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## Combining accelerator and reactor measurements of $\theta_{13}$ : the first result

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ABSTRACT: The lepton mixing angle  $\theta_{13}$ , the only unknown angle in the standard three-flavor neutrino mixing scheme, is finally measured by the recent reactor and accelerator neutrino experiments. We perform a combined analysis of the data coming from T2K, MINOS, Double Chooz, Daya Bay and RENO experiments and find  $\sin^2 2\theta_{13} = 0.096 \pm 0.013(\pm 0.040)$  at  $1\sigma$  ( $3\sigma$ ) CL and that the hypothesis  $\theta_{13} = 0$  is now rejected at a significance level of  $7.7\sigma$ . We also discuss the near future expectation on the precision of the  $\theta_{13}$  determination by using expected data from these ongoing experiments.

KEYWORDS: Neutrino Physics, Standard Model

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## 1 Introduction

The accelerator search for  $\nu_e$  appearance [1]<sup>1</sup> and the precision measurement of reactor neutrino disappearance [2, 3] are both viable ways to measure  $\theta_{13}$ , which has been, until very recently, the unique unknown mixing angle of the lepton flavor mixing matrix [4]. It must be stressed that the experimental redundancy for measuring  $\theta_{13}$  may be justified because of the complementary nature of the two types of experiments, as discussed, for example, in [3, 5]. While the reactor experiments provide a clean measurement of  $\theta_{13}$  which is free from degeneracy [6–8], the accelerator measurement can enjoy the interplay with the CP phase  $\delta_{\text{CP}}$ , which connotes the possibility of extension of the experiment to an upgraded phase to search for CP violation.

It is very fortunate to see that the era of simultaneous measurement of  $\theta_{13}$  by accelerator and reactor has just arrived. In June of 2011 the T2K group reported six clean events of  $\nu_e$  appearance, implying 2.5  $\sigma$  indication for non-zero  $\theta_{13}$  [9] with a best fit value comparable to the CHOOZ limit [10] (see also [11–13]). It was soon followed by the MINOS collaboration which reported also indication of non-zero  $\theta_{13}$  [14]. At the end of 2011, one of the reactor  $\theta_{13}$  experiments, Double Chooz [15], reported their first result, constraining  $\theta_{13}$  to a range  $\sin^2 2\theta_{13} = 0.086 \pm 0.051$  at 68 % CL [16, 17].<sup>2</sup>

Very recently we were surprised by the announcement of another two reactor  $\theta_{13}$  experiments. First, Daya Bay [18], which reported a measurement of  $\theta_{13}$  as accurate as  $\sin^2 2\theta_{13} = 0.092 \pm 0.017$  at 68 % CL. The significance level for non-zero  $\theta_{13}$  obtained by them is 5.2

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<sup>1</sup>For an updated version see <http://neutrino.kek.jp/jhfnu/loi/loi.v2.030528.pdf>.

<sup>2</sup>For the official Double Chooz results see also [http://doublechooz.in2p3.fr/Status\\_and\\_News/status\\_and\\_news.php](http://doublechooz.in2p3.fr/Status_and_News/status_and_news.php).

$\sigma$  [19]. Second, RENO [20, 21], which reported  $\sin^2 2\theta_{13} = 0.113 \pm 0.023$  at 68 % CL, excluding a non-zero  $\theta_{13}$  at  $4.9 \sigma$  [22]. Though still limited by both statistics and systematics (except for Daya Bay whose systematics is already small), these results, together with the aforementioned accelerator data, constitutes the most valuable information on  $\theta_{13}$  to date. Therefore, we believe that it is a meaningful step to attempt a combined analysis of these data set.

The issue of possible nonzero  $\theta_{13}$  has been discussed in the context of global analyses which include the solar and the atmospheric neutrino data even before [23–25] or after [26, 27] the T2K result [9]. However, given the current precision on the determination of  $\theta_{13}$ , such global fits seem unnecessary in this specific context. Hence, in this paper we restrict ourselves to a combined analysis of the accelerator and the reactor  $\theta_{13}$  experiments only.

## 2 Analysis details

We analyze the available accelerator data from T2K [9] and MINOS [14] in the  $\nu_\mu \rightarrow \nu_e$  appearance channel in combination with the very recent Double Chooz [16, 17], Daya Bay [19] and RENO [22] reactor data in the  $\bar{\nu}_e \rightarrow \bar{\nu}_e$  disappearance channel. We will also make some prognostication to the near future. The simulations were performed using a modified version of GLoBES [28].

### 2.1 Accelerator experiments: T2K and MINOS

The T2K experiment uses a narrow  $2.5^\circ$  off-axis  $\nu_\mu$  beam generated at J-PARC in Tokai which is directed to the Super-Kamiokande detector of fiducial mass 22.5 kt located in Kamioka 295 km away from J-PARC. In order to reproduce the T2K allowed region in the  $\sin^2 2\theta_{13} - \delta_{\text{CP}}$  plane, reported in figure 6 of ref. [9], we have simulated the T2K signal in the  $\nu_\mu \rightarrow \nu_e$  appearance channel in a similar way as done in ref. [5]. We took the neutrino fluxes from the letter of intent of the Hyper-Kamiokande project [29] and the background from [9]. The cross sections and energy dependent efficiencies for charged current quasi-elastic (CC-QE) and non quasi-elastic (CC-NQE) events are simulated in a similar manner as in [5] to reproduce the energy spectra given in [29].

