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From Double Chooz to Triple Chooz — Neutrino Physics at the Chooz Reactor Complex

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Abstract

We discuss the potential of the proposed Double Chooz reactor experiment to measure the neutrino mixing angle $\sin^2 2\theta_{13}$. We especially consider systematical uncertainties and their partial cancellation in a near and far detector operation, and we discuss implications of a delayed near detector startup. Furthermore, we introduce Triple Chooz, which is a possible upgrade scenario assuming a second, larger far detector, which could start data taking in an existing cavern five years after the first far detector. We review the role of the Chooz reactor experiments in the global context of future neutrino beam experiments. We find that both Double Chooz and Triple Chooz can play a leading role in the search for a finite value of $\sin^2 2\theta_{13}$. Double Chooz could achieve a sensitivity limit of $\sim 2 \cdot 10^{-2}$ at the 90% confidence level after 5 years while the Triple Chooz setup could give a sensitivity below 10^{-2}.

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1 Introduction

Neutrino oscillations have now clearly been established for solar, atmospheric and reactor neutrinos, as well as with neutrino beams. However, these oscillations can still be described by an effective two neutrino picture to a very good approximation. This is a consequence of the smallness of the third mixing angle θ_{13} and the fact that the solar mass splitting Δm_{21}^2 is much smaller than the atmospheric mass splitting Δm_{31}^2. Establishing generic three flavour effects by measuring a finite value for the third mixing angle θ_{13} is therefore one of the most important tasks for future neutrino experiments. For a concise review and description of the current status see Ref. [1]. A finite value of θ_{13} is crucial for the search for leptonic CP violation, too. Since CP violating effects are proportional to θ_{13}, discovering a finite value of θ_{13} or excluding a certain range of values is a key information for the planning of future long baseline neutrino beam experiments. Therefore, we discuss in this paper the potential to limit or measure θ_{13} with Double Chooz, which is currently the most advanced reactor project. In addition, we consider the Triple Chooz upgrade option, which could benefit from an existing cavern where a second large far detector could be constructed. We also discuss how a timely information on $\sin^2 2\theta_{13}$ will influence the choice of technology for the second generation neutrino beam facilities.

The outline of the paper is as follows. In Sec. 2, we present some general remarks on the neutrino oscillation framework and we discuss implications for reactor anti-neutrino disappearance measurements. In Sec. 3, we describe the simulated experimental setups of Double Chooz and a potential upgrade to Triple Chooz. We then discuss in Sec. 4 the systematical errors at Double Chooz and we present their implementation within our analysis. Next, in Sec. 5, we present the results of our simulations for the sensitivity and the precision of $\sin^2 2\theta_{13}$. Here, we provide also a detailed discussion of the quantitative impact of the systematical uncertainties. Finally, we assess the role of Double Chooz and eventually Triple Chooz in the global context of $\sin^2 2\theta_{13}$ measurements with reactors and future neutrino beam experiments.

2 Neutrino oscillation framework

As discussed in previous studies [2–6], reactor experiments can play a crucial role for measurements of the third small neutrino mixing angle θ_{13}. An important aspect is that such a measurement in the $\bar{\nu}_e$-disappearance channel does not suffer from correlations with unknown parameters, such as the CP phase δ_{CP}. Correlations with the other oscillation parameters were also found to be negligible [5]. This can easily be seen in the expansion of the full oscillation probability in the small parameters $\sin^2 2\theta_{13}$ and $\alpha \equiv \Delta m_{21}^2/\Delta m_{31}^2$ up to second order:

$$1 - P_{\bar{e}\bar{e}} \simeq \sin^2 2\theta_{13} \sin^2 \Delta_{31} + \alpha^2 \Delta_{31}^2 \cos^4 \theta_{13} \sin^2 2\theta_{12} , \tag{1}$$

where $\Delta_{31} = \Delta m_{31}^2 L/4E$, L is the baseline, and E the neutrino energy. Matter effects can also be safely ignored for such short baselines of $L = 1 \sim 2$ km. For a measurement at the first oscillation maximum and $\sin^2 2\theta_{13} > 10^{-3}$ even the second term in Eq. (1) becomes negligible[1]. Unless stated differently, we use the following input oscillation parameters (see *e.g.* Refs. [7–10]):

$$\Delta m_{31}^2 = 2.5 \cdot 10^{-5}\ \mathrm{eV}^2\ ; \quad \sin^2 2\theta_{23} = 1 \tag{2}$$

$$\Delta m_{21}^2 = 8.2 \cdot 10^{-3}\ \mathrm{eV}^2\ ; \quad \sin^2 2\theta_{12} = 0.83 \tag{3}$$

Our analysis is performed with a modified version of the GLoBES Software [11], which allows a proper treatment of all kinds of systematical errors which can occur at a reactor experiment such as Double Chooz. This is important since the sensitivity of a reactor experiment to $\sin^2 2\theta_{13}$ depends crucially on these systematical uncertainties [5]. The importance of systematical errors becomes obvious from Eq. (1), since a small quantity has to be measured as a deviation from 1.

3 Experimental setups

The basic idea of the Double Chooz experiment is a near and a far detector which are as similar as possible in order to cancel systematical uncertainties. The two detectors are planned to have the same fiducial mass of 10.16 t of liquid scintillator. However, there are also some unavoidable differences, such as the larger muon veto in the near detector. The thermal power of the reactor is assumed to be $2 \cdot 4.2$ GW (two reactor cores). The Double Chooz setup can benefit from the existing Chooz cavern at a baseline of $L = 1.05$ km from the reactor cores. This allows a faster startup of the far detector in order to collect as much statistics as possible at the larger baseline. For the near detector, a new underground cavern must be built close to the reactor cores. In this paper, we assume 100 m for the baseline of the near detector [12]. Being so close to the reactor, it can catch up with the statistics of the far detector. As our standard scenario in this paper, we assume that the near detector starts 1.5 years after the far detector. We refer to the initial phase without the near detector as phase I, and to the period in which both the near and far detectors are in operation as phase II. Typically this leads for the far detector to 19 333 unoscillated events per year, corresponding to $1.071 \cdot 10^6$ events per year in the near detector [12].

Besides the Double Chooz experiment, we discuss a potential Triple Chooz upgrade after a few years by construction of a second, larger far detector. Another existing cavern at roughly the same baseline from the Chooz reactor cores can be used for this purpose. This is a very interesting option, since this second cavern should be available around 2010, and one could avoid large civil engineering costs and save time. In particular, one could essentially spend all of the money for a typical second generation reactor experiment on the detector. We therefore consider a 200 t liquid scintillating detector with costs comparable to other proposed next generation reactor experiments [13]. The ultimate useful size of such a detector strongly depends on the level of irreducible systematics such as the bin-to-bin error, which will be discussed in greater detail in the following sections.

