Abstract

We discuss ways to explore non-standard interactions (NSI) which neutrinos may possess by expressing them as effective four Fermi operators with coefficients of the order of $M_N = M_{NP}^2 \times 10^{-2}(10^{-4})$ for energy scales of new physics as $M_{NP} \sim 1(10)$ TeV. Neutrino Factory is a prime candidate for such apparatus that can reach the extreme precision. I describe a two detector setting, one at baseline $L = 3000$ km and the other at $L = 7000$ km, which is able to solve the notorious $\nu_3$ NSI confusion, and possibly also the two-phase confusion. The resultant sensitivities to off-diagonal NSI elements $\xi_{e\mu}$ are excellent, $\xi_{e\mu} \sim 10^{-3}$ and $\xi_{\mu\tau} \sim 10^{-4}$. Our results suggest a new picture of neutrino factory as a hunting machine for NSI while keeping its potential of precision measurement of lepton mixing parameters. Sensitivities to NSI by T2KK and the related settings are also discussed.

1. Introduction

This conference is subtitled as "Ten Years after the Neutrino Oscillations". It refers an unforgettable event which occurred in Neutrino 1998 conference in Takayama, Japan. The presentation by Kajita-san of atmospheric neutrino observation by Super-Kamiooka group\footnote{Written version of a talk presented at the Fourth International Workshop on Neutrino Oscillations in Venice (NOV 2008), Venice, Italy, 15-18, April 2008.} gave the first evidence for neutrino oscillation\footnote{In 1986 the KAMIOOKA detector started its phase II operation aimed at lowering energy threshold to observe solar neutrinos, which soon blossomed as neutrino detection from SN 1987A.}, which received a long lasting ovation. But, as Koshiba-san pointed out in his presentation\footnote{In 1986 the KAMIOOKA detector started its phase II operation aimed at lowering energy threshold to observe solar neutrinos, which soon blossomed as neutrino detection from SN 1987A.}, there was a prehistory to that event. The KAMIOOKA experiment\footnote{In 1986 the KAMIOOKA detector started its phase II operation aimed at lowering energy threshold to observe solar neutrinos, which soon blossomed as neutrino detection from SN 1987A.} reported the deficit of muon-like events in its atmospheric neutrino observation in 1988\footnote{In 1986 the KAMIOOKA detector started its phase II operation aimed at lowering energy threshold to observe solar neutrinos, which soon blossomed as neutrino detection from SN 1987A.}, the anomaly in ratio of muon-type to electron-type neutrino events in 1992\footnote{In 1986 the KAMIOOKA detector started its phase II operation aimed at lowering energy threshold to observe solar neutrinos, which soon blossomed as neutrino detection from SN 1987A.}, and then the anomaly in the angle dependence of muon-type events in 1994\footnote{In 1986 the KAMIOOKA detector started its phase II operation aimed at lowering energy threshold to observe solar neutrinos, which soon blossomed as neutrino detection from SN 1987A.}. In particular, the latter is strongly indicative of neutrino oscillation. The prehistory is reflected by the fact that the speaker in Neutrino 1998 represented not only Super-Kamiooka group but also KAMIOOKA collaboration, as recollected in my slides in this conference.
Ten years from Takayama declaration, as everybody knows, has been full of excitement. The solar neutrino experiment\(^{11}\), which was pioneered by Ray Davis 40 years ago\(^{12}\), finally wrote its conclusion that the cause of the solar neutrino problem is not due to our ignorance of interior of the sun but to neutrino--antineutrino transformation\(^{13}\). The KamLAND reactor neutrino experiment\(^ {14}\) gave the first proof that neutrino oscillation takes place also in the 1-2 sector of the MNS matrix with parameters appropriate for the solar neutrino decay. By excluding various other mechanism of neutrino--antineutrino transformation, it solved the solar neutrino problem. It is in press to see evidence for spectral distortion of reactor antineutrinos at more than 5\(^{15}\). The evidence for atmospheric neutrino oscillation was followed by confirmation by the accelerator neutrino experiments, one in Japan\(^ {16}\) and the other in US\(^ {17}\). Now, everybody agrees that neutrinos have masses and they oscillate.