Energy smearing and the consequent migration of events were taken into account in our calculations by using a Gaussian energy resolution function with width 85 (130) MeV for CC-QE (CC-NQE) events. For CC-NQE events, following the procedure described in the appendix of [5], a shift of 350 MeV was introduced in the Gaussian smearing function in order to take into account the significant difference between true and reconstructed neutrino energy. In reproducing the current T2K result we assumed  $1.43 \times 10^{20}$  POT and 23% systematic uncertainty in the absolute normalization.

The MINOS experiment uses the NuMI beamline and operates with a near detector located on-site at Fermilab, and a far detector located 735 km away in the Soudan Underground Laboratory. The near (far) detector consists of 0.98 kt (5.4 kt) of alternating layers of steel and plastic scintillator. In order to reproduce the MINOS allowed region in the  $\sin^2 2\theta_{13} - \delta_{\text{CP}}$  plane, given in figure 3 of ref. [14], we have simulated the  $\nu_e$  signal using the same procedure as in ref. [30] but with the background and systematic uncertainties

taken from [14]. We assumed a total exposure of  $8.2 \times 10^{20}$  POT, but a tuning of the normalization was needed in order to obtain the correct number of signal events.

## 2.2 Reactor experiments: Double Chooz, Daya Bay and RENO

Double Chooz (DC) is a reactor antineutrino oscillation experiment [15] based on the CHOOZ-B Nuclear Power Station. The experiment is a double detector apparatus (each detector with a fiducial volume of  $10.3 \text{ m}^3$ ) based on liquid scintillator, though until 2013 they will be taking data only with their far detector located at 1.05 km from the two  $4.27 \text{ GW}_{\text{th}}$  reactor cores.

To simulate the  $\bar{\nu}_e \rightarrow \bar{\nu}_e$  disappearance reported by DC collaboration in refs. [16, 17] we have performed a calculation based on the far detector specification and reactor fuel composition given in ref. [15], with systematic uncertainties, background and efficiency, and other additional information according to [16, 17].

Before analyzing the real data, we first tried to reproduce the expected visible energy spectra obtained by the Monte Carlo (MC) simulations of the DC collaboration, in the absence and presence of oscillation shown (respectively, by the blue dotted and red solid histograms) in figure 3 of [16]. Indeed, in our attempt to reproduce the visible energy spectra, we have noticed that these spectra exhibit significant *distortions* if compared to the corresponding spectra as a function of the true prompt energy, which, of course, can not be measured directly.

In order to mimic such a rather strong *distortions*, which are due to various effects taken into account in the MC simulations by the DC collaboration, we first introduce an energy smearing effects using a Gaussian energy resolution function with a width  $\sigma_E = 12\% \sqrt{(E/\text{MeV})} + 0.15 \text{ MeV}$ . We note that due to the 2nd term in  $\sigma_E$ , we can reproduce rather well the spectra after taking into account the additional corrections described below. We, however, stress that the inclusion or omission of the 2nd term in  $\sigma_E$  does not alter much the allowed parameter region of  $\sin^2 2\theta_{13}$  and  $\delta_{CP}$  presented in this paper, though it affects the  $\chi_{\text{min}}^2$  values.

In addition to the energy smearing we have further taken into account, in an approximate way, two kinds of corrections which were actually introduced in the analysis by the DC collaboration [31].<sup>3</sup> in order to understand their data. The first one is a non linearity correction. This is based on the energy calibration by using several sources performed by the DC collaboration. Roughly speaking, the observed visible energies (or to be more precise the number of photoelectrons) tend to be overestimated (underestimated) for energy larger (smaller) than  $\sim 1.5 \text{ MeV}$  for up to a few percent, when compared to the ones predicted by MC simulations. Note that the correction is energy dependent, see [31]. The second correction is the one based on the  $Z$ -dependence calibration, which shows that the observed energy tends to be underestimated when the neutrino event occurs in the region far from the center of the detector, for up to a few percent [31]. We note that, after taking into account these two corrections in addition to the energy smearing, we can reproduce reasonably well the energy spectra shown in figure 3 of [16].

<sup>3</sup>Relevant information to be available at <http://doublechooz.in2p3.fr/Status.and.News/>.

Daya Bay (DB) experiment measures  $\bar{\nu}_e$  from six 2.9 GW<sub>th</sub> reactors grouped into three pairs of nuclear power plants (NPP) using six detectors deployed in a near-far arrangement allowing to compare rates at various baselines. There are two near detectors at 364 m from the Daya Bay NPP, one near detector at 480 m (528 m) from Ling Ao (Ling Ao-II) NPP and three far detectors at 1912 m (1540 m) from Daya Bay (Ling Ao and Ling Ao-II) NPP [19]. Each one of these identical detectors is made of a 5 m diameter cylindrical stainless steel vessel which holds a 3.1 m diameter inner vessel and a 4 m diameter outer vessel. The inner vessel holds 20 ton of Gadolinium-doped liquid scintillator (the target) which is shielded from the 20 ton liquid scintillator in the outer acrylic vessel by 37 ton of mineral oil. We have implemented in our simulation the systematic uncertainties and the background in accordance with [19]. In this paper, for DB, we do not consider the energy spectrum but restrict ourselves to the rates only analysis, as done in ref. [18], even for our near future analysis to be discussed in section 4. The reason is that DB's systematic uncertainty for the rate only analysis is already quite small and their data are still statistically limited and hence it seems that the spectrum information would not play an important role for the time being.

