Phenomenology of future neutrino oscillation experiments

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Abstract
I give a brief overview of the phenomenology related to the measurements of the last unknown lepton mixing angle θ_{13}, CP violation (CPV) in neutrino oscillations, and the neutrino mass hierarchy (MH). Sensitivities of upcoming reactor and accelerator experiments to θ_{13} are discussed, showing that within a few years values of $\sin^2 2\theta_{13} \gtrsim 10^{-2}$ will be probed, while CPV and MH measurements will be very difficult with that generation of experiments. I make some selected remarks on CPV and MH determinations with a subsequent generation of experiment consisting of a high precision/high luminosity oscillation facility. In particular, I emphasize the possibility to explore synergies of such an advanced accelerator facility with a huge multi-purpose detector.

1 Introduction

Neutrino oscillations have been firmly established in the last ten years or so by a beautiful series of experiments with neutrinos from the sun [1], the Earth's atmosphere [2], nuclear reactors [3], and accelerators [4, 5]. While these measurements have discovered and confirmed the dominant effective 2-flavor oscillation modes, it will be the purpose of the upcoming generation of oscillation experiments to discover sub-leading effects. This includes the tasks: (i) the determination of the small lepton mixing angle θ_{13}, (ii) establishing CP violation (CPV) in neutrino oscillations, which corresponds to a value of the Dirac CP phase $\delta_{\rm CP} \neq 0, \pi$, and (iii) identification of the type of the neutrino mass hierarchy (MH), which can be normal ($\Delta m^2_{31} > 0$) or inverted ($\Delta m^2_{31} < 0$), where $\Delta m^2_{31} \equiv m^2_3 - m^2_1$.

Other crucial measurements in the neutrino sector are the determination of the absolute neutrino mass scale. This can be done by investigations of the electron spectrum from Tritium β-decay close to the endpoint, or by the search for neutrino-less double-beta decay [6]. An observation of the latter process would imply that lepton number is not conserved and that neutrinos are Majorana particles [7]. This would be a ground-breaking discovery with far reaching consequences for our understanding of how to extend the Standard Model of particle physics in order to provide mass to neutrinos [8] and for the Leptongenesis mechanism to generate the Baryon number in the universe. A determination of the absolute neutrino mass will have important implications for cosmology [9].

While the title of my presentation has been "Neutrino Phenomenology" I focus the discussion in the following on the phenomenology of upcoming and future oscillation experiments. This choice is due to space limitations and the main theme of this conference. But I emphasize here the importance of the absolute mass measurements mentioned in the previous paragraph. The present status of neutrino oscillations is discussed in [10–12]. Furthermore, I concentrate on the standard three-flavor picture. The importance to look for non-standard effects has been discussed in [10, 13].

2 Upcoming oscillation experiments and the road towards θ_{13}

There are several neutrino oscillation experiments currently under construction, which are expected to start data taking soon. These are the reactor neutrino experiments Double Chooz [14], Daya Bay [15], RENO [16] and the accelerator experiments T2K [17] and NOνA [18], see [19]. The main goal of these experiments is the search for the last unknown mixing angle θ_{13}.

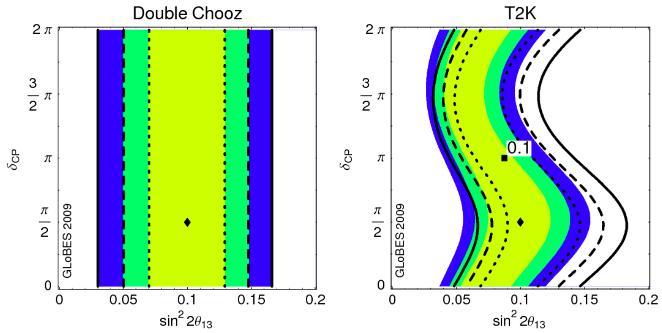

Fig. 1: Fits in the θ_{13}-$\delta_{\rm CP}$ plane for $\sin^2 2\theta_{13} = 0.1$ and $\delta_{\rm CP} = \pi/2$ for Double Chooz and T2K. A normal simulated hierarchy is assumed. The contours refer to 1σ, 2σ, and 3σ (2 d.o.f.). The fit contours for the right fit hierarchy are shaded (colored), the ones for the wrong fit hierarchy fit are shown as curves. The best-fit values are marked by diamonds and boxes for the right and wrong hierarchy, respectively, where the minimum χ^2 for the wrong hierarchy is explicitly shown [21].

