Mass hierarchy sensitivity of medium baseline reactor neutrino experiments with multiple detectors Postprint

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Abstract

We report the neutrino mass hierarchy (MH) sensitivity of medium baseline reactor neutrino experiments with multiple detectors. Sensitivity of determining the MH can be significantly improved by adding a near detector and combining both the near and far detectors. The size of the sensitivity improvement is related to accuracy of the individual mass-splitting measurements and requires strict control on the relative energy scale uncertainty of the near and far detectors. We study the impact of both baseline and target mass of the near detector on the combined sensitivity. A figure-of-merit is defined to optimize the baseline and target mass of the near detector and the optimal selections are 13 km and 4 kton respectively for a far detector with the 20 kton target mass and 52.5 km baseline. As typical examples of future medium baseline reactor neutrino experiments, the optimal location and target mass of the near detector are selected for JUNO and RENO-50. Finally, we discuss distinct effects of the neutrino spectrum uncertainty for setups of a single detector and double detectors, which indicate that the spectrum uncertainty can be well constrained in the presence of the near detector.

Full Text

Preamble

Mass Hierarchy Sensitivity of Medium Baseline Reactor Neutrino Experiments with Multiple Detectors

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We report the neutrino mass hierarchy (MH) sensitivity of medium baseline reactor neutrino experiments with multiple detectors. Sensitivity for determining the MH can be significantly improved by adding a near detector and combining data from both near and far detectors. The magnitude of this improvement depends on the accuracy of individual mass-splitting measurements and requires strict control of the relative energy scale uncertainty between the near and far detectors. We study the impact of both baseline and target mass of the near detector on the combined sensitivity. A figure-of-merit is defined to optimize the baseline and target mass of the near detector, yielding optimal selections of approximately 13 km and approximately 4 kton respectively for a far detector with 20 kton target mass and 52.5 km baseline. As typical examples of future medium baseline reactor neutrino experiments, optimal locations and target masses are selected for JUNO and RENO-50. Finally, we discuss distinct effects of neutrino spectrum uncertainty for single-detector and double-detector setups, showing that spectrum uncertainty can be well constrained when a near detector is present.

Introduction

Medium baseline reactor neutrino experiments can determine the neutrino mass hierarchy (MH) by precisely measuring the fine structure of the neutrino energy spectrum from reactors [1–5]. Reactor and accelerator neutrino experiments measured an unexpectedly large value of the neutrino mixing angle in 2012 [6–10], implying that MH determination is feasible within the next one or two decades using next-generation neutrino oscillation experiments. Experiments using accelerator neutrinos with ~1000 km baseline [11], atmospheric neutrinos sensitive to the 1-20 GeV energy range [12, 13], and reactor neutrinos at medium baseline ~50 km have been proposed to determine the neutrino MH [14–17]. Among these possibilities, medium baseline reactor neutrino experiments such as JUNO (Jiangmen Underground Neutrino Observatory) [18–20] and RENO-50 [21–24] have the potential to determine the neutrino MH using large liquid scintillator detectors (~20 kton) with unprecedented energy resolution.

Key requirements for MH determination in reactor neutrino experiments are powerful nuclear power plants (NPPs), large detector mass, and good energy resolution. Sensitivity studies at JUNO show that a 20 kton detector E_vis(MeV) is mandatory with energy resolution of 3%/ to achieve significance better than 3 after 6 years of running [18]. Several ideas have been proposed to improve MH sensitivity of reactor neutrino experiments, including combining mass splitting measurements from accelerator neutrino experiments [18], synergy between different MH probes in reactor and atmospheric neutrino oscillation experiments [25], and using two identical half-size detectors at near and far sites [26, 27].

In this work, we discuss MH sensitivity improvement using near detector (ND) and far detector (FD) configurations in medium baseline reactor neutrino experiments. A figure-of-merit considering both sensitivity and experimental cost is defined to optimize the baseline and target mass of the ND. For a fixed total mass of ND and FD, the distribution of target mass between ND and FD and the ND baseline can be optimized. The optimization is applied to realistic reactor core distributions for JUNO and RENO-50. Finally, we discuss distinct effects of neutrino spectrum uncertainty for single-detector and double-detector setups.

The remainder of this work is organized as follows. Section 2 introduces the analysis method for MH sensitivity in medium baseline reactor neutrino experiments. Section 3 addresses sensitivity improvement with an ND, and Section 4 optimizes the ND baseline and target mass. Section 5 discusses the impact of energy spectrum shape uncertainty, and Section 6 concludes.

