Systematics in Superbeam Experiments

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Abstract

Superbeam experiments may allow to measure the leptonic CP phase, provided θ_{13} is not too small. We study the obtainable sensitivity in the T2HK setup with a special focus on systematics, where we include for the first time a near detector in the calculation. We find that even for an idealized near detector, there remain systematic errors which do not cancel in the near to far detector comparison. We identify the relevant parameter combinations. We show that if the uncertainty on the ratio of ν_e to ν_μ quasi-elastic neutrino cross section times efficiency is larger than 2 %, T2HK is systematics limited. We comment on T2KK, where we find that having a third detector does not provide specific benefits for the cancellation of systematics.

1. Introduction

Neutrino oscillations have been established as the leading mechanism for flavour transitions in solar [1, 2] and atmospheric [6] neutrinos. Neutrino oscillations imply that neutrinos have mass in contradiction to the Standard Model. Most theories for neutrino mass generation point to very high energy scales which are inaccessible by collider experiments. The fact, that neutrinos are massive opens completely new phenomenological possibilities and in order, to fully exploit these it is necessary to study neutrinos with great precision. A new generation of experiments beyond the existing ones is required to measure θ_{13}, to test whether θ_{23} is maximal, to determine the neutrino mass hierarchy and to discover leptonic CP violation. The determination of the mass hierarchy and the discovery of CP violation are beyond the reach of currently approved experiments [4] and a larger number of possible setups is discussed, see *e.g.* [5].

Among the candidates for the next generation of high precision experiments are so called superbeam experiments, where 'super' refers to the very high beam power of $\mathcal{O}(1\,\mathrm{MW})$ and detectors with fiducial masses in excess of 100 kt. These experiments will have ν_e and $\bar{\nu}_e$ appearance samples at the level of 10^4 events for $\sin^2 2\theta_{13} = 0.1$. Thus statistical errors can be below 1% and systematic errors will start to dominate. In most of the previous literature, *ad hoc* values for the systematical errors have been assumed. With '*ad hoc*' we mean, that these values typically were smaller than any previously achieved values. Typically a near detector was invoked to justify the low levels of systematics. This near detector, however, remained virtual, *i.e.* it was not specified what type or combination of types the near detector should be and thus it was not included in the sensitivity calculation.

In these proceedings, we will describe results published in [21], were we studied the T2HK setup and explicitly included a near detector in our calculation. The goal was to explore to which extent a near detector on its own can control systematic errors. Note, that the goal of that paper and also of these proceedings is not to advocate specific values of systematic errors.

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2. Qualitative Features

Before we go into the details of the numerical calculation we would like to give a qualitative discussion based on total event rates and a subset of possible backgrounds. Whereas, this qualitative discussion can be no substitute for a thorough numerical investigation it allows to capture the essential physics. Most of the qualitative feature of the subsequently shown numeric results can be understood based on this simple analysis.

The total number of ν_e and ν_μ events in near detector (ND) and far detector (FD) can be written as

$$n_{\nu_\mu}^{\mathrm{ND}} = \frac{N_{\mathrm{ND}}}{L_{\mathrm{ND}}^2}\,\Phi_{\nu_\mu}\,\sigma_{\nu_\mu}\epsilon_{\nu_\mu} \tag{1}$$

$$n_{\nu_e}^{\mathrm{ND}} = \frac{N_{\mathrm{ND}}}{L_{\mathrm{ND}}^2}\left[\Phi_{\nu_e}\,\sigma_{\nu_e}\epsilon_{\nu_e} + n_{\mathrm{NC}}^{\mathrm{ND}}\right] \tag{2}$$

$$n_{\nu_\mu}^{\mathrm{FD}} = \frac{N_{\mathrm{FD}}}{L_{\mathrm{FD}}^2}\,\Phi_{\nu_\mu}\,P(\nu_\mu\to\nu_\mu)\,\sigma_{\nu_\mu}\epsilon_{\nu_\mu} \tag{3}$$

