CP, T and CPT violation in future long baseline experiments

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Abstract. I give a short overview about the possibilities and problems related to the measurement of CP violation in long baseline experiments. Special attention is paid to the issue of degeneracies and a method for their resolution is quantitatively discussed. The CP violation reach for different experiments is compared in dependence of $\sin^2 2\theta_{13}$ and Δm^2_{21}. Furthermore a short comment about the possible effects of matter induced T violation is made. Finally the limits on CPT violation obtainable at a neutrino factory are shown.

1. CP violation

In contrast to the quark sector CP violation in the lepton sector can be potentially large. This has spurred great interest in the possible measurement of the leptonic Dirac-type CP-phase δ_{CP} especially in the context of a planed neutrino factory [1, 2]. The principal observable is the CP-odd probability difference $\Delta P^{CP}_{\alpha\beta} = P_{(\alpha\rightarrow\beta)} - P_{(\bar{\alpha}\rightarrow\bar{\beta})}$. Since the neutrinos travel a long distance trough the Earth matter one has to include matter effects. The Earth is however CP-asymmetric by itself, thus it introduces a non-vanishing $\Delta P^{CP}_{\alpha\beta}$ even if $\delta_{CP} = 0$. This makes it difficult to use $\Delta P^{CP}_{\alpha\beta}$ as measure of δ_{CP}. Furthermore there are, due to the form of the oscillation probabilities, strong correlations among several oscillation parameters. Besides that a long baseline experiment does not measure the probabilities themselves but event rates. There are many systematical uncertainties in translating a rate measurement into a measurement of the probability. In addition to those problems the oscillation probabilities allow for different sets of parameters which give approximately the same probabilities. This is known as the degeneracy problem. In observing only the transition between electron and muon neutrinos or anti-neutrinos there remain three possible degeneracies: the $(\delta_{CP}, \theta_{13})$ ambiguity [3], the signΔm^2_{31} degeneracy [4] and the $(\theta_{23}, \pi/4 - \theta_{23})$ degeneracy [5]. Those degeneracies can have a substantial impact on the ability of a given experiment to reach its physics goals. The results shown in the following are a small subset of the results obtained in [6].

The setups considered are listed in table 1. Further details can be found in [6]. Of all the systematical errors considered in [6] the most important for the JHF setups is the background normalization uncertainty, whereas the NuFact setups are in general little hindered by systematical errors.

In [6] a complete analysis of the multi parameter correlations was performed, taking into account external information on Δm^2_{21} provided by KamLand and on the

JHF-SK	JHF-HK	NuFact-I	NuFact-II
22.5 kt	1 000 kt	10 kt	50 kt
water Cherenkov	water Cherenkov	magnetized iron calorimeter	magnetized iron calorimeter
0.75 MW	4 MW	0.75 MW	4 MW
5 years	8 years	5 years	8 years

Table 1. Definition of experimental setups.

matter density provided by geophysics. For Δm^2_{21} an error of 15% and for the matter density an error of 5% is assumed. The biggest source of correlation errors for all setups is the correlation between θ_{13} and δ_{CP}. This is an intrinsic effect which is very hard to fight. For the NuFact scenarios the matter density plays a crucial rule and one should seek to improve the knowledge on this quantity.

The $(\theta_{23}, \pi/4 - \theta_{23})$ degeneracy has only little impact on the determination of δ_{CP} in all cases. The influence of the $(\delta_{CP}, \theta_{13})$ ambiguity is strongest at a NuFact and its effects strongly depend on subtle details of the expected detector performance, a detailed discussion is given in appendix B of [6]. The signΔm^2_{31} degeneracy however has a substantial effect on the ability to determine δ_{CP}, especially at a NuFact it may be rather cumbersome. In figure 1 the CP violation reach in the $\sin^2 2\theta_{13}$-Δm^2_{21} plane is shown for all four setups including degeneracies, correlations, systematics and backgrounds. The trench in the left hand panel for the NuFact-II case is due to the signΔm^2_{31} degeneracy. One possibility among many others [7, 8] to resolve

