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Terrestrial neutrino experiments and the search for leptonic CP violation

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Abstract. Terrestrial neutrino experiments could be the ideal tool to investigate CP violation in the leptonic sector if the θ_{13} angle of the PMNS matrix is sufficiently high. This condition will be tested by several future long-baseline detectors (Phase I experiments). We discuss the interplay among these experiments and possible synergies. It is shown that, without a dedicated $\bar{\nu}$ run, Phase I experiments cannot reach a sensitivity able to ground (or discourage in a definitive manner) the building of the Phase II projects that are aimed at the determination of the leptonic CP phase. In fact, this capability is almost saturated by high energy beams like CNGS, especially for high values of the ratio $\Delta m^2_{21}/|\Delta m^2_{31}|$. Moreover, we discuss the interplay between on-peak and off-peak experiments and the constraints to the PMNS matrix in case of early evidence for $\nu_\mu \to \nu_e$ oscillations at the athmospheric scale (high θ_{13}).

PACS. 14.60.Pq Neutrino mass and mixing

1 Introduction

CP violation in the leptonic sector could be explored by terrestrial neutrino experiments provided that two conditions related to the mass differences and mixing of neutrinos are fulfilled. The phenomena connected to the CP phase arise from the full three-family interference; they can be detected studying subdominant perturbations of the leading $\nu_\mu \to \nu_\tau$ transition at the atmospheric scale. Hence, if the mass square difference driving the oscillations at the solar scale is completely negligible with respect to the one driving the atmospheric neutrino oscillations, CP effects become unobservable. The recent KAMLAND result strongly supports a high value of the solar Δm^2, corresponding to the LMA solution of the solar neutrino puzzle ($5\ 10^{-5} < \Delta m^2_{12} < 2\ 10^{-4}$ eV^2). Therefore, this result places future proposed experiments searching for CP violation on a firmer ground since it guarantees that subdominant effects will not be suppressed to an unobservable level ($\alpha \equiv \Delta m^2_{sol}/\Delta m^2_{atm} \ll 10^{-2}$). There is, however, a second condition which, at present, remains unconstrained. As for the case of CKM physics, CP violating effects depend on the size of the Jarlskog invariant. Differently from the quark case, the leptonic Jarlskog invariant is enhanced by the large mixing angles θ_{23} and θ_{12}. On the other hand, due to the null result of the CHOOZ and PALO VERDE experiments, the full three-flavor mixing of neutrinos is still unestablished and only upper limits on the $\sin^2 2\theta_{13}$ parameter have been drawn ($\sin^2 2\theta_{13} < \mathcal{O}(10^{-1})$). Moreover, no theoretical inputs are available to constrain the size of θ_{13} in a convincing manner, so that its experimental determination is mandatory. This determination will be carried out by "Phase I" experiments (e.g. JHF-SK or NuMI Off-Axis). Their outcome will encourage (in case of evidence for ν_e appearance) or discourage (null result) the construction of Phase II projects like HyperKamiokande, the Beta Beams or the Neutrino Factories, aimed at the investigation of the size of the CP phase δ. In the following we discuss the limitation of the Phase I/Phase II strategy and possible synergies among the next generation long baseline experiments (MINOS, ICARUS, OPERA, JHF-SK and NuMI-OA). We also discuss the scenarios which can result from high values of θ_{13} (greater than $\sim 7^o$).

2 On-peak and off-peak experiments

The Phase I experiments quoted above employ baselines in the 300-700 km range. In most of the cases, the neutrino energy is optimized to maximize the oscillation probability at the atmospheric scale for the corresponding baseline ($\langle E_\nu \rangle \simeq 0.7 - 3$ GeV). The CNGS experiments, however, make use of a high energy beam, well beyond the kinematic threshold for τ production ($\langle E_\nu \rangle \simeq 17$ GeV). In all cases the subleading oscillations at the solar scale are suppressed by at least one order of magnitude compared with the atmospheric ones. Hence, the $P_{\nu_\mu \to \nu_e}$ oscillation probability can be Taylor expanded in the small parameters