Analysis Method

Before considering MH sensitivity improvement with an ND, we first calculate sensitivity for a single detector at medium baseline. We adopt experimental parameters similar to JUNO: a 20 kton liquid scintillator detector, 52.5 km baseline, 36 GW_th reactor thermal power, 3%/ E_vis(MeV) energy resolution, and six years of data taking. Default neutrino oscillation parameters are taken as m^2, $\sin^2 2$ = m^2 = (m^2 = (7.53±0.18)×10 eV^2)/2 = 2.48 × 10 ^{3} eV^2 + m^2 (9.3 ± 0.8) × 10 ^{2}, and $\sin^2$ = 0.846 ± 0.021 [28]. A parameterized reactor neutrino flux model from Ref. [29] predicts the neutrino energy spectrum for inverse beta decay reactions in the detector. To fully explore the fine structure, the spectrum is divided into 200 equal-size bins between 1.8 MeV and 8.0 MeV. The neutrino event rate at the detector is calculated to be ~60/day assuming 80% detection efficiency, consistent with JUNO expectations in Ref. [18].

The least squares method is used for neutrino energy spectrum fitting, with a standard ^{2} function incorporating proper nuisance parameters and penalty terms:

i (1 + ϱ_R + r w_rϱ_r + ϱ_d + ϱ_i)]^2

where d is the detector index, i denotes the bin number, M is the measured spectrum, T is the predicted spectrum, ϱ’ s with different indexes are nuisance parameters corresponding to different systematic uncertainties, and ’ s with different indexes are standard deviations assuming Gaussian systematic uncertainties [30]. Systematic uncertainties include correlated (absolute) reactor uncertainty (_R = 2%), uncorrelated (relative) reactor uncertainty (_r = 0.8%), spectrum shape uncertainty (_s = 1%), and detector-related uncertainty (_d = 1%).

Variations of $\sin^2$ and m^2 within allowed ranges have negligible effects on the best-fit ^{2} value. Precise measurement of $\sin^2$ with 3% uncertainty is expected from Daya Bay after 2017, inducing variation ~0.2 in the best-fit ^{2} value. For fast ^{2} minimization, we fix all mixing angles and mass splittings except m^2. Thus ^{2} is a function of m^2, and the best-fit value ^{2}_min is obtained by scanning m^2.

The MH discriminator is obtained using both normal hierarchy (NH) and inverted hierarchy (IH) models to fit the simulated neutrino spectrum generated by the NH model: min(NH) − ^{2}_min(IH)|. Simulation studies assuming IH as the true model yield consistent conclusions with NH assumptions. Below we illustrate results for the NH model.

For the default single-detector case like JUNO, MH sensitivity is found to be $^2 \sim$ 16.3, consistent with Ref. [18] without considering real reactor core distribution.

Sensitivity Improvement Due to Near Detector

We now add an ND and calculate combined MH sensitivity by incorporating the ND neutrino energy spectrum information into Eq. (1). A common set of oscillation parameters is used for spectrum predictions of both ND and FD.

To illustrate sensitivity improvement, we assume an ND with 10 kton target mass and 30 km baseline as an initial choice. The dot-dashed, solid, and dashed lines in Fig. 1 [Figure 1: see original paper] show ^{2} as functions of m^2. True NH is assumed to generate the experimental energy spectrum, and black lines show ^{2} values using the NH model to fit the spectrum. Therefore, best-fit (minimal) ^{2} values for the NH case are 0. Conversely, best-fit ^{2} values for the IH case equal the MH discriminator defined in Eq. 2, which are 26.8, 3.7, and 16.3 respectively. Comparing different ND and FD combinations, we have ^{2}_com,min > ^{2}_2,min, demonstrating MH sensitivity improvement by combining near and far detectors, where ^{2}_com,min, ^{2}_1,min, and ^{2}_2,min represent sensitivities for combined, ND-only, and FD-only scenarios.

This improvement can be explained as follows. Using standard least squares, the ^{2} distribution is approximately parabolic and can be expressed as:

^{2} ^{2}_min + (x - x_best)^2/ ^{2}

where x denotes variable m^2, x_best and represent the best-fit value and uncertainty of m^2, and ^{2}_min is the minimal ^{2} value. We use ^{2}_i (i=1,2) to represent ^{2} functions for ND and FD respectively. The combined ^{2} can be approximated as ^{2}_com ^{2}_1 + ^{2}_2 when statistical uncertainty dominates. The combined best-fit value of m^2 can be expressed analytically as:

x_com,best (x_1,best ^{2}_2 + x_2,best ^{2}_1)/(^{2}_1 + ^{2}_2)

The corresponding best-fit value of the combined measurement is used as input to Eq. 5 to calculate combined sensitivity ^{2}_com. Alternatively, we can directly calculate combined sensitivity by fitting Eq. 1 with inputs from both ND and FD. As shown in Fig. 3 [Figure 3: see original paper], these two approaches yield consistent results, confirming Eq. 5 as a good approximation for combined sensitivity. The optimal baseline to maximize MH sensitivity for a 10 kton ND is around 15 km.