[1] Note that the numerical simulations with GLoBES are not based on Eq. (1), but on the full three-flavour oscillation probability.

4 Systematical errors at Double Chooz

A reactor neutrino experiment depends on a variety of different systematical errors, which are the most important limiting factor for $\sin^2 2\theta_{13}$ measurements. Any deficit in the detected neutrino flux could be attributed either to oscillations or to a different reactor neutrino flux Φ. The systematical flux uncertainty is consequently the dominant contribution which must be minimized. In past experiments, the flux was deduced from the thermal power of the reactor, which can only be measured at the level of a few percent. However, in next generation reactor experiments such as Double Chooz, a dedicated identical near detector will be used to precisely measure the unoscillated neutrino flux close to the reactor core such that the uncertainty in Φ cancels out. In addition, the near detector eliminates, in principle, the uncertainties in the neutrino energy spectrum, the interaction cross sections, the properties of the liquid scintillator (which is assumed to be identical in both detectors), and the spill-in/spill-out effect. The latter occurs if the neutrino interaction takes place inside the fiducial volume, but the reaction products escape the fiducial volume or vice-versa. However, cancellation of systematical errors for a simultaneous near and far detector operation works only for the uncertainties that are correlated between both detectors. Any uncorrelated systematical error between near and far detector must therefore be well controlled. The knowledge of the fiducial detector mass or the relative calibration of normalization and energy reconstruction are, for instance, partly uncorrelated uncertainties and are therefore not expected to cancel completely. In addition, backgrounds play a special role, as some of the associated uncertainties are correlated (*e.g.*, the radioactive impurities in the detector), while others are not. In particular, since the overburden of the near detector is smaller than that of the far detector, the flux of cosmic muons will be higher for the near detector site. This requires a different design for the outer veto and different cuts in the final data analysis, which again introduces additional uncorrelated systematical errors.

Another complication in the discussion of cancellation of correlated uncertainties in Double Chooz is the fact that the near detector is supposed to start operation about 1.5 years later than the far detector. Therefore, only those systematical errors which are correlated between the detectors *and* which are not time-dependent can be fully eliminated. This applies to the errors in the cross-sections, the properties of the scintillator, and the spill-in/spill-out effects. However, it only partly applies to systematical uncertainties in the background. In particular, the errors in the reactor flux and spectrum will be uncorrelated between phase II, where both detectors are in operation, and phase I, where only the far-detector operates. The reason for this is the burn-up and the periodical partial replacement of fuel elements. The different systematical uncertainties discussed so far are summarized in Table 1 together with their magnitudes we assume for Double Chooz.

For the proper implementation of all relevant correlated and uncorrelated systematical uncertainties, together with an appropriate treatment of the delayed near detector start up, we modified the χ^2-analysis of the GLoBES Software and defined a χ^2-function which incorporates all the relevant uncertainties. The numerical simulation assumes the events to follow the Poisson distribution, but for illustrative purposes it is sufficient to consider the Gaussian approximation which is very good due to the large event rates in Double Chooz. The total χ^2 is composed of the statistical contributions of the far detector in phase I, $\chi^2_{F,I}$,

		Correlated	Time-dependent	Value for DC
1	Reactor flux normalization	yes	yes	2.0%
2	Reactor spectrum	yes	yes	2.0% per bin
3	Cross Sections	yes	no	
4	Scintillator Properties	yes	no	2.0%
5	Spill-in/spill-out	yes	no	
6	Fiducial mass	no	no	
7	Detector normalization	no	yes	0.6%
8	Analysis cuts	no	no	
9	Energy calibration	no	yes	0.5%
10	Backgrounds	partly	partly	1.0%

Table 1: Systematical errors in reactor neutrino experiments (see text for details). The second column indicates which errors are correlated between near and far detector while the third column classifies which effects are time-dependent. Finally, the fourth column gives specific values we assume for the Double Chooz experiment.

the far detector in phase II, $\chi^2_{F,II}$, and the near detector in phase II, $\chi^2_{N,II}$, as well as a term χ^2_{pull} describing the constraints on the systematics:

$$\chi^2 = \chi^2_{F,I} + \chi^2_{F,II} + \chi^2_{N,II} + \chi^2_{\text{pull}}\,, \tag{4}$$

where

$$\chi^2_{F,I} = \sum_i \frac{\left[(1 + a_{F,\text{fid}} + a_{\text{norm}} + a_{\text{shape},i})T_{F,I,i} \;+\; (1 + a_{F,\text{fid}} + a_{\text{bckgnd}})B_{F,I,i} - O_{F,I,i}\right]^2}{O_{F,I,i}}\,, \tag{5}$$

$$\chi^2_{F,II} = \sum_i \frac{\left[(1 + a_{F,\text{fid}} + a_{\text{norm}} + a_{\text{drift}})T_{F,II,i} \;+\; (1 + a_{F,\text{fid}} + a_{\text{bckgnd}})B_{F,II,i} - O_{F,II,i}\right]^2}{O_{F,II,i}}\,, \tag{6}$$

$$\chi^2_{N,II} = \sum_i \frac{\left[(1 + a_{N,\text{fid}} + a_{\text{norm}} + a_{\text{drift}})T_{N,II,i} + (1 + a_{N,\text{fid}} + a_{\text{bckgnd}})B_{N,II,i} - O_{N,II,i}\right]^2}{O_{N,II,i}}\,, \tag{7}$$

$$\chi^2_{\text{pull}} = \frac{a^2_{F,\text{fid}}}{\sigma^2_{F,\text{fid}}} + \frac{a^2_{N,\text{fid}}}{\sigma^2_{N,\text{fid}}} + \frac{a^2_{\text{norm}}}{\sigma^2_{\text{norm}}} + \frac{a^2_{\text{drift}}}{\sigma^2_{\text{drift}}} + \frac{a^2_{\text{bckgnd}}}{\sigma^2_{\text{bckgnd}}} + \sum_i \frac{a^2_{\text{shape},i}}{\sigma^2_{\text{shape},i}}\,. \tag{8}$$

In these expressions, $O_{F,I,i}$ denotes the event number in the i-th bin at the far detector in phase I, $O_{F,II,i}$ the corresponding event number in phase II and $O_{N,II,i}$ the event number in the near detector during phase II. These event numbers are calculated with GLoBES assuming the values given in Eqs. (2) and (3) for the oscillation parameters. The $T_{F,I,i}$, $T_{F,II,i}$ and $T_{N,II,i}$ are the corresponding theoretically expected event numbers in the i-th bin and are calculated with a varying fit value for θ_{13}. The other oscillation parameters are kept fixed, but we have checked that marginalizing over them within the ranges allowed by other neutrino experiments does not change the results of the simulations. This is in accordance with Ref. [5].

