

Physics of Neutrino Oscillation Experiments in the near future

September 23, 2012

International Symposium on Neutrino Physics and Beyond
in Shenzhen, China

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On March 8 this year, we heard a great news of discovery of

$$\sin^2 2\theta_{13} \sim 0.1$$

from DayaBay, which was confirmed in less than a month by RENO.

The discovery advanced our knowledge on lepton flavor physics significantly, and we now have a realistic hope that the lepton flavor sector will soon be measured as accurately as the quark flavor sector with quark masses and the CKM mixing matrix.

Let me stay in this talk within the 3 neutrino model, as the most conservative framework in which effects from sterile neutrinos and additional interactions can be recognized as anomalies.

Three neutrino model has 9 parameters:

- 3 masses m_1, m_2, m_3
- 3 angles $\theta_{23}, \theta_{12}, \theta_{13}$
- 3 phases $\delta_{\text{MNS}}, \alpha_1, \alpha_2$

Neutrino oscillation experiments can measure 6 out of the 9 parameters:

- 2 mass-squared differences $m_2^2 - m_1^2, m_3^2 - m_1^2$
- 3 angles $\theta_{23}, \theta_{12}, \theta_{13}$
- 1 phase δ_{MNS}

Both mass-squared differences and **ALL** 3 angles have been measured.

The tasks of the future neutrino oscillation experiments are to determine:

- the mass hierarchy $m_3^2 - m_1^2 > 0$ or $m_3^2 - m_1^2 < 0$
- the CP phase δ_{MNS}
- the octant degeneracy $\sin^2 \theta_{23} > 0.5$ or $\sin^2 \theta_{23} < 0.5$

besides **sharpening** of the existing measurements and search for **new physics**.

Late in April, Yifang Wang told me about this symposium in Shenzhen near DayaBay. Shortly after I accepted his invitation, I proposed my colleagues to study the following three subjects, which are all boosted by the discovery of relatively large θ_{13} :

- Reactor anti-neutrino oscillation experiments at medium baseline length, $10 \text{ km} < L < 100 \text{ km}$ at $1 \text{ MeV} < E < 8 \text{ MeV}$.
- Accelerator neutrino oscillation experiments at two long baselines, T2K ($L = 295 \text{ km}$) + Tokai-to-Oki ($L = 653 \text{ km}$) at $0.5 \text{ GeV} < E < 2 \text{ GeV}$.
- Atmospheric neutrino oscillation experiments with a huge detector such as PINGU in IceCube, $2000 \text{ km} < L < 13000 \text{ km}$ at $2 \text{ GeV} < E < 20 \text{ GeV}$.

This talk is based on the following recent studies with my collaborators:

- Determination of mass hierarchy with intermediate baseline reactor anti-neutrino experiments
by Shao-Feng Ge, KH, Naotoshi Okamura, Yoshitaro Takaesu
[arXiv:1210.xxxx\[hep-ph\]](https://arxiv.org/abs/1210.xxxx)
- Physics potential of neutrino oscillation experiment with a far detector in Oki Island along the T2K baseline
by KH, Takayuki Kiwanami, Naotoshi Okamura, Ken-ichi Senda
[arXiv:1209.2763\[hep-ph\]](https://arxiv.org/abs/1209.2763)

PHYSICAL REVIEW D **78**, 111103(R) (2008)

Determination of the neutrino mass hierarchy at an intermediate baseline

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(Received 21 July 2008; revised manuscript received 24 October 2008; published 10 December 2008)

It is generally believed that neutrino mass hierarchy can be determined at a long baseline experiment, often using accelerator neutrino beams. Reactor neutrino experiments at an intermediate baseline have the capability to distinguish normal or inverted hierarchy. Recently, it has been demonstrated that the mass hierarchy could possibly be identified using Fourier transform to the L/E spectrum if the mixing angle $\sin^2(2\theta_{13}) > 0.02$. In this study, a more sensitive Fourier analysis is introduced. We found that an ideal detector at an intermediate baseline (~ 60 km) could identify the mass hierarchy for a mixing angle $\sin^2(2\theta_{13}) > 0.005$, without requirements on accurate information of reactor neutrino spectra and the value of Δm_{32}^2 .

DOI: 10.1103/PhysRevD.78.111103

PACS numbers: 13.15.+g, 14.60.Lm, 14.60.Pq

LIANG ZHAN, YIFANG WANG, JUN CAO, AND LIANGJIAN WEN

PHYSICAL REVIEW D 78, 111103(R) (2008)

$$\begin{aligned}\phi(E) = & 0.58 \exp(0.870 - 0.160E - 0.091E^2) \\ & + 0.30 \exp(0.896 - 0.239E - 0.0981E^2) \\ & + 0.07 \exp(0.976 - 0.162E - 0.0790E^2) \\ & + 0.05 \exp(0.793 - 0.080E - 0.1085E^2),\end{aligned}\quad (2)$$

where four exponential terms are contributions from isotopes ^{235}U , ^{239}Pu , ^{238}U , and ^{241}Pu in the reactor fuel, respectively.

The leading-order expression for the cross section [17] of inverse- β decay ($\bar{\nu}_e + p \rightarrow e^+ + n$) is

$$\sigma^{(0)} = 0.0952 \times 10^{-42} \text{ cm}^2 (E_e^{(0)} p_e^{(0)} / 1 \text{ MeV}^2), \quad (3)$$

where $E_e^{(0)} = E_\nu - (M_n - M_p)$ is the positron energy when neutron recoil energy is neglected, and $p_e^{(0)}$ is the positron momentum. The survival probability of $\bar{\nu}_e$ can be expressed as [18]

$$\begin{aligned}P_{ee}(L/E) = & 1 - P_{21} - P_{31} - P_{32} \\ P_{21} = & \cos^4(\theta_{13}) \sin^2(2\theta_{12}) \sin^2(\Delta_{21}) \\ P_{31} = & \cos^2(\theta_{12}) \sin^2(2\theta_{13}) \sin^2(\Delta_{31}) \\ P_{32} = & \sin^2(\theta_{12}) \sin^2(2\theta_{13}) \sin^2(\Delta_{32}),\end{aligned}\quad (4)$$

where $\Delta_{ij} = 1.27 \Delta m_{ij}^2 L/E$, Δm_{ij}^2 is the neutrino mass-squared difference ($m_i^2 - m_j^2$) in eV 2 , θ_{ij} is the neutrino mixing angle, L is the baseline from reactor to $\bar{\nu}_e$ detector in meters, and E is the $\bar{\nu}_e$ energy in MeV.

$P_{ee}(L/E)$ has three oscillation components P_{21} , P_{31} , P_{32} .

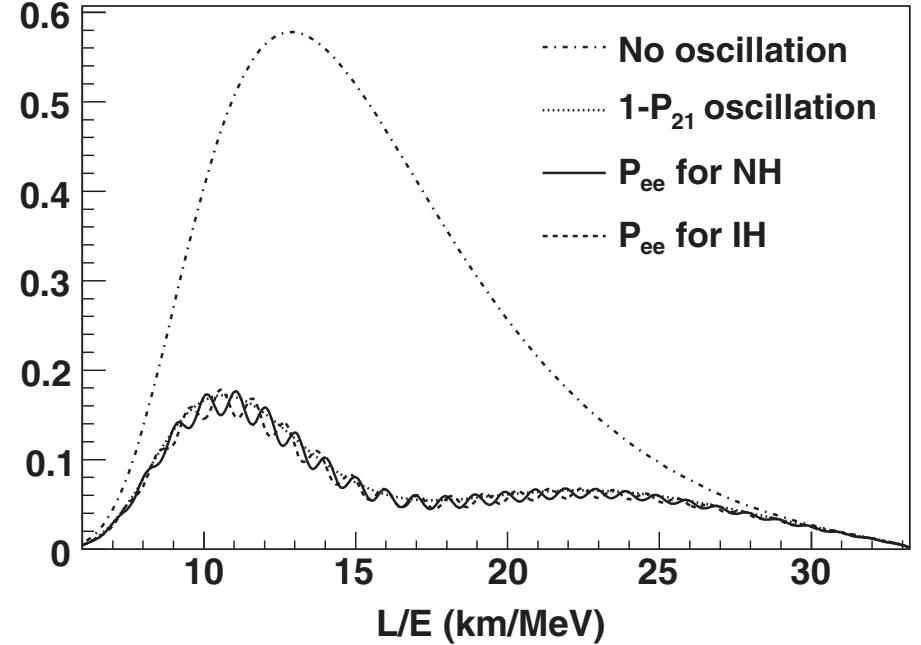
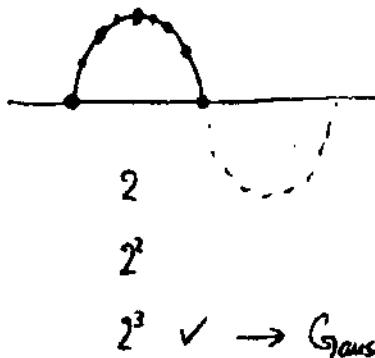


FIG. 1. Reactor neutrino spectra at a baseline of 60 km in L/E space for no oscillation (dashed-dotted line), $1 - P_{21}$ oscillation (dotted line) and P_{ee} oscillation in the cases of NH and IH, assuming $\sin^2(2\theta_{13}) = 0.1$.

on the neutrino energy spectra and much smaller binning than the energy resolution, is difficult for the mass hierarchy study.

