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Getting the most from NOνA 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 NOνA 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 (θ_{12} and θ_{23}) and may involve a small third one (θ_{13}) in the neutrino mixing matrix and two mass squared differences, $\Delta m^2_{ji} \equiv m^2_j - m^2_i$, with $m_{j,i}$ the neutrino masses, one driving the atmospheric (Δm^2_{31}) and the other one the solar (Δm^2_{21}) neutrino oscillations. The mixing angles θ_{12} and θ_{23} control the solar and the atmospheric neutrino oscillations, while θ_{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 1.27×10^{20} protons on target exposure of the MINOS far detector [11]. A recent global fit [14] (see also Ref. [15]) provides the following 3σ allowed ranges for the atmospheric mixing parameters:

$$|\Delta m^2_{31}| = (1.9 - 3.2) \times 10^{-3}\mathrm{eV}^2, \qquad 0.34 < \sin^2\theta_{23} < 0.68 \ . \tag{1}$$

The sign of Δm^2_{31}, $\mathrm{sign}(\Delta m^2_{31})$, cannot be determined with the existing data. The two possibilities, $\Delta m^2_{31} > 0$ or $\Delta m^2_{31} < 0$, correspond to two different types of neutrino mass ordering: normal hierarchy and inverted hierarchy. In addition, information on the octant in which θ_{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] $\Delta m^2_{21} = 7.9 \times 10^{-5}$ 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 3σ 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 θ_{13}, the CP–violating phase δ and the neutrino mass hierarchy (or equivalently sign(Δm^2_{31})). 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 ν_e appearance experiments T2K [18] and NOνA [19], both exploiting the off-axis technique [20]. For our analysis, unless otherwise stated, we will use a representative value of $|\Delta m^2_{31}| = 2.4 \times 10^{-3}$ eV^2 and $\sin^2 2\theta_{23} = 1$. For the solar oscillation parameters Δm^2_{21} and θ_{12}, we will use the best fit values quoted in this introductory section.

2. Formalism

The mixing angle θ_{13} controls $\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$ conversions in long-baseline ν_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, θ_{13}. Therefore, with the possibility of the first measurement of θ_{13} being made by a 1-to 2-km baseline reactor experiment, the long-baseline off-axis ν_e appearance experiments, T2K [18] and NOνA [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, δ. Consider the probability $P(\nu_\mu \to \nu_e)$ in the context of three-neutrino mixing in the presence of matter [22], represented by the matter parameter a, defined as $a \equiv G_F n_e/\sqrt{2}$, where n_e is the average electron number density over the baseline, taken to be constant throughout the present study. Defining $\Delta_{ij} \equiv \frac{\Delta m^2_{ij} L}{4E}$, a convenient and precise approximation is obtained by expanding to second order in the following small parameters: θ_{13}, Δ_{21}/Δ_{32}, Δ_{21}/aL and Δ_{21}. The result is (details of the calculation can be found in Ref. [23], see also Ref. [24]) [1]:

$$P_{\nu_\mu\nu_e} \simeq \left| \sin\theta_{23}\sin 2\theta_{13}\left(\frac{\Delta_{31}}{\Delta_{31} - aL}\right)\sin(\Delta_{31} - aL)e^{-i(\Delta_{32}+\delta)} + \cos\theta_{23}\sin 2\theta_{12}\left(\frac{\Delta_{21}}{aL}\right)\sin(aL)\right|^2 \quad (2)$$

where L is the baseline and $a \to -a$, $\delta \to -\delta$ for $P_{\bar{\nu}_\mu\bar{\nu}_e}$. Suppose $P_{\nu_\mu\nu_e} < P_{\bar{\nu}_\mu\bar{\nu}_e}$: 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 ν, $\bar{\nu}$ 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 δ and of sign(Δm^2_{31}) could be extracted. However, different sets of values of CP–conserving and violating parameters, (θ_{13}, θ_{23}, δ, sign(Δm^2_{31})), 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 $\langle E\rangle/L$ 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 $\sin^2 2\theta_{13} > 0.01$: assume that matter effects are negligible for the short baseline, then at the same $\langle E\rangle/L$, if the oscillation probability at the long baseline is larger than the oscillation probability at the short baseline, one can conclude that the hierarchy is normal, since matter effects enhance the neutrino oscillation probabilities for the normal hierarchy. For the inverted hierarchy the oscillation probability for the long baseline is suppressed relative to the short baseline

3. Our strategy: only neutrino running and two detectors

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 $\langle E\rangle/L$ is the same for the two experiments. Here we explain the advantages of such an strategy versus the commonly exploited neutrino-antineutrino comparison.