Reactor experiments aim at this goal by exploring the disappearance of $\bar{\nu}_e$. The corresponding survival probability is given to very good accuracy by

$$P_{ee} = 1 - \sin^2 2\theta_{13} \sin^2 \frac{\Delta m^2_{31} L}{4E_\nu} \,, \tag{1}$$

where E_ν is the neutrino energy and L is the distance from the neutrino source to the detector. This simple dependence shows that reactor experiments provide a clean measurement of $\sin^2 2\theta_{13}$, not affected by correlation or degeneracies with other unknown parameters [20]. The main issue in such an experiment are statistical and systematical errors, where the latter are going to be addressed by comparing data for near and far detectors. In contrast, the Superbeam experiments look for the appearance of ν_e from a beam consisting initially mainly of ν_μ. At leading order in the small parameters $\sin 2\theta_{13}$ and $\tilde{\alpha} \equiv \sin 2\theta_{12} \Delta m^2_{21} L/4E_\nu$ the relevant oscillation probability (in vacuum, for simplicity) is

$$\begin{aligned} P_{\mu e} &= \sin^2 2\theta_{13} \, \sin^2 \theta_{23} \, \sin^2 \Delta + \tilde{\alpha}^2 \, \cos^2 \theta_{23} \\ &+ \sin 2\theta_{13} \sin 2\theta_{23} \, \tilde{\alpha} \sin \Delta \cos(\Delta \pm \delta_{\rm CP}) \,, \end{aligned} \tag{2}$$

where $\Delta \equiv \Delta m^2_{31} L/4E_\nu$, and '+' ('$-$') holds for neutrinos (anti-neutrinos). This expression shows that there is a complicated correlation of $\sin^2 2\theta_{13}$ with other parameters, especially with the CP phase $\delta_{\rm CP}$. This effect is illustrated in Fig. 1, where the allowed region in the plane of $\sin^2 2\theta_{13}$ and $\delta_{\rm CP}$ is shown for Double Chooz and T2K. For the T2K Superbeam the allowed regions show a typical 'S'-shape, reflecting the trigonometric dependence of the probability on $\delta_{\rm CP}$. Furthermore, solutions with the wrong mass hierarchy introduce another ambiguity in the interpretation. On the other hand, the figure shows that a reactor experiment can determine $\sin^2 2\theta_{13}$ unambiguously.

In Ref. [21] the potential of this next generation of experiments towards the three tasks mentioned above has been evaluated. Tab. 1 summarizes the key parameters of the considered experiments, for further details see [21]. The analysis is performed by using the GLoBES software [22]; the corresponding `glb`-files are available at the GLoBES web-page [22] including detailed technical information on the simulation. In all cases the strategy is to follow as close as possible the original Letters of Intent or Technical Design Reports. We have made sure that our sensitivities agree with the "official" curves from the corresponding collaborations under the same assumptions.

In Ref. [21] various performance indicators have been considered for the nominal configurations of the experiments, such as sensitivity to θ_{13}, potential for large θ_{13}, accuracy to the atmospheric parameters

Setup	t_ν [yr]	$t_{\bar{\nu}}$ [yr]	$P_{\rm Th}$ or $P_{\rm Target}$	L [km]	Detector technology	$m_{\rm Det}$
Double Chooz	-	3	8.6 GW	1.05	Liquid scintillator	8.3 t
Daya Bay	-	3	17.4 GW	1.7	Liquid scintillator	80 t
RENO	-	3	16.4 GW	1.4	Liquid scintillator	15.4 t
T2K	5	-	0.75 MW	295	Water Cerenkov	22.5 kt
NOνA	3	3	0.7 MW	810	TASD	15 kt

Table 1: Summary of the standard setups for the upcoming oscillation experiments at their nominal luminosities.

θ_{23}, $|\Delta m^2_{31}|$, CP-violation, and mass hierarchy. In the following we show as an important result the prospective time evolution of the sensitivity to θ_{13}. These calculations are based as much as possible on official statements of the collaborations. Although the assumed schedules and proton beam plans may turn out to be not realistic in some cases, our toy scenario will be illustrative to show the key issues for the individual experiments within the global neutrino oscillation context. The sensitivities are shown as a function of time assuming that data are continuously analyzed and results are available immediately.

