Getting the most from NO\(\nu\)A and T2K

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Abstract. The determination of the ordering of the neutrino masses (the hierarchy) is probably a crucial prerequisite to understand the origin of lepton masses and mixings and to establish their relationship to the analogous properties in the quark sector. In this talk, we follow an alternative strategy to the usual neutrino–antineutrino comparison: we exploit the combination of the neutrino-only data from the NO\(\nu\)A and the T2K experiments by performing these two off-axis experiments at different distances but at the same \(\langle E \rangle/L\), \(\langle E \rangle\) being the mean neutrino energy and \(L\) the baseline. This would require a minor adjustment to the proposed off-axis angle for one or both of the proposed experiments.

1. Introduction
During the last several years the physics of neutrinos has achieved a remarkable progress. The experiments with solar [1, 2, 3, 4, 5, 6], atmospheric [7], reactor [8], and also long-baseline accelerator [9, 11] neutrinos, have provided compelling evidence for the existence of neutrino oscillations, implying non zero neutrino masses. The data quoted above require two large mixing angles (\(\theta_{12}\) and \(\theta_{23}\)) and may involve a small third one (\(\theta_{13}\)) in the neutrino mixing matrix and two mass squared differences, \(\Delta m_{ji}^2 \equiv m_j^2 - m_i^2\), with \(m_{ji}\) the neutrino masses, one driving the atmospheric (\(\Delta m_{31}^2\)) and the other one the solar (\(\Delta m_{21}^2\)) neutrino oscillations. The mixing angles \(\theta_{12}\) and \(\theta_{23}\) control the solar and the atmospheric neutrino oscillations, while \(\theta_{13}\) is the angle limited by the data from the CHOOZ and Palo Verde reactor experiments [12, 13].

The Super-Kamiokande [7] and K2K [9] data are well described in terms of dominant \(\nu_\mu \to \nu_\tau\) (\(\bar{\nu}_\mu \to \bar{\nu}_\tau\)) vacuum oscillations. The MINOS Collaboration has recently reported their first neutrino oscillation results from 1.27 \(\times 10^{20}\) protons on target exposure of the MINOS far detector [11]. A recent global fit [14] (see also Ref. [15]) provides the following 3\(\sigma\) allowed ranges for the atmospheric mixing parameters:

\[
|\Delta m_{31}^2| = (1.9 - 3.2) \times 10^{-3} \text{eV}^2, \quad 0.34 < \sin^2 \theta_{23} < 0.68 .
\] (1)

The sign of \(\Delta m_{31}^2\), \(\text{sign}(\Delta m_{31}^2)\), cannot be determined with the existing data. The two possibilities, \(\Delta m_{31}^2 > 0\) or \(\Delta m_{31}^2 < 0\), correspond to two different types of neutrino mass ordering: normal hierarchy and inverted hierarchy. In addition, information on the octant in which \(\theta_{23}\) lies, if \(\sin^2 2\theta_{23} \neq 1\), is beyond the reach of present experiments.

The 2-neutrino oscillation analysis of the solar neutrino data, in combination with the KamLAND spectrum data [16], shows that the solar neutrino oscillation parameters lie in the
low-LMA (Large Mixing Angle) region, with best fit values [14] \( \Delta m_{21}^2 = 7.9 \times 10^{-5} \text{ eV}^2 \) and \( \sin^2 \theta_{12} = 0.30 \).

A combined 3-neutrino oscillation analysis of the solar, atmospheric, reactor and long-baseline neutrino data [14] constrains the third mixing angle to be \( \sin^2 \theta_{13} < 0.041 \) at the 3\( \sigma \) C.L.

The future goals in the study of neutrino properties will be to measure precisely the already known oscillation parameters and to obtain information on the unknown ones, namely \( \theta_{13} \), the CP-violating phase \( \delta \) and the neutrino mass hierarchy (or equivalently \( \text{sign}(\Delta m_{31}^2) \)). In this talk [17], we concentrate on the extraction of the neutrino mass hierarchy by combining the Phase I (neutrino-data only) of the long-baseline \( \nu_e \) appearance experiments T2K [18] and NO\( \nu \)A [19], both exploiting the off-axis technique [20]. For our analysis, unless otherwise stated, we will use a representative value of \( |\Delta m_{31}^2| = 2.4 \times 10^{-3} \text{ eV}^2 \) and \( \sin^2 \theta_{23} = 1 \). For the solar oscillation parameters \( \Delta m_{21}^2 \) and \( \theta_{12} \), we will use the best fit values quoted in this introductory section.