Since neutrino masses all appear in the frequency domain as shown in Eq. (4), a Fourier transform of $F(L/E)$ shall enhance the sensitivity to the mass hierarchy. The frequency spectrum can be obtained by the following Fourier sine transform (FST) and Fourier cosine transform (FCT):

On the mass hierarchy determination with reactor neutrino oscillation
2012.08.23



RENO1

6%
2%
1%

$$P_{ee} = 1 - 0.84 \sin^2 \left(\frac{\delta m_{12}^2}{4E} L \right) - 0.10 \sin^2 \left(\frac{\delta m_{31}^2}{4E} L \right)$$

$$+ 0.03 \cos \left(\frac{\delta m_{12}^2}{2E} L \right) \sin^2 \left(\frac{\delta m_{31}^2}{4E} L \right)$$

$$= 0.015 \min \left(\frac{\delta m_{12}^2}{2E} L, \min \left(\frac{|\delta m_{31}^2|}{2E} L \right) \right)$$

$0, \frac{\pi}{2}, \pi$

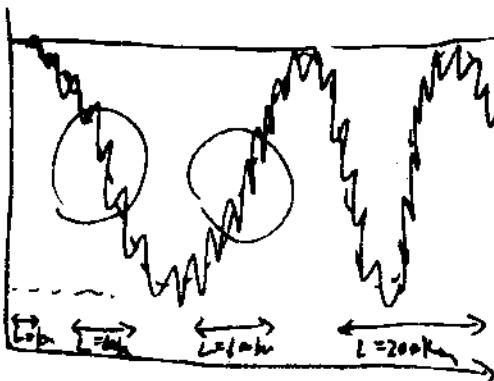
$\frac{1}{15} \approx 7\%$

$\frac{39}{2} \pi \pm \pi$

$$\left(\delta m_{31}^2 = 0 \pm 0 \right)$$

$\times 30$

$P_{\bar{\nu}_e \rightarrow \bar{\nu}_e}$



$\log(L/E)$

$E = 2MeV - 7MeV$

$F_{ij,1}$

$F_{ij,2}$

$F_{ij,3}$

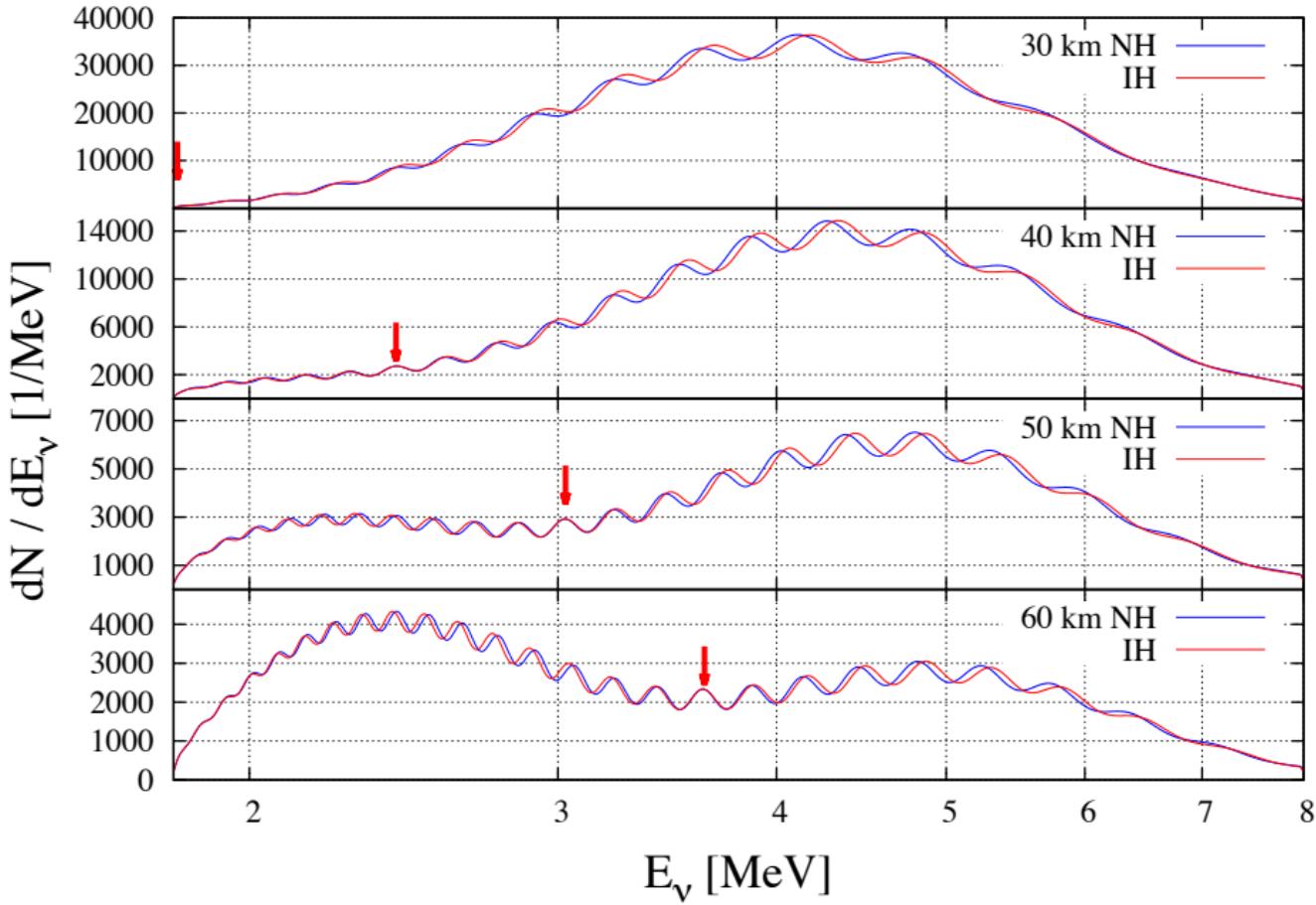
$\Delta N / \text{bin}$

of events/bin
 $dL = 0km, V = 5km^3,$
 $P_{ee} = 0.64, 1 \text{ year},$

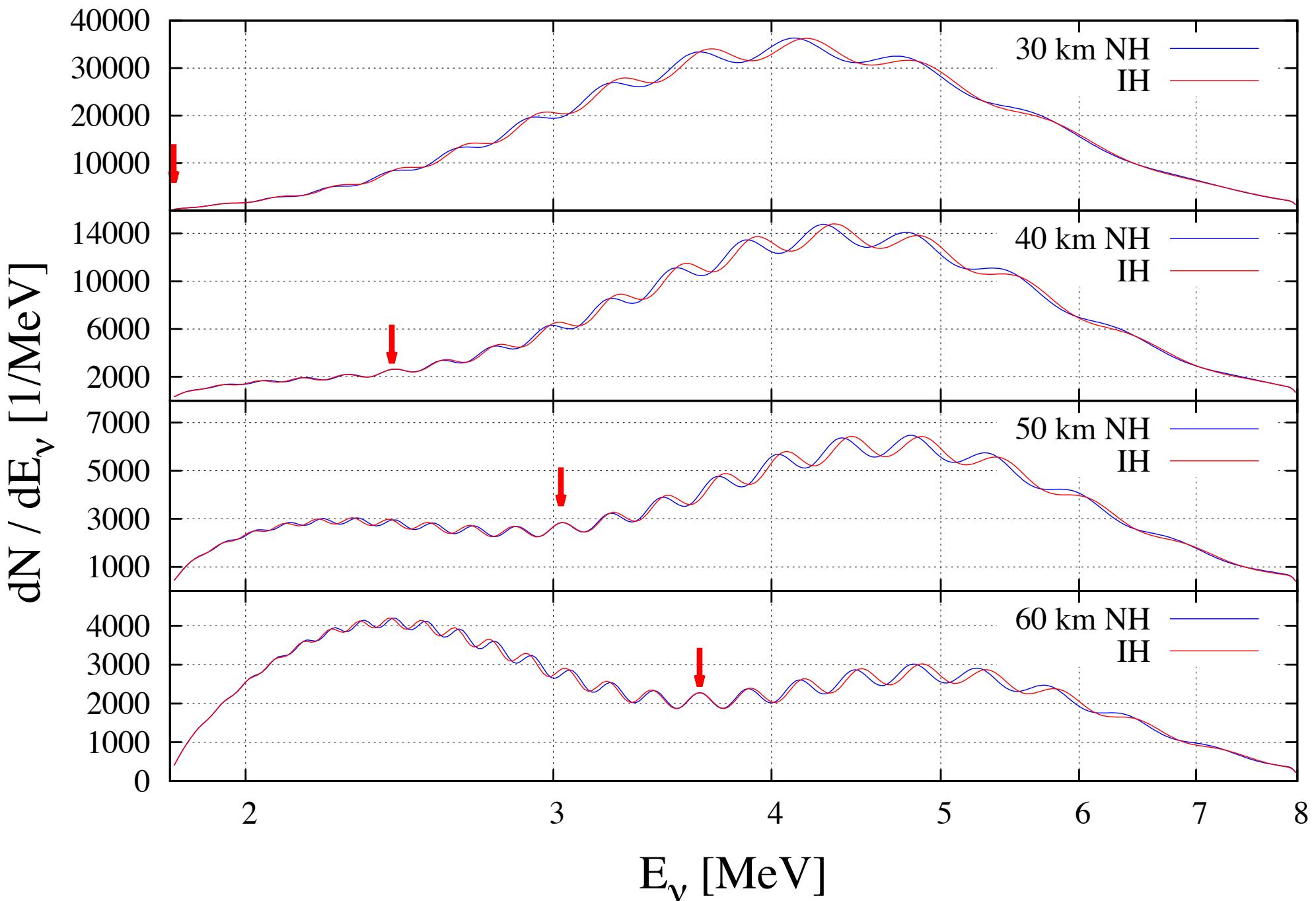
$L = 0km$

E_ν

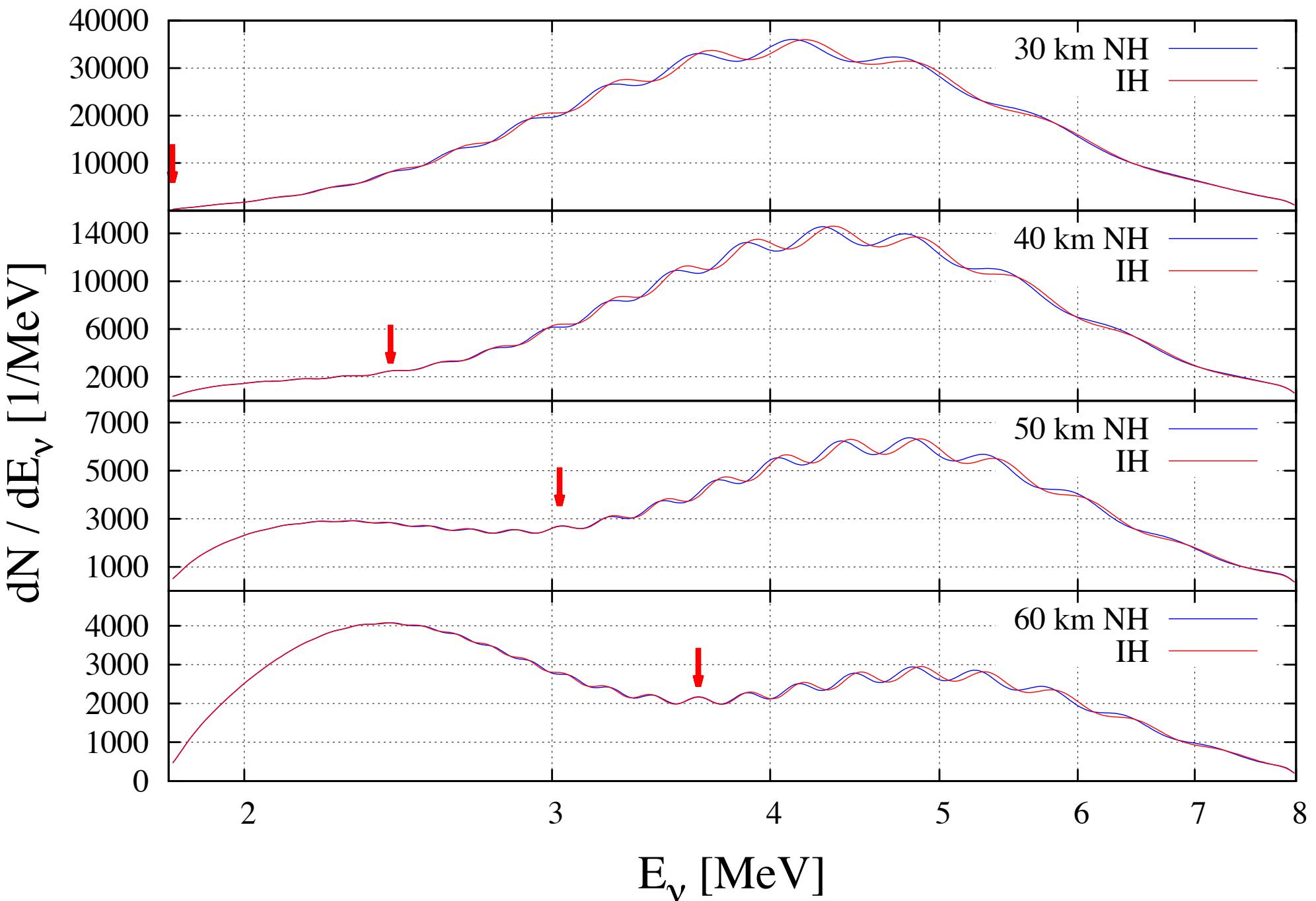
$20\text{GW}_{\text{th}}, 5\text{ton}, 5\text{ years}, \delta E_{\text{vis}}/E_{\text{vis}} = 0\%/\sqrt{E_{\text{vis}}}$



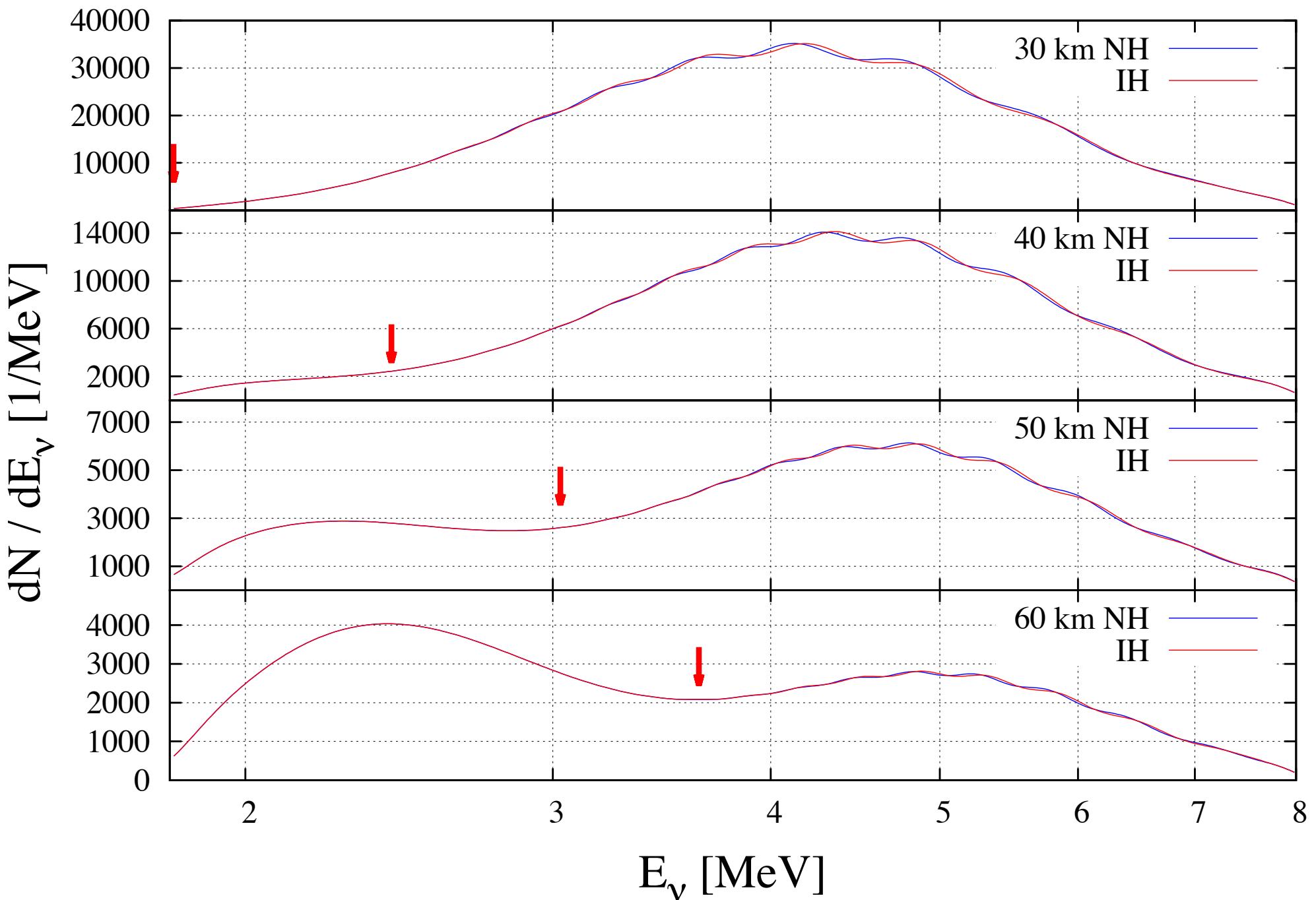
$20\text{GW}_{\text{th}}, 5\text{kton}, 5 \text{ years}, \delta E_{\text{vis}}/E_{\text{vis}} = 1.5\%/\sqrt{E_{\text{vis}}}$

