivity of NUFACT to non-standard neutrino interactions we adopt the general Hamiltonian given by

$$\hat{H} = K \begin{pmatrix} 0 & 0 & 0 \\ 0 & \Delta_{21} & 0 \\ 0 & 0 & \Delta_{31} \end{pmatrix} K^\dagger + \begin{pmatrix} V_e(r) & 0 & 0 \\ 0 & 0 & \epsilon_{\mu\tau}^f V_f(r) \\ 0 & \epsilon_{\mu\tau}^f V_f(r) & \epsilon'_{\mu\tau} V_f(r) \end{pmatrix}. \quad (2)$$

containing both non-universal (NU) and flavour-changing (FC) interactions characterized by diagonal and off-diagonal entries in eq. (2).

Note that, as usual, the matter potentials for neutrinos and anti-neutrinos differ in sign. In contrast, we assume that the new interactions are CP conserving. As a result the epsilon values have the same sign for neutrinos and anti-neutrinos. In the most general case the non-standard interactions might violate CP and the resulting phases could therefore affect the evolution. We will not consider this more complicated case in the following discussion.

In addition to the five standard parameters (three angles and two mass splittings, if CP conservation is assumed) which describe the oscillation among three neutrinos there are, in the present scheme, also the  $\epsilon_{\alpha\beta}$  and  $\epsilon'_{\alpha\beta}$  parameters characterizing the NSI of the neutrinos. Of the three possible channels, we choose to analyze in detail here only the  $\nu_\mu - \nu_\tau$  transitions closely related to the atmospheric anomaly<sup>3</sup>. The others will be discussed elsewhere.

The relative importance of masses and NSI in the propagation of neutrinos is difficult to predict from basic principles and it is rather model-dependent. From a phenomenological point of view, however, atmospheric data imply that NSI can only play a sub-leading role [20] in  $\nu_\mu - \nu_\tau$  transitions.

---

<sup>3</sup> For this reason we have neglected the  $\epsilon_{\alpha\beta}$  and  $\epsilon'_{\alpha\beta}$  involving the first generation in Eq. (2)

In order to gain some insight in the interplay between oscillation and NSI it is useful to reduce the problem to a two neutrino case by taking the limit  $\Delta m_{12}^2 \rightarrow 0$ . In this case the rotation in the 12-subspace also drops out, and therefore also the CP-phase becomes irrelevant [10]. This approximation is quite accurate for the  $\nu_\mu - \nu_\tau$  transition at the energies and baselines considered for a neutrino factory experiment. In this limit only five parameters remain: three OSC parameters  $\theta_{23}$ ,  $\theta_{13}$  and  $\Delta m_{31}^2$  and our two NSI parameters  $\epsilon_{\mu\tau}$  and  $\epsilon'_{\mu\tau}$ . Neglecting  $\theta_{13}$  the transition probability is given by [29]:

$$P(\nu_\mu \rightarrow \nu_\tau) = \frac{B^2}{B^2 + C^2} \sin^2 \left( \frac{L}{2} \sqrt{B^2 + C^2} \right), \quad (3)$$

$$\Delta_{13} = \frac{\Delta m_{31}^2}{2E},$$

$$B = \Delta_{13} \sin 2\theta_{23} + 2\epsilon_{\mu\tau} V_f, \quad (4)$$

$$C = \Delta_{13} \cos 2\theta_{23} + \epsilon'_{\mu\tau} V_f. \quad (5)$$

### 3 Simulating neutrino factory long baseline experiments

In testing the effect of non-standard interactions in the  $\nu_\mu - \nu_\tau$  transition it is essential to have a detector which is able to identify  $\nu_\tau$  events with a high efficiency. We are fully aware that this is a very difficult goal to achieve in the design of a large detector ( $m \simeq 10$  kt). However, this work is partially intended to show the benefits of such a detector in probing physics beyond the standard model. We will assume a detector with a mass of 10 kt which is able to detect and identify  $\nu_\tau$  interactions above a threshold of 4 GeV with a constant efficiency of  $\eta = 0.33$ . Basically there are the following observables:

$$\mu^- \rightarrow \begin{cases} \bar{\nu}_e \rightarrow \bar{\nu}_\tau & n^-(\bar{\nu}_\tau) \\ \nu_\mu \rightarrow \nu_\tau & n^-(\nu_\tau) \end{cases}, \quad \mu^+ \rightarrow \begin{cases} \nu_e \rightarrow \nu_\tau & n^+(\nu_\tau) \\ \bar{\nu}_\mu \rightarrow \bar{\nu}_\tau & n^+(\bar{\nu}_\tau) \end{cases}. \quad (6)$$

As will be clear in section 4 the ability to identify the charge of the tau is *not* necessary for this particular transition and therefore not assumed. This leaves us with only two observables:

$$n^- := n^-(\bar{\nu}_\tau) + n^-(\nu_\tau), \quad n^+ := n^+(\nu_\tau) + n^+(\bar{\nu}_\tau). \quad (7)$$

where  $n^-$  and  $n^+$  denote the event numbers arising from the neutrino factory operating in the two polarities.

