

# Status of a hybrid three-neutrino interpretation of neutrino data

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## Abstract

We re-analyse the non-standard interaction (NSI) solutions to the solar neutrino problem in the light of the latest solar as well as atmospheric neutrino data. The latter require oscillations (OSC), while the former do not. Within such a three-neutrino framework the solar and atmospheric neutrino sectors are connected not only by the neutrino mixing angle  $\vartheta_{13}$  constrained by reactor and atmospheric data, but also by the flavour-changing (FC) and non-universal (NU) parameters accounting for the solar data. Since the NSI solution is energy-independent the spectrum is undistorted, so that the global analysis observables are the solar neutrino rates in all experiments as well as the Super-Kamiokande day-night measurements. We find that the NSI description of solar data is slightly better than that of the OSC solution and that the allowed NSI regions are determined mainly by the rate analysis. By using a few simplified *ansätze* for the NSI interactions we explicitly demonstrate that the NSI values indicated by the solar data analysis are fully acceptable also for the atmospheric data.

In the appendix we present an updated analysis combining the latest data from all solar neutrino experiments with the first results from KamLAND. We show that, although NSI still gives an excellent description of the solar data, the inclusion of KamLAND excludes at more than  $3\sigma$  the NSI hypothesis as a solution to the solar neutrino problem.

*Key words:* neutrino oscillations, solar and atmospheric neutrinos, neutrino mass and mixing, non-standard neutrino interactions

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## 1 Introduction

The wealth of data from solar [1,2] and atmospheric neutrinos [3,4,5,6] has put neutrino physics in the spotlight and physicists are asking what is it that makes solar and atmospheric neutrinos convert. The most popular possibility is that of neutrino oscillations, expected in most theories of neutrino mass [7]. Indeed an excellent joint description of solar and atmospheric data is obtained in this case [8,9]. However, more often than not, models of neutrino masses are accompanied by non-standard interactions (NSI) of neutrinos [10]. These can have non-universal (NU) or flavour-changing (FC) components, which typically co-exist. The simplest NSI does not involve additional interactions beyond those mediated by the Standard Model electroweak gauge bosons: it is simply the nature of the leptonic charged and neutral current interactions which is non-standard because of the complexity of neutrino mixing [7]. On the other hand NSI can also be mediated by the exchange of new particles with mass at the weak scale such as in some supersymmetric models with R-parity-violating [11,12] interactions. Such non-standard flavour-violating physics can arise even in the absence of neutrino mass [13,14].

Such varieties of non-standard interactions of neutrinos affect their propagation in matter [15]. The magnitude of the effect depends on the interplay between conventional mass-induced neutrino oscillation features in matter and those genuinely engendered by the NSI, which do not require neutrino mass [16,17]. These may have a variety of phenomenological implications [17,18] and have been considered in the context of atmospheric [19,20], as well as astrophysical neutrino sources [21]. The impact of non-standard

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interactions of neutrinos has also been considered from the point of view of future experiments involving solar neutrinos [22] as well as the upcoming neutrino factories [23,24].

In this paper we re-consider the case of NSI solutions to the solar neutrino problem [25] taking into account the recent charged current measurement at the Sudbury Neutrino Observatory (SNO) [2], the 1258-day Super-Kamiokande (SK) data and the previous solar neutrino data [1]. In contrast to previous work we consider a three-neutrino NSI analysis and study also the dependence of the solar neutrino NSI solution on the neutrino mixing angle  $\vartheta_{13}$  whose value is presently constrained mainly by the reactor neutrino data [26]. Due to its energy-independent nature, the NSI solution is in excellent agreement with the flat spectral energy distribution observed in the Super-Kamiokande experiment. Thus we focus first on the determination of the allowed solutions by considering only the total rates of the solar neutrino experiments. We find that these solutions provide excellent descriptions of the solar rates, including the recent SNO charged current (CC) result. Then we study the impact of the day-night data from Super-Kamiokande measurements and show that the NSI solutions are consistent with the non-observation of day-night variations. Finally, and more important, using simplified *ansätze* for the NSI interactions we analyse the impact of the NSI description of solar data on the atmospheric data, showing how they are fully acceptable also for the latter.

This paper is organized as follows. In section 2 we discuss the neutrino evolution and conversion probabilities in the presence of NSI, in section 3 we summarize the calculational and fit procedures we adopt. In section 4 we discuss the impact of the NSI solar solution on the atmospheric data analysis, and in section 5 we summarize our results.