The key assumptions for our toy scenario are as follows. Double Chooz starts late 2009 and runs 1.5 years with far detector only, then with far and near detector. RENO and Daya Bay start mid 2010 and mid 2011, respectively, with all detectors on-line. T2K starts late 2009 with virtually 0 MW beam power, which increases linear to 0.75 MW reached in 12/2012. From then we assume the full target power of 0.75 MW. The beam runs only with neutrinos. NOνA starts mid 2012 with full beam (0.7 MW), but 2.5 kt detector mass only. Then the detector mass increases linearly to 15 kt in 01/2014. From then we assume the full detector mass of 15 kt. The beam runs with neutrinos first, until the equivalent of three years operation at nominal luminosity (c.f., Tab. 1) is reached, i.e., 03/2016. Then it switches (possibly) to anti-neutrinos and runs at least until 2019.

We show the θ_{13} sensitivity limit (bound on θ_{13} in case of no signal) as a function of time in Fig. 2 (left). We observe that the global sensitivity limit will be dominated by reactor experiments. As soon as operational, Daya Bay will dominate the global limit. For Daya Bay, time is not critical, but matching the systematics or statistics goals is.[1] If the assumed schedules of both, Double Chooz and Daya Bay are matched, Double Chooz will dominate the θ_{13} sensitivity for about two years in the absence of RENO. If available, RENO, on the other hand, will dominate the θ_{13} sensitivity if it is operational significantly before the end of 2011. As a peculiarity, the θ_{13} sensitivity of NOνA is improved by switching to anti-neutrinos. However, the global limit will at that time be dominated by the reactor experiments.

The θ_{13} discovery potential (smallest θ_{13} which can be distinguished from zero) is shown in Fig. 2 (right) as a function of time. For the beam experiments, the dependence on the true value of $\delta_{\rm CP}$ is shown as shaded region, whereas the reactor experiments are not affected by the true $\delta_{\rm CP}$. There is a small dependence on the true mass hierarchy for the beam experiments, here we choose a true normal hierarchy. The comparison of the left and right panels in Fig. 2 shows that suitable values of $\delta_{\rm CP}$ may significantly improve the discovery potential of beams compared to their sensitivity limit. Indeed, for favorable values of $\delta_{\rm CP}$ the discovery reach of beams can be similar to the one of Daya Bay, whereas the sensitivity limit is more like the one from Double Chooz.

[1] The Daya Bay assumptions of a systematical error of 0.18%, fully uncorrelated among all detectors is more aggressive than for other reactor experiments. For example, if the systematic error is at the level of 0.6% (such as assumed in Double Chooz) and uncorrelated among modules, the Daya Bay sensitivity of $\sin^2 2\theta_{13} = 0.0066$ deteriorates to $\sin^2 2\theta_{13} \simeq 0.01$. If on the other hand the systematic error is 0.38% (the Daya Bay "baseline" value) and assumed to be fully correlated among modules at one site the limit would correspond roughly to the one obtained for an uncorrelated error of $0.38\% \times \sqrt{N} \simeq 0.76\%$ for $N = 4$ modules at the far site. This will lead to a limit of $\sin^2 2\theta_{13} \simeq 0.012$ [23].

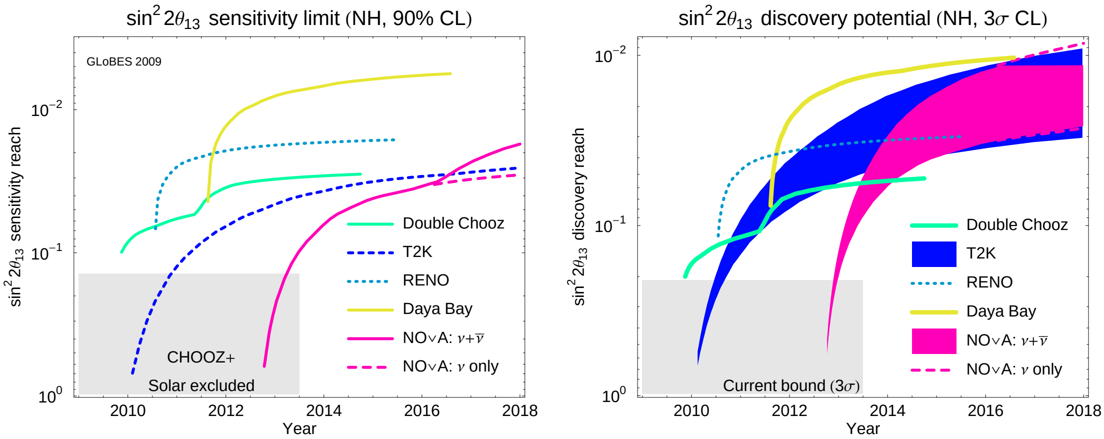

Fig. 2: Left: Evolution of the θ_{13} sensitivity limit as a function of time (90% CL), i.e.,, the 90% CL limit which will be obtained if the true θ_{13} is zero. Right: Evolution of the θ_{13} discovery potential as a function of time (3σ CL), i.e.,, the smallest value of θ_{13} which can be distinguished from zero at 3σ. The bands reflect the (unknown) true value of $\delta_{\rm CP}$. In both panels we assume normal hierarchy [21].

