Overview of Reactor Neutrino

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Many thanks to Jia Jie Ling, Liang Jian Wen for suggestions and discussions.

Overview

- The historical role of reactor neutrino experiments.
- The recent short baseline reactor neutrino experiments.
  - The measurement of θ_{13}.
  - The reactor neutrino spectrum measurement.
  - Search of new physics at reactor neutrino experiments.
    - Light sterile neutrino.
    - Wave-packet Impact.
    - Other exotic topics.
- The future medium baseline reactor neutrino experiments.

The Historical Role of Reactor Neutrino Experiments

The measurement of different oscillation parameters

The solar and atmospheric neutrino experiments suggest the existences of neutrino oscillations. However, the whole picture of neutrino oscillation is not revealed yet:

- Solar neutrino: $\nu_e \to \nu_\mu$ and ν_τ, gives the hint that there exist a $\Delta m^2 \lesssim 10^{-4}$ eV^2 and also a mixing angle $\sin^2\theta \sim 0.3$.
- Atmospheric neutrino: $\nu_\mu \to \nu_\tau$, gives the hint that there exist a $\Delta m^2 \sim 10^{-3}$ eV^2 and also a mixing angle $\sin^2\theta \sim 0.5$.

To understand the whole picture of ν oscillation and precisely measure certain oscillation parameters, we need reactor neutrino experiments (with different baselines).

Oscillation parameters involve reactor ν experiments

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 2} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

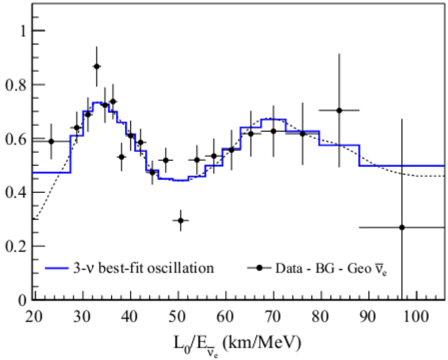
$$\tan^2\theta_{12} \equiv \frac{|U_{e2}|^2}{|U_{e1}|^2},\ U_{e3} \equiv \sin\theta_{13} e^{-i\delta}$$

$$\begin{aligned} P_{ee} =& 1 - \cos^4(\theta_{13})\sin^2(2\theta_{12})\sin^2\frac{\Delta m^2_{21} L}{4E} \\ & - \sin^2(2\theta_{13})[\sin^2(\theta_{12})\sin^2\frac{\Delta m^2_{32} L}{4E} + \cos^2(\theta_{12})\sin^2\frac{\Delta m^2_{31} L}{4E}] \end{aligned}$$

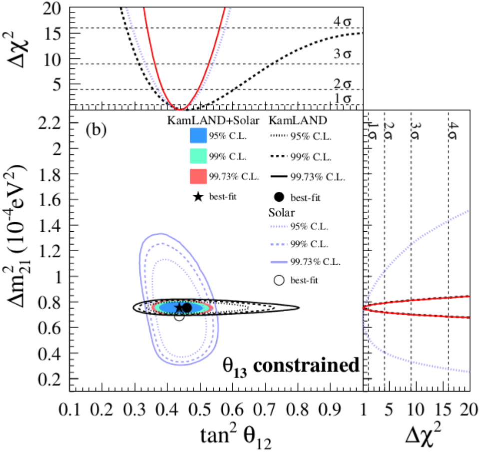
KamLAND – a long baseline reactor neutrino experiment

Solar neutrino experiments first provided the evidences of potential neutrino oscillation. Afterwards, KamLAND, a reactor experiment with effective baseline $\sim$ 180 km, provided a complementary results to solar ν measurements and also a solid proof of oscillation pattern.

There existed other hypotheses to explain the disappearance of $\bar{\nu}_e$, such as neutrino decay, decoherence due to quantum gravity, Lorentz violation, etc. However, they are strongly constrained due to the KamLAND result



The constraints from KamLAND + Solar



Role of KamLAND:

- Discovery of oscillation pattern and measure Δm^2_{21} precisely
- Complementary result to solar neutrino.