In calculating the event rate spectra in a neutrino factory experiment and for the treatment of the matter profile we follow the description given in ref. [43]. For the  $\nu_\tau$  appearance channel we use the cross-section given in [44], the  $\bar{\nu}_\tau$  cross-section is assumed to be one half of this. We will show that neglecting the tau mass [29] is not a good approximation especially for neutrino energies below 20 GeV. We also take the energy resolution of the detector into account by modeling it as a Gaussian, as described in ref. [45]. The neutrino factory delivers  $2 \cdot 10^{20}$  useful muon decays of each polarity per year for a period of 5 years. The energy of the neutrino factory is indicated in each figure since it plays a crucial role in probing non-standard interactions.

We now describe the Statistical Method we employ. In order to estimate the sensitivity to new physics we adopt the following definition of  $\chi^2$  [45]

$$\chi^2 = 2 \left( n^+ - n_{\text{OSC}}^+ \right) + 2n_{\text{OSC}}^+ \ln \frac{n_{\text{OSC}}^+}{n^+} + 2 \left( n^- - n_{\text{OSC}}^- \right) + 2n_{\text{OSC}}^- \ln \frac{n_{\text{OSC}}^-}{n^-}. \quad (8)$$



where  $n_{\text{OSC}}^{\pm}$  stands for the event rates which are expected in the absence of NSI. This is readily obtained by leaving all parameters as in the calculation of  $n^{\pm}$  except that  $\epsilon_{\mu\tau}$  and  $\epsilon'_{\mu\tau}$  are set to zero. Thus  $\chi^2$  has two degrees of freedom, therefore a value of 9.2 corresponds to 99% CL. Considering only total rates, the sum over the energy bins is performed before  $\chi^2$  is calculated, whilst for an energy spectrum this sum is performed after calculating  $\chi^2$  for each bin.

The above  $\chi^2$  is suitable to investigate the possible sensitivity to the new effects arising from non-standard interactions. In order to get reliable sensitivity limits it would be necessary in general to take into account possible parameter correlations and to evaluate the  $\nu_{\tau}$ -appearance together with  $\nu_{\mu}$ -disappearance and  $\nu_{\mu}$ -appearance. However for the  $\nu_{\mu} - \nu_{\tau}$  transition this complication is less relevant to the extent the relevant parameters  $\sin^2 2\theta_{23}$  and  $\Delta m_{31}^2$  that could be correlated with the NSI parameters are already well determined by present atmospheric data. As a consequence our results are basically unaffected by taking into account these correlations. We have in fact verified this by an explicit statistical analysis similar to that in ref. [45]. The situation would be different for the  $\nu_e - \nu_{\tau}$  transition since this mode is controlled by  $\sin^2 2\theta_{13}$  which is subject to much higher uncertainties. For this reason this mode will be discussed elsewhere [46].