2. A Bold Question

The important goal of the next generation accelerator\(^ {18-21}\) and the reactor neutrino experiments is to measure\(^ {13}\). Fortunately, rich program exists to serve for this purpose. If\(^ {13}\) is large enough we may be able to proceed to search for leptonic CP violation. If the experiments have sufficient sensitivities to the matter effect, they may be able to determine the neutrino mass hierarchy.

Suppose in some day all these goals are met and the MNS matrix elements are measured with precision comparable to those of CKM matrix\(^ {22-23}\). Then, one might ask; "Is this the final goal of neutrino experiments?" I argue that the answer is NO. Of course, my argument cannot be a solid one. Let me, however, mention it anyway.

Neutrinos are proved to be useful probe into physics beyond the Standard Model. Why should we believe that it is merely an accident?

Cosmological neutrinos will soon become one of our machines for probing nature\(^ {24}\). It is natural to suspect that they will bring us something entirely new.

People already suspected several candidates; Non-standard interactions, quantum decoherence, Lorentz-invariance violation, etc.

In this talk, I concentrate on non-standard interactions (NSI)\(^ {25,26,27}\), which might be possessed by neutrinos\(^ {1}\). My presentation will be based on the two references\(^ {20,31}\). There exist numerous references which devoted to this topic. Therefore, I

\(^{5}\) Of course, I do not say that the items above complete the all that should be in the list. For example, Majorana nature of neutrino must be demonstrated, so important to understand leptogenesis\(^ {28}\), for example, as emphasized by Yoshimura-san in his talk\(^ {29}\).
would like to apologize, before start, to those who are not mentioned in my reference.
More bibliography is contained in these papers.

3. Non-Standard Interactions of Neutrinos

Suppose that there is a new physics at energy scale greater than \( 1 \text{ TeV} \). I denote the energy scale as \( M_{FP} \). Then, it is natural to expect that higher-dimensional operators would exist which gives rise to effective new interactions of neutrinos with matter.\(^{32,33}\)

\[
L^{\text{NSI}}_{\nu} = 2^P \sum_{P} \left[ G_{FP} (\nu_L)^* (\nu_P) \right];
\]

where \( G_{FP} \) is the Fermi constant, and \( P \) stands for the index running over fermion species in the earth, \( f = e, u, d \), in which we follow \(^{34}\) for notation. \( P \) stands for a projection operator and is either \( P_L = \frac{1}{2}(1 - \gamma^5) \) or \( P_R = \frac{1}{2}(1 + \gamma^5) \).

To summarize its effects on neutrino propagation it is customary to introduce the \( " \) parameters, which are de ned as \( \frac{\nu_{ij}}{\nu_{ii}} \) where \( n_e \) is the number density of the fermion species \( f \) in matter. Approximately, the relation \( \nu_{ij} P^P F_m P + 3 \nu_{ii} P + 3 \nu_{ii} \) holds because of a factor of \( 3 \) larger number of u and d quarks than electrons in iso-singlet matter. Using the \( " \) parameters the neutrino evolution equation which governs the neutrino propagation in matter is given as

\[
\begin{align*}
\frac{dN_{\nu}}{dt} &= \begin{pmatrix}
0 & 1 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \n0 & 1 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \n0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \n0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \n0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \n0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \n0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \n0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \n0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \n0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0
\end{pmatrix} \begin{pmatrix}
\nu_{e1} \\nu_{e2} \\nu_{e3} \\nu_{\mu1} \\nu_{\mu2} \\nu_{\mu3} \\nu_{\tau1} \\nu_{\tau2} \\nu_{\tau3} \\nu_{\nu}
\end{pmatrix}
\end{align*}
\]

where \( E \) is the energy and \( n_e \) denotes the electron number density along the neutrino trajectory in the earth. \( m_{ij} \) is the neutrino mass and \( m_{e} \) with neutrino mass \( m_{e} \). The phase of \( " \) parameters may provide new signatures

