Determination of mass hierarchy with reactor neutrino experiment

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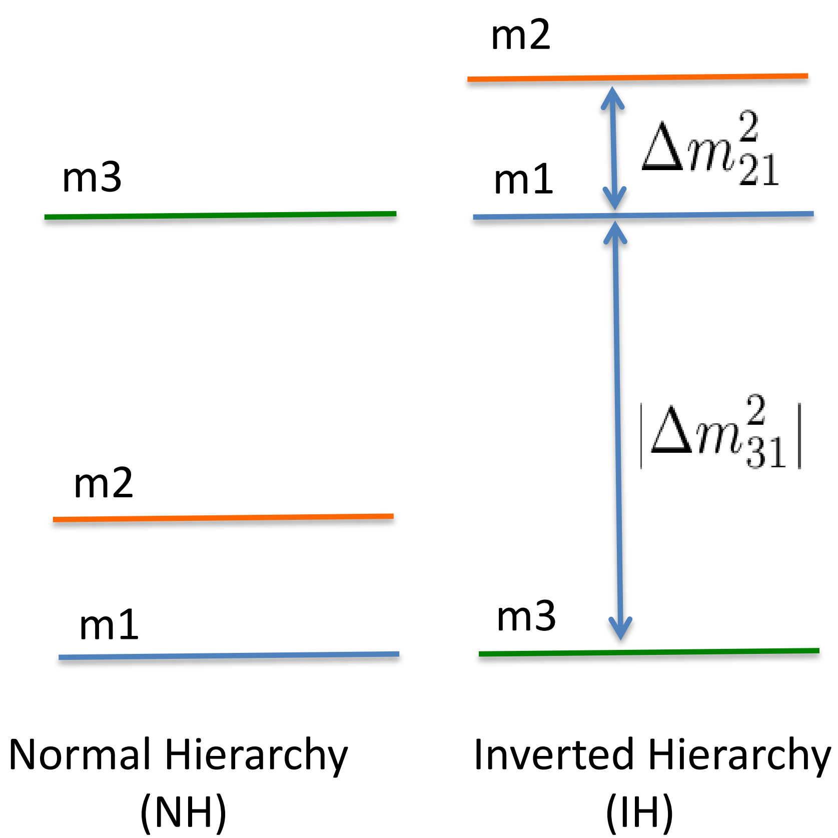
Introduction

- DayaBay and RENO observed large θ_{13}
- There is a possibility that neutrino mass hierarchy is determined by observing reactor neutrino oscillation at $\mathcal{O}(10)$ km away
- In this talk, I discuss the sensitivity of the future medium baseline reactor experiments for determining mass hierarchy

Mass Hierarchy



If we assume there are 3 types of netrinos, there are 6 possible mass hierarchies.

We know

$$\Delta m^2_{21} = m^2_2 - m^2_1 \sim 7.5 \times 10^{-5}$$
$$\Delta m^2_{21} < |\Delta m^2_{31}| \sim 2.3 \times 10^{-3}$$

There are two possibilities left, NH and IH.

$$\Delta m^2_{31} \equiv \begin{cases} m^2_3 - m^2_1 > 0 & \text{(NH)} \\ m^2_3 - m^2_1 < 0 & \text{(IH).} \end{cases}$$

Which one is realized in Nature?

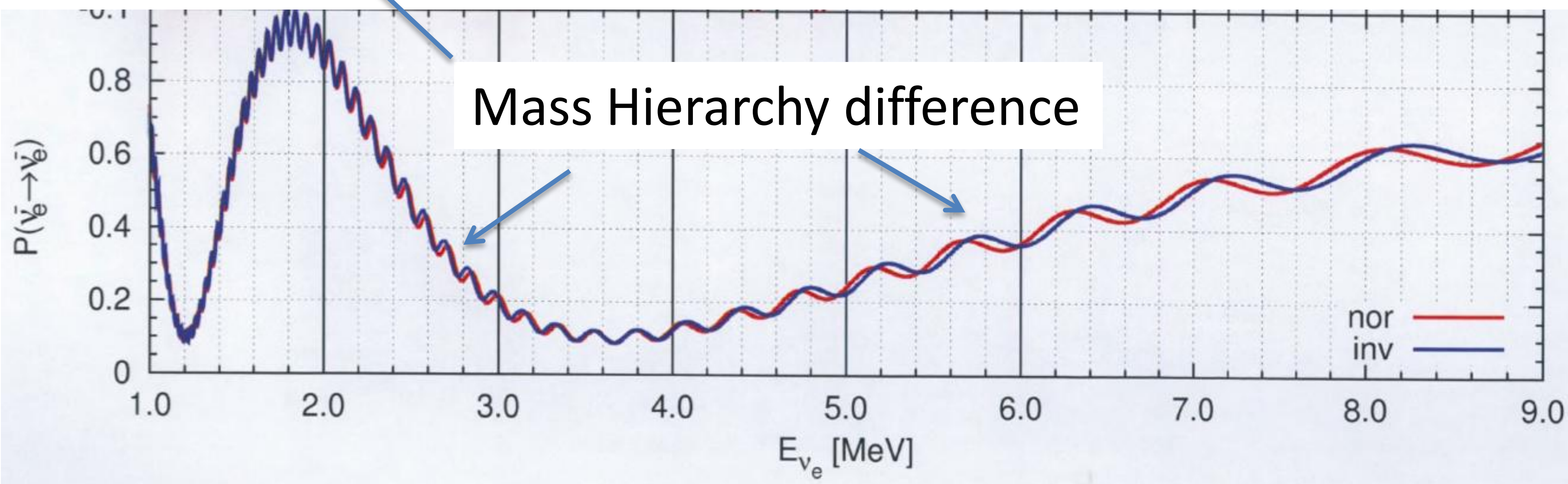
Long standing and big ISSUE.