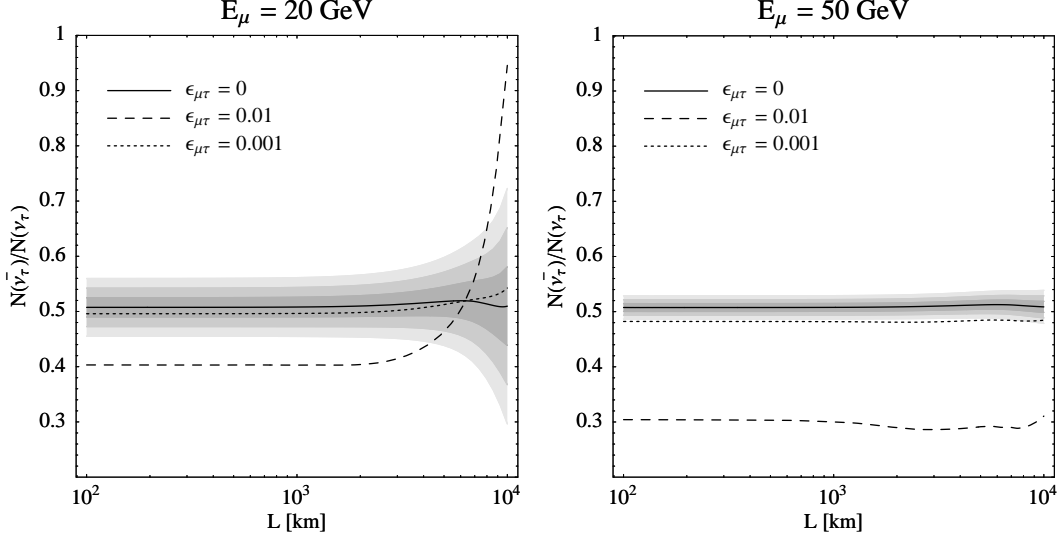
## 4 Results

In order to highlight the effect of the non-standard interactions, we show in figure 1 the change in the ratio of  $\bar{\nu}_{\tau}$  events (which arise from  $\bar{\nu}_{\mu}$ ) to  $\nu_{\tau}$  events (which arise from  $\nu_{\mu}$ ) for different values of the FC parameter  $\epsilon_{\mu\tau}$ . If no NSI interactions are present this ratio is basically constant 0.5 (black solid lines)

since this transition is only very weakly influenced by ordinary matter effects due coherent forward scattering off the electrons [15]. The value of 0.5 simply reflects the ratio of the cross-section for  $\bar{\nu}$  and  $\nu$ . The grey shaded bands show the Gaussian  $1\sigma$ ,  $2\sigma$  and  $3\sigma$  errors on the standard ratio in the absence of NSI neutrino interactions. The dashed lines indicate the deviation from this for different values of the FC parameter  $\epsilon_{\mu\tau}$ . One sees that for  $\epsilon_{\mu\tau}$  at the per cent level the difference is rather significant as long as the baseline is shorter than about 7000 km. For the left hand panel with an muon energy of 20 GeV these errors increase drastically with the baseline. This is due to the geometrical  $L^{-2}$  loss of flux at large distances. Comparing the two panels one can easily see the importance of high energies in order to obtain optimal sensitivity to the new physics. We have fixed the OSC parameters as follows:  $\sin^2 2\theta_{12} = 0.78$  and  $\Delta m_{21}^2 = 3.3 \cdot 10^{-5} \text{ eV}^2$  (suitable to account for the LMA solution of the solar neutrino anomaly),  $\sin^2 2\theta_{23} = 0.97$  and  $\Delta m_{31}^2 = 3.1 \cdot 10^{-3} \text{ eV}^2$  (suitable to account for the atmospheric anomaly) and  $\sin^2 2\theta_{13} = 0.02$  in agreement with reactor results. Finally we have assumed CP conservation,  $\delta_{CP} = 0$  and also exact universality,  $\epsilon'_{\mu\tau} = 0$ . The measurement of this ratio would require charge identification of the tau. It is shown here only for illustrative purposes.

Note that the ratio in Fig. 1 contains only one part of the information contained in the event rates. For this reason we will use the  $\chi^2$  as defined in equation 8 in order to calculate the sensitivity bounds to non-standard interactions.

Before we do that let us highlight the important role played by present atmospheric data by presenting Fig. 2. For the coming plots we use a baseline of 732 km and a muon energy of 50 GeV. All other parameters are kept fixed as previously to:  $\sin^2 2\theta_{13} = 0.02$ ,  $\sin^2 2\theta_{12} = 0.78$ ,  $\delta_{CP} = 0$ ,  $\Delta m_{31}^2 =$