\( \text{NSI} \) comes in not only into neutrino propagation but also to neutrino production and detection processes.\(^{22}\) The current bounds on \( n^{\nu}_{FP} \) are obtained at 90% CL\(^{34}\) and at 95% CL\(^{37}\). When translated (in a bold way) into the \( " \) parameters de ned above they may read as follows:\(^{38}\)

\[
\begin{align*}
2^P \quad 4 < \nu_{ee} < 2 \times 10^4 \quad \nu_{\mu} \quad j > 3 \times 10^4 \quad \nu_{\tau} \quad j < 1.9 \times \nu_{\nu} \quad j < 0.9 \times \nu_{\nu} \quad j < 0.25 \times \nu_{\nu} \quad j < 18 \times \mu
\end{align*}
\]

I emphasize that it is important to constrain the \( \text{NSI} \) parameters by various experiments. The bound placed by the atmospheric\(^{30,40}\) and the solar neutrino

\(^d\) There remains a serious question of whether effective dimension six operators like \( (1) \) which are consistent with severe constraints on charged lepton counterpart which is related by \( SU(2) \) gauge rotation. This point which was first addressed in \(^{33}\) is emphasized to me by Belen Gavela.\(^{35}\).
experiments\textsuperscript{42} are extensively discussed. It is also proposed that several low energy neutrino experiments may be able to place equally severe constraints on NSI\textsuperscript{43,44,45}. The bounds from them are placed on the product of NSI at the source and the detection.

In this talk I concentrate on hunting NSI parameters during neutrino propagation. It is the part that can be dealt with in a model-independent manner and free from the "unitarity violation". By contrast, the way NSI comes into production and detection processes is model-dependent\textsuperscript{46}. Therefore, categorizing the model predictions is necessary before taking them into account. Moreover, I call the readers' attention to the fact that upon construction of the neutrino factory the near detector sitting in front of the storage ring will give stringent bounds on NSI, possibly even severer ones than currently in agin\textsuperscript{34}. Even in the case where the effects of NSI in three different places are comparable in size, it is unlikely that the feature obtained in our study with only propagation "s are completely cancelled by the effects of "s in production and detection processes.

As a theorist the natural question for me to ask is: What would be the amplitude of "? On dimensional ground the operator in \textsuperscript{(1)} is suppressed by $M_N^2 \rho$\textsuperscript{36}. Since we normalize the operator with Fermi constant $G_F", "m" must be of the order of $(M_N = M_{\nu_P})^2 \approx 0.01 (0.0001) \text{ if } M_{\nu_P} = 1 (10) \text{ TeV}$. Therefore, the apparatus has to have sensitivity to the interactions with strength of 0.01% - 1% of weak interactions to look for the effects of NSI. This is a highly demanding requirement.

4. Which Apparatus?

Let us consider which apparatus may be required to meet the condition of search for new interactions 100 - 10,000 times weaker than weak interactions. To make a rough estimate let me assume, for brevity, that sensitivity to $f_{13}$ is comparable to that of $\nu_{i}$. I expect, very roughly, that sensitivity to $\sin^2 2 \theta_{13}$ is up to 0.01 in conventional muon neutrino superbeam experiments\textsuperscript{47}, which can be translated into a sensitivity of 0.05. Thus, most probably, superbeam is not the right apparatus as a machine to hunt NSI. (We will however comments on its sensitivity later.)

As is well known, the alternative apparatus which is capable for looking into effects of smaller $f_{13}$ is either neutrino factory\textsuperscript{48} or beta beam\textsuperscript{49}. Then, they are the good candidates for apparatus for hunting NSI. In my talk I concentrate on neutrino factory, leaving beta beam capability a subject of future studies by experts. For earlier analyses of NSI effects in neutrino factory, see e.g.,\textsuperscript{50,51,52,53,54,55}. We

\textsuperscript{46} It appears to me that the main difference between our and the "unitarity violation" approach exists in that the latter chooses to specify a model (or a class of models) to allow them to relate the propagation "s to the production and the detector "s.