$\overline{\nu}_e \rightarrow \overline{\nu}_e$ Oscillation

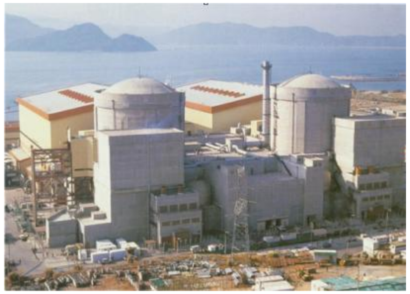
$$P_{ee} = 1 - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2(\Delta_{21}) - \sin^2 2\theta_{13}\sin^2(|\Delta_{31}|) - \sin^2\theta_{12}\sin^2 2\theta_{13}\sin^2(\Delta_{21})\cos(2|\Delta_{31}|) \pm \frac{\sin^2\theta_{12}}{2}\sin^2 2\theta_{13}\sin(2\Delta_{21})\sin(2|\Delta_{31}|)$$

$$\Delta_{ij} \equiv \frac{\Delta m^2_{ij} L}{4E_\nu}, \quad (\Delta m^2_{ij} \equiv m_i^2 - m_j^2)$$

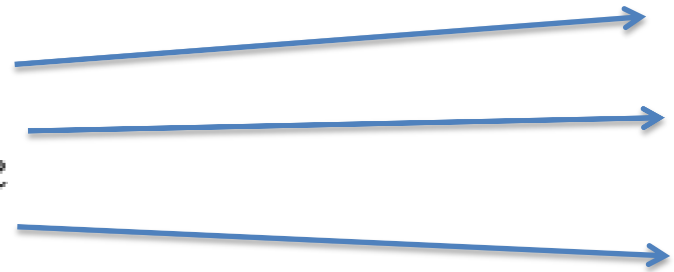