RENO is the reactor experiment which receives neutrinos from the YongGwang Nuclear Power Plant located 400 km from Seoul in which six 2.8 GW<sub>th</sub> reactors are lined up. They use two 16 t liquid scintillator identical detectors, the near (far) detector located at roughly 300 m (1.3 km) from the reactors. RENO has been taking data with both detectors since August 2011. In order to simulate RENO  $\bar{\nu}_e$  disappearance signal we performed rate-only analysis, using the background, energy resolution and the systematic uncertainties given in ref. [21, 22].

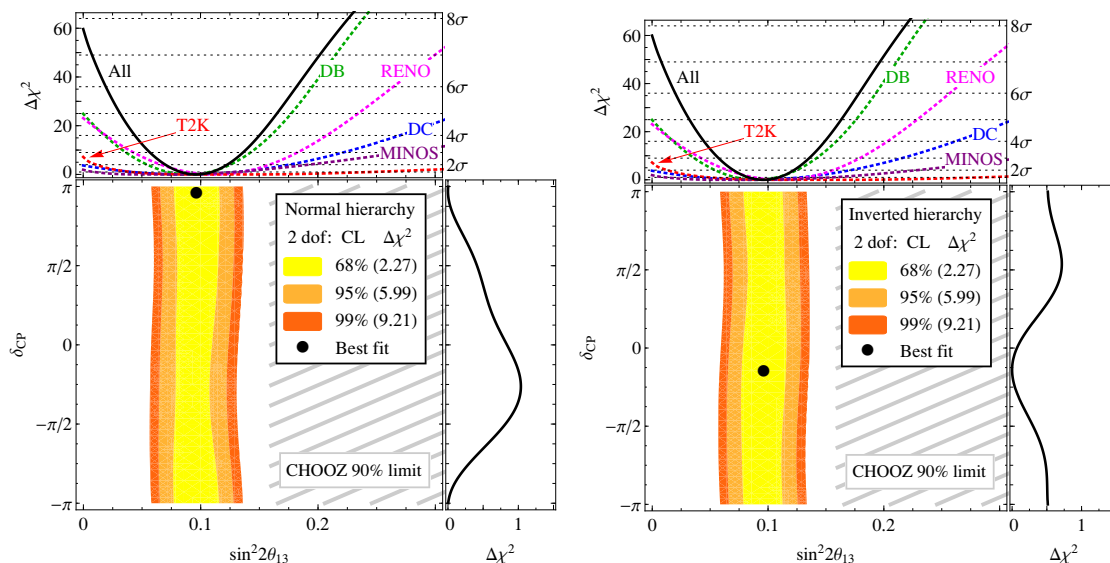
In DC, DB and RENO simulations we have used the new reactor antineutrino flux calculations [32, 33]. This has little impact on our results, since DC is normalized to Bugey-4 cross section and the other reactor experiments have near detectors.

### 3 Analysis results: current status

#### 3.1 Combining accelerator and reactor data

Before combining the accelerator and reactor neutrino data we have verified that we are able to reproduce quite well the individual result of each experiment T2K [9], MINOS [14], DC [17], DB [19] and RENO [22]. Here we present our combined analysis of these experiments.

In figure 1 we show the allowed region obtained in our combined analysis. The yellow, orange, and red bands correspond, respectively, to 68%, 95%, 99% CL regions for 2 degree of freedom (dof). We also show the behavior of  $\Delta\chi^2$  for 1 dof as a function of  $\sin^2 2\theta_{13}$  (attached to top), and as a function of  $\delta_{CP}$  (attached to right side) in each panel. For T2K, DB and RENO, only the total rate was considered, whereas for MINOS (DC) we used data of 7 (18) energy bins. However, we have checked that T2K allowed region does not change much if we also take into account the spectrum information. In our fit we have explicitly assumed one of the mass hierarchies (normal or inverted) as input and varied  $\sin^2 2\theta_{23}$  and  $|\Delta m_{32}^2|$ , imposing Gaussian priors based on the atmospheric neutrino experiments [34]



**Figure 1.** Allowed region in  $\sin^2 2\theta_{13} - \delta_{CP}$  plane for T2K, MINOS, Double Chooz (DC), Daya Bay (DB) and RENO combined at 68%, 95% and 99% CL for 2 dof, assuming normal (left panel) or inverted (right panel) mass hierarchy. We also show the  $\Delta\chi^2$  behavior as a function of  $\sin^2 2\theta_{13}$  (top) and as a function of  $\delta_{CP}$  (right) in each case. As a reference we also show the 90%CL exclusion limit from CHOOZ [10].

and MINOS [35] results. We observe that if we combine only T2K and DC (not shown in figure 1), our allowed regions agree very well with the result shown in [17] for the same fixed values of  $\sin^2 2\theta_{23}$  and  $|\Delta m_{32}^2|$ .