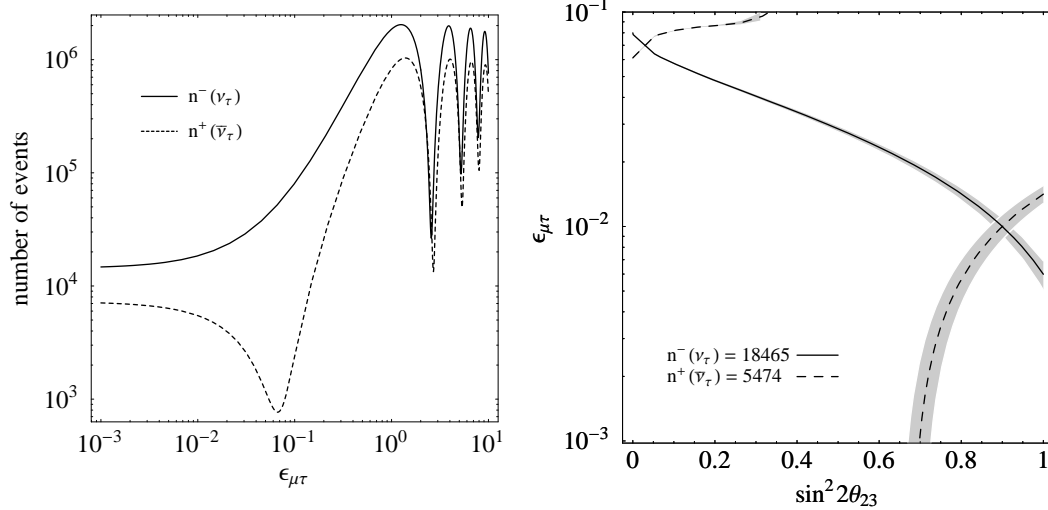


**Figure 1.** These figures show the ratio of observed  $\bar{\nu}_\tau$  events from  $\bar{\nu}_\mu$  to the observed  $\nu_\tau$  events from  $\nu_\mu$  as a function of the baseline. The grey shaded bands indicate the Gaussian  $1\sigma$ ,  $2\sigma$  and  $3\sigma$  statistical error on this ratio. The black solid line indicates the OSC prediction whereas the dashed lines indicate the deviation from this for different values of the FC parameter  $\epsilon_{\mu\tau}$ . The other parameters are  $\sin^2 2\theta_{12} = 0.78$ ,  $\Delta m_{21}^2 = 3.3 \cdot 10^{-5} \text{ eV}^2$ ,  $\sin^2 2\theta_{23} = 0.97$ ,  $\Delta m_{31}^2 = 3.1 \cdot 10^{-3} \text{ eV}^2$ ,  $\sin^2 2\theta_{13} = 0.02$ ,  $\delta_{CP} = 0$  and  $\epsilon'_{\mu\tau} = 0$ .

$3.1 \cdot 10^{-3} \text{ eV}^2$ ,  $\Delta m_{21}^2 = 3.3 \cdot 10^{-5} \text{ eV}^2$  and  $\epsilon'_{\mu\tau} = 0$ . In the left hand panel the dependence of the event rates for the  $\nu_\mu - \nu_\tau$  transition (solid line) and for the  $\bar{\nu}_\mu - \bar{\nu}_\tau$  transition (dashed line) on the FC parameter  $\epsilon_{\mu\tau}$  is shown for a fixed value of  $\sin^2 2\theta_{23} = 0.9$ . For very small  $\epsilon_{\mu\tau}$  values the event rates in both channels are nearly independent of  $\epsilon_{\mu\tau}$  and their ratio simply reflects the ratio of the cross sections. For increasing values of  $\epsilon_{\mu\tau}$  we now see that neutrinos and anti-neutrinos behave in a opposite way. This due to the fact that  $V_f$  has a different sign for neutrinos and anti-neutrinos. This behavior is also what would be expected from a linearized version of eq. 3 as given in ref. [29]. At  $\epsilon_{\mu\tau} \simeq 0.01$  however this simple picture breaks down, the non-linearities of eq. 3 become very important. Note that the transition probability only depends on  $B^2$ . If the two terms contributing to  $B$  become of the same order of magnitude, i.e.  $\Delta_{13} \sin 2\theta_{23} \simeq 2\epsilon_{\mu\tau} V_f$  then the difference between the sum of the two and their difference becomes maximal. Therefore the ratio of the anti-

neutrino rates to the neutrino rates becomes minimal. Increasing  $\epsilon_{\mu\tau}$  further makes the difference between neutrinos and anti-neutrinos smaller again. For large values of  $\epsilon_{\mu\tau}$  the oscillation term  $\Delta_{13} \sin 2\theta_{23}$  becomes negligible and  $\epsilon_{\mu\tau}$  plays both the role of a mixing angle and provides the leading contribution to the mass splitting. This leads to a strong oscillating behavior in the event rates and also in the ratio, since there are slightly shifted zeroes of the oscillation term  $\sin^2(L/2\sqrt{B^2 + C^2})$ . Thus there are in principle many degenerate points in this case as can be seen from the right hand panel. Here lines of constant event rates for the  $\nu_\mu - \nu_\tau$  transition (solid line) and for the  $\bar{\nu}_\mu - \bar{\nu}_\tau$  transition (dashed line) in the  $\sin^2 2\theta_{23} - \epsilon_{\mu\tau}$  plane are shown. There are two points where the dashed and solid lines cross. These points have exactly the same physical observables and are therefore not distinguishable in an experiment which uses only the total event rates. However the point in the upper left corner can be excluded by using the information of atmospheric neutrinos that  $\sin^2 2\theta_{23} > 0.8$  and  $\epsilon_{\mu\tau} < 0.02$  [20]. There are also many more possible solutions for  $\epsilon_{\mu\tau}$  values larger than 0.1. In order to improve the knowledge on  $\epsilon_{\mu\tau}$  it is therefore necessary to include atmospheric data.