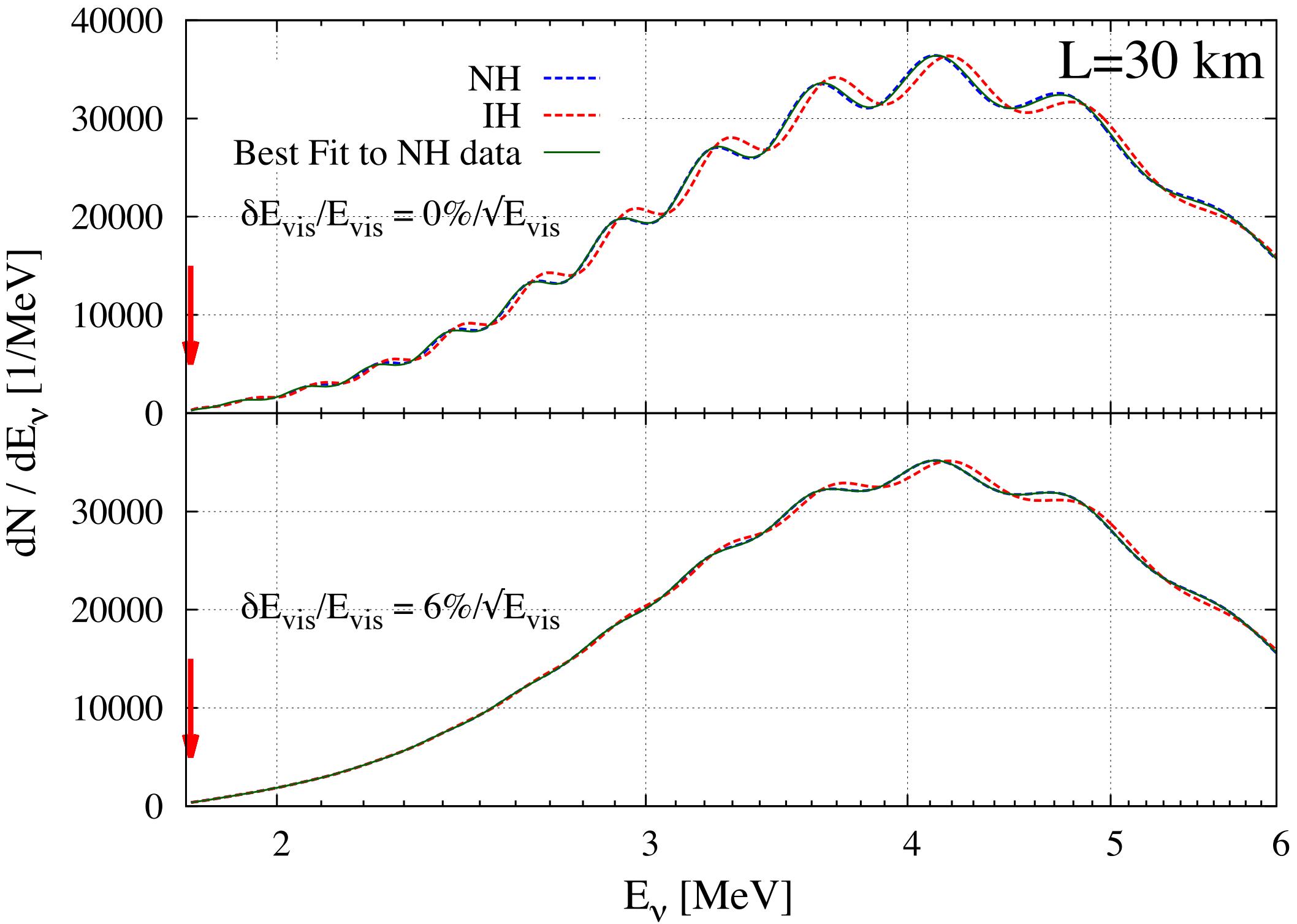


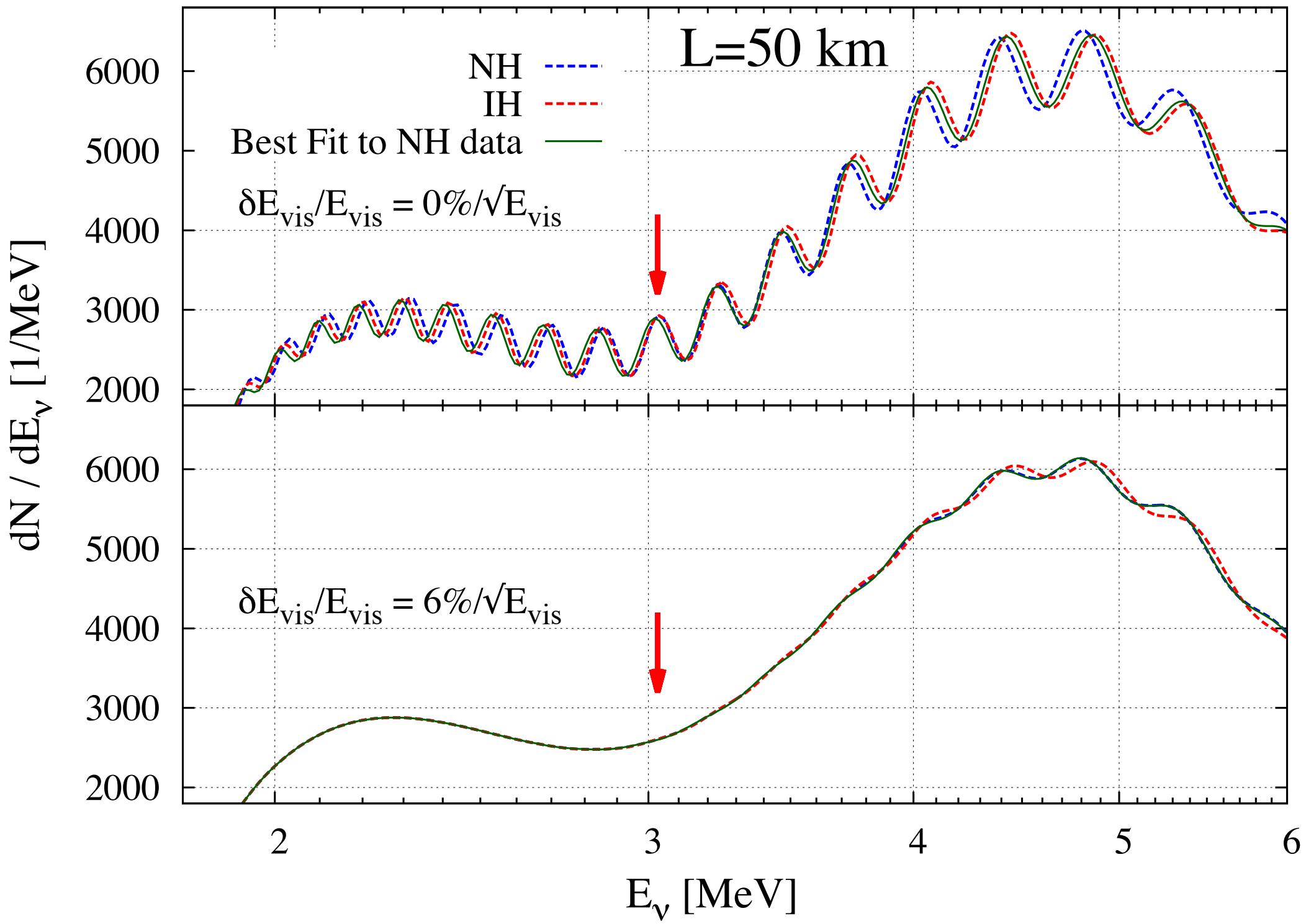
$20\text{GW}_{\text{th}}, 5\text{kton}, 5 \text{ years}, \delta E_{\text{vis}}/E_{\text{vis}} = 3\%/\sqrt{E_{\text{vis}}}$

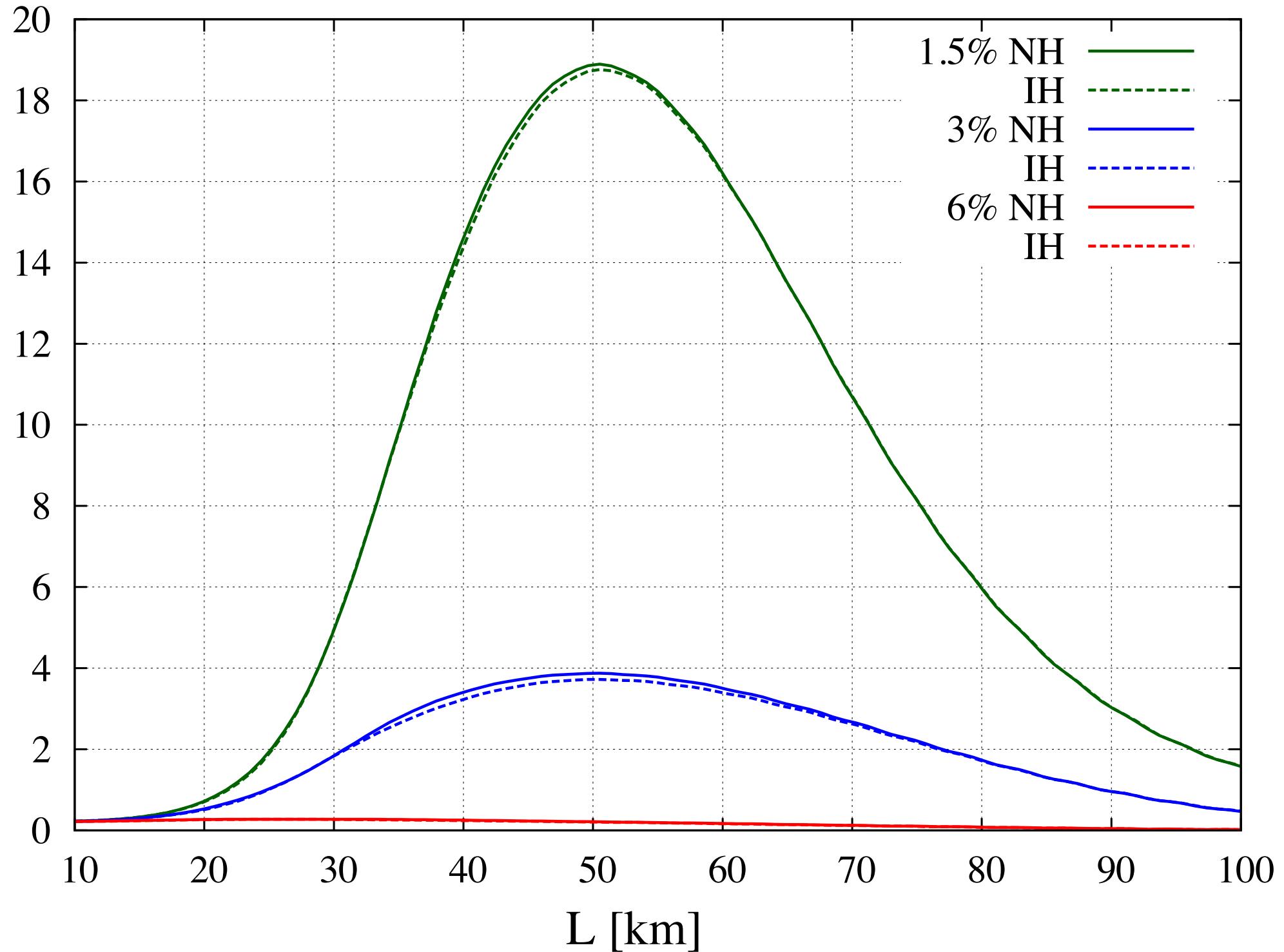


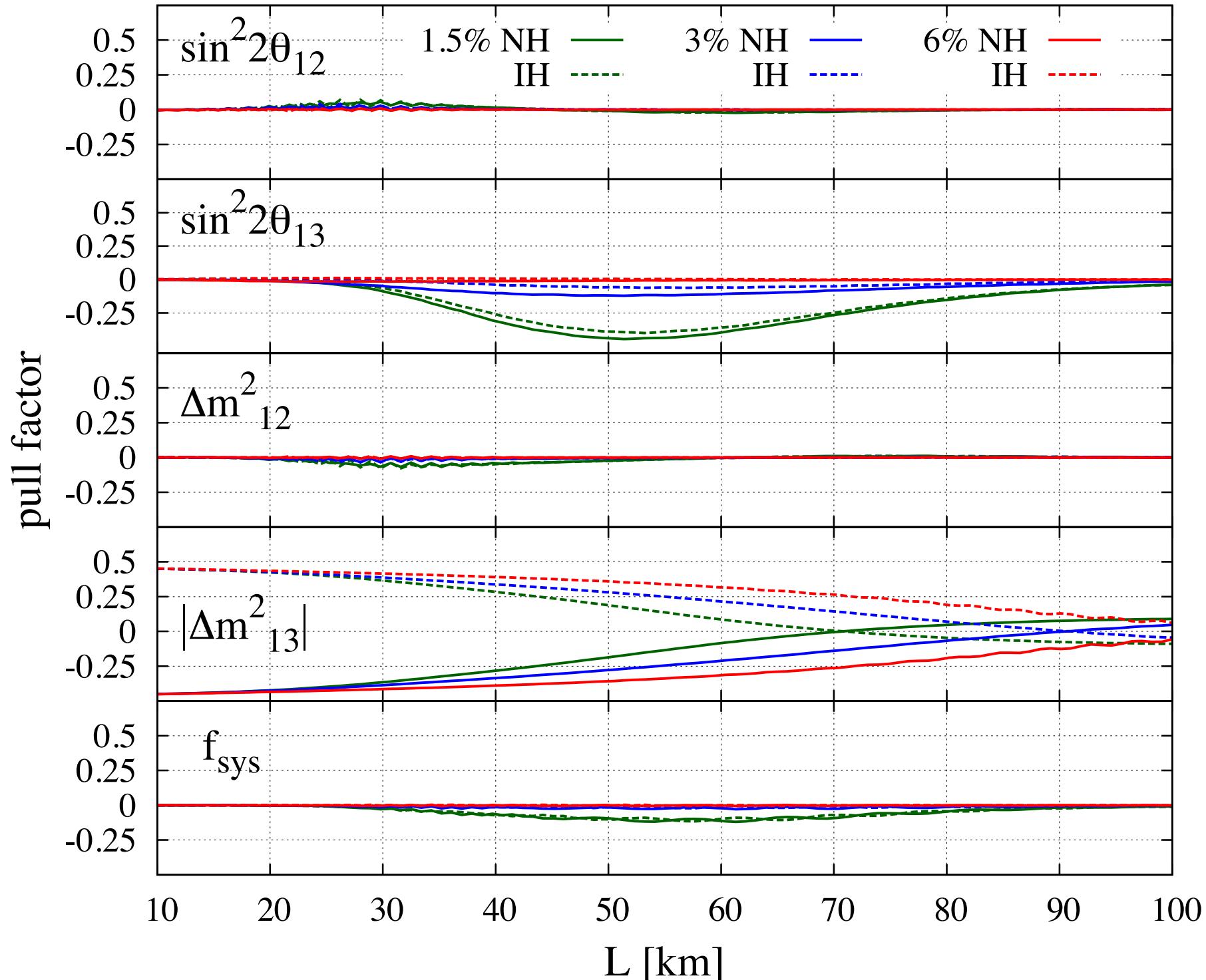
$20\text{GW}_{\text{th}}, 5\text{kton}, 5 \text{ years}, \delta E_{\text{vis}}/E_{\text{vis}} = 6\%/\sqrt{E_{\text{vis}}}$