We have neglected possible detector systematic uncertainties in this study. As seen from Eq. 5, sensitivity improvement from ^{2}_ext depends on uncertainties in mass-splitting measurements for both ND and FD. In our case, and are dominated by statistical uncertainties. The relative difference between two best-fit mass-splitting values (x ,best - x ,best) is about 0.7%. Consequently, mass-splitting uncertainty at the 1% level would largely reduce ^{2}_ext. However, only uncorrelated uncertainties in mass-splitting measurements contribute to the best-fit difference, while correlated uncertainties cancel out. The main systematic uncertainties for mass-splitting measurement are energy scale uncertainties. MH sensitivity improvement requires strict control of relative energy scale uncertainties, e.g., below the 0.5% level.

Optimization of Target Mass and Baseline

The best-fit value and uncertainty of m^2 as a function of baseline for the ND are shown in Fig. 2 [Figure 2: see original paper]. For a single-detector experiment like JUNO [18], the baseline was optimized at ~52.5 km for MH determination. Sensitivity ^{2} is approximately proportional to target mass, but target mass is constrained by technical challenges and experimental cost, with current selection at 20 kton. Using an ND in combination with the FD can reduce requirements for FD target mass. Proper selection of ND target mass and baseline can improve MH sensitivity even when total target mass of ND and FD remains at 20 kton.

In optimizing ND target mass and baseline, we first fix FD target mass and baseline, making ^{2}_2,min, x_2,best, and fixed in Eq. 5. Given an ND target mass, x ,best and ^{2}_ext are functions of baseline, and an optimal baseline can be obtained by maximizing combined sensitivity ^{2}_com. At the optimal ND baseline, larger target mass always increases MH sensitivity due to improved ND statistics. However, larger target mass increases cost and technical challenges. We therefore propose a figure-of-merit:

F = ^{2}_com/(M + M)

where M and M are target masses of ND and FD respectively, and F represents optimal sensitivity per unit target mass. Given a total target mass, the target mass ratio between ND and FD can be optimized by maximizing F. Current JUNO and RENO-50 proposals are special cases with M = 0, where F is nearly constant because ^{2} is approximately proportional to target mass when statistics dominate.

We first study optimization in an ideal case without real reactor core distribution, then examine realistic reactor core distributions for JUNO and RENO-50, providing optimal ND locations and target masses.

Ideal Case

We consider an ideal case with single baseline from reactor to detector. Similar to JUNO, we assume total reactor thermal power of 36 GW and fix FD baseline at 52.5 km. For a single-detector configuration, figure-of-merit is F   16.3/20   0.815, nearly constant when detector target mass varies.

FD target mass is set to typical values of 10 kton, 20 kton, 30 kton, and 40 kton. Given an FD target mass, we vary ND target mass and baseline and calculate figure-of-merit F for optimization. Results are shown in Fig. 4 [Figure 4: see original paper], where over a large parameter space of ND target mass and baseline, MH sensitivity improves compared to single-detector configuration. When baseline is too small, the double-detector configuration can be worse than single-detector because ^{2}_1,min   0 and ^{2}_ext,min cannot compensate for adding equivalent target mass at the FD. The optimal target mass is ~4 kton and baseline ~13 km for a 20 kton FD.

Contours in Fig. 4 show that optimal baseline lies in the 10–15 km region, approximately independent of FD target mass. However, optimal ND target mass depends on FD target mass.

Fixing ND baseline at 13 km and varying the ND-to-FD target mass ratio for different total target masses yields Fig. 5 [Figure 5: see original paper]. The optimal ND target mass changes with FD target mass, but the target mass ratio M /M remains relatively stable at ~0.2.

JUNO

In realistic cases, multiple reactor cores exist in one NPP with non-identical baselines to the detector. This baseline difference reduces MH determination sensitivity [18]. We study MH sensitivity improvement from an ND for JUNO, optimizing ND baseline and target mass.

Ten reactor cores exist in Yangjiang and Taishan NPPs for JUNO. We adopt baseline and power setups from [18] for MH sensitivity calculations, obtaining $^2 = 11.6$ for JUNO with realistic reactor core distribution, compared to $^2 = 16.3$ for the ideal identical-baseline case. Thus F   11.6/20   0.58 for the current JUNO far detector.