2. Formalism

The mixing angle \( \theta_{13} \) controls \( \nu_\mu \rightarrow \nu_e \) and \( \bar{\nu}_\mu \rightarrow \bar{\nu}_e \) conversions in long-baseline \( \nu_e \) appearance experiments and the \( \bar{\nu}_e \) disappearance in short-baseline reactor experiments. Present and future reactor neutrino experiments [21], conventional neutrino beams and future long baseline neutrino experiments could measure, or set a stronger limit on, \( \theta_{13} \). Therefore, with the possibility of the first measurement of \( \theta_{13} \) being made by a 1-to 2-km baseline reactor experiment, the long-baseline off-axis \( \nu_e \) appearance experiments, T2K [18] and NO\( \nu \)A [19], need to adjust their focus to emphasize other physics topics. The most important of these questions is the form of the mass hierarchy, normal versus inverted and the measurement of leptonic CP violation, which in a three neutrino oscillation framework is directly related to the existence of a CKM-like CP-phase, \( \delta \). Consider the probability \( P(\nu_\mu \rightarrow \nu_e) \) in the context of three-neutrino mixing in the presence of matter [22], represented by the matter parameter \( a \), defined as \( a = G_F n_e / \sqrt{2} \), where \( n_e \) is the average electron number density over the baseline, taken to be constant throughout the present study. Defining \( \Delta_{ij} \equiv \frac{\Delta m_{ij}^2 L}{4E} \), a convenient and precise approximation is obtained by expanding to second order in the following small parameters: \( \theta_{13}, \frac{\Delta_{21}}{\Delta_{31}}, \frac{\Delta_{21}}{aL} \) and \( \Delta_{21} \). The result is (details of the calculation can be found in Ref. [23], see also Ref. [24])

\[
P_{\nu_\mu\nu_e} \simeq \left| \sin \theta_{23} \sin 2\theta_{13} \left( \frac{\Delta_{31}}{31 - aL} \right) \sin (\Delta_{31} - aL) e^{-i(\Delta_{31} + \delta)} + \cos \theta_{23} \sin 2\theta_{12} \left( \frac{\Delta_{21}}{aL} \right) \sin (aL) \right|^2
\]

(2)

where \( L \) is the baseline and \( a \rightarrow -a, \delta \rightarrow -\delta \) for \( P_{\bar{\nu}_\mu\nu_e} \). Suppose \( P_{\nu_\mu\nu_e} < P_{\bar{\nu}_\mu\nu_e} \); in vacuum, this implies CP violation. On the other hand, in matter, this implies CP violation only for the normal hierarchy but not necessarily for the inverted hierarchy around the first oscillation maximum. The different index of refraction for neutrinos and antineutrinos induces differences in the \( \nu, \bar{\nu} \) propagation that could be misinterpreted as CP violation [25]. Typically, the proposed long baseline neutrino oscillation experiments have a single detector and plan to run with the beam in two different modes, neutrinos and antineutrinos. In principle, by comparing the probability of neutrino and antineutrino flavor conversion, the values of the CP-violating phase \( \delta \) and of sign(\( \Delta m_{31}^2 \)) could be extracted. However, different sets of values of CP-conserving and violating parameters, \( (\theta_{13}, \theta_{23}, \delta, \text{sign}(\Delta m_{31}^2)) \), lead to the same probabilities of neutrino and antineutrino conversion and provide a good description of the data at the same confidence level. This problem is known as the problem of degeneracies in the neutrino parameter space [26, 27, 28, 29, 30] and severely affects the sensitivities to these parameters in future long-baseline experiments. Many strategies have been advocated to resolve this issue. Some

\[1\] The author would like to thank S. Parke for the shorter version of the oscillation probability below.
of the degeneracies might be eliminated with sufficient energy or baseline spectral information. In practice, statistical errors and realistic efficiencies and backgrounds limit considerably the capabilities of this method. Another detector [27, 31, 32, 33, 34] or the combination with another experiment [35, 36, 37, 38, 39, 40, 41, 42, 43, 44] would, thus, be necessary.