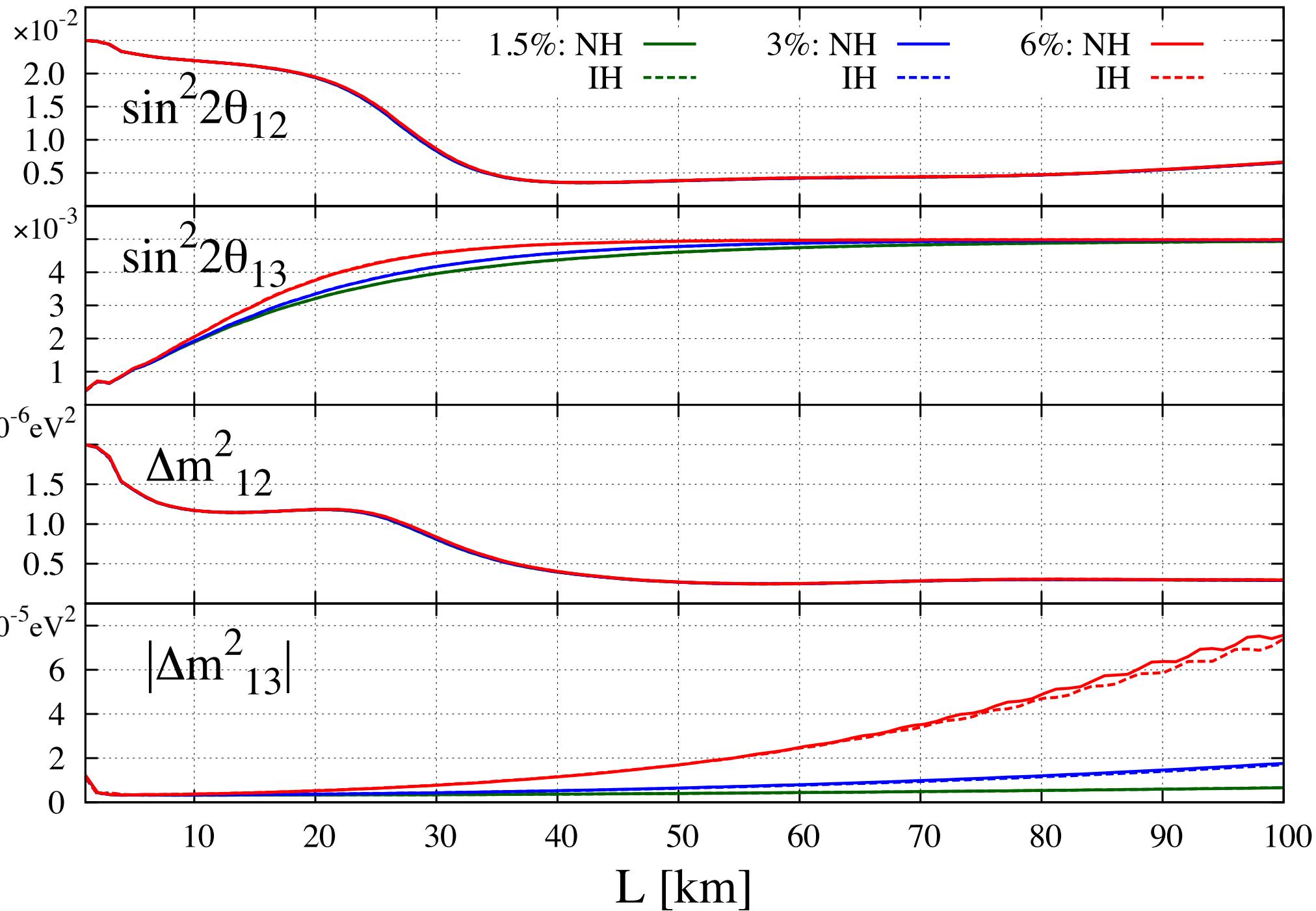




$\Delta\chi^2$ 



Statistical Error



Physics potential of neutrino oscillation experiment
with a far detector in Oki Island
along the T2K baseline

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Abstract

Some of these experiments observe the survival probability of ν_μ and $\bar{\nu}_\mu$ which are generated in the atmosphere by the cosmic ray [2]. Accelerator based long baseline experiments [3, 4, 5] also measure the ν_μ survival probability. From the combined results of these experiments [2]-[5], the mass-squared difference and the mixing angle are obtained as

$$\sin^2 2\theta_{\text{ATM}} > 0.90 \quad (90\% \text{C.L.}), \quad (1a)$$

$$|\delta m_{\text{ATM}}^2| = (2.35^{+0.11}_{-0.08}) \times 10^{-3} \text{eV}^2. \quad (1b)$$

The sign of the mass-squared difference, eq. (1b), cannot be determined from these experiments. The SK collaboration also reported that the atmospheric neutrino oscillates into the active neutrinos [6].

The combined results of the solar neutrino observations [7, 8], which measure the survival probability of ν_e from the sun, and the KamLAND experiment [9], which measure the $\bar{\nu}_e$ flux from the reactors at distances of a few 100 km, find

$$\sin^2 2\theta_{\text{SOL}} = 0.852^{+0.024}_{-0.026}, \quad (2a)$$

$$\delta m_{\text{SOL}}^2 = (7.50^{+0.19}_{-0.20}) \times 10^{-5} \text{eV}^2, \quad (2b)$$

where the sign of mass-squared difference has been determined by the matter effect inside the sun [13]. The SNO experiment determined that ν_e from the sun changes into the active neutrinos [8].

Recently another new reactor experiment, the DayaBay experiment [17], announced that they have measured the neutrino mixing angle as

$$\sin^2 2\theta_{\text{RCT}} = 0.092 \pm 0.016 \text{ (stat.)} \pm 0.005 \text{ (syst.)}, \quad (7)$$

which is more than 5σ away from zero. The RENO collaboration, which also measure the reactor $\bar{\nu}_e$ survival probability, shows the evidence of the non-zero mixing angle;

$$\sin^2 2\theta_{\text{RCT}} = 0.113 \pm 0.013 \text{ (stat.)} \pm 0.019 \text{ (syst.)}, \quad (8)$$

from a rate-only analysis, which is 4.9σ away from zero.

Since the MiniBooNE experiment [12] did not confirm the LSND observation of rapid $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillation [18], there is no clear indication of experimental data which suggests more than three neutrinos. Therefore the $\nu_\mu \rightarrow \nu_e$ appearance analysis of T2K [14] and MINOS[15] presented above assume the 3 neutrino model, with the 3×3 flavor mixing, the MNS (Maki-Nakagawa-Sakata) matrix [19]

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}, \quad (9)$$

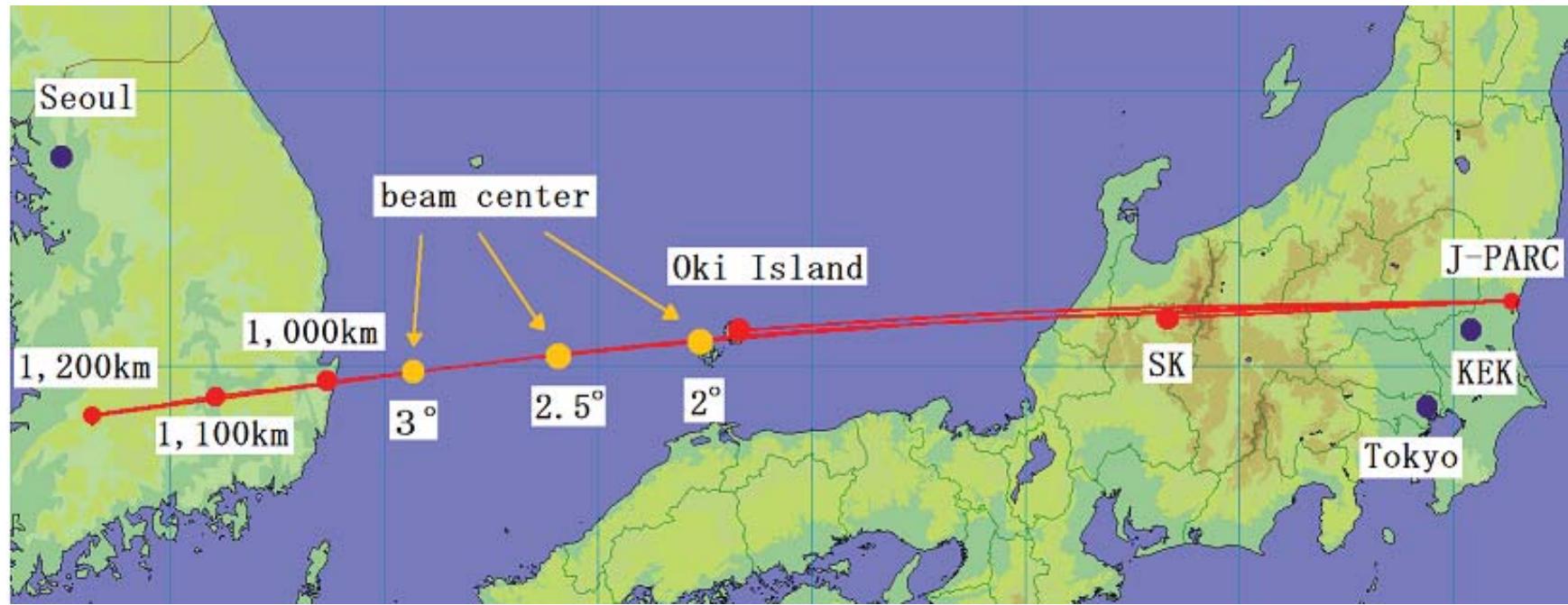


Figure 1: The surface map of the T2K, T2KO, and T2KK experiment. The yellow blobs show the center of the neutrino beam for the T2K experiment at the sea level, where the number in the white box is the off-axis angle at SK.