α and $\sin 2\theta_{13}$:

$$
\begin{aligned}
P_{\nu_\mu\to\nu_e} \simeq{}& \sin^2 2\theta_{13}\,\sin^2\theta_{23}\frac{\sin^2[(1-\hat{A})\Delta]}{(1-\hat{A})^2} \\
&- \alpha\sin 2\theta_{13}\,\xi\sin\delta\sin(\Delta)\frac{\sin(\hat{A}\Delta)}{\hat{A}}\frac{\sin[(1-\hat{A})\Delta]}{(1-\hat{A})} \\
&+ \alpha\sin 2\theta_{13}\,\xi\cos\delta\cos(\Delta)\frac{\sin(\hat{A}\Delta)}{\hat{A}}\frac{\sin[(1-\hat{A})\Delta]}{(1-\hat{A})} \\
&+ \alpha^2\cos^2\theta_{23}\sin^2 2\theta_{12}\frac{\sin^2(\hat{A}\Delta)}{\hat{A}^2} \\
\equiv{}& O_1 + O_2(\delta) + O_3(\delta) + O_4 \quad . \qquad (1)
\end{aligned}
$$

In this formula $\Delta \equiv \Delta m^2_{31}L/(4E)$ and the terms contributing to the Jarlskog invariant are split into the small parameter $\sin 2\theta_{13}$, the $\mathcal{O}(1)$ term $\xi \equiv \cos\theta_{13}\sin 2\theta_{12}\sin 2\theta_{23}$ and the CP term $\sin\delta$; $\hat{A} \equiv 2\sqrt{2}G_F n_e E/\Delta m^2_{31}$ with G_F the Fermi coupling constant and n_e the electron density in matter. Note that the sign of $\hat{A}$ depends on the sign of Δm^2_{31} which is positive (negative) for normal (inverted) hierarchy of neutrino masses. Figure 1 shows the size of the $O_1 \ldots O_4$ terms for a typical "on-peak" experiment, i.e. an experiment where the neutrino energy and baseline has been tuned to be at the maximum of the oscillation probability. A few comments are in order. For high values of θ_{13}, the O_1 term completely dominates. Hence, experiments with limited sensitivity to this mixing angle (e.g. MINOS) are able to perform a "pure" θ_{13} measurement, similar to the one that can be carried out by reactor experiments which operate in $\bar{\nu}_e$ disappearance mode and, therefore, have no sensitivity to the CP phase. Going deeper and deeper in the exploration of the θ_{13} parameter range (JHF-SK and NuMI-OA), CP effects start to be sizable and interferences between O_1 and O_2 take place ($\delta - \theta_{13}$ correlation). These considerations hold both for JHF-SK and NuMI-OA. However, the latter exhibits an additional sensitivity to the sign of Δm^2_{atm}. It comes from matter effects which are enhanced by the higher energy and baseline of NuMI compared to JHF. On the other hand, ICARUS and OPERA can be considered "off-peak" experiments. The fact that these experiments are not at the oscillation maximum implies a dumping of the oscillation probability proportional to Δ^2, which is only partially compensated by the rise of the ν_e cross-section interaction, and the dominance of the O_1 and O_3 terms instead of O_1, O_2. Despite the much higher energy, the CNGS experiments are insensitive to matter effects at leading order (O_1). This property is due to the cancellation of the $1-\hat{A}$ terms, resulting from the "off-peak" configuration $(1-\hat{A})\Delta \ll 1$.

3 Phase I → Phase II strategy

It is not difficult to show that neither the on-peak nor the off-peak experiments are optimal Phase I experiments. We expect these experiments to perform a pure measurement of θ_{13} in order to assess the possibility of exploring