## 2 Neutrino Evolution in the presence of NSI

The most general form of three-neutrino evolution Hamiltonian in the flavor base  $(\nu_e, \nu_\mu, \nu_\tau)$ , in the presence of NSI can be given as

$$\mathbf{H} = \frac{1}{2E} \mathbf{R} \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & \Delta m_{32}^2 \end{pmatrix} \mathbf{R}^\dagger + \sqrt{2} G_F N_e(\vec{r}) \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} + \sqrt{2} G_F N_f(\vec{r}) \begin{pmatrix} 0 & \varepsilon_{12} & \varepsilon_{13} \\ \varepsilon_{12} & \varepsilon_{22} & \varepsilon_{23} \\ \varepsilon_{13} & \varepsilon_{23} & \varepsilon_{33} \end{pmatrix}; \quad (1)$$

where  $E$  is the energy,  $G_F$  Fermi's constant,  $\Delta m_{32}^2 \equiv m_3^2 - m_2^2 \equiv \Delta m_{\text{atm}}^2$  and  $N_e(\vec{r})$  is the number density of electrons along the neutrino trajectory. In our calculations of the  $\nu_e$  survival probability we use the electron and neutron number densities in the Sun from the SSM [27], while for the Earth matter effects we use the density profile given in the Preliminary Reference Earth Model (PREM) [28].

In Eq. (1)  $\varepsilon_{ij}$  parametrize the deviation from standard neutrino interactions. For example  $\sqrt{2} G_F N_f(\vec{r}) \varepsilon_{1\ell}$  is the forward scattering amplitude of the FC process  $\nu_e + f \rightarrow \nu_\ell + f$ , while  $\sqrt{2} G_F N_f(\vec{r}) \varepsilon_{\ell\ell}$  represents the difference between the non-standard component of the  $\nu_e + f$  and the  $\nu_\ell + f$  elastic forward scattering amplitudes. The quantity  $N_f(\vec{r})$  is the number density of the fermion  $f$  along the path  $\vec{r}$  of the neutrinos propagating in the Sun or the Earth. We consider two cases, depending on the NSI model, in which the neutrino interaction occurs with down-type or up-type quarks. For the case of non-standard interactions on electrons [22] one would have also to take into account the effect of the NSI also in the neutrino detection cross section.

Note that for simplicity we have set the mass splitting  $\Delta m_{21}^2$  of the first two neutrinos to zero, so that the corresponding mixing angle  $\vartheta_{12}$  can be eliminated. This is justified as we are mainly interested in isolating the effect of the NSI in the description of solar neutrino data. In contrast we assume the most general NSI flavour structure, consistent with CP conservation. Under

these assumptions, we have [29]:

$$\mathbf{R} = \begin{pmatrix} c_{13} & 0 & s_{13} \\ -s_{23}s_{13} & c_{23} & s_{23}c_{13} \\ -s_{13}c_{23} & -s_{23} & c_{23}c_{13} \end{pmatrix}, \quad (2)$$

where we used the notation  $c_{ij} \equiv \cos \vartheta_{ij}$  and  $s_{ij} \equiv \sin \vartheta_{ij}$ . Similarly to the usual oscillation case [30] the  $\nu_e$  survival probability  $P_{ee}$  can be written as

$$P_{ee} = c_{13}^4 P_{ee}^{\text{eff}} + s_{13}^4, \quad (3)$$

where  $P_{ee}^{\text{eff}}$  is the electron survival probability in an effective  $2 \times 2$  model described by the Hamiltonian

$$\mathbf{H}^{\text{eff}} \equiv [\mathbf{R}^\dagger \mathbf{V} \mathbf{R}]_{2 \times 2} = \sqrt{2} G_F N_e(\vec{r}) \begin{pmatrix} c_{13}^2 & 0 \\ 0 & 0 \end{pmatrix} + \sqrt{2} G_F N_f(\vec{r}) \begin{pmatrix} 0 & \varepsilon_{\text{eff}} \\ \varepsilon_{\text{eff}} & \varepsilon'_{\text{eff}} \end{pmatrix} \quad (4)$$

with the effective  $\varepsilon_{\text{eff}}$  and  $\varepsilon'_{\text{eff}}$  given in terms of the original  $\varepsilon_{ij}$  parameters as

$$\varepsilon_{\text{eff}} = c_{13}(\varepsilon_{12}c_{23} - \varepsilon_{13}s_{23}) - s_{13}[\varepsilon_{23}(c_{23}^2 - s_{23}^2) + (\varepsilon_{22} - \varepsilon_{33})c_{23}s_{23}], \quad (5)$$

$$\begin{aligned} \varepsilon'_{\text{eff}} = & \varepsilon_{22}c_{23}^2 - 2\varepsilon_{23}c_{23}s_{23} + \varepsilon_{33}s_{23}^2 + 2s_{13}c_{13}(\varepsilon_{13}c_{23} + \varepsilon_{12}s_{23}) \\ & - s_{13}^2(\varepsilon_{33}c_{23}^2 + \varepsilon_{22}s_{23}^2 + 2\varepsilon_{23}s_{23}c_{23}). \end{aligned} \quad (6)$$