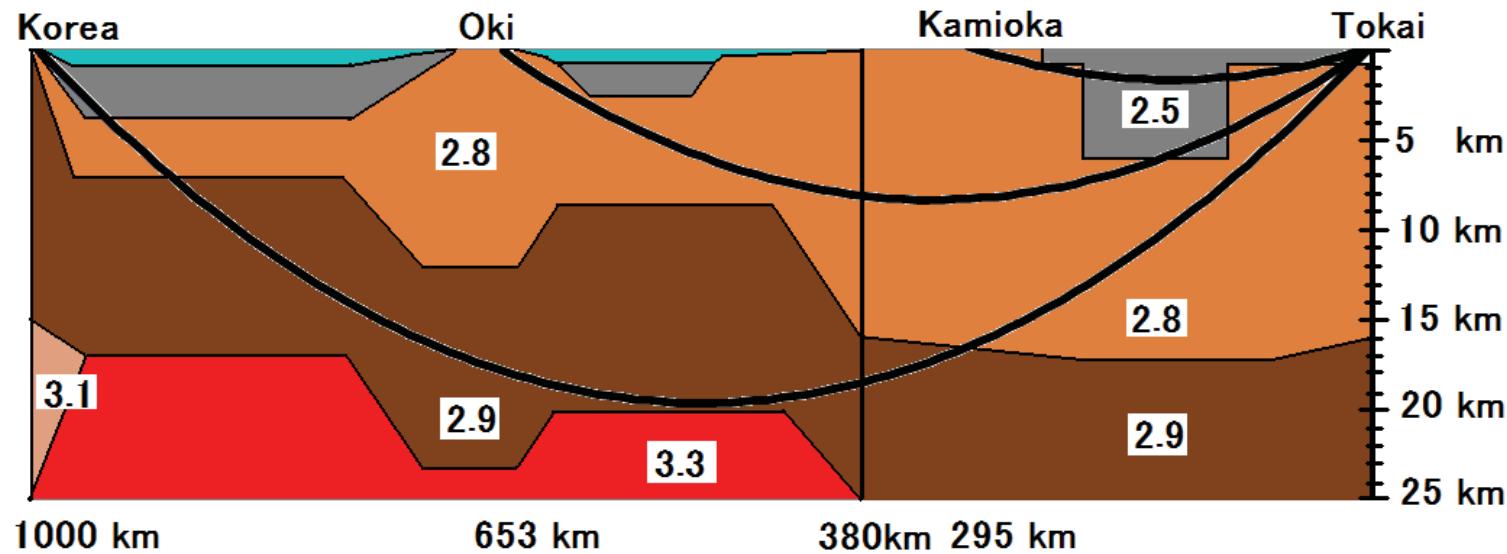


Figure 2: The cross section view of the T2K, T2KO, and T2KK experiments along the baselines, which are shown by the three curves. The horizontal scale gives the distance from J-PARC along the arc of the earth surface and the vertical scale measures the depth of the baseline below the sea level. The numbers in the white boxes are the average matter density in units of g/cm^3 [35]-[42].

Under the same conditions that give eq. (17) for the ν_μ survival probability, the ν_e appearance probability can be approximated as [30]

$$P_{\nu_\mu \rightarrow \nu_e} = 4 \sin^2 \theta_{\text{ATM}} \sin^2 \theta_{\text{RCT}} \left\{ (1 + A^e) \sin^2 \left(\frac{\Delta_{13}}{2} \right) + \frac{B^e}{2} \sin \Delta_{13} \right\} + C^e, \quad (22)$$

where we retain both linear and quadratic terms of Δ_{12} and a_0 . The analytic expressions for the correction terms A^e , B^e and C^e are found in Ref.[30]. For our semi-quantitative discussion below, the following numerical estimates [30] for $\sin^2 2\theta_{\text{ATM}} = 1$ and $\sin^2 2\theta_{\text{SOL}} = 0.852$ suffice:

$$\begin{aligned} A^e &\simeq 0.37 \frac{\bar{\rho}}{3\text{g/cm}^3} \frac{L}{1000\text{km}} \frac{\pi}{\Delta_{13}} \left(1 - \frac{\sin^2 2\theta_{\text{RCT}}}{2} \right) \\ &\quad - 0.29 \left| \frac{\Delta_{13}}{\pi} \right| \sqrt{\frac{0.1}{\sin^2 2\theta_{\text{RCT}}}} \left[1 + 0.18 \frac{\bar{\rho}}{3\text{g/cm}^3} \frac{L}{1000\text{km}} \frac{\pi}{\Delta_{13}} \right] \sin \delta_{\text{MNS}}, \end{aligned} \quad (23a)$$

$$\begin{aligned} B^e &\simeq -0.58 \frac{\bar{\rho}}{3\text{g/cm}^3} \frac{L}{1000\text{km}} \left(1 - \frac{\sin^2 2\theta_{\text{RCT}}}{2} \right) \\ &\quad + 0.30 \left| \frac{\Delta_{13}}{\pi} \right| \left[\sqrt{\frac{0.1}{\sin^2 2\theta_{\text{RCT}}}} \cos \delta_{\text{MNS}} - 0.11 \right] \left[1 + 0.18 \frac{\bar{\rho}}{3\text{g/cm}^3} \frac{L}{1000\text{km}} \frac{\pi}{\Delta_{13}} \right]. \end{aligned} \quad (23b)$$

The first term in A^e in eq. (23a) is sensitive not only to the matter effect but also to the mass hierarchy pattern, since $\Delta_{13} \sim \pi$ ($-\pi$) for the normal (inverted) hierarchy around the oscillation maximum $|\Delta_{13}| \sim \pi$. For the normal (inverted) hierarchy, the magnitude of the $\nu_\mu \rightarrow \nu_e$ transition probability is enhanced (suppressed) by about 10% at Kamioka, 24% at Oki Island, and 37% at $L \sim 1000$ km in Korea, around the first oscillation maximum, $|\Delta_{13}| \sim \pi$. When L/E_ν is fixed at $|\Delta_{13}| \sim \pi$, the difference between the two hierarchy cases grows with L , because the matter effect grows with E_ν . Within the allowed range of the model parameters, the difference of the A^e between SK and a far detector at Oki or Korea becomes

$$A_{\text{peak}}^e(L = 653\text{km}) - A_{\text{peak}}^e(L = 295\text{km}) \simeq \pm 0.13, \quad (24a)$$

$$A_{\text{peak}}^e(L \sim 1000\text{km}) - A_{\text{peak}}^e(L = 295\text{km}) \simeq \pm 0.26, \quad (24b)$$

where the upper sign corresponds to the normal, and the lower sign for the inverted hierarchy. The hierarchy pattern can hence be determined by comparing $P_{\nu_\mu \rightarrow \nu_e}$ near the oscillation maximum $|\Delta_{13}| \simeq \pi$ at two vastly different baseline lengths [26]-[30], **independently** of the sign and magnitude of $\sin \delta_{\text{MNS}}$.

In eq. (23b), it is also found that the first term in B^e , which shifts the oscillation phase from $|\Delta_{13}|$ to $|\Delta_{13} + B^e| = |\Delta_{13}| \pm B^e$, is also sensitive to the mass hierarchy pattern. As in the case for A^e , the difference in B^e between SK and a far detectors is found

$$B_{\text{peak}}^e(L = 653\text{km}) - B_{\text{peak}}^e(L = 295\text{km}) \simeq \mp 0.10, \quad (25a)$$

$$B_{\text{peak}}^e(L \sim 1000\text{km}) - B_{\text{peak}}^e(L = 295\text{km}) \simeq \mp 0.20, \quad (25b)$$

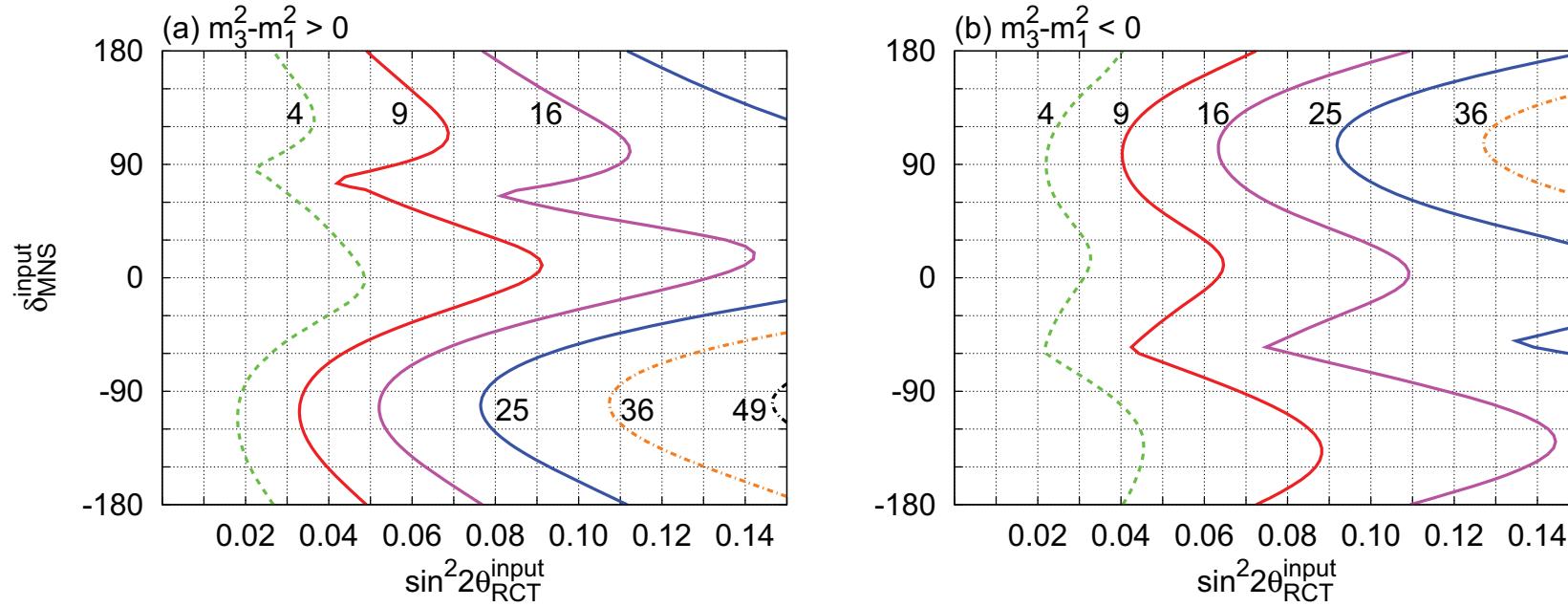


Figure 10: The $\Delta\chi^2_{\min}$ contour plot for the T2KO experiment to exclude the wrong mass hierarchy in the plane of $\sin^2 2\theta_{\text{RCT}}$ and δ_{MNS} . The left figure is for the normal hierarchy and the right one is for the inverted hierarchy. The OAB combination for both figures is 3.0° at SK and 1.4° at Oki Island with 2.5×10^{21} POT for both ν_μ and $\bar{\nu}_\mu$ focusing beams. Contours for $\Delta\chi^2_{\min} = 4, 9, 16, 25, 36, 49$ are shown. All the input parameters other than $\sin^2 2\theta_{\text{RCT}}$ and δ_{MNS} are shown in eqs. (28) and (29).