The Recent Short Baseline Reactor Neutrino Experiments : Daya Bay, Reno and Double Chooz

The last unknown parameter in Standard Model – θ_{13}

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 2} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

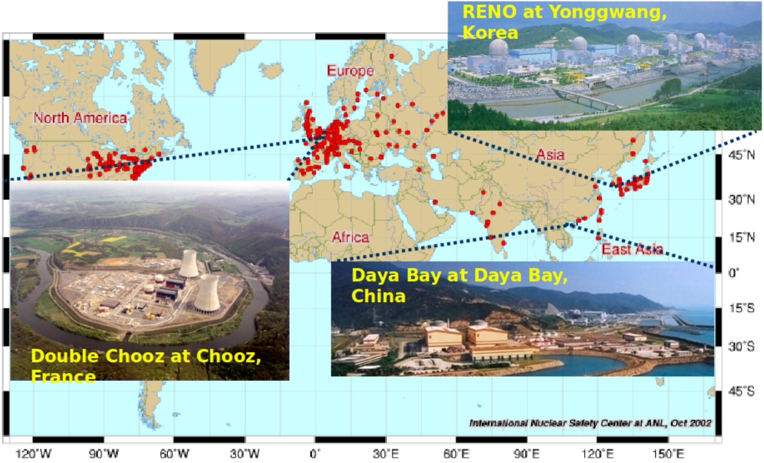
$$U_{e3} \propto \sin\theta_{13}$$

$$\begin{aligned} P_{ee} =& 1 - \cos^4(\theta_{13})\sin^2(2\theta_{12})\sin^2\frac{\Delta m^2_{21}L}{4E} \\ & - \sin^2(2\theta_{13})[\sin^2(\theta_{12})\sin^2\frac{\Delta m^2_{32}L}{4E} + \cos^2(\theta_{12})\sin^2\frac{\Delta m^2_{31}L}{4E}] \end{aligned}$$

The value of Δm^2_{32} ($\approx \Delta m^2_{31}$) has been measured by MINOS and other experiments. However, the oscillation amplitude $\sin^2(2\theta_{13})$ was not determined before 2012.

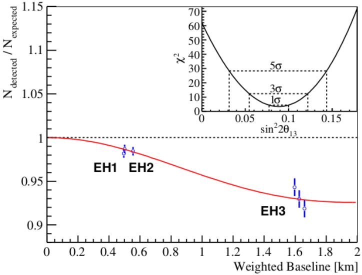
Therefore, we need short baseline reactor neutrino experiment(s) to measure the deficit of $\bar{\nu}_e$ flux due to θ_{13}.

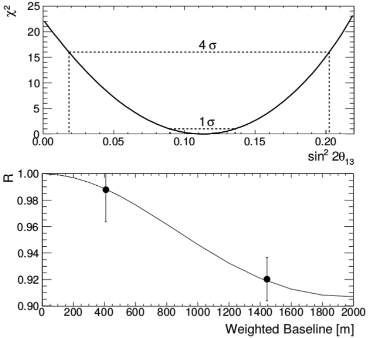
Daya Bay, Reno and Double Chooz



Measurement of θ_{13} and Δm^2_{32}

Measure θ_{13} with relative measurement





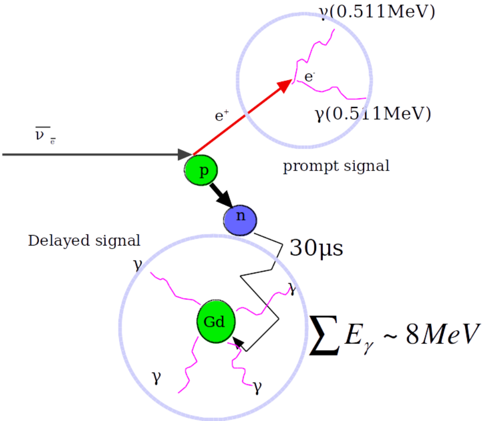
From Chin. Phys. C37 011001 and Phys. Rev. Lett. 108, 191802 (2012)

The figures show signal deficits at the far detector(s) relative to the near detector(s) at Daya Bay (left) and RENO (right), indicating the size of the θ_{13}-driven oscillation.

The detection of $\bar{\nu}_e$ at reactor neutrino experiment

Detection process: Inverse Beta Decay (IBD)

$$\bar{\nu}_e + p \to e^+ + n$$
$$E_\nu \approx T_{e^+} + T_n + (M_n - M_p) + m_{e^+}$$

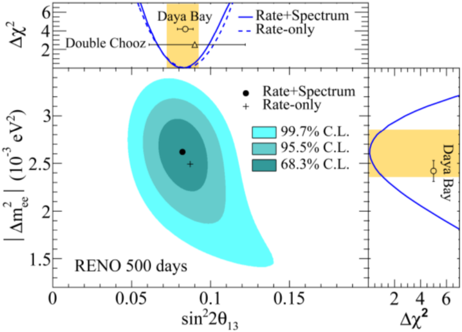


Advantages of SBL reactor experiments in measuring θ_{13}

- Independent of the mass hierarchy;
- Independent of the CP phase;
- Large statistics (due to the short baseline);
- A free neutrino source;
- Comparing with other oscillation experiments, there are less background.