We conclude that at 95% CL, the allowed range for  $\theta_{13}$  is given as  $0.070 < \sin^2 2\theta_{13} < 0.122$  irrespectively of the mass hierarchy for 1 dof. In the case of normal (inverted) mass hierarchy, the best fit point is given by  $\sin^2 2\theta_{13} = 0.096$  ( $\sin^2 2\theta_{13} = 0.096$ ) and  $\delta_{CP} = 0.97\pi$  ( $\delta_{CP} = -0.14\pi$ ) which correspond to  $\chi_{\min}^2/(24 - 2) = 1.57$  (1.55). At the moment, there is not much significance in the preferred value of  $\delta_{CP}$ . We can also see the contribution of each individual experiment to the determination of  $\sin^2 2\theta_{13}$ . Currently DB is the most powerful experiment in constraining  $\sin^2 2\theta_{13}$  from both ends. Before DB and RENO announced their results T2K was the most effective experiment in excluding a vanishing value of  $\sin^2 2\theta_{13}$ , but allowed for higher values of  $\sin^2 2\theta_{13}$  than MINOS and DC. The combination of the five experiments can now exclude  $\sin^2 2\theta_{13} = 0$  at  $7.7 \sigma$  CL, irrespectively of the mass hierarchy.

### 3.2 Potential hint on CP violation

It was proposed in [36] that hints of CP violation could be obtained by combining accelerator and reactor measurements. In this method, determining  $\text{sgn}(\sin \delta_{CP})$  is essentially the goal to reach. At this moment, however, change in  $\Delta\chi^2$  is quite mild,  $\lesssim 1.0$ , as  $\delta_{CP}$  is varied, as we can see from figure 1. Clearly, it is not possible to make any definitive statements about which sign of  $\sin \delta_{CP}$  is preferred. Nevertheless, we may say that the region  $\text{sgn}(\sin \delta_{CP}) > 0$  ( $\text{sgn}(\sin \delta_{CP}) < 0$ ) is slightly preferred in the normal (inverted)

mass hierarchy case. This tendency could become clearer by future accumulation of the data, as shown in section 4.

We note that another hint of  $\text{sgn}(\sin \delta_{\text{CP}})$  is provided by the three flavor analysis of the SK atmospheric neutrino data [37, 38], which indicates, though mildly, the negative  $\sin \delta_{\text{CP}}$  region, which is more prominent in the inverted hierarchy case. We believe that the issue of preferred region of  $\delta_{\text{CP}}$  deserves careful watching with accumulation of various experimental data in the future.

#### 4 Expectation: one year from now

We now make some predictions for the possible situation of  $\theta_{13}$  in the near future, about one year from now. For definiteness, in our simulations for the future expectation, we assume the true parameters to be our best fit value  $\sin^2 2\theta_{13} = 0.096$ ,  $\delta_{\text{CP}} = 0.97\pi$  and the normal hierarchy scheme, though we confirmed that the results do not change much even if the inverted hierarchy (with the corresponding best fit values) was assumed. We do not consider MINOS in our predictions because the impact of the improvement of MINOS sensitivity to  $\theta_{13}$  appears to be limited. We include the energy spectrum information in the analysis of T2K. We used the same priors as before for  $|\Delta m_{32}^2|$  and  $\sin^2 2\theta_{23}$ . While this may seem too conservative, these uncertainties mainly have an effect on the upper bound on  $\sin^2 2\theta_{13}$ .

We take the same systematic uncertainties and the backgrounds claimed by the experiments, as in the previous section. (For T2K and DC, we also considered the case with reduced systematic uncertainties, see the footnote 5 and text below.) We assume that DC have been taking data since April 2011 with averaged 77.5% data taking efficiency for physics and 76% reactor power efficiency to take into account reactor off periods. For RENO, we set the data taking to start at August 2011 and used the efficiencies and DAQ live times (proportionally) given in ref. [20].

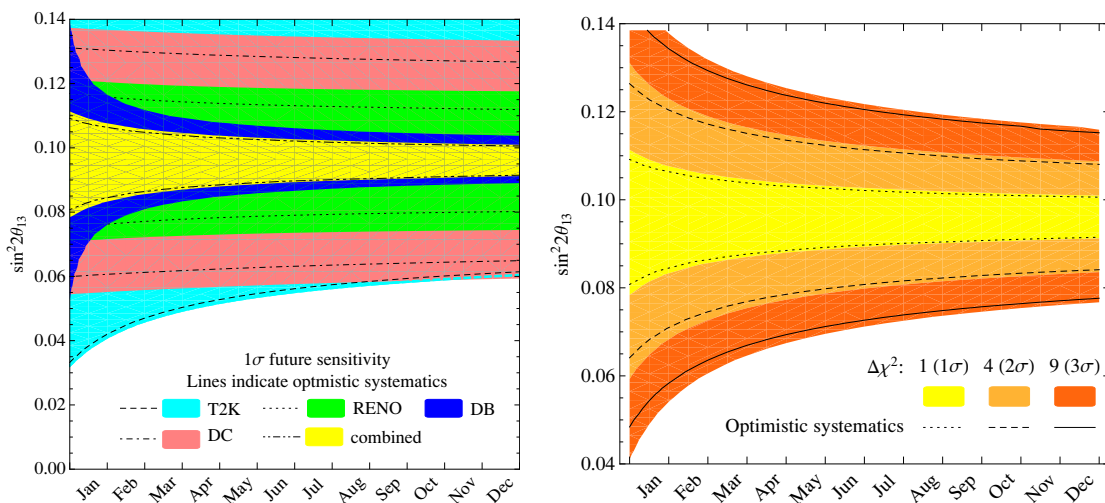
We assume T2K will resume its operation in January 2012 with their proposed integrated luminosity of  $10^{21}$  POT/year.<sup>4</sup> For concreteness, we assume the present configuration of DB throughout the year. As they increase the number of detectors in the far experimental hall one can shift our results by the appropriate number of days/months to roughly account for that.