$$n_{\nu_e}^{\mathrm{FD}} = n_{\nu_e}^{\mathrm{FD,sig}} + n_{\nu_e}^{\mathrm{FD,bg}} \tag{4}$$

with

$$n_{\nu_e}^{\mathrm{FD,sig}} = \frac{N_{\mathrm{FD}}}{L_{\mathrm{FD}}^2}\Phi_{\nu_\mu}\,P(\nu_\mu\to\nu_e)\,\sigma_{\nu_e}\epsilon_{\nu_e}\,, \tag{5}$$

$$n_{\nu_e}^{\mathrm{FD,bg}} = \frac{N_{\mathrm{FD}}}{L_{\mathrm{FD}}^2}\left[\Phi_{\nu_e}\,P(\nu_e\to\nu_e)\,\sigma_{\nu_e}\epsilon_{\nu_e} + n_{\mathrm{NC}}^{\mathrm{FD}}\right]. \tag{6}$$

Here N is the total normalization (number of target nuclei), σ_{ν_α} is the charged current cross section for ν_α, ϵ_{ν_α} is the detection efficiency for ν_α (assumed to be identical for ND and FD), $P(\nu_\beta\to\nu_\alpha)$ is the probability for a neutrino of flavour β to oscillate into flavour α, Φ_{ν_β} is the initial neutrino flux, and L is the distance from the detector to the source. For the ν_e signal we account for the intrinsic ν_e beam contamination and the background from neutral current (NC) interactions $n_{\mathrm{NC}}\times N/L^2$. For the the disappearance channel we assume that backgrounds can be neglected. Note, that the efficiency ϵ and the cross section σ appear as product and therefore we can define an effective cross section

$$\tilde\sigma_{\nu_\alpha} := \sigma_{\nu_\alpha}\epsilon_{\nu_\alpha}\,. \tag{7}$$

Unfortunately many of the of the quantities appearing in equations (1) to (6) are subject to considerable uncertainties. The most important error sources are a lack of information about cross sections and fluxes. Hence, the data from the near detector has to serve to predict the events in the far detector for a given oscillation hypothesis.

It is well known that this can be done efficiently for a disappearance measurement. Using equations (1) and (3) one finds

$$n_{\nu_\mu}^{\mathrm{FD}} = n_{\nu_\mu}^{\mathrm{ND}}\,\frac{N_{\mathrm{FD}}}{N_{\mathrm{ND}}}\,\frac{L_{\mathrm{ND}}^2}{L_{\mathrm{FD}}^2}\;P(\nu_\mu\to\nu_\mu)\,. \tag{8}$$

Under the assumption, that the uncertainty on $N_{\mathrm{FD}}/N_{\mathrm{ND}}\times L_{\mathrm{ND}}^2/L_{\mathrm{FD}}^2$ is negligible, a complete cancellation of all systematical errors happens – at least in this idealized discussion – since the same combination of $\tilde\sigma$ and Φ appears in ND and FD.

For an appearance experiment, however, the situation is very different. We can identify two regimes: first, close to the sensitivity limit (*i.e.*, small $\sin^2 2\theta_{13}$), where the ν_e signal is dominated by backgrounds and second the regime of large $\sin^2 2\theta_{13}$, where the actual signal is much larger than the background. Therefore, one expects that in the first regime, the errors on the background are important, whereas for the second regime the errors on the ν_e signal itself should be more important. The numerical calculations will show, that for T2HK the transition between the two regimes occurs roughly at $\sin^2 2\theta_{13} \simeq 0.01$.