\textsuperscript{47} If we have to go to dimension eight operators their effective strength would be at most $(M_N = M_{\nu_P})^4 \approx 10^4$ even for $M_{\nu_P} = 1 \text{ TeV}$.\textsuperscript{56}
will see that the sensitivity to NSI by neutrino factory is fantastic.

5. Problems in Neutrino Factory Search for NSI

Unfortunately, it is known that one has to encounter inherent troubles in doing neutrino factory search for NSI. There exist two types of confusion problem:

1. NSI confusion \(^{51,52}\); The effects of non-vanishing \(\theta_{13}\) can be mimicked by some of the NSI elements "s.

Two-phase confusion \(^{54}\); The effects of leptonic Kobayashi-Maskawa (KM) phase \(\delta\) can be imitated by the phases of the NSI elements "s, which will be denoted as \(\theta_{13}\).

The former confusion is fatal for precision \(\theta_{13}\) measurement, while the latter one serious for identifying nature of CP violation even if it were observed.

It is not difficult to understand the causes of the two types of confusion. In Fig. 1 presented are the bi-probability plots in \(P(e^+ e^-) P(e^+ e^-)\) space \(^{56}\). The neutrino energy is taken to be \(E = 30\) GeV and the baseline \(L = 3000\) km. The blue and the red ellipses correspond to the case of positive and negative "\(e\). Except for the case with "\(e\), these two are barely distinguishable. The orange ellipses are the bi-probability diagram without NSI. There are so many of them because they are results of varying \(\theta_{13}\). The point is that, apart from the case with "\(e\), the blue and the red ellipses are completely "absorbed" into the background of orange ellipses. Namely, the system with NSI can be mimicked by adjusting \(\theta_{13}\), the NSI confusion.

The two-phase confusion is also easy to understand. Let us ignore the solar \(m_{21}\) assuming that it gives relatively small effect. The system is then reduced to an effective two generation problem. In such a system, CP violating phase \(\delta\) must be unique if a single type of diagonal NSI element is introduced, because effects of the KM type phase must be (effectively) absent. Therefore, the two phases and must come together, the reasoning spelled out in \(^{30}\). It was shown in perturbative computation \(^{54}\) that it is via the form \(\theta_{13}\). This is nothing but the cause of the two-phase confusion.

6. Two-Detector Setting in Neutrino Factory

We ask questions: What is the way to look for effects of NSI with highest possible sensitivities? What is the way to resolve the two confusion problems? I argue that the two-detector setting, one at baseline 3000 km and the other at 7000 km, is the answer to these questions. It may be regarded as neutrino factory version of the two-detector setting discussed earlier \(^{57,58}\). Nonetheless, we will observe that the synergy between the two detectors in the present case is far more spectacular than the other cases.
Figure 1: Bi-probability plots in $P(\nu_e \rightarrow \nu_e)$ space at $L = 3000$ km, for $E = 30$ GeV, computed numerically using the constant matter density $\rho = 3.6 \text{g/cm}^3$ with the electron number density per nucleon equals to 0.5. The both axes is labeled in units of $10^{-4}$. In each panel only the indicated particular $\varepsilon$ is turned on. The upper (lower) panels, from left to right, correspond to the case of non-vanishing $\varepsilon_{ee}$, $\varepsilon_{e\mu}$, and $\varepsilon_{e\tau}$ ($\varepsilon_{\mu\mu}$, $\varepsilon_{\mu\tau}$), respectively. The red and the blue ellipses are for positive and negative signs of $\varepsilon$, respectively, for the cases with (from left to right) $\sin^2 \theta_{13} = 0.0005, 0.001$, and 0.0015, as indicated in the heading. In the left and right lower panels the ellipses with positive and negative sign of $\varepsilon$ overlap almost completely and each individual curve is not visible. The green ellipses which correspond to the same three values of $\sin^2 \theta_{13}$ but without NSI are clearly visible.