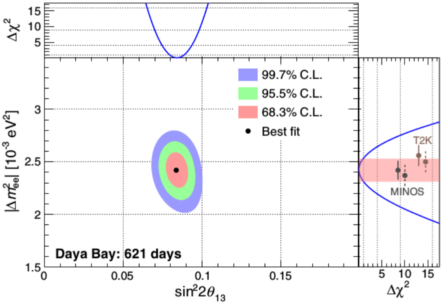
Measurements of θ_{13} and Δm^2_{32} from SBL experiments

From Reno



$\sin^2 2\theta_{13} = 0.082 \pm 0.01$
Phys. Rev. Lett. 116, 211801

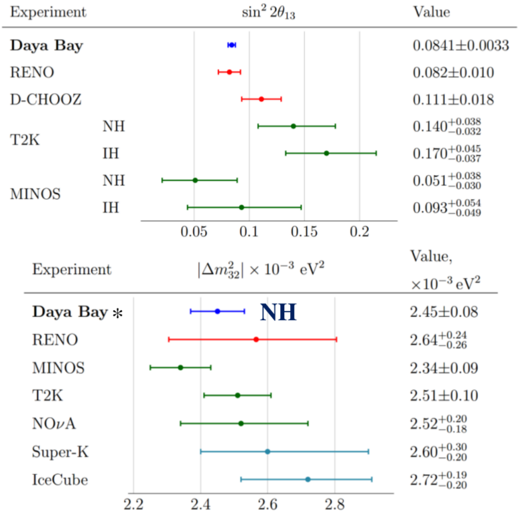
From Daya Bay



$\sin^2 2\theta_{13} = 0.084 \pm 0.005$
Phys. Rev. Lett. 115, 111802

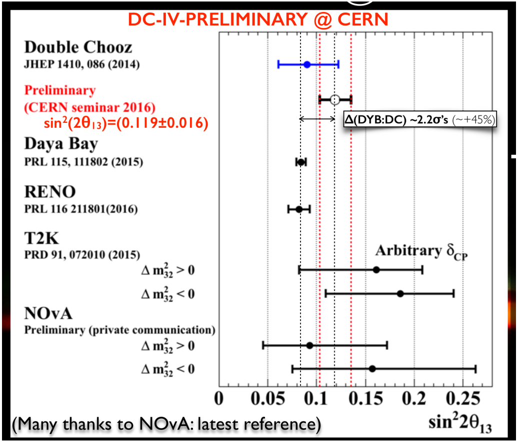
The previous result from Double Chooz : $\sin^2 2\theta_{13} = 0.088 \pm 0.033$, from *JHEP 01 (2016) 163*.

Measurements of θ_{13} and Δm^2_{32} from different experiments



*** Fit with full 3-flavor oscillation formula assuming normal mass hierarchy.**

The most updated result from Double Chooz



The result from Double Chooz: $\sin^2 2\theta_{13} = 0.119 \pm 0.016$. Around 2σ inconsistent with the measurement from Daya Bay.

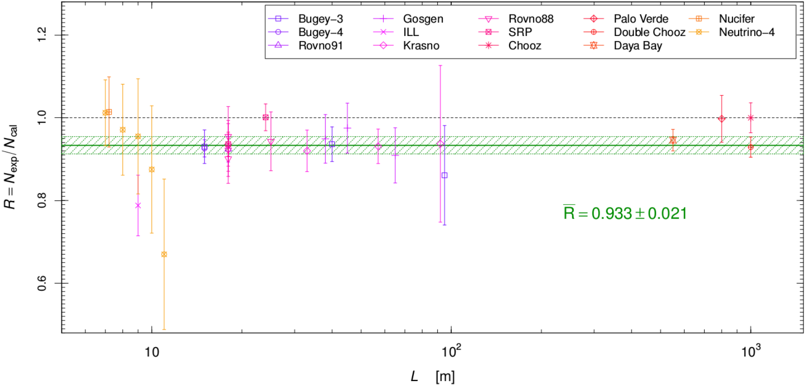
The measurement of Δm^2 is not released yet.