Note that even though we have assumed the most general NSI flavour structure, the final propagation of solar neutrinos can be described effectively as a two-dimensional evolution Hamiltonian depending only on the mixing angle  $\vartheta_{13}$  and on two effective NSI parameters  $(\varepsilon_{\text{eff}}, \varepsilon'_{\text{eff}})$ .

### 3 Analysis Method

In our description of the solar neutrino data [1] we adopt the same analysis techniques already described in Refs. [8,31,32] using the latest theoretical standard solar model (SSM) best-fit fluxes and estimated uncertainties [27]. For the neutrino conversion probabilities we use the results calculated numerically as indicated above.

Since the parameter space is three-dimensional, the allowed regions for a given C.L. are defined as the set of points satisfying the condition

$$\chi_{\text{sol}}^2(\varepsilon_{\text{eff}}, \varepsilon'_{\text{eff}}, \vartheta_{13}) - \chi_{\text{sol},\text{min}}^2 \leq \Delta\chi^2(\text{C.L.}, 3 \text{ d.o.f.}), \quad (7)$$

In our numerical calculations we use the survival/conversion probabilities of solar electron neutrinos valid over a generous range of NSI parameters  $(\varepsilon_{\text{eff}}, \varepsilon'_{\text{eff}})$ . On the other hand, we use the relevant reaction cross sections and efficiencies for the all experiments employed in Ref. [8,31,32]. For the SNO case the CC cross section for deuterium was taken from [33].

For what concerns the fit of the total rates, we take into account the results of the Homestake, GALLEX/GNO, SAGE and Super-Kamiokande experiments, together with the latest SNO CC result. Thus we have 5 experimental data, which we fit in terms of the 3 parameters  $\varepsilon_{\text{eff}}, \varepsilon'_{\text{eff}}$  and  $\vartheta_{13}$ ; therefore, the total number of degrees of freedom is 2.

In addition to total rates, we also take into account the Super-Kamiokande “zenith angle spectrum” [1], which includes both the spectral information on the final lepton energy (8 bins) and the information on the zenith angle distribution which results from neutrino interactions inside the Earth (1-day and 6-night bins). This data sample contains a total of  $44 = 6 \times 7 + 2$  bins. Thus the number of degrees of freedom is 5 (rates) + 44 (zenith-spectrum) - 1 (free normalization) - 3 (fit parameters) = 45.

In Figs. 1 and 2 we present the allowed regions in the  $(\varepsilon_{\text{eff}}, \varepsilon'_{\text{eff}})$  parameter space for different values of  $\sin^2 \vartheta_{13}$ , assuming non-standard interactions of neutrinos with  $d$ -type (Fig. 1) and  $u$ -type (Fig. 2) quarks. The shaded areas refer to the 90%, 95%, 99% and 99.7% C.L. with 3 degrees of freedom, and the best fit point is indicated by a star. Let us now comment some of their features. The first thing to notice from Figs. 1 and 2 is that the amount of NU is large. Nevertheless this is allowed by experiment and therefore consistent. We note also that the NSI strength required in the case of interaction with  $u$ -type quarks is smaller than for the case of  $d$ -type quarks.

Notice also that  $\varepsilon_{\text{eff}}$  can only be large over a very narrow  $\varepsilon'_{\text{eff}}$  region close to 0.57, a fact which will be used shortly. More importantly, we note that the quality of the solar fit becomes progressively worse as  $\vartheta_{13}$  increases, in a way similar to what happens in a three-neutrino OSC scenario [8,34]. This indicates

