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Short and Medium baseline Reactor Neutrino Experiments

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Reactor neutrino experiments allowed during the last years to observe that the last unmeasured neutrino oscillation mixing angle θ_{13} not only was different from zero but also this angle was relatively large and just below the previous limits. Some anomalies have then been observed related to the expectations on reactor neutrino flux and to the shape of the neutrino spectrum. These anomalies are still under investigation by very short baseline reactor neutrino experiments. The observed large value of θ_{13} allows now the observation of an eventual CP violation in the leptonic sector, but also to be sensitive to the neutrino mass hierarchy using medium baseline reactor neutrino experiments.

Keywords: neutrino oscillations, mass hierarchy, reactor neutrinos, short baseline, medium baseline.

1. Introduction

Nuclear reactors are copious neutrino sources used to study the neutrino properties. The neutrino detection method used since the first observation of neutrinos by F. Reines and C. Cowan in 1956 remains the same up to today. This method uses the inverse beta decay (IBD) of an antineutrino interacting with a proton of the detector target producing a positron annihilating with an electron (prompt signal) and a neutron captured after (delayed signal).

Up to 2012, reactor neutrino experiments were using only one “far” detector to extract their results. The unoscillated neutrino spectrum was extracted using the reactor predictions taking into account the reactor operation conditions. In order to reduce the systematic errors, new generation experiments as Double Chooz, Daya Bay and RENO, used near detectors to monitor the reactor neutrino flux. This allowed to measure for the first time the last neutrino oscillation mixing angle θ_{13} ¹⁻³. The measurement accuracy achieved up to now by these experiments allow to perform high precision measurements.

2. Short baseline neutrino experiments

By 2011, three short baseline reactor neutrino experiments started taking data with the main objective to measure the mixing angle θ_{13} or at least set a severe limit on this parameter. These experiments were Double Chooz in France¹, Daya Bay² in China and RENO³ in South Korea. The configuration of detectors and reactors for the three projects is depicted by Fig. 1. Double Chooz disposes of two detectors and two reactors, Daya Bay of three reactors and three detector sides, and RENO

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of six reactors and two detectors clearly identified as near and far detectors. Table 1 gives the present reactor power, the detector volume, overburden and starting date of the experiments.

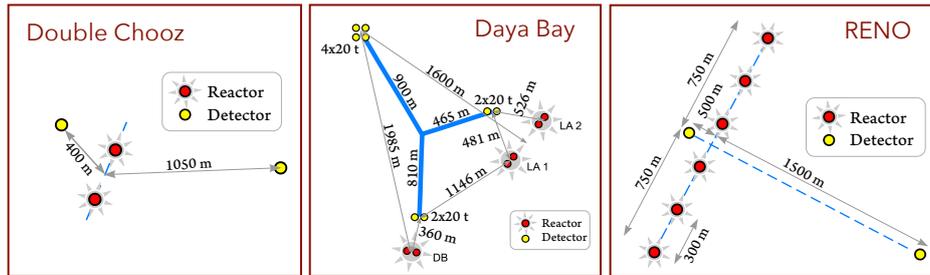


Fig. 1. Reactor and detector configuration for Double Chooz, Daya Bay and RENO experiments.

Table 1. Reactor power, detector volume, overburden and starting date of the experiment.

Experiment	Reactor power (GWth)	Volume (tons)	overburden (near/far-mwe)	start of data taking
Double Chooz	8.5	2x6	80/300	April 2011
Daya Bay	17.4	8x20	270/950	August 2011
RENO	16.8	2xyy	90/440	August 2011

The detectors of all three experiments are similar. They mainly include the liquid scintillator target doped with Gadolinium to reduce the neutron lifetime to about $30 \mu\text{s}$, a gamma catcher filled with liquid scintillator without Gadolinium to detect escaping gammas from the neutrino target, a buffer protecting from the PMT radioactivity and a veto for cosmic ray rejection. For each experiment, the detectors on all locations are identical in order to reduce the systematic errors. Fig. 2 presents the far Double Chooz detector.

3. θ_{13} measurement

In 2011 all three experiments, Double Chooz, Daya Bay and RENO, have started taking data. Double Chooz has started with only the far detector (the near detector was only ready beginning of 2015), while Daya Bay was disposing of six detectors over 8. RENO had started with a complete configuration. End of 2011, Double Chooz has presented the first results¹ with a significance of excluding a zero θ_{13} value of 1.7σ . It has been followed by Daya Bay (March 2012)² and RENO (April 2012)³ reporting a non-zero significance of 5.2σ and 4.9σ , respectively. Fig. 3 shows the neutrino energy spectrum of the three experiments at that time.