Reactor Neutrino Flux Problems

The reactor neutrino anomaly

[Mention et al, PRD 83 (2011) 073006; updated in White Paper, arXiv:1204.5379]

New reactor $\bar{\nu}_e$ fluxes [Mueller et al, PRC 83 (2011) 054615; Huber, PRC 84 (2011) 024617]



$\approx 3.2\sigma$ deficit $\Delta m^2_{SBL} \gtrsim 0.5\,eV^2 \gg \Delta m^2_{ATM} \gg \Delta m^2_{SOL}$

From C.Giunti's talk at Neutrino 2016

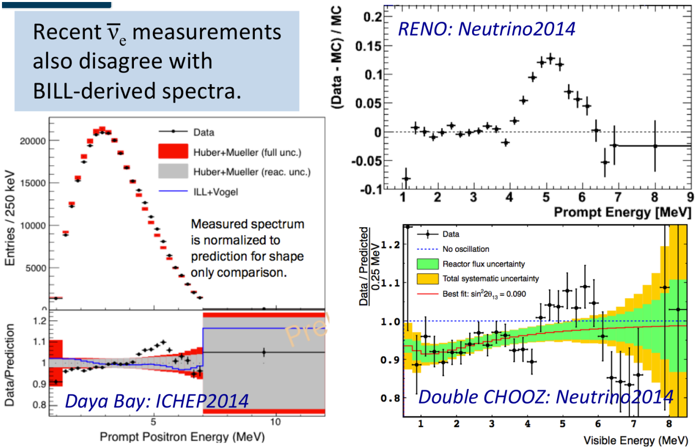
The problem of reactor neutrino spectrum

Up to now, the reactor neutrino flux is not precisely determined yet. Generally speaking, the uncertainty of reactor flux could cause problems to reactor neutrino experiment.

The previous calculation of β decay spectrum estimates that the uncertainties of $\bar{\nu}_e$ would be around a few percent. However, recently, there are studies suggest that the uncertainties may have been underestimated. — *A.C.Hayes, et. al. Phys.Rev.Lett. 112, 202501 (2014)*; *D.A.Dwyer, T.J.Langford, Phys.Rev.Lett. 114, 012502 (2015)*

The 5 MeV bump

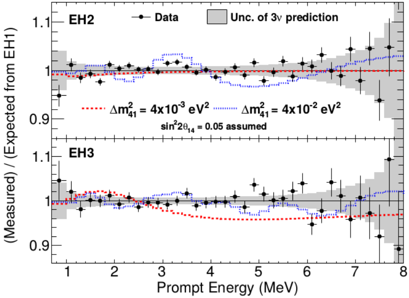
Moreover, Daya Bay, Reno and Double Chooz also find an excess of events at $E_\nu = 5$ - 7 MeV, compared with Huber and Mueller's calculations.

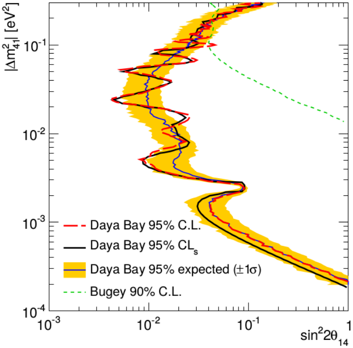


Reference *Phys.Rev.Lett. 114, 012502 (2015)* provided another calculation which agree with the measurements better.

Hunt of New Physics at Reactor Neutrino Experiments

The constraints on “3+1” framework from Daya Bay





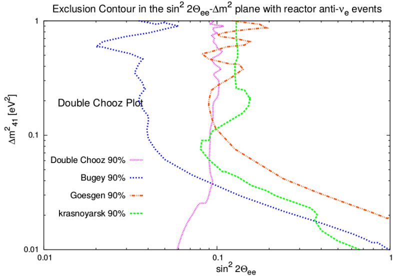
From arXiv:1607.01174

Left:Prompt energy spectra observed at EH2 (top) and EH3 (bottom), divided by the prediction from EH1 with the three-neutrino best fit oscillation parameters.

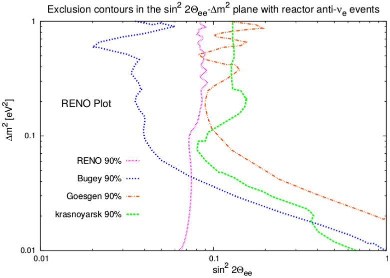
Right: Exculsion contours from Daya Bay analysis, with the assumption of $\Delta m^2_{32} > 0$ and $\Delta m^2_{41} > 0$.