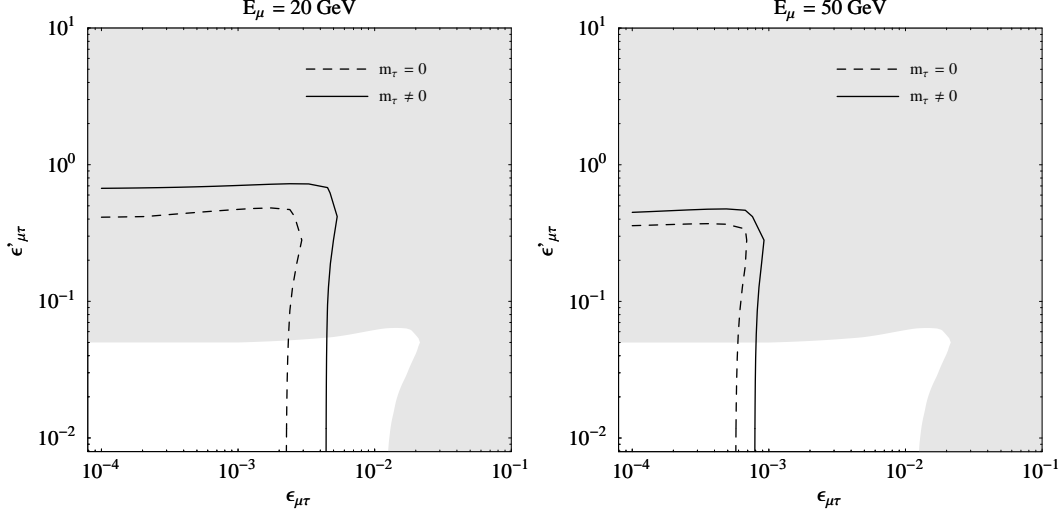
We now come to our final results. In figures 3 and 4 we present our calculated Nufact sensitivities to non-standard neutrino interactions shown as black solid lines for three different muon energies 20 GeV, 50 GeV, 100 GeV and 150 GeV. The baseline has been chosen as 732 km. The dashed lines show the bounds which would be obtained by neglecting the tau mass threshold [29] in the cross-section. It is clearly visible that especially for low energies this is not a good approximation, since for example at 20 GeV one loses about 80 % of the events. For comparison we also indicate with the grey shaded area the region presently excluded by the latest atmospheric data. These bounds are taken from [20]. The parameters were fixed as in Fig. 1:  $\sin^2 2\theta_{23} = 0.97$ ,



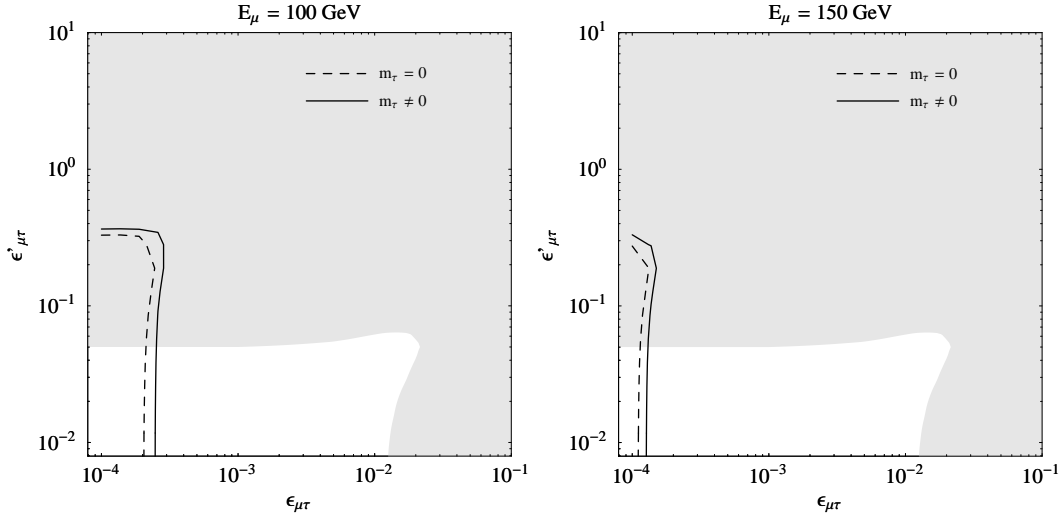
**Figure 2.** In the right hand panel lines of constant event rates of the  $\nu_\mu \rightarrow \nu_\tau$  transition (solid line) and of the  $\bar{\nu}_\mu \rightarrow \bar{\nu}_\tau$  transition (dashed lines) are shown in the  $\sin^2 2\theta_{23} - \epsilon_{\mu\tau}$  plane. The grey shaded band indicate the Gaussian  $3\sigma$  errors on these numbers. The left hand panel shows a section across the right hand figure at  $\sin^2 2\theta_{23} = 0.9$ . The baseline for both plots is 732 km and the muon energy is 50 GeV. All other parameters are kept fixed to:  $\sin^2 2\theta_{13} = 0.02$ ,  $\sin^2 2\theta_{12} = 0.78$ ,  $\delta_{CP} = 0$ ,  $\Delta m_{31}^2 = 3.1 \cdot 10^{-3} \text{ eV}^2$ ,  $\Delta m_{21}^2 = 3.3 \cdot 10^{-5} \text{ eV}^2$  and  $\epsilon'_{\mu\tau} = 0$ .