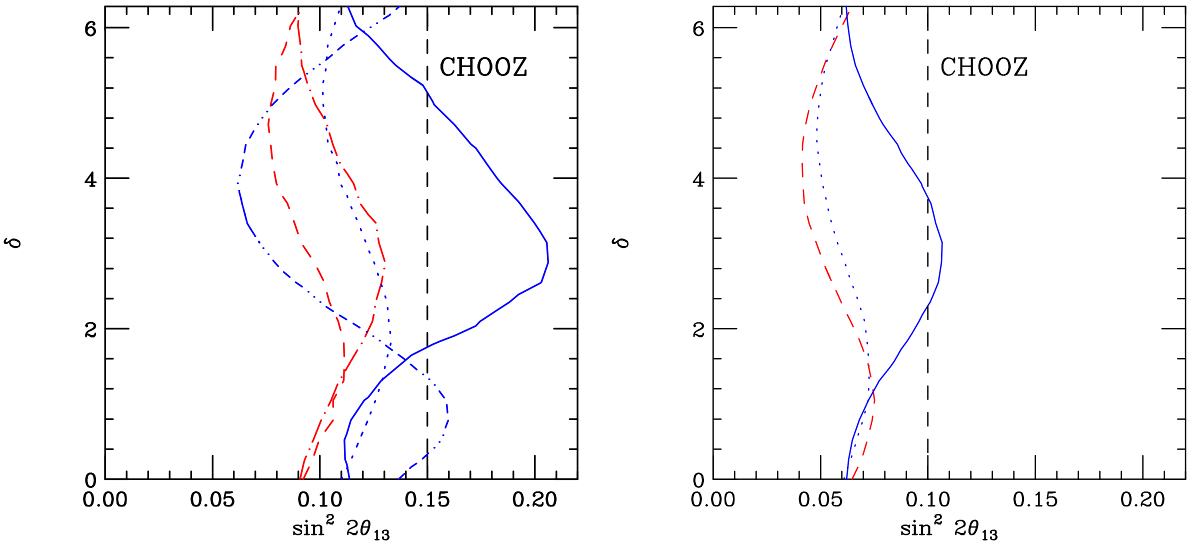
Suppose we compute the oscillation probabilities $P_{\nu_\mu\nu_e}$ and $P_{\bar\nu_\mu\bar\nu_e}$ for a given set of oscillation parameters and the CP-phase δ is varied between 0 and 2π: we obtain a closed CP trajectory (an ellipse) in the bi–probability space of neutrino and antineutrino conversion [28]. In general, the ellipses overlap for a large fraction of values of the CP–phase δ 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 $\mathrm{sign}(\Delta m^2_{31})$ extremely difficult, i. e., the $\mathrm{sign}(\Delta m^2_{31})$-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 $\langle E\rangle/L$ of the near and far experiments is the same, at first order, the ratio of the slopes reads [37]

$$\frac{\alpha_+}{\alpha_-} \simeq 1 + 4\left(a_{\mathrm{N}}L_{\mathrm{N}} - a_{\mathrm{F}}L_{\mathrm{F}}\right)\left(\frac{1}{\Delta_{31}} - \frac{1}{\tan(\Delta_{31})}\right) , \tag{3}$$

where α_+ and α_- 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 $\langle E\rangle/L$ 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 $\langle E\rangle/L$.

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 ν_e appearance experiments, T2K and NOνA. T2K utilizes a steerable



(a) $\Delta m^2_{31} = 2.4 \times 10^{-3}$ eV^2

(b) $\Delta m^2_{31} = 3 \times 10^{-3}$ eV^2

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° *and NO*ν*A far detector at* 12 *km off-axis, in solid blue), T2K at an off-axis angle of* 2.5° *and NO*ν*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° *and NO*ν*A far detector at* 12 *km off-axis (dotted blue curve). (b) The same as (a) but assuming that* $\Delta m^2_{31} = 3.0 \times 10^{-3}$ *eV*^{2} *and only for the three most representative combinations.*

neutrino beam from JHF and Super-Kamiokande and/or Hyper-Kamiokande as the far detector. The beam will peak at 0.65 GeV by placing the detector off-axis by an angle of 2.5° at 295 km. NOνA proposes to use the Fermilab NuMI beam with a baseline of 810 km with a 30 kton low density tracking calorimeter with an efficiency of 24%. Such a detector would be located 12 km off-axis, resulting in a mean neutrino energy of 2 GeV. While for the T2K experiment matter effects are non negligible, albeit small [47], matter effects are quite significant for NOνA. Therefore, the condition (a) is satisfied, since $(aL)_{\mathrm{NO}\nu\mathrm{A}} \simeq 3(aL)_{\mathrm{T2K}}$. What about the condition (b)? A back-of-the-envelope calculation indicates that the current off-axis detector locations are not such that $\langle E \rangle / L$ of the two experiments is the same. However, by placing the detector(s) in slightly different off-axis location(s), one can manage the $\langle E \rangle / L$ of the two experiments to be exactly the same. This neutrino-data strategy would only need half of the time of data taking (because we avoid the antineutrino running), when compared to the standard one (i.e. running in neutrinos and antineutrinos at a fixed energy, E, and baseline, L).

4. Optimizing the NOνA and T2K detector locations

In this section we present what could be achieved if NOνA 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 NOνA experiment, we assume 6.5×10^{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 $\Delta m^2_{31} = 2.4 \times 10^{-3}$ eV^2 (left panel) and $\Delta m^2_{31} = 3 \times 10^{-3}$ eV^2 (right panel) (in light of the recent MINOS results, we explore here the impact of a larger Δm^2_{31}). We show as well the corresponding CHOOZ bound for $\sin^2 2\theta_{13}$. A larger value of Δm^2_{31} implies more statistics and consequently a sensitivity improvement: see Fig. (1) (b), where for the sake of illustration only the three most representative configurations are shown.

If both T2K and NOνA 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° but we change the location of the NOνA 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 δ 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 NOνA 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°, 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° off-axis and the NOνA detector placed at 13 km off-axis.

The combination of data from an upgraded phase (Phase II) of the T2K and/or NOνA 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 Δm^2_{31}.

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 $\Delta m^2_{31} = 2.4 \times 10^{-3}$ 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 ν_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 NOνA experiments. We conclude that the optimal configuration for these experiments would be 14 km off-axis for the NOνA far detector and 2.5° 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 $\Delta m^2_{31} = 2.4 \times 10^{-3}$ eV^2) or if $\sin^2 2\theta_{13} > 0.07$ (for $\Delta m^2_{31} = 3 \times 10^{-3}$ eV^2). A modest upgraded next Phase of both NOνA 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 $\Delta m^2_{31} = 2.4 \times 10^{-3}$ eV^2) and to $\sin^2 2\theta_{13} > 0.025$ (for $\Delta m^2_{31} = 3 \times 10^{-3}$ eV^2).

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