A unified analysis of the reactor neutrino program towards the measurement of the $\theta_{13}$ mixing angle

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Abstract. We presented a detailed quantitative discussion of the measurement of the leptonic mixing angle $\theta_{13}$ through currently scheduled reactor neutrino oscillation experiments. We focussed on Double Chooz (Phase I & II), Daya Bay (Phase I & II) and RENO experiments. We performed a unified analysis, including systematics, backgrounds and accurate experimental setup in each case. Each identified systematical uncertainty and background impact has been assessed on experimental setups following published data when available and extrapolating from Double Chooz acquired knowledge otherwise. We sum up, here, a new common analysis of their sensitivities to $\sin^2(2\theta_{13})$ and study the impact of the different systematics based on the pulls approach. Through this generic statistical analysis we discuss the advantages and drawbacks of each experimental setup.

1. A quick introduction to reactor neutrino physics
Nuclear reactors are abundant sources of $\nu_e$ with an energy range extending approximately from 1 to 10 MeV. Reactor neutrino experiments measure the reactor $\nu_e$ spectrum at a given distance. The rate and spectrum distortion analyses then allow to access the survival probability:

$$P_{ee} = 1 - \sin^2(2\theta_{13}) \sin^2(1.27 \Delta m^2_{31} L/E),$$

with $L$, the distance in km between the reactor and the detector, $E$ the $\nu_e$ energy in MeV, $\Delta m^2_{31} = m_3^2 - m_1^2$ the mass squared difference in eV$^2$ between the heaviest and the lightest neutrino mass eigenstates and $\theta_{13}$ is the last unknown parameter of the MNSP neutrino mixing matrix. Typical values for $L$ are around 1 to 2 km to locate the detector at the first oscillation minimum for a high sensitivity to $\theta_{13}$ measurement. Using a single detector to measure this survival probability, as for previous reactor experiments, leads to rely on a model of the $\nu_e$ source. The sensitivity on $\theta_{13}$ is then limited by the systematic knowledge on the reactor $\nu_e$ flux. Next to come reactor experiments use the concept of multi-detector setup (near/far) observing the same sources to cancel systematical uncertainties associated to $\nu_e$ productions and interactions. The sensitivity to the measurement of $\theta_{13}$ with such an experiment then mostly rely on the matching of the detectors in order to cancel as most as possible the systematical uncertainties. Nevertheless as far as the number of sources and detectors increases, this cancellation becomes more tricky, and a careful inclusion of systematical uncertainties is required. These systematical uncertainties may be classified according to their origin: either they come from the knowledge on the $\nu_e$ reactor production, from the detector knowledge uncertainties or from the analysis (event selections). We invite the reader to consult [1] for further explanations on the systematic classifications for reactor neutrino experiments.
2. Comparing reactor neutrino experiments with the pull analysis

The calculation of $\nu_e$ interaction rates in detectors is a convolution of the $\nu_e$ flux spectrum, the cross section, the oscillation probability, the detector efficiency with the energy response function. We based our event rates computations on an extended version of the numerical code developed for Double Chooz [1, 2]. These computations take into account the characteristics of each experimental setup as the number of reactors, detectors, locations, overburdens, efficiencies, operating time, and so on [1]. The resulting event rates, form the basis of a $\chi^2$ pull-approach analysis [3], where systematical uncertainties as well as backgrounds are included. The two Double Chooz [2] and Daya Bay [4] proposals take a careful inventory of systematics, compiled in [1] for comparison.

In this discussion we are interested in assessing how much a given experiment sensitivity relies on the systematic knowledge (how many systematics, and which impact on the sensitivity). The idea is to break down the total $\Delta \chi^2 = \chi^2(\sin^2(2\theta_{13})|_{\text{lim}}) - \chi^2_{\text{min}}$ into sub-parts $\delta \chi^2_i$, each associated to a given systematical uncertainty. These $\delta \chi^2_i$ represent the relative contributions of systematical uncertainties to the overall $\Delta \chi^2$. The systematic “weights” is thus studied and a classification of their impact on $\sin^2(2\theta_{13})$ sensitivity can be given.

Among the systematical uncertainties included, two of them, associated to reactor spectrum uncertainties ($\sigma_{\text{abs}}$ and $\sigma_{\text{shp}}$ for theoretical rate and shape modelization of reactor spectra, both at the level of 2 %) are quite well cancelled with multi-identical detector concept. However three other systematical uncertainties require a special care in the comparison of the different experiments: the uncertainties on the thermal power of each reactor ($\sigma_{\text{pwr}}$), on the relative normalization of event rates between detectors ($\sigma_{\text{rel}}$) and on the energy scale of each detector ($\sigma_{\text{sc}}$).