In the regime of small $\sin^2 2\theta_{13}$, where backgrounds dominate, the role of the ND is to measure the background as precisely as possible to make its contribution to the error budget small. If we assume that the backgrounds in the near and far detector are the same we obtain, that the background in the FD can be predicted by the ν_e events in the ND from equation (2):

$$n_{\nu_e}^{\mathrm{FD,bg}} = n_{\nu_e}^{\mathrm{ND}} \, \frac{N_{\mathrm{FD}}}{N_{\mathrm{ND}}} \frac{L_{\mathrm{ND}}^2}{L_{\mathrm{FD}}^2} \,. \tag{9}$$

Of course, in reality, one has to ask how well the assumption of equal backgrounds in near and far detector are full filled. For one, we neglected the effect of oscillation on the background, which, however, is going to be very small for small θ_{13}. Secondly, and more important is the issue of whether NC backgrounds are the same in the two detectors. Also, the statistical error of the near detector measurement can not be neglected since the beam intrinsic background only constitutes $\sim 1\%$ of the total beam flux.

In the case of large $\sin^2 2\theta_{13}$, where the error on the signal dominates we find from equation (5), that the combination $\Phi_{\nu_\mu} \times \tilde{\sigma}_{\nu_e}$ is relevant, which cannot be determined by the ND, and equations (1) and (5) combine to

$$n_{\nu_e}^{\mathrm{FD,sig}} = n_{\nu_\mu}^{\mathrm{ND}} \, \frac{N_{\mathrm{FD}}}{N_{\mathrm{ND}}} \frac{L_{\mathrm{ND}}^2}{L_{\mathrm{FD}}^2} \, \frac{\tilde{\sigma}_{\nu_e}}{\tilde{\sigma}_{\nu_\mu}} \, P(\nu_\mu \to \nu_e) \,. \tag{10}$$

Clearly, the effective cross sections do not cancel, namely the ratio $\tilde{\sigma}_{\nu_e}/\tilde{\sigma}_{\nu_\mu}$ survives. The ability to discover CPV largely depends on the ability to compare the neutrino and anti-neutrino appearance signals, therefore it may be useful to investigate the ratio of the corresponding event rates:

$$\frac{n_{\nu_e}^{\mathrm{FD,sig}}}{n_{\bar{\nu}_e}^{\mathrm{FD,sig}}} = \frac{n_{\nu_\mu}^{\mathrm{ND}}}{n_{\bar{\nu}_\mu}^{\mathrm{ND}}} \, \frac{\tilde{\sigma}_{\nu_e}}{\tilde{\sigma}_{\nu_\mu}} \, \frac{\tilde{\sigma}_{\bar{\nu}_\mu}}{\tilde{\sigma}_{\bar{\nu}_e}} \, \frac{P(\nu_\mu \to \nu_e)}{P(\bar{\nu}_\mu \to \bar{\nu}_e)} \,. \tag{11}$$

From these considerations we conclude that one of the following combinations of quantities has to be known in order to predict the signal for the CPV measurement:

$$\left(\frac{\tilde{\sigma}_{\nu_e}}{\tilde{\sigma}_{\nu_\mu}} , \frac{\tilde{\sigma}_{\bar{\nu}_e}}{\tilde{\sigma}_{\bar{\nu}_\mu}} \right) \quad \text{or} \quad \left(\frac{\tilde{\sigma}_{\nu_e}}{\tilde{\sigma}_{\bar{\nu}_e}} , \frac{\tilde{\sigma}_{\nu_\mu}}{\tilde{\sigma}_{\bar{\nu}_\mu}} \right) \quad \text{or} \quad \left(\frac{\Phi_{\nu_\mu}}{\Phi_{\bar{\nu}_\mu}} , \frac{\tilde{\sigma}_{\nu_e}}{\tilde{\sigma}_{\bar{\nu}_e}} \right) . \tag{12}$$

The first two combinations follow from equation (11): if either the flavour ratio of effective cross sections for neutrino and anti-neutrinos separately or the neutrino/anti-neutrino ratio for ν_e and ν_μ separately are known with good precision then the high statistics ν_μ and $\bar{\nu}_\mu$ samples from the ND allow to predict the CPV signal in the FD. Note that this does not require knowledge on the double ratio $(\tilde{\sigma}_{\nu_e}/\tilde{\sigma}_{\nu_\mu})/(\tilde{\sigma}_{\bar{\nu}_e}/\tilde{\sigma}_{\bar{\nu}_\mu})$. The last combination in equation (12) follows directly from equation (5): If ν_μ and $\bar{\nu}_\mu$ fluxes, as well as ν_e and $\bar{\nu}_e$ effective cross sections are known the signal can directly be predicted without the need of the ND.