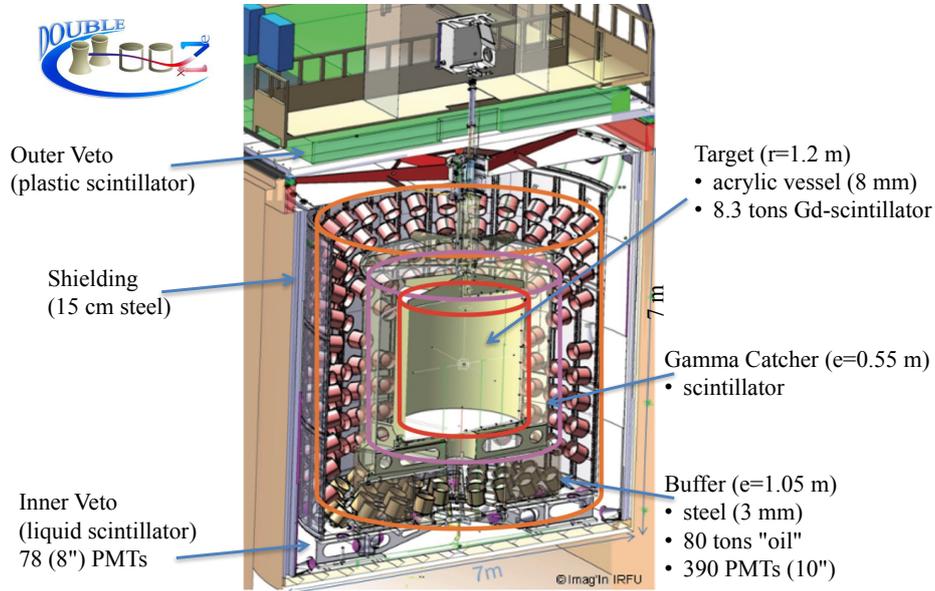


Fig. 2. The Far Double Chooz detector.

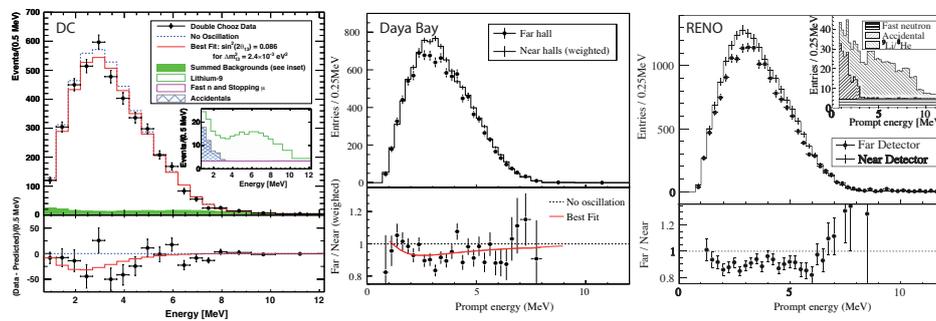


Fig. 3. Observed energy spectrum of the prompt signal for Double Chooz, Daya Bay and RENO experiments as published in 2012.

The latest results for the three experiments for $\sin^2 2\theta_{13}$ give:

- Double Chooz: 0.119 ± 0.016 (*stat.* + *syst.*) (using data collected up to 2016)⁴
- Daya Bay: 0.0841 ± 0.0027 (*stat.*) ± 0.0019 (*syst.*) (using data collected up to July 2015)⁵
- RENO: 0.086 ± 0.006 (*stat.*) ± 0.005 (*syst.*) (using data collected up to September 2015)⁶

As it can be seen, Daya Bay already reached a 3.9% accuracy on θ_{13} while RENO and Double Chooz remain at 9.1% and 13.4%, respectively. Fig. 4 shows the dependence of the $\bar{\nu}$ disappearance probability on L/E for Daya Bay and RENO. The observed shape is as expected by the neutrino oscillation formalism. By fitting this distribution the parameter $\Delta m_{ee}^2 = \cos^2 \theta_{12} |\Delta m_{21}^2| + \sin^2 \theta_{12} |\Delta m_{32}^2|$ can directly be extracted from the probability distribution:

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) \approx 1 - \underbrace{\cos^4 \theta_{13} \sin^2 \theta_{12} \sin^2 \left(\frac{\Delta m_{21}^2 L}{4E_\nu} \right)}_{\text{small for } L=\text{few km}} - \sin^2 2\theta_{13} \sin^2 \left(\frac{\Delta m_{ee}^2 L}{4E_\nu} \right)$$

The extracted values for Δm_{ee}^2 are^{5,6}:

- Daya Bay: $[2.50 \pm 0.06 \text{ (stat.)} \pm 0.06 \text{ (syst.)}] \times 10^{-3} \text{eV}^2$
- RENO: $[2.61 \pm_{-0.16}^{+0.06} \text{ (stat.)} \pm_{-0.09}^{+0.09} \text{ (syst.)}] \times 10^{-3} \text{eV}^2$

Using the Daya Bay value one can get:

$$\begin{aligned} \Delta m_{32}^2 &= [2.45 \pm 0.06 \text{ (stat.)} \pm 0.06 \text{ (syst.)}] \times 10^{-3} \text{eV}^2 \text{ for Normal Hierarchy} \\ &= [2.56 \pm 0.06 \text{ (stat.)} \pm 0.06 \text{ (syst.)}] \times 10^{-3} \text{eV}^2 \text{ for Inverted Hierarchy} \end{aligned}$$

with a world average of $[2.52 \pm 0.04] \times 10^{-3} \text{eV}^2$ for Normal Hierarchy. It has to be noted that for Daya Bay the systematic error is of the order of the statistical one not leaving room for improvement without further reduction of the systematic errors.