The use of only a neutrino beam could help in resolving the type of hierarchy when two different long-baselines are considered [36, 37, 45, 46]. It was shown in ref. [37] that if the \( \frac{\langle E \rangle}{L} \) for the two different experiments is approximately the same then the allowed regions for the two hierarchies are disconnected and thus this method for determining the hierarchy is free of degeneracies. Naively, we can understand this method in the following way for \( \sin^2 2\theta_{13} > 0.01 \):

Following the line of thought developed by Minakata, Nunokawa and Parke [37], we exploit the neutrino data from two experiments at different distances and at different off-axis locations [17]. The off-axis location of the detectors and the baseline must be chosen such that the \( \frac{\langle E \rangle}{L} \) is the same for the two experiments. Here we explain the advantages of such an strategy versus the commonly exploited neutrino-antineutrino comparison.

Suppose we compute the oscillation probabilities \( P_{\nu_\mu \nu_e} \) and \( P_{\bar{\nu}_\mu \bar{\nu}_e} \) for a given set of oscillation parameters and the CP-phase \( \delta \) is varied between 0 and \( 2\pi \): we obtain a closed CP trajectory (an ellipse) in the bi–probability space of neutrino and antineutrino conversion [28]. In general, the ellipses overlap for a large fraction of values of the CP–phase \( \delta \) for every allowed value of \( \sin^2 2\theta_{13} \). This indicates that, generically, a measurement of the probability of conversion for neutrinos and antineutrinos cannot uniquely determine the type of hierarchy in a single experiment. This makes the determination of \( \text{sign}(\Delta m^2_{31}) \) extremely difficult, i. e., the \( \text{sign}(\Delta m^2_{31}) \)-extraction is not free of degeneracies.

In the case of bi–probability plots of neutrino–neutrino conversions at different distances (which will be referred as near (N) and far (F)), the overlap of the two bands, which implies the presence of a degeneracy of the type of hierarchy with other parameters, is controlled by the slope and the width of the bands. Using the fact that matter effects are small \( (aL \ll \Delta_{13}) \), we can perform a perturbative expansion and assuming that the \( \frac{\langle E \rangle}{L} \) of the near and far experiments is the same, at first order, the ratio of the slopes reads [37]

\[
\frac{\alpha_+}{\alpha_-} \simeq 1 + 4(a_N L_N - a_F L_F) \left( \frac{1}{\Delta_{31}} - \frac{1}{\tan(\Delta_{31})} \right)
\]

where \( \alpha_+ \) and \( \alpha_- \) are the slopes for normal and inverted hierarchies, and \( a_F \) and \( a_N \) are the matter parameters for the two experiments. The separation among the ellipses for the two hierarchies increases as the matter parameter times the path length for the two experiments does. The width of the ellipses is crucial: even when the separation between the central axes of the two regions is substantial, unless the ratio \( \frac{\langle E \rangle}{L} \) is kept close to constant, the width of the ellipses will grow rapidly and the ellipses will overlap. Consequently, we have to satisfy two conditions in order to optimize the determination of the neutrino mass hierarchy: (a) maximize the difference in the factor \( aL \) for both experiments and (b) minimize the ellipses width by performing the two experiments at the same \( \frac{\langle E \rangle}{L} \).

The most promising way to optimize the sensitivity to the hierarchy with relatively near term data is therefore to focus on the neutrino running mode and to exploit the Phase I data of the long-baseline off-axis \( \nu_e \) appearance experiments, T2K and NO\( \nu \)A. T2K utilizes a steerable
Figure 1. (a) 90% CL hierarchy resolution (2 d.o.f) for different possible combinations: the default one (T2K at an off-axis angle of $2.5^\circ$ and NO$\nu$A far detector at 12 km off-axis, in solid blue), T2K at an off-axis angle of $2.5^\circ$ and NO$\nu$A far detector at 13 km off-axis (long dash-dot red curve), at 14 km off-axis (short dashed red curve), at 16 km off-axis (three dots-three dashes blue curve) and T2K at an off-axis angle of $2^\circ$ and NO$\nu$A far detector at 12 km off-axis (dotted blue curve). (b) The same as (a) but assuming that $\Delta m^2_{31} = 3.0 \times 10^{-3} \text{eV}^2$ and only for the three most representative combinations.

