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# JUNO's prospects for determining the neutrino mass ordering

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The flagship measurement of the JUNO experiment is the determination of the neutrino mass ordering. Here we revisit the prospects of the JUNO experiment to make this determination by 2030, using the current global knowledge of the relevant neutrino parameters as well as current information on the reactor configuration and the critical parameters of the JUNO detector. We pay particular attention to the non-linear detector energy response.

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## 1. Introduction

Many of the neutrino oscillation parameters are measured with good precision today. There is, nevertheless, an important open question that influences the better determination of some of these parameters: what is the neutrino mass ordering?

From the combined analysis of current data, one finds that there is a small preference at $\sim 2.5\sigma$ confidence level (C.L.) for normal ordering, see Ref. [1]. However, this preference arises from several tensions appearing in the different data sets, in particular the measurements of $\delta$ in T2K and NOvA for normal ordering, or the measurements of $\Delta m^2_{31}$ in reactor and accelerator experiments for inverted ordering. There is yet to be an experiment which could measure the mass ordering on its own.

The use of $\bar{\nu}_e$ from nuclear reactors with a medium-baseline detector to determine the mass ordering, exploring genuine three generation effects as long as $\sin^2\theta_{13} \gtrsim$ few %, was first proposed in [2]. This idea was further investigated in [3] for a general experiment and more recently in [4]. The Jiangmen Underground Neutrino Observatory (JUNO) [5], a 20 kton liquid scintillator detector located in the Guangdong Province at about 53 km from the Yangjiang and Taishan nuclear power plants in China, will be the first experiment to implement this idea. JUNO aims in the first few years to measure $\Delta m^2_{21}$, $\sin^2\theta_{12}$ and $|\Delta m^2_{ee}|$ with a precision $\lesssim 1\%$ to be finally able, after approximately 8 years, to determine the neutrino mass ordering at $3\sigma$ confidence level (C.L.). One can appreciate the difficulty in establishing the mass ordering with this setup by noticing that after 8 years (2400

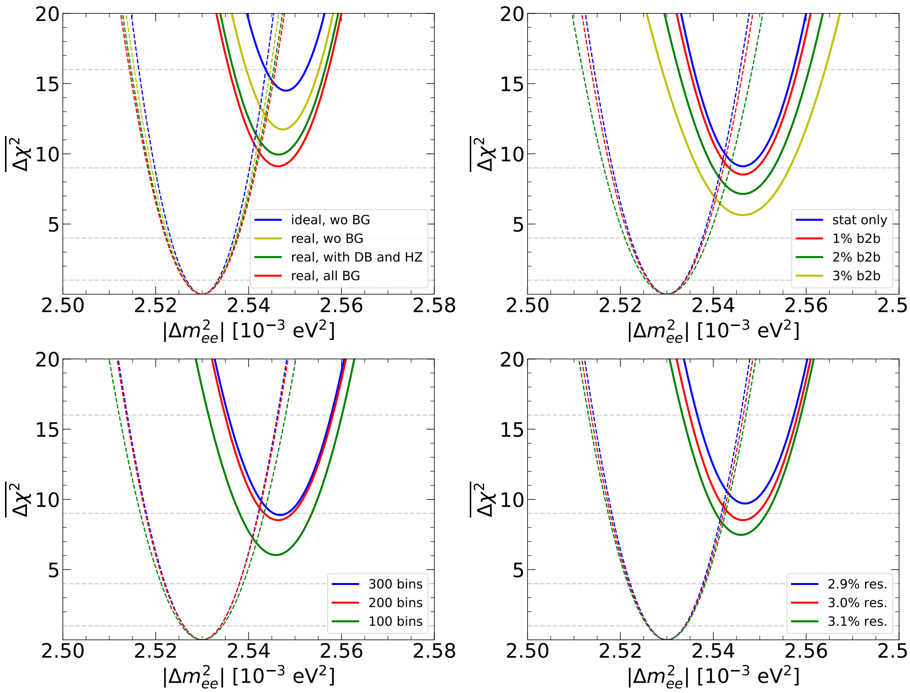


**Figure 1:** The effects of the real reactor core-detector baseline distribution as well as of the two types of backgrounds: from the distant reactors Daya Bay (DB) and Huizhou (HZ) as well as from other sources (accidental, cosmogenic, etc.). Also shown are the effects of varying the number of bins, the energy resolution and the flux shape uncertainty.

days) of data taking, the difference in the number of events for normal ordering (NO) and inverted ordering (IO) is only a few tens of events per energy bin which is smaller than the statistical uncertainty in each bin. We quantify the sensitivity to measure the mass ordering at JUNO taking into account most up-to-date experiment descriptions and knowledge on the neutrino oscillation parameters. The results presented here are based on Ref. [6].