Based on this discussion it is obvious that the ratio of ν_e to ν_μ cross sections plays a special role. The extent to which this ratio can be predicted by theory in the relevant energy range is far from clear and we refer the reader for a detailed discussion to section III of [21].

3. Results

For the T2HK setup we assume a water Cerenkov detector with a fiducial mass of 500 kt and proton beam of 4 MW power for 10^7 s a year. We take 2 years of neutrino running and 6 years of anti-neutrino running. The baseline is 295 km and the matter density is taken to be $2.8\,\mathrm{g\,cm^{-3}}$. This setup is based on [7]. For the near detector we assume an otherwise identical detector but with a fiducial mass of 0.1 kt and a distance of 2 km. We use an energy independent, *i.e.* flat near far ratio. All numerical calculations are done with the GLoBES software [8, 9]. For a more detailed description of the simulation we refer to section IV and the appendices of [21].

Figure 1 shows the systematical error and their default values as considered in this work. These errors can be grouped into detector normalization, energy calibration, initial fluxes, cross sections (which in our convention include efficiencies) and errors on NC and CC backgrounds. All together we have 27 such errors. The default values we use are representative of the current status, but are not intended to be taken as the ones which would be encountered in the actual analysis. The purpose of this is work is not to advocate specific values but to show what types of systematic can be constrained by a near detector and which can not. For the latter category solid external information is required.

3.1. CP violation at T2HK

In figure 2, we show the $3\,\sigma$ sensitivity of T2HK to discover CP violation. Here, the analysis is restricted to the range $0 \leq \delta_{CP}^{\mathrm{true}} \leq \pi/2$ and we do not take into account the $\mathrm{sgn}\Delta m^2$ degeneracy. In computing the χ^2-values we allowed θ_{13} to vary freely, but fixed all other oscillation parameters to their input values of $\Delta m^2_{31} = 2.4 \cdot 10^{-3}\,\mathrm{eV}^2$, $\sin^2\theta_{23} = 0.5$, $\Delta m^2_{21} = 7.9 \cdot 10^{-5}\,\mathrm{eV}^2$ and $\sin^2\theta_{12} = 0.3$. Neglecting sub-leading correlations and degeneracies allows to focus on systematics related issues.

The lower, black solid curve shows the result for statistical errors only, *i.e.* fixing all 27 pulls at 0. We see, that in this case the sensitivity improves monotonically with increasing θ_{13}. The sensitivity including all 27 pulls at their default values is shown by the upper solid black line. The deterioration is quite large, especially for large θ_{13}. In figure 1 we also investigate how this result depends on each single source of systematic error. There, we show what happens to the smallest value of δ_{CP} for which CPV can be established at $3\,\sigma$ for a value of $\sin^2 2\theta_{13} = 0.03$. The red bars show the result of switching off the corresponding error, whereas the blue bars show the result of multiplying the corresponding error by a factor of 5. No single error source has a large impact on its own, which highlights the importance of performing a comprehensive study of a large number of systematical errors simultaneously.

In figure 2 we also study the impact of a better determination of the cross sections, which in principle could come from experiments like MINERVA [10] or SciBooNE [11]. Even a constraint at the level of 1% (which presumably is unrealistic) would alleviate the systematics problem only partially.