$B_{F,I,i}$, $B_{F,II,i}$ and $B_{N,II,i}$ denote the expected background rates, which we assume to be 1% of the corresponding signal rates. This means in particular, that the background spectrum follows the reactor spectrum. In reality, backgrounds will have different spectra, however, as long as these spectra are known, this actually makes it easier to discriminate between signal and background because the spectral distortion caused by backgrounds will be different from that caused by neutrino oscillations. If there are unknown backgrounds, we must introduce bin-to-bin uncorrelated errors, which will be discussed in section 5.

As systematical errors we introduce the correlated normalization uncertainty $\sigma_{\rm norm} = 2.8\%$ (describing the quadratic sum of the reactor flux error, the uncertainties in the cross sections and the scintillator properties, and the spill in/spill out effect) and the fiducial mass uncertainty for near and far detector $\sigma_{N,\rm fid} = 0.6\%$ and $\sigma_{F,\rm fid} = 0.6\%$. Furthermore, to account for errors introduced by the delayed startup of the near detector, we allow an additional bias to the flux normalization in phase II with magnitude $\sigma_{\rm drift} = 1\%$ per year of delay. We also introduce a shape uncertainty $\sigma_{{\rm shape},i} = 2\%$ per bin in phase I, which describes the uncertainty in the reactor spectrum. It is completely uncorrelated between energy bins. Note that in phase II a possible shape uncertainty is irrelevant as it will be canceled by the near detector. We assume a background normalization uncertainty of $\sigma_{\rm bckgnd} = 40\%$. Finally, we introduce a 0.5 % energy calibration error which is implemented as a re-binning of $T_{F,I,i}$, $T_{F,II,i}$ and $T_{N,II,i}$ before the χ^2 analysis (see App. A of Ref. [5]). It is uncorrelated between the two detectors, but we neglect its time dependence, since we have checked that it hardly affects the results.

5 Physics potential

In this section, we present the numerical results of our analysis and we discuss the performance of Double Chooz and the Triple Chooz upgrade. First, we discuss the quantitative impact of the systematical uncertainties introduced in the last section. In Fig. 1, we assume a reactor experiment with identical near and far detectors located at a baseline of 1.05 km which are running simultaneously. Note that this is neither the initial Double Chooz setup, where the near detector will be added with some delay, nor the Triple Chooz setup, which would have two different far detectors at slightly different baselines. Fig. 1 is nevertheless interesting, since it allows to compare the principal strength of the Double Chooz and Triple Chooz setups. The vertical black lines in Fig. 1 correspond to 5 years of *full* Double Chooz operation (5 yrs × 10.16 t × 8.4 GW), 10 years of *full* Double Chooz operation (10 yrs × 10.16 t × 8.4 GW) and 5 years of *full* Double Chooz + 5 years Triple Chooz ([5 yrs × 10.16 t + 5 yrs × 210.16 t] × 8.4 GW), respectively. The sensitivity of an experiment with the integrated luminosity of $\sim 10^3\,\mathrm{GW\,t\,yrs}$, such as Double Chooz, is quite independent of the bin-to-bin error as can be seen from Fig. 1. This is not surprising and has been already discussed in detail in Ref. [5]. Therefore, a sensitivity down to $\sin^2 2\theta_{13} = 0.02$ is certainly obtainable. The situation is somewhat different for an experiment of the size of Triple Chooz. From discussions in Ref. [5] it is expected that the $\sin^2 2\theta_{13}$ sensitivity limit at a reactor experiment of the size of Triple Chooz should be quite robust with respect to systematical uncertainties associated to the normalization, since the normalization is determined with good accuracy from the very good statistics and from additional spectral information. This robustness can be seen in Fig. 1 where the sensitivity limit at the 90% confidence level for different sets of systematical errors is shown as function of the total

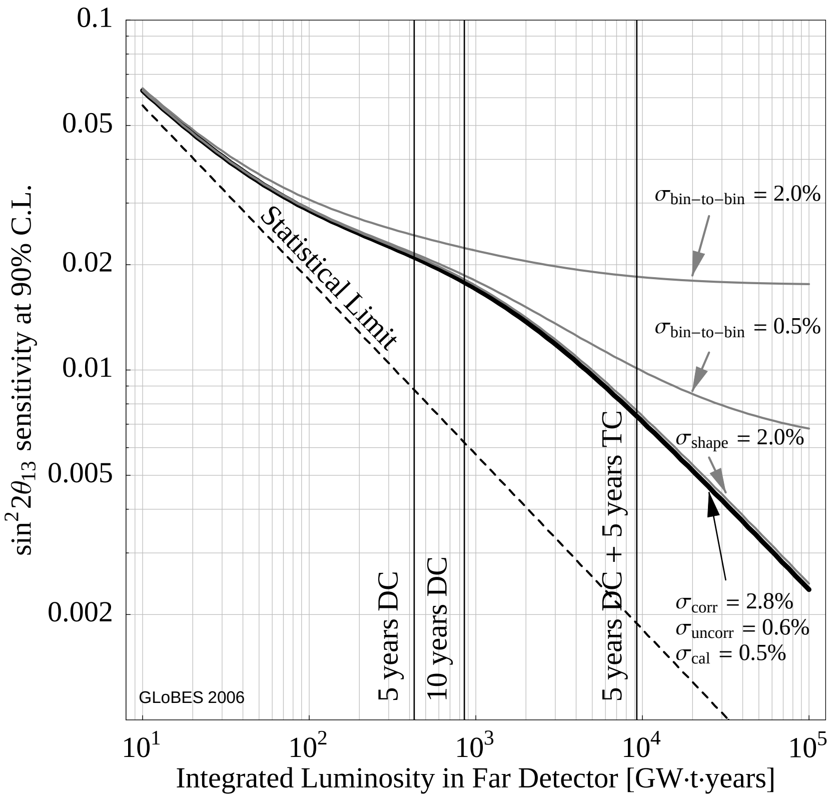

Figure 1: The impact of systematical uncertainties on the $\sin^2 2\theta_{13}$ sensitivity limit at the 90% confidence level as function of the total integrated luminosity for a reactor experiment with near and far detector (both taking data from the beginning). The integrated luminosity is given by the product of reactor power, far detector mass and running time in GW t yrs. The vertical lines indicate the exposure in 5 years of Double Chooz operation (left), 10 years of Double Chooz (middle), and 5 years Double Chooz + 5 years Triple Chooz (right). We still neglect the effects of a delayed near detector startup and of the different baselines of the two far detectors in Triple Chooz. The plot illustrates that for high luminosities it is crucial to control the uncorrelated uncertainties, in particular the bin-to-bin errors.