Mass Hierarchy difference



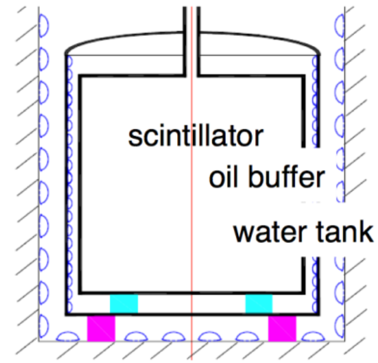
Reactor neutrino experiment



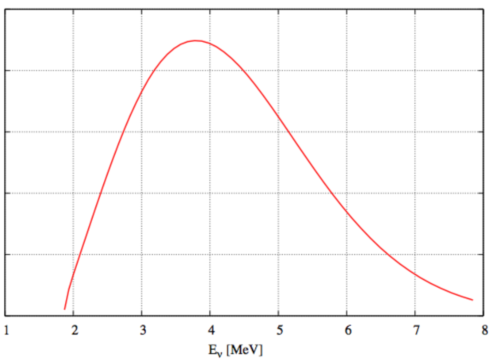
$\overline{\nu}_e$



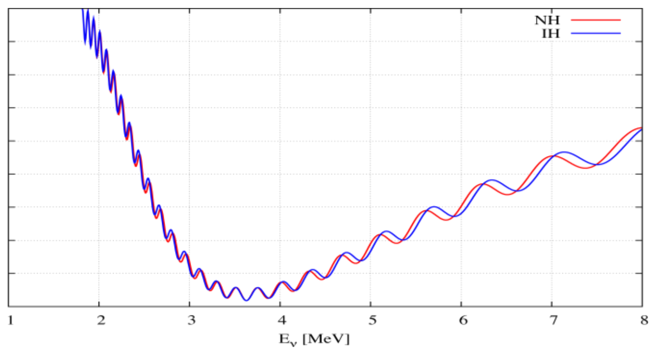
$\overline{\nu}_e + p \to e^+ + n$



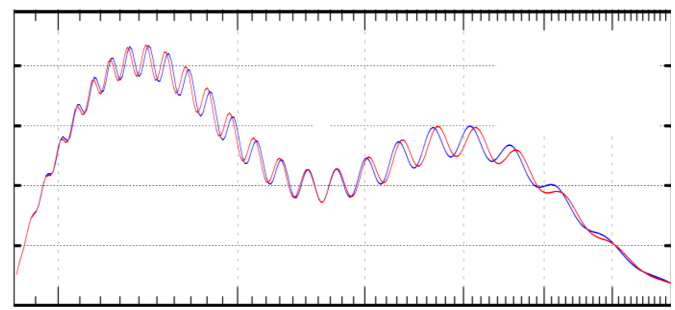
Flux @ Reactor



Pee



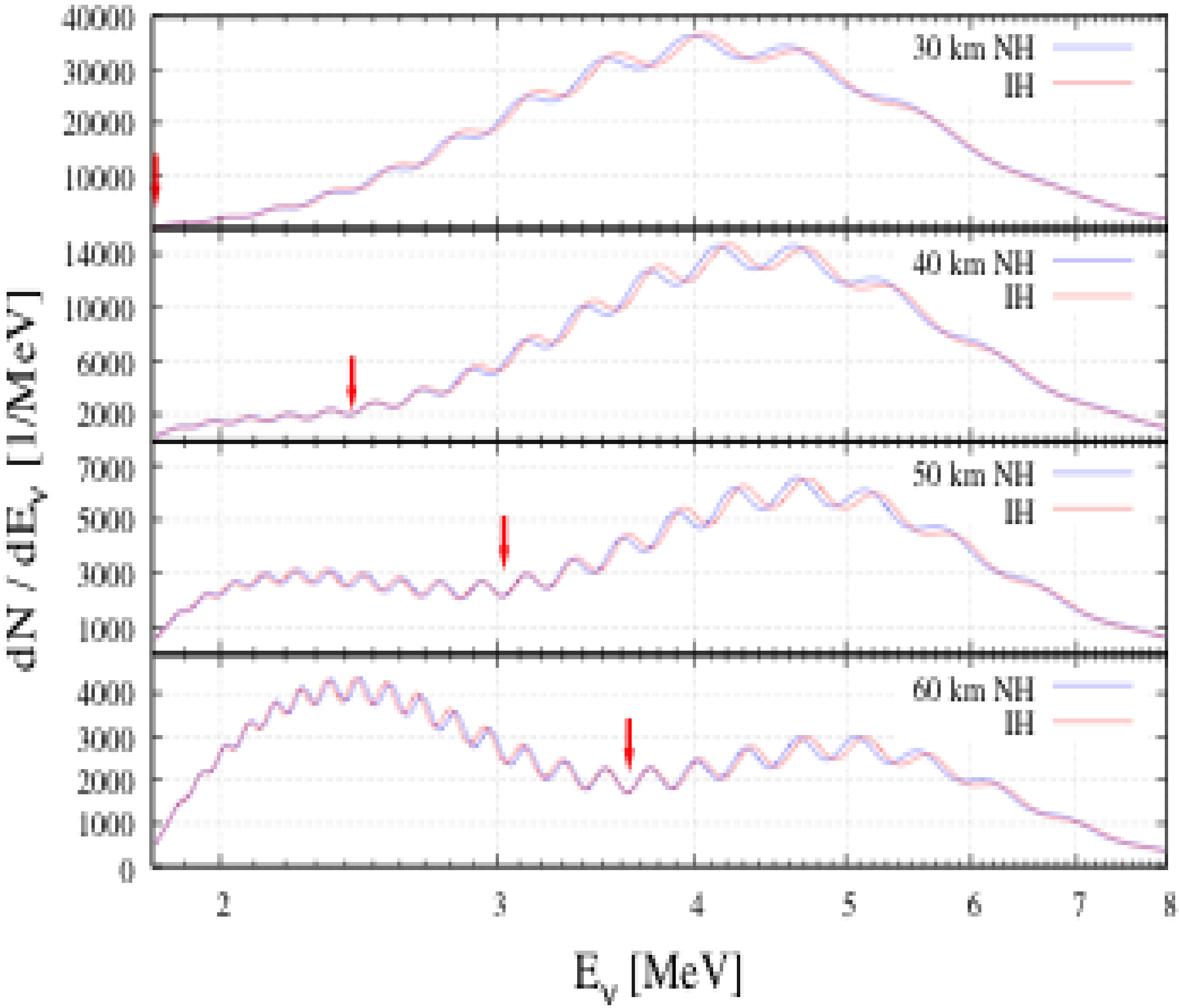
$\overline{\nu}_e$ @ far detector



$$\frac{dN}{dE_{vis}^{obs}} = \frac{N_p T}{4\pi L^2} \int_{E_{thr}}^{\infty} dE_\nu \frac{dN}{dE_\nu} P_{ee}(L, E_\nu)\, \sigma_{IBD}(E_\nu)$$