## 2. Experimental parameters

We first estimate the sensitivity taking into account several of the experimental parameters. Going from an idealized configuration with all reactors at the same distance to the detector to the real distribution, as well as adding background contributions has an important effect on the measurement as indicated in the upper left panel of Fig. 1. In the figure we also indicate the effect of varying the energy resolution (lower right panel), the number of bins (lower left panel), and the effect of the flux-shape uncertainty (upper right panel). The simulation of JUNO follows the discussion presented in Refs. [5, 7, 8]. From here on we use the configuration with 200 bins, a 3% energy resolution and a flux shape uncertainty of 1%.

## 3. Oscillation parameters

The true value of neutrino oscillation parameters also has an important effect on the sensitivity. In Fig. 2 we show the correlated variation of the $\overline{\chi^2}_{\rm min}$[IO] as a function of ($\sin^2\theta_{12}$, $\Delta m^2_{21}$) holding ($\sin^2\theta_{13}$, $\Delta m^2_{ee}$) fixed as well as a function of ($\sin^2\theta_{13}$, $\Delta m^2_{ee}$) holding ($\sin^2\theta_{12}$, $\Delta m^2_{21}$) fixed. Even varying these parameters within $3\sigma$ of their current best fit, there are very significant changes to the $\overline{\chi^2}_{\rm min}$[IO] contour plots. This implies that JUNO's prospect for the determination of the neutrino mass ordering could be improved or weakened by Nature's choice for the true values of these oscillation parameters. The values that were used in Ref. [5] are shown by the gray stars

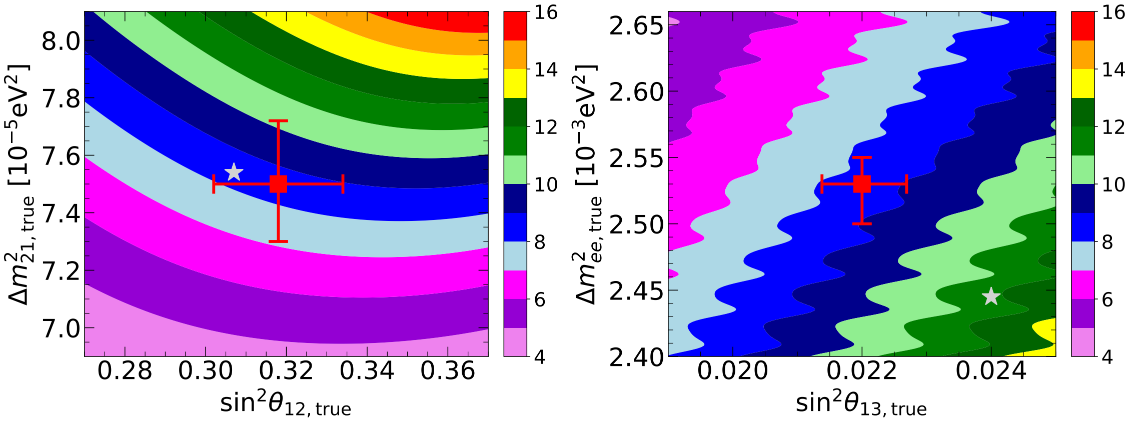


**Figure 2:** Contours of $\overline{\chi^2}_{\rm min}$[IO] as the oscillation parameters are varied: left panel varying ($\sin^2\theta_{12}$, $\Delta m^2_{21}$) holding ($\sin^2\theta_{13}$, $\Delta m^2_{ee}$) fixed at their best fit values, right panel varying ($\sin^2\theta_{13}$, $\Delta m^2_{ee}$) holding ($\sin^2\theta_{12}$, $\Delta m^2_{21}$) fixed at their best fit values. The red cross is the current best fit point whereas the gray star is the value of the parameters used in [5].

in these figures. Note that our results, in this subsection, are in good agreement with the result obtained in Ref. [9], where a similar analysis has been performed.

## 4. Monte Carlo analysis

Next, we consider the effects of fluctuating the number of events in each bin. We evaluate the impact of this fluctuations on the mass ordering determination by performing a simulation of 60000 JUNO pseudo-experiments for each exposure and obtain the distributions given in Fig. 3. To generate this figure, we create a fake data set $\{N_i^0, i = 1, \ldots, N_{\text{bins}}\}$ using the neutrino oscillation parameters from Ref. [1]. The fluctuated spectrum $\{N_i^f, i = 1, \ldots, N_{\text{bins}}\}$ is generated by creating normal distributed random values around $N_i^0 \pm \sqrt{N_i^0}$. We analyze this fluctuated spectrum for NO and IO and add the corresponding $\Delta\chi^2 \equiv \chi^2_{\text{min}}[\text{IO}] - \chi^2_{\text{min}}[\text{NO}]$ value to a histogram. The corresponding $\Delta\chi^2$ distributions are shown in the left panel of Fig. 3 for 4, 8 and 16 years of exposure. These distributions are Gaussian with corresponding central values $\Delta\chi^2 = 3.4, 6.7$ and 12.4 and standard deviations 3.4, 4.7 and 6.1, respectively. Our pseudo-experiments reveal that after 8 years in only 31% of the trials JUNO can determine the neutrino mass ordering at the level of $3\sigma$ C.L. or better. We also find that there is even a non negligible probability (~8%) to obtain the wrong mass ordering, *i.e.,* $\Delta\chi^2 < 0$. For a shorter (longer) exposure of 4 (16) years, 5% (71%) of the pseudo-experiments rule out IO at $3\sigma$ or more. In these cases in about 16% (2%) of the trials the IO is preferred.