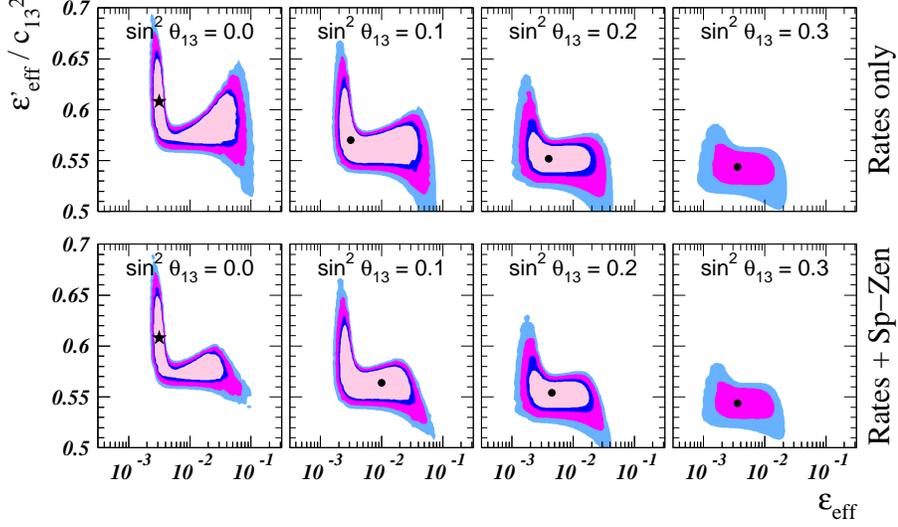


Figure 1. Allowed NSI regions indicated by the fit of the solar rates (upper panels) and global solar data (lower panels) for different values of  $\vartheta_{13}$ , assuming non-standard interactions of neutrinos with  $d$ -type quarks. The shaded areas refer to the 90%, 95%, 99% and 99.7% C.L. with 3 degrees of freedom. The best fit point is indicated by a star.

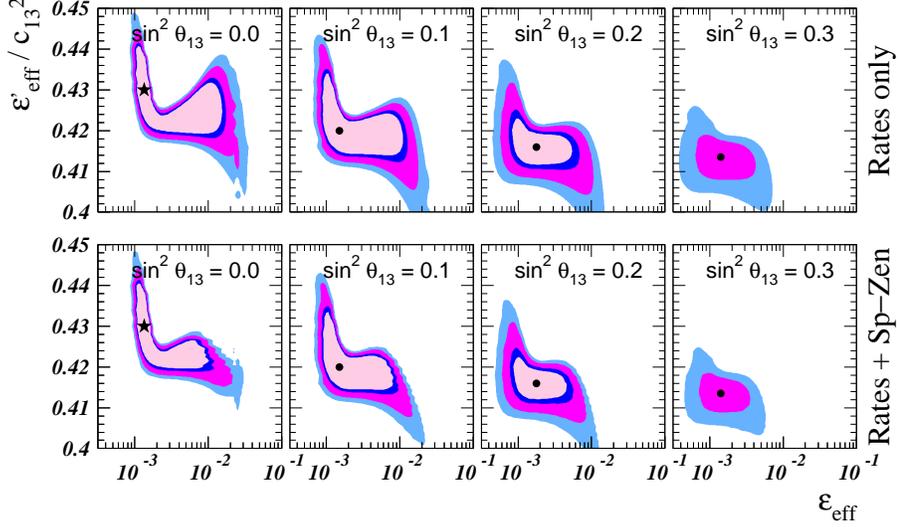


Figure 2. Same as Fig. 1 but for the case of non-standard interactions of neutrinos with  $u$ -type quarks.

that, although with less sensitivity,  $\vartheta_{13}$  can be constrained solely by solar data, irrespective of reactor data, also in the context of the NSI mechanism. In Fig. 3 we present the dependence of  $\Delta\chi^2$  as a function of  $\sin^2 \vartheta_{13}$ . The *solid* line refers to non-standard interactions of neutrinos with  $d$ -type quarks, and only the information from total rates is used, while for the *dashed* line also the spectrum-zenith distribution of Super-Kamiokande is included in the fit. The

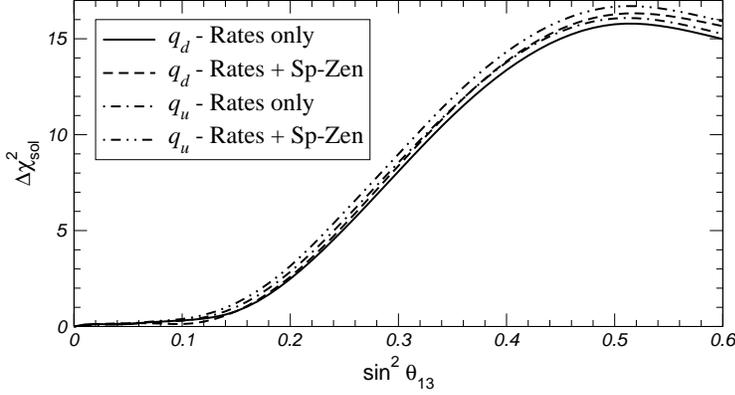


Figure 3. Dependence of  $\Delta\chi^2$  as a function of  $\sin^2 \vartheta_{13}$ , for different NSI solutions.

two *dotted-dashed* lines refer to non-standard interactions of neutrinos with  $u$ -type quarks, both with and without the spectrum-zenith information.