Constraints on "3+1" framework from SBL experiments

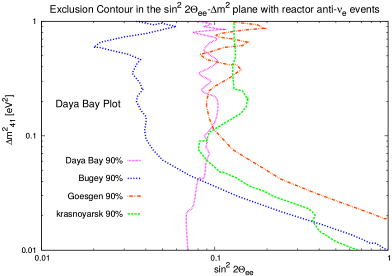
Double Chooz (*arXiv:1206.2172*)



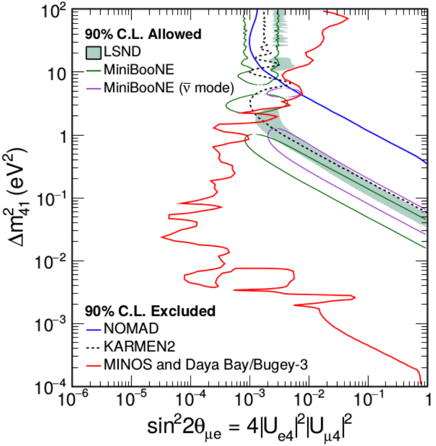
Reno (*arXiv:1206.2172*)



Daya Bay (*arXiv:1206.2172*)



Combined analysis from Daya Bay, Bugey and MINOS data

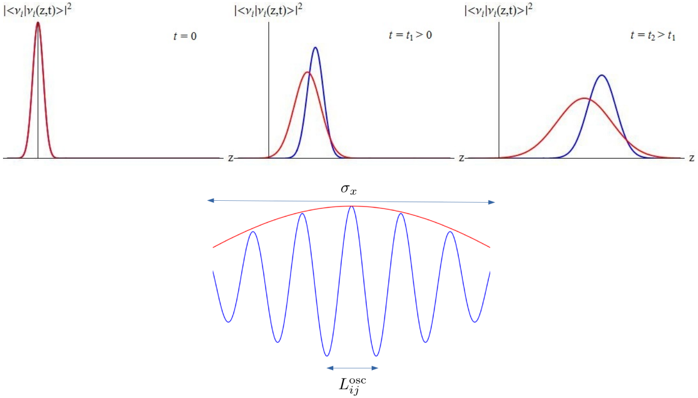


From arXiv:1607.01177

The combined 90% C.L. limit on $\sin^2 2\theta_{\mu e}$ from MINOS and Daya Bay/Bugey-3 data. The LSND and MiniBooNE 90% C.L. allowed regions are also shown for comparison. Regions of parameter space to the right of the red contour are excluded.

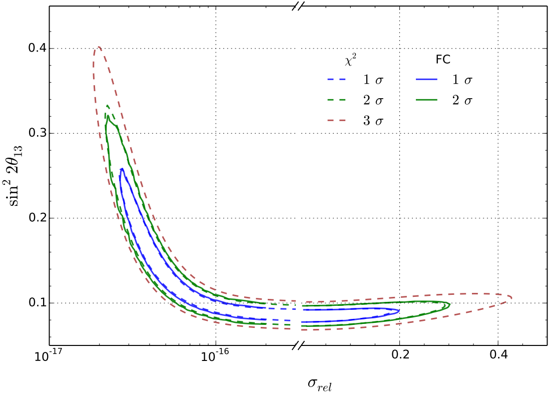
Decoherence effect due to wave-packet treatment

Conventionally, plane-wave description for the neutrinos is adopted in most oscillation experiments. However, in reality, as neutrino production and detection are localized events, there must be finite intrinsic uncertainties, and the neutrino should be described by a wave-packet.



More details can be referred to references *arXiv:1608.01161* and *EPJC 76, 310 (2016)*

Constraints of wave-packet impact from Daya Bay data



Allowed regions of ($\sin^2 2\theta_{13}$, $\sigma_{\rm rel}$) parameters obtained from Daya Bay. $\sigma_{\rm rel}$ is the relative energy uncertainty and describes the signifiance of wave-packet impact. Note the break in the abscissa and the change from a logarithmic to linear scale.
More details can be referred to reference *arXiv:1608.01161*

Other potential new physics studies at reactor neutrino experiments

- Non-Standard Interaction (NSI) — The study of NSI is a model-independent way to parametrize all potential effects on ν oscillation due to new physics. More details and studies at reactor neutrino experiments can be referred to references *JHEP 12 (2011) 001*, *JHEP 07 (2015) 060* and *Nucl. Phys. B 888 (2014) 137*.
- Test of Lorentz Violation — Attempts to use violation of Lorentz Invariance to explain the data in oscillation experiments. More details and the studies at reactor neutrino experiments can be referred to reference *Phys. Rev. D 86, 112009*.
- Neutrino Decay — More details and the studies at reactor neutrino experiments can be referred to reference *JHEP 11 (2015) 001* and *PRL 94, 081801 (2005)*.
- Decoherence due to quantum gravity — More details and the studies at reactor neutrino experiments can be referred to reference *Phys.Rev.D76:033006* and *PRL 94, 081801 (2005)*.