4. Optimizing the NO$\nu$A and T2K detector locations

In this section we present what could be achieved if NO$\nu$A and T2K setups are carefully chosen, focusing on the physics potential of the combination of their future data. We define the Phase I of the experiments as follows. For the T2K experiment, we consider 5 years of neutrino running and SK as the far detector with a fiducial mass of 22.5 kton and 70% detection efficiencies. For the NO$\nu$A experiment, we assume $6.5 \times 10^{20}$ protons on target per year, 5 years of neutrino running and the detector described in the previous section.

We summarize the results in Figs. (1), where we present the exclusion plots in the $\sin^2 2\theta_{13}, \delta$ plane for a measurement of the hierarchy at the 90% CL for the several possible combinations.
assuming that nature’s solution is the normal hierarchy and $\Delta m_{31}^2 = 2.4 \times 10^{-3} \text{ eV}^2$ (left panel) and $\Delta m_{31}^2 = 3 \times 10^{-3} \text{ eV}^2$ (right panel) (in light of the recent MINOS results, we explore here the impact of a larger $\Delta m_{31}^2$). We show as well the corresponding CHOOZ bound for $\sin^2 2\theta_{13}$. A larger value of $\Delta m_{31}^2$ implies more statistics and consequently a sensitivity improvement: see Fig. (b), where for the sake of illustration only the three most representative configurations are shown.

If both T2K and NO$\nu$A run in their default configurations the combination of their future Phase I data (only neutrinos) will not contribute much to our knowledge of the neutrino sector, see the solid blue line in Figs. (1). If we fix the T2K off-axis location to its default value of 2.5$^\circ$ but we change the location of the NO$\nu$A detector to 14 km the improvement is quite remarkable, see the short dashed red line in Figs. (1): the sensitivity to the mass hierarchy has a milder dependence on the CP-phase $\delta$ once that the $\langle E \rangle/L$ of the two experiments is chosen to be the same. The best sensitivity to the hierarchy extraction is clearly achieved when the NO$\nu$A experiment is at 14 km off-axis and the T2K off-axis angle is the default one. If the T2K off-axis angle is slightly modified to 2$^\circ$, see the dotted lines in Figs. (1) it would be possible to reproduce the results from the combination of the data from T2K located at 2.5$^\circ$ off-axis and the NO$\nu$A detector placed at 13 km off-axis.

The combination of data from an upgraded phase (Phase II) of the T2K and/or NO$\nu$A experiments (by increasing the proton luminosities, the years of neutrino running and/or the mass of the far detectors) will obviously increase the statistics and will shift the sensitivity curves depicted in Fig. (1) (a), similarly to the effect of increasing $\Delta m_{31}^2$.

If the nature’s choice for the neutrino mass ordering is the inverted hierarchy, the sensitivity curves depicted in Fig. (1) (a) will be shifted but in the opposite direction, making the case for the Phase II of both experiments stronger, especially if $\Delta m_{31}^2 = 2.4 \times 10^{-3} \text{ eV}^2$.

5. Conclusions
The most promising way to extract the neutrino mass hierarchy is to make use of the matter effects and exploit the neutrino data from two near-term long baseline $\nu_e$ appearance experiments performed at the same $\langle E \rangle/L$, provided $\sin^2 2\theta_{13}$ is within their sensitivity range or within the sensitivity range of the next-generation $\bar{\nu}_e$ disappearance reactor neutrino experiments. Such a possibility could be provided by the combination of the data from the Phase I of the T2K and NO$\nu$A experiments. We conclude that the optimal configuration for these experiments would be 14 km off-axis for the NO$\nu$A far detector and 2.5$^\circ$ off-axis for the T2K experiment. The combination of their expected results could provide a 90% confidence level resolution of the neutrino mass hierarchy if $\sin^2 2\theta_{13} > 0.11$ (for $\Delta m_{31}^2 = 2.4 \times 10^{-3} \text{ eV}^2$) or if $\sin^2 2\theta_{13} > 0.07$ (for $\Delta m_{31}^2 = 3 \times 10^{-3} \text{ eV}^2$). A modest upgraded next Phase of both NO$\nu$A and T2K experiments (by increasing a factor of five their expected Phase I statistics) could shift the 90% CL limits quoted above to $\sin^2 2\theta_{13} > 0.03$ (for $\Delta m_{31}^2 = 2.4 \times 10^{-3} \text{ eV}^2$) and to $\sin^2 2\theta_{13} > 0.025$ (for $\Delta m_{31}^2 = 3 \times 10^{-3} \text{ eV}^2$).

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