$\sin^2 2\theta_{13} = 0.02$ ,  $\sin^2 2\theta_{12} = 0.78$ ,  $\delta_{CP} = 0$ ,  $\Delta m_{31}^2 = 3.1 \cdot 10^{-3} \text{ eV}^2$ , and  $\Delta m_{21}^2 = 3.3 \cdot 10^{-5} \text{ eV}^2$ . One sees that the limits on the FC parameter  $\epsilon_{\mu\tau}$  can be improved by approximately two orders of magnitude by a high energy neutrino factory. For the low energy option (leftmost panel) the improvement in the sensitivity at a neutrino factory is very small compared to the present atmospheric bound. Note that the sensitivity on  $\epsilon'_{\mu\tau}$  attainable at a long baseline neutrino factory is worse than the present bounds by atmospheric data.

Note also that the above bounds *do not* require tau charge identification. This is possible because the  $\nu_e - \nu_\tau$  transition is suppressed by  $\sin^2 2\theta_{13}$  (restricted to be smaller than 0.1 by the Chooz experiment [36]) and ordinary matter effects do not come into play at the distance of 732 km considered here. In fact we have explicitly checked that our results are unchanged if the signs of the NSI parameters get reversed (in all possible combinations) with respect to what we have assumed. This approximation might break down at baselines longer



**Figure 3.** Here the sensitivity limits in the  $\epsilon_{\mu\tau}$ - $\epsilon'_{\mu\tau}$  plane of a neutrino factory compared to atmospheric neutrino data are shown for an energy resolution of 50%. For comparison we also indicate with the grey shaded area the region presently excluded by the latest atmospheric data, taken from [20]. All bounds are at 99% CL. The dashed line is obtained by neglecting the tau mass and is only shown for comparison. The black lines are calculated with the correct cross-section. All other parameters are kept fixed to: values suitable to account for the present neutrino anomalies. Details in text.



**Figure 4.** Same as in Fig. 3 but for higher Nufact energies.

than 1000 km or so.

## 5 Discussion and Conclusions

We have considered the potential of a long baseline neutrino factory in probing non-standard neutrino-matter interactions. We have found that the sensitivity to flavour-changing NSI can be substantially improved with respect to present atmospheric neutrino data, especially at energies higher than 50 GeV or so, where the effect of the tau mass is small. For example, a 100 GeV NUFACT can probe FC neutrino interactions at the level of few  $|\varepsilon| < \text{few} \times 10^{-4}$  at 99 % C.L. The analysis we have presented requires no tau charge identification and is based only on total event numbers, with a modest energy resolution at the 50 % level. In order to be useful for more refined studies a good detector energy resolution is required: for a 50% energy resolution the results are basically the same as those obtained when considering only total rates. It is doubtful whether a better resolution can be achieved in practice for the channel considered here because of hadronic tau decays. Finally note that the quality of the atmospheric data plays a crucial role in setting this limit by removing unwanted degeneracies in predicted event numbers. In contrast the sensitivity on  $\epsilon'_{\mu\tau}$  attainable at a long baseline neutrino factory is worse than the present bounds by atmospheric data. The role of a NUFACT in probing interactions is also complementary to efforts to probe for similar flavour-changing effects in the charged lepton sector and has the advantage of being totally model independent.

### Acknowledgments

We would like to thank Michele Maltoni and Hiroshi Nunokawa for very useful discussions. This work was supported by Spanish grant PB98-0693, by the

European Commission RTN network HPRN-CT-2000-00148, by the European Science Foundation network grant N. 86. PH was supported by a fellowship of the European Commission Research Training Site contract HPMT-2000-00124 of the host group.