You may ask why a detector at 7000 km? In the present context, there are two reasonings to motivate a far detector at 7000 km, which is sometimes called as the magic baseline, $\frac{L}{\Delta\theta} = 59$.

It was shown in a previous study [50] that the baseline comparable to the magic baseline gives the best sensitivity to measurement of the earth matter density. The relevant figure drawn by Uchinami-kun for his M. thesis is pasted in my previous Venice report [61] as Fig. 1. (For a related work, see [62].) Measuring the matter density is equivalent to determine $\varepsilon_{ee}$ in our present language. Then, it is natural to suspect that a detector at the magic baseline can be a sensitive tool for detecting the effects of diagonal $\varepsilon_{\nu}$'s.

The magic baseline is characterized as the baseline where the solar oscillation amplitude vanishes [63], and hence the effect of CP phase is absent. Thanks
to this property a detector at $L = 7000$ km may be powerful in detecting effects of o-diagonal $\nu$s.

Because of the latter property it has been proposed\cite{64,59} that a second detector at the magic baseline is a powerful tool for resolving the conventional parameter degeneracy\cite{64,56,65}, in particular its intrinsic part. In fact, it allows us to have even higher sensitivity to o-diagonal $\nu$s. This is demonstrated in Fig.\[2,\] in which the bi-probability plots in $P(e \rightarrow \mu)$ space at $L = 7200$ km are presented. As is clear in Fig.\[2,\] the ellipses without NSI shrink into points because of the absence of dependence, giving orange strips when $\theta_{13}$ is varied. On the other hand, the ellipses with NSI stand out. This property is nothing but the secret behind extremely high sensitivity to NSI which we will discover later.

In fact, we observe a prominent feature in systems with $\nu_e$ and $\nu_e$ that (1) the ellipses shrink to lines, and (2) they look identical. These features are easy to understand if one derives the approximate analytic formulas of oscillation probabilities. See\cite{30} for details. The one with $\nu_e$ is given as

\[
P(e \rightarrow \nu_e) = 4 \frac{\sin^2 \theta_{13}}{\sin^2 \theta_{13} + \sin^2 \theta_{23} \theta^2_{13}} \frac{m^2}{E} \int_0^\frac{e^2 L}{4E} + \frac{4ac_{23} \sin^2 \theta_{13}}{(a \ m^2_{31})^2} \frac{h}{2} m^2_{31} s_{13} f \cos( + e) + c_{23} a_{f} f \sin^2 \frac{m^2_{31} L}{4E} : (4)
\]

\[\]

Figure 2: The same as in Fig.1 but for the baseline $L = 7200$ km, the magic baseline, with the matter density $= 4.5$ g/cm$^3$. The same values of $|$ are used in each panel.
The corresponding formula for anti-neutrinos can be obtained by making the replacement $a!a, e!e$. The formula with $"e$ can be obtained by replacing $c_{23} e$ by $s_{23} e$ in the second line of Eq. (4), which explains the feature (2) above. The property (1), shrunken ellipse, is also evident by looking into (4); since there is only $\cos( + e )$ dependence the ellipse must shrink into a line. Notice that at magic baseline the solar $m_{21} e$ effect is absent and hence the two phase has to come together, as we have argued before and as indicated in (4).

7. How Does the Two-Detector Setting Solve $^{13}$NSI Confusion?

Before we discuss the sensitivity to NSI, let us first address the question of how the problem of $^{13}$NSI confusion can be solved by the two detector setting at $L = 3000$ and $7000$ km. Unless we are able to solve this problem it is not practical to speak about neutrino factory as a hunting tool for NSI. It should be noticed that if NSI exists at the magnitude we anticipate in the present discussion and the effects of $^{13}$NSI is comparable to that we inevitably have such the confusion. Therefore, this is not the problem only for neutrino factory, but for any other apparatus which explore such region of mixing parameters.