Finally in Table 1 we present the best-fit points and goodness-of-fit of oscillation and NSI solutions to the solar neutrino problem. Since the neutrino mixing angle  $\vartheta_{13}$  is strongly constrained by reactor neutrino data [26] we set, for definiteness,  $\vartheta_{13} = 0$  in what follows. This way we have only two degrees of freedom. The numbers in the table refer to a restricted analysis using only  $\Delta m_{21}^2$  and the neutrino mixing angle  $\vartheta_{12}$  for the pure OSC case and only  $\varepsilon_{\text{eff}}$  and  $\varepsilon'_{\text{eff}}$  for the pure NSI case. We see that the pure two-parameter NSI solution is somewhat better than the corresponding pure OSC solution.

Solution	$\Delta m_{21}^2$	$\tan^2(\vartheta_{12})$	$\varepsilon_{\text{eff}}$	$\varepsilon'_{\text{eff}}$	$\chi_{\text{min}}^2$	G.O.F.
LMA	$2.4 \times 10^{-5}$	0.31	0	0	2.2	53%
SMA	$7.8 \times 10^{-6}$	$1.6 \times 10^{-3}$	0	0	4.0	26%
NSI (d)	0	0	$3.2 \times 10^{-3}$	0.61	0.60	90%
NSI (u)	0	0	$1.3 \times 10^{-3}$	0.43	0.62	89%

Table 1

Best-fit points and goodness-of-fit of oscillation and NSI solutions to the solar neutrino problem, including only rates.

## 4 How about atmospheric neutrinos?

So far we have given a description of solar neutrino data in terms of NSI interactions. We now turn to the issue of atmospheric neutrinos. In principle one could imagine a pure NSI description of the atmospheric data itself [19]. However, it has recently been shown that, while it may fit the contained atmospheric data, such a description can not reconcile them with the up-going muon data. The sensitivity of the atmospheric data to the NSI follows mainly from the fact that the wide energy range of the atmospheric neutrino data sample, from the sub-GeV events up to the up-going samples of MACRO and Super-Kamiokande [4,3,5,6] is enough to manifest the energy-dependence characteristic of the atmospheric neutrino conversion mechanism. On this basis it has been shown how, taken altogether, the atmospheric data leave very little room for NSI and can tolerate the existence of NSI only at a sub-leading level [20].

The main question for us then is to evaluate whether the NSI description of solar neutrino data is in conflict with the atmospheric data sample. The danger lies in the fact that, in contrast to a pure oscillation description of the neutrino data [8], even when the value of the third neutrino mixing angle  $\vartheta_{13}$  (presently constrained mainly by the reactor neutrino data) is taken to zero, the solar and atmospheric sectors are still coupled with each other through the postulated NSI interactions whose strength is fixed, as described above, in order to account for the solar data.

A full description of the atmospheric and solar neutrino data in terms of a hybrid OSC+NSI description is, at the moment, prohibitive in view of the complexity of the problem. It suffices to remind the reader that we expect ten relevant independent parameters in this case: in addition to the five relevant CP conserving oscillation parameters of Ref. [8] (two mass splittings and three angles) there are five new NSI parameters characterizing the magnitude of FC and NU CP conserving non-standard interactions.

Thus we are forced to make a simplifying *ansatz*. For definiteness we consider

the two following choices of the NSI matrix:

$$(a) : \begin{pmatrix} 0 & \varepsilon_{12} & \varepsilon_{13} \\ \varepsilon_{12} & \varepsilon_{22} & \varepsilon_{23} \\ \varepsilon_{13} & \varepsilon_{23} & \varepsilon_{33} \end{pmatrix} = \begin{pmatrix} 0 & \varepsilon/\sqrt{2} & -\varepsilon/\sqrt{2} \\ \varepsilon/\sqrt{2} & \varepsilon' & 0 \\ -\varepsilon/\sqrt{2} & 0 & \varepsilon' \end{pmatrix} \quad (8)$$

and

$$(b) : \begin{pmatrix} 0 & \varepsilon_{12} & \varepsilon_{13} \\ \varepsilon_{12} & \varepsilon_{22} & \varepsilon_{23} \\ \varepsilon_{13} & \varepsilon_{23} & \varepsilon_{33} \end{pmatrix} = \begin{pmatrix} 0 & 0 & -\sqrt{2}\varepsilon \\ 0 & \varepsilon' & 0 \\ -\sqrt{2}\varepsilon & 0 & \varepsilon' \end{pmatrix}. \quad (9)$$

With each of these choices the five new NSI parameters are reduced to the two parameters involved in the description of the solar data, as explained previously in sections 2 and 3. In fact for both of these choices, once we set  $\vartheta_{13} = 0$  and  $\vartheta_{23} = 45^\circ$  (see below), we have simply  $\varepsilon_{\text{eff}} = \varepsilon$  and  $\varepsilon'_{\text{eff}} = \varepsilon'$ . For definiteness we focus here on the case of neutrino non-standard interactions with down-type quarks in Eq. (1).