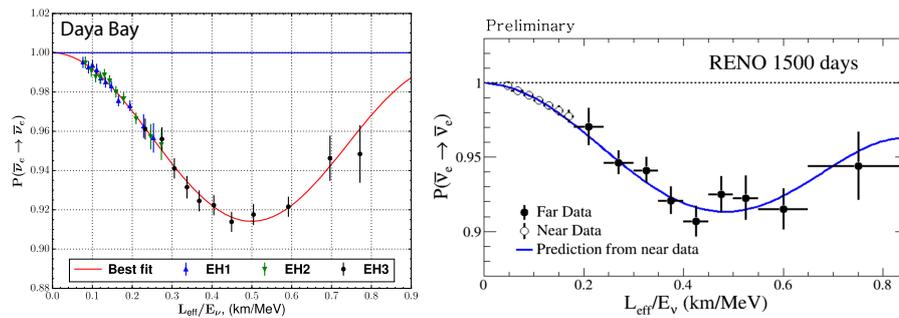


Fig. 4. Reactor antineutrino survival probability as a function of L_{eff}/E_ν for Daya Bay and RENO experiments.

Fig. 5 presents $\sin^2 2\theta_{13}$ versus Δm_{ee}^2 for Daya Bay⁵ and RENO⁶ experiments.

All these precision results have been obtained using an extensive calibration program mainly based on radioactive sources deployed inside the detectors. A better background reduction and understanding of the systematic errors also helped. For

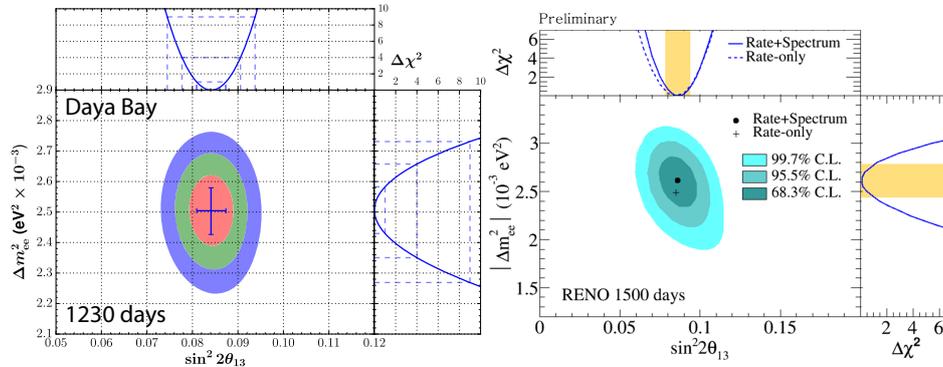


Fig. 5. $\sin^2 2\theta_{13}$ versus Δm_{ee}^2 for Daya Bay and RENO experiments.

Daya Bay, the remaining uncertainty on energy reconstruction is kept at the level of 1%. For this experiment, the energy resolution is given by:

$$\frac{\sigma_E}{E_{rec}} = \sqrt{0.016^2 + \frac{0.081^2}{E_{rec}} + \frac{0.026^2}{E_{rec}^2}}$$

giving an energy resolution of 8.7% at 1 MeV.

4. Reactor Neutrino Anomalies

With the achieved energy resolution Double Chooz, Daya Bay and RENO are able to better measure the reactor neutrino energy spectrum. All three experiments reported an excess around 5 MeV compared to predictions^{6–8}. Fig. 6 presents the neutrino energy distribution compared to predictions for the three experiments. The excess around 5 MeV depends on the reactor thermal power excluding an external origine. Some possible explanations already have been presented in several publications (see e.g.⁹) based on β -decay branch contribution (thousands of individual beta-decay branches) of the main isotopes contributing to the neutrino production. This bump could also be explained by considering residual non-linearities of the experiments¹⁰. Further investigations are ongoing but this shows the fragility of the predicted spectrum.