arXiv: 1210.8141

$\overline{\nu}_e$ Energy distribution @ far detector

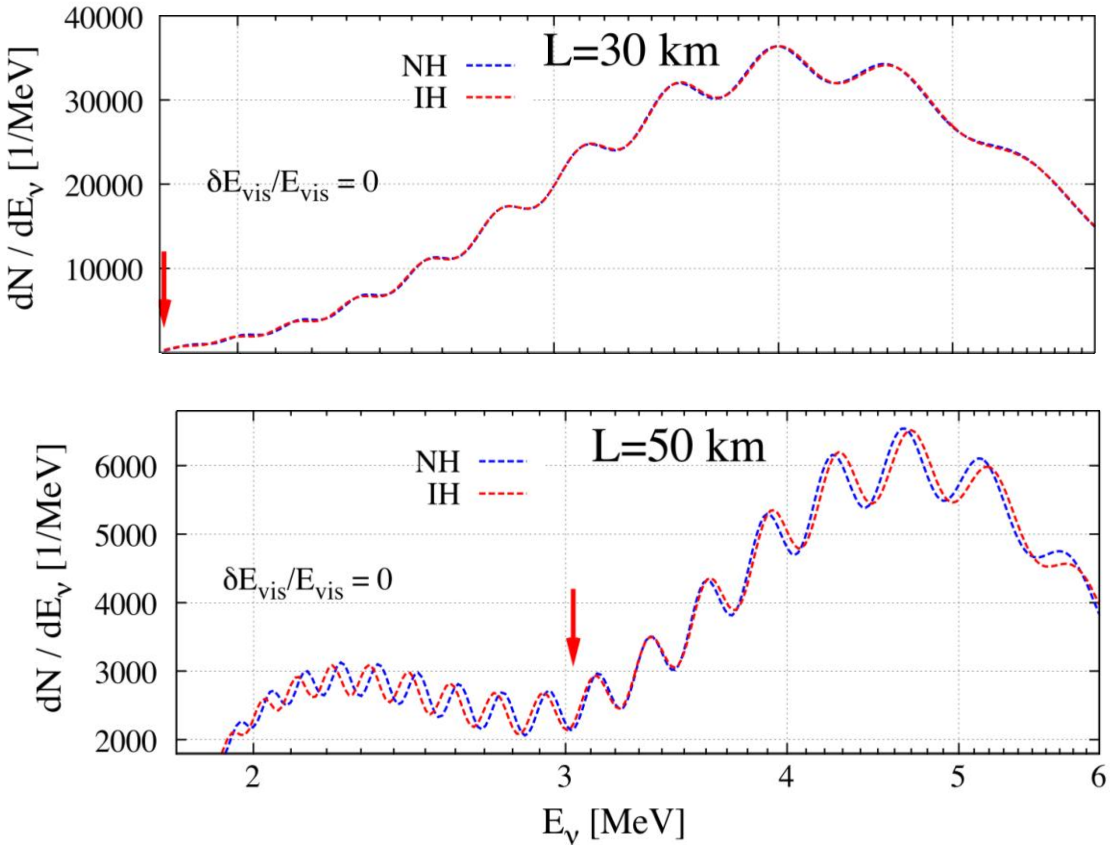


We want to observe the NH-IH difference
in the energy distribution
at a far detector

Let's observe it!

… but
There are obstacles…

Obstacle1: $\delta|\Delta m^2_{31}|$



@ < 30 km, the NH-IH difference is totally absorbed by a small shift of

$\delta|\Delta m^2_{31}|$

within its uncertainty.

@ L > 30 km, the NH-IH difference cannot be totally absorbed.