On the other hand, the discussion in the previous section suggests, that a constraint on the ratio of σ_{ν_e} to σ_{ν_μ} could be very effective. This is shown by the blue

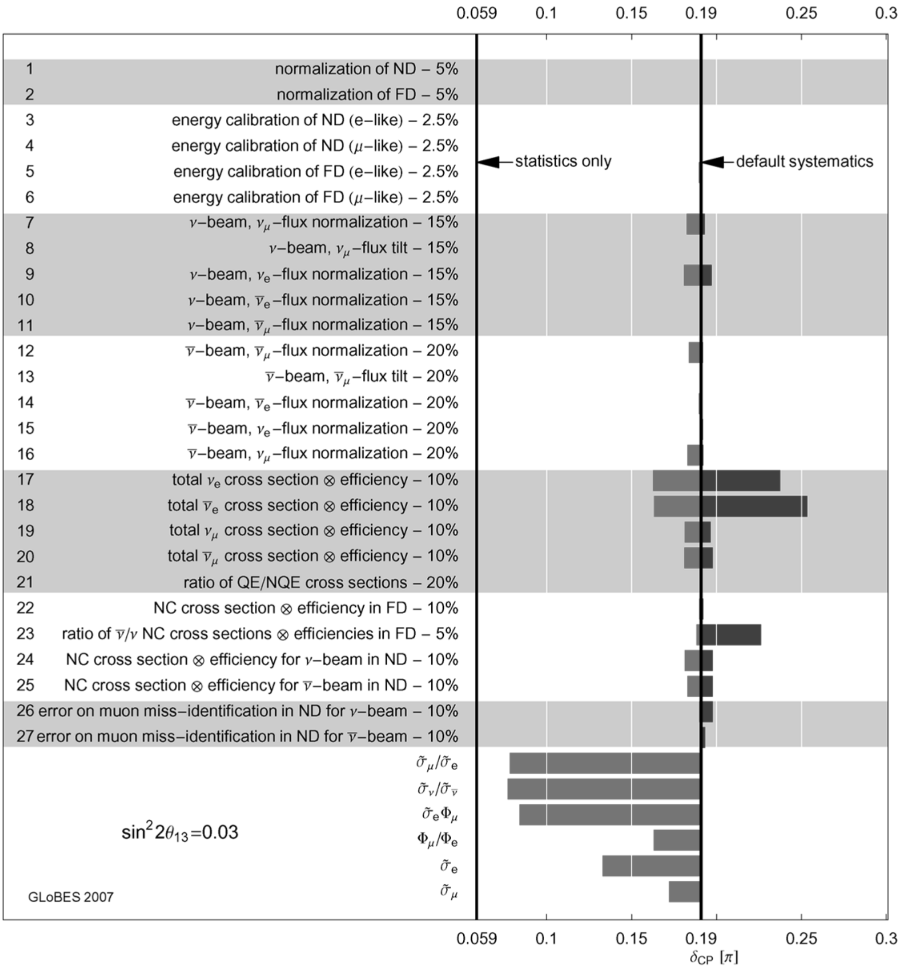

Fig. 1 List of the systematical uncertainties and the adopted default values, as well as the impact of various systematics on the T2HK sensitivity to CPV for $\sin^2 2\theta_{13} = 0.03$. The abscissa shows the smallest δ_{CP} in $[0, \pi/2]$ for which CPV can be established at 3σ. We show how the sensitivity is affected if each of the 27 pulls is switched off (red) or the error is multiplied by 5 (blue). The lower 6 rows show the impact when certain combinations of pulls are constrained at 2%: the ratio of ν_e to ν_μ cross sections times efficiencies (for neutrinos and anti-neutrinos), the ratio of neutrino and anti-neutrino cross sections times efficiencies (for e and μ-like events), the product of ν_μ flux times ν_e cross section times ν_e efficiency (for neutrinos and anti-neutrinos), the ratio of e to μ fluxes (for neutrinos and anti-neutrinos), ν_e and $\bar{\nu}_e$ cross sections times efficiencies, ν_μ and $\bar{\nu}_\mu$ cross sections times efficiencies. From [21].