The Future Reactor Neutrino Experiments :

Neutrino Mass Hierarchy Identification

Determine the mass hierarchy at medium baseline

Short baseline experiments can only measure two flavor approximation:

$$P_{\bar{e}\bar{e}} \approx 1 - \sin^2(2\theta_{13})\sin^2(\frac{(\Delta m^2_{31})L}{4E}) + \text{ subleading terms.} \qquad (1)$$

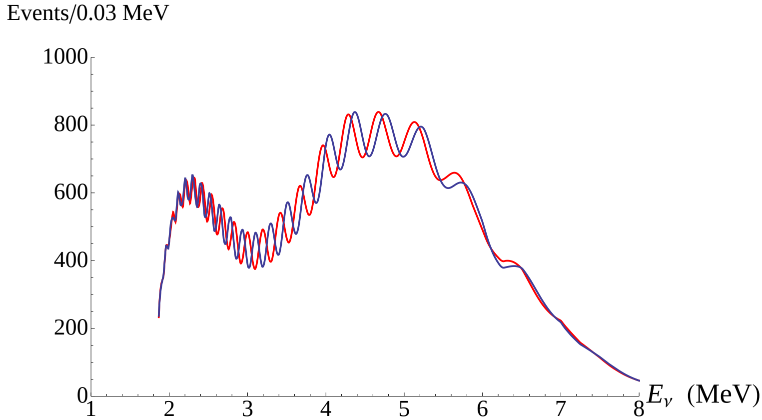
To determine MH, the subleading terms corresponding to Δm^2_{21} must be measured as well $\Rightarrow$ baseline has to be long enough.

In Normal Hierarchy (NH), $\Delta m^2_{31} = \mid \Delta m^2_{32} \mid + \Delta m^2_{21}$.
In Inverted Hierarchy (IH), $\Delta m^2_{31} = \mid \Delta m^2_{32} \mid - \Delta m^2_{21}$.

$$\begin{aligned} P_{\bar{e}\bar{e}} = 1 &- \cos^4(\theta_{13})\sin^2(2\theta_{12})\sin^2(\frac{\Delta m^2_{21} L}{4E}) \\ &- \sin^2(2\theta_{13})\cos^2(\theta_{12})\sin^2(\frac{(|\Delta m^2_{32}| \pm \Delta m^2_{21})L}{4E}) \\ &- \sin^2(2\theta_{13})\sin^2(\theta_{12})\sin^2(\frac{\Delta m^2_{32} L}{4E}). \qquad (2) \end{aligned}$$

Moreover, since $\frac{\Delta m^2_{21}}{\Delta m^2_{31}} \sim 0.03$ and $\sin^2(2\theta_{13}) \sim 0.1$, the detector resolution has to be fine and the statistics has to be large.

Determine the mass hierarchy at reactor neutrino experiment

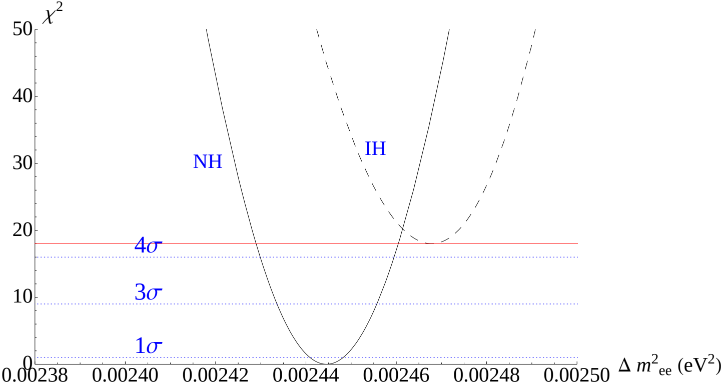


Expected neutrino visible energy spectrum for plane wave neutrino oscillation at 53 km for NH (blue) and IH (red).

The identification of mass hierarchy mainly depends on the shape information.

The sensitivity of determining MH at JUNO or RENO-50

The plot of χ^2 VS Δ $\mathrm{m_{ee}}$ (Yu-Feng Li et.al. PRD 88, 013008)



simulation from GLoBES

The solid curve corresponds to NH, dashed curve corresponds to IH.

Please refer to the next talk for more details about JUNO.