As for the data here we use the totality of sub- and multi-GeV ( $e, \mu$ ) atmospheric neutrino data [3,4] as well as Super-Kamiokande stop and through-going muon data, and MACRO through-going muons [5,6].

In the lower panels of Fig. 4 we show the allowed region in the plane  $(\varepsilon, \Delta m_{32}^2)$  from the analysis of atmospheric neutrino data. The remaining undisplayed parameters are set to  $\vartheta_{13} = 0$  (indicated by a combination of reactor and atmospheric data [26]),  $\vartheta_{23} = 45^\circ$  (indicated by the standard atmospheric data analysis) and  $\varepsilon' = 0.57$  (indicated by the solar data analysis presented in sections 2 and 3). In the upper panels we show the dependence of  $\Delta\chi_{\text{atm}}^2$  as a function of  $\varepsilon$  when  $\Delta m_{32}^2$  is “integrated out”.

From Fig. 4 we see that in both cases the value of  $\Delta m_{32}^2$  is essentially unaffected by the inclusion of non-standard interaction in the  $\nu_\mu \rightarrow \nu_e$  and  $\nu_\tau \rightarrow \nu_e$  channels, up to values of 10 % or so. This is analogous to what was already found in Ref. [20] for the  $\nu_\mu \rightarrow \nu_\tau$  channel. We also note that in model (a) values of  $\varepsilon \approx 0.07$  are preferred, since in this case a small contribution of FC actually helps in improving the SK contained  $\nu_e$  data. This phenomenon is analogous to having a small but finite solar mass splitting  $\Delta m_{21}^2$ , see Ref. [35]. However, a value of  $\varepsilon = 0$  is clearly in agreement with the data, as expected

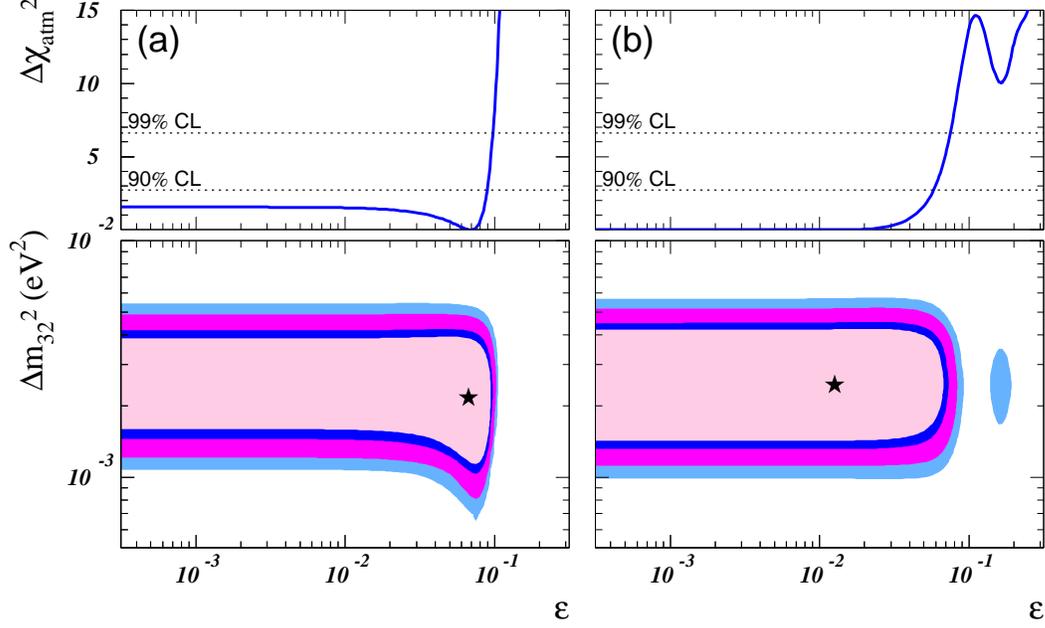


Figure 4. Allowed region (90%, 95%, 99%, 99.73% C.L. with 2 d.o.f.) in the plane  $(\epsilon, \Delta m_{32}^2)$  from the analysis of atmospheric neutrino data, for each of the two *ansätze* given in Eqs. (8) (left panels) and (9) (right panels). The best fit point is denoted as a star. We fix the undisplayed parameters to  $\vartheta_{13} = 0$ ,  $\vartheta_{23} = 45^\circ$  and  $\epsilon' = 0.57$ . The top panels show the behavior of  $\Delta\chi_{\text{atm}}^2$  as a function of  $\epsilon$  when  $\Delta m_{32}^2$  is integrated out.