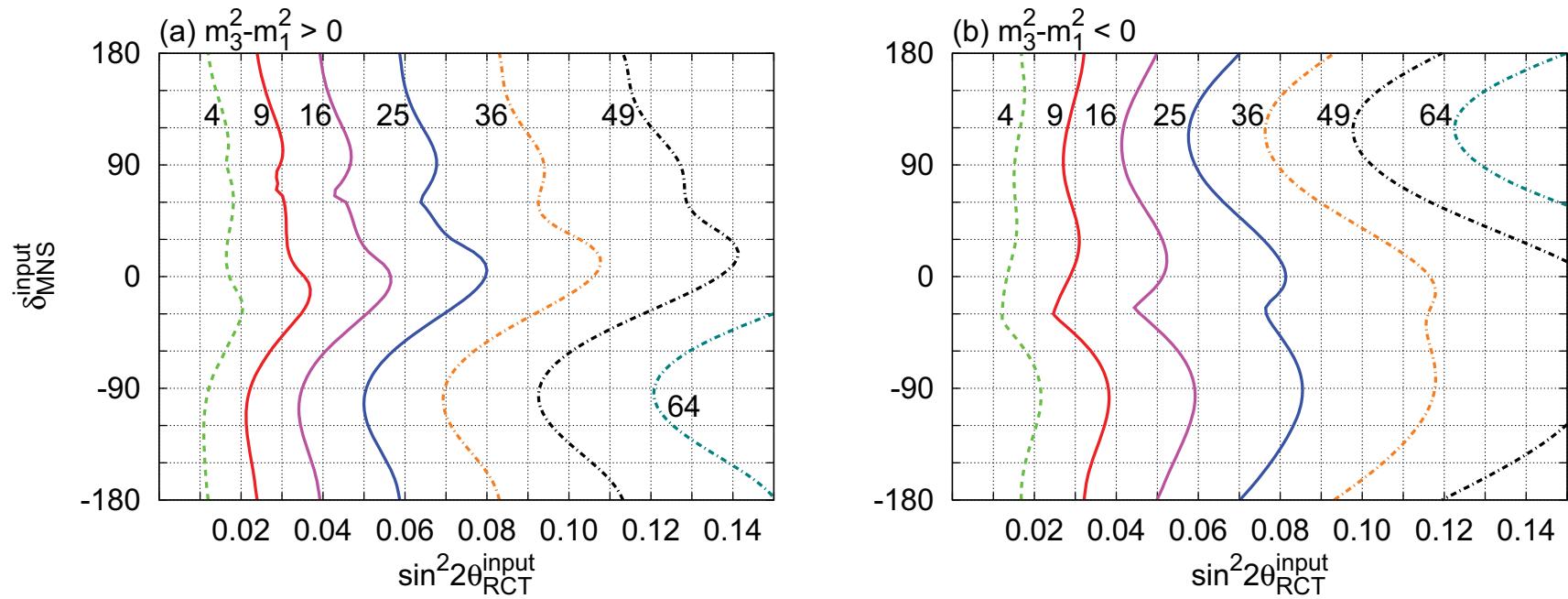


Figure 11: The same as Fig. 10, but for T2KK experiment with the optimum OAB combination, 3.0° OAB at SK and 0.5° OAB at $L = 1000\text{km}$. $\Delta\chi^2_{\min}$ values are given along the contours.

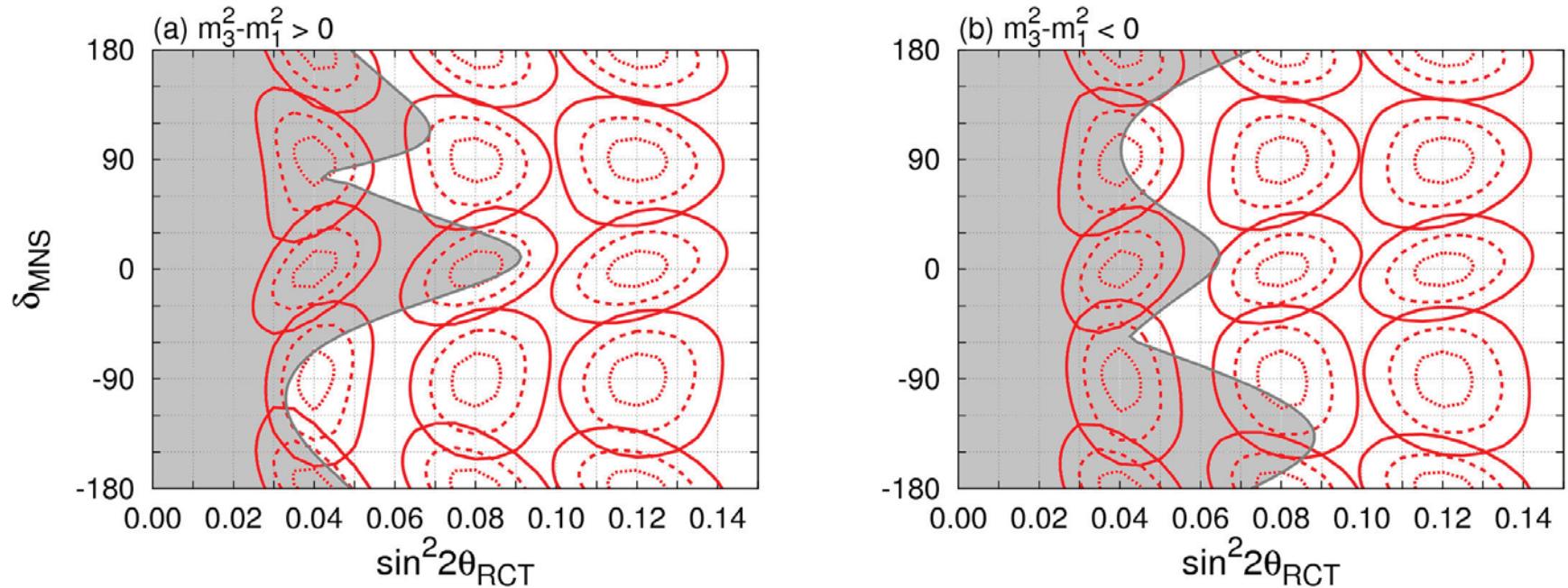


Figure 12: The $\Delta\chi^2$ contour plot for the T2KO experiment in the plane of $\sin^2 2\theta_{\text{RCT}}$ and δ_{MNS} when the mass hierarchy is assumed to be normal (left) or inverted (right). Allowed regions in the plane of $\sin^2 2\theta_{\text{RCT}}$ and δ_{MNS} are shown for the combination of 3.0° OAB at SK and 1.4° at Oki Island with 2.5×10^{21} POT each for ν_μ and $\bar{\nu}_\mu$ focusing beams. The input values of $\sin^2 2\theta_{\text{RCT}}$ is 0.04, 0.08, and 0.12 and δ_{MNS} is 0° , 90° , 180° , and 270° . The other input parameters are given in eqs. (28) and (29). The dotted-lines, dashed-lines, and solid-lines show $\Delta\chi^2_{\min} = 1, 4$, and 9 respectively. The blue shaded region has “mirror” solutions for the wrong mass hierarchy giving $\Delta\chi^2_{\min} < 9$.

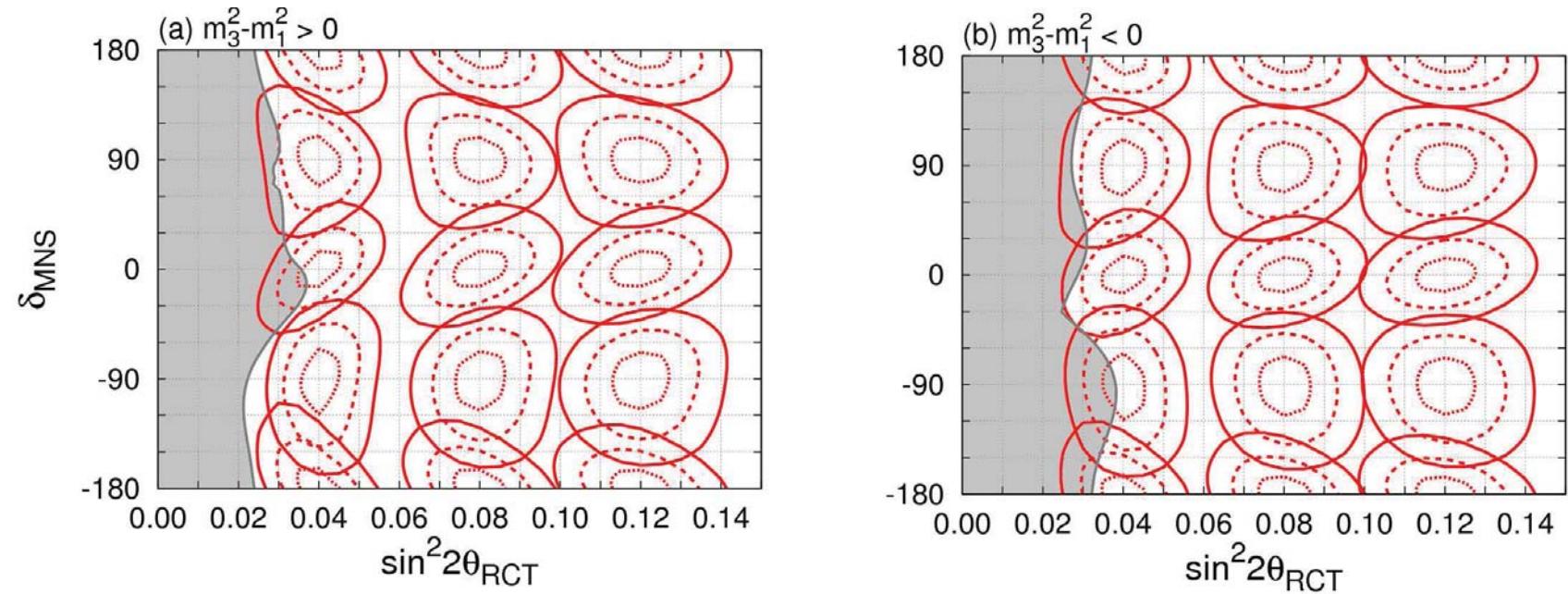


Figure 13: The same as Fig. 12, but for T2KK experiment with 3.0° OAB at SK and 0.5° OAB at $L = 1000\text{km}$.