In the concept of identical detectors, correlated uncertainties between detectors ($\sigma_{\text{abs}}$ for the normalization and $\sigma_{\text{shp}}$ for the shape uncertainties of the spectra) should weakly impact the sensitivity (at the level of near detector “precision”). This is automatically the case if the near detector successfully monitors the nuclear power plant cores. Two of the quoted experimental setups reach this goal: Double Chooz with its two identical detector (phase II) and Daya Bay with its full installation of eight detectors (the phase II). Double Chooz has one dominant systematic: the relative normalization uncertainty ($\sigma_{\text{rel}}$). The second most important contribution comes from the relative energy scale uncertainty ($\sigma_{\text{sc}}$). Daya Bay full installation is mostly limited by the relative normalization uncertainty too. A weaker impact of the relative energy scale uncertainties, compared to Double Chooz, comes from the better far site distance to the nuclear power plant cores. The uncertainty on the energy scale matches less the oscillation induced distortion. However, Daya Bay sensitivity to $\sin^2(2\theta_{13})$ still depends a little bit on the knowledge of each reactor power ($\sigma_{\text{pwr}}$). On the other hand, three of the studied experimental setups still rely on theoretical knowledge of the spectrum ($\sigma_{\text{abs}}$ and $\sigma_{\text{shp}}$) and nuclear power plant cores associated uncertainties ($\sigma_{\text{pwr}}$): Double Chooz single detector in phase I, Daya Bay phase I with four detectors and RENO. In particular, the Daya Bay phase I installation is sensitive to several systematics, and especially the reactor power uncertainties. Taking data on a longer time scale (3 years, for instance) with such a detector configuration will not improve the $\sin^2(2\theta_{13})$ sensitivity as much. Moreover, for Daya Bay phase I, no near site monitors the Ling Ao I reactor. This makes the Daya Bay phase I setup an intermediate between a two identical near/far detector experiment and a single far detector configuration. Since the near site is farther away from the reactor cores, theoretical uncertainties on the spectrum have a larger impact than in Double Chooz phase II. Also, since the average distance of Daya Bay phase I far site is closer, the oscillation pattern matches slightly better the energy scale associated distortion (bigger contribution than in Double Chooz phase II). The RENO far site location is the best among the quoted setups in cancelling the impact of the relative and absolute energy scale uncertainties. However, this experiment relies on the precision with which each core power can
be determined. Moreover, the near detector is a bit farther away than in the Double Chooz phase II case, which explains why the global reactor νe rate is less effectively determined and have a larger contribution than in Double Chooz phase II to the final sin²(2θ13) sensitivity.

We illustrate on Figure 1 three systematic scenarios: best, central and worst cases. The common systematic framework (central) is what experimentalists believe to be achievable, without any further R&D. Each contribution is separately assessed, but we also show on this graph the total impact by summing the effect of the three discussed systematics (σ_pwr, σ_rel and σ_scl) to their respective best, central and worst values. We also illustrate the impact of the true central value of ∆m²_{31} on the sensitivity. In this representation, we show the ratio of the computed sensitivity sin²(2θ_{13})_{b,w} for the best (resp. worst) case over the sensitivity sin²(2θ_{13})_{c} for standard central systematic values. The “Total” bar shows that in Daya Bay and RENO the sensitivity can vary from 0.6 to 1.2 – 1.3 of the baseline case, for experimental systematics ranging from a “best” to a “worst” scenario. In the case of Double Chooz, the impact of systematics is less significant, at the level of 20 % on both sides. In the Double Chooz and Daya Bay phase I cases, the sensitivity could be worsened for best fit values of ∆m²_{31} below 2.5 × 10^{-3} eV². In Daya Bay phase II, the sensitivity is quite stable over the current allowed range for ∆m²_{31} with only a 5 % effect on sensitivity.

3. Conclusion
In this work we have presented a detailed comparative analysis of the sensitivities to sin²(2θ_{13}) of upcoming and proposed reactor experiments. An important result of this work is that the total thermal power available for an experiment, a figure of merit that has been often used as a strong argument to “rank” different projects, has a modest impact on the success of an experiment. Large powers are only available in multi-core sites, which are very difficult to monitor. The associated systematics can be overwhelming with respect to the benefit from the statistics. This is very nicely exemplified by the case of RENO, which would reach the same sensitivity with just 2 of its 6 reactors on, and by Daya Bay phase I, which results to be just half way between Double Chooz phase I and II. This pull analysis also shows that the impact of the backgrounds on the χ² is minor with respect to other systematics. Backgrounds, at least in our simulation, are therefore not critical in any of the analyzed experiments.

Double Chooz is an optimized experiment in the sense of robustness with respect to systematics for a goal sensitivity in the 0.02–0.03 range. Daya Bay phase II is adequate to reach a sensitivity at the level of 0.01. However, a simpler experiment for this class of sensitivity would be a scaled-up variant of Double Chooz, with a very close near site at 150 m and a 1.5 km baseline for the far site. At the Diablo Canyon power plant [6], where two 3.19 GWth cores are operational and modest civil engineering works would be required, four 20 t detectors (2 near, 2 far) would give a sensitivity of 0.013 after 3 years of data taking.

References
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Figure 1. Double Chooz, Daya Bay and RENO sensitivities as a function of the size of the main systematics. The common systematic framework is what experimentalists believe to be achievable, without any further R&D. The common framework is used to compute the reference $\sin^2(2\theta_{13})$ sensitivity of each setup (value on top of each graph). Then each systematic ($\sigma_{\text{pwr}}, \sigma_{\text{rel}}, \sigma_{\text{scl}}$) impact on sensitivity is separately computed and illustrated as ratio $R = \sin^2(2\theta_{13})_{\text{best or worst}} / \sin^2(2\theta_{13})_{\text{baseline}}$ on each graph. The overall impact changing all three systematics together is also illustrated with the “Total” label. Moreover we also provide a quick guess on $\sin^2(2\theta_{13})$ sensitivity behaviour as a function of $\Delta m^2_{31}$ best fit value provided by other experiments. For the Daya Bay Phase II experiment, where possible correlation between detectors on a same site may happen, we take $\sigma_{\text{rel}}$ half correlated and half uncorrelated between detectors of a same site, and completely uncorrelated between detectors of different sites (see [1] for details).