On the left panel of figure 2 we show the expected  $1\sigma$  uncertainty on the determination of  $\sin^2 2\theta_{13}$  as a function of time, for the different experiments. We employ the following color code for the bands: pink for DC, green for RENO, light blue for T2K, blue for DB and yellow for the combination.

We observe that, at this moment, DB with six detectors is the most powerful experiment among the four and dominates the final combined result. RENO, the next powerful one, would have dominated the combination at the very beginning of this year. However, as soon as their result becomes dominated by systematic uncertainties they cannot improve

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<sup>4</sup>We know that this assumption no longer holds. However, we remain with it because we do not know for sure the real situation of the T2K experiment in 2012. Therefore, as far as T2K is concerned, our predictions can be viewed as optimistic.



**Figure 2.** On the left panel, we show the expected  $1\sigma$  uncertainty on  $\sin^2 2\theta_{13}$  for the case where the true value of  $\sin^2 2\theta_{13} = 0.096$  and  $\delta_{CP} = 0.97\pi$  (current best fit for the normal hierarchy) as a function of the months in 2012 for DC, RENO, T2K, DB as well as the combined case. On the right panel, we show the expected  $1-3\sigma$  uncertainties on  $\sin^2 2\theta_{13}$  as a function of time for the same input but only for the combined case. On the left panel we indicate the effect of the improved systematics considered for T2K and DC by the dashed and dash-dotted lines, respectively, whereas their impact on the combined analysis is indicated by the dotted line on the left panel and by the dotted, dashed and solid lines on the right panel (see legends in the plots). In fitting, the hierarchy is assumed to be unknown.

their sensitivity much. To do that they will have to improve their systematics and/or do a spectrum analysis. DB, due to its high reactor power, overall detector mass and smaller systematic uncertainty, quickly becomes the most powerful experiment and remains so throughout the year. DC sensitivity can not improve much with only the far detector. Regarding the bound on  $\sin^2 2\theta_{13}$  from below in 2012, T2K is comparable to DC, however both will not reach the discriminability of RENO and DB.

We note that although a reduction of systematic uncertainties by  $\sim 30-50\%$  for T2K and DC <sup>5</sup> have some impact on the individual results of these experiments, it does not essentially affect the accuracy of determination of  $\theta_{13}$  based on the combined data in the present circumstances. On the other hand, a possible reduction of RENO backgrounds can fairly affect the final sensitivity to  $\theta_{13}$ . See figure 2. The improvement in T2K is less visible probably because it is still dominated by statistical error.

On the right panel of figure 2, we show the  $1\sigma - 3\sigma$  uncertainty regions for the determination of  $\sin^2 2\theta_{13}$  as a function of time for all experiments combined. Here the yellow,

<sup>5</sup>For the DC experiment we use for each systematic uncertainty the best value between the one quoted in their proposal and the one presented in their latest paper [16]. We also apply a 30% reduction of the number of their background events. For T2K we assume about 50% reduction of systematic uncertainties, arbitrarily re-scaling the current normalization uncertainty to 10%. For RENO, we only contemplate the possibility of reducing the backgrounds by 40% at the cost of decreasing the near and far detector signal in 10% and 3%, respectively, while for DB we do not consider any reduction of the systematics due to the already extraordinarily low systematics of this experiment.



orange and red bands correspond, respectively, to  $1\sigma$ ,  $2\sigma$ , and  $3\sigma$  regions. From this analysis we conclude that within 1 year, the uncertainty on the determination of  $\sin^2 2\theta_{13}$  at  $1\sigma$  CL may be reduced from 0.013 to  $\sim 0.005$ . We have verified that this is also true for the case where the true mass hierarchy is the inverted one.

At the same time, the hypothesis of a vanishing  $\sin^2 2\theta_{13}$  could be rejected at a level of very high significance. We have verified, under the above stated assumptions, that by the middle (end) of 2012, the  $\sin^2 2\theta_{13} = 0$  hypothesis could be rejected with a significance larger than  $11\sigma$  ( $14\sigma$ ), if the future data is consistent with the current best fit point. We confirm that the impact of the improvement of systematics for T2K and DC on the combined analysis is quite small also for the 2 and 3  $\sigma$  regions (see dashed and solid lines on the right panel of figure 2).