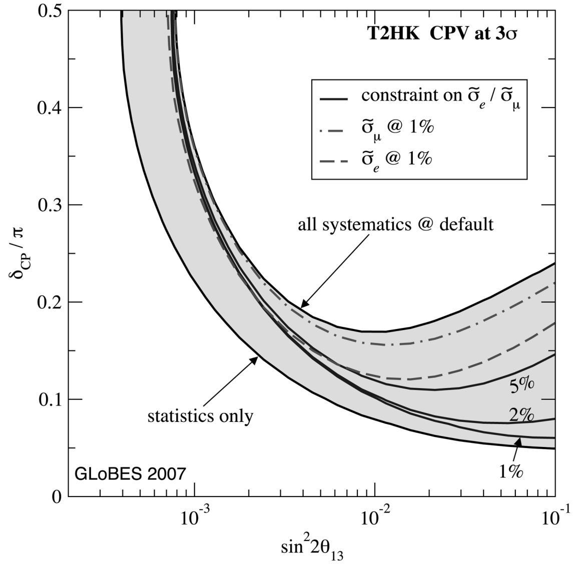

Fig. 2 T2HK CPV sensitivity at 3σ for our default choice of systematical errors according to Fig. 1 and for statistical errors only (curves delimiting the shaded region). We show also the sensitivity if certain constraints on the product of cross sections times efficiencies $\tilde{\sigma}$ are available: 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. From [21].

(gray) lines. Already a constraint of 2% nearly restores the initial statistics-only sensitivity for large θ_{13}. For small θ_{13} the problem is different, as discussed in section 2., and the dominating error source are the background errors which do not depend on the cross section ratio. In figure 1 we see, that the same effect can be achieved by constraining any of the combinations given in equation 12.

In figure 3, we show the dependence of the CPV discovery reach as function of the luminosity or exposure of the experiment for large $\sin^2 2\theta_{13} = 0.03$. We scale simultaneously the beam power and the far detector mass between the T2K values of 0.77 MW, 22.5 kt and the T2HK values of 4 MW, 500 kt. The running time and near detector mass stays fixed at 2+6 years and 0.1 kt, respectively. As expected, systematics become more important when the exposure is large, since statistical errors get small. Obviously, one can compensate for systematic errors by increasing the exposure, although this may not be cost effective. As an extreme case, we find that if one would be able to constrain the ratio $\tilde{\sigma}_{\nu_e}/\tilde{\sigma}_{\nu_\mu}$ to 2%, T2HK would be able to obtain the *same* physics sensitivity with 1/10 of exposure.

In the left hand panel of figure 4 we study the impact of spectral information by comparing a rate-only analysis with our default spectral analysis. For the statistics-only cases we observe that the sensitivity does not depend on the inclusion of spectral information. This indicates, that indeed just two numbers, *i.e.* the total number of ν_e and $\bar{\nu}_e$ events contain all the information about CP violation. This, of course, is only true to the extent it is permissible to neglect the intrinsic degeneracy. Secondly, this simple picture breaks down once systematics is included. Here spectral information is the key to separate oscillation physics from unwanted systematic errors. This result indicates that the systematics discussion might be different in the context of a wide band neutrino beam as discussed

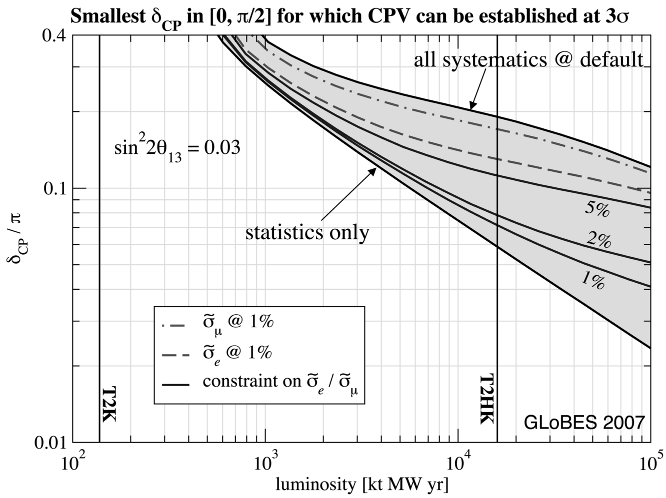

Fig. 3 CPV sensitivity at 3σ as a function of exposure for a true value $\sin^2 2\theta_{13} = 0.03$ for our default choice of systematical errors according to Fig. 1 and for statistical errors only (curves delimiting the shaded region). The ratio of neutrino to anti-neutrino running is kept constant at 1 : 3. Furthermore we show 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. From [21].

in [2, 13, 3].