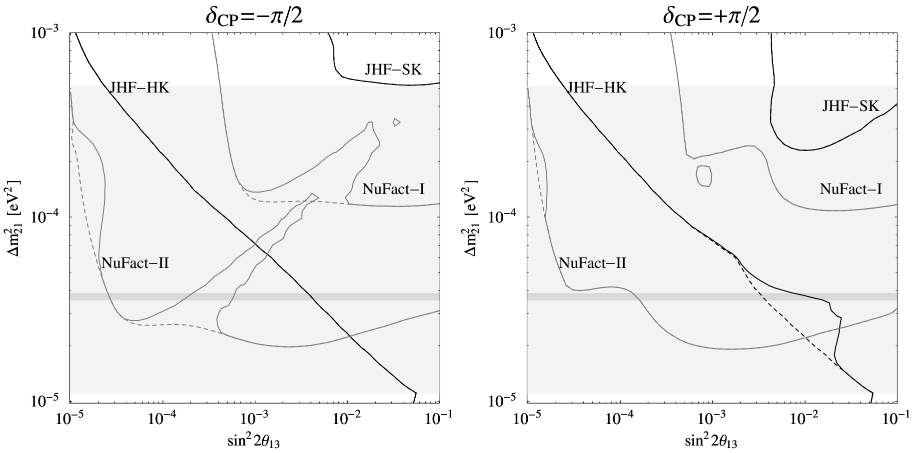

Figure 1. The sensitivity to CP violation for all experiments (as labeled in the plots) at the 2σ confidence level, plotted as function of $\sin^2 2\theta_{13}$ and Δm^2_{21}. The left–hand plot shows the case of $\delta_{\rm CP} = -\pi/2$ and the right–hand plot the case of $\delta_{\rm CP} = +\pi/2$. Solid curves refer to taking into account all degenerate solutions and dashed curves to taking into account the best–fit manifold only. The gray shaded regions refer to the allowed LMA region for Δm^2_{21} (light gray) and the best–fit value for Δm^2_{21} (dark gray).

the correlation between δ_{CP} and θ_{13} and to break the $(\delta_{CP}, \theta_{13})$ ambiguity is to use the so called "magic baseline". The condition for the magic baseline is given by

$\sin(\Delta m^2_{31} L/(4E) \quad 2VE/\Delta m^2_{31}) = 0 \Leftrightarrow VL/2 = n\pi$ [5], this gives for Earth densities a baseline $L \simeq 8\,100\,\mathrm{km}$. At this special distance all terms in the appearance probability proportional to Δm^2_{21} and $(\Delta m^2_{21})^2$ vanish identically for all energies and values of Δm^2_{31}, *i.e.* the appearance probability reduces to the one in a two neutrino case. Thus all correlations and degeneracies connected to δ_{CP} disappear. The drawback of this

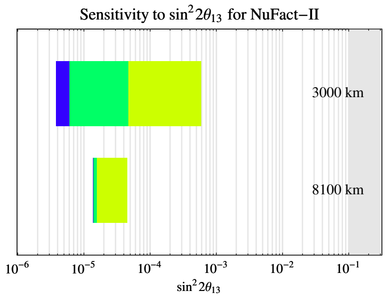

Figure 2. The sensitivity to $\sin^2 2\theta_{13}$ at baselines of 3 000 km and 8 100 km. The dark grey shading indicates the impact of systematics, the medium grey shading the impact of the correlations and the light grey shading stands for the effect of degeneracies.

very long baseline is that the event rates decrease. But in figure 2 it is clearly visible that the gain in sensitivity by avoiding the effects of δ_{CP} (rightmost edge) is much larger than the effects of the diminished statistics (leftmost edge), thus the sensitivity is increased by one order of magnitude.

2. T and CPT violation

In vacuum the CP-odd and T-odd probability differences are identical. This does not hold in matter. In principle it is therefore possible that matter profile asymmetries introduce a fake CP violation and increase the error in the measurement of δ_{CP}. However in [9] it is shown that, for in terrestial experiments conceivable matter asymmetries, this effects turns out to be negligibly small.

CPT violation would manifest itself in a neutrino oscillation experiment by the presence of two different Δm^2 scales or mixing angles for neutrinos and anti-neutrinos. Thus in order to estimate the sensitivity of a neutrino factory to CPT violation one just needs to evaluate the level of accuracy which can be obtained in the measurement of Δm^2_{31} and θ_{23}. At a standard NuFact relative asymmetries in the mass splittings of order $< 10^{-1}$ and in the mixing angles in the order of $< 10^{-2}$ could be detected, as it is shown in [10].

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