3 CP violation and the neutrino mass hierarchy

3.1 Phenomenology

In the case a non-vanishing value of θ_{13} the possibility of CP violation in neutrino oscillations opens up, which implies that the vacuum oscillation probabilities are different for neutrinos and anti-neutrinos. From Eq. 2 one finds

$$P_{\bar\nu_\mu\to\bar\nu_e} - P_{\nu_\mu\to\nu_e} = \sin 2\theta_{13}\sin 2\theta_{23}\,\tilde\alpha\,\sin 2\Delta\,\sin\delta_{\rm CP}\,. \tag{3}$$

Hence, the CP asymmetry is suppressed by the small numbers $\sin 2\theta_{13}$ and $\tilde\alpha$, is proportional to $\sin\delta_{\rm CP}$, and hence, CP is violated for values of $\delta_{\rm CP} \neq 0, \pi$. In a real experiment, however, $P_{\bar\nu_\mu\to\bar\nu_e} - P_{\nu_\mu\to\nu_e}$ can never be directly observed, but it has to be inferred from the event rates obtained in the neutrino and anti-neutrino running modes. They will always be different, since the neutrino and anti-neutrino fluxes and cross sections are different, and in general the matter effect leads to different oscillation probabilities, even if $\delta_{\rm CP} = 0$ or π. The conventional strategy for the search for CPV is to assume standard three-flavor oscillations and standard matter effect, and extract the value of $\delta_{\rm CP}$ by performing a parametric fit to the data, subject to all kinds of uncertainties including neutrino fluxes, cross sections, and experimental parameters.

Let us now discuss the determination of the neutrino mass hierarchy. It can be shown from Eq. 2 that the vacuum oscillation probability is invariant under the transformation [24, 25]

$$\Delta m^2_{31} \to -\Delta m^2_{31}\,, \qquad \delta_{\rm CP} \to \pi - \delta_{\rm CP}\,. \tag{4}$$

This is usually called the sgn(Δm^2_{31})-degeneracy. The key to break the degeneracy and determine the neutrino mass hierarchy is the matter effect [26]. The size of the matter effect is controlled by the dimensionless parameter

$$A \equiv \left|\frac{2E_\nu V}{\Delta m^2_{31}}\right| \simeq 0.09\left(\frac{E_\nu}{\rm GeV}\right)\left(\frac{|\Delta m^2_{31}|}{2.5\times 10^{-3}\,{\rm eV}^2}\right)^{-1}\,. \tag{5}$$

where V is the matter potential. For experiments at the first oscillation maximum, $|\Delta m^2_{31}|L/2E_\nu \simeq \pi$, we have

$$A \simeq 0.02\left(\frac{L}{100\,{\rm km}}\right)\,. \tag{6}$$

It can be shown, e.g., [27], that terms linear in A cannot break the sgn(Δm^2_{31})-degeneracy. Moreover, if the matter effect cannot be neglected but the degeneracy cannot be lifted, the sensitivity to CPV can be destroyed. While in vacuum the degeneracy according to Eq. 4 does not mix CP violating and conserving values of $\delta_{\rm CP}$, this is no longer true in the presence of matter effects. In this case it may happen that the sgn(Δm^2_{31})-degenerate solution is located at a CP conserving value of $\delta_{\rm CP}$, even if the true value is CP violating.

In order to break the degeneracy one has to be sensitive to higher order terms in A, i.e., it is necessary to go the the regime of strong matter effect $A \gtrsim 0.2$. This requires baselines $L \gtrsim 1000$ km and energies $E_\nu \gtrsim 3$ GeV. For $A \approx 1$ the matter effect leads to a resonance [28] in $\nu_\mu \to \nu_e$ oscillations. The resonance condition is

$$\pm\frac{2E_\nu V}{\Delta m^2_{31}} = \cos 2\theta_{13} \approx 1\,, \tag{7}$$

where '$+$' ('$-$') holds for neutrinos (anti-neutrinos). This condition can be fulfilled for neutrino if $\Delta m^2_{31} > 0$ (normal hierarchy) and for anti-neutrinos if $\Delta m^2_{31} < 0$ (inverted hierarchy). Therefore, the determination of the MH amounts to finding out whether the resonance occurs for neutrinos or anti-neutrinos.