integrated luminosity in the far detector (given by the product of reactor power, detector mass and running time in GW t yrs). As can be seen in Fig. 1, the performance at luminosities associated with Triple Chooz decreases immediately if in addition bin-to-bin errors are introduced which are uncorrelated between near and far detector. These uncorrelated bin-to-bin errors are added to the χ^2 function in the same way as σ_{shape} was introduced in Eqs. (4) to (8) for each bin independently, but uncorrelated between the two detectors. These uncertainties could, for instance, come from uncorrelated backgrounds and different cutting methods necessary if the detectors are not 100% identical. Thus, especially for the Triple Chooz setup, these uncertainties have to be under control, because they can spoil the overall performance. The bin-to-bin error is used here as a parameterization for yet unknown systematical effects and is an attempt to account for the worst case. Thus, in a realistic situation, the bin-to-bin error would have to be broken down into individual known

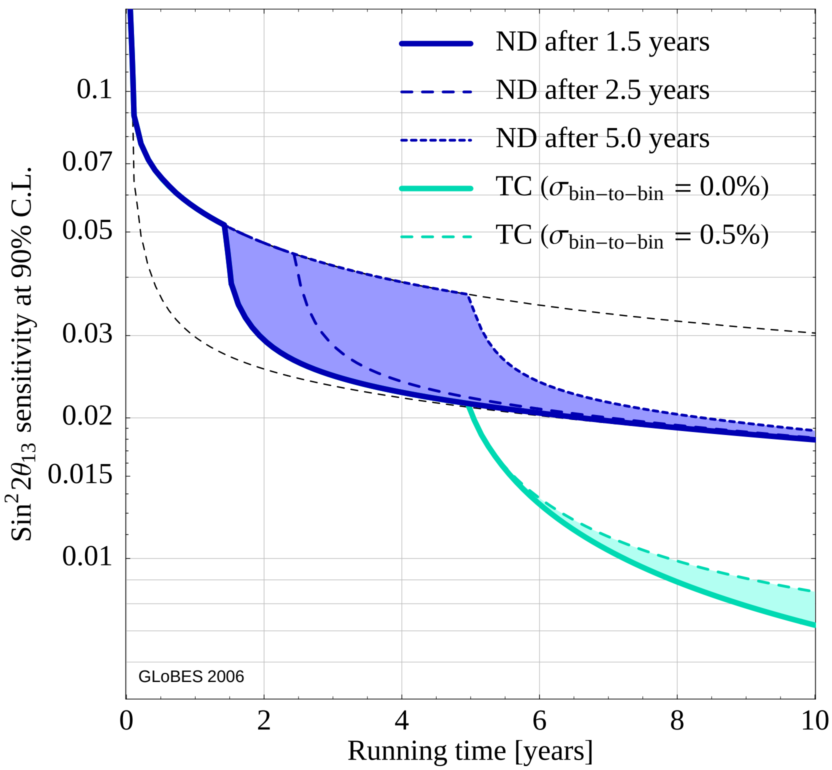

Figure 2: The $\sin^2 2\theta_{13}$ sensitivity limit at the 90 % confidence level achievable at Double Chooz for three different delayed startup times of the near detector, and of the Triple Chooz Scenario, where the second far detector is added after 5 years of Double Chooz running.

components and thus the impact would be less severe. If bin-to-bin errors were excluded, the evolution of the sensitivity limit would already enter a second statistics dominated regime (curve parallel to dashed statistics only curve), since the systematical uncertainties could be reduced due to the spectral information in the data (see also Ref. [5] for explanations). Note that the σ_{shape} uncertainty does not affect the $\sin^2 2\theta_{13}$ sensitivity in a sizeable manner, since it is correlated between near and far detector and therefore cancels out.

The evolution of the $\sin^2 2\theta_{13}$ sensitivity limit at the 90% confidence level as a function of the running time is shown in Fig. 2. Here the upper thin dashed curve indicates the limit which could be obtained by the far detector of Double Chooz alone (*i.e.*, no near detector is assumed, which corresponds to phase I continuing up to 10 years), while the lower thin dashed curve shows the limit which could be obtained if the near detector started data taking together with the far detector (*i.e.*, phase I is absent, while phase II continues up to 10 years). The near detector improves the sensitivity considerably, but even the far detector alone would quickly improve the existing Chooz limit. The solid blue (black) curve corresponds to the standard Double Chooz scenario, where the near detector starts operation 1.5 years after the far detector. It can be seen that the $\sin^2 2\theta_{13}$ limit improves strongly after the startup of the near detector and converges very fast to the curve corresponding to a near detector in operation from the beginning. Thus, the Double Chooz performance does not suffer from the delayed near detector startup in the end. This "delayed startup" is in fact not a delay, but it allows a considerably quicker startup of the whole experiment, utilizing the fact that no civil engineering is necessary at the site of the far detector. There have been performed similar calculations by the Double Chooz collaboration [14], concerning the evolution of the $\sin^2 2\theta_{13}$ sensitivity with a 1.5 years duration of phase I, followed by a phase II scenario, which are in good agreement with the corresponding curves in Fig. 2. However, there are slight differences especially for the evolution of the $\sin^2 2\theta_{13}$ sensitivity in phase I. These come from the inclusion of spectral information in Fig. 2, whereas in the calculations in Ref. [14] only total rates were taken into account. The dashed and dotted blue (black) curves in Fig. 2 show the evolution of the sensitivity limit, if the near detector were operational not 1.5 years after the far detector, but 2.5 or 5 years, respectively. Again, the sensitivity limit improves quickly as soon as the near detector is available and quickly approaches the limit with a near detector from the beginning. The main reason for this is, that the overall sensitivity is ultimately dominated by the uncorrelated systematical uncertainties and not by statistics. Furthermore, Fig. 2 shows the evolution of the $\sin^2 2\theta_{13}$ sensitivity limit for the Triple Chooz setup, both without uncorrelated bin-to-bin errors (solid cyan/grey curve) and with $\sigma_{\text{bin-to-bin}} = 0.5\%$ (dashed cyan/grey curve). It is assumed that the second far detector starts operation 5 years after the first far detector. In the Triple Chooz simulation, we have assumed the uncorrelated normalization and energy calibration errors of the second far detector to be 1% each. This is slightly larger than the 0.6% resp. 0.5% in the original Double Chooz reflecting that the design of the new detector would have to be different from that of the two original detectors. It can be seen that the Triple Chooz scenario could achieve a 90% confidence level sensitivity limit below $\sin^2 2\theta_{13} = 10^{-2}$ after less than 8 years of total running time (5 years Double Chooz + 3 years Triple Chooz), even if small bin-to-bin errors were allowed to account for backgrounds or detector characteristics that are not fully understood. If bin-to-bin errors are absent, the sensitivity will improve by about 10%. The plot shows that the Triple Chooz setup can compete with the sensitivity expected from other second generation precision reactor experiments. It also demonstrates that the precision of reactor experiments could be further improved in a timely manner. The improved $\sin^2 2\theta_{13}$ limits or measurements could be valuable input for planning and optimizing the second generation neutrino beam experiments.