by the excellent quality of the oscillation fit for the pure  $\nu_\mu \rightarrow \nu_\tau$  vacuum oscillations. We see that in both schemes the values of  $\epsilon$  allowed by the solar data analysis are fully acceptable also for the atmospheric data. However in model (a) there is a small tension between the solar best fit point ( $\epsilon = 0.003$ ) and the atmospheric data (which prefer, with  $\Delta\chi^2 = 1.6$ , a value  $\epsilon = 0.07$ ), so that some slight change in the shape of the solar allowed region might be expected when atmospheric data are also included. This effect does not appear in ansatz (b), for which any value of  $\epsilon$  below 0.03 is practically equivalent.

## 5 Conclusions

In this paper we have re-analysed the non-standard interaction solutions to the solar neutrino problem in the light of the recent SNO measurement as well as the 1258–day Super-Kamiokande data. In contrast to previous work we have used a three-neutrino interpretation of the solar data analysis, displaying how results depend on the neutrino mixing angle  $\vartheta_{13}$  which is constrained mainly

by the reactor neutrino data. More importantly, we have checked consistency of the NSI interpretation of solar data with the good agreement that the atmospheric data sample shows with the OSC interpretation. We have found that the status of such energy-independent solution to the solar neutrino problem is slightly better than that of the OSC solution. While these NSI solutions exist for reasonable values of the flavour-changing interaction strength  $\varepsilon_{\text{eff}}$  they require a somewhat large value of the non-universal parameters, suggesting that the solar conversion channel must involve  $\nu_\tau$ . We have also analysed the implications of the solar NSI solution for atmospheric neutrinos, generalizing the study in Ref. [20] so as to analyse the sensitivity of atmospheric data also to the NSI parameters involved in the solar neutrino channel. By using two simplified *ansätze* for the NSI interactions we have explicitly demonstrated that the values of  $\varepsilon$  allowed by the solar data analysis are fully acceptable also for the atmospheric data. This establishes that the NSI description of the solar neutrino data is not in conflict with the atmospheric data sample. For one of these models we noted the existence of a slight conflict between the solar best fit point ( $\varepsilon = 0.003$ ) and the atmospheric data (which prefer, with  $\Delta\chi^2 = 1.6$ , a value  $\varepsilon = 0.07$ ), which suggests that some slight change in the shape of the solar allowed region might be expected within a fully global description of both solar and atmospheric data. Our simplified *ansätze* are justified to the extent that the complexity of the analysis makes a full description close to impossible, and possibly un-illuminating. We find it significant, however, that the present understanding of solar and atmospheric neutrino data does not, as yet, require solar neutrino oscillations or solar neutrino mixing. This may have profound implications for model-building, especially in view of the difficulties in accommodating bi-large mixing-type solutions within the framework of unified theories. From an experimental point of view we find it worth pointing that the energy dependence characteristic of the oscillation mechanism has only been demonstrated for the case atmospheric, not solar neutrino conversions, as yet. One may argue that our NSI hypothesis is somewhat artificial. However one should bear in mind the fact that most models neutrino masses are accompanied by non-standard interactions of neutrinos and there are, in fact, some in which NSI are unaccompanied by neutrino mass effects. The soundness of hybrid schemes such as the ones indicated here may indicate more subtle new ways for accounting for the presently observed neutrino anomalies from first principles. We look forward to new solar neutrino experiments to probe neutrino NSI with improved sensitivities, such as suggested

in Ref. [22], as well as to the prospects of future neutrino factories performing correlated OSC-NSI studies, as suggested in [23,24].

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## Appendix: Implications of the KamLAND result.