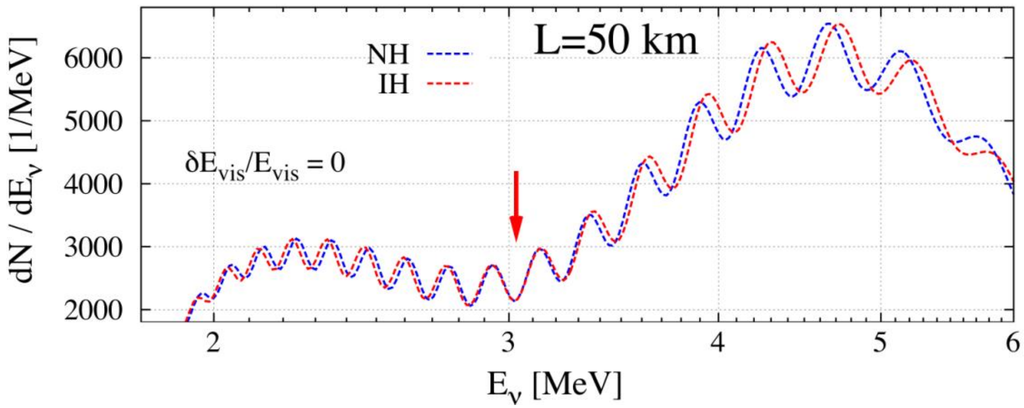
We need a far detector at L > 30 km

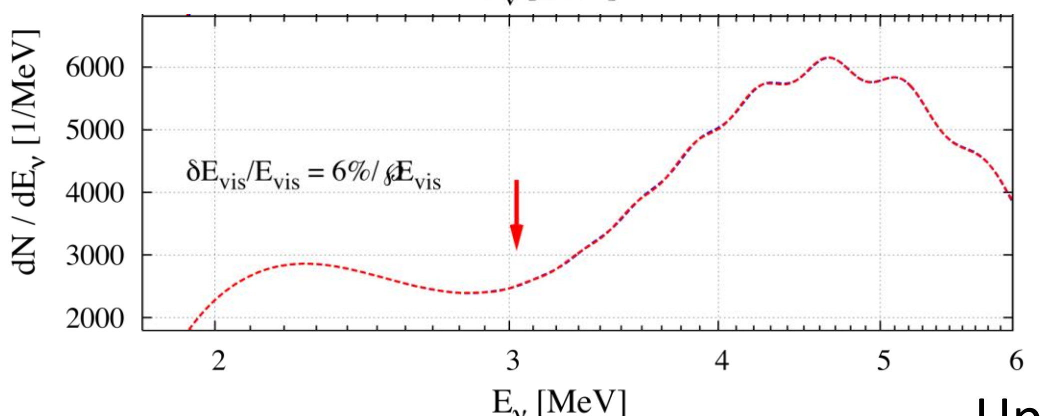
There is the optimal baseline length to determine mass hierarchy.

Obstacle2: finite Energy Resolution

$$\frac{\delta E}{E} = \sqrt{\left(\frac{a}{\sqrt{E/\mathrm{MeV}}}\right)^2 + b^2}$$

a: statistical error part
b: systematic error part





After smearing with the detector Energy resolution, the NH-IH difference Can be absorbed again.

Upper limit on the Energy Resolution

We estimate

– Optimal baseline length
– Energy resolution required
– Expected uncertainties of neutrino parameters

Assuming an experiment with
20 GW 5kton (12% free proton) 5 years
exposure.

Analysis method

We calculate the neutrino energy distribution for NH or IH,

$$\frac{dN^{NH(IH)}}{dE^{obs}} = \frac{N_p T}{4\pi L^2} \int dE_\nu \frac{dN}{dE_\nu} P_{ee}(L, E_\nu) \sigma_{IBD}(E_\nu) G(E^{true} - E^{obs}, \delta E)$$

Energy Resolution smearing (Gaussian)

* $\frac{dN^{NH(IH)}}{dE^{obs}}$ corresponds to the averaged observed distribution. We don't consider the fluctuation of data from experiment to experiment in this talk.

We introduce bining and prepare "data", the number of events in each bin.

$$N_i^{NH(IH)} = \int_{E_i^{obs}}^{E_{i+1}^{obs}} dE^{obs} \frac{dN^{NH(IH)}}{dE^{obs}} \qquad (i = 1, \cdots, \mathrm{nbins})$$

We then perform the standard χ^2 analysis to this "data" (next slide).

Analysis method cont.

$$\chi^2 = \chi^2_{para} + \chi^2_{sys} + \chi^2_{stat}$$

Y	$\sin^2 2\theta_{12}$	$\sin^2 2\theta_{13}$	Δm^2_{21} eV^2	$\lvert\Delta m^2_{31}\rvert$ eV^2	f_{sys}
Y^{input}	0.857	0.089	7.50×10^{-5}	2.32×10^{-3}	1
δY	0.024	0.005	0.20×10^{-5}	0.1×10^{-3}	0.03