In the right hand panel of figure 4 the effect of the near detector is illustrated. This clearly, indicates the huge improvement a near detector yields for small values of $\sin^2 2\theta_{13}$.

3.2. T2KK

In this section we would like to comment on the case, where we split the detector mass of 500 kt into two pieces and move one piece to Korea with a baseline of 1050 km. We consider only the same off-axis angle at both locations like in [8, 16]. Our analysis now includes a near detector, one far detector of 250 kt in Kamioka and one far detector of 250 kt in Korea. We will focus only on the ability to determine CP violation in this setup. Of course, we are aware that the main motivation for the T2KK setup is the determination of the mass hierarchy. This in turn does also impact the CP sensitivity since the sgnΔm^2 degeneracy also affects the CP sensitivity. Thus our statements in the following about T2KK are not to be understood as an appraisal on a global basis. We are very narrowly only focusing on the issue of systematics.

In the left hand panel of figure 5, we compare the sensitivities of T2HK (gray shaded area), *i.e.* 500 kt detector in Kamioka with the one of T2KK (blue/dark gray lines). With all systematics at their default values, we get a somewhat better sensitivity of T2KK at large $\sin^2 2\theta_{13}$. However, if precise information on the ratio of effective cross sections is available, the performances are very similar. We do not see an improved cancellation of systematics, rather that the signal becomes more distinct due to the wider range in L/E covered by the three detector setup. Based on this result it seems not necessary to demand the same off-axis angle both in Japan and Korea. This may be relevant in the context of the results presented

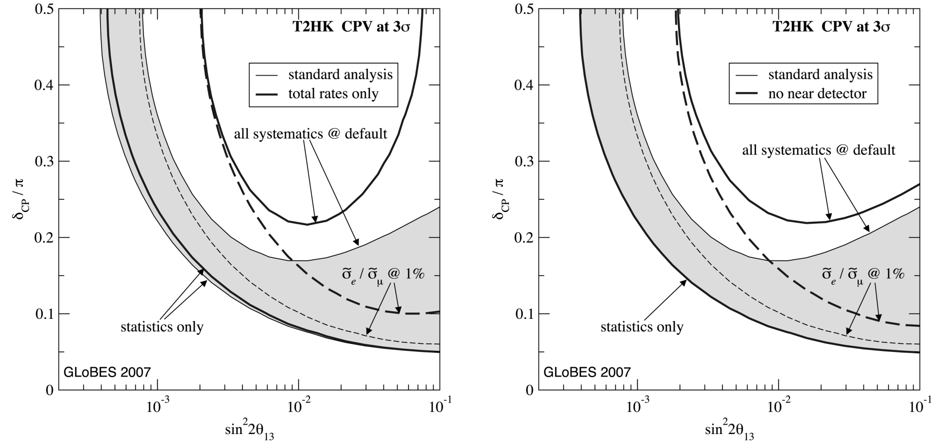

Fig. 4 T2HK CPV sensitivity at 3σ for a total rate measurement only (left) and without a near detector (right) for our default choice of systematical errors according to Fig. 1 and for statistical errors only. The dashed curves correspond to an external accuracy of 1% on the ratios $\tilde{\sigma}_{\nu_e}/\tilde{\sigma}_{\nu_\mu}$ for neutrinos and anti-neutrinos. The shaded regions correspond to our standard analysis and are identical to the one in Fig. 2. From [21].

in [17, 18], which seem to prefer different off-axis angles in order to optimize the overall physics sensitivity.

In the right hand panel of figure 5, we try to find the optimal distribution of detector mass between Japan and Korea. The optimum depends on the size of systematics. In the case of no systematics Japan is the preferred location. Once we account for non-zero systematics also a dependence on θ_{13} is found, rendering any fine tuning difficult.