As was shown in [10], muon disappearance experiments measure $\Delta m^2_{\mu\mu} \equiv \sin^2\theta_{12}\Delta m^2_{31} + \cos^2\theta_{12}\Delta m^2_{32}$, whose relationship to $|\Delta m^2_{ee}|$ is given by $|\Delta m^2_{ee}| = |\Delta m^2_{\mu\mu}| \pm \cos 2\theta_{12}\Delta m^2_{21}$, where the positive (negative) sign is for NO (IO). Therefore, by using muon disappearance measurements we have a constraint on the allowed $|\Delta m^2_{ee}|$'s for the two mass orderings, $|\Delta m^2_{ee}|\,[\text{NO}] - |\Delta m^2_{ee}|\,[\text{IO}] = 2\cos 2\theta_{12}\Delta m^2_{21} \approx 0.06 \times 10^{-3}\,\text{eV}^2$, i.e. $|\Delta m^2_{ee}|\,[\text{IO}]$ is 2.4% *smaller* than $|\Delta m^2_{ee}|\,[\text{NO}]$. Of course, the measurement uncertainty on $|\Delta m^2_{\mu\mu}|$ must be smaller than this 3.1% difference for this measurement to impact the confidence level at which the false mass ordering is eliminated.

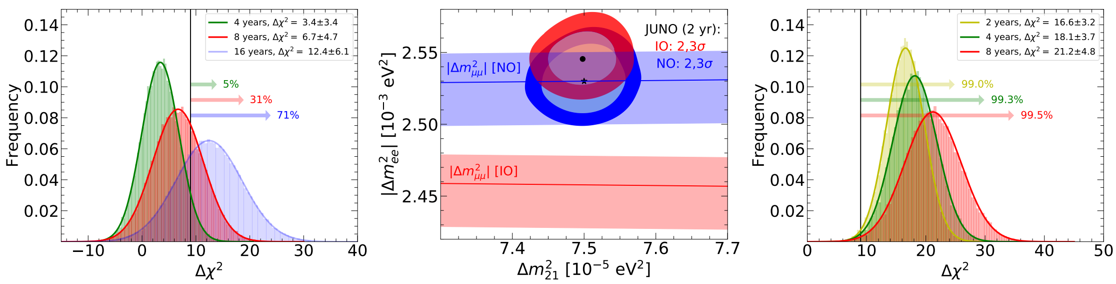


**Figure 3:** Left: Distributions of the $\Delta\chi^2 \equiv \chi^2_{\text{min}}[\text{IO}] - \chi^2_{\text{min}}[\text{NO}]$ values obtained in the analyses of 60 k trial pseudo-experiments where statistical fluctuations of the trial data have been taken into account for three different exposures: 4 (green), 8 (red) and 16 (blue) years. Center: The ellipses are the allowed regions for JUNO in the $\Delta m^2_{21}$ versus $|\Delta m^2_{ee}|$ plane for NO and IO after 2 years. The best fit for NO (IO) is depicted by a black star (dot). We also show, as red (for IO) and blue (for NO) bands, the $1\sigma$ CL allowed regions by the current global fit constraint on $|\Delta m^2_{\mu\mu}|$. Right: As in the left panel, but for 2, 4 and 8 years of exposure at JUNO, and in combination with the results from the current global analysis of neutrino oscillation data.

The short baseline reactor experiments, Daya Bay and RENO, measure the same $|\Delta m^2_{ee}|$ for both orderings with uncertainties much larger than JUNO's uncertainty. This physics is illustrated in the central panel of Fig. 3 where we show the allowed region in the plane $\Delta m^2_{21}$ versus $|\Delta m^2_{ee}|$ by JUNO for NO (blue) and IO (red) after 2 years of data taking and the corresponding $1\sigma$ CL allowed region by the current global fit constraint on $|\Delta m^2_{\mu\mu}|$. We see that the global fit and JUNO NO regions overlap while the corresponding IO regions do not. This tension between the position of the best fit values of $|\Delta m^2_{ee}|$ for IO with respect to NO gives extra leverage to the data combination. Therefore, combining JUNO's measurement of $|\Delta m^2_{ee}|$ with other experiments, in particular T2K and NOvA, expressed by the current global fit turns out to be very powerful in unraveling the neutrino mass ordering at a high confidence level. As a result with only two years of JUNO data taking the mass ordering is determined at better than $3\sigma$ in 99% of the trials, see right panel of Fig. 3. Of course, the actual value of $\overline{\chi^2}_{\rm min}[\rm IO]$ will depend on the value of $|\Delta m^2_{ee}|$ measured by JUNO and the updates of the other experiments used in the global fit.

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