$$\chi^2_{para} = \left\{\frac{(\sin^2 2\theta_{12})^{fit} - (\sin^2 2\theta_{12})^{input}}{\delta \sin^2 2\theta_{12}}\right\}^2 + \left\{\frac{(\sin^2 2\theta_{13})^{fit} - (\sin^2 2\theta_{13})^{input}}{\delta \sin^2 2\theta_{13}}\right\}^2 + \left\{\frac{(\Delta m^2_{21})^{fit} - (\Delta m^2_{21})^{input}}{\delta \Delta m^2_{21}}\right\}^2 + \left\{\frac{(|\Delta m^2_{31}|)^{fit} - (|\Delta m^2_{31}|)^{input}}{\delta |\Delta m^2_{31}|}\right\}^2 .$$

$$\chi^2_{sys} = \left(\frac{f^{fit}_{sys} - f^{input}_{sys}}{\delta f_{sys}}\right)^2$$

$$\chi^2_{stat} = \sum_i \left(\frac{N_i^{fit} - N_i^{NH(IH)}}{\sqrt{N_i^{NH(IH)}}}\right)^2$$

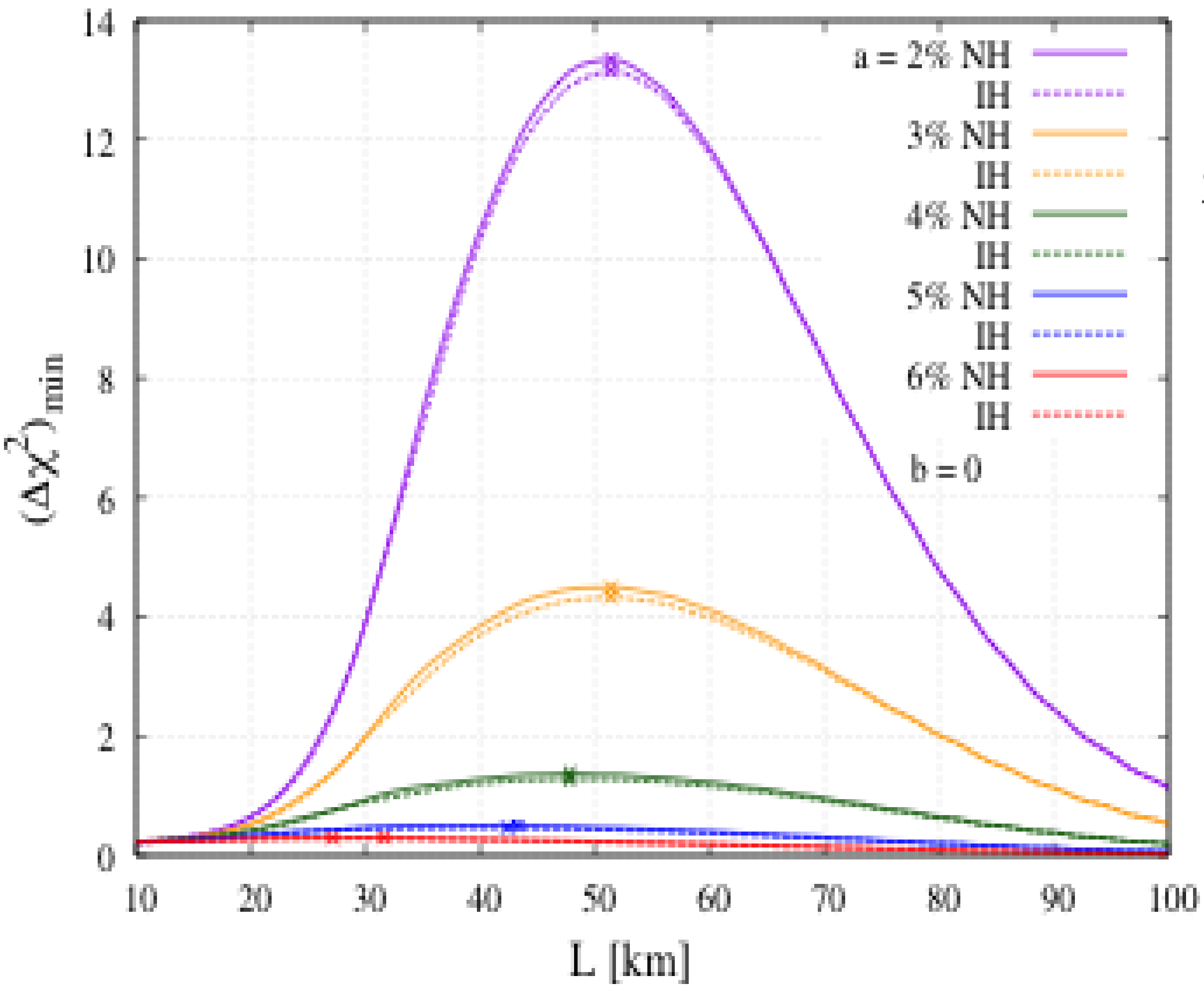
$$\Delta\chi^2 = \chi^2 - \chi^2_{min}$$

The sensitivity to determine MH: $\sqrt{(\Delta\chi^2)_{min}}$

* We consider zero bin-size limit.
The sensitivity should be considered as the maximum sensitivity.