We have so far considered a 200t detector for Triple Chooz and one may wonder how an even larger detector, which easily fits into the large existing cavern, would perform. A larger detector implies even higher values of integrated far detector luminosity. From Fig. 1 one can immediately see that the achievable value of $\sigma_{\mathrm{bin-to-bin}}$ determines the performance, *i.e.* if one can benefit from the larger detector mass or if the sensitivity is already saturated by $\sigma_{\mathrm{bin-to-bin}}$. From Fig. 1 one can read off that for 100t or 200t $\sigma_{\mathrm{bin-to-bin}} < 0.5\%$ should be achieved. A 500t detector would require $\sigma_{\mathrm{bin-to-bin}} < 0.1\%$ in order to obtain an improvement of the sensitivity limit to the level of $5 \cdot 10^{-3}$.

Fig. 3 shows the dependence of the $\sin^2 2\theta_{13}$ sensitivity of Double Chooz on the true value of Δm^2_{31}. Such a parametric presentation makes sense, since Δm^2_{31} will be known relatively precisely by then from the MINOS experiment. The sensitivity again is shown for four different scenarios: 5 years with the far detector of Double Chooz only (dashed black curve

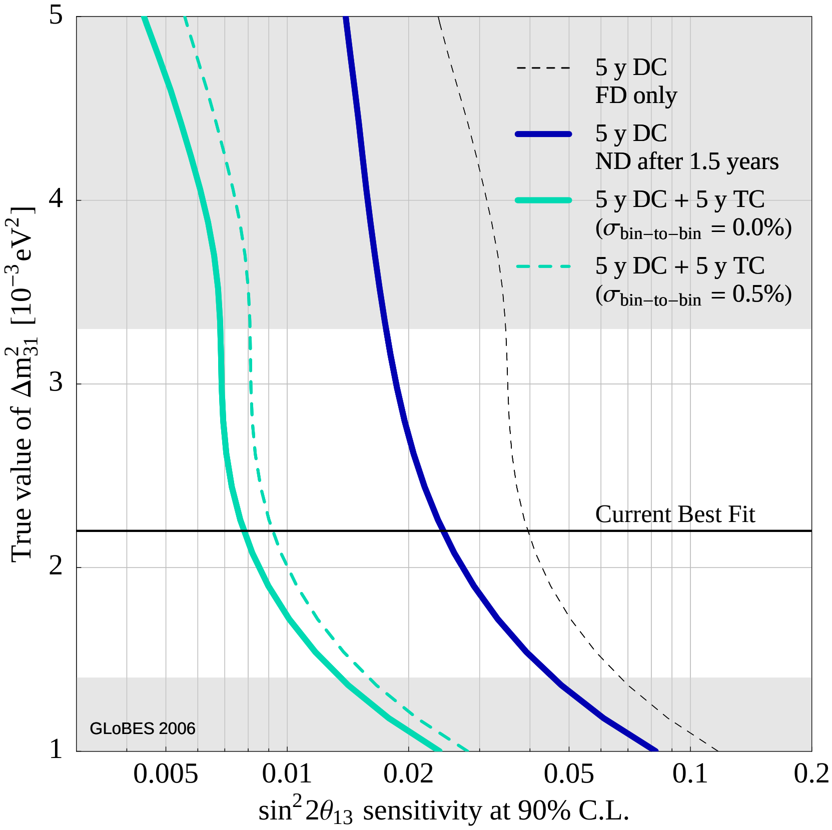

Figure 3: The sensitivity limit for $\sin^2 2\theta_{13}$ at the 90% confidence level as a function of the true value of Δm^2_{31}. The curves correspond to the following setups: a 5-year run of only the Double Chooz far detector without near detector (dashed blue/black curve to the right), a 5-year run of Double Chooz with near detector after 1.5 years (solid blue/black curve), and a 5-year run of Double Chooz followed by a 5-year run of Triple Chooz without bin-to-bin errors (solid cyan/grey curve) and with a 0.5% bin-to-bin error (dashed cyan/grey curve). The light grey areas show the 3σ excluded regions for Δm^2_{31} from a global fit [10], the horizontal line indicates the corresponding best fit value.

to the right), 5 years of Double Chooz with a near detector after 1.5 years (solid blue/black curve), and finally the Triple Chooz scenario with and without bin-to-bin errors, where the second far detector is starting operation 5 years after the first far detector (cyan/grey curves). We also show the curves for a region of Δm^2_{31} parameter space that is already excluded by current global fits (upper grey-shaded region; see, *e.g.*, Refs. [7–10]). One can easily see that a larger true value of Δm^2_{31} would be favorable for an experiment at the relatively short baseline of $L \sim 1.05$ km between the reactor and the Double Chooz detector. As can be seen in Fig. 3, the setup with only a far detector and the Triple Chooz setup show a characteristic dip around $\Delta m^2_{31} \approx 3 \cdot 10^{-3}\,\mathrm{eV}^2$. This effect is due to the normalization errors and can be understood as follows: If the true Δm^2_{31} is very small, the first oscillation maximum lies outside the energy range of reactor neutrinos. For $\Delta m^2_{31} \approx 2 \cdot 10^{-3}\,\mathrm{eV}^2$, the first maximum enters at the lower end of the spectrum. Therefore oscillations cause a spectral distortion which cannot be mimicked by an error in the flux normalization. But