3.2 CPV and MH with upcoming experiments?

While the primary goal for the upcoming experiments discussed in Sec. 2 is the discovery of the yet unknown mixing angle θ_{13}, it might also be interesting to ask the question, whether there is some chance to address also CPV and MH, in case θ_{13} is relatively large. Therefore, we investigate whether "modest upgrades" to the proposed setups of T2K and NOνA might allow to address these issues. With "modest upgrades" we mean modifications of existing equipment and infrastructure. This includes a longer running time and an upgraded beam power for both accelerator experiments and the addition of anti-neutrino running in T2K. To be specific, we assume that a proton driver is installed for T2K, which increases the beam power from 0.75 to 1.66 MW, linearly from 2015 to 2016 [29], and for NOνA we assume a linear increase from 0.7 to 2.3 MW from March 2018 to March 2019 according to "Project X" [30]. We consider these upgraded beams for T2K and NOνA combined with reactor data, and we have performed a global optimization for the switching between neutrinos and anti-neutrinos in both beams.

Fig. 3 shows the discovery potential as a function of true $\sin^2 2\theta_{13}$ and fraction of true $\delta_{\rm CP}$ for times from 2015 to 2025. From the upper row of this figure we conclude that at the 90% confidence level, there will be hints for the MH and CPV for $\sin^2 2\theta_{13} \gtrsim 0.05$ for most values of $\delta_{\rm CP}$ around 2025. However, certainly a 90% CL is not sufficient to make any meaningful statement about a discovery. Therefore, we show in the lower row of Fig. 3 the corresponding results at 3σ CL. Obviously the sensitivity regions reduce drastically. Still, assuming both beams upgraded, a fully optimized neutrino/anti-neutrino run plan, and data from reactors, a non-negligible discovery potential at 3σ will be reached in 2025. The mass hierarchy can be identified for $\sin^2 2\theta_{13} \gtrsim 0.05$ for about 20% to 40% of $\delta_{\rm CP}$ values, whereas CPV can be discovered for $\sin^2 2\theta_{13} \gtrsim 0.02$ for 25% of $\delta_{\rm CP}$ values. In both cases, MH and CPV, there is sensitivity for values of $\delta_{\rm CP}$ around $3\pi/2$ ($\pi/2$) if the true hierarchy is normal (inverted). This is related to the sign of the matter effect, see, e.g., Ref. [31] for a discussion.

Although "minor upgrades" of existing facilities may provide a non-negligible sensitivity to CPV and the MH, there is high risk associated with this strategy, since for about 75% of all possible values for $\delta_{\rm CP}$ no discovery will be possible at the 3σ level. Therefore, we conclude that the upcoming generation of oscillation experiments may lead to interesting indications for the mass hierarchy and CP violation, but it is very likely that an experiment beyond the upcoming Superbeams (including reasonable upgrades) will be required to confirm these hints. A significant increase of exposures is needed, which implies the need to push beam luminosities as well as detector sizes beyond the present state-of-the-art. The considered options for such a subsequent generation of experiments are high-precision oscillation experiments based on a Superbeam, a Beta Beam, or a Neutrino Factory. Such facilities have been extensively discussed at