On reactor antineutrino anomaly, the latest results from Daya Bay⁷ and RENO¹¹ give for the antineutrino flux compared to the Huber¹³/Mueller¹² model (Fig. 7):

- Daya Bay: $R = 0.946 \pm 0.020$
- RENO: $R = 0.946 \pm 0.021$

while the world average including Daya Bay⁷ results becomes $R = 0.9430 \pm 0.008(\text{exp.}) \pm 0.023(\text{model})$. The deficit of observed reactor neutrino flux relative to

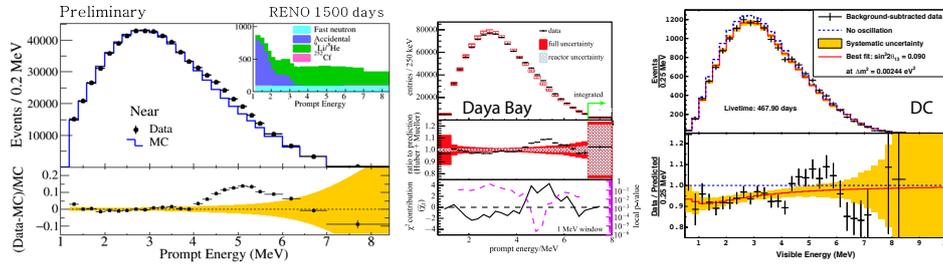


Fig. 6. Measured neutrino energy spectrum compared to predictions for RENO, Daya Bay and Double Chooz.

the prediction of about 6% indicates an overestimated flux or possible oscillations to sterile neutrinos.

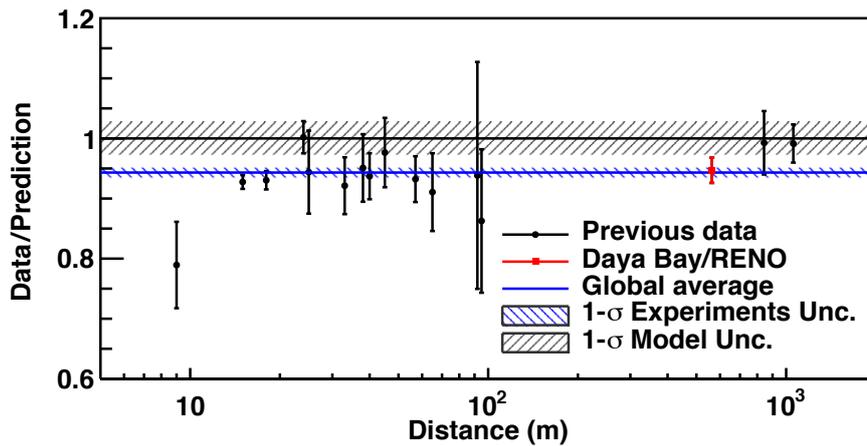


Fig. 7. Neutrino flux measurements versus the baseline compared to predictions.

Daya Bay has studied the reactor neutrino flux and spectrum evolution with the reactor fuel isotope composition¹⁴ using 2.2 million IBDs detected by four of its detectors. Fig. 8 shows the relative IBD yield per fission as a function of ²³⁹Pu and ²³⁵U fractions, for four neutrino energy ranges. A clear energy-dependent evolution is observed that induce a change in spectral shape as fuel composition evolves.

Fig. 9 presents the neutrino cross-section/fission as a function of the effective fission fraction of ²³⁹Pu and ²³⁵U, compared to the Huber-Mueller model prediction (rescaled by 5.1% just for better slope comparison). The hypothesis of a constant antineutrino flux as a function of the ²³⁹Pu fission fraction is rejected with a signif-

ificance corresponding to 10σ . The measured evolution of the reactor neutrino flux is by 3.1σ incompatible with the predictions. This indicates that the uncertainties of model calculations are underestimated. For this study, only the four primary fission isotopes, ^{235}U , ^{238}U , ^{239}Pu and ^{241}Pu , are taken into account representing more than 99.7% of the total fissions.

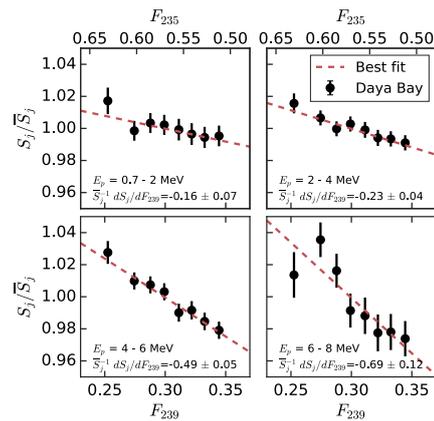


Fig. 8. Relative neutrino flux measurements versus the ^{235}U and ^{239}Pu fission fractions for four energy ranges.

Fig. 10 presents the neutrino IBD yield per fission of ^{239}Pu versus the one of ^{235}U . It is clearly seen that the disagreement with the model comes from the ^{235}U evolution. A possible explanation, with 2.8σ significance, is that there is an overestimation of the antineutrino flux from ^{235}U in reactor models, instead of an anomaly produced by sterile neutrinos. Tentatives by independent analyses to combine these new Daya Bay data with all previous data coming from many other experiments have the tendency to decrease the importance of ^{235}U isotope effect¹⁵. However, this new Daya Bay observation constitutes an unaccounted systematic error by the reactor models.