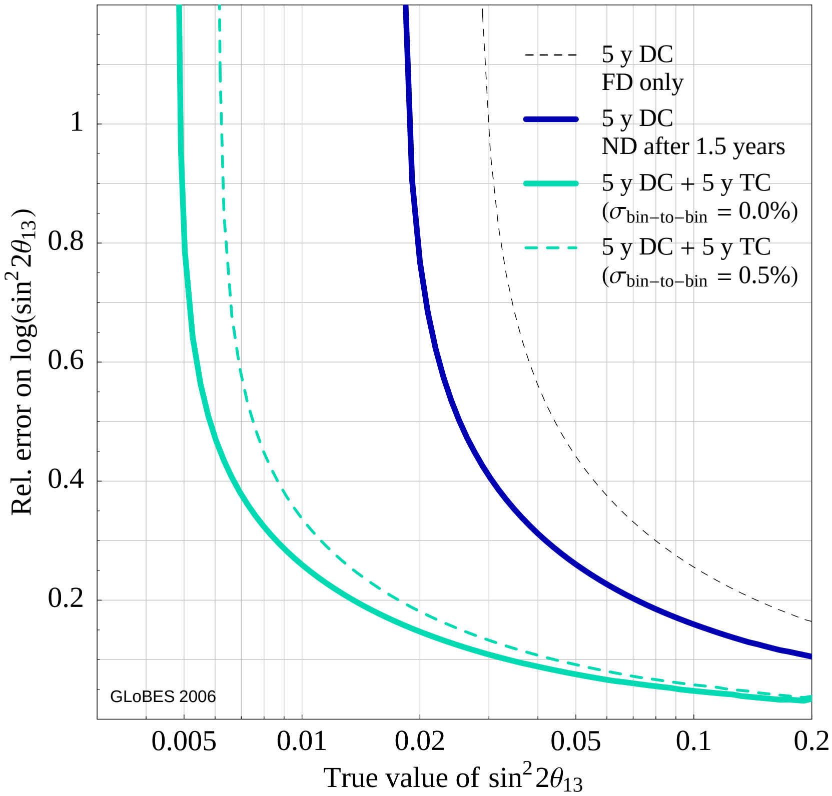

Figure 4: The precision of the $\sin^2 2\theta_{13}$ measurement at the 90% confidence level as a function of the true value of $\sin^2 2\theta_{13}$. The curves correspond to the following setups: a 5-year run of only the Double Chooz far detector without near detector (dashed blue/black curve to the right), a 5-year run of Double Chooz with near detector after 1.5 years (solid blue/black curve), and a 5-year run of Double Chooz followed by a 5-year run of Triple Chooz without bin-to-bin errors (solid cyan/grey curve) and with a 0.5% bin-to-bin error (dashed cyan/grey curve).

with increasing true Δm^2_{31}, a larger part of the relevant energy range is affected by the oscillations. This behaviour could also come from a normalization error which decreases the sensitivity to $\sin^2 2\theta_{13}$ in the region around $\Delta m^2_{31} \approx 3 \cdot 10^{-3}\,\mathrm{eV}^2$. For even larger $\Delta m^2_{31} \gtrsim 4 \cdot 10^{-3}\,\mathrm{eV}^2$, the second oscillation maximum enters the reactor spectrum, which again causes a characteristic spectral distortion.

Up to now, we have only considered the achievable $\sin^2 2\theta_{13}$ sensitivity limit. If a finite value were observed, reactor experiments could determine $\sin^2 2\theta_{13}$ with a certain precision, since no correlations with the unknown CP phase δ_{CP} would exist. For a large reactor experiment, this might allow the first generation beam experiments, T2K and NOvA to have a first glimpse on CP violation [15]. Fig. 4 shows the precision to $\sin^2 2\theta_{13}$ for the different considered setups. This precision is defined as

$$\text{Rel. error on } \sin^2 2\theta_{13} = \left| \frac{\log(\sin^2 2\theta_{13}^{(u)}) - \log(\sin^2 2\theta_{13}^{(d)})}{\log(\sin^2 2\theta_{13}^{(\text{true})})} \right| , \tag{9}$$

where $\log(\sin^2 2\theta_{13}^{(u)})$ and $\log(\sin^2 2\theta_{13}^{(d)})$ are the upper and lower bounds of the 90% confidence region, and $\log(\sin^2 2\theta_{13}^{(\mathrm{true})})$ is the true value assumed in the simulation (same definition as in Ref. [5]). The plot confirms the expectation that the precision is better for a larger value of $\sin^2 2\theta_{13}$. The ability to measure $\sin^2 2\theta_{13}$ is then completely lost for true values near the sensitivity limit.

6 Role in the global context and complementarity to beam experiments

In order to discuss the role of the Double Chooz and Triple Chooz setups in the global context, we show in Fig. 5 a possible evolution of the $\sin^2 2\theta_{13}$ discovery potential (left) and $\sin^2 2\theta_{13}$ sensitivity limit (right) as function of time. In the left panel of Fig. 5, we assume that $\sin^2 2\theta_{13}$ is finite and that a certain unknown value of δ_{CP} exists. The bands in the figure reflect the dependence on the unknown value of δ_{CP}, *i.e.*, the actual sensitivity will lie in between the best case (upper) and worst (lower) curve, depending on the value of δ_{CP} chosen by nature. In addition, the curves for the beam experiments shift somewhat to the worse for the inverted mass hierarchy, which, however, does not qualitatively affect this discussion. The right panel of the figure shows the $\sin^2 2\theta_{13}$ limit which can be obtained for the hypothesis $\sin^2 2\theta_{13} = 0$, *i.e.*, no signal. Since particular parameter combinations can easily mimic $\sin^2 2\theta_{13} = 0$ in the case of the neutrino beams, their final $\sin^2 2\theta_{13}$ sensitivity limit is spoilt by correlations (especially with δ_{CP}) compared to Double Chooz[2]. The two panels of Fig. 5 very nicely illustrate the complementarity of beam and reactor experiments: Beams are sensitive to δ_{CP} (and the mass hierarchy for long enough baselines), reactor experiments are not. On the other hand, reactor experiments allow for a "clean" measurement of $\sin^2 2\theta_{13}$ without being affected by correlations.

There are a number of important observations which can be read off from Fig. 5. First of all, assume that Double Chooz starts as planned (solid Double Chooz curves). Then it will quickly exceed the $\sin^2 2\theta_{13}$ discovery reach of MINOS, especially after the near detector is online (left panel). For some time, it would certainly be the experiment with the best $\sin^2 2\theta_{13}$ discovery potential. If a finite value of $\sin^2 2\theta_{13}$ were established at Double Chooz, the first generation superbeam experiments T2K and NOvA could try to optimize a potential anti-neutrino running strategy. The breaking of parameter correlations and degeneracies might in this case be even achieved by the synergy with the Triple Chooz upgrade (similar to Reactor-II in Ref. [5]). For the $\sin^2 2\theta_{13}$ sensitivity, *i.e.*, if there is no $\sin^2 2\theta_{13}$ signal, the best limit will come from Double Chooz already from the very beginning even without near detector. Together with the near detector, this sensitivity cannot be exceeded by the superbeams without upgrades, because these suffer from the correlation with δ_{CP}. Double Chooz has altogether an excellent chance to observe a finite value of θ_{13} first. If θ_{13} were zero or tiny, then Double Chooz would be an extremely good exclusion machine. It could exclude a large fraction of the parameter space already a few years before the corresponding

[2] Note that we define the $\sin^2 2\theta_{13}$ sensitivity limit as the largest value of $\sin^2 2\theta_{13}$ which fits (the true) $\sin^2 2\theta_{13} = 0$ at the given confidence level. Therefore, this definition has no dependence on the true value of δ_{CP}, and the fit δ_{CP} is marginalized over (*cf.*, App. C of Ref. [15]).