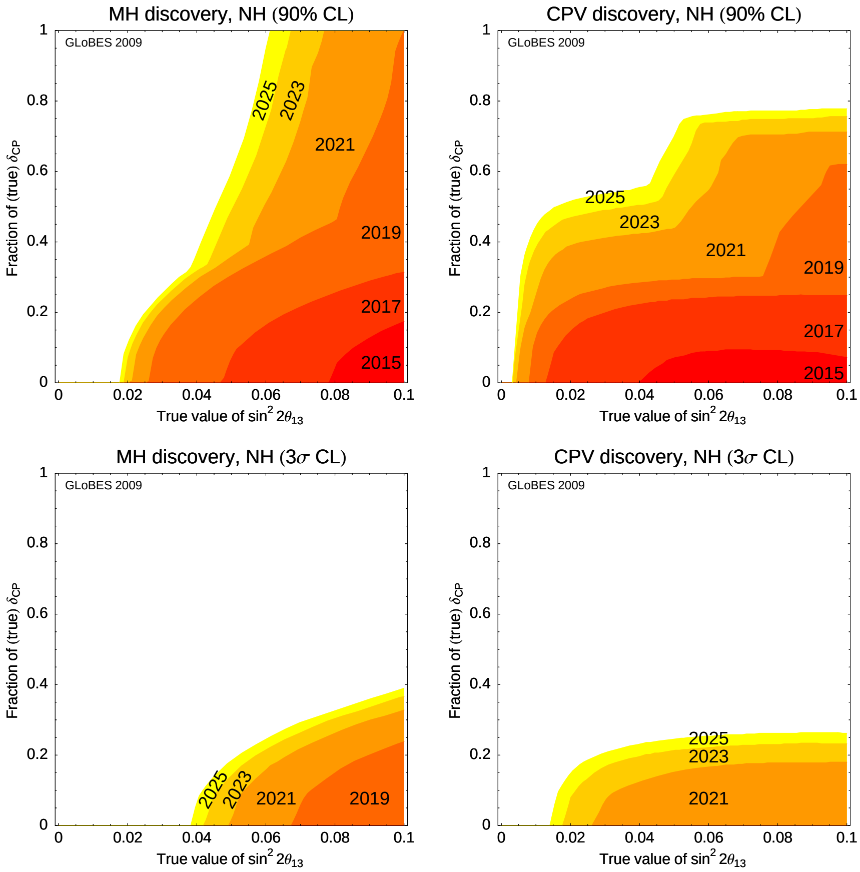

Fig. 3: Mass hierarchy (left panels) and CP violation (right panels) discovery potentials as a function of true $\sin^2 2\theta_{13}$ and fraction of true $\delta_{\rm CP}$ for T2K+NOνA (including beam upgrades and global $\nu/\bar{\nu}$-optimization) and reactor experiments. The upper panels are for 90% CL, the lower panels for 3σ CL. The different shadings corresponds to different points in time [21].

the conference. Comparative physics sensitivity studies have been performed [32] and are ongoing [33, 34]. In the following two sub-sections I want to make some remarks on selected aspects of the CPV and MH measurements.

3.3 The CPV measurement in Superbeam experiments and systematical uncertainties

In Ref. [35] we have investigated the impact of systematic uncertainties on the sensitivity to CPV of Superbeam experiments. We have studied the impact of a large number of possible systematical errors (see Fig. 1 of that paper), and as a specific example we chose T2HK (the T2K beam upgraded to 4 MW and a 500 kt water Cerenkov detector at Kamioka "HyperKamiokande"). However, our main results should be applicable to all Superbeam experiments using a narrow band beam. We implemented a realistic description of the far detector and a near detector is explicitly included in the simulation. The crucial observation is that in an appearance experiment not all uncertainties cancel between near and far detectors. The main result is summarized Fig. 4.

We can identified two qualitatively different regimes depending on the size of θ_{13}. For small values, close to the sensitivity limit, the main issue is the uncertainty on the background. In this case the performance depends on the ability of the near detector to predict the background in the far detector. In the regime of large θ_{13} ($\sin^2 2\theta_{13} \gtrsim 0.01$, which is probably the more interesting range for this type of

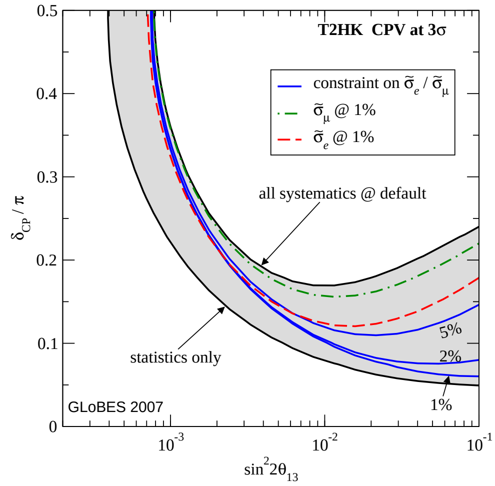

Fig. 4: T2HK CPV sensitivity at 3σ for a default choice of systematical errors and for statistical errors only (curves delimiting the shaded region). We show also the sensitivity if certain constraints on the product of cross sections times efficiencies $\tilde{\sigma}$ are available: 1% accuracies on $\tilde{\sigma}_{\nu_e}$ and $\tilde{\sigma}_{\nu_\mu}$ for neutrinos and anti-neutrinos, and 5%, 2%, 1% accuracies on the ratios $\tilde{\sigma}_{\nu_e}/\tilde{\sigma}_{\nu_\mu}$ for neutrinos and anti-neutrinos [35].

experiments) backgrounds are a minor issue and the uncertainty on the signal itself dominates. We find that the impact of systematics even with a near detector is rather strong in this regime. For instance, for T2HK at $\sin^2 2\theta_{13} = 0.1$ the smallest $\delta_{\rm CP}$ for which CPV can be established increases from 0.05π for the statistics only case to 0.24π when systematics are included.