Daya Bay doesn't report indications that the 5 MeV "bump" could come from a particular isotope. Improvements in systematic uncertainties and increasing statistics could help to better understand this particular problem.

Using the spectrum of L/E of Fig. 4 and the probability of having a 4th sterile neutrino family:

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) \approx 1 - \cos^4 \theta_{14} \sin^2 \theta_{13} \sin^2 \left(\frac{\Delta m_{ee}^2 L}{4E_\nu} \right) - \sin^2 2\theta_{14} \sin^2 \left(\frac{\Delta m_{41}^2 L}{4E_\nu} \right)$$

exclusion limits can be established. Fig. 11 shows the exclusion limits obtained by RENO experiment¹¹ and the one obtained combining Daya Bay¹⁶ results with those of MINOS and Bugey-3.

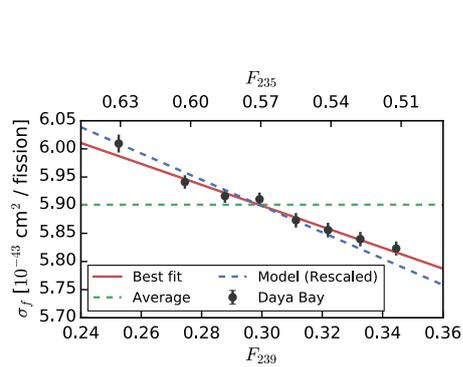


Fig. 9. Measured IBD yield versus the ^{235}U and ^{239}Pu fission fractions compared to predictions.

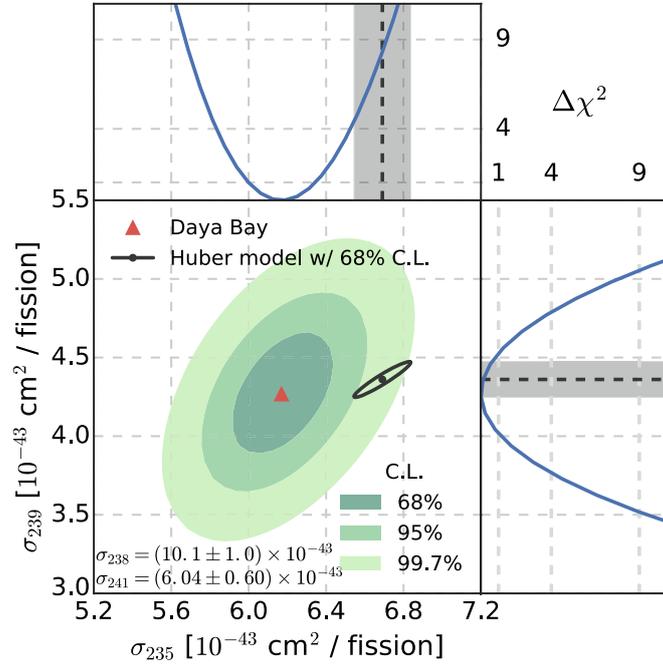


Fig. 10. IBD yield/fission for ^{235}U and ^{239}Pu compared to predictions.

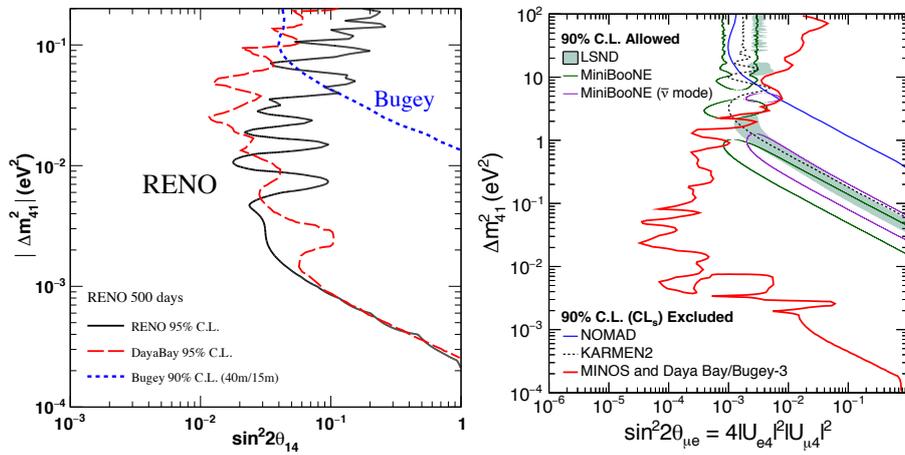


Fig. 11. Exclusion plots for sterile neutrino searches.