4. Conclusions

In these proceedings we presented the results published in [21]. We studied the impact of a large number of possible systematic errors on the physics sensitivity of a superbeam experiment. We focused our discussion on the discovery of leptonic CP violations as previous works indicate that this is the most difficult measurement with respect to systematics. Our results are based on a realistic simulation of the far detector and we explicitly include a near detector. The purpose of our work is not to advocate or endorse certain values for systematic errors but to show to which extent a near detector can control these errors in an appearance experiment. Our main result is, that the cancellation of systematics between near and far detector remains incomplete. Therefore, more information than the near detector can provide is required in order to control systematic errors.

There are two different regimes, depending on the size of θ_{13}: for small $\sin^2 2\theta_{13} < 0.01$, the error on the number of background events determines the sensitivity to CP violation, whereas for large $\sin^2 2\theta_{13} > 0.01$, the error on the signal itself is more important. In this latter case, the near detector is only partially useful and more information is needed. We identified three combinations of parameters, of which at least one has to be known with very good accuracy at the level of 2%. The three combinations are: 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; the ratios of the effective cross sections between neutrinos and anti-neutrinos, for ν_e and ν_μ; the initial flux of ν_μ and the effective ν_e cross section, both for neutrinos and anti-neutrinos. Effective cross is

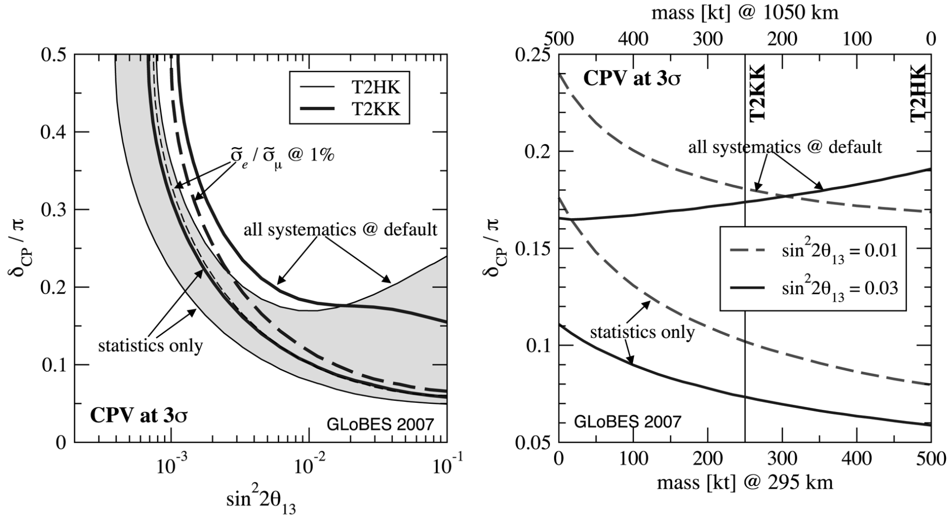

Fig. 5 Left hand panel: sensitivity to CPV at 3σ for T2HK and T2KK. Right hand panel: sensitivity to CPV at 3σ for two values of $\sin^2 2\theta_{13}$ by changing the detector mass between Kamioka and Korea. From [21].

nothing but a shorthand for the product of cross section and efficiency.

To accurately constrain any of these ratios, it necessary to measure cross sections and efficiencies separately with good precision. The ratio of $\sigma_{\nu_e}/\sigma_{\nu_e}$ can be predicted by nuclear physics, maybe even with sufficient accuracy. This possibility certainly deserves further study. In principle, a combination of very good knowledge on the initial neutrino fluxes and a very sophisticated, large near detector may be able to directly constrain the product of $\phi_{\nu_\mu}\sigma_{\nu_e}\epsilon_{\nu_e}$ and thus to predict the signal with very small errors. This possibility and the requirements on flux and the near detector system are explained in more detail in [21].

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