The results presented in this articles are based on [30]. Therefore, the readers are advised to consult the reference whenever more detailed informations are necessary. In short our analysis assumed: The number of muons decays per year is $10^{21}$, the exposure considered is 4 (4) years for neutrino (anti-neutrino), and each detector mass is assumed to be 50 kton. The efficiency is assumed to be 100% and the background is ignored.

In Fig.3 and Fig.4, presented are the allowed regions projected into the plane of $\sin^2 2 \theta_{13}$ corresponding to the cases with various combinations of NSI parameters which are turned on. The input parameters are taken as $\sin^2 2 \theta_{13} = 0.001, \delta = 2$, and $" = 0$. In the top panels (which show the constraint placed by the detector at $L = 3000$ km) the $^{13}$NSI confusion is clearly visible in most cases except for the panels involving $"e$. Despite the vanishing input of NSI parameters, the freedom of adjusting them to nonvanishing values during the t creates the $^{13}$NSI confusion. An exceptional situation occurs in the systems with $"e$; The $^{13}$NSI confusion is much milder than that in other systems. This is, of course, expected from the behavior of ellipses in Fig.1.

We notice that the extent of the confusion depend on many things, e.g., on which combination of NSI parameters are turned on. In particular, the confusion is much severer for smaller $^{13}$NSI as shown in Fig.5 in which $\sin^2 2 \theta_{13} = 0.0001$. For the corresponding graph for the cases with $"e$ and for dependence on , see Figs. 14 and Figs. 7-10, respectively, in [30].

\footnote{A less severely, one may regard this setting as 5+ 5 years running with 80% e efficiency, which may not be so far from the reality.}
Figure 3: Allowed regions projected into the plane of $\sin^2 2\theta_{13}$—corresponding to the case where the input parameters are $\sin^2 2\theta_{13} = 0.001$ and $\theta_1 = 3\pi/2$ and no non-standard interactions (or all the $\epsilon$'s are zero), for $E = 50$ GeV and the baseline of $L = 3000$ km (upper panels), 7000 km (middle horizontal panels) and combination (lower panels). The was performed by varying freely 4 parameters, $\theta_{13}$, and 2 $\epsilon$'s where $\epsilon_{ee}$ and $\epsilon_{\tau\tau}$ are marginalized (left panels), $\epsilon_{ee}$ and $\epsilon_{\tau\tau}$ are marginalized (middle panels) and $\epsilon_{ee}$ and $\epsilon_{\tau\tau}$ are marginalized (right panels).

We observe in the bottom panels in Fig.3, Fig.4, and Fig.5 that the confusion is resolved by adding the informations gained by the detector at $L = 7000$ km which are shown in the middle panels. The far detector has little sensitivity to $\epsilon_{\tau\tau}$, as expected, but it has a good sensitivity to $\theta_{13}$, and hence has potential of resolving the $\theta_{13}$ NSI confusion. This is analogous to the role played by the far detector at the magic baseline which helps resolving the conventional neutrino parameter degeneracy.

8. Synergy of Two Detectors and Sensitivity to NSI

Now, we turn to our original problem, the sensitivity to NSI possessed by the two-detector setting. The power of the synergy by the two-detector setting is enormous; let us see it in Fig.6 and Fig.7; seeing is believing!
Figure 4: The same as in Fig. 3 but for different combination of 2 "s to which the t to $\sin^2 2\theta_{13}$ and $\varepsilon_{e\mu}$ marginalized; $\varepsilon_{ee}$ (left panels), $\varepsilon_{e\tau}$ (middle panels) and $\varepsilon_{e\mu}$ (right panels).

In Fig. 6 and Fig. 7 presented are the allowed regions in space spanned by two of the NSI parameters $\sigma$ which are turned on in these particular simulations. The top, the middle, and the bottom panels are for the detector at $L = 3000$ km, $L = 7000$ km, and the two detector combined, respectively.