## References

- [1] C. Quigg, Nucl. Instrum. Meth. A **451** (2000) 1.
- [2] C. Albright *et al.*, hep-ex/0008064.
- [3] B. Autin *et al.*, CERN-SPSC-98-30.
- [4] Y. Fukuda *et al.*, Super-Kamiokande Coll., Phys. Rev. Lett. **81** (1998) 1562; Phys. Rev. Lett. **82**, 2644 (1999).
- [5] Y. Fukuda *et al.*, Kamiokande Coll., Phys. Lett. B **335** (1994) 237; R. Becker-Szendy *et al.*, IMB Coll., Nucl. Phys. B (Proc. Suppl.) **38** (1995) 331; W.W.M. Allison *et al.*, Soudan Coll., Phys. Lett. B **449** (1999) 137; M. Ambrosio *et al.*, MACRO Coll., Phys. Lett. B **434** (1998) 451.
- [6] Super-Kamiokande presentations in winter conferences: C. McGrew in *Neutrino Telescopes 2001*, Venice, Italy, March 2001, to appear; T. Toshito in *Moriond 2001*, Les Arcs, France, March 2001, to appear; For a review see T. Kajita and Y. Totsuka, Rev. Mod. Phys. **73** (2001) 85.
- [7] M. Spurio *et al.*, MACRO Coll., hep-ex/0101019; B. Barish, MACRO Coll., Talk given at *Neutrino 2000*, 15–21 June 2000, Sudbury, Canada.
- [8] B.T. Cleveland *et al.*, Astrophys. J. **496** (1998) 505; K.S. Hirata *et al.*, Kamiokande Coll., Phys. Rev. Lett. **77** (1996) 1683; W. Hampel *et al.*, GALLEX Coll., Phys. Lett. B **447** (1999) 127; D.N. Abdurashitov *et al.*, SAGE Coll., Phys. Rev. Lett. **83** (1999) 4686; Phys. Rev. **C 60** (1999) 055801; V. Gavrin (SAGE Collaboration), Nucl. Phys. Proc. Suppl. **B 91** (2001) 36; M. Altmann *et al.* (GNO Collaboration), Phys. Lett. **B 490** (2000) 16; E. Bellotti *et al.* (GNO Collaboration), Nucl. Phys. Proc. Suppl. **B 91** (2001) 44; Y. Fukuda *et al.* (Super-Kamiokande Collaboration), Phys. Rev. Lett. **81** (1998) 1158; Erratum **81** (1998) 4279; Phys. Rev. Lett. **82** (1999) 1810; Y. Suzuki (Super-Kamiokande

- Collaboration), Nucl. Phys. Proc. Suppl. **B 91** (2001) 29; S. Fukuda *et al.* (Super-Kamiokande Collaboration), Phys. Rev. Lett. **86** (2001) 5651.
- [9] M. Gell-Mann, P. Ramond, R. Slansky in Supergravity, ed. by D. Freedman *et al.*, (North Holland, 1979), T. Yanagida, KEK lectures, ed. O. Sawada *et al.* (1979).
- [10] J. Schechter and J. W. F. Valle, Phys. Rev. D **22** (1980) 2227.
- [11] R Mohapatra, G Senjanovic, Phys. Rev. D **23** (1981) 165.
- [12] J. W. F. Valle, Prog. Part. Nucl. Phys. **26** (1991) 91.
- [13] M. C. Gonzalez-Garcia, M. Maltoni, C. Pena-Garay and J. W. F. Valle, Phys. Rev. D **63** (2001) 033005; G. L. Fogli, E. Lisi, A. Marrone, D. Montanino and A. Palazzo, Talk given at 36th Rencontres de Moriond on Electroweak Interactions and Unified Theories, Les Arcs, France, 10-17 Mar 2001.
- [14] J. W. F. Valle, Phys. Lett. B **199** (1987) 432.
- [15] L. Wolfenstein, Phys. Rev. D **17**, 2369 (1978); S.P. Mikheev and A.Yu. Smirnov, Sov. J. Nucl. Phys. **42**, 913 (1985).
- [16] M. Guzzo, A. Masiero and S. Petcov, Phys. Lett. **B260**, 154 (1991); E. Roulet, Phys. Rev. **D44**, 935 (1991); V. Barger, R. J. N. Phillips and K. Whisnant, Phys. Rev. **D44**, 1629 (1991); S. Bergmann, Nucl. Phys. **B515**, 363 (1998); E. Ma and P. Roy, Phys. Rev. Lett. **80**, 4637 (1998).
- [17] M. C. Gonzalez-Garcia *et al.*, Phys. Rev. Lett. **82** (1999) 3202.
- [18] N. Fornengo, M. C. Gonzalez-Garcia and J. W. F. Valle, JHEP **0007** (2000) 006.
- [19] P. Lipari and M. Lusignoli, Phys. Rev. D **60** (1999) 013003. G. L. Fogli, E. Lisi, A. Marrone and G. Scioscia, Phys. Rev. D **60** (1999) 053006.