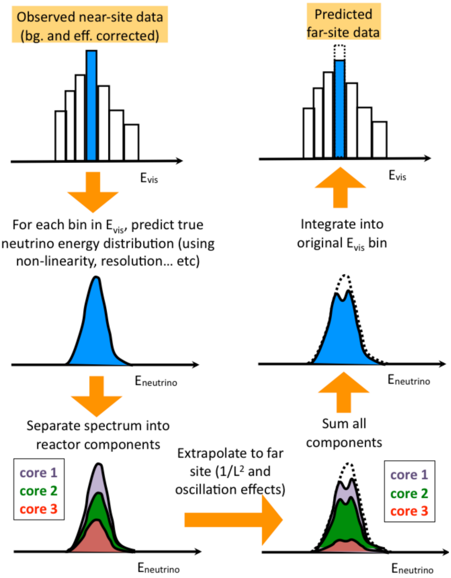
Summary

Conclusion

- Reactor neutrino experiments provide the strong evidences of oscillation pattern and also complementary result to solar neutrino.
- Short baseline reactor neutrino experiments provide the most precise measurement on the last unknown mixing angle θ_{13}.
- There are discrepancies between the spectrum measured by the short reactor experiments (Daya Bay, Reno and Double Chooz) and the prediction by Huber and Mueller. The reason is not confirmed yet.
- Reactor neutrino experiments (JUNO and RENO-50) at medium baseline are expected to determine the neutrino mass hierarchy at 3-4 σ C.L.
- Besides the standard neutrino oscillation parameters, reactor neutrino experiments can also address many important topics in new physics.


Thank You

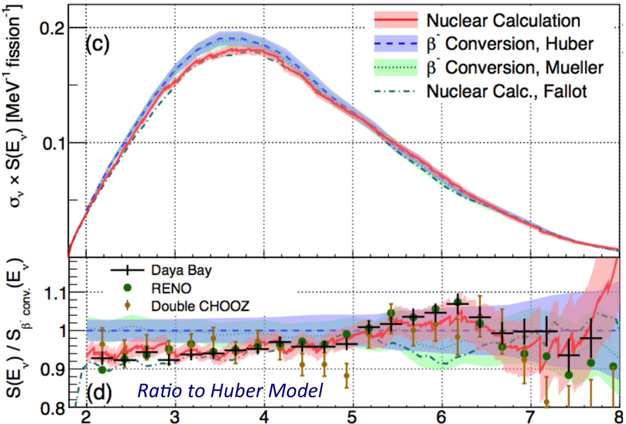
Appendix — The principle of relative measurement.



Appendix — Different calculations and measurements of the reactor flux

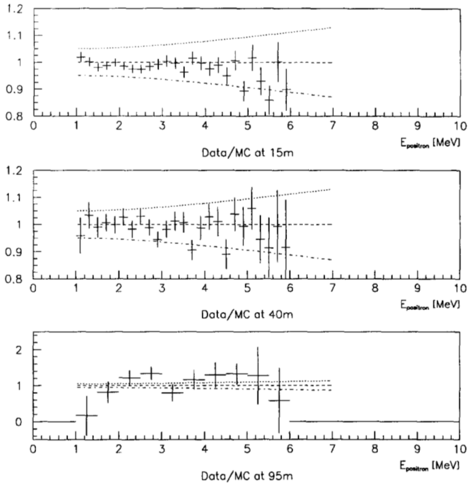
The reactor ν spectrum measured by Daya Bay, Double Chooz and Reno appear to be different with Huber and Mueller's calculation.

Reference *Phys.Rev.Lett. 114, 012502 (2015)* provided another calculation based on recent measurements, but a high resolution and statistic measurement is still necessary in order to measure / calculate the $\bar{\nu}_e$ spectra more precisely.

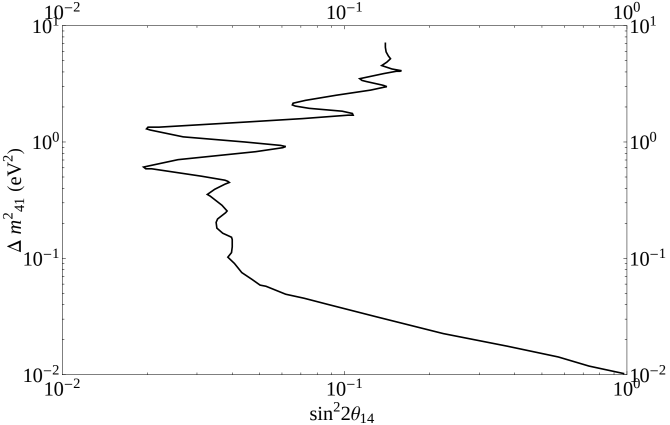


Appendix – Bugey Experiment

Bugey is a very short baseline reactor experiment with three detectors locating at 15 km, 40 km and 95 km from the source. They claimed that they didn't observe any oscillation. This implies that the sterile oscillation is absence in Bugey Experiment.