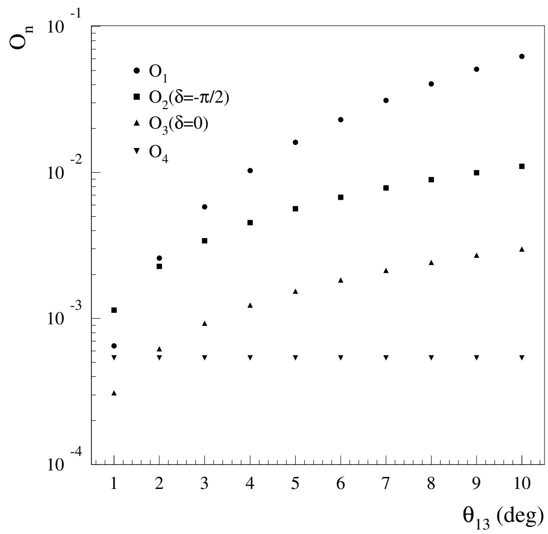

Fig. 1. Contribution of the $O_1 \ldots O_4$ terms to the oscillation probability for JHF-SK

CP violation through Phase II detectors. Alternatively, the data taking should be optimized to allow for decoupling of the effects driven by the size of the θ_{13} angle from the ones driven by the δ phase. Figure 2 shows the $\sin^2 2\theta_{13}$ sensitivity at 90% CL as a function of δ for JHF-SK and CNGS (ICARUS and OPERA combined). Note that for positive values of the CP phase, the δ dependence of JHF-SK has the worst possible behavior for a Phase I experiment, since the minimum sensitivity to $\sin^2 2\theta_{13}$ is achieved at maximum CP violation (maximum discovery potential of Phase II setups). This is clearly related to the choice of a neutrino beam instead of antineutrinos[1]. Similarly, in case of normal hierarchy, the CNGS exhibits maximum sensitivity to θ_{13} for no CP violation ($\delta = 0$).

The fact that these Phase I experiments are not optimal to take decisions on the physics reach of Phase II projects is particularly clear in case of null result. If no evidence of $\nu_\mu \to \nu_e$ oscillation is gained after the Phase I data taking, it will be impossible to lift the $\delta - \theta_{13}$ correlation without additional external information; i.e. it is impossible to decide whether the lack of events is due to the smallness of θ_{13} or it is the outcome of a cancellation effect between a *large* value of θ_{13} and a *large* value of δ. An additional source of ambiguity is present when matter effects are non-negligible (MINOS and NuMI-OA) and the sign of Δm^2_{atm} is unknown. Hence, the only value of θ_{13} that can be safely excluded without a dedicated antineutrino run is the largest value of $\sin^2 2\theta_{13}$ which fits the null hypothesis at the selected confidence level. Clearly, this implies a deterioration of the experimental sensitivity [1]. The size of the cancellation effect increases for high values of Δm^2_{sol}.

[1] The event rate expected for antineutrinos at same oscillation probability is about a factor of three lower than for neutrinos due to the lower π^- flux and $\bar{\nu}_e$ CC cross-section.