Results

Sensitivity for mass hierarchy



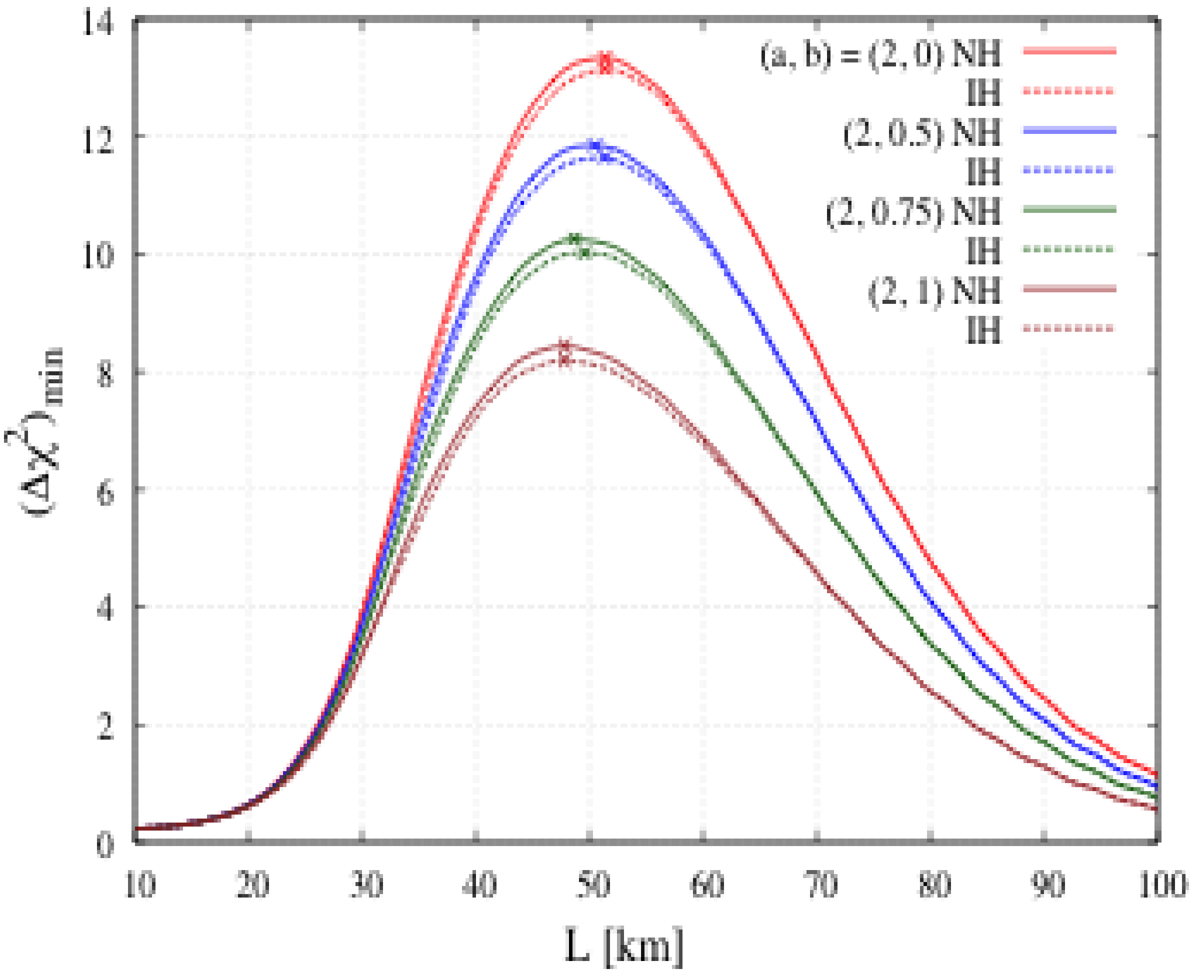
20 GW 5kton 5 years

$$\frac{\delta E}{E} = \sqrt{\left(\frac{a}{\sqrt{E/\text{MeV}}}\right)^2 + b^2}$$