The original version of the present paper showed that a pure NSI description of solar data with massless and unmixed neutrinos is slightly better than the favoured LMA-MSW solution. Moreover, the NSI values indicated by the solar data analysis do not spoil the successful oscillation description of the atmospheric data, establishing the overall consistency of a hybrid scheme in which only atmospheric data are explained in terms of neutrino oscillations. However, the recent results of the KamLAND collaboration [36] reject non-oscillation solutions in the solar sector under the assumption of CPT invariance, in such a way that solutions based on NSI should be strongly disfavoured by KamLAND results. In this appendix, we re-evaluate the status of NSI solutions of the solar neutrino problem, in the light of the first KamLAND data.

The KamLAND experiment is a reactor neutrino experiment whose detector is located at the Kamiokande site. Most of the  $\bar{\nu}_e$  flux incident at KamLAND comes from nuclear plants at distances 80-350 km from the detector, making the average baseline of about 180 km, long enough to provide a sensitive probe of the LMA-MSW region. The target for the  $\bar{\nu}_e$  flux consists of a spherical transparent balloon filled with 1000 tons of non-doped liquid scintillator, and the antineutrinos are detected via the inverse neutron  $\beta$ -decay process  $\bar{\nu}_e + p \rightarrow e^+ + n$ . The KamLAND collaboration has for the first time measured the disappearance of neutrinos produced in a power reactor. They observe

a strong evidence for the disappearance of neutrinos during their flight over such distances, giving the first terrestrial confirmation of the solar neutrino anomaly and also establishing the oscillation hypothesis with man-produced neutrinos.

In this appendix we perform a combined analysis of the solar neutrino data with the first KamLAND results in terms of neutrino non-standard interactions with matter, setting for definiteness  $\vartheta_{13} = 0$ . The analysis of solar neutrino data includes the most recent results from all experiments [37], as well as the latest measurements from SNO [38] presented in the form of 34 data bins (See Ref. [39] for a detailed explanation of the new solar analysis). The details of the theoretical Monte-Carlo and statistical analysis of the KamLAND results are given in Ref. [40]; in particular, the KamLAND  $\chi^2$ -function is calculated assuming a Poisson distribution of the experimental data, as described in Sec. IV of that paper.

In Table 2 we present the best-fit points for the oscillation and NSI solutions to the solar neutrino problem obtained in our analysis, together with its corresponding value of  $\chi^2$ . The value of  $\chi_{\text{sol}}^2$  confirms our previous result: NSI picture gives a good description of the solar neutrino data. In fact, for the case of neutrino NSI with  $up$  quarks we obtain a slightly better fit than for the LMA-MSW solution.

The inclusion of the latest solar data sample [37,38] does not change the status nor the allowed regions of the NSI solution in any significant way. In contrast, the inclusion of KamLAND data in the analysis changes dramatically the situation. Note that for the KamLAND experiment matter effects are very small, and can therefore safely be neglected. As a result, the NSI solutions predict no reduction in the  $\bar{\nu}_e$  flux, in conflict with what is observed at KamLAND. This worsens the status of the NSI hypothesis, (reflected in the corresponding  $\chi_{\text{sol+KL}}^2$  values, in Table 2) with respect to that of the LMA-MSW solution, which predicts the correct suppression factor observed at KamLAND. From our analysis we obtain that the description in terms of neutrino NSI with *down* quarks is rejected with a  $\Delta\chi^2 = 14.2$ , corresponding to  $3.8\sigma$ , with respect to LMA-MSW, while NSI of neutrinos with quarks of type  $up$  are rejected at  $3.6\sigma$  level ( $\Delta\chi^2 = 12.8$ ) as the explanation for the solar neutrino anomaly plus the KamLAND disappearance of neutrinos.

Solution	$\Delta m_{21}^2$	$\tan^2(\vartheta_{12})$	$\varepsilon_{\text{eff}}$	$\varepsilon'_{\text{eff}}$	$\chi_{\text{sol}}^2$	$\chi_{\text{sol+KL}}^2$
LMA-MSW	$7.2 \times 10^{-5}$	0.46	0	0	65.8	71.9
NSI (d)	0	0	$3.2 \times 10^{-3}$	0.62	66.9	86.1
NSI (u)	0	0	$1.3 \times 10^{-3}$	0.44	65.5	84.7

Table 2

Best-fit points of oscillation and NSI solutions to the solar neutrino problem before and after the inclusion of the KamLAND data in the analysis

In summary, we have shown that the inclusion of KamLAND data in the analysis of the solar neutrino anomaly excludes the interpretation based on neutrino non-standard interactions with matter at more than  $3\sigma$ . Therefore, non-standard interactions may at best play a sub-leading role in solar neutrino propagation. In fact, one may use the confirmation of the LMA-MSW oscillation solution together with the experimental data from KamLAND and solar neutrino experiments in order to determine improved restrictions on NSI parameters.

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