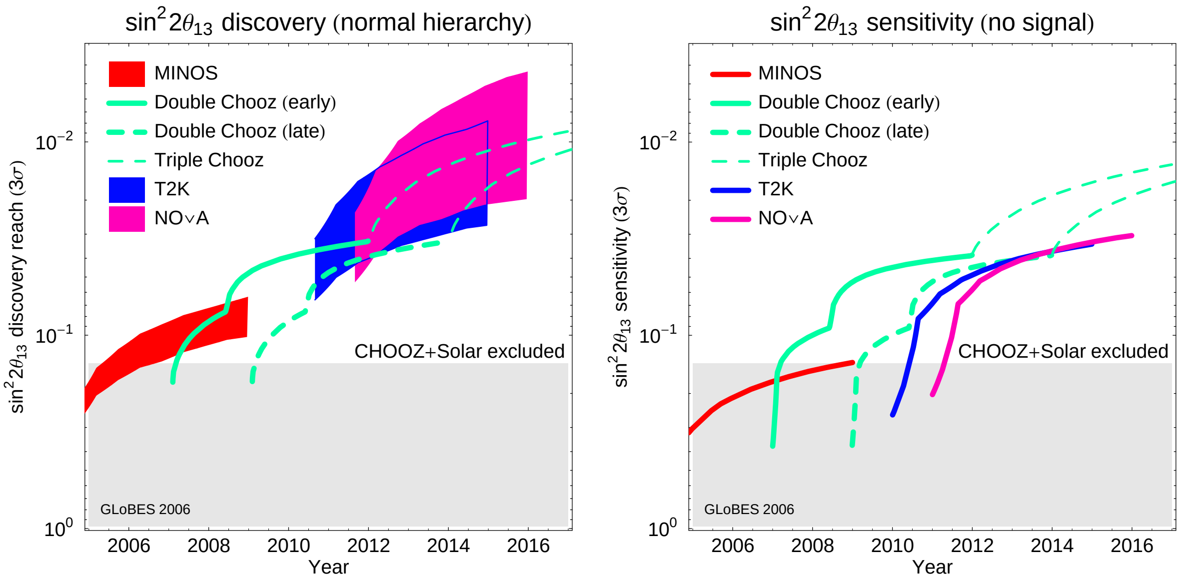

Figure 5: A possible evolution of the $\sin^2 2\theta_{13}$ discovery potential (left) and $\sin^2 2\theta_{13}$ sensitivity/exclusion limit (right) at 3σ as function of time including statistics, systematics, and correlations (3σ). The bands reflect for the neutrino beam experiments the dependence on the unknown value of δ_{CP}, *i.e.*, the actual sensitivity evolution will lie in between the best case (upper) and worst (lower) curve depending on the value of δ_{CP} chosen by nature. All experiments are assumed to be operated five years and the beam experiments are operated with neutrino running only. The full detector mass is assumed to be available right from the beginning for the beam experiments, *i.e.*, the starting times are chosen accordingly. Double Chooz is assumed to start data taking with the near detector 1.5 years after the far detector, where two possible far detector starting times are shown. In addition, the possible upgrade to Triple Chooz is included after five years of data taking. Though the starting times of the experiments have been chosen as close as possible to those stated in the respective LOIs, they have to be interpreted with care. A normal mass hierarchy is assumed for this plot and for an inverted hierarchy, the accelerator-based sensitivities are expected to shift down somewhat. The calculations (including time evolution) of the beams are based on the experiment simulations in Refs. [11,15–17] using GLoBES [11]. This Figure is similar to the ones that can be found in Refs. [18,19].

superbeams.

One can also read off from Fig. 5 that the starting time of the near detector of Double Chooz is time-critical (*cf.*, dashed Double Chooz curves). Especially from the left panel, one can see that the near detector has to start taking data considerably before 2010 in order to be competitive to the superbeams. Also, to achieve the maximal synergy, it will be important that the information from Double Chooz is available roughly around 2010 as we will discuss later on. Note that the superbeams do not in all cases have a better $\sin^2 2\theta_{13}$ discovery potential. This holds especially if the true $\delta_{\mathrm{CP}} \sim \pi/2$ (*cf.*, *e.g.*, Ref. [20]) and the mass hierarchy is inverted. In this case, Double Chooz may still discover $\sin^2 2\theta_{13}$ if the near detector starts 2010 or later. However, this scenario only holds for a very small fraction of the parameter space.