However, we were able to identify crucial combinations of parameters, which, when well constrained (at the level of $\lesssim 2\%$) can restore the sensitivity nearly to its statistics only value, namely

– the ratios of the effective ν_μ and ν_e cross sections $\tilde{\sigma}_{\nu_\mu}/\tilde{\sigma}_{\nu_e}$ for neutrinos and anti-neutrinos, or
– the ratios of the effective cross sections between neutrinos and anti-neutrinos, for ν_e and ν_μ, or
– the initial flux of ν_μ and the effective ν_e cross section, both for neutrinos and anti-neutrinos.

With the effective cross section $\tilde{\sigma}$ we mean here the product between physical cross section and detection efficiency. The success of a Superbeam experiment in the regime $\sin^2 2\theta_{13} \gtrsim 0.01$ will depend to a significant degree on the information available on at least one of these combinations.

Theoretical cross section calculations indicate that the uncertainty on the ratio $\sigma_{\nu_\mu}/\sigma_{\nu_e}$ might actually be at the level of few percent in the T2K energy range of around 700 MeV. However, this result has not been tested experimentally. We stress that this would be a crucial input in the analysis of a Superbeam experiment which is not based on any data. Future cross section experiments such as for example MINERνA may provide a measurement of σ_{ν_μ} at the 5% level. However, from present perspective it seems difficult to obtain a precise measurement for electron neutrino and anti-neutrino cross sections, which are essential for predicting the appearance signal. Maybe the only places where these cross sections can be measured in the relevant energy range are Beta Beams or a Neutrino Factory. Note that the absolute normalization of the cross sections is needed, which always is subject to uncertainties on initial fluxes. Precise information on fluxes may be obtained from Hadron production experiments, such as MIPP, HARP or NA61/SHINE.

The results of [35] indicate that spectral information plays an important role in limiting the effect of systematical uncertainties. This suggests that the behavior of a wide band Superbeam will be different. Without a detailed simulation it is hard to estimate quantitatively whether the impact of systematics is significantly less than in the case of the off-axis configuration considered here, and clearly investigations along these lines would be an interesting topic for future work.

For a Beta Beam in principle similar considerations apply as in the case of the Superbeam, however there are some important differences. First, the initial flux of electron neutrinos is known to good precision. Second, since the signal here is ν_μ appearance, the relevant cross sections are much easier to measure at a MINERνA type experiment. Hence, it seems easier to constrain the Beta Beam equivalent of the last combination of quantities listed above, namely ν_e fluxes and ν_μ cross sections. As already mentioned, a close detector at a Beta Beam would probably be an ideal place to measure the electron cross sections needed for a Superbeam experiment. In particular, in the combination of a Beta Beam and a Superbeam (such as for example the CERN to MEMPHYS @ Frejus configuration [36]), each furnished with near and far detectors, many systematics should cancel in principle.

The optimal facility concerning systematics seems to be a Neutrino Factory. In this case intense fluxes of all four flavors $\Phi_{\nu_e}, \Phi_{\bar{\nu}_e}, \Phi_{\nu_\mu}, \Phi_{\bar{\nu}_\mu}$ are available at the near detector, and they are known with very good precision. Hence, all cross sections can be measured accurately at the near detector, which allows to predict the appearance signal in the far detector basically free of systematics on fluxes and cross sections. A study along these lines has been performed in [37]. We note, however, that in case of the Neutrino Factory another important systematics (at large θ_{13}) is the uncertainty on the matter density. Its effect on the CP violation sensitivity has been discussed in [38] together with possibilities to reduce it.