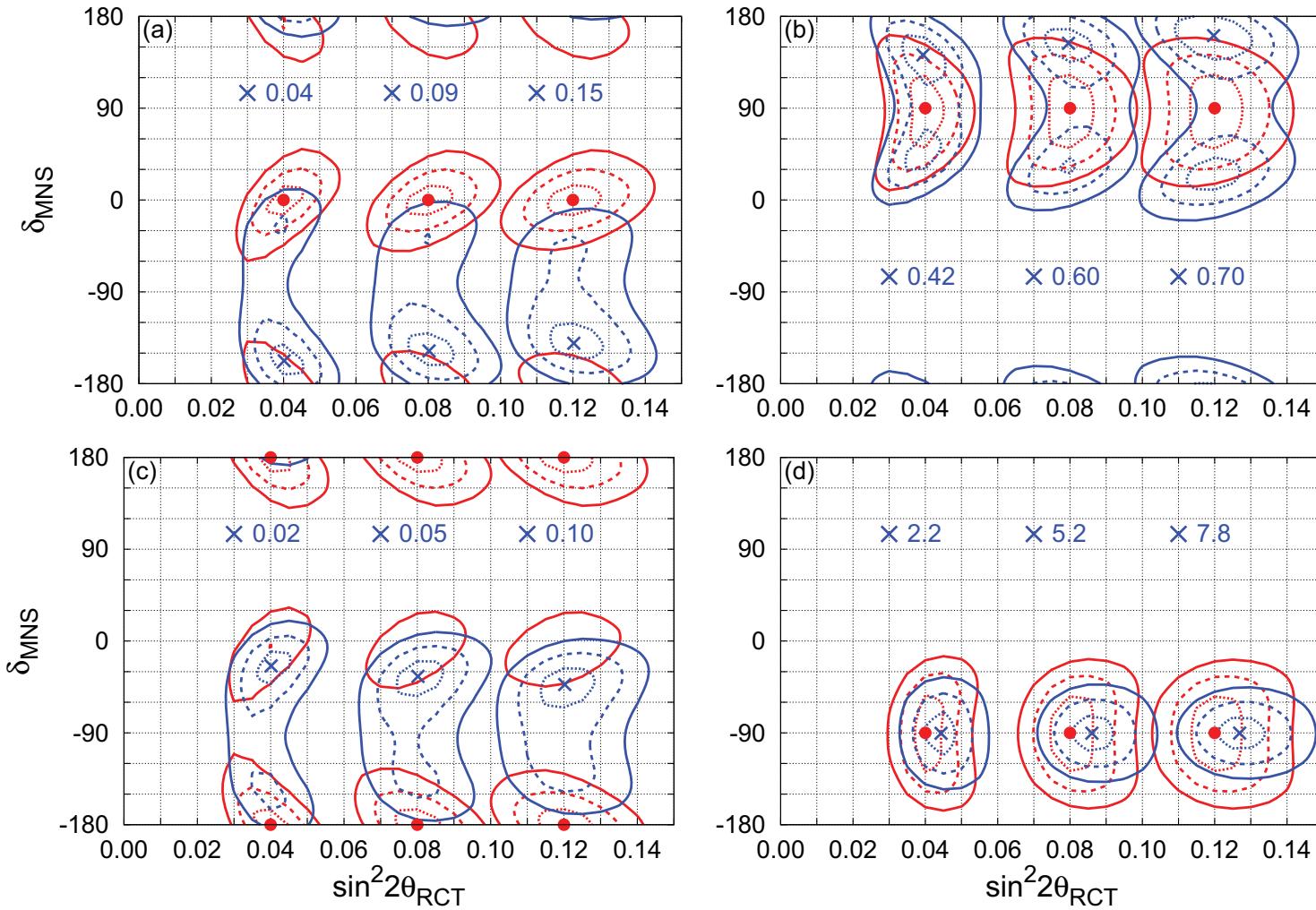


Figure 14: The $\Delta\chi^2_{\min}$ contour plot for the T2K₁₂₂ experiment in the plane of $\sin^2 2\theta_{\text{RCT}}$ and δ_{MNS} when the mass hierarchy is assumed to be normal ($m_3^2 - m_1^2 > 0$). Allowed regions in the plane of $\sin^2 2\theta_{\text{RCT}}$ and δ_{MNS} are shown for experiments with 2.5×10^{21} POT each for ν_μ and $\bar{\nu}_\mu$ focusing beam at 3.0° off-axis angle. The input values of $\sin^2 2\theta_{\text{RCT}}$ are 0.04, 0.08, and 0.12 and δ_{MNS} are 0° (a), 90° (b), 180° (c), and 270° (d). The other input parameters are listed in eqs. (29) and (28). The red dotted-lines, dashed-lines, and solid-lines show $\Delta\chi^2_{\min} = 1, 4$, and 9 contours, respectively, when the right mass hierarchy is assumed in the fit, whereas the blue contours give $\Delta\chi^2_{\min}$ measured from the local minimum value (shown besides the \times symbol) at the cross point when the wrong hierarchy is assumed in the fit.

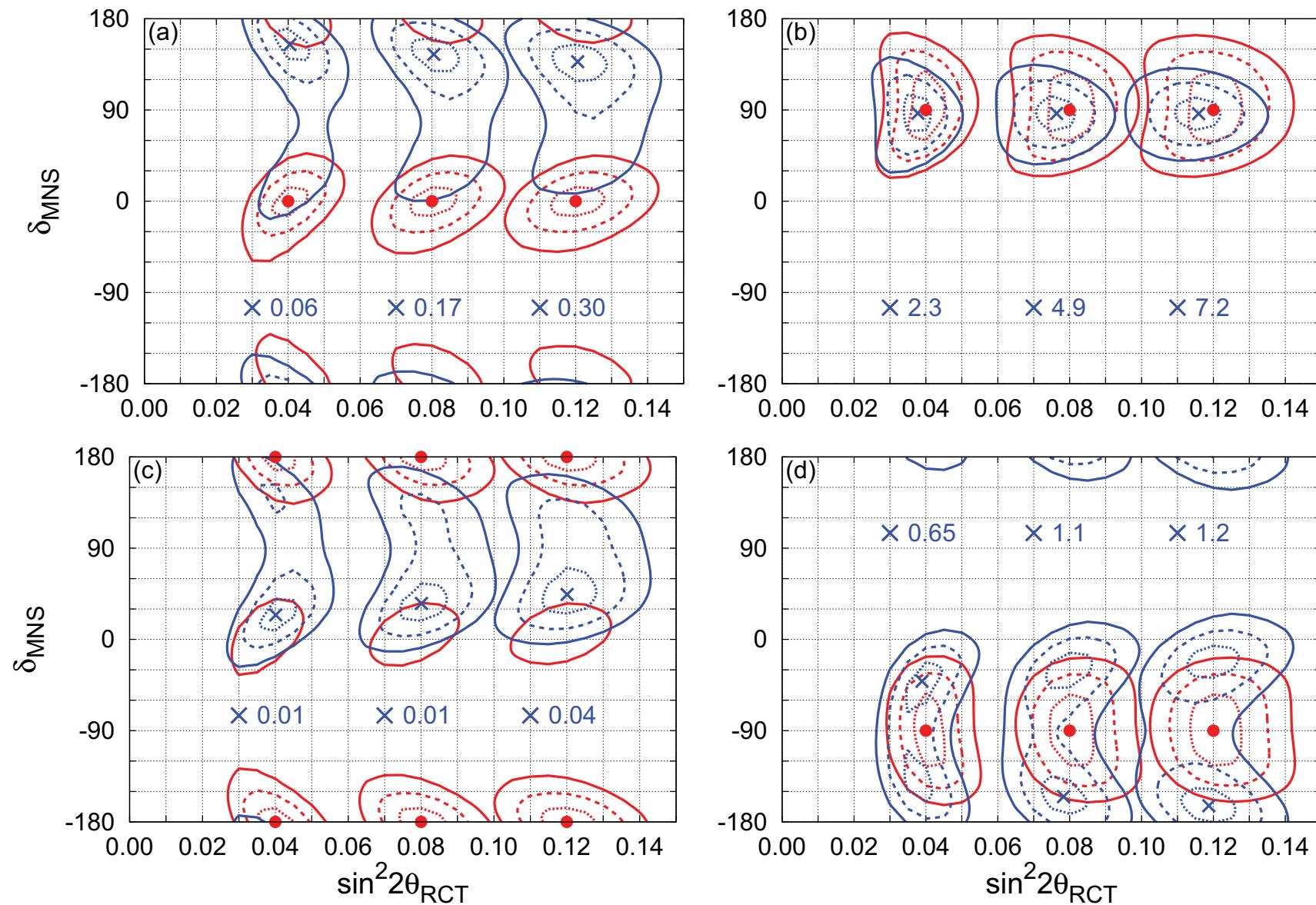


Figure 15: The same as Fig. 14, but for the inverted mass hierarchy ($m_3^2 - m_1^2 < 0$).

Summary

- Intermediate baseline reactor anti-neutrino oscillation experiments like Dayabay2 and RENO2 can
 - (1) determine the mass hierarchy
 - (2) measure $\sin^2 \theta_{12}$ and $m_2^2 - m_1^2$ very accurately with very fine energy resolution $dE/E < 0.03/\sqrt{E/\text{MeV}}$.
- T2K+Korea and/or Oki is a very cost effective one-beam two-detector LBL neutrino oscillation experiment, which can
 - (1) determine the mass hierarchy
 - (2) measure δ_{MNS}
 - (3) determine $\sin^2 \theta_{23} > 0.5$ or $\sin^2 \theta_{23} < 0.5$