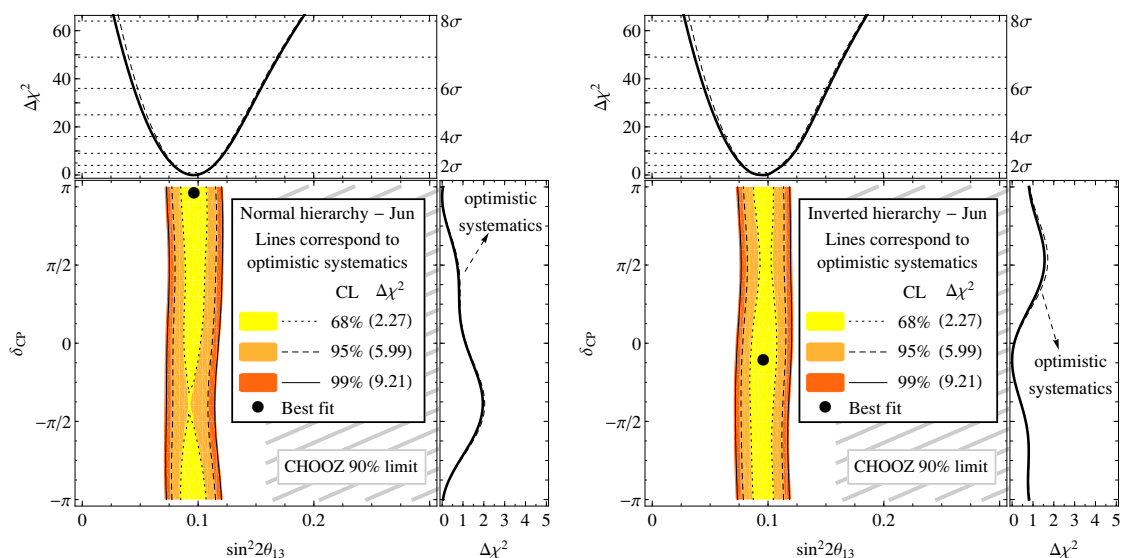
In figures 3 and 4, using the same format as in figure 1, we show the allowed region in the  $\sin^2 2\theta_{13} - \delta_{CP}$  plane expected in June and in December of 2012, respectively, that could be achieved by combining T2K, MINOS, DC, DB and RENO data. As input, we used the best fit point for the normal hierarchy and fitted for each normal and inverted mass hierarchy. As expected, from the right panel of figure 2, the impact of the reduction of the systematic uncertainties we considered in this work on the determination of the parameter regions, as well as in the behavior of  $\Delta\chi^2$  (indicated by the dashed lines in figures 3 and 4), is quite small as far as the results expected in the near future ( $\sim 1$  year) are concerned.

Finally, we note that at the end of this year the combined  $\Delta\chi^2$  for different values of  $\delta_{CP}$  is expected to be  $\sim 1-4$ , depending on the fitted hierarchy. This might be used as a hint on which region of  $\delta_{CP}$  is preferred, but this still will not be strong enough to definitively pin down the value of  $\delta_{CP}$  with high significance. For future prospects on the reactor-accelerator combined method, see also [39].

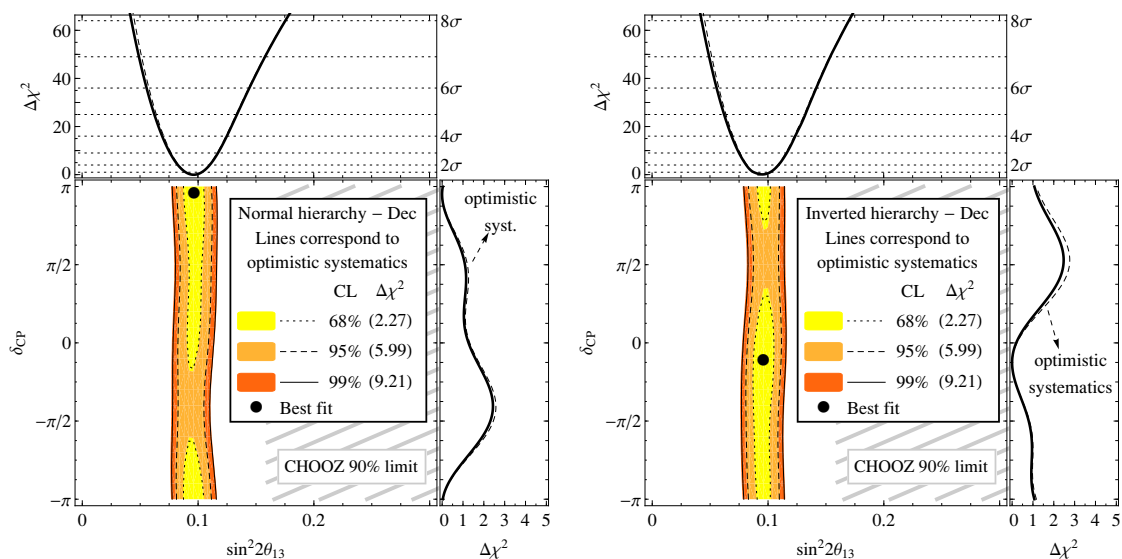
## 5 Conclusion

We performed a combined analysis of the currently available accelerator and reactor data which provide a very significant evidence of non-zero  $\theta_{13}$ . Being outside of the experimental collaborations our simulation may be incomplete by lack of sufficient information on backgrounds, systematic uncertainties, efficiencies, etc. However, we believe that we did a reasonable job and our results serve as an independent confirmation of the analyses provided by the experimental groups.

It is encouraging to see that the confidence level for non-zero  $\sin^2 2\theta_{13}$  now reaches  $\simeq 7.7\sigma$  thanks, in particular, to DB and RENO, in addition to T2K, MINOS and DC experiments. Still in this year, we will have indisputable evidence for non zero  $\theta_{13}$ . We predict that if the future data continues to be compatible with the current best fit value  $\sin^2 2\theta_{13} = 0.096$ , by the middle (end) of 2012  $\sin^2 2\theta_{13}$  will be known within  $\pm 0.007$  ( $\pm 0.005$ ) at 68% CL. Finally, we also studied the impact of the possible reduction of the systematic uncertainties for DC (by 30%) and T2K (roughly by half), as well as for RENO backgrounds (by 40%) while forfeiting signal efficiency (3% in the far detector). We have, however, found that the reduction of errors do not affect in a significant way the combined sensitivity at the end of 2012.