In Fig. 6, we notice a remarkable synergy by the near (3000 km) and the far (7000 km) detectors. Normally, one does not expect that such a tiny allowed region emerges in the bottom panel by combining the ones in the top and the middle panels. The secret behind the extreme synergy is in the CP phase; The region of apparent overlap between regions in the top and the middle panels differs in the $\tau$ value of $\sigma$, and therefore disappear when two detectors are combined. It implies that keeping the solar $m_{21}^2$ is crucial to make the synergy active. Though it may sound trivial, I note that this effect is dropped in many of the earlier treatment of NSI.

We have concluded as follows in our paper: The sensitivities to off-diagonal $\sigma$'s are excellent, $\sigma_{ee} \sigma_{e\tau} \sim 10^{-3}$ and $\sigma_{ee} \sigma_{e\mu} \sim 10^{-4}$, while the ones for the diagonal $\sigma$'s are acceptable, $\sigma_{ee} \sigma_{e\tau} \sim 0.1(0.2)$ at 3 CL and 2 DOF. These
9. Two-Phase Confusion

Our treatment in \cite{30} does not contain full treatment of the two-phase confusion, but a partial one. We allowed negative values of $\theta_{13}$, which can be interpreted as allowing two discrete values of phase $\theta_{13} = 0$ and $\pi$. Therefore, we can in principle address the question of the two-phase confusion, its discrete version, in our treatment.

In Fig.\ref{fig:Figure5} we show the similar allowed regions but obtained in analysis with nonzero input values of NSI. In the middle panels in Fig.\ref{fig:Combined}, which correspond to constraints imposed by the far detector, there are two discrete solutions of $\theta_{13}$. It is nothing but
Figure 6: Allowed regions projected into the plane of 2 NSI parameters, \(\sin^2 \theta_{13}\) and \(\delta\) marginalized \(\sin^2 \theta_{13} = 0.001\) and \(\delta = \pi/4\). The thin dashed lines are to indicate the input values of \(\delta\). The treatment was performed by varying freely 4 parameters, \(\theta_{13}\), and 2 \(\sin^2\)'s with \(\theta_{13}\) and being marginalized.

Figure 6: Allowed regions projected into the plane of 2 NSI parameters, \(\sin^2 \theta_{13}\) and \(\delta\) marginalized \(\sin^2 \theta_{13} = 0.001\) and \(\delta = \pi/4\). The thin dashed lines are to indicate the input values of \(\delta\). The treatment was performed by varying freely 4 parameters, \(\theta_{13}\), and 2 \(\sin^2\)'s with \(\theta_{13}\) and being marginalized.

remnant of the two-phase confusion. Notice that there is no chance of resolving the confusion only by the detector at the magic baseline, as indicated in the expression of the oscillation probability in (4).

Again the synergy of the near and the far detectors makes it possible to resolve the discrete version of the two-phase confusion, as indicated in the bottom panels in Fig.8. Though our treatment in (30) did not allow us to fully address the issue, we expect that the two-phase confusion will be resolved by the two detector setting.

10. Sensitivity to NSI by T2KK and the Related Settings

So far we have con ned ourselves into neutrino factory, and apparently there is little room for superbeam experiments as commented earlier. But, it is not completely
true. As far as (2-3) (or ) sector of the MNS matrix is concerned superbeam experiments with tuned beam energy to the one corresponding to the oscillation maximum is competitive to neutrino factory $^{13,67,68}$.

Therefore, I briefly discuss NSI sensitivity achievable by some of the superbeam experiments. For brevity I treat only three options with an upgraded beam of 4 MW from J-PARC:

Kamiooka-Korea setting: Two identical detectors one at Kamiooka and the other in Korea each 0.27 M tonducational mass

Kamiooka-only setting: A single 0.54 M ton detector at Kamiooka

Korea-only setting: A single 0.54 M ton detector at some other in Korea.