3.4 The MH and synergies of accelerator and non-accelerator measurements

The sensitivity of long-baseline experiments to the MH crucially depends on the value of θ_{13}. For very small values $\sin^2 2\theta_{13} \lesssim 10^{-2}$ its measurement becomes exceedingly difficult, and because of the reasons discussed in Sec. 3.1 only experiments with baselines $L \gtrsim 1000$ km can do the job. These could be an experiment from Fermilab to the DUSEL site (e.g., a wide-band Superbeam [39] or a low-energy Neutrino Factory [40, 41]), or a "standard" Neutrino Factory, which typically has two baselines of order 3000 km and 7000 km, see e.g., [38]

However, if θ_{13} turns out to be relatively large, $\sin^2 2\theta_{13} \gtrsim 10^{-2}$, also experiments with somewhat shorter baselines may be able to address the MH measurement by exploring synergies of complementary data. In particular, many of the discussed long-baseline experiments use a huge detector (e.g., water Cerenkov or liquid Argon, see [42] and several contributions to this conference) which will unavoidable record atmospheric neutrinos with unprecedented statistics. In Ref. [43] we pointed out that three-flavor effects in atmospheric neutrino oscillations provide valuable complementary information which can be used to resolve degeneracies in the long-baseline data.

Here we illustrate the synergies from a combined LBL+ATM analysis at the examples of the T2K phase II experiment (T2HK) with the HyperKamiokande detector of 450 kt fiducial mass, and two experiments with beams from CERN to a 450 kt detector at Frejus (MEMPHYS) [36], namely the SPL Superbeam and a $\gamma = 100$ Beta Beam (βB). The LBL experiments are simulated with the GLoBES software [22], and a general three-flavor analysis of ATM data is performed [36, 43, 44]. For each experiment we assume a running time of 10 years, where the neutrino/anti-neutrino time is chosen as 2+8 years for SPL and T2HK, and 5+5 years for the Beta Beam. The Superbeam powers are taken as 4 MW and for the Beta Beam we assume $5.8\,(2.2) \times 10^{18}$ He (Ne) decays/yr, see [36] for details.

In Fig. 5 we show the sensitivity to the neutrino mass hierarchy. For LBL data alone there is practically no sensitivity for the CERN–MEMPHYS experiments (because of the very small matter effects due to the relatively short baseline of 130 km), and the sensitivity of T2HK depends strongly on the true value of $\delta_{\rm CP}$. The non-trivial sensitivity of the SPL+βB combination without ATM data is based on a subtle effect due to the interplay of CP, T, and CPT conjugated oscillation channels [27, 45]. Indeed, this combination offers data from all possible channels ($\nu_\mu \to \nu_e, \nu_e \to \nu_\mu, \bar{\nu}_\mu \to \bar{\nu}_e, \bar{\nu}_e \to \bar{\nu}_\mu$). However, with the LBL+ATM combination all experiments can identify the mass hierarchy at 2σ CL provided $\sin^2 2\theta_{13} \gtrsim 0.02 - 0.03$. Let us stress that according to Fig. 2 we will know very soon whether θ_{13} is in that range.

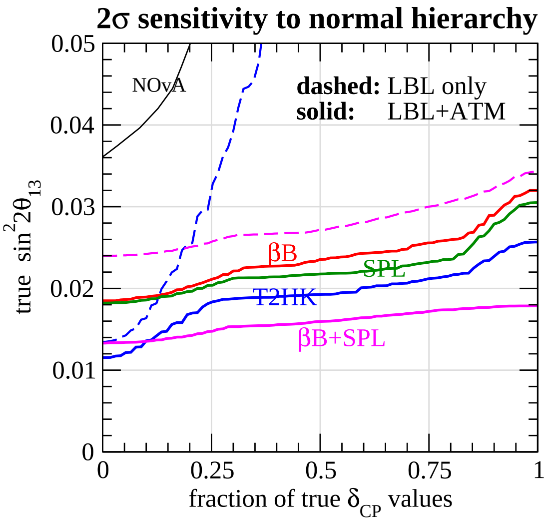

Fig. 5: Sensitivity at 2σ to the neutrino mass hierarchy as a function of $\sin^2 2\theta_{13}$ and $\delta_{\rm CP}$ for $\theta_{23}^{\rm true} = \pi/4$ and a true normal hierarchy. Solid curves correspond to LBL+ATM data combined, the dashed curves correspond to LBL data-only. βB and SPL without ATM have no sensitivity to the hierarchy [36].

In the opinion of the author it is important to combine any advanced neutrino beam with a detector capable of a rich physics program, also beyond the long-baseline measurements, such as for example the search for proton decay or neutrinos of astrophysical origin, see, e.g., [42]. Therefore, synergies such as the one discussed in this subsection should be explored. In Ref. [46] we pointed out the possibility to use such a (non-magnetized) multi-purpose detector also in the context of a (low energy) Neutrino Factory, especially if θ_{13} is relatively large. While the feasibility of this idea remains to be demonstrated, we think that the overall physics gain of such a combination could be high, and further investigations in this direction should be pursued.

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