5. Plans and Prospects

Double Chooz will continue data taking up to beginning of 2018 after which the detector decommissioning will start. The experiment will profite of this phase to well

measure the number of protons in each part of its detectors in order to decrease the systematic errors. RENO will take data up to end of 2018 with a possible extension up to 2021. The goal will be to reach a precision of 6% on θ_{13} . Daya Bay plans to take data up to 2020. The goal is to reach a 3% systematic error on θ_{13} by better understanding of the systematic errors (non-linearities, calibration,...) and better background reduction. Fig. 12¹⁷ summarises the uncertainty evolution on θ_{13} and $|\Delta_{ee}^2|$.

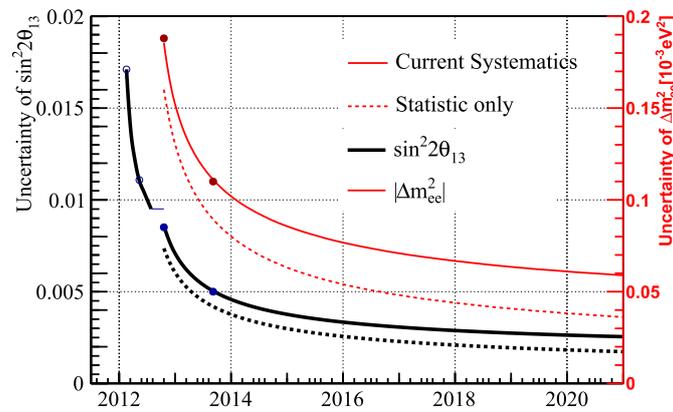


Fig. 12. Daya Bay uncertainty evolution.

6. Medium baseline experiments

Within the context of relatively large θ_{13} , medium baseline reactor experiments could determine the neutrino mass hierarchy, provided that they will have a sufficient (and challenging) energy resolution^{18–22}. Indeed, the survival probability of reactor neutrinos can be written as:

$$\begin{aligned}
 P(\bar{\nu}_e \rightarrow \bar{\nu}_e) &\approx 1 - \cos^4 \theta_{13} \sin^2 2\theta_{12} \sin^2 \left(\frac{\Delta m_{21}^2 L}{4E_\nu} \right) \\
 &\quad - \sin^2 2\theta_{13} \sin^2 \left(\frac{\Delta m_{31}^2 L}{4E_\nu} \right) \\
 &\quad - \sin^2 \theta_{12} \sin^2 2\theta_{13} \sin^2 \left(\frac{\Delta m_{21}^2 L}{4E_\nu} \right) \cos \left(\frac{2|\Delta m_{31}^2| L}{4E_\nu} \right) \\
 &\quad \pm \frac{\sin^2 \theta_{12}}{2} \sin^2 2\theta_{13} \sin \left(\frac{2\Delta m_{21}^2 L}{4E_\nu} \right) \sin \left(\frac{2|\Delta m_{31}^2| L}{4E_\nu} \right)
 \end{aligned}$$

The \pm at the fourth term is for Normal and Inverted hierarchy. It has to be noted

that this probability doesn't depend on the CP violation parameter δ_{CP} , also the matter effect for the considered baselines is negligible.

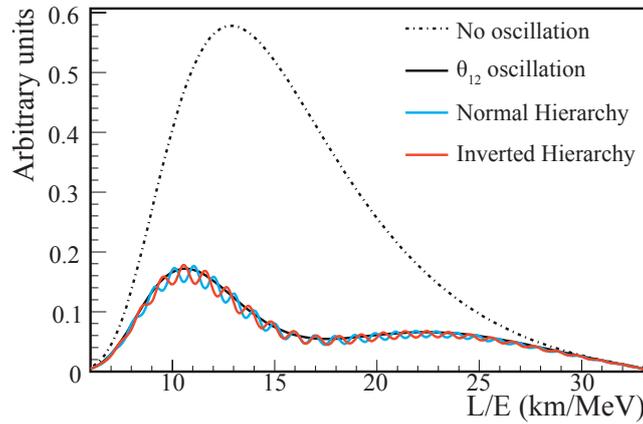


Fig. 13. Neutrino energy spectrum for both hierarchies compared to the unoscillated spectrum.

The experiments must be placed at a distance to maximise the contribution of this last term in order to be significantly sensitive to the neutrino mass hierarchy. It comes out that this distance must be around 50 km. Fig. 13 presents the oscillated neutrino energy spectrum for the two hierarchies compared to the unoscillated one. It can be clearly seen that a very good energy resolution is needed to discriminate the two cases.

Two projects propose to exploit this effect, JUNO²³ in China and RENO50²⁴ in South Korea. Both experiments propose to use a large (~ 20 kt) liquid scintillator detectors. Thanks to the size of these detectors, other physics subjects can be treated together with the reactor neutrino program, as the detection of supernova explosions and relic neutrinos, solar and atmospheric neutrinos, geoneutrinos, proton lifetime and exotic searches.