The distance between Yangjiang and Taishan NPPs is 77 km, making it impossible to position one ND at 10–20 km baseline from both. We consider separate NDs for Yangjiang and Taishan. For Yangjiang NPP, no suitable ND location exists as the possible position would be in the sea along the perpendicular line to six reactor cores. Therefore we only consider an ND for Taishan NPP. Locations of the planned four reactor cores in Taishan are identified using Google Earth maps. We seek a location with nearly equal baselines to all four reactor cores, with actual baseline differences around 0.01 km. Figure-of-merit F combining the current JUNO detector with a 4 kton ND is shown in Fig. 6 [Figure 6: see original paper]. For comparison, figure-of-merit is F   0.58 for the current

JUNO FD. In Fig. 6, F becomes smaller than 0.58 as ND baseline increases due to interference from Yangjiang NPP to the ND. This effect disappears for RENO-50 because only one NPP is considered.

In conclusion, an ND with 11 km baseline and 4 kton target mass can improve MH sensitivity by ^{2} = 6.62, while adding 24 kton target mass at the current JUNO site only improves sensitivity by 2.32.

RENO-50

We study MH sensitivity improvement from an ND for RENO-50. RENO-50 plans to build an 18 kton detector at Mt. GuemSeong with ~47 km baseline from the Hanbit NPP at YongGwang with total thermal power 16.5 GW, assuming 3%/ E__vis(MeV) energy resolution [22]. We calculate MH sensitivity for RENO-50, finding ^{2} 6.87 for six years of data taking, implying >3 significance can be obtained from ~10 years of data, consistent with Ref. [24]. The figure-of-merit is F 6.87/18 0.38 for RENO-50. The difference in figure-of-merit between JUNO and RENO-50 is mainly due to reactor power.

Adding a 4 kton ND, we calculate F as a function of ND baseline as shown in Fig. 7 [Figure 7: see original paper]. In ND site selection, we minimize baseline differences to reactor cores, with actual baseline differences ~0.018 km for the candidate site.

Impact of the Energy Spectrum Shape Uncertainty

The observed event excess at ~5 MeV [31–33] and recent re-evaluations of reactor neutrino flux indicate that reactor energy spectrum shape uncertainty may be underestimated [34–36], potentially reaching 4% or larger. Therefore, investigating reactor shape uncertainty effects in double-detector configurations is important.

As shape uncertainty changes, the m^2 uncertainty in the ND shown in Fig. 2 changes accordingly, affecting ND baseline optimization. Following the same FD setup as Sec. IV-A, we fix ND target mass at 10 kton and study the relationship between optimal ND baseline and reactor shape uncertainty, shown in Fig. 8 [Figure 8: see original paper]. The top panel shows ^{2} as a function of baseline for different reactor shape uncertainties, while the bottom panel shows optimal ND baseline versus reactor shape uncertainty. Optimal baseline varies between 8–20 km, increasing with larger shape uncertainty.

Another way to demonstrate MH sensitivity improvement from the ND is through near-far relative measurement. With larger reactor shape uncertainty for the FD, precise reactor spectrum measurement from the ND can constrain shape uncertainty. For comparison, we consider a 10 kton near detector at 13 km and a 20 kton far detector at 52.5 km baseline for the double-detector configuration, versus a 30 kton detector at 52.5 km baseline for the single-detector configuration. MH sensitivity versus reactor shape uncertainty is shown in Fig.

9 [Figure 9: see original paper]. The solid line shows single-detector sensitivity, and the dashed line shows double-detector sensitivity. As shape uncertainty increases, ^{2} for the single-detector configuration decreases rapidly, while ^{2} for the double-detector configuration first decreases then stabilizes. Fig. 9 shows that single-detector MH sensitivity with 1% (2%) shape uncertainty approximates double-detector sensitivity with 2.1% (4.2%) shape uncertainty for the same total target mass. As shape uncertainty approaches infinity, ^{2} for the single-detector configuration approaches zero and no information can be extracted from the energy spectrum. However, due to ND constraints, the double-detector configuration can determine MH with high sensitivity.

Conclusion

In this work we have studied MH sensitivity of medium baseline reactor neutrino experiments with multiple detectors. Sensitivity can be improved by combining near and far detectors but requires strict control of relative energy scale uncertainties. A figure-of-merit is constructed to optimize ND baseline and target mass. Results are presented for an ideal case with identical baseline and for realistic JUNO and RENO-50 cases. Additionally, due to ND constraints on neutrino energy spectrum measurement, the double-detector configuration can reduce the impact of shape uncertainty from reactor neutrino flux predictions.

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Note: Figure translations are in progress. See original paper for figures.