**Figure 3.** Predicted allowed region in the  $\sin^2 2\theta_{13} - \delta_{CP}$  plane for T2K, MINOS, DC, DB and RENO combined at 68%, 95% and 99% CL for 2 dof in the middle (June) of 2012, assuming normal (left panel) or inverted (right panel) mass hierarchy and as input the normal hierarchy best fit point of our current analysis.



**Figure 4.** Same as in figure 3 but for the end of the year (December 2012).

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## References

- [1] THE T2K collaboration, Y. Itow et al., *The JHF-Kamioka neutrino project*, [hep-ex/0106019](#) [INSPIRE].
- [2] V. Martemyanov, L. Mikaelyan, V. Sinev, V. Kopeikin and Y. Kozlov, *The Kr2Det project: Search for mass 3 state contribution  $|U(e3)|^2$  to the electron neutrino using a one reactor - two detector oscillation experiment at Krasnoyarsk underground site*, *Phys. Atom. Nucl.* **66** (2003) 1934 [[hep-ex/0211070](#)] [INSPIRE].
- [3] H. Minakata, H. Sugiyama, O. Yasuda, K. Inoue and F. Suekane, *Reactor measurement of  $\theta_{13}$  and its complementarity to long baseline experiments*, *Phys. Rev. D* **68** (2003) 033017 [*Erratum ibid.* **D 70** (2004) 059901] [[hep-ph/0211111](#)] [INSPIRE].
- [4] Z. Maki, M. Nakagawa and S. Sakata, *Remarks on the unified model of elementary particles*, *Prog. Theor. Phys.* **28** (1962) 870 [INSPIRE].
- [5] K. Hiraide et al., *Resolving  $\theta_{23}$  degeneracy by accelerator and reactor neutrino oscillation experiments*, *Phys. Rev. D* **73** (2006) 093008 [[hep-ph/0601258](#)] [INSPIRE].
- [6] J. Burguet-Castell, M. Gavela, J. Gomez-Cadenas, P. Hernández and O. Mena, *On the measurement of leptonic CP-violation*, *Nucl. Phys. B* **608** (2001) 301 [[hep-ph/0103258](#)] [INSPIRE].
- [7] H. Minakata and H. Nunokawa, *Exploring neutrino mixing with low-energy superbeams*, *JHEP* **10** (2001) 001 [[hep-ph/0108085](#)] [INSPIRE].
- [8] G.L. Fogli and E. Lisi, *Tests of three flavor mixing in long baseline neutrino oscillation experiments*, *Phys. Rev. D* **54** (1996) 3667 [[hep-ph/9604415](#)] [INSPIRE].
- [9] T2K collaboration, K. Abe et al., *Indication of electron neutrino appearance from an accelerator-produced off-axis muon neutrino beam*, *Phys. Rev. Lett.* **107** (2011) 041801 [[arXiv:1106.2822](#)] [INSPIRE].
- [10] CHOOZ collaboration, M. Apollonio et al., *Search for neutrino oscillations on a long baseline at the CHOOZ nuclear power station*, *Eur. Phys. J. C* **27** (2003) 331 [[hep-ex/0301017](#)] [INSPIRE].
- [11] F. Boehm et al., *Final results from the Palo Verde neutrino oscillation experiment*, *Phys. Rev. D* **64** (2001) 112001 [[hep-ex/0107009](#)] [INSPIRE].
- [12] K2K collaboration, S. Yamamoto et al., *An Improved search for  $\nu_{\mu} \rightarrow \nu_e$  oscillation in a long-baseline accelerator experiment*, *Phys. Rev. Lett.* **96** (2006) 181801 [[hep-ex/0603004](#)] [INSPIRE].