- [20] N. Fornengo, M. Maltoni, R. Tomas and J. W. Valle, hep-ph/0108043, Phys. Rev. D, in press.
- [21] H. Nunokawa, Y. Z. Qian, A. Rossi and J. W. F. Valle, Phys. Rev. D **54** (1996) 4356.
- [22] D. Grasso, H. Nunokawa and J. W. F. Valle, Phys. Rev. Lett. **81** (1998) 2412.
- [23] S. Bergmann, M. M. Guzzo, P. C. de Holanda, P. I. Krastev and H. Nunokawa, Phys. Rev. D **62** (2000) 073001.
- [24] L. J. Hall, V. A. Kostelecky and S. Raby, Nucl. Phys. **B267** 415 (1986).
- [25] R. Barbieri, L. Hall and A. Strumia, Nucl. Phys. B **445**, 219 (1995).
- [26] L.J. Hall and M. Suzuki, Nucl. Phys. **B231** (1984) 419; G.G. Ross and J.W. F. Valle, Phys. Lett. **151B** (1985) 375; J. Ellis, G. Gelmini, C. Jarlskog, G.G. Ross and J.W. F. Valle, Phys. Lett. **150B** (1985) 142.
- [27] M. Fukugita and T. Yanagida, Phys. Lett. B **206** (1988) 93.
- [28] S. Geer, Phys. Rev. D **57** (1998) 6989 [Erratum-ibid. D **59** (1998) 039903].
- [29] A. M. Gago, M. M. Guzzo, H. Nunokawa, W. J. Teves and R. Zukanovich Funchal, Phys. Rev. D **64** (2001) 073003.
- [30] L. M. Johnson and D. W. McKay, Phys. Rev. D **61** (2000) 113007; A. Datta, R. Gandhi, B. Mukhopadhyaya and P. Mehta, Phys. Rev. D **64** (2001) 015011; M. C. Gonzalez-Garcia, Y. Grossman, A. Gusso and Y. Nir, Phys. Rev. D **64** (2001) 096006.
- [31] J. Schechter and J. W. F. Valle, Phys. Rev. D **23** (1981) 1666.
- [32] A. Zee, Phys. Lett. B **93**, 389 (1980) [Erratum-ibid. B **95**, 461 (1980)].
- [33] K. S. Babu, Phys. Lett. B **203** (1988) 132.
- [34] M. Hirsch and J. W. Valle, Phys. Lett. B **495** (2000) 121.

- [35] M. Maltoni, T. Schwetz and J. W. Valle, Phys. Lett. B **518** (2001) 252; M.C. Gonzalez-Garcia, M. Maltoni and C. Peña-Garay, hep-ph/0108073.
- [36] M. Apollonio *et al.* [CHOOZ Collaboration], Phys. Lett. B **466** (1999) 415.
- [37] Q. R. Ahmad *et al.* [SNO Collaboration], Phys. Rev. Lett. **87** (2001) 071301.
- [38] V. Barger *et al.*, hep-ph/0106207; G. L. Fogli, E. Lisi, D. Montanino and A. Palazzo, Phys. Rev. D **64** (2001) 093007; J.N. Bahcall *et al.*, JHEP **0108** (2001) 014; A. Bandyopadhyay *et al.*, Phys. Lett. B **519** (2001) 83; P. Creminelli *et al.*, JHEP **0105** (2001) 052.
- [39] M. C. Gonzalez-Garcia, P. C. de Holanda, C. Pena-Garay and J. W. F. Valle, Nucl. Phys. B **573** (2000) 3.
- [40] M. Kachelrieß, A. Strumia, R. Tomàs and J.W.F. Valle, hep-ph/0108100.
- [41] R. Mohapatra, J. W. F. Valle, Phys. Rev. D **34**, 1642 (1986); D. Wyler and L. Wolfenstein, Nucl. Phys. B **218**, 205 (1983).
- [42] J. Bernabeu, A. Santamaria, J. Vidal, A. Mendez and J. W. F. Valle, Phys. Lett. B **187** (1987) 303. M. Dittmar *et al* Nucl. Phys. B **332**, 1 (1990). N. Rius and J. W. F. Valle, Phys. Lett. B **246** (1990) 249. M. C. Gonzalez-Garcia and J. W. F. Valle, Mod. Phys. Lett. A **7** (1992) 477. A. Ilakovac, Phys. Rev. D **62** (2000) 036010.
- [43] M. Freund, P. Huber, M. Lindner, Nucl. Phys. B **585** (2000) 105.
- [44] E. A. Paschos and J. Y. Yu, hep-ph/0107261.
- [45] M. Freund, P. Huber and M. Lindner, Nucl. Phys. B **615** (2001) 331.
- [46] P. Huber *et al.*, in preparation.