The second option is nothing but the one described in LO I of T2K experiment as its second phase$^{13}$, which I call T2K II. The first one is sometimes dubbed as T2K K
Figure 8: These graphs are similar to those presented in Fig. 6 but for non-vanishing input values of $\eta$; $\eta_{ee} = 0.1$, $\eta_e = 0.01$ and $\eta = 0.2$. We note that only the input values of 2 $\eta$'s are set to be non-zero at the same time. The thin dashed lines indicate the corresponding non-zero values of $\eta$ for each panel.

(abbreviation of Tokai-to-Kamiooka-Korea) $\omega$ a modified version of T2K II by dividing the detector into 2 and bring one of them to Korea $^{58}$.)

In Fig. 8 presented are the sensitivities to NSI elements $\eta$ and $\eta'$ achievable by, from top to bottom, T2K II, the Korea-only setting, and by T2K K. They are the results obtained by a truncated treatment of the sector done in $^{31}$. Though not spectacular the both T2K II and T2K K have reasonable sensitivities to NSI; The sensitivities of three experimental setups at 2 CL can be read off from Fig. 9. The approximate 2 CL sensitivities of the Kamiooka-Korea setup for $\sin^2 2\theta_{13} = 0.045$ ($\sin^2 13 = 0.5$) are:

\[ j^* \quad j < 0.03 \quad (0.03); \quad j^* \quad j < 0.3 \quad (1.2); \quad (5) \]

As I repeatedly emphasize, it is no more than a temporary name for idea of such apparatus. Even in the case people prefer one which succeeds to T2K, the last letter is naturally the name of place (Pohang, for example) where Korean detector is placed.
Figure 9: The allowed regions in "space" for 4 years neutrino and 4 years anti-neutrino running. The upper, the middle, and the bottom three panels are for the Kamio-only setting, the Korea-only setting, and the Kamio+Korea setting, respectively. The left and the right panels are for cases with $\sin^2 \theta_{23} = 0.45$ and 0.5, respectively. The red, the yellow, and the blue lines indicate the allowed regions at 1, 2, and 3 CL, respectively, for 2 degrees of freedom. The input value of $m_{3\nu}$ is taken as $2.5 \times 10^{-3} \text{eV}^2$.

Here, we neglected a barely allowed region near $j^* = 2,3$, which is already excluded by the current data. The bound on $j^*$ above modestly improves the current bound obtained by analyzing atmospheric neutrino data of Super-Kamio and MACRO.

The sensitivity to NSI by T2K II is slightly better than that of T2KK. I note, however, that if we examine a wider class of new physics such as quantum decoherence, Lorentz violation, etc., the overall performance of T2K is the best among the above three settings, always remaining as the next best if not the best.

11. Bounds from Ongoing and Near Future Experiments

It is a legitimate question to ask to what extent the ongoing and the near future experiments are powerful. Sensitivities to NSI by the MINOS experiments are ex-
am ined in [69,70,71]. The sensitivities to "parameters are of order unity. Possible contribution by OPERA experiment is also examined [72,73,74] which however does not alter the situation. Combination of superbeam experiments with reactor is also considered [75] which entailed the sensitivities $\theta_{13}$ for NSI in propagation.

12. Conclusion

I have raised a question of whether a successful precision measurement of neutrino masses and the lepton mixing parameters is the last word for future neutrino experiments. As a possible candidate for "the answer is No" options, I examined the possibility that non-standard neutrino interactions outside the Standard Model can be uncovered by neutrino factory experiments. It, however, raises two serious issues, the $\theta_{13}$ NSI confusion and the two-phase confusion, which we proposed to be resolved by the near (3000 km) – far (7000 km) two detector setting. I would like to emphasize that the results obtained in our analysis is strongly indicative of the feature that neutrino factory can be used as a discovery machine for NSI while keeping its primary function of performing precision measurement of the lepton mixing parameters. I also touched upon the sensitivity to NSI search by some superbeam type experiments which utilizes neutrino beam from J-PARC.

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