6.1. JUNO

The JUNO detector will be located in the South of China near Jiangmen at a distance of 53 km from the nuclear power plants of Yangjiang and Taishan. The thermal power of these two nuclear power plants is expected to be between 26 GWth and 35 GWth by the beginning of next decade. JUNO plans to collect 100 kIBDs over 6 years to determine the neutrino mass hierarchy.

Fig. 14 illustrates the observed neutrino spectrum which could be observed by JUNO together with the main background contributions. Thanks to the ability to observe the “solar” and “atmospheric” oscillation contributions in the same de-

tector, JUNO will be able to precisely measure the oscillation parameters Δm_{21}^2 , Δm_{ee}^2 and $\sin^2 \theta_{12}$. Table 2 presents the JUNO performance for these parameters compared to the current accuracy. A sub-percent precision on all three parameters is expected.

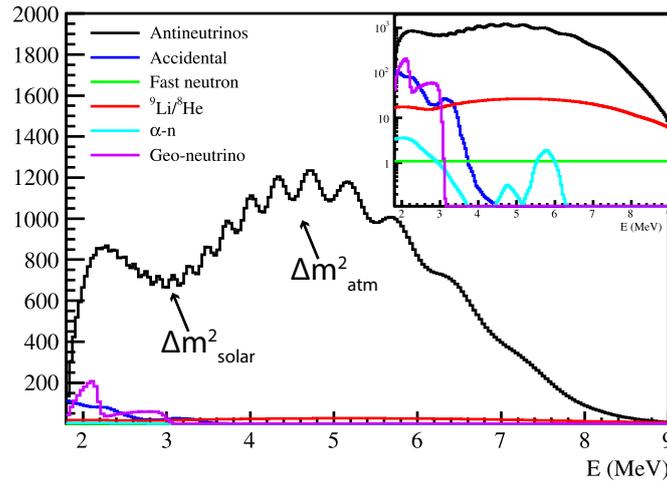


Fig. 14. Neutrino energy spectrum with main background contributions.

Table 2. Precision measurements with the JUNO detector.

	current precision	JUNO precision
Δm_{21}^2	2.3%	0.6%
Δm_{ee}^2	4%	0.5%
$\sin^2 \theta_{12}$	6%	0.7%

For the mass hierarchy determination, JUNO has to reach an energy resolution of at least 3% at 1 MeV. For this, JUNO detector must be able to detect more than 1200 photoelectrons per deposited MeV. To achieve this, JUNO, compared to previous liquid scintillator detectors, plans to optimise the liquid scintillator quality and composition²⁵. The photocathode coverage will also considerably increase to reach a value of nearly 80%. The two last points to be improved is the photomultiplier quantum efficiency and the calibration of the detector.

6.1.1. The JUNO detector

The JUNO central detector will be spherical compared to the cylindrical shape of SuperKamiokande. A schematic view of the JUNO detector is depicted by Fig. 15.

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The neutrino interactions will occur inside an acrylic sphere (12 cm thick) immersed in water (35 kt) and containing the liquid scintillator and having a diameter of 35.4 m. Outside this sphere a mechanical structure will support all 20" PMTs (about 17000). In between the 20" PMTs small PMTs (3") will be placed to mainly increase the energy dynamic range of the whole system. All the surrounding water will be used as Water Cherenkov veto detector with about 2000 20" PMTs. In order to compensate the earth magnetic field significantly degrading the PMT detection performance, two magnetic coils, a vertical and horizontal ones, will be placed inside the veto detector. On top of the central detector, a Top Tracker will be placed in order to well study the cosmogenic background. This Top Tracker based on plastic scintillator strips consists of a recycling of the OPERA Target Tracker²⁶.