- [13] THE MINOS collaboration, P. Adamson et al., *New constraints on muon-neutrino to electron-neutrino transitions in MINOS*, *Phys. Rev. D* **82** (2010) 051102 [[arXiv:1006.0996](#)] [[INSPIRE](#)].
- [14] MINOS collaboration, P. Adamson et al., *Improved search for muon-neutrino to electron-neutrino oscillations in MINOS*, *Phys. Rev. Lett.* **107** (2011) 181802 [[arXiv:1108.0015](#)] [[INSPIRE](#)].
- [15] DOUBLE CHOOZ collaboration, F. Ardellier et al., *Double CHOOZ: a search for the neutrino mixing angle  $\theta_{13}$* , [hep-ex/0606025](#) [[INSPIRE](#)].
- [16] DOUBLE CHOOZ collaboration, Y. Abe et al., *Indication for the disappearance of reactor electron antineutrinos in the Double CHOOZ experiment*, *Phys. Rev. Lett.* **108** (2012) 131801 [[arXiv:1112.6353](#)] [[INSPIRE](#)].
- [17] H. de Kerrect, *First results from the Double-Chooz experiments*, talk given at the 6<sup>th</sup> *International Workshop on Low energy neutrino physics*, November 9–12, Seoul National University, South Korea (2011), <http://workshop.kias.re.kr/lownu11/>.
- [18] DAYA-BAY collaboration, X. Guo et al., *A precision measurement of the neutrino mixing angle  $\theta_{13}$  using reactor antineutrinos at Daya-Bay*, [hep-ex/0701029](#) [[INSPIRE](#)].
- [19] DAYA-BAY collaboration, F. An et al., *Observation of electron-antineutrino disappearance at Daya Bay*, [arXiv:1203.1669](#) [[INSPIRE](#)].
- [20] RENO collaboration, J. Ahn et al., *RENO: an experiment for neutrino oscillation parameter  $\theta_{13}$  using reactor neutrinos at Yonggwang*, [arXiv:1003.1391](#) [[INSPIRE](#)].
- [21] K.K. Joo, *Status of the RENO Reactor Neutrino Experiment*, talk given at the 6<sup>th</sup> *International Workshop on Low energy neutrino physics*, November 9–12, Seoul National University, South Korea (2011), <http://workshop.kias.re.kr/lownu11/>.
- [22] J.K. Ahn et al., *Observation of reactor electron antineutrino disappearance in the RENO experiment*, [arXiv:1204.0626](#) [[INSPIRE](#)].
- [23] G. Fogli, E. Lisi, A. Marrone, A. Palazzo and A. Rotunno, *Hints of  $\theta_{13} > 0$  from global neutrino data analysis*, *Phys. Rev. Lett.* **101** (2008) 141801 [[arXiv:0806.2649](#)] [[INSPIRE](#)].
- [24] T. Schwetz, M. Tortola and J.W. Valle, *Three-flavour neutrino oscillation update*, *New J. Phys.* **10** (2008) 113011 [[arXiv:0808.2016](#)] [[INSPIRE](#)].
- [25] M. Gonzalez-Garcia, M. Maltoni and J. Salvado, *Updated global fit to three neutrino mixing: status of the hints of  $\theta_{13} > 0$* , *JHEP* **04** (2010) 056 [[arXiv:1001.4524](#)] [[INSPIRE](#)].
- [26] G. Fogli, E. Lisi, A. Marrone, A. Palazzo and A. Rotunno, *Evidence of  $\theta_{13} > 0$  from global neutrino data analysis*, *Phys. Rev. D* **84** (2011) 053007 [[arXiv:1106.6028](#)] [[INSPIRE](#)].
- [27] T. Schwetz, M. Tortola and J. Valle, *Where we are on  $\theta_{13}$ : addendum to 'Global neutrino data and recent reactor fluxes: status of three-flavour oscillation parameters'*, *New J. Phys.* **13** (2011) 109401 [[arXiv:1108.1376](#)] [[INSPIRE](#)].
- [28] P. Huber, J. Kopp, M. Lindner, M. Rolinec and W. Winter, *New features in the simulation of neutrino oscillation experiments with GLOBES 3.0: General Long Baseline Experiment Simulator*, *Comput. Phys. Commun.* **177** (2007) 432 [[hep-ph/0701187](#)] [[INSPIRE](#)].
- [29] K. Abe et al., *Letter of Intent: The hyper-Kamiokande experiment — detector design and physics potential*, [arXiv:1109.3262](#) [[INSPIRE](#)].
- [30] J. Kopp, P.A. Machado and S.J. Parke, *Interpretation of MINOS data in terms of non-standard neutrino interactions*, *Phys. Rev. D* **82** (2010) 113002 [[arXiv:1009.0014](#)] [[INSPIRE](#)].

- [31] J. Maeda and T. Matsubara, private communication.
- [32] T. Mueller et al., *Improved predictions of reactor antineutrino spectra*, *Phys. Rev. C* **83** (2011) 054615 [[arXiv:1101.2663](#)] [[INSPIRE](#)].
- [33] P. Huber, *On the determination of anti-neutrino spectra from nuclear reactors*, *Phys. Rev. C* **84** (2011) 024617 [*Erratum ibid.* **C 85** (2012) 029901] [[arXiv:1106.0687](#)] [[INSPIRE](#)].
- [34] SUPER-KAMIOKANDE collaboration, R. Wendell et al., *Atmospheric neutrino oscillation analysis with sub-leading effects in Super-Kamiokande I, II and III*, *Phys. Rev. D* **81** (2010) 092004 [[arXiv:1002.3471](#)] [[INSPIRE](#)].
- [35] MINOS collaboration, P. Adamson et al., *Measurement of the neutrino mass splitting and flavor mixing by MINOS*, *Phys. Rev. Lett.* **106** (2011) 181801 [[arXiv:1103.0340](#)] [[INSPIRE](#)].
- [36] H. Minakata and H. Sugiyama, *Exploring leptonic CP-violation by reactor and neutrino superbeam experiments*, *Phys. Lett. B* **580** (2004) 216 [[hep-ph/0309323](#)] [[INSPIRE](#)].
- [37] T. Kajita, *Recent results from atmospheric neutrino experiments*, *Nucl. Phys. (Proc. Suppl.)* **217** (2011) 157.
- [38] SUPER-KAMIOKANDE collaboration, Y. Takeuchi, *Results from Super-Kamiokande*, [arXiv:1112.3425](#) [[INSPIRE](#)].
- [39] P. Huber, M. Lindner, T. Schwetz and W. Winter, *First hint for CP-violation in neutrino oscillations from upcoming superbeam and reactor experiments*, *JHEP* **11** (2009) 044 [[arXiv:0907.1896](#)] [[INSPIRE](#)].