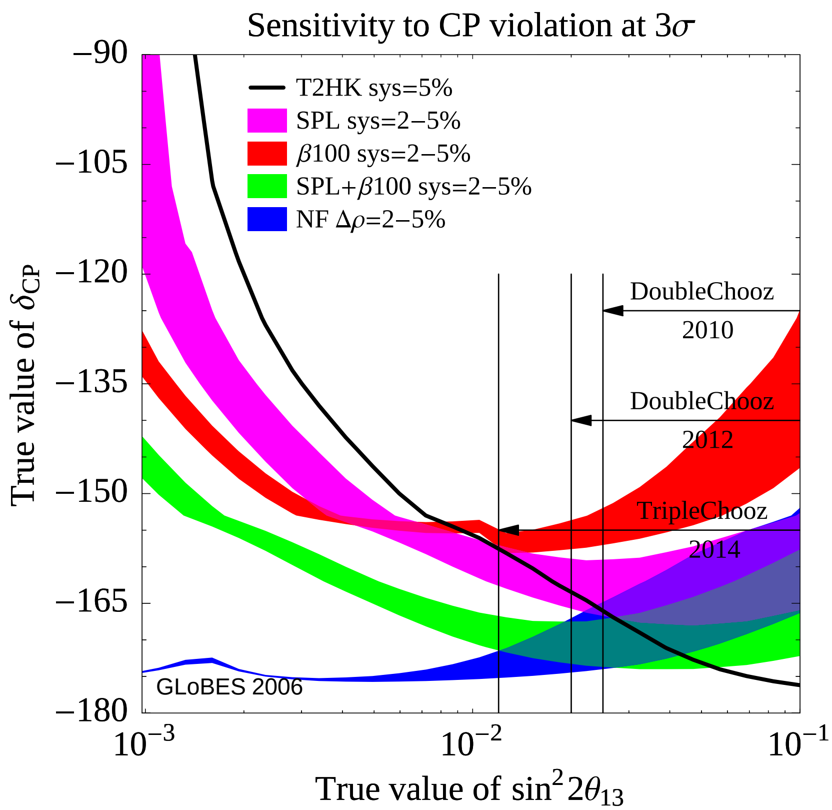

Figure 6: $\sin^2 2\theta_{13}$ sensitivity limits at the 90% confidence level of Double and Triple Chooz in comparison to the $3\,\sigma$ discovery reaches (above curves) for CP violation of various, second generation beam experiments. All curves have been calculated with GLoBES [11] including correlations and degeneracies. For all setups, the appropriate disappearance channels have been included. The beta beam is lacking muon neutrino disappearance, which is replaced by a 10% precision on Δm^2_{31} (corresponding to the T2K disappearance information). In all cases systematics between neutrinos, anti-neutrinos, appearance, and disappearance is uncorrelated. For all setups with a water Cherenkov detector, the systematics applies both to background and signal, uncorrelated. The neutrino factory (NF) assumes $3.1 \cdot 10^{20}$ μ^+ decays per year for 10 years and $3.1 \cdot 10^{20}$ μ^- decays for 10 years. It has one detector with $m = 100\,\mathrm{kt}$ at 3000 km and another detector with 30 kt at 7000 km. The density errors between the two baselines are uncorrelated. The systematics are 0.1% on the signal and 20% on the background, uncorrelated. The detector threshold and the other parameters are taken from Ref. [16] and approximate the results of Ref. [21]. The beta beam (β100) assumes $5.8 \cdot 10^{18}$ He decays per year for five years and $2.2 \cdot 10^{18}$ Ne decays per year for five years. The detector mass is 500 kt. The detector description and the glb-file is from Ref. [22]. The SPL setup is taken from Ref. [23], and the detector mass is 500 kt. The T2HK setup is taken from Ref. [16] and closely follows the LOI [24]. The detector mass is 1 000 kt and it runs with 4 MW beam power, 6 years with anti-neutrinos and 2 years with neutrinos. The systematic error on both background and signal is 5%.

Triple Chooz is a very interesting upgrade option for Double Chooz. Fig. 5 shows that it could play an important role, since it would have a sensitivity reaching into the discovery range of the neutrino beam experiments T2K and NOνA. In the case of a value of $\sin^2 2\theta_{13}$

not too far below the current CHOOZ bound, this might even lead to the possibility to restrict the CP parameter space. Note, however, that a delayed startup would eliminate the $\sin^2 2\theta_{13}$ discovery opportunity. In either case, if the true θ_{13} is small, Double Chooz with a later Triple Chooz upgrade will give the best exclusion limits for the coming 10 years. Note that in the staged approach of Triple Chooz, the original Double Chooz experiment serves as a testbed for the upgrade. Thus, systematical uncertainties will be well understood, so that a reliable sensitivity prediction for Triple Chooz will be possible.

Double Chooz and Triple Chooz will play a central role in selecting the optimal technology for the second generation beam experiments. Fig. 6 shows the sensitivity to CP violation at $3\,\sigma$ confidence level ($\Delta\chi^2 = 9$) for several approaches that are currently being discussed. Sensitivity to CP violation is defined, for a given point in the θ_{13}-δ-plane (above curves), by being able to exclude $\delta = 0$ and $\delta = \pi$ at the given confidence level. In Fig. 6, clearly two regimes can be distinguished: very large $\sin^2 2\theta_{13} \geq 0.01$ and very small $\sin^2 2\theta_{13} \leq 0.01$. At large θ_{13}, the sensitivity to CP violation is basically completely determined by factors such as systematic errors or matter density uncertainty. Thus the question of the optimal technology cannot be answered with confidence at the moment, since for most of the controlling factors the exact magnitude can only be estimated. The technology decision for large θ_{13}, therefore, requires considerable R&D. On the other hand, in the case of small θ_{13} the optimal technology seems to be a neutrino factory[3] quite independently from any of the above mentioned factors. The branching point between the two regimes is around $\sin^2 2\theta_{13} \sim 0.01$ which coincides with the sensitivities obtainable at the Chooz reactor complex. Moreover, the information from Chooz would be available around 2010 which is precisely the envisaged time frame for the submission of a proposal for those second generation neutrino beam facilities. Thus the Double Chooz results are of central importance for the long term strategy of beam-based neutrino physics.

7 Summary and conclusions

We have analyzed the physics potential of new reactor neutrino experiments at the Chooz reactor complex. A first very realistic and competitive option is the Double Chooz project. Our simulations show that it could be the leading experiment in the search for a finite value of $\sin^2 2\theta_{13}$ in the coming years. Therefore, Double Chooz, if timely performed, has excellent chances to detect the first signal of a finite value of $\sin^2 2\theta_{13}$. Such an early discovery would be very important for the superbeam optimization in terms of antineutrino running to discover mass hierarchy and CP violation, and the choice of the optimal technology for second-generation superbeams or beta beams. Provided that $\sin^2 2\theta_{13} \gtrsim 0.04$, Double Chooz would provide such an early signal for a finite value of $\sin^2 2\theta_{13}$ at relatively low cost. In addition, Double Chooz can provide and dominate an excellent limit for $\sin^2 2\theta_{13}$ if $\sin^2 2\theta_{13}$ is very small, because it is hardly affected by correlations. In the case of an exactly vanishing true value of $\sin^2 2\theta_{13} = 0$, Double Chooz could set an upper limit of $\sin^2 2\theta_{13} < 0.018$ at the 90% confidence level after 10 years which can hardly be exceeded by the superbeams. However, Double Chooz will not replace the need for the superbeams,

[3]Not shown in figure 6 is the $\gamma = 350$ beta beam [25], which could play the role of a neutrino factory.

because superbeams have a much better $\sin^2 2\theta_{13}$ discovery potential and, if $\sin^2 2\theta_{13}$ is large, are sensitive to $\delta_{\rm CP}$ and the neutrino mass hierarchy. In summary, Double Chooz is an exclusion machine, whereas superbeams are discovery machines, both providing very complementary information.

We have also discussed a very interesting upgrade option for Double Chooz, which we call "Triple Chooz". Similar to Double Chooz, Triple Chooz could benefit from an existing underground cavern, which would reduce the costs significantly. The existing cavern would also allow a faster realization of the experiment, since no major civil construction would be necessary. Triple Chooz would also benefit from the existing experience and infrastructure of Double Chooz. Our simulations show that the Triple Chooz upgrade could compete with other planned second generation reactor experiments. Triple Chooz with a fiducial mass of 200 t could measure $\sin^2 2\theta_{13}$ with a precision better than 10% at the 90% confidence level down to true values of $\sin^2 2\theta_{13} \simeq 0.04$ and achieve a sensitivity level well below $\sin^2 2\theta_{13} \lesssim 10^{-2}$ if the true value is zero. Arriving early at this "branching point" could be very important for the technology choice between a superbeam upgrade and neutrino factory (or higher gamma beta beam) program. In summary, our study shows that both Double Chooz and Triple Chooz would be very well positioned in the global neutrino oscillation program.

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