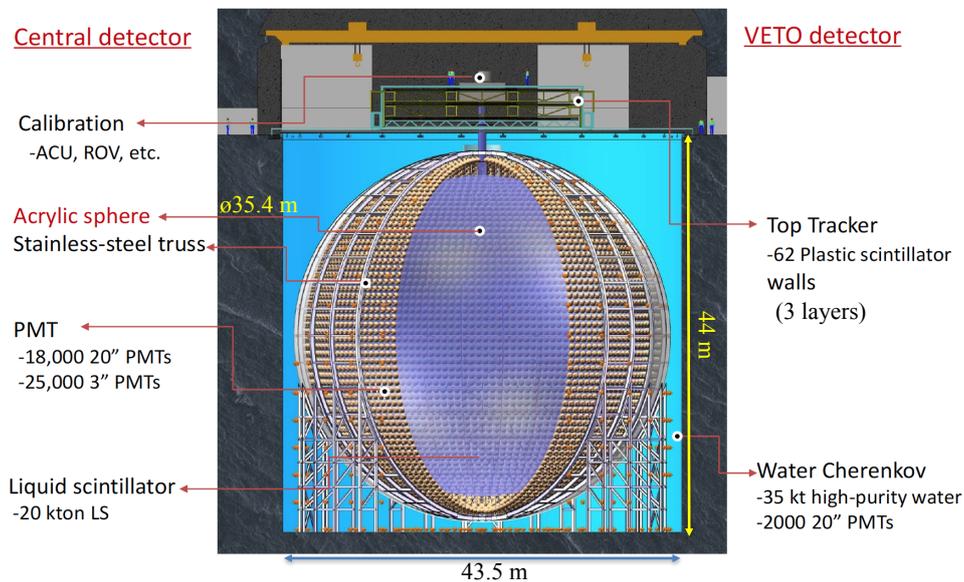


Fig. 15. Schematic view of the JUNO detector.

All parts of the detector are in an R&D period or in a construction phase. The 20" PMTs will be provided by NNVT (15000) and Hamamatsu (5000) companies. The HZC company will provide all the 25000 3" PMTs. The delivery and tests of the 20" PMTs have already started. A distillation plant has been installed in the Daya Bay site for tests in order to find the best way to produce the JUNO liquid scintillation. Very promising results have already been obtained up to now with an attenuation length higher than 22 m (20 m required).

Taking as example Daya Bay, JUNO has elaborated a very extensive calibration program to well calibrate all the detector positions at various energies. This includes displacement of radioactive sources with ultrasonic positioning system for energy

calibration, and fast 1 ns laser system for timing calibration.

The excavations of the underground laboratory to host the JUNO detector have started beginning of 2015. A 1300 m length slope tunnel to reach the detector (overburden of 700 m of rock) and a vertical shaft are already excavated. The civil engineering will finish by beginning of 2019 when the installation of the detector will start. The data taking period is supposed to start beginning of next decade.

6.1.2. Mass hierarchy performance

The JUNO performance to solve the neutrino mass hierarchy problem using the above described detector is shown by Fig. 16. This Fig. shows the χ^2 difference between the two hierarchies versus the parameter $|\Delta m_{ee}^2|$ in case of normal hierarchy (similar performance is obtained in case of inverted hierarchy). This $\Delta\chi^2$ is of the order of 11 ($\sigma \sim 3.3$) in real conditions and could go up to 16 ($\sigma \sim 4$) in case the dispersion of the reactors in both nuclear plants is ignored.

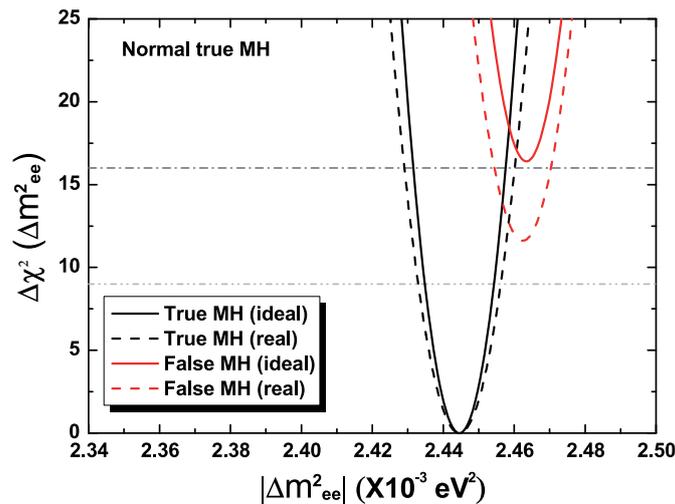


Fig. 16. Mass hierarchy JUNO performance.

6.2. RENO50

RENO50 has a similar physics program and proposal than JUNO with a liquid scintillator cylindrical detector (18 kt) instead of a spherical one. This project proposes to use the same nuclear plants than those used by the RENO experiment with the detector placed at a distance of 50 km away. An extensive R&D period took place up to summer 2017 in many directions as in liquid scintillator purification

and reduction of radioactivity. Unfortunately, efforts to obtain a full construction fund failed. For this reason, the Collaboration decided to stop the project.

6.3. Conclusions

Short baseline reactor experiments are greatly contributing in the understanding of neutrino oscillations and in measuring the oscillation parameters. They allowed in 2012 to measure the last unmeasured oscillation angle θ_{13} and thus opened the way to observe a possible CP violation in the neutrino sector and determine the neutrino mass hierarchy as well. These experiments also contribute to better understand the so called neutrino anomalies and are setting limits on sterile neutrino existence.

Thanks to the relatively large θ_{13} value, medium baseline reactor experiments, as JUNO, could determine the neutrino mass hierarchy provided that they will have a very good energy resolution better than 3% at 1 MeV. These experiments can also measure precisely three of the oscillation parameters allowing to start unitarity tests of the PMNS mixing matrix. The very large volume (~ 20 kt) of these experiments will allow them to also have a very rich astroparticle physics program.

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