a < 3% for $(\Delta\chi^2)_{min} > 9$

Optimal L ~ 50 km

Systematic Error of Resolution



20GW 5kton 5 years

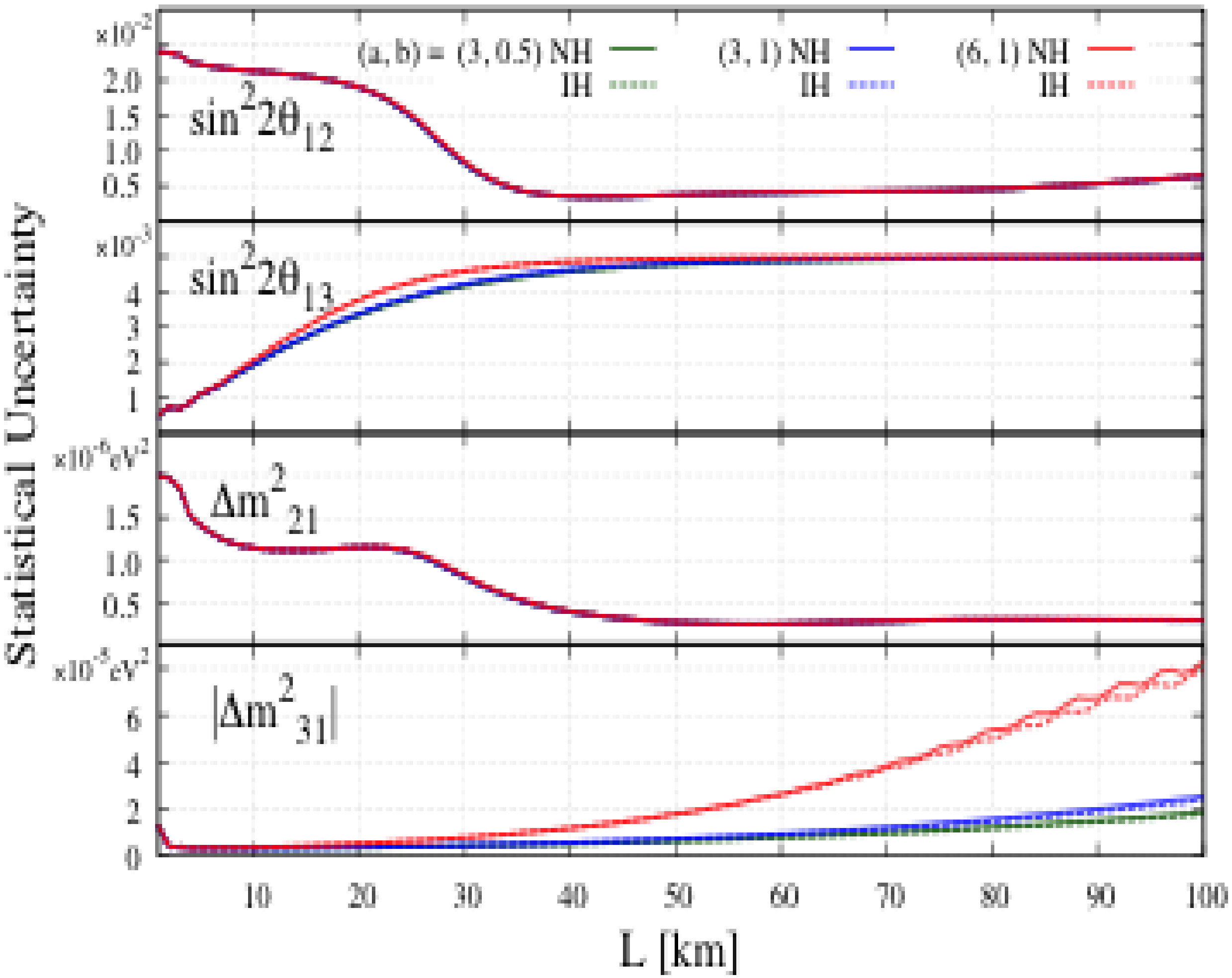
$$\frac{\delta E}{E} = \sqrt{\left(\frac{a}{\sqrt{E/\mathrm{MeV}}}\right)^2 + b^2}$$

b < 1% for $(\Delta\chi^2)_{min} > 9$

Larger b

→ Shorter optimal L

Uncertainties of Parameters



Parameter measurements are not very sensitive to the Energy resolution

~ 0.5% level of uncertainties can be achieved for

$\sin^2 2\theta_{12}$

Δm^2_{21}

$|\Delta m^2_{31}|$

Summary

- We study the sensitivity of a future medium baseline reactor neutrino experiment for MH determination.
- For 20 GW 5kton 5 years exposure,
  - optimal baseline length ~ 50 km
  - < 3% statistical & < 1% systematic errors of Energy Resolution is required
  - 0.5% level of accuracy for Neutrino Parameters

* This study gives the minimum requirement for the energy resolution.

* More realistic study is very sensitive to the environment, such as distribution of reactors within ~100 km from the far detector (J.Evslin et.al, arXiv:1209.2227).

Thank you