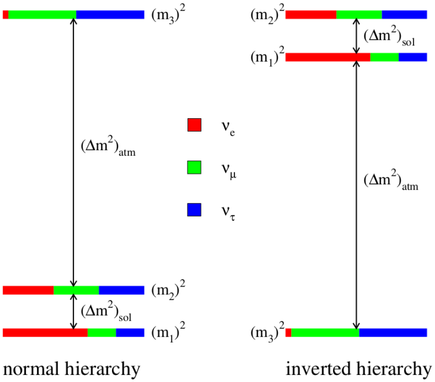
Appendix – Constraints on "3+1" framework from Bugey



90% C.L. exculsion contours from previous Bugey experiment.

From Nuclear Physics B 434 (1995) 503-532

Appendix – The problem of identifying neutrino mass hierarchy



The short baseline reactor experiments could measure Δm^2_{31} (or, $\Delta m^2_{ee} \approx \Delta m^2_{31} \approx \Delta m^2_{32}$ in the case of Daya Bay). However, they could not be determine the sign of Δm^2_{31} as they are not sensitive to the subleading terms in the probability formula.

Appendix – Quantify the sensitivity of MH identification

Assume that the nature is Normal Hierarchy,
then we fit both the NH and IH with the least-square methods by scanning over the parameter Δm^2:

$$\begin{aligned} \Delta m^2 &= \frac{1}{2}(\Delta m^2_{31} + \Delta m^2_{32}) \\ &= \frac{1}{2}(2\Delta m^2_{32} + \Delta m^2_{21}) \qquad \text{for NH} \\ \text{or } &= \frac{1}{2}(2\Delta m^2_{32} - \Delta m^2_{21}) \qquad \text{for IH} \end{aligned}$$

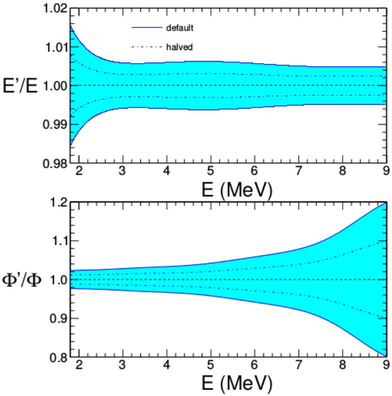
Then we calculate

$$\chi^2_{\mathrm{NH}} = \sum_i^{N_{\mathrm{bins}}} \frac{(M^i - T^i_{\mathrm{NH}}(\Delta m^2))^2}{M^i}, \qquad \chi^2_{\mathrm{IH}} = \sum_i^{N_{\mathrm{bins}}} \frac{(M^i - T^i_{\mathrm{IH}}(\Delta m^2))^2}{M^i},$$

where M^i is the measured event rate (assumed to correspond to NH) in the ith energy bin, T^i is the expected event rate of NH (or IH) depending on Δm^2.

Appendix – Large structure as uncertainties of reactor flux

The uncertainties of reactor spectrum are larger than previously expected.

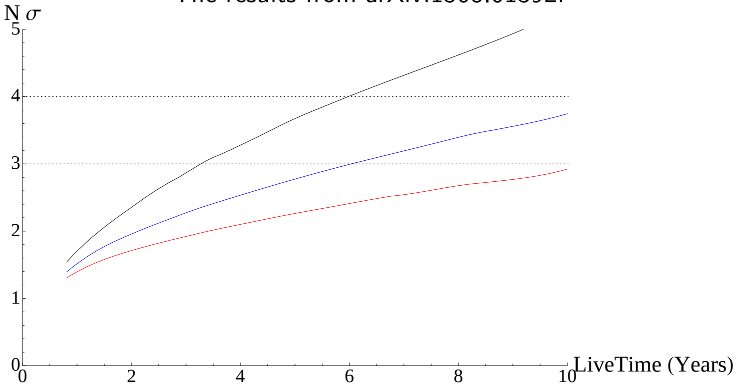


The $\pm 1\sigma$ error bands for energy-scale deviations (top panel) and flux-shape variations (bottom panel) from *PRD 92, 093001*.

The upper panel is from the non-linearity study in Daya Bay. The lower panel is based on the 1 σ error band from *PRL. 114, 012502 (2015).*

Appendix – Recalculate the sensitivity of JUNO

The results from arXiv:1508.01392:



Black curve — Consider constraints of (θ_{12}, θ_{13}, $\Delta m^2_{\mathrm{solar}}$, Δm^2_{ee}) + Normalization error.

Blue curve — + uncertainties of energy-scale variations.

Red curve — + uncertainties of flux-shape variation.

Appendix – The un-oscillated reactor ν spectrum calculated by "Huber and Muller" and "D.Dwyer and T.J.Langford"