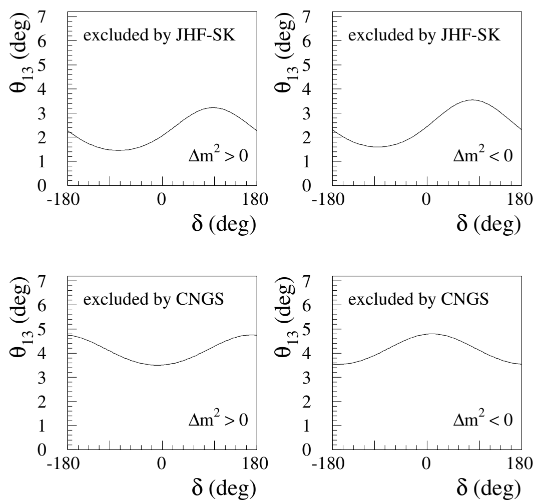

Fig. 2. $\sin^2 2\theta_{13}$ sensitivity at 90% CL versus δ

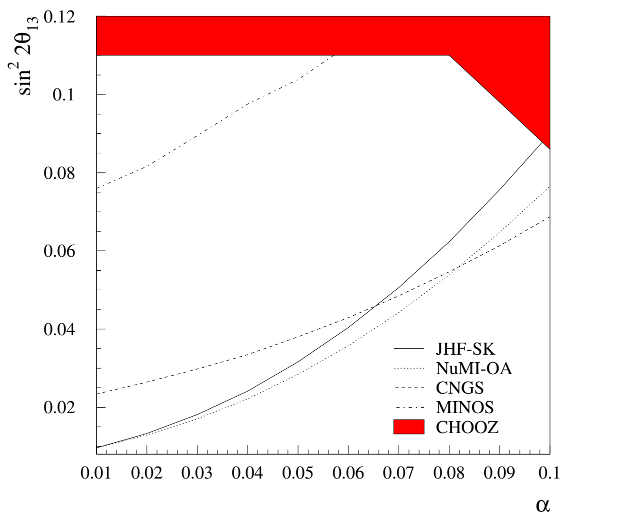

Fig. 3. $\sin^2 2\theta_{13}$ sensitivity at 90% CL versus $\alpha \equiv \Delta m^2_{21}/|\Delta m^2_{31}|$

Figure 3 shows the effective $\sin^2 2\theta_{13}$ sensitivity versus α for mass ratios up to 10^{-1}. As expected, the Phase I experiments loose their capability to perform a "pure" $\sin^2 2\theta_{13}$ measurement in the high-LMA region of Δm^2_{21}, where the precision is comparable with the present CHOOZ limits. Anyway, also in the low-LMA regime JHF-SK and NuMI-OA do not improve significantly the limits that can be obtained by ICARUS and OPERA combined. This limitation can be overcome by a proper antineutrino run of JHF-SK or running synergically JHF-SK and NUMI-OA in ν and $\bar{\nu}$ mode. In particular, even if NuMI-OA starts later than JHF-SK and with lower statistics due to the $\bar{\nu}$ choice, it still retains a significant discovery potential in the parameter region where the $\delta - \theta_{13}$ cancellation effect takes place.

4 Large values of θ_{13}

For high values of θ_{13} ($\theta_{13} \geq 7^\circ$) CNGS could be able to establish $\nu_\mu \to \nu_e$ oscillations at 3σ level for any value of δ [2,3]. In this scenario, a very strong improvement in the measurement of the angle (as a function of δ) is obtained after the JHF-SK data taking. The plots of Fig. 4 show the 90% CL allowed region after 8 years of CNGS data taking combined with a 5-year ν run of JHF-SK (we assume JHF-SK to start about three years later than CNGS). The left (right) plots refer to $\theta_{13} = 10^\circ$, inverted (normal) hierarchy and $\delta = -90^\circ$ (upper), $\delta = 0^\circ$ (middle), $\delta = 90^\circ$ (lower plot). Note that the combined (θ_{13}, δ) band has no more uniform width, as it would be for JHF-SK alone, and shrinking of the region around $\delta = \pm 90^\circ$ results from the combination of experiments with different (θ_{13}, δ) patterns. Clearly, it is possible to lift explicitly the (θ_{13}, δ) correlation after a $\bar{\nu}$ run. For the optimization of the JHF-SK $\nu + \bar{\nu}$ data taking in case of positive signal, we refer to [4].

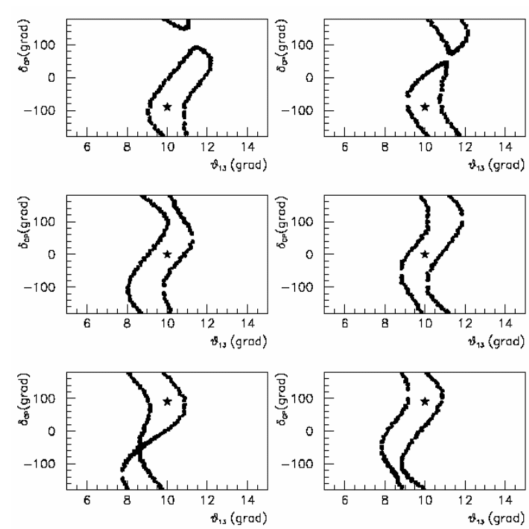

Fig. 4. Left plots: 90% CL allowed region after 8 years of CNGS data taking combined with a 5-year ν run of JHF-SK for $\theta_{13} = 10^\circ$, inverted hierarchy and $\delta = -90^\circ$ (upper), $\delta = 0^\circ$ (middle), $\delta = 90^\circ$ (lower plot). The plots on the right show the